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2018

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Permanent link: https://doi.org/10.4095/313307

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Recommended citation
Stockmal, G.S., 2018. A comprehensive review and reappraisal of the Howell Creek structure: indication of multiple extension events in the southern Canadian Rocky Mountains, southeastern British Columbia and southwestern Alberta; Geological Survey of Canada, Open File 8504, 81 p. https://doi.org/10.4095/313307

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ABSTRACT

The Howell Creek structure was first mapped 60 years ago as a structural window (fenster) through the Lewis Thrust, where Upper Cretaceous foreland basin strata are bounded on all sides by Mesoproterozoic through Triassic platformal strata. Later interpretations ranged from the involvement of cryptic thrust and normal faults to a coherent gravitational slide. None of these, however, has adequately accounted for all available observations and constraints within the context of structural styles and physiography normally encountered in thin-skinned thrust-and-fold belts. Recent GIS map compilation required a reappraisal of these interpretations.

Rather than a structural window, the Howell Creek structure is interpreted to lie entirely within the Lewis Thrust sheet. The Howell Fault, which places Upper Cretaceous Alberta Group strata onto Mississippian to Triassic strata and bounds the Cretaceous exposures to the southeast, is considered to be a low-angle normal fault. It may have formed initially as a footwall cut-off, splaying from and merging structurally upward with a thrust fault (the Twentynine Mile Creek Fault) that bounds the Cretaceous exposures to the southwest. Much of the Twentynine Mile Creek Fault was reactivated as a normal fault prior to the well-known Oligocene normal fault motion on the large-offset Flathead Fault, which lies to the east and north of the Howell Creek structure. The Shepp Fault, which is antithetic to but closely associated with the Flathead Fault, truncates the Twentynine Mile Creek Fault north of the Howell Creek structure. The Twentynine Mile Creek Fault reappears north of the Flathead Fault as the Squaw Fault, which is also reinterpreted as a normal-sense-reactivated thrust fault, explaining unusual structures near Flathead Pass. The northwest boundary of the Cretaceous exposures in the Howell Creek structure is marked by the reinterpreted and newly named Fuel Creek Fault, which is a small-displacement down-to-the-southeast normal fault. It is probably contemporaneous with the larger Harvey Fault, which

bounds the Cretaceous exposures to the northeast and is a down-to-the-southwest normal fault related to the development of the Flathead half-graben.

Normal-sense motion on the Twentynine Mile Creek, Howell, and Squaw faults clearly predates the Flathead and Harvey faults, by virtue of high-angle cross-cutting relationships, and may also predate or even coincide with development of sub-Lewis Thrust contractional duplex structures. The age of the Flathead Fault is constrained by the Early to early Late Oligocene Kishenehn Formation that fills the half-graben above the fault. Isolated exposures of Kishenehn Formation lie within and immediately adjacent to the Howell Creek structure. Balanced structural reconstructions indicate erosion of a minimum of 1.5 km of Paleozoic and Mesozoic strata after initial normal-sense motion on the Twentynine Mile Creek and Howell faults, but prior to deposition of the Kishenehn Formation. Coupled with estimates of Oligocene and earlier erosion rates, this suggests that local normal-sense motion on the Twentynine Mile Creek, Howell, and Squaw faults could have occurred prior to the end of regional contractional deformation of the southern Canadian Rocky Mountains, perhaps developing above an active sub-Lewis Thrust duplex structure.

INTRODUCTION

The Howell Creek structure in the southeastern Canadian Cordillera (Figure 1) was first mapped and named by Price (1958), who recognized the unusual occurrence of Upper Cretaceous foreland basin strata structurally overlying Mississippian to Triassic platformal strata, but also structurally underlying Mesoproterozoic to Mississippian strata, all located approximately 20 km southwest of the principal trace of the regional east-directed Lewis Thrust. Described by Jones (1977) as “one of the most enigmatic features of the Canadian Rocky Mountains”, the structural inlier has been interpreted in profoundly different ways by a series of authors spanning over 50 years. A reappraisal of these interpretations was undertaken in conjunction with recent Geological Survey of Canada (GSC[1]) GIS map compilation (McMechan and Stockmal, 2015; Stockmal and Fallas, 2015; Stockmal and McMechan, 2015). This reappraisal has implications for the interpretation of associated nearby structures, such as the Squaw Creek structure approximately 20 km north of Howell Creek, as well as our understanding of the regional structural evolution of the southern Canadian Rocky Mountains, including the extent and timing of extensional deformation.

STRUCTURAL SETTING

The southeasternmost Canadian Cordillera is dominated by the Lewis Thrust, which at that latitude separates the Foothills belt to the east from the Rocky Mountains to the west (Bally et al, 1966; Figure 1). The thrust superimposes a thick succession of Mesoproterozoic rift-basin and Paleozoic platformal strata above closely imbricated Jurassic and Cretaceous foreland basin strata (figures 1 and 2). It is traceable along strike for approximately 440 km, from the vicinity of Steamboat Mountain, Montana (Mudge and Earhart, 1980), to the Kananaskis River Valley, Alberta (Price, 1965b; McMechan, 2012), 180 km north of the Howell Creek structure. At its leading edge, the Lewis Thrust has a displacement of approximately 55-60 km near the international border, as constrained by seismic

[1] All GSC products cited here are available for free download at the GEOSCAN website: geoscan.nrcan.gc.ca.

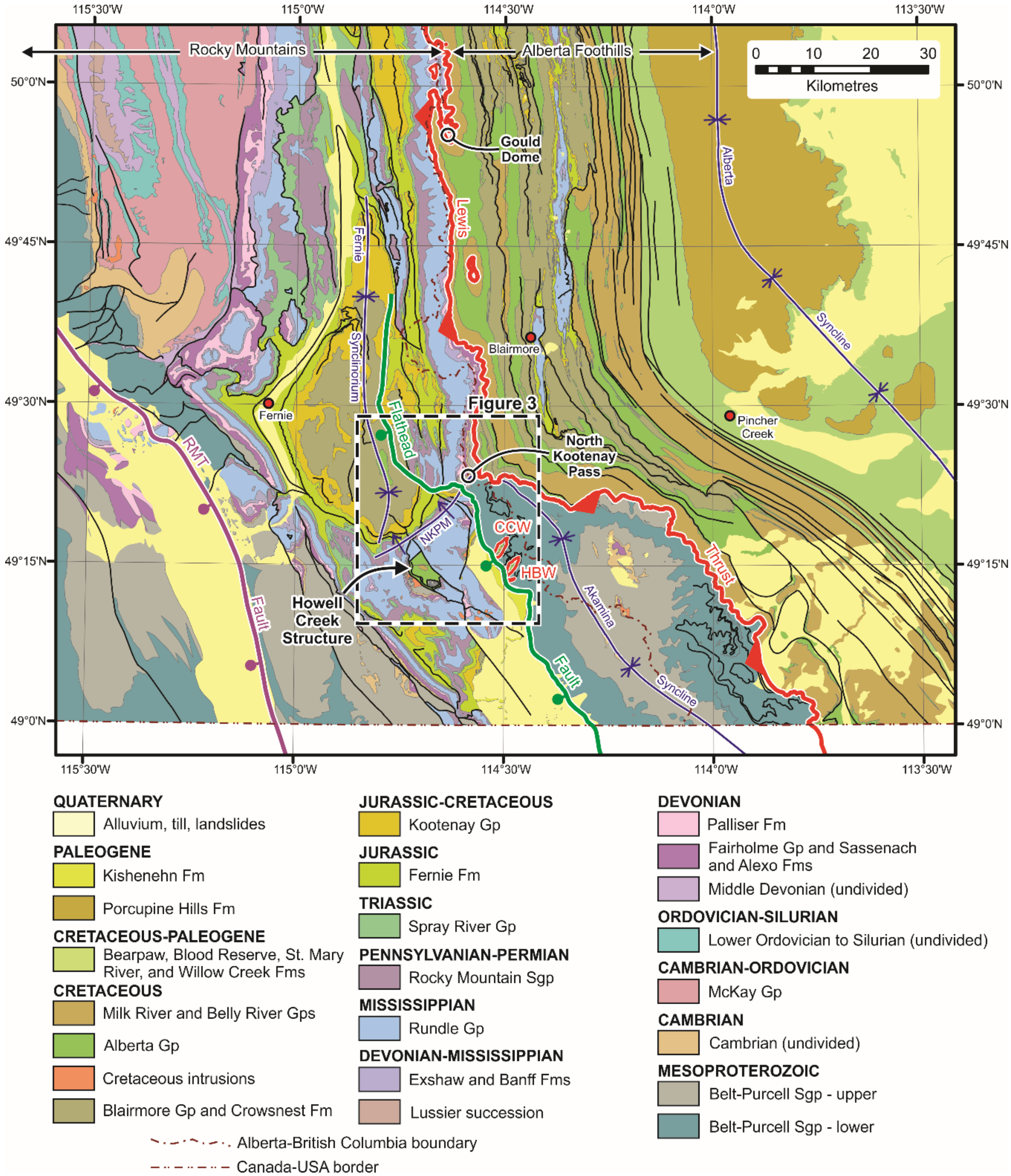


***Figure 1:** Regional setting of the Howell Creek structure within the southeasternmost Canadian Cordillera. At this latitude the Lewis Thrust (in red) separates the Rocky Mountains, which are bounded to the west by the Rocky Mountain Trench Fault (in purple), from the Alberta Foothills, which are bounded to the east by the axis of the Alberta Syncline. South of North Kootenay Pass, the Lewis Thrust is exposed at the Cate Creek and Haig Brook windows (labeled CCW and HBW, respectively), in the immediate footwall of the normal-sense Flathead Fault (in green). NKPM = North Kootenay Pass Monocline;*

RMT = Rocky Mountain Trench. Principal, named faults are shown as black lines, non-symbolized for clarity. Red circles mark principal towns. Dashed box indicates area of Figure 3. Generalized geology after Leech (1959), Price (2013), McMechan and Stockmal (2015), Stockmal and Fallas (2015), and Stockmal and McMechan (2015).

interpretation of the autochthonous footwall cut-off through Mesoproterozoic strata (van der Velden and Cook, 1994) coupled with detailed palinspastic restoration of sub-Lewis Thrust duplex structures involving Paleozoic and Mesozoic strata (Fermor and Moffat, 1992). Motion on the Lewis Thrust is inferred to have begun at ca. 75 Ma on the basis of apatite fission track thermochronology (Osadetz et al., 2004; Feinstein et al., 2007), which coincided with late Campanian transgression and deposition of the marine Bearpaw Formation in the adjacent foreland basin (Catuneanu et al, 2000). Radiometric dating of Lewis Thrust fault gouge at Grizzly Creek, near its northern termination, and at Gould Dome (Figure 1) yielded ages of 72.3 ± 2.3 Ma and 51.5 ± 2.2 Ma, respectively (van der Pluijm et al, 2006), suggesting protracted development or local late-stage reactivation.

A large lateral ramp occurs in the hanging wall of the Lewis Thrust at the latitude of North Kootenay Pass (figures 1 and 3), where the thrust cuts up-section to the north through approximately 3 km of Mesoproterozoic Belt-Purcell Supergroup strata over an along-strike distance of approximately 20 km, with the most abrupt portion of this ramp cutting out 1 km of strata over a distance less than 3 km (Price, 1965a, 1965b; Dahlstrom, 1970; Fermor and Price, 1987). This lateral ramp is expressed within the Lewis Thrust sheet as the northeast-trending North Kootenay Pass Monocline, which can be followed from the eponymous pass to west of the axis of the Fernie Synclinorium (Price, 1962; Figure 1). Southeast of North Kootenay Pass, where the Lewis Thrust carries a thick and internally little deformed succession of Belt-Purcell strata, the trace of the thrust swings abruptly to the east, as do the traces of structurally underlying imbricate thrusts in the Foothills belt (Figure 1). This deflection may reflect the mechanical influence of the inversion of the thick Belt-Purcell basin and its incorporation into the advancing thrust wedge (Boyer, 1995).

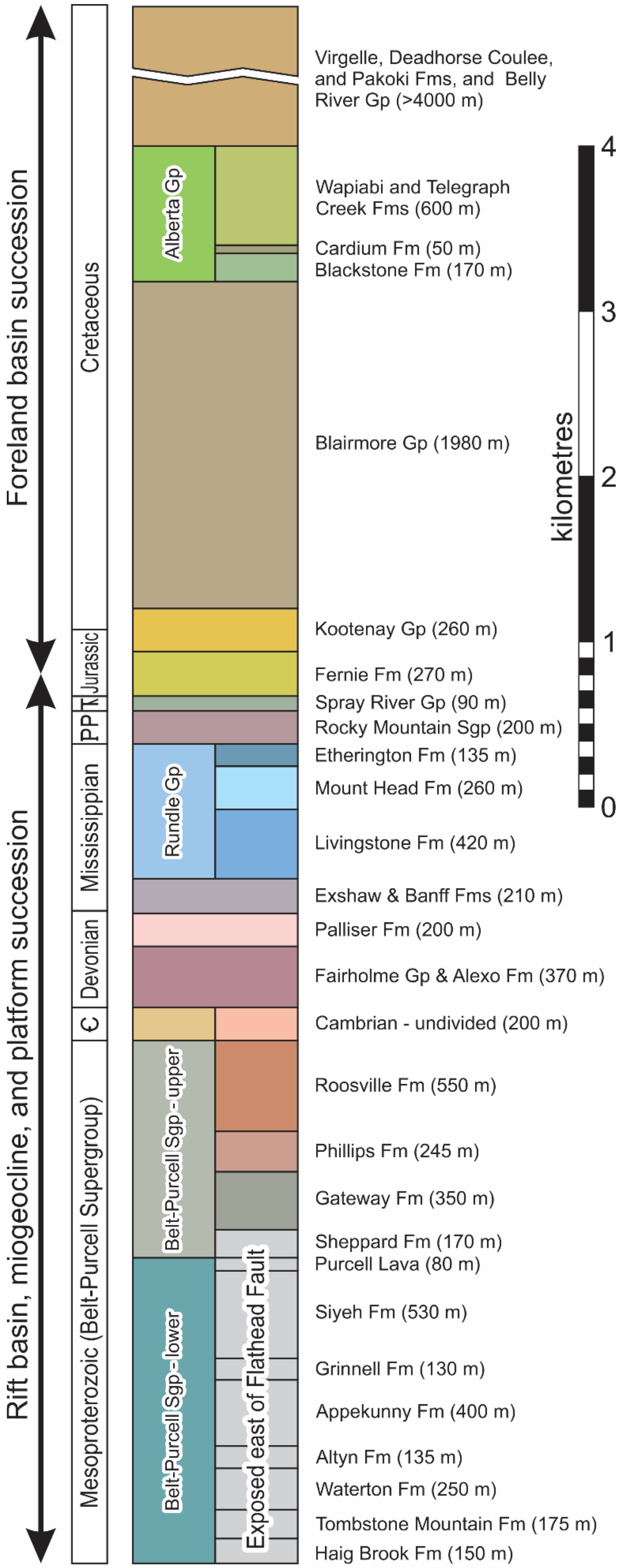


Figure 2: *Generalized stratigraphic column, including thicknesses specific to the Howell Creek area. Where units are represented by two colours, those on left side correspond to grouped units shown in figures 1, 3, 4, and 23. Foreland basin units younger than the Belly River Group, shown in Figure 1, are not included here. Stratigraphic thicknesses from Price (1962, 1965b), Jones (1966), McMechan (1981), and Ollerenshaw (1981).*

The Howell Creek structure lies near the crest of a structural culmination, located southeast of the North Kootenay Pass Monocline and along strike to the south-southeast from the Fernie Synclinorium (figures 1 and 3), which itself lies in the hanging wall of the large-displacement (>13 km near the international border; McMechan, 1981), normal-sense Flathead Fault, inferred to be Oligocene in age on the basis of graben fill (Kishenehn Formation). The Flathead Fault merges smoothly downward with the Lewis Thrust, which is broadly folded east of the Flathead Fault above a large duplex stack of Paleozoic and Mesozoic strata (Bally et al, 1966; McMechan, 1981; Fermor and Moffat, 1992). Two windows through the Lewis Thrust are exposed in the footwall of the Flathead Fault, at Cate Creek and Haig Brook (figures 1 and 3), where the Haig Brook Formation, the locally oldest unit of the Mesoproterozoic Belt-Purcell Supergroup (Figure 2), is thrust onto Cretaceous strata in a nearly flat-on-flat structural relationship (Fermor and Price, 1987; Fermor and Moffat, 1992).

PREVIOUS INTERPRETATIONS

Kinematic explanations of the Howell Creek structure fall broadly into two groups, according to whether the Upper Cretaceous rocks comprising the outlier lie either: (1) below the Lewis Thrust sheet, where one or more of the bounding faults is a fault-offset segment of the Lewis Thrust itself (Price, 1958, 1959, 1962, 1965a, 1965b, 2013; Dahlstrom, 1970); or (2) within the Lewis Thrust sheet. This second category encompasses four proposed interpretations, where these Upper Cretaceous strata may have been: (2a) overthrust by a major supra-Lewis sheet prior to it being down-dropped on regional, steeply dipping, and locally cryptic normal faults (Oswald, 1964); (2b) faulted upward into an inferred, cryptic, supra-Lewis sheet (Jones, 1964, 1966); (2c) down-dropped by a low-angle normal fault that merges with a normal-sense reactivated thrust fault (Labrecque and Shaw, 1973; Fermor and Moffat, 1992); or (2d) cryptically emplaced as a large but structurally coherent gravitational slide (Jones, 1977). More recent detailed mapping by Skupinski and and Legun (1989), Legun (1993), and Brown and Cameron (1999), along and adjacent to the boundaries of the Howell Creek structure, and regional cross-sections by Osadetz et al. (2004) and Hardebol (2010), provide additional constraints and points of view that bear on these widely disparate interpretations.

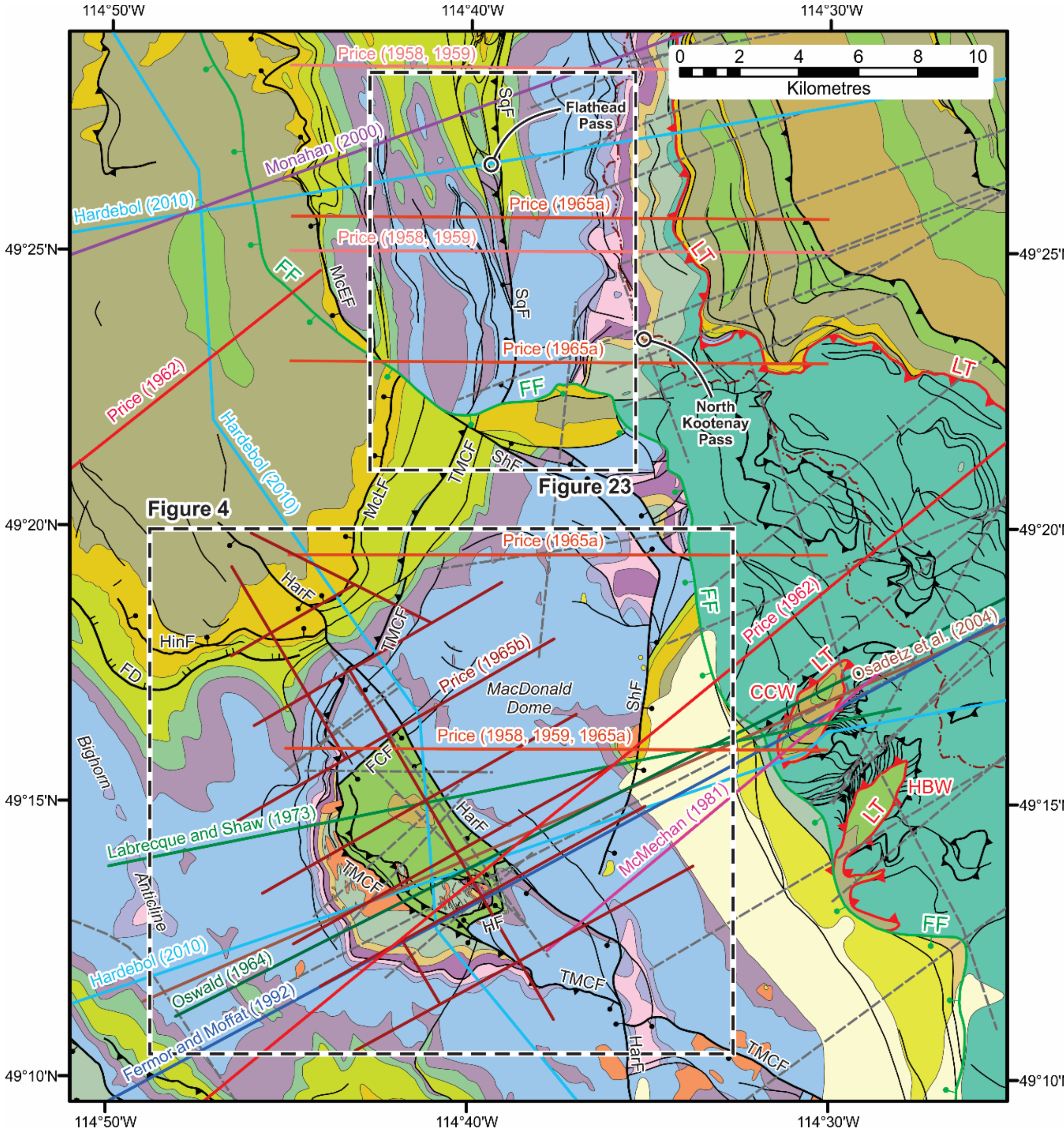


Figure 3: *Detail of Figure 1 in the vicinity of the North Kootenay Pass Monocline showing generalized geology and locations of published structural sections (see data accompanying Stockmal and Fallas, 2015). Section traces relevant to the Howell Creek structure are shown in colour and labeled; other structural sections, including some coloured and labeled in Figure 4, are shown by grey dashed lines. Unit colours as defined in Figure 1. Principal, named faults are symbolized as thrust or normal faults by triangular "teeth" or stick-and-ball, respectively. CCW = Cate Creek Window; FCF = Fuel Creek Fault; FD = Fernie Detachment; FF = Flathead Fault (in green); HBW = Haig Brook Window; HF = Howell Fault; HarF = Harvey Fault; HinF = Hinge Fault; LT = Lewis Thrust*

(in red); McEF = McEvoy Fault; McLF = McLatchie Fault; ShF = Shepp Fault; SqF = Squaw Fault; TMCF = Twentynine Mile Creek Fault. Dashed boxes indicate areas of figures 4 and 23. Generalized geology after Stockmal and Fallas (2015).

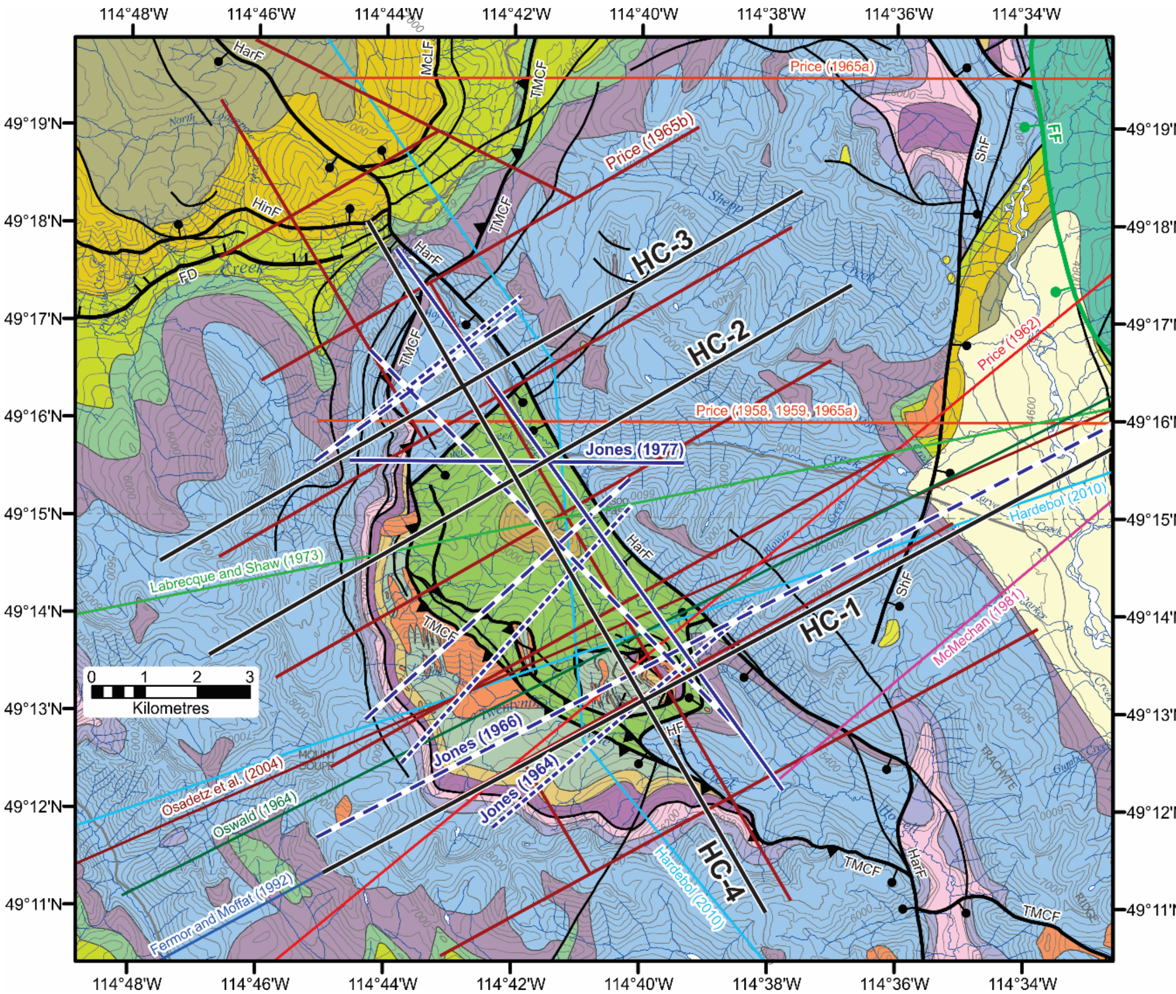


Figure 4: *Detail of Figure 3 on topographic base, showing locations of published structural sections, including those of Jones (1964, 1966, 1977) as dark blue short-dashed, long-dashed, and solid lines, respectively. Only one of grid of the dark red structural sections by Price (1965b) is labeled for clarity (see Figure 11, below). Black solid lines indicate locations of new sections presented here; section HC-1 overlies that of Fermor and Moffat (1992), and extends to the northeast across the Cate Creek Window (see Figure 3). Unit colours as defined in Figure 1. See Figure 3 caption for fault abbreviations.*

Although these interpretations may differ substantially, most provided information such as field observations and map interpretations (structural attitudes, stratigraphic contacts, and fault and fold traces) that were digitized, compiled, and evaluated for this study. Many of these previous interpretations were illustrated with cross-sections, resulting in a dense grid of structural section traces across and in the vicinity of the Howell Creek structure (figures 3 and 4; see GIS data accompanying Stockmal and Fallas, 2015).

PRICE (1958, 1959, 1962, 1965A, 1965B, 2013)

Price (1958) interpreted the Upper Cretaceous rocks of the Howell Creek structure to be bounded on the southwest and northwest by the Lewis Thrust (Figure 5). The Lewis Thrust was interpreted as being structurally cross-cut and uplifted by a younger, unnamed east-directed thrust that bounds the Upper Cretaceous rocks to the southeast (later named the Howell Fault by Price, 1959). Together with the later, cross-cutting Harvey normal fault, these faults effectively form a window through the Lewis Thrust sheet (Figure 5). The part of the Howell Creek structure north of 49°15′N (Figure 6) was examined in the field, with the remainder shown in Figure 5 interpreted using aerial photographs (Price, 1958, p. 177-182).

Price (1958) described two segments of the Lewis Thrust. On the southwest side of the Howell Creek structure the thrust is steeply southwest-dipping, placing undifferentiated Mesoproterozoic Belt-Purcell through Devonian strata, intruded by a trachyte and syenite body, onto Upper Cretaceous strata (Figure 5). On the northwest side, the Lewis Thrust is interpreted as flat-lying, placing Mississippian Rundle Group strata onto Upper Cretaceous strata (figures 5 and 6). Regarding this second segment, Price (1958, p. 179) stated:

> "This fault appears to be relatively flat. It has been interpreted as a gently warped thrust fault as shown in cross-section B–B' of Figure 6 [reproduced here in Figure 5], and apparently represents another part of the Lewis thrust fault. Windows are assumed to occur in it along the headwaters of the north fork of Harvey Creek, and at the headwaters of Lodgepole Creek [see labeled

headwaters in Figure 5], where fine-grained, dark grey sandstones typical of the Alberta group are exposed in a stream cut in an area rimmed by exposures of Paleozoic carbonate rocks."

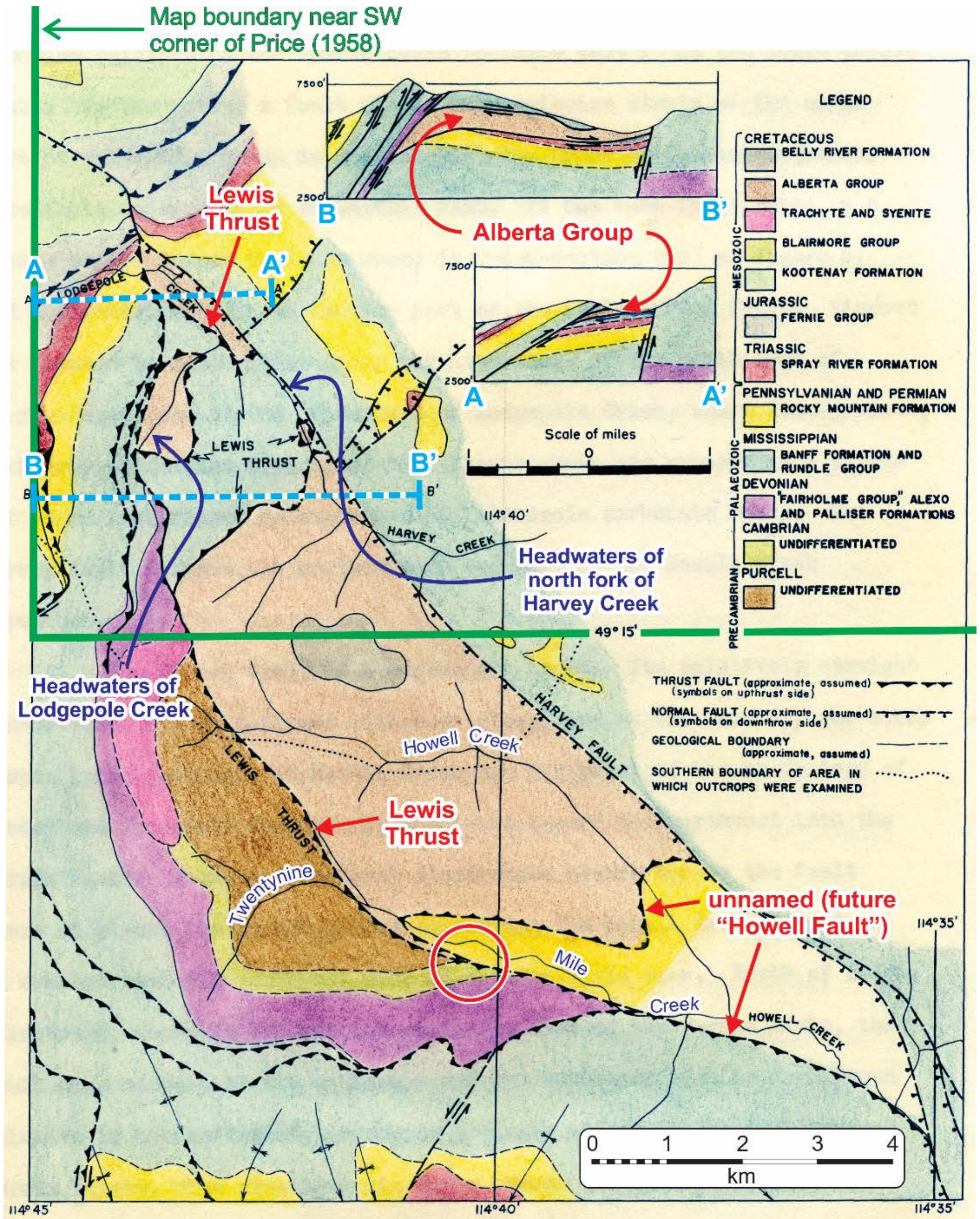


Figure 5: *Annotated reproduction of figure 6 of Price (1958, p. 178), showing a sketch map of the Howell Creek structure and two local cross-sections (traces highlighted by dashed blue lines). Note that section B–B' is a simplification of the west end of section*

E–F shown in Figure 6. Red circle indicates point of merger between the traces of the Lewis Thrust and the yet-to-be-named Howell Fault.

This exposure[2] of interpreted Alberta Group strata at the headwaters of Lodgepole Creek was also visited by Jones (1966; see below).

The interpreted thrust fault bounding Upper Cretaceous strata to the southeast, subsequently named the Howell Fault by Price (1959), was described by Price (1958, p. 180):

> "On the basis of photo-geologic interpretation, a relatively flat thrust fault is believed to occur beneath the Upper Cretaceous sequence near the south end of the Howell Creek structure … and to place the Upper Cretaceous strata above the Rocky Mountain formation (see the sketch map of Figure 6 [shown here in Figure 5]). This fault appears to have cut the Lewis thrust sheet and to have displaced a western part of the thrust sheet, together with a slice of the underlying Upper Cretaceous strata, over an eastern part of the thrust sheet. The fault appears to merge with the Lewis thrust to the south, and a single thrust fault repeats the Palaeozoic sequence of the Lewis thrust sheet at the southeast end of the Howell Creek structure. To the north, the fault is probably represented on the northwest side of the Harvey fault by the thrust faults which thicken the Fernie-Spray River interval in McLatchie Creek Valley."

The unnamed principal fault in McLatchie Creek Valley, subsequently identified as the "Howell thrust" by Price (1965b), is labeled in Figure 6 on the northeast side of the Harvey Fault.

[2] Original field notes and annotated aerial photographs of R.A. Price are archived with the Geological Survey of Canada – Calgary. This outcrop was recorded as station P658, visited on July 8, 1957, and located on aerial photograph BC 1537:39 (August 22, 1952). Field notes state: "Rocky Mtn ? (or Banff)" [sic], with addition of "BIGHORN". The field description is: "qtzite dk grey to black fgd" [sic], followed by "beds 12" thick ca 4' exposed along dip slope" [sic]. These notes suggest that Price was initially uncertain as to the formation assignment of this apparently small outcrop, but later concluded that it was an exposure of the Bighorn, now known as the Cardium Formation.

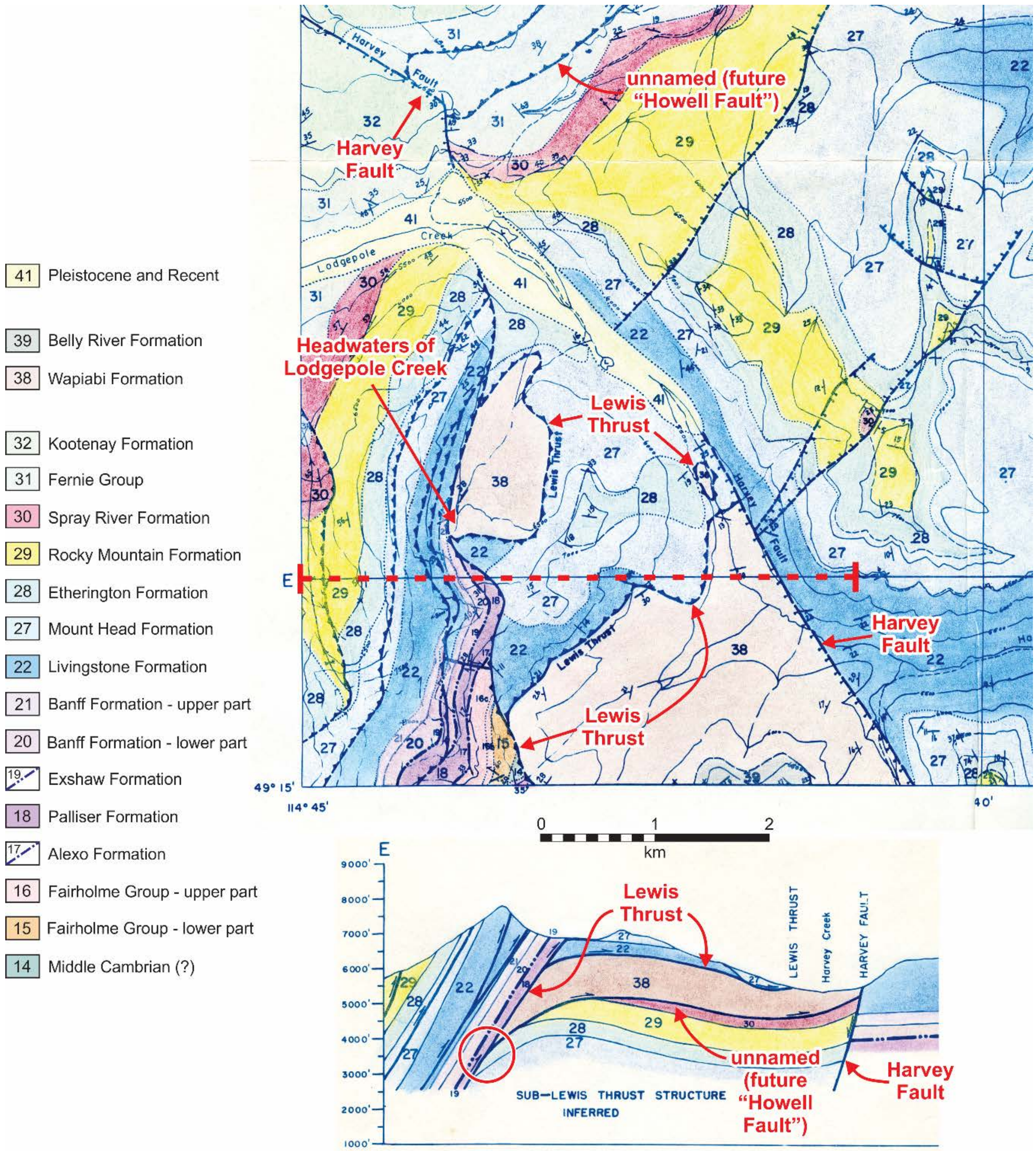


Figure 6: *Annotated reproduction of southwest corner of unpublished Ph.D. thesis map of Price (1958), and west end of cross-section E–F (the extent of the illustrated section is indicated by the dashed red line). Red circle indicates inferred interpretation of the merger between the Lewis Thrust and the yet-to-be-named Howell Fault.*

Note that Price (1958) stated the yet-to-be-named Howell Fault "appears to have cut the Lewis thrust sheet", but also it "appears to merge with the Lewis thrust to the south”. The point of intersection of the fault traces is marked by the red circle in Figure 5. Although Price (1958) did not discuss the nature of the merger of these faults as it appears in his cross-sections, a comparison of the circled points on the map in Figure 5 and the cross-section in Figure 6 (which also appears in a smaller, simplified form in Figure 5) suggests that this intersection was viewed by him as forming a single down-dip branch line.

Price’s (1958) interpretation of this fault as a thrust, rather than a low-angle normal fault or possibly a normal-sense reactivated thrust, was consistent with contemporary views of the regional structure (e.g., the fenster interpretation was supported in Dahlstrom et al., 1962, p. 385). Regarding the general structural style of the area, Price (1958, p. 132) stated:

> “Two genetically and temporally distinct groups of structures occur, each possessing its own complexity in detail. The older group is characterized by thrust faults, sub-parallel to bedding with associated folds. These faults define individual thrust plates which are associated with and are genetically similar to the Lewis thrust sheet. … The younger group of structures is characterized by high-angle faults, most or all of which are normal faults. These faults define individual blocks which have undergone differential vertical displacements and have been tilted or rotated generally toward the east and northeast.”

Comparison of the southwest corners of the unpublished thesis map of Price (1958; Figure 6), GSC Map 1-1959 (Price, 1959), and GSC Map 1154A (Price, 1965a), indicates no change in interpretation of the Lewis Thrust north of 49˚15′N between these map versions, with the minor exception of an inferred thrust fault added within the assumed window near the headwaters of Lodgepole Creek. However, differences in cross-section interpretation between Price (1958), and Price (1959) and subsequent publications (Figure 7) reflect changes that accommodate omission of strata across apparent thrust faults, and a reassessment of the structural position of the branch line noted above.

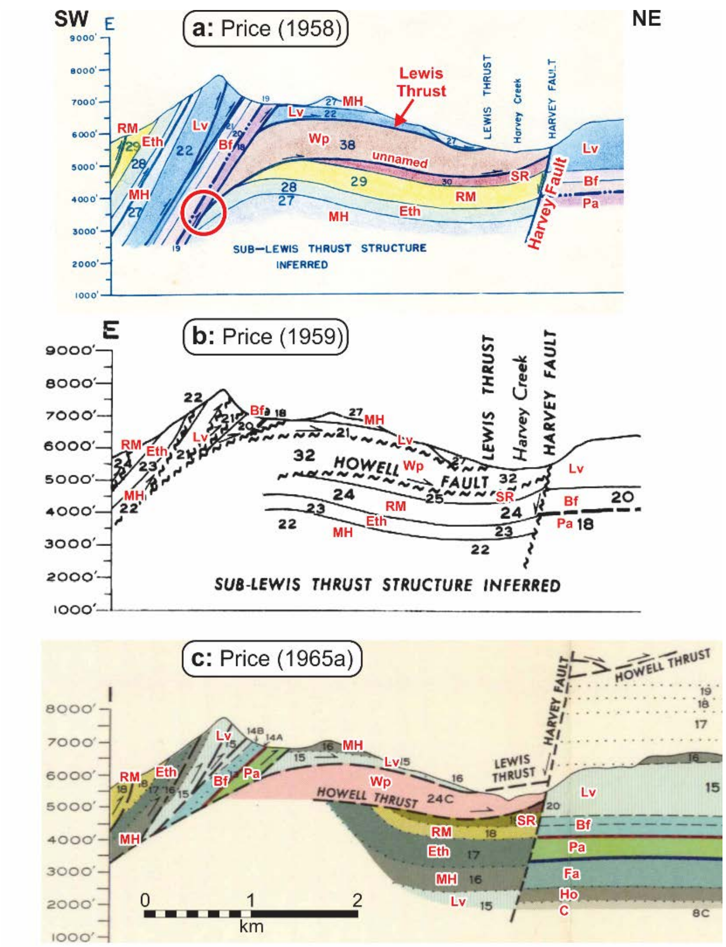


Figure 7: *Comparison of successive, annotated, cross-sectional interpretations along the identical line of section (section B–B' in Figure 5 and west end of section E–F in Figure 6). (a) West end of section E–F of Price (1958). (b) West end of section E–F of Price (1959). (c) West end of section I–J of Price (1965a). Stratigraphic abbreviations, in ascending order (see also Figure 2): C = Middle Cambrian, undivided; Ho = Hollebeke Fm; Fa = Fairholme Gp; Pa = Palliser Fm; Bf = Banff Fm; Lv = Livingstone Fm; MH = Mount Head Fm; Eth = Etherington Fm; RM = Rocky Mountain Sgp; SR = Spray River Fm; Wp = Wapiabi Fm.*

As noted above, Price (1959) is the first appearance of the name "Howell Fault". Although its trace does not appear on this map, the labelled fault appears in the southernmost cross-section, E–F (Figure 7b). This cross-section differs significantly from the equivalent cross-section of Price (1958; compare Figure 7a with 7b) in two ways: (1) beneath the high ridge to the west the Lewis Thrust is shown as cutting stratigraphically down-section in the direction of transport; and (2) the speculative details of the down-dip merger of the Lewis Thrust and Howell Fault are excluded. With respect to the first point, Price (1959, "Descriptive Notes") described the Howell, Barnes, and Squaw Creek faults as eastward-directed thrusts "imposed discordantly on the earlier northwest-trending structures." He also stated "Stratigraphic omissions occur locally across these later discordant thrust faults”, but did not explicitly consider that omissions might reflect normal-sense reactivation of thrust faults.

The milestone 1:126,720 scale compilation and mapping effort of Price (1962) provided an unparalleled regional view of the structural style of the southeastern Canadian Cordillera. With respect to the Howell Creek structure, that region south of 49°15′N, previously interpreted using aerial photographs (Price, 1958, 1959), was mapped in detail by Price (1962; Figure 8). Among the substantial revisions by Price (1962) of his previous aerial photo interpretations were the identification of the Phillips Formation (figures 2 and 8) as the oldest Mesoproterozoic rocks carried by the interpreted Lewis Thrust, and the mapped position of this thrust on the ridge between Howell Creek and Twentynine Mile Creek, where its shallow southwest dip results in a highly sinuous trace across topography (compare figures 5 and 8). On the ridge, this fault carries an east-dipping and apparently folded Mesoproterozoic through Middle Devonian succession that was intruded by inferred Early Cretaceous or younger trachyte and syenite, as illustrated in cross-section G–H of Price (1962; Figure 9). Note that the Howell Fault of Price (1959; Figure 7b) is termed the Howell Thrust by Price (1962; Figure 8).

Cross-section G–H of Price (1962) illustrated the regional implications of the fenster interpretation of the Howell Creek structure (Figure 9). In particular, the Lewis Thrust is required to cut down-section in the transport direction through approximately 4.8 km of strata (see local thicknesses in Figure 2), from near the top of the Mississippian Mount Head Formation to the Proterozoic Haig Brook Formation (mapped as Waterton Formation at that time; see Fermor and Price, 1987). Although Devonian Fairholme Group is the youngest unit in the immediate hanging wall of the Lewis Thrust in cross-section G–H, upper Mount Head Formation (stratigraphic level marked by the purple dashed line in Figure 9) is

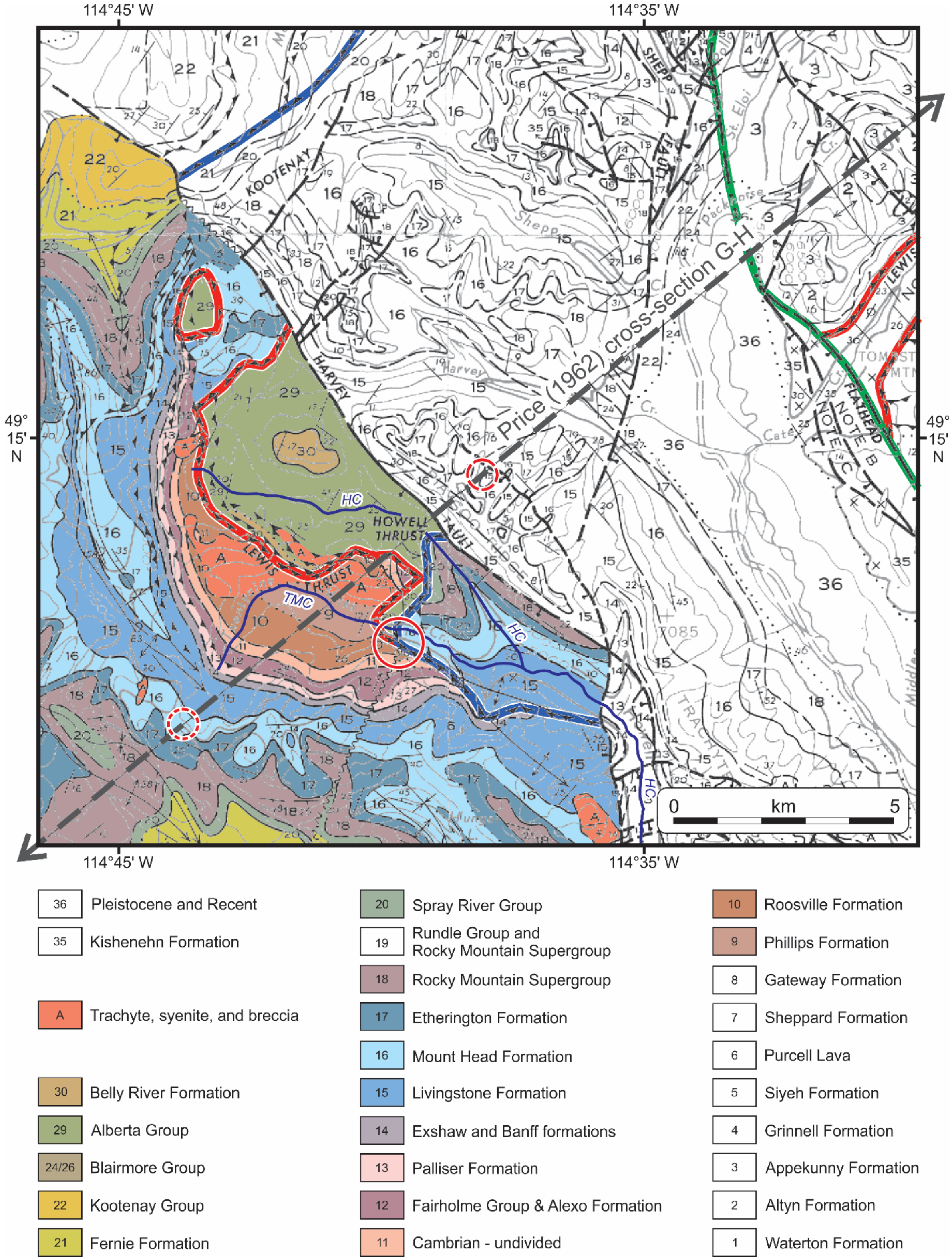
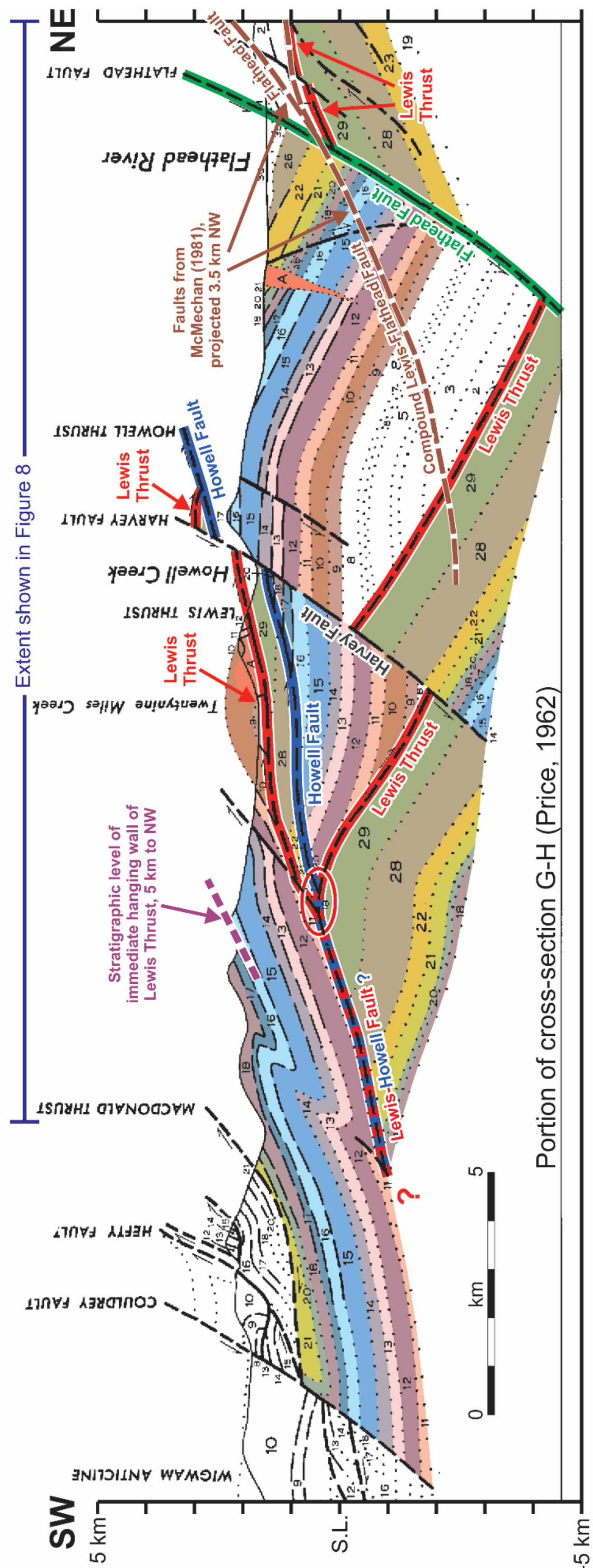


Figure 8: *Annotated and coloured portion of Price (1962) that encompasses the Howell Creek structure and part of the Cate Creek Window east of the Flathead Fault (see Figure 3). Only those units in the hanging wall of the Harvey Fault, or emphasized in Figure 9, are*



coloured. The Lewis Thrust, Howell Thrust, and Flathead Fault are highlighted as red, blue, and green lines, respectively. Solid red circle indicates point of merger between the traces of the Lewis and Howell thrusts. Black dashed line is location of structural section G-H of Price (1962), which extends well beyond the area illustrated. Long-dashed and short-dashed red circles indicate intersections of the up-dip and down-dip branch lines between the Lewis and Howell thrusts, illustrated in Figure 9, with the line of section G-H.

Figure 9: *Annotated and coloured portion of structural section G–H of Price (1962). The portion of this section crossing Figure 8 is shown by the labeled blue line. Major faults coloured as noted in Figure 8 caption; units coloured as in Figure 8 legend. Original section of Price (1962) did not include fault labels. Fault labels are consistent with the map of Price (1962) and subsequent illustration and discussion of Price (1965b). Subsurface portion of the Lewis Thrust inferred to be reactivated during motion on the Howell Fault is shown as a blue and red dashed line. Red ellipse indicates interpreted down-dip*

merger of the Lewis and Howell thrusts; interpreted up-dip merger is eroded on footwall side of the Harvey Fault. Purple short-dashed line indicates highest stratigraphic level carried in the immediate hanging wall of the Lewis Thrust in the Howell Creek structure (see figures 6 and 8). Brown long-dashed lines are projected positions of the Lewis Thrust, Flathead Fault, and the compound Lewis-Flathead Fault from McMechan (1981, figure 3.16; see section location in figures 3 and 4).

interpreted by Price (1958, 1959, 1962) to overlie Alberta Group strata on the northwest boundary of the Howell Creek structure (figures 6 and 8). This large magnitude of down-cutting must occur over a cross-strike distance of approximately 9 km (Figure 9) or less. In spite of this unusual requirement, which is a situation not displayed at this scale by any exposed or otherwise known structure in this region, the possibility of normal-sense motion on the Howell Fault was not explicitly considered by Price (1962), although it was by Price (1965b; see below).

The classic GSC Memoir by Price (1965b; which contains Price, 1965a) included a detailed and well-illustrated discussion of the Howell Creek structure, which he summarized (p. 107):

> “(its) most striking feature is the occurrence within the structure of strata of the Upper Cretaceous Alberta Group and Belly River Formation, bounded on all sides by older rocks along faults with stratigraphic separations of between 4,000 and 15,000 feet [approximately 1200 to 4500 m]. The interpretation of relationships across the principal faults forms the basis for determining whether the Upper Cretaceous strata are allochthonous and a part of the Lewis thrust sheet, or autochthonous and exposed in windows through the thrust sheet.”

Price (1965b) reiterated that the Howell Creek structure is a tectonic window, involving exposure of the Lewis Thrust along its western margin. His figure 16, which is a map and fence diagram of cross-strike and along-strike structural sections, illustrated his interpretation in detail. Figure 10 is an annotated reproduction of the fence diagram; the section locations are shown in figures 3, 4,

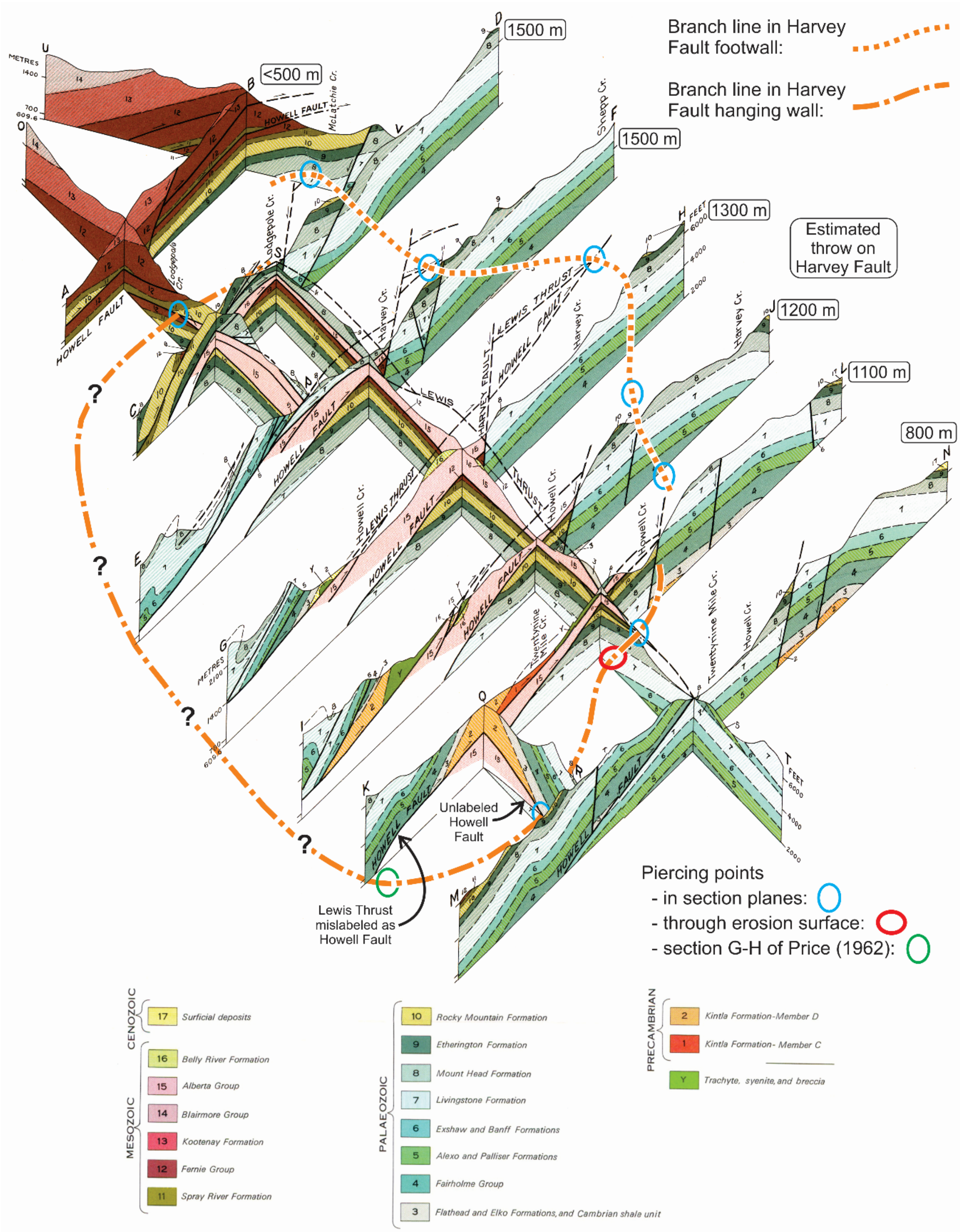


Figure 10: *Annotated and modified reproduction of fence diagram from Price (1965b, part of his figure 16). Lines of section are shown as dark red lines in figures 3, 4, and 11. The implied branch line (orange) between the Lewis Thrust and Howell Fault is shown as offset across the Harvey Fault, with a different line style for footwall (dotted) versus hanging wall*

(dash-dot). Piercing points constraining the branch line are shown as blue, red, and green ovals, where the green oval corresponds to the branch line circled in Figure 9 (section G–H of Price, 1962; see also Figure 11). Vertical offsets (throws) across the Harvey Fault, estimated from this diagram, are indicated at the northeast (upper right) ends of the cross-strike sections. Note corrections to the original figure near bottom. In the legend, Kintla Formation-Member C and Kintla Formation-Member D are equivalent to Phillips and Roosville formations, respectively.

and 11 (dark red lines forming a grid). The position of the interpreted branch line between the Lewis Thrust and the Howell Fault is shown in Figure 10 on both sides of the Harvey Fault. The abrupt change in trend of the branch line from the footwall (northeast, or upper right in Figure 10) side of the Harvey Fault, where it is sub-parallel to regional structural strike, to the hanging wall (southwest, or lower left) side, where it is at a very high angle to regional strike, illustrates the non-cylindrical geometry of this interpretation. The trailing-edge branch line, indicated by question

Figure 11: *Simplified map of the Howell Creek structure based on Price (1962, 1965b) showing grid of structural sections making up the fence diagram of Figure 10 (dark red solid lines), vertical projection of the branch line between the Lewis Thrust and the Howell Fault shown in Figure 10 (orange lines; long-dashed in hanging wall of Harvey Fault, short-dashed in footwall), location of section G-H of Price (1962; red long-dashed line), and positions of leading-edge and trailing-edge branch lines shown on section G–H (Price, 1962; blue circles).*

marks in Figure 10, is not shown on the original fence diagram of Price (1965b). However, as shown in Figure 11, this trailing-edge position is interpreted on section G–H of Price (1962; Figure 9).

Although the cross-strike sections of the fence diagram are partly obscured by the strike-parallel sections, the interpreted throw on the Harvey Fault at each of these can be estimated, as shown in Figure 10. Over an along-strike distance of ~11 km, throw increases steadily from ~800 m in the southeast to ~1500 m just northwest of the Alberta Group exposures, and then very abruptly decreases to less than 500 m over a distance of ~2.5 km toward the northwest termination of the fault (Figure 10), which lies a few kilometres north of Lodgepole Creek (figures 3, 4 and 11; Price, 1962, 1965b, 2013). This abrupt decrease in interpreted throw on the Harvey Fault is an artifact of the Lewis Thrust interpretation of Price (1958, 1959, 1962, 1965a,b), as discussed below.

Figures 17, 18, 19, and 20 of Price (1965b, p. 108, 110, 112, and 114) schematically illustrate aspects of his interpretation of the Howell Creek structure. His figure 17 is reproduced here in Figure 12, where normal-sense and thrust-sense options are considered for the Howell Fault. With respect to the normal-sense option Price (1965b, p. 109) stated:

> "Downthrow to the west along the west-dipping Howell fault involves a lateral extension of the Lewis thrust sheet and … implies that the prominent fault that overlies the Upper Cretaceous strata and has up to 3 miles of stratigraphic separation is a thrust fault that lies above and is distinct from the Lewis Thrust Fault; but no thrust faults of this magnitude have been observed above the Lewis thrust around the periphery of the Howell Creek structure."

The existence of a "prominent" overlying thrust fault, which was justifiably dismissed by Price (1965b), was considered by Oswald (1964) and also bears on the interpretation of Jones (1964), as discussed below. However, the options considered by Price (1965b, his figure 17) and shown here in Figure 12 are not exhaustive. He only considered cases where in cross-section the Howell Fault and an overlying thrust merge upward (yellow circles in Figure 12). A normal-sense alternative that does not require a supra-Lewis thrust sheet was proposed by Labrecque and Shaw (1973), as detailed below.

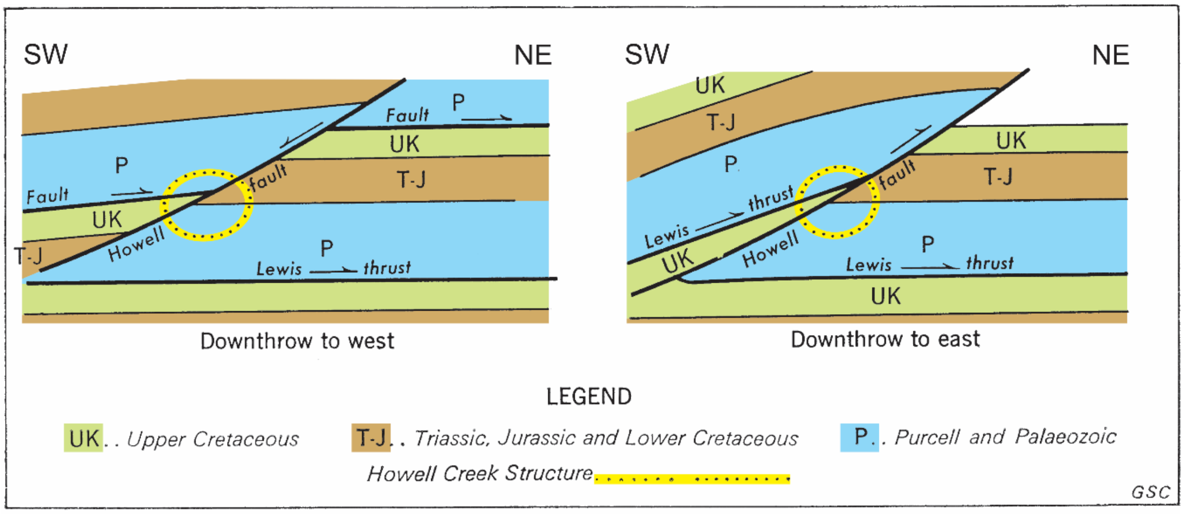


Figure 12: *Coloured reproduction of figure 17 of Price (1965b; p. 108). The illustrated normal fault option for the Howell Fault (labeled "Downthrow to west") requires the emplacement of a supra-Lewis thrust sheet for which no evidence exists. Although neither Oswald (1964) nor Jones (1964) are cited by Price (1965b), this diagram effectively argues against both of these alternative explanations of the Howell Creek structure.*

The Howell Creek structure as interpreted on the 1:125,000 scale GSC A-Series compilation map by Price (2013) is essentially identical to the 1:126,720 scale GSC Preliminary Map of Price (1962). The substantive differences are that Price (2013) does not differentiate the individual formations of the Rundle Group (see Figure 2), and all contacts and faults are shown as solid lines obscuring the confidence levels at which they were originally mapped. Figure 13a shows a simplified map based on Price (1962, 1965b, 2013) for comparison with alternative interpretations. Figure 14a shows a simplified version of a portion of cross-section G-H of Price (1962; compare with Figure 9), reproduced and annotated after Jones (1966; see below).

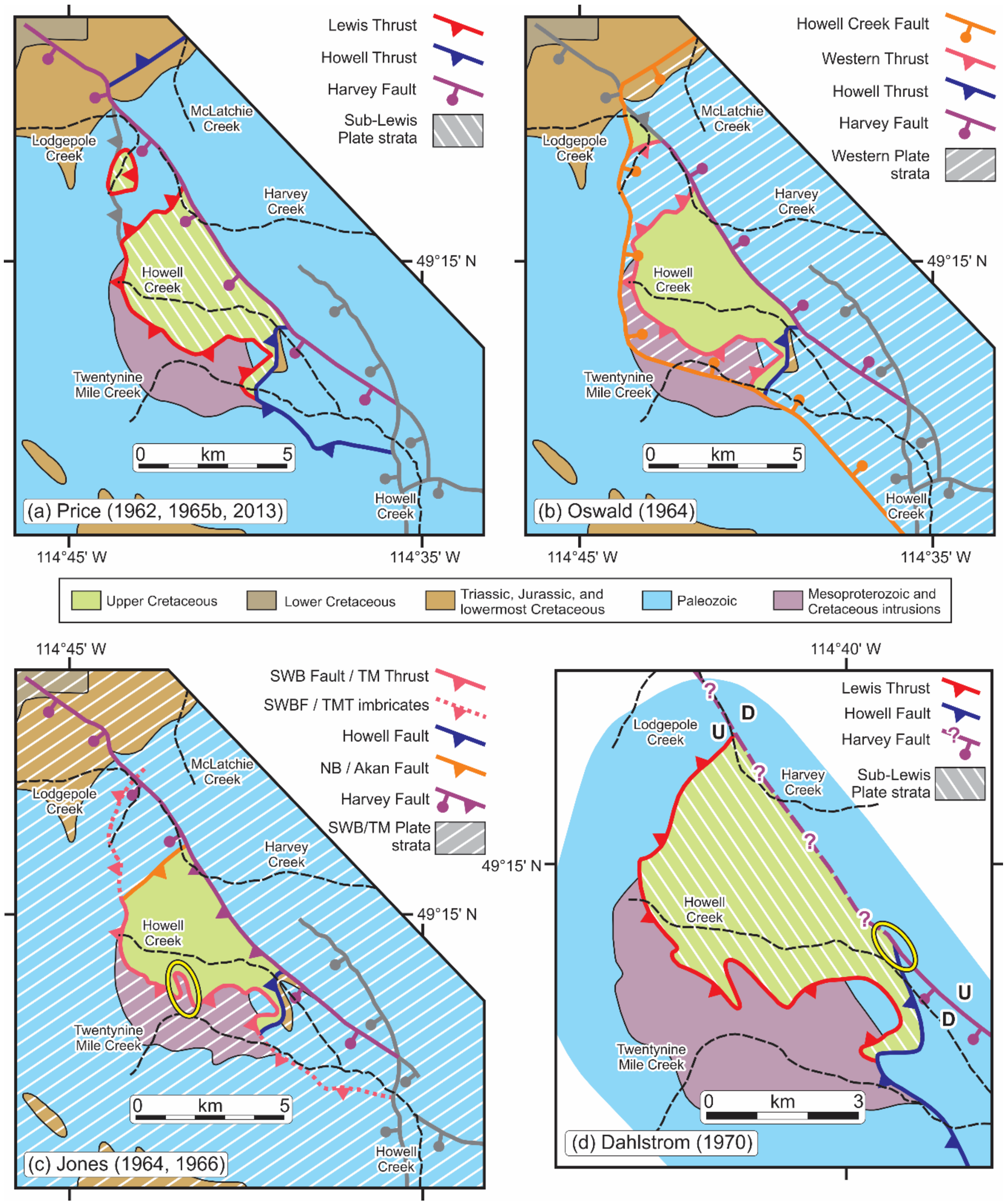
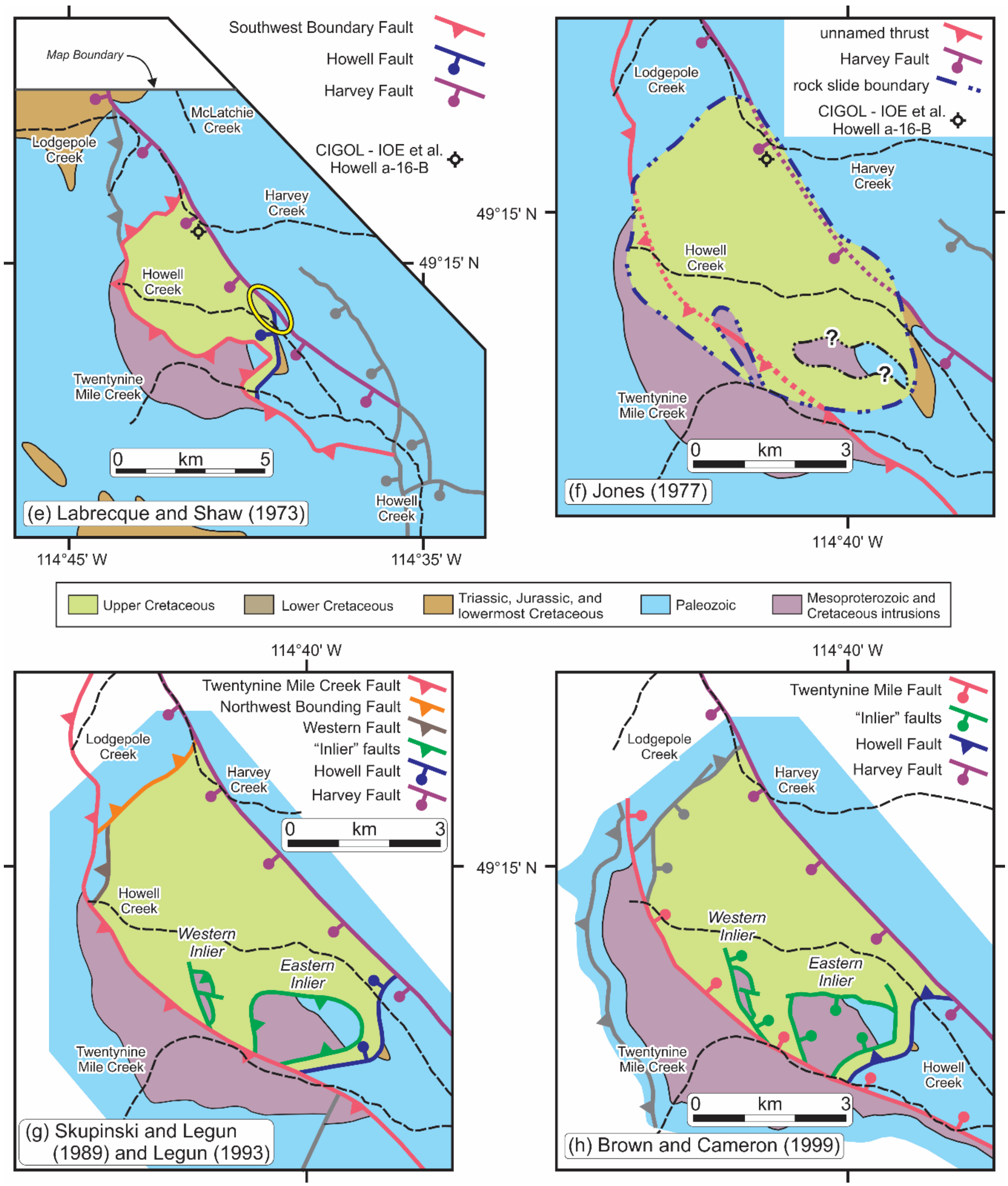


Figure 13 (two panels): *Simplified geological maps illustrating the principal differences in interpretations between various authors. (a) Price (1962, 1965b, 2013). Imbricate thrusts in the footwall of the Lewis Thrust, which include intrusive as well as Cretaceous rocks (see Figure 8), are excluded here. (b) Oswald (1964). (c) Jones (1964, 1966). Yellow oval indicates detail added by Jones (1966). SWB = Southwest Boundary; TM = Twentynine Mile; NB = North Boundary. (d) Dahlstrom (1970); map is attributed to A.E. Kliske of*

Chevron. D = down; U = up. (e) Labrecque and Shaw (1973); note location of Howell a–16–B well. Yellow oval marks interpreted smooth merger of the Howell and Harvey faults. (f) Jones (1977); boundary indicated by question marks encompasses an enigmatic occurrence of older rocks above the inferred slide. (g) Skupinski and Legun (1989) and Legun (1993). (h) Brown and Cameron (1999).



The interpretation of Price (1958, 1959, 1962, 1965a, 1965b, 2013) is considered to be highly unlikely, for four principal reasons:

(1) It requires the Lewis Thrust to cut very steeply down-section in its hanging wall, in the transport direction, through nearly 5 km of stratigraphy. The kinematic challenge imposed by this requirement is clear in Figure 9, which includes the projected position of the compound Lewis-Flathead Fault from McMechan (1981). As shown in Figure 9, Price (1962) interpreted the Flathead Fault to cross-cut and offset the Lewis Thrust, but Bally et al. (1966) demonstrated that the Flathead Fault merges smoothly with the Lewis Thrust, forming a compound fault at depth (see discussion below of Dahlstrom, 1970). Balanced cross-sections constructed by McMechan (1981) suggest there is insufficient room for the Lewis Thrust to cut down-section as required by Price (1958, 1959, 1962, 1965a, 1965b, 2013).

(2) It implies that the Mesoproterozoic through Mesozoic succession was broadly but substantially folded prior to propagation of the sub-horizontal Lewis Thrust through them (see figure 18A of Price, 1965b, p. 110), but that later folding of the Lewis Thrust by sub-Lewis structures effectively unfolded these exposed hanging wall rocks, as seen in Figure 9.

(3) Although it is kinematically admissible, the formation of the Howell Fault in relation to the Lewis Thrust, as implied by Figure 9 and illustrated schematically by Price (1965b, figure 18, p. 110), is difficult to understand mechanically. This requires formation of a major out-of-sequence thrust that initially branches downward from the Lewis Thrust into its footwall and subsequently slices upward into and through the full thickness of the Lewis sheet, cross-cutting and offsetting the Lewis Thrust (~9 km displacement; Figure 9).

(4) The close spatial correspondence of Cretaceous intrusions to the Howell Creek structure as well as MacDonald Dome (figures 1 and 3) suggests that no large-cumulative-displacement faults cross-cut this area, otherwise this would represent an unlikely spatial coincidence (a point made by Jones, 1966; see below). As implied by Figure 9, the interpretation of Price (1962, 1965a, 1965b) requires just such a coincidence, where the intrusions in the hanging wall of the Howell Fault are fortuitously thrust above similar intrusions in its footwall.

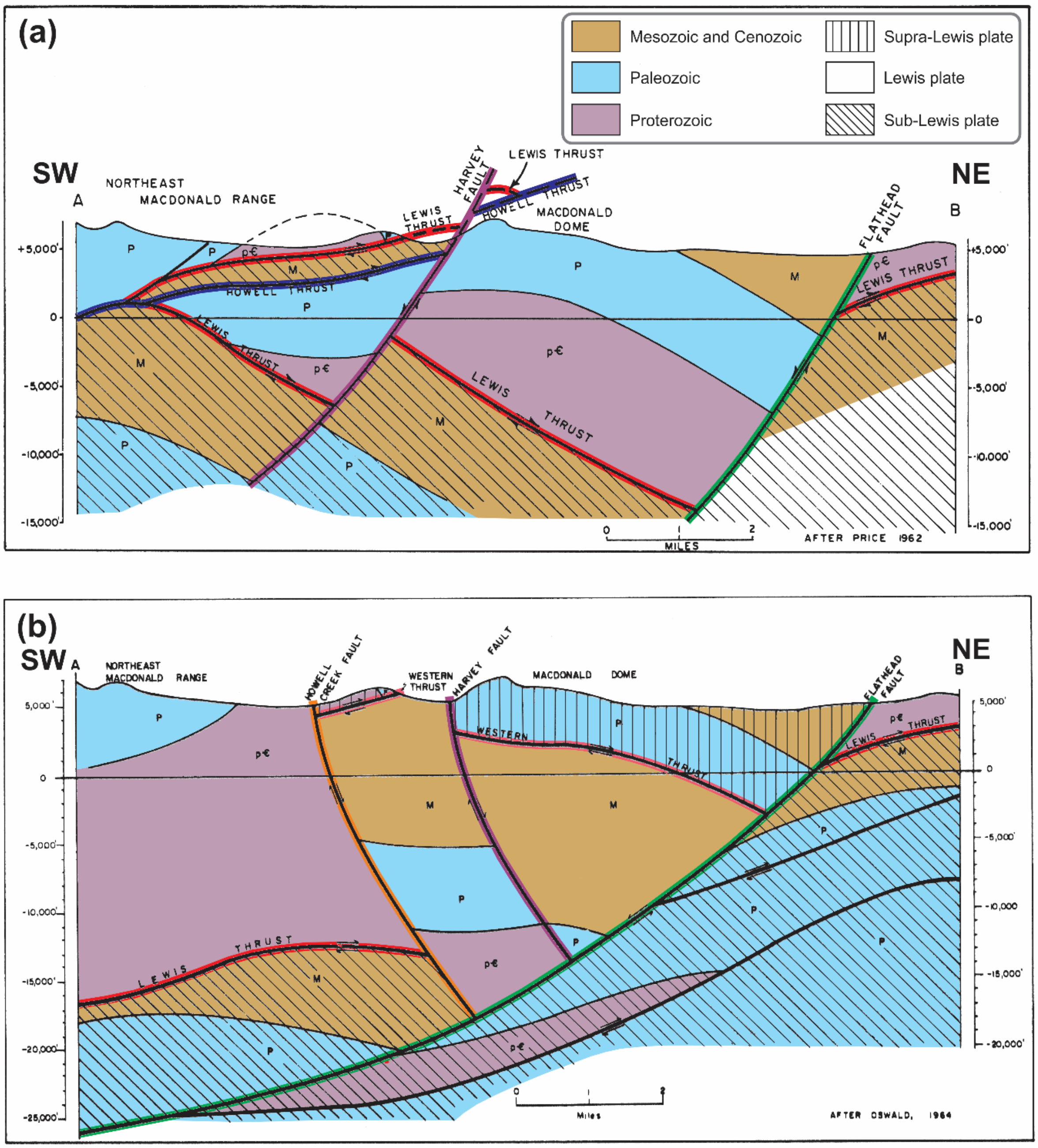
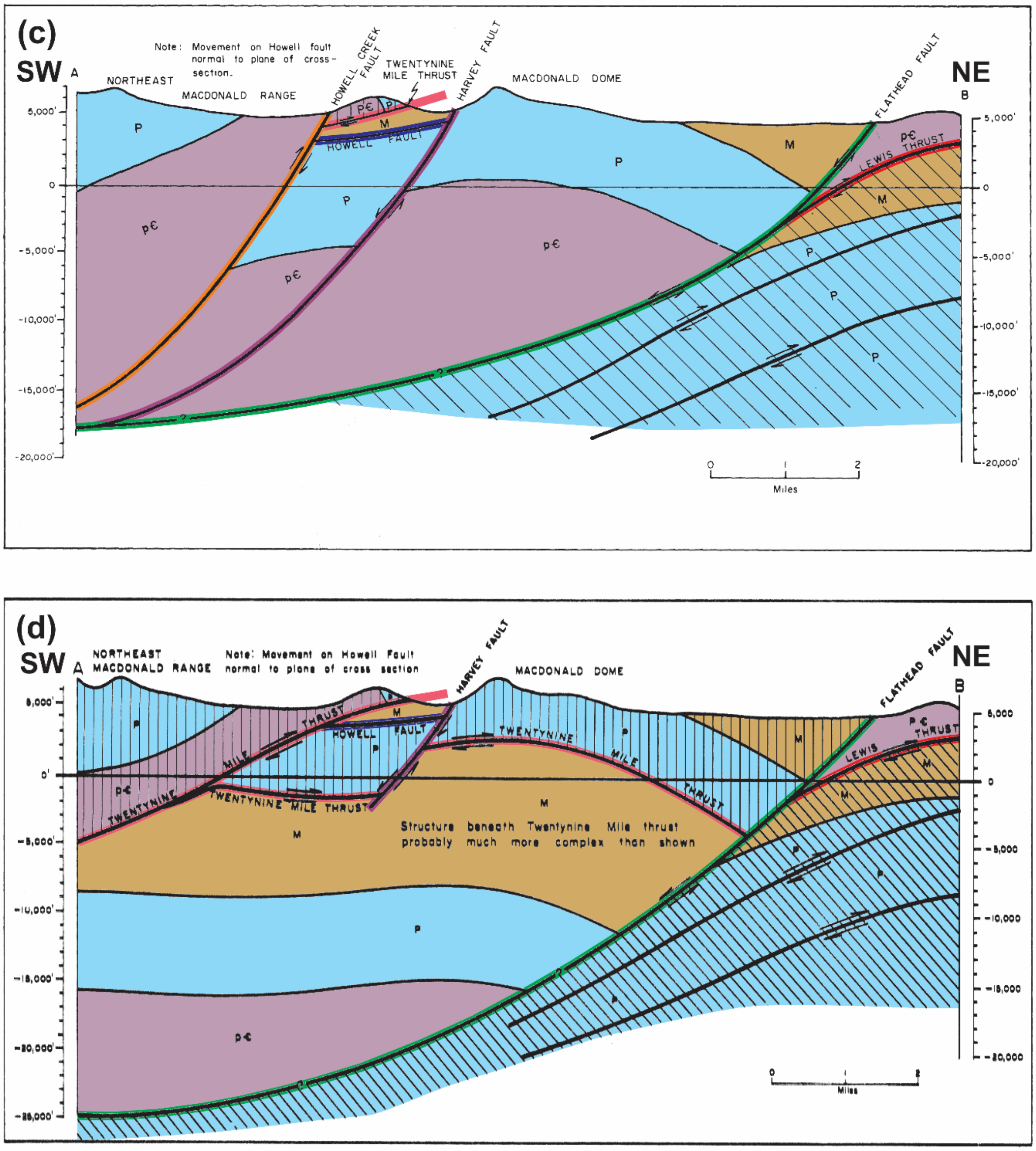


Figure 14 (two panels): *Coloured reproductions of lower portions of figures 49, 50, 51, and 52 from Jones (1966), showing generalized comparisons of interpretations (excluded upper portions of these figures show simplified maps). Jones (1966) showed these cross-sections as approximately coincident with section G–H of Price (1962; see Figure 8). Legend in part (a) applies to all parts of the figure; note the distinctions, using cross-hatching, between the Lewis plate and underlying or inferred overlying thrust plates. (a) Price (1962). (b) Oswald (1964). (c) Hybrid interpretation combining Oswald (1964) and*

Jones (1966). (d) Jones (1966); this figure is a simplification of part of his detailed cross-section A–A′.



OSWALD (1964)

Oswald (1964, p. 363) rejected Price's (1962) interpretation of the Howell Creek structure as a window similar to those at Cate Creek and Haig Brook on the basis of the age of hanging wall strata:

> "… Precambrian strata west of the Howell Creek "window" are much younger than those surrounding the windows to the east. It would be a violation of the cardinal principle of thrust belt structure, that thrust faults cut up section in the direction of motion, to suggest that the fault on the west side of the Howell Creek structure is a part of the fault which surrounds the windows to the east."

Instead, Oswald (1964) hypothesized that a previously unrecognized major supra-Lewis Thrust sheet overrode the Upper Cretaceous rocks at Howell Creek. This supra-Lewis sheet, which he called the Western Thrust plate, was interpreted as down-dropped and preserved in a large graben but entirely removed elsewhere by subsequent erosion. The east side of this graben was identified as either the Shepp Fault (interpreted as a west-dipping normal fault by Oswald, 1964; see location in Figure 3) or the Flathead Fault, whereas the west side was a largely contrived east-dipping normal fault he called the Howell Creek Fault (Figure 13b; not to be confused with the Howell Fault). The trace of this proposed fault either followed the traces of west-dipping thrust faults mapped by Price (1959, 1962) that lie immediately west of his "Lewis Thrust", or crossed areas of poor to no exposure. The cross-sectional interpretation of Oswald (1964; shown in generalized form in Figure 14b) was not located on any of his map figures, but its estimated location is shown in figures 3 and 4 (labeled dark green line).

Oswald (1964, p. 365) offered a stratigraphic argument for the existence of the Western Thrust, although no data are provided or cited:

> "In the east, the Mississippian stratigraphy of the Lewis plate, at Flathead Pass [Figure 3, near top], is closely comparable to that seen in the Bighorn Anticline in the west [Figure 3, far left]. The intervening area of the MacDonald Dome [between the Harvey and Shepp faults; Figure 3, below centre] exposes a section of Mississippian differing from the Lewis plate stratigraphy and resembling that west of the Bighorn Anticline, in the Lizard Range [southwest of Fernie, B.C.; Figure 1]."

On this basis Oswald (1964) proposed that MacDonald Dome is allochthonous with respect to the Lewis Thrust sheet, carried on the Western Thrust, the root zone of which must be west of the Bighorn Anticline. In his interpretation, the only preserved bedrock trace of the Western Thrust lies immediately east of his Howell Creek Fault, and coincides with the trace of the Lewis Thrust as mapped by Price (1962) between its intersection with the Howell Fault and the headwaters of Lodgepole Creek (Figure 13b). Oswald (1964; p. 376) considered the very small to non-existent stratigraphic offset across the hypothetical Howell Creek Fault to be a coincidental juxtaposition of similar-age strata in wholly different thrust sheets. In addition to his unique interpretation of the Howell Creek Fault, he interpreted the normal-sense Harvey Fault as east-dipping (Figure 13b), in contrast to all previous and subsequent authors.

The Howell Thrust as mapped by Price (1962) is noted briefly by Oswald (1964, p. 376):

> "Since it is a structural maxim that thrust faults put older rocks onto younger, the Howell Thrust must be a second generation structure in which the footwall rocks of the early structure are now the hanging wall rocks of the Howell Thrust. It is not known whether the early structure was a normal or a thrust fault."

No further explanation of this fault or the omission of strata across it was provided.

Oswald's (1964) interpretation of the Howell Creek structure can be rejected because it is clearly at odds with the known constraints (e.g., direction of dip and sense of offset on major faults, the wholly unsupported Howell Creek Fault, and the lack of evidence of a root zone for the Western Thrust). However, together with Jones (1964), these are the first attempts to offer alternatives to Price (1958, 1959, 1962), and may have provoked the argument against a supra-Lewis thrust sheet presented by Price (1965b) and illustrated here in Figure 12.

JONES (1964, 1966)

Jones (1964), which was published simultaneously with Oswald (1964), also emphasized the "structural problem" posed by the Lewis Thrust interpretation of Price (1958, 1959, 1962), that (p. 359): "it has cut up-section in the down-dip direction, something that no other thrust in the area is known to have done, contrary to one of the most fundamental rules of thrusting in layered sequences." Like Oswald (1964), Jones (1964) proposed that the Upper Cretaceous strata originated from within rather than beneath the Lewis Thrust sheet. However, unlike Oswald (1964), who invoked normal faults to down-drop these strata from a higher structural position (Figure 14b), he interpreted them to have been structurally uplifted from below.

Jones (1964) interpreted four faults as bounding the Cretaceous strata (Figure 13c), the traces of which are nearly coincident with traces of three faults mapped by Price (1958, 1959, 1962; Figure 13a).

- To the southeast, the Howell Fault is as mapped by Price (1958, 1959, 1962), interpreted as a thrust striking nearly perpendicular to the Harvey Fault. Jones (1964) estimated its dip as 30° to 45° northwest, with Cardium Formation or perhaps Blackstone Formation thrust onto Spray River Group.
- To the southwest, the folded Southwest Boundary Fault coincides with the sinuous but overall northwest-striking portion of the Lewis Thrust of Price (1958, 1959, 1962). Jones (1964, p. 357) stated: "The thrust merges with the Howell fault south of the window and it is not clear whether the southeastward continuation [short-dashed magenta line in Figure 13c] is the Southwest Boundary thrust, a subsidiary of it, or the Howell fault. It is probably not the Howell fault, for it strikes normal to the sector of the Howell fault on the edge of the adjacent fenster."
- To the northwest, the North Boundary Fault replaced the northeast-trending segment of the Lewis Thrust of Price (1958, 1958, 1962). Jones (1964, p. 358)

argued it has a steep rather than shallow dip, as “suggested by the relatively straight surface trace over irregular topography”. He interpreted it as a northwest-directed reverse fault with at least 2 km of throw. The thrust north of the merger of the Southwest Boundary and North Boundary faults (short-dashed magenta line in Figure 13c) was unnamed, but is shown in cross-section (Jones, 1964, his section C–C’) to splay upward from the Southwest Boundary Fault in the subsurface.

- To the northeast, the trace of the Harvey Fault is as mapped by Price (1962), but Jones (1964) interpreted a more complex history of motion involving reverse-sense reactivation along only that segment between the North Boundary and Howell faults (Figure 13c).

Adjacent to these four boundaries, Jones (1964, p. 355) noted: “Except on the southwest margin [the Howell Fault], the Wapiabi shales and Cardium sandstones at the edges of the window, close to the boundary faults, dip steeply inwards and show a tendency to strike parallel to the faults.”

Jones (1964) hypothesized that following emplacement and broad folding of the Southwest Boundary sheet above the Lewis sheet, it was cross-cut and down-dropped to the southwest by the Harvey Fault. With movements of blocks kinematically restricted by the Harvey Fault, “Relative movement of the blocks north of the North Boundary fault and south of the Howell fault downwards and towards each other partly peeled off a sliver of Cardium and younger beds from the Blackstone shale beneath the thrust, forcing them upwards, together with the central part of the thrust sheet.” (Jones (1964, p. 360-361). He interpreted the Harvey Fault to be reactivated, with net reverse-sense offset, along the segment between the Howell and North Boundary faults (Figure 13c) to accommodate northwest-southeast contraction and consequent structural uplift of the Cretaceous strata between them.

Although Jones' (1964) conceptualization was illustrated with cross-sections (locations in Figure 4), the proposed fault displacements present serious kinematic challenges in three dimensions.

- His interpretation requires that both the Howell and North Boundary faults simultaneously cut (i.e., offset) but also either merge with or terminate against the Southwest Boundary Fault, resulting in topologically impossible cut-off relationships.
- The smoothly continuous hanging wall shared by the exposed portion of the Southwest Boundary Fault and the two unnamed imbricates (compare figures 8 and 13c) is not compatible with these imbricates splaying from the Southwest Boundary Fault at depth.
- The Southwest Boundary Fault, exposed only between its intersections with the Howell and North Boundary faults (Figure 13c), must lie in the sub-surface in the footwalls of the Howell, North Boundary, and Harvey faults, and also underlie MacDonald Dome. Jones (1964, p. 361) argues that east of the Flathead Fault, where no trace of the Southwest Boundary Fault sheet exists, it was entirely removed by erosion.

The D.Sc. thesis by Jones (1966) encompassed the Howell Creek structure, the structural windows through the Lewis Thrust exposed at Cate Creek and Haig Brook, the intervening MacDonald Dome, and the Paleogene Kishenehn Formation deposited primarily in association with the Flathead Fault (Figure 3). Regarding the Lewis Thrust interpretation of Price (1959), Jones (1966, p. 92) stated: "The controversy that arose from Price's correlation of this thrust with the Lewis thrust exposed on the opposite side of the Flathead fault was the main reason for the author's decision to study the area in greater detail." Among his new observations was a revisiting of the isolated outcrop at the headwaters of Lodgepole Creek interpreted by Price (1958, p. 179) as "sandstones typical of the Alberta group", as noted above. Referring to the structural window inferred by Price (1958, 1959, 1962) near the headwaters of Lodgepole Creek (figures 5, 6, and 8), Jones (1966,

p. 126) stated: “The strata previously mapped as Upper Cretaceous are actually in the Rocky Mountain and Rundle groups.”

His conclusions were essentially identical to Jones (1964), but the Southwest Boundary and North Boundary faults were renamed the Twentynine Mile Thrust and Akan Fault, respectively (Figure 13c). Regarding the Akan Fault, mapped by Price (1958, 1959, 1962) as a nearly flat-lying portion of the Lewis Thrust, Jones (1966, p. 127) stated: “… detailed mapping … indicates that the trace of the fault is almost straight. Such a trace, in an area of considerable relief, is indicative of a fault having a steep dip.”

Jones (1966) mapped the Twentynine Mile Thrust as having a significantly more sinuous trace than previously recognized. In addition to underlying the ridge between Twentynine Mile and Howell creeks, as mapped by Price (1962; Figure 8), Jones (1966) mapped this fault as underlying a portion of an adjacent ridge to the east, where it carries Mesoproterozoic as well as Cretaceous intrusive rocks. This feature, circled in yellow in Figure 13c, was mapped in greater detail by Skupinski and Legun (1989) and Brown and Cameron (1999).

Jones (1966) noted the close spatial association of irregular and distributed alkaline igneous intrusions, which are sparse to virtually absent elsewhere in the southern Canadian Rockies, with the Howell Creek structure as well as normal faults within and adjacent to MacDonald Dome (figures 1 and 3). He stated that “any theory of the origin of the window must account for the distribution of intrusions surrounding it” (Jones, 1966, p. 92).

Jones (1966, p. 135-148) reviewed and illustrated the interpretations of Price (1958, 1959, 1962) and Oswald (1964) and presented two alternatives (Figure 14). The first alternative interpretation, considered the “simplest possible” (p. 141), invoked normal-sense motion on the Howell Fault. The second alternative and preferred interpretation was an expansion of Jones (1964).

The first alternative interpretation of Jones (1966) combined elements of Oswald (1964) and Jones (1964), but interpreted both the shallowly northwest-dipping Howell Fault and the steeply southeast-dipping Akan Fault as normal faults, with displacement in the dip direction (i.e., opposite in sense to the interpretation of Jones, 1964, shown in Figure 13c). The shallowly dipping Twentynine Mile Thrust, nearly equivalent to the Western Thrust of Oswald (1964), was interpreted to be overridden by the steeply dipping Howell Creek Fault (Figure 14c). The large-displacement Twentynine Mile Thrust must root somewhere to the west, but unlike Oswald (1964; Figure 14b) it does not underlie MacDonald Dome (Figure 14c). Jones (1966, p. 151-152) dismissed this first alternative largely because of the implied extreme spatial coincidence of the Cretaceous intrusive rocks carried by the far-travelled Twentynine Mile Thrust with those across MacDonald Dome. An option not considered by Jones (1966) was interpreting the Howell Creek and Twentynine Mile faults shown in Figure 14c as a single, folded thrust. This could have led to an explanation similar to that of Labrecque and Shaw (1973; see below).

The second and preferred interpretation of Jones (1966; Figure 14d) is essentially equivalent to Jones (1964). In spite of presenting new detailed cross-sections, including a strike-parallel section that shows fault cut-off relationships that contradict those in the cross-strike sections (see locations in Figure 4), this interpretation suffers from the same issues as Jones (1964) and is therefore not viable.

DAHLSTROM (1970)

The landmark publication by Dahlstrom (1970) presented and explained many of the fundamental modern kinematic structural geology concepts of thin-skinned thrust-and-fold belts. Along with the highly influential paper by Bally et al.

(1966), Dahlstrom (1970) helped promote the southern Canadian Rocky Mountains as a global archetype for thin-skinned structural styles.

Dahlstrom (1970) briefly discussed the Howell Creek structure and partly supported the interpretation of Price (1958, 1959, 1962, 1965b), concluding that “the principal thrust fault in the window is therefore the Lewis thrust” (p. 386; see also his figure 58, p. 389, redrawn here as Figure 13d). His argument, however, which involved tracing the continuity of the Lewis sheet around the northern termination of the Flathead Fault (see Figure 1), merely demonstrated that the Mesoproterozoic and Paleozoic strata surrounding the Howell Creek structure must lie within or be carried by the Lewis sheet, but it does not demonstrate that the fault bounding the Cretaceous strata on the west is the Lewis Thrust. Dahlstrom (1970) did not refer to the Howell Fault by name, but described it as “a second generation thrust” (p. 387). Neither did he refer to the Harvey Fault by name, but northwest of its intersection with the Howell Fault it is labeled as a “fault of undetermined type” (denoted by question marks in Figure 13d), with the down-thrown side to the northeast.

Dahlstrom’s (1970) explanation of the apparent down-cutting of the Lewis Thrust in the direction of transport differs significantly from that proposed by Price (1958, 1959, 1962, 1965b), which he described as “improbable to say the least” (p. 390). He invoked normal-sense reactivation of part of a pre-existing thrust fault, where a later listric normal fault merges downward with a low-angle thrust surface. This reactivation results in a “compound fault” with both early thrust and later normal-sense displacement, across which stratigraphic section can be omitted (see figure 56 of Dahlstrom, 1970, p. 387).

Dahlstrom (1970) does not illustrate this concept with a cross-section explicitly across the Howell Creek structure. However, his discussion and a block diagram illustration (his figure 61, p. 393) involves normal-sense displacement on the Flathead Fault, which is known to merge downward with the folded Lewis

Thrust (Bally et al., 1966; noted above) resulting in the Lewis being a “compound fault” at depth. Dahlstrom (1970) implies that a portion of this compound fault was cross-cut and thrust upward by the “second generation” Howell Fault, which merged with and reactivated the pre-existing Harvey Fault (Figure 13d). Although the development of such a compound fault can result in substantial omission of strata across it, the Mesoproterozoic to Paleozoic rocks exposed west of the Howell Creek structure cannot have been thrust upward from the immediate hanging wall of the compound Lewis-Flathead Fault. The right-hand side of Figure 9 is overlain by the projected positions of the Lewis, Flathead, and compound Lewis-Flathead faults as constrained by McMechan (1981; labeled brown lines, Figure 9). The hanging wall cut-offs of Paleozoic strata exposed across Macdonald Dome (between Flathead Fault and the Howell Creek structure) and the implied underlying Proterozoic succession are all located east of the Harvey Fault, and therefore cannot have been thrust upward by the Howell Fault as proposed by Dahlstrom (1970).

LABRECQUE AND SHAW (1973)

The interpretation of Labrecque and Shaw (1973) utilized subsurface constraints provided by the CIGOL–IOE et al. Howell a–16–B well, drilled in 1970 and spudded in Cretaceous strata adjacent to Harvey Creek (see location in Figure 13e). The well intersected a fault, interpreted as the Howell Fault, only 322 m below the surface, which placed Cretaceous Cardium Formation onto Mississippian Mount Head Formation. In sharp contrast to previous authors, they interpreted the Howell Fault as a west- to southwest-directed normal fault rather than a thrust, which down-dropped Upper Cretaceous rocks from a higher level in the Lewis Thrust sheet. The well also intersected the Harvey Fault, firmly establishing its steep southwest dip and constraining its offset.

Their map interpretation (Figure 13e; north boundary at 49°16′30″N) involves subtle but important differences from those of previous authors. The fault bounding the Cretaceous exposures to the southwest and northwest, called the Lewis Thrust by Price (1958, 1959, 1962, 1965a,b; Figure 13a) and the Western Thrust by Oswald (1964; Figure 13b), is named the Southwest Boundary Fault by Labrecque and Shaw (1973; partly following Jones, 1964). They differed from these previous authors by continuing this fault to the southeast, past its merger with the Howell Fault (Figure 13e), although its continuation farther southeast beyond its intersection with mapped normal faults was not addressed. In accord with the interpretation of Jones (1964, 1966), they show no structural windows through this fault near the headwaters of either Lodgepole or Harvey creeks, although their cross-section (Figure 15) clearly shows the northern portion of the Southwest Boundary Fault as being nearly bed-parallel, as interpreted originally by Price (1958, 1959, 1962, 1965a,b). Their map was truncated to the north, as indicated in Figure 13e. The mapped trace of the Howell Fault was shown as merging smoothly with the Harvey Fault (highlighted by yellow oval in Figure 13e), as indicated in their cross-section (Figure 15).

Labrecque and Shaw (1973, p. 120) recognized that their single cross-section and partial restoration (Figure 15), which included an interpreted sub-Kishenehn erosion surface, did not fully address the complexities of the mapped geology:

> "Whereas we have a good degree of confidence in the restoration for the particular line of section, we are quite aware that the structure in this area has many complications and changes quite rapidly along strike. We believe, however, that it will serve conceptually for a restoration of the entire area."

Some features in figures 13e and 15 are either poorly supported by known map or stratigraphic constraints, or are not internally consistent. In addition, Labrecque and Shaw (1973) did not consider the along-strike implications. These shortcomings are discussed and addressed by the new interpretation presented below.

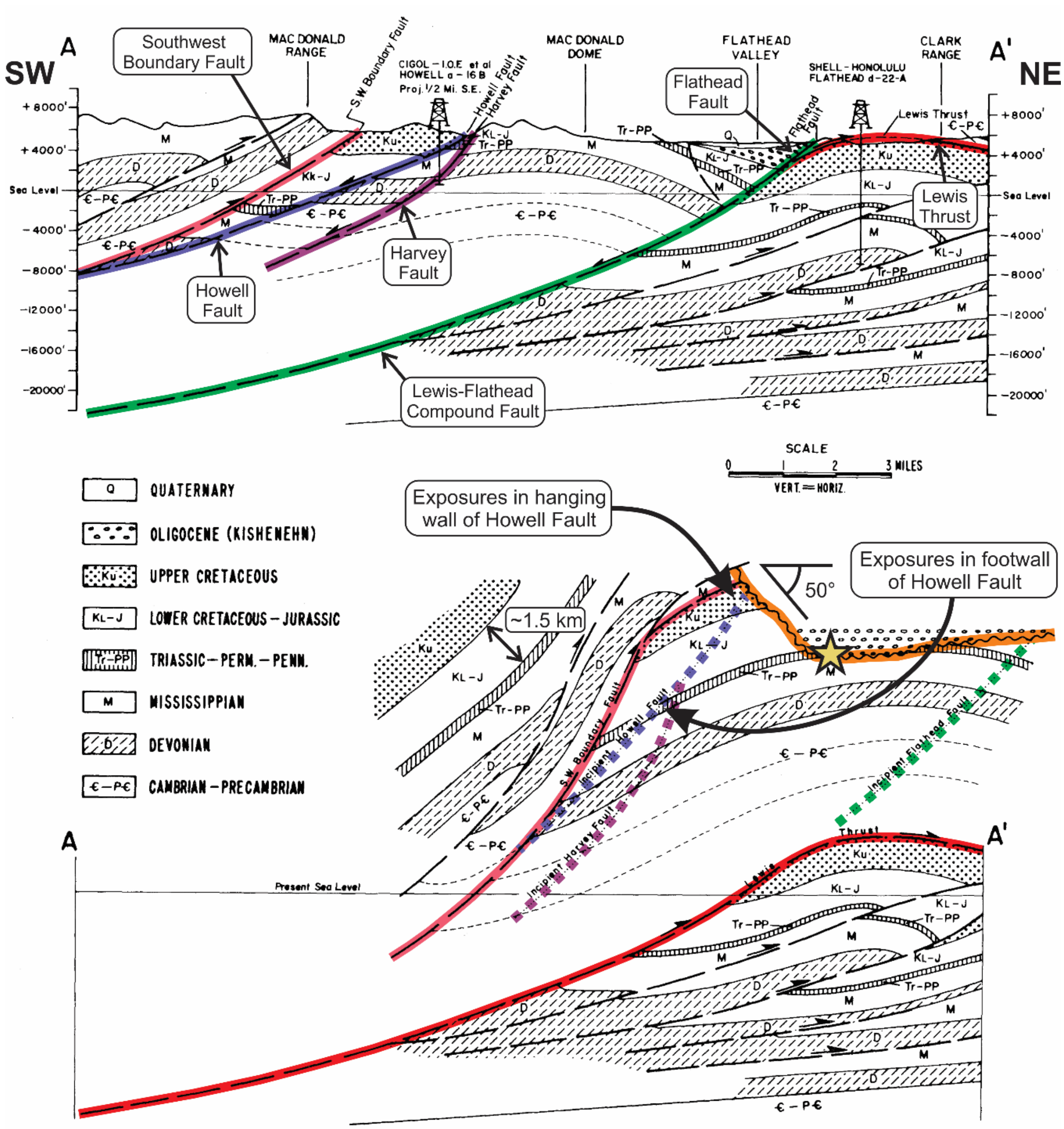


Figure 15: *Annotated reproduction of figure 2 of Labrecque and Shaw (1973), showing their cross-section A–A' (location shown here in figures 3 and 4) and a reconstruction prior to extension on the Howell, Harvey, and Flathead faults. Note the inferred sub-Kishenehn unconformity (highlighted in orange) in the restored section, which is shown as sub-horizontal in the hanging wall of the incipient Flathead Fault (dotted green line), but rapidly steepens to approximately 45° to the west. Although not explicitly stated by Labrecque and*

Shaw (1973), the position of the lowest point of this reconstructed unconformity (indicated by the yellow star) was probably constrained by observations of Jones (1969).

The normal-sense interpretation of the Howell Fault proposed by Labrecque and Shaw (1973) differs significantly from the scenario considered by Price (1965b; Figure 12). Comparison of figures 12 and 16 shows the essential differences between these interpretations.

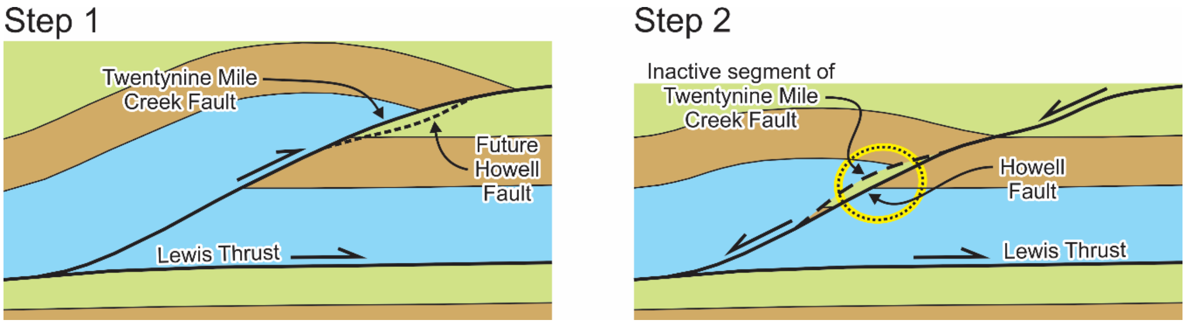


***Figure 16:** Schematic cross-sections, drawn in a style similar to Figure 12, illustrating the interpretation of Labrecque and Shaw (1973).*

JONES (1977)

The interpretation of Jones (1964, 1964) was effectively invalidated by the CIGOL–IOE et al. Howell a–16–B well reported by Labrecque and Shaw (1973). Although Jones (1977) did not directly challenge the normal-fault interpretation of Labrecque and Shaw (1973), he proposed that the Howell Creek structure could be interpreted as a large (20 km^2) but fully coherent gravitational rock slide (Figure 13f). He conjectured that the apparently consistent exposure of either Cardium Formation or upper Blackstone Formation at the margins of the structure (Jones, 1964, 1966) reflected a weak near-bedding-parallel detachment surface.

Jones (1977; p. 874) again dismissed the low-angle thrust interpretation for the northwest boundary of the Howell Creek structure:

> “the relatively straight trace of the Mississippian edge suggests that the contact between it and the adjacent Cretaceous has a steep dip, whatever its nature may be. A mile to the northwest, a small tectonic window mapped by Price (1959), which would have confirmed the presence of a low-angle thrust, does not exist. Purportedly Upper Cretaceous sandstone overthrust by Mississippian, is actually Permo-Pennsylvanian sandstone of the Rocky Mountain Formation, in normal stratigraphic continuity with the adjacent Mississippian.”

Among his observations was that the hilltop exposures of intruded Mesoproterozoic to Devonian strata between Howell and Twentynine Mile creeks are isolated from exposures to the southwest (Figure 13f) and that “the whole hillside down to Twenty-nine [sic] Mile Creek consists of Wapiabi shale strewn with large slumped blocks of older rocks including limestone and syenite” (Jones, 1977; p. 873). These observations are partially at odds with the detailed mapping by later workers (see below), but are indicative of bedrock exposures of Alberta Group strata along or adjacent to Twentynine Mile Creek. The southernmost margin of his inferred slide encompassed these Cretaceous exposures, leaving the isolated occurrence of much older hilltop exposures “still an enigma” (Jones, 1977, p. 876). This occurrence, along with a smaller block 1 km to the west (Figure 13f; shown as nearly encompassed by the inferred slide boundary), were suggested to “have been deposited on the Howell Creek slide after its emplacement” (Jones, 1977, p. 877). Within the main isolated hilltop block is “a curious occurrence of small, irregular masses of conglomerate, similar to those of the Kishenehn Formation”, dated with palynomorphs as Upper Eocene to Lower Oligocene, overlying Devonian Fairholme Group strata (Jones, 1977, p. 877).

Jones (1977) further conjectured that 20 km north of the Howell Creek structure, in Squaw Creek Valley (along the trace of the Squaw Fault; Figure 3), a much smaller (2 km^2) but again largely coherent rock slide occurs where Price (1965a, 1965b) mapped curious east-dipping to sub-vertical west-directed thrusts above the Squaw Fault. These structures are considered in detail and reinterpreted below.

The gravitational slide interpretation of Jones (1977) is highly unlikely for three reasons:

(1) The proposed slide masses are structurally coherent, showing no evidence for internal extension or disaggregation that should accompany long-distance transport down a slope.

(2) No explanation is provided for the creation of the 4+ km-deep “hole” into which the slide moved, nor for the fortuitous, adjacent preservation of the Upper Cretaceous strata that slid coherently into it.

(3) The occurrence of intruded Mesoproterozoic through Devonian on the hill between Howell and Twentynine Mile creeks is termed “an enigma” (p. 876), but is not explained by the slide hypothesis.

Skupinski and Legun (1989), and Legun (1993)

Skupinski and Legun (1989) focussed on the alkalic (trachyte-syenite) intrusive rocks mapped by Price (1962, 1965b) on the ridge between Howell and Twentynine Mile creeks (figures 8 and 13a), and to a lesser extent the ridge to the west mapped in the footwall of the Lewis Thrust by Price (1962, 1965b; Figure 8), and the hanging wall of the Southwest Boundary Fault by Jones (1966; Figure 13c). Their detailed page-figure map (approximate scale 1:16,660) showed that the southwestern slope of this ridge was underlain by considerably less intrusive material than mapped by Price (1962, 1965b). Their mapping of the moderately northeast-dipping and variably intruded Mesoproterozoic and Paleozoic strata down this slope appears to contradict Jones (1977; p. 873; see above), who stated this slope is largely underlain by Wapiabi Formation shale (compare figures 13f and 13g).

Skupinski and Legun (1989) did not directly address the regional structural setting of the Howell Creek structure. However, they adopted the informal name "southwestern thrust" for the fault identified as the Lewis Thrust by Price (1958, 1959, 1962, 1965b). Although not identified by name, with respect to the Howell Fault they commented (p. B29-B31): "The southeast border of the tectonic window is marked by an enigmatic fault which places Upper Cretaceous shales on top of Paleozoic carbonate rocks. The juxtaposition suggests a normal fault but Price (1965) presents arguments that the fault is a steeply dipping thrust. The continuation of this fault at Twentynine Mile Creek has been the subject of much controversy."

Legun (1993) briefly described mapping undertaken subsequent to Skupinski and Legun (1989) and made a direct illustrated map-view comparison between his interpretation and that of Price (1965b; compare figures 13a and 13g), but did not provide a cross-section. In a substantial departure from all previous interpretations, including Skupinski and Legun (1989), he identified two fault-bounded structural inliers (which he called "outliers") within the Howell Creek structure (Western Inlier and Eastern Inlier; Figure 13g). These inliers are interpreted as structurally separate from and lying in the footwall of the through-going and steeply southwest dipping Twentynine Mile Creek Fault (70° or greater southwest dip immediately south of the Western Inlier; p. 117).

Legun (1993; p. 119) estimated the attitudes of the faulted north and east boundaries encompassing the Eastern Inlier using results of gold exploration drilling[3] (Fox and Cameron, 1989) coupled with the mapped trace of the boundary across topography, and the attitudes of the south and west boundaries using the surface trace only. He stated the north boundary "dips steeply to the south", the east boundary "dips about 30˚ to the west" (which is essentially parallel to the underlying Howell Fault; see Price, 1965b, p. 107), the south boundary "near Twentynine Mile Creek appears to dip to the north-northwest", and the west

[3] Legun (1993) cited Cameron and Fox (1989), rather than Fox and Cameron (1989).

boundary “is steep near Twentynine Mile Creek based on its surface trace”. In spite of these assessments, the trace of this fault clearly indicates it is dipping shallowly to the southwest, as mapped by Price (1962, 1965b) and shown in Figure 9. Legun (1993) interpreted the southwestern corner of the Eastern Inlier as overridden by the Twentynine Mile Creek Fault, but emphasized that the Western Inlier “is surrounded by Cretaceous shale” (p. 119; Figure 13g).

Southeast of its interpreted high-angle intersection with the Howell Fault, Legun (1993) shows the Twentynine Mile Creek Fault as corresponding to the Southwest Boundary Fault of Labrecque and Shaw (1973; compare figures 13e and 13g). To the northwest, between the south end of the Western Inlier and Howell Creek, the Twentynine Mile Creek Fault trace closely corresponds to that of the Lewis Thrust of Price (1965b).

West and northwest of the Upper Cretaceous exposures Legun (1993) identified two distinct reverse or thrust faults he called the Western and Northwest Bounding faults, respectively (Figure 13g). He shows the south end of the Western Fault terminating against the Twentynine Mile Creek Fault at a high angle, and interprets it as being overridden (Legun, 1993, p. 119). On the basis of its trace across the topographic ridge north of Howell Creek (Figure 13g), which closely corresponds to the trace of the Lewis Thrust of Price (1965b) across this ridge (Figure 13a), Legun (1993) estimated a 50° westerly dip. The north end of the Western Fault is shown terminating at a high angle against the Northwest Bounding Fault, but this relationship is not discussed.

With respect to the attitude of the Northwest Bounding Fault, Legun (1993, p. 117) stated:

> “The northwest bounding fault is exposed along the Lodgepole Creek road [immediately west and parallel to Harvey Creek at this location; see Figure 13g] juxtaposing Paleozoic limestone over Cretaceous shale. A shallow dip of less than 10˚ to the northwest was measured. To the northeast this thrust

> fault terminates against the Harvey fault. To the southwest its trace is straight over steep topography, indicating a steepening of dip. Against the fault, Upper Cretaceous sandstones strike parallel and dip steeply southeast."

No previous or subsequent author has mapped or otherwise described an outcrop exposing this faulted contact (e.g., Price, 1965b, shows this fault trace as assumed), nor has new fieldwork revealed such an exposure along or adjacent to this road. Legun's (1993) description of a straight trace and therefore a relatively steep dip, with adjacent moderately to steeply southeast dipping Upper Cretaceous strata, matches the observations of Jones (1964, 1966, 1977), who interpreted this fault as steeply dipping to the southeast. Near Harvey Creek, Legun (1993) shows a significantly straighter trace for this fault than does Price (1958, 1959, 1965b), suggesting it is steeply dipping along its length (compare figures 6 and 13g).

Northeast and southeast of the Cretaceous exposures, Legun (1993) showed the traces of the Harvey and Howell faults as slightly offset from those of Price (1965b), but these differences are not significant to the interpretation. Legun (1993) interpreted the Howell Fault as a low-angle normal fault (Figure 13g), but he speculated that the base of the Upper Cretaceous sequence might be an unconformity (p. 119).

The detailed map observations of Skupinski and Legun (1989), and some of the map-scale interpretations of Legun (1993) have been incorporated into the new map compilation (Stockmal and Fallas, 2015), as discussed below.

BROWN AND CAMERON (1999)

Brown and Cameron (1999) described gold occurrences in association with the Howell Creek intrusives. They provided detailed page-figure maps of the Howell Creek structure overall, as well as the Eastern Inlier within it. A simplification of their interpretation, illustrated in Figure 13h, shows a number of sharp contrasts with previous interpretations. Although Brown and Cameron (1999) cite both Skupinski and Legun (1993) and Legun (1993), comparison of figures 13g and 13h indicates they interpreted an opposite sense of motion on almost every mapped fault except the Harvey Fault. Concentrating mainly on the intrusive rocks and economic geology, they provided no justification for their map interpretations, limiting their discussion of structure to one paragraph:

> "Detailed mapping of the HCS [Howell Creek structure], in particular the Eastern Outlier [Inlier], has documented the relationship between many of the bounding faults and the upper Cretaceous strata exposed in the core of the window. The current juxtaposition of units is attributed to high angle normal faults related to the Flathead Fault. The parallel eastern boundary fault of the Eastern Outlier [Inlier] and the Howell Thrust to the east could represent low angle structures."

As discussed below, the detailed map observations of Brown and Cameron (1999) have been incorporated into the new map compilation (Stockmal and Fallas, 2015).

FERMOR AND MOFFAT (1992), OSADETZ ET AL. (2004), AND HARDEBOL (2010)

Structural sections by Fermor and Moffat (1992), Osadetz et al. (2004), and Hardebol (2010) cross the Howell Creek structure as shown in figures 3 and 4 (labeled dark blue, red-brown, and light blue lines, respectively). These provide additional complementary insights into the regional setting.

The most detailed, publicly available, balanced, regional cross-section is that of Fermor and Moffat (1992).Their palinspastic restoration of structures in the Lewis Thrust footwall indicated a substantially larger magnitude of sub-Lewis shortening than previously recognized (61.5 km, versus approximately 40 km derived from Bally et al., 1966). As noted above, this results in a smaller magnitude of displacement on the Lewis Thrust (~55-60 km) than commonly cited (e.g., Feinstein et al. 2007). Constrained by well and proprietary seismic data, this cross-section illustrates the setting of the Howell Creek structure in the hanging wall of the listric Flathead Fault, which lies above the west flank of a large sub-Lewis duplex of Paleozoic rocks that fold and structurally elevate the Lewis Thrust, as exposed at the Cate Creek and Haig Brook windows (figures 1 and 3). Where the Howell Creek structure is explicitly labeled on their cross-section, the Upper Cretaceous rocks lie above an unidentified normal fault that merges down-dip to the west with an unidentified overriding thrust fault.

Assessment of the low-temperature thermochronology of the Lewis Thrust sheet by Osadetz et al. (2004) included a simplified cross-section based on Fermor and Moffat (1992), and a partial restoration to a time prior to extension on the Howell, Harvey, and Flathead faults (see also slight modification in Feinstein et al, 2007). The location of the Howell Creek structure is labeled on their cross-section, though neither fault bounding the Upper Cretaceous exposures is labeled by name or by sense of movement. The geometry of intersection between these bounding faults suggests that the upper fault was cut and carried by the lower fault, consistent with Price (1962, 1965b), although the Osadetz et al. (2004) cross-section does not extend far enough west to make this relationship clear. Similar to Labrecque and Shaw (1973), the partially restored cross-section of Osadetz et al. (2004) included a schematic approximation of the Early Oligocene erosion surface prior to extension. However, this surface is shown only to the east of the Howell Creek structure, and does not incorporate the mapping by Jones (1966, 1969) of Kishenehn Formation overlying Livingstone Formation less than 2 km from the Harvey Fault.

Hardebol (2010) presented three regional cross-sections (see also earlier versions in Hardebol et al., 2007, 2009) and one strike-parallel section, in support of model-oriented studies addressing the complex thermal history across the kinematically evolving thrust belt. The strike-parallel section and one of the strike-perpendicular sections traverse the Howell Creek structure (locations in figures 3 and 4). Although Hardebol (2010; p. 14) credits Labrecque and Shaw (1973) with correctly interpreting the structural setting of the Upper Cretaceous strata at Howell Creek, his highly generalized regional-scale sections (his figure 2.2) portray the Howell Creek structure as a thin down-dropped block containing a stratigraphically continuous section from Upper Cretaceous down to basal Devonian. However, his strike-parallel section nicely illustrates the regional structural high upon which the Howell Creek structure is located, which he attributed to one or more thick slices of Paleozoic strata underlying the Lewis Thrust sheet (apparently following the strike-perpendicular interpretation of Fermor and Moffat, 1992), with lateral ramps to both north and south.

NEW INTERPRETATION

HOWELL CREEK STRUCTURE

The principle differences in previous interpretations of the Howell Creek structure concern the faults that bound the Upper Cretaceous strata, rather than the stratigraphic identities of the rocks juxtaposed across them (Figure 13). Incremental mapping and re-evaluation of the structure over time has resulted not only in the series of interpretations presented above, but also a wealth of observations that constrain these bounding structures. The firm observations (as opposed to interpretations) of successive authors are not strongly contradictory, with a few notable exceptions. Compilation of observations and assessment of these previous interpretations using aerial photographs, draped Google Earth™ imagery, and limited field observations has led to a new, integrated view of the Howell Creek structure (Figure 17; Stockmal and Fallas, 2015).

The Howell Fault, which bounds the Upper Cretaceous strata to the southeast, is interpreted as a normal fault, consistent with map constraints and the results of the CIGOL–IOE et al. Howell a–16–B well (Labrecque and Shaw, 1973). Compilation of detailed mapping by Price (1965b), Jones (1966), and Brown and Cameron (1999), coupled with the observations of Labrecque and Shaw (1973) and limited new mapping, indicate a shallowly northwest-dipping fault juxtaposing

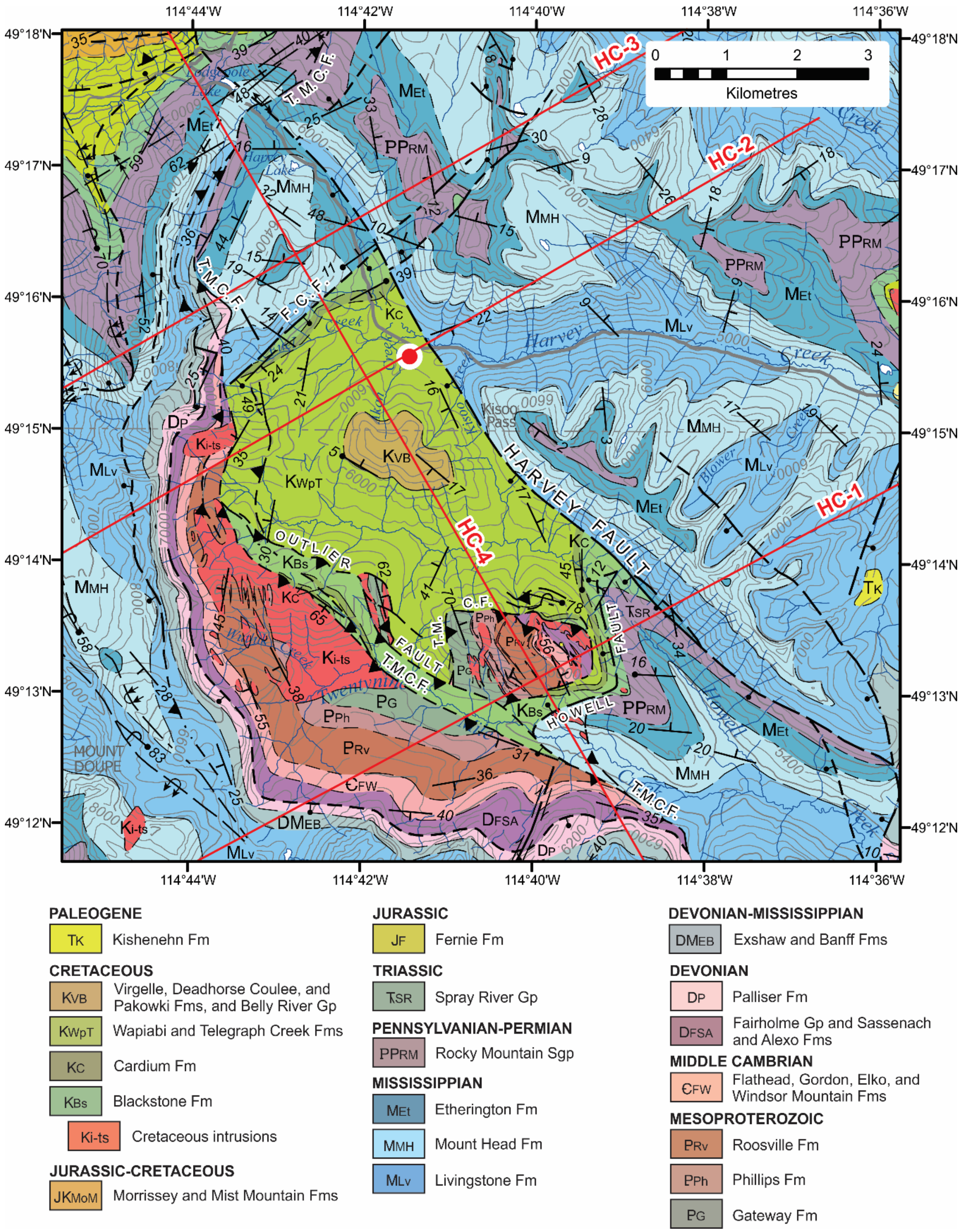


Figure 17: *New map interpretation of the Howell Creek structure. Figure derived from digital data in Stockmal and Fallas (2015), which includes complete source information for all observations. Locations of structural sections in figures 19, 20, 21, and 22 are shown as labeled red lines; full extents of these lines of section, with the exception of the northeast*

end of HC-1, are shown in Figure 4. Red-filled circle indicates location of the CIGOL–IOE et al. Howell a–16–B well. Confidence levels of mapped contacts, faults, and folds are indicated by solid, long-dashed, and short-dashed lines, corresponding to defined, approximate, and inferred, respectively (see data in Stockmal and Fallas, 2015). Note Kishenehn Formation (yellow) unconformably above Livingstone Formation near 49°13'50"N, 114°36'W (from Jones, 1966, 1969). F.C.F. = Fuel Creek Fault; T.M.C.F. = Twentynine Mile Creek Fault.

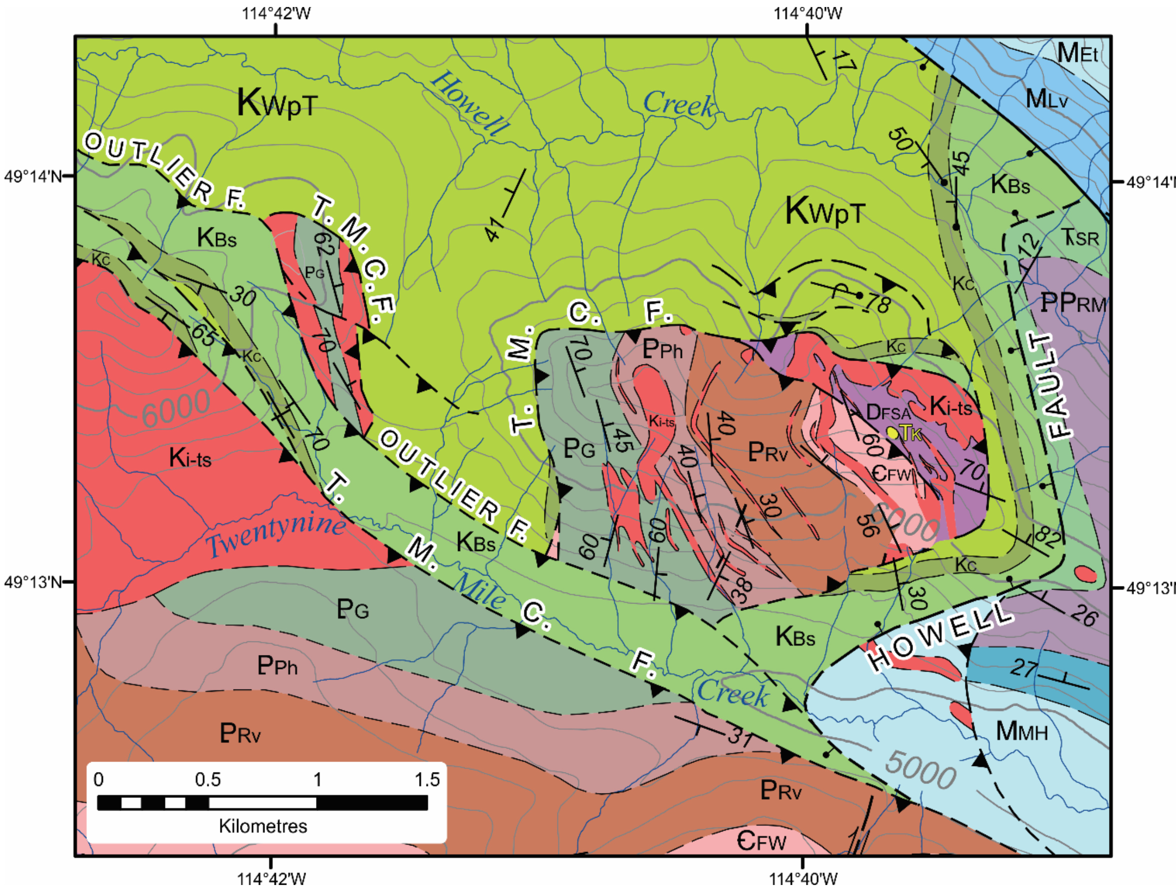


Figure 18: *Detailed map of the two structural inliers carried on the Twentynine Mile Creek Fault, which are truncated to the southwest by the Outlier Fault. Unit colours and labels defined in Figure 17. Note small outcrop of Kishenehn Formation (yellow) unconformably above Devonian strata at 49°13'23"N, 114°39'40"W, near the east end of the larger inlier (from Jones, 1977). T.M.C.F. = Twentynine Mile Creek Fault.*

Blackstone Formation above, against Mount Head Formation and Spray River Group below. The footwall includes a small thrust that merges with the Howell

Fault (figures 17 and 18). This interpretation implies that the Upper Cretaceous exposures at Howell Creek lie between the Howell and Twentynine Mile Creek faults as shown schematically in Figure 16.

Southwest of the Upper Cretaceous exposures, compilation of detailed mapping by Price (1965b), Jones (1966), Skupinski and Legun (1989), and Brown and Cameron (1999), coupled with observations discussed by Jones (1977) and Legun (1993), indicate a through-going thrust, here named the Twentynine Mile Creek Fault (Figure 17; Stockmal and Fallas, 2015). Southeast of the Howell Creek structure this fault has little to no stratigraphic offset immediately west of the Harvey Fault (Figure 4). The Howell Fault is interpreted to merge smoothly with the Twentynine Mile Creek Fault, but this is largely unconstrained. To the northwest, the Twentynine Mile Creek Fault places locally intruded Mesoproterozoic, Cambrian, and Devonian strata over Alberta Group strata, where the latter appear to be thrust-imbricated (figures 17 and 18). Although partly interrupted by minor thrust-, normal-, and cross-faults, the hanging wall of the fault remains essentially intact as its trace progressively curves to the north-northeast (figures 4 and 17). The interpretation of the Twentynine Mile Creek Fault shown here differs from that of Legun (1993) in that included in its hanging wall are those rocks that he placed in the hanging wall of his Western Fault (Figure 13g).

Northwest of the Upper Cretaceous exposures, the Fuel Creek Fault (Figure 17; Stockmal and Fallas, 2015) is interpreted as steeply dipping, consistent with the mapping and arguments of Jones (1964, 1966, 1977). It terminates against the Twentynine Mile Creek Fault to the southwest, and the Harvey Fault to the northeast (Figure 17). Its trace is nearly identical to that of the Akan Fault of Jones (1966), but the Fuel Creek Fault is interpreted as a small-offset down-to-the-southeast normal fault, as discussed below. Detailed mapping and observations by Jones (1966, 1977), coupled with limited new observations, indicate that Alberta Group strata in the hanging wall of the Fuel Creek Fault dip shallowly to moderately southeast (Figure 17). Rundle Group strata exposed in the immediate footwall dip shallowly to moderately northeast (Figure 17).

The Harvey Fault bounds the Upper Cretaceous strata to the northeast, in accord with all previous interpretations except Jones (1977; Figure 13). All observations, including the results of the CIGOL–IOE et al. Howell a–16–B well (Labrecque and Shaw, 1973), indicate it is a moderately to steeply dipping down-to-the-southwest normal fault (Figure 17). Approximately 3.5 km south of its intersection with the Howell Fault, McMechan (1981) estimated 1.7 km of displacement (1.4 km of throw) on the Harvey Fault (location of figure 3.16 of McMechan, 1981, is shown in Figure 4). Map relationships and well data (see new cross-sections, below) indicate that displacement on the Harvey Fault decreases progressively to the northwest, in contrast to the interpretation of Price (1965b; see Figure 10).

Figure 18 shows the map compilation encompassing the inliers identified by Legun (1993), based on detailed mapping by Price (1965b), Jones (1966), Skupinski and Legun (1989), Legun (1993), and Brown and Cameron (1999), coupled with observations discussed by Jones (1977) and Legun (1993). The inliers consist of intruded Gateway Formation through Fairholme Group strata, identical to the stratigraphy carried by the Twentynine Mile Creek Fault immediately to the southwest (Figure 18). The fault underlying the inliers is identified as the Twentynine Mile Creek Fault, consistent with the overall folded thrust interpretation of Price (1962, 1965b; see figures 8 and 9). The newly interpreted Outlier Fault (Stockmal and Fallas, 2015; the “outlier” in this instance is the Howell Creek structure itself) accommodates the occurrence of fault-repeated Alberta Group strata west of the western inlier, which crop out significantly upslope from the inlier, but east of the main through-going trace of the Twentynine Mile Creek Fault (Figure 18). South of the eastern inlier, the inferred Outlier Fault partly reconciles conflicting observations of Jones (1977) in comparison to Skupinski and Legun (1989) and Brown and Cameron (1999); Jones (1977; p. 873; see above) stated that Alberta Group shale cropped out on this hillside down to the creek, but he did not clearly specify where these observations were made.

A few kilometres southeast of the Howell Creek structure the Twentynine Mile Creek Fault has little to no stratigraphic offset (figures 3 and 4), as noted above. It is interpreted as offset across the younger Harvey Fault (as mapped by McMechan, 1981) and to continue to the southeast along the trace of a normal fault mapped by Price (1962, 1965b, 2013) that cuts inferred mid-Cretaceous intrusions before disappearing beneath Quaternary cover in Flathead Valley (Figure 3). North of the Howell Creek structure the Twentynine Mile Creek Fault is inferred to follow McLatchie Creek Valley (Stockmal and Fallas, 2015; McLatchie Creek headwaters are labeled in Figure 13), where Triassic Spray River Group is thrust over Jurassic Fernie Formation (figures 3 and 4; Price, 1965a).

Three structural cross-sections and one strike-parallel section across the Howell Creek structure have been constructed (figures 19, 20, 21, and 22; see locations in figures 4 and 17). The strike-perpendicular sections (HC-1, HC-2, and HC-3) are area-balanced with constant stratigraphic thicknesses except in obviously thickened fold hinges; each is accompanied by a palinspastic restoration. Very minor westward thickening of strata is expected across the area, but thicknesses were assumed constant for simplicity. Although these sections are 2-D, they were constructed jointly to describe the general 3-D geometry.

Section HC-1 (Figure 19) overlies the cross-section of Fermor and Moffat (1992; see figure 4), and incorporates their interpretation of the Lewis Thrust and sub-Lewis structure, which includes a duplex stack with ~4.0 km of structural relief that broadly folds the overlying Lewis Thrust. On this line of section, offset across the Harvey Fault is ~1050 m, constrained by mapped relationships and stratigraphic thicknesses. The Harvey Fault clearly post-dates the Howell Fault, on the basis of the mapped cross-cutting relationship (Figure 17). The folded Twentynine Mile Creek Fault underlies the two inliers, and is cross-cut by the

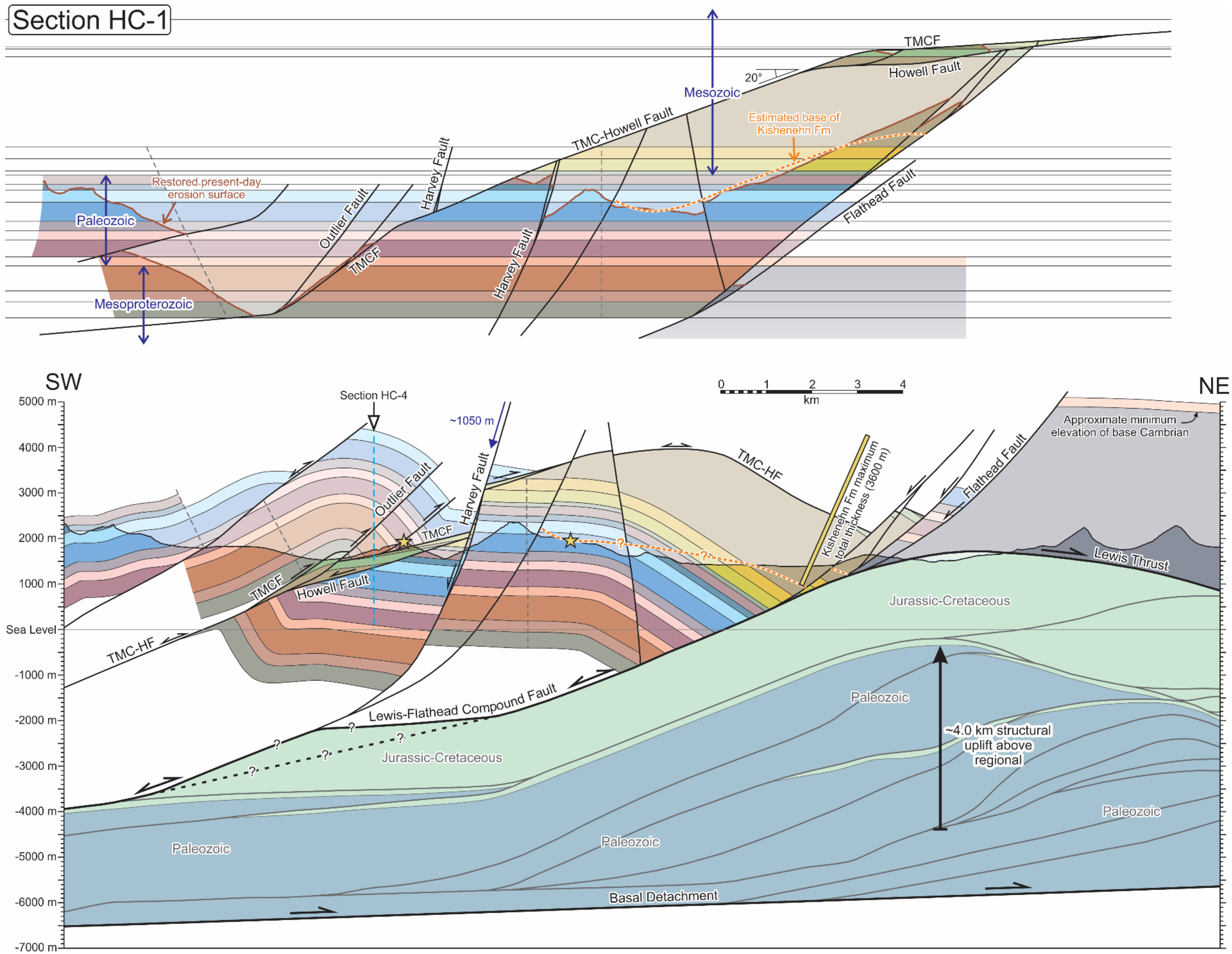

Section HC-1
TMCF
Howell Fault
20°
Mesozoic
Estimated base of Kishenehn Fm
TMC-Howell Fault
Flathead Fault
Harvey Fault
Outlier Fault
TMCF
Harvey Fault
Restored present-day erosion surface
Paleozoic
Mesoproterozoic
SW
NE
5000 m
4000 m
3000 m
2000 m
1000 m
Sea Level
-1000 m
-2000 m
-3000 m
-4000 m
-5000 m
-6000 m
-7000 m
Section HC-4
~1050 m
0 1 2 3 4
km
Outlier Fault
Harvey Fault
TMCF
TMCF
Howell Fault
TMC-HF
TMC-HF
Kishenehn Fm maximum total thickness (3600 m)
Flathead Fault
Approximate minimum elevation of base Cambrian
Lewis Thrust
Jurassic-Cretaceous
Lewis-Flathead Compound Fault
Jurassic-Cretaceous
Paleozoic
~4.0 km structural uplift above regional
Paleozoic
Paleozoic
Paleozoic
Basal Detachment

Figure 19 (previous page): *Structure section HC-1 and palinspastic reconstruction; see location in figures 4 and 17. Stratigraphic unit colours and thicknesses as indicated in Figure 2. Grey dashed lines are "loose lines" to aid in visualizing deformation, which are perpendicular to bedding in the deformed section. Vertical blue dashed line indicates location of section HC-4. Yellow stars indicate projected positions of Kishenehn Formation outcrops shown in figures 17 and 18, and short-dashed orange lines show estimated base of this unit east of Harvey Fault in both the deformed and restored sections. The maximum preserved subsurface thickness of Kishenehn Formation occurs near the international border (McMechan, 1981). Geometry of the Lewis Thrust, the compound Lewis-Flathead Fault and sub-Lewis structures are from Fermor and Moffat (1992; see for details; strata are grouped here for simplicity as Paleozoic and Jurassic-Cretaceous). Constraints on the flat-ramp-flat trajectory of the compound Lewis-Flathead Fault through the Jurassic-Cretaceous section shown by Fermor and Moffat (1992) are unknown, but a smoother alternative path is indicated (short-dashed black line). Approximate minimum elevation of base Cambrian, shown in the footwall of the Flathead Fault and carried by the Lewis Thrust, determined from thicknesses of Mesoproterozoic strata (Figure 2) coupled with known structural thickening (Fermor and Price, 1987; Fermor and Moffat, 1992). TMCF = Twentynine Mile Creek Fault; TMC-HF = Twentynine Mile Creek–Howell Fault.*

small-displacement Outlier Fault, which branches upward from the Howell Fault. Strata in the hanging wall of the Twentynine Mile Creek Fault are shown as anticlinally folded, consistent with the general interpretation of Price (1962, 1965b).

The Twentynine Mile Creek Fault is shown as cutting through the inter-limb and fore-limb of a pre-existing fold pair, consistent with the large folds mapped west of the Howell Creek structure that includes the Bighorn Anticline (figures 3 and 4, and sections HC-2 and HC-3, discussed below); alternatively, this structure could be interpreted as a fault-propagation fold. A low-angle normal fault in the hanging wall of the Twentynine Mile Creek Fault is one of a handful of local faults that may be normal-sense reactivated thrusts (Figure 17). The palinspastic restoration (Figure 19, top) was constructed with a 20° dip relative to bedding for the Twentynine Mile Creek–Howell Fault above the level constrained by mapped relationships, consistent with the mapped cut-off angles in the footwall of the Howell Fault (Figure 19, bottom).

In the absence of independent constraints, equal magnitudes of normal-sense heave for the Twentynine Mile Creek–Howell Fault were assumed in sections HC-1, HC-2, and HC-3 (below). In comparison to the 20° relative dip in section HC-1, this assumption yields slightly steeper fault dips in sections HC-2 and HC-3. Shallower dips would simply imply larger magnitudes of initial thrust displacement on the Twentynine Mile Creek Fault, as well as larger subsequent normal-sense displacements involving the Howell Fault. The reconstruction suggests that the Howell Fault formed as a footwall cut-off to the Twentynine Mile Creek Fault.

Section HC-2 (Figure 20) is constrained by the CIGOL–IOE et al. Howell a–16–B well, which is interpreted to intersect both the Howell and Harvey faults. Combined map and well constraints indicate an offset across the Harvey Fault of ~850 m (throw on nearby section G–H of Price, 1965b, shown in Figure 10, is ~1300 m). The Howell Fault cross-cuts strata at low angles in both its hanging wall and its footwall (Figure 20), similar to the interpretation of section HC-1 (Figure 19).

Section HC-3 (Figure 21) illustrates the interpretation of Rundle Group strata exposed northwest of the Fuel Creek Fault (Figure 17) as the southwestern flank of MacDonald Dome, down-dropped ~450 m across the Harvey Fault (throw on nearby section E-F of Price, 1965b, shown in Figure 10, is ~1500 m). This interpretation is in sharp contrast to the interpretations of most previous authors (with the exception of Jones, 1964, 1966, 1977; Figure 13). As shown in Figure 21, northwest of the Fuel Creek Fault the Howell Fault and the overlying Upper Cretaceous strata are interpreted to have been removed by erosion.

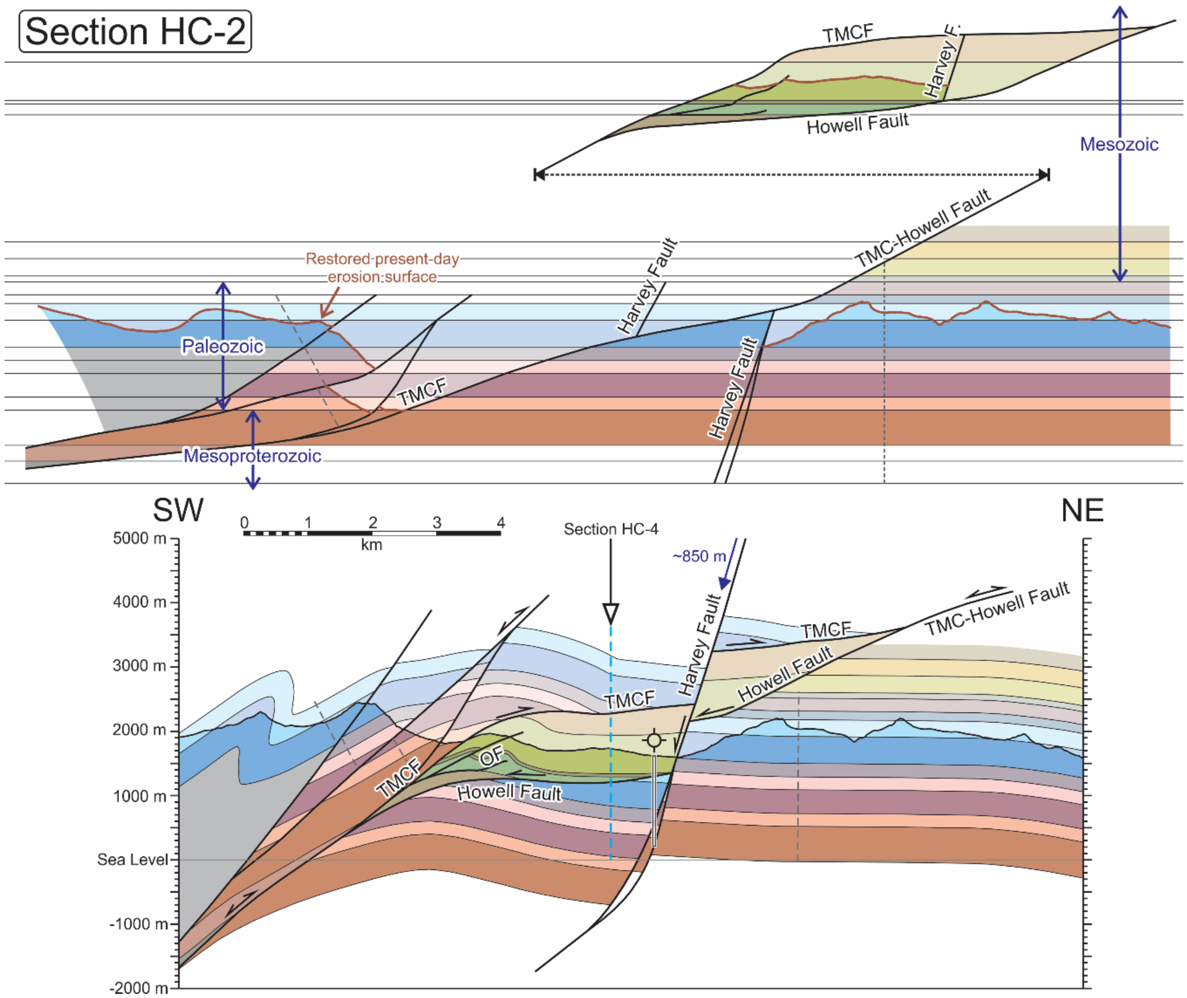


Figure 20: *Structure section HC-2 and palinspastic reconstruction; see location in figures 4 and 17. The horizontal offset of the TMC-HF in the reconstructed section does not represent an actual offset; it merely saves space in the figure.*

Normal-sense offsets across the Harvey Fault in the new interpretation are in better accord with the available constraints than the interpretation of Price (1965b). As indicated in Figure 10, Price (1965b) interpreted throw across the Harvey Fault to increase from ~800 m in the southeast to ~1500 m in the northwest, before abruptly decreasing farther northwest, north of Lodgepole Creek. The new interpretation, using map and well constraints, indicates offset increasing monotonically from northwest to southeast, with estimates of 450 m, 850 m, and 1050 m at cross-sections HC-3, HC-2, and HC-1, respectively (figures 21, 20, and 19). These are consistent with the estimate of ~1.7 km by McMechan (1981; noted above) at a point a few kilometres southeast of the Howell Creek structure (see cross-section location in figures 3 and 4).

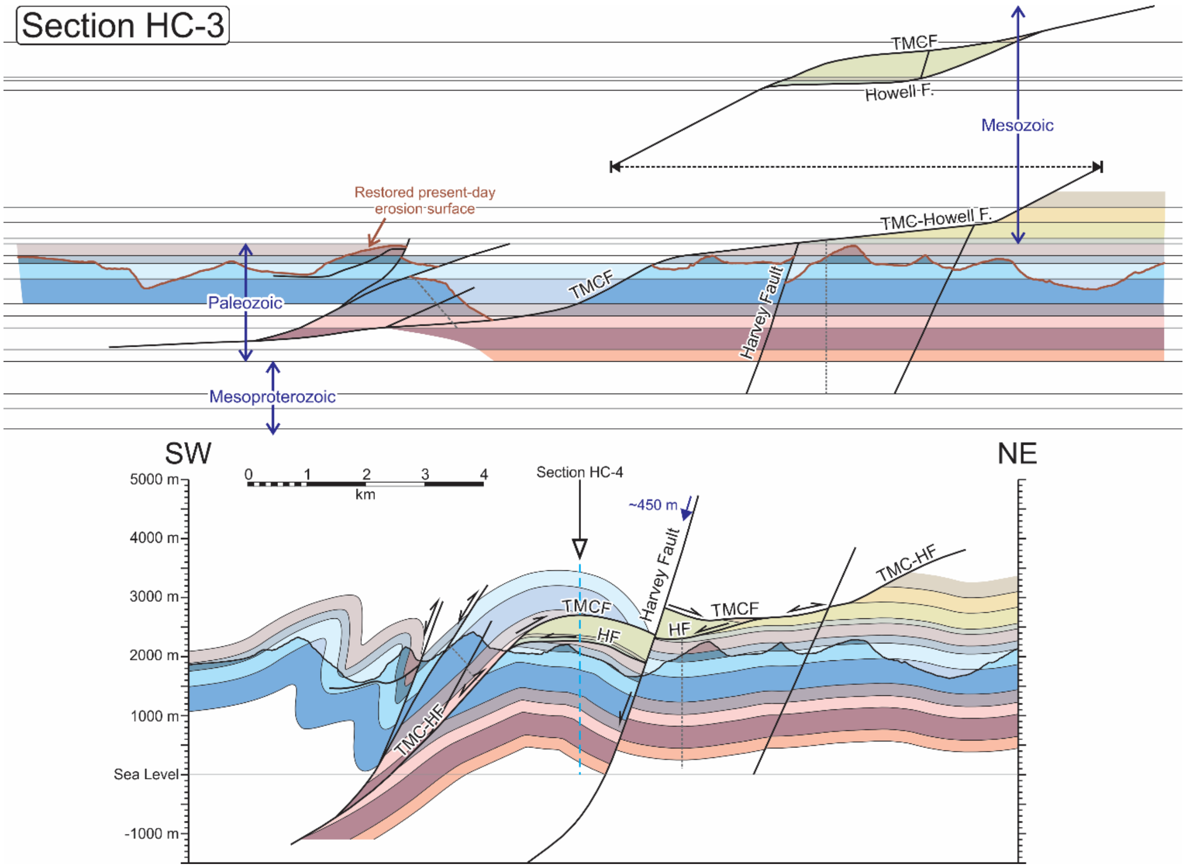


Figure 21: *Structure section HC-3 and palinspastic reconstruction; see location in figures 4 and 17. The horizontal offset of the TMC-HF in the reconstructed section does not represent an actual offset; it merely saves space in the figure.*

Section HC-4 (Figure 22) illustrates the 3-D nature of the Howell Creek structure, and the along-strike relationships between the Howell, Twentynine Mile Creek, Outlier, and Fuel Creek faults. Interpreted down-to-the-southeast normal-sense motion across the Fuel Creek Fault is ~200 m. This modest displacement is sufficient to offset the shallowly dipping Howell Fault such that it underlies the Upper Cretaceous strata to the southeast, but is entirely eroded to the northwest. The compound Twentynine Mile Creek–Howell Fault is folded across the oblique North Kootenay Pass Monocline (figures 13, 4, and 17) suggesting that motion on this fault at least partly predated development of the monocline (discussed below).

Note that the interpretation northwest of the Fuel Creek Fault (Figure 22) could be slightly adjusted to accommodate the observations and interpretation of Price (1958; noted above), of exposure of Cardium Formation near the headwaters of Lodgepole Creek. On section HC-4, the eroded branch line between the Twentynine Mile Creek and Howell faults could be moved downward to the northwest, to lie in the shallow subsurface, and the Cardium Formation cut-off could lie near or at this branch line. On the map, this would result in a narrow slice of Cardium Formation bounded above by the Twentynine Mile Creek Fault and below by the sub-parallel Howell Fault.

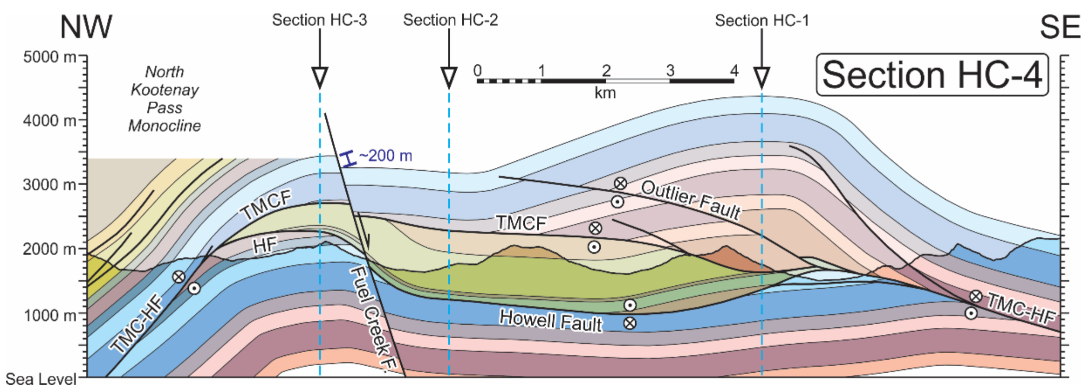


Figure 22: *Structure section HC-4; see location in figures 4 and 17. Circle and "X" symbol represents the tail end of an arrow, showing relative motion into the plane of the section away from the viewer. Circle and "dot" symbol represents the head of an arrow, showing relative motion out of the plane of the section toward the viewer.*

As noted above, Jones (1966) emphasized the close spatial association of alkaline igneous intrusions (called the Flathead intrusions by Brown and Cameron, 1999) with the Howell Creek structure and nearby normal faults. He argued that the rocks hosting these intrusions should all lie in the same thrust sheet; otherwise, their juxtaposition would be an unlikely coincidence. Normal-sense reactivation of a pre-existing thrust, as proposed by Labrecque and Shaw (1973) and adapted in the new interpretation, easily accounts for this spatial correspondence because the normal-sense motion on the Twentynine Mile Creek Fault nearly equals the preceding thrust-sense motion (figures 19, 20, and 21).

SQUAW CREEK STRUCTURE

North-northeast of the Howell Creek structure, the Twentynine Mile Creek Fault is interpreted to follow the trace of a thrust mapped by Price (1965a) along the floor of McLatchie Creek Valley to its intersection with the Shepp Fault (figures 3 and 23; Stockmal and Fallas, 2015). North of the Flathead Fault, the Squaw Fault is interpreted as the fault-offset equivalent to the Twentynine Mile Creek Fault (Figure 23), similar to the equivalence drawn by Price (1965b, p. 109) between the Squaw and Howell thrusts. Segments of the Squaw Fault clearly show both thrust-sense and normal-sense cumulative offset (Price, 1958, 1959, 1965a; figures 23 and 24), similar to segments of the Twentynine Mile Creek Fault, as noted above. Price (1965b, p. 104) interpreted the apparent normal-sense offset across the Squaw Fault as the result of overprinting contractional structures: "These relationships … indicate that the Squaw thrust has been discordantly superimposed across earlier

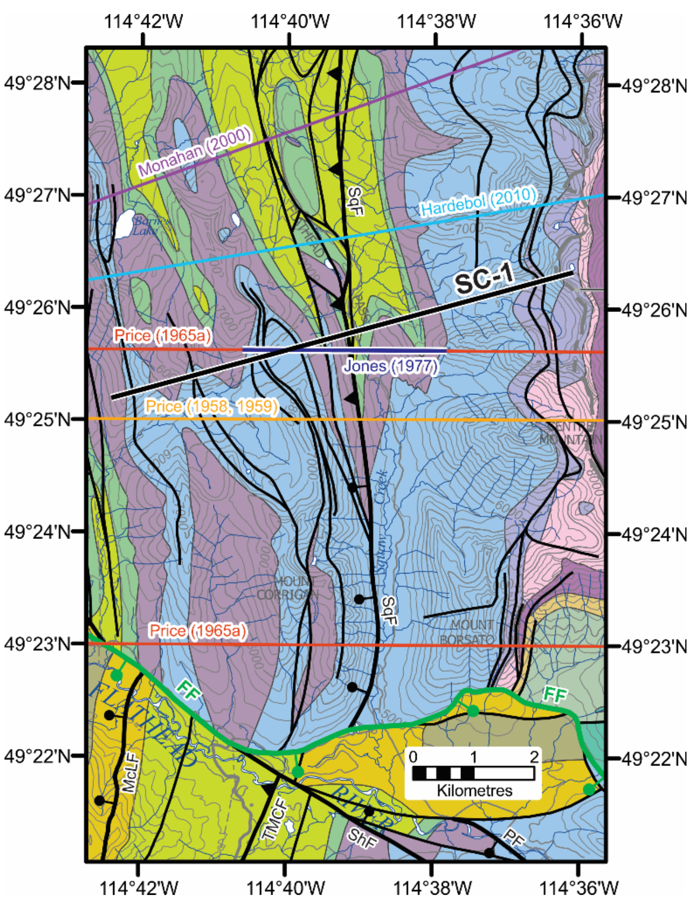


***Figure 23:** Detail of Figure 3 on topographic base, centred on Squaw Creek and Flathead Pass, showing locations of published structural sections. Note that section of Jones (1977) overlies one section of Price (1965a). Section SC-1 is shown in Figure 25c. Unit colours as defined in Figure 1. See Figure 3 caption for fault abbreviations.*

northwest-striking folds and has in part at least truncated and offset these structures.” He did not explicitly consider that these relationships might reflect normal-sense reactivation of thrust faults, in spite of some faults mapped by him that suggest this behaviour. A prime example is the “Flathead fault” of Price (1965a), which is now recognized as the McEvoy Fault (Figure 3; Ollerenshaw, 1981; see Stockmal and Fallas, 2015).

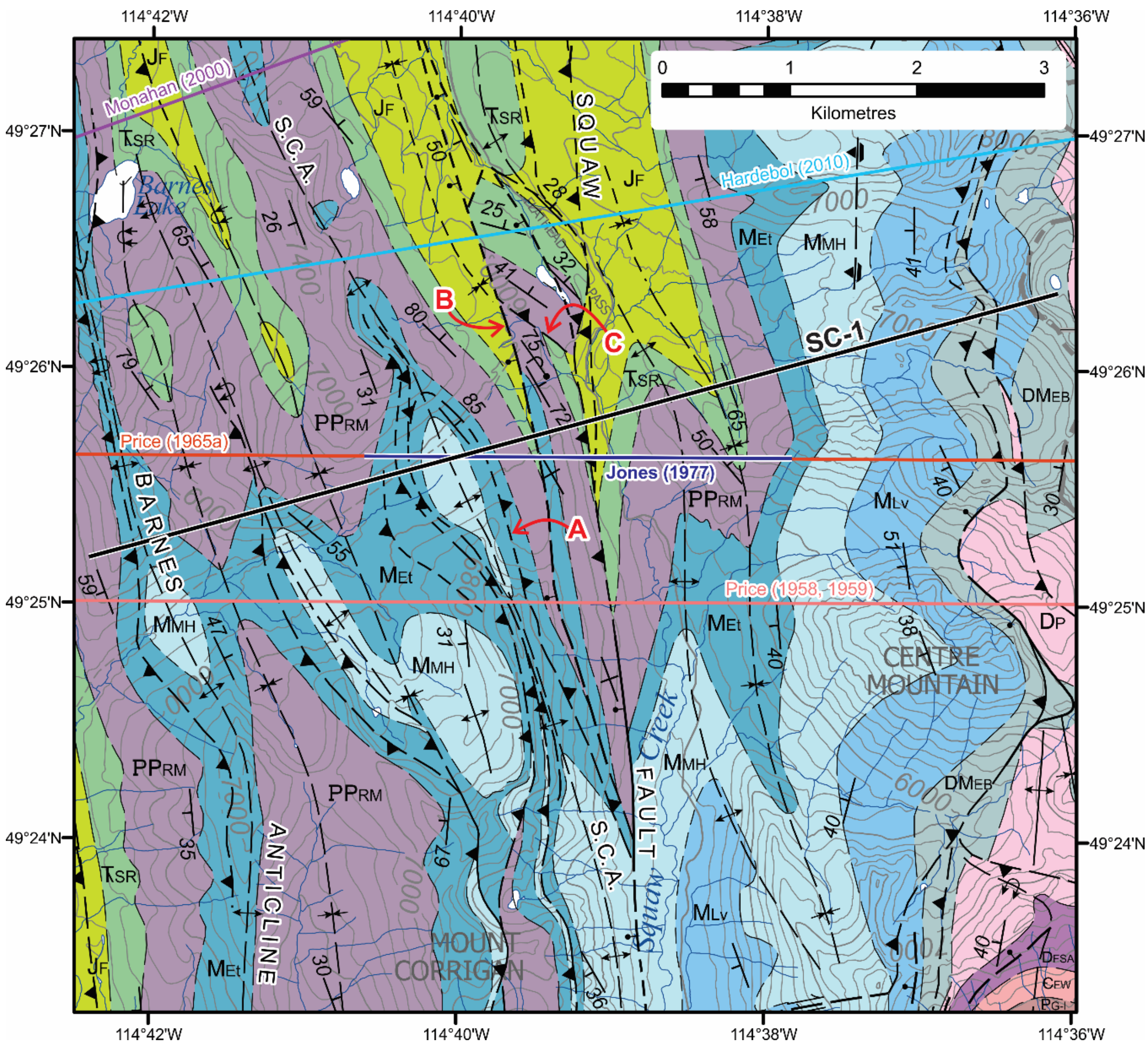


Figure 24: *New map interpretation of the Squaw Creek structure. Figure derived from digital data in Stockmal and Fallas (2015). Structural sections of Price (1965a; red line) and Jones (1977; dark blue line), and new section SC-1 (black line) are shown in Figure 25. Confidence levels of mapped contacts, faults, and folds are indicated by solid, long-dashed, and short-dashed lines, corresponding to defined, approximate, and inferred,*

respectively (see data in Stockmal and Fallas, 2015). S.C.A. = Squaw Creek Anticline. Features "A", "B", and "C" (red letters and arrows) are discussed in the text.

Southwest of Flathead Pass (49°26′30″N, 114°39′15″W; Figure 24), Price (1958, 1959, 1965a) mapped two east-dipping but west-directed thrust faults on the east flank of the Squaw Creek Anticline, which appear in cross-section C-D of Price (1965a; Figure 25a). Price (1965b, p. 105) interpreted these unusual features, which "thicken the stratigraphic sequence in this limb of the anticline and terminate to the east against the underlying Squaw thrust", to "terminate at depth in the core of the overridden syncline." Although he inferred that these were "flexural-slip thrust faults" that accommodated folding of the Squaw Creek Anticline and the corresponding syncline to the east, prior to being truncated and overridden by the Squaw Fault (Figure 25a), his cross-section is not balanced.

Jones (1977; p. 878) interpreted the "curious … Squaw Creek structure" as a gravitational slide (Figure 25b), similar to his interpretation for the Howell Creek structure (Figure 13f), stating that the interpretation of Price (1965a) involved "mechanics and geometry [that] are hard to envisage". His gravitational slide interpretation for Squaw Creek suffers from most of the same problems as noted above for Howell Creek, but Jones (1977) did draw attention to the unusual nature of the interpretation of Price (1965a).

Figure 25c presents an alternative, balanced cross-sectional interpretation for the Squaw Creek structure that is consistent with the Squaw Fault being a normal-sense reactivated thrust fault, and in addition explains some of the detailed structure mapped by Price (1965a) in the vicinity of Flathead Pass that was not explicitly discussed by him or illustrated in cross-section. Faults labeled "A" and "B" in Figure 25c correspond with the back-thrusts labeled in Figure 25a. Fault "A" is interpreted as an early east-directed thrust that was folded across the Squaw Creek Anticline, and was subsequently cross-cut by fault "B", which is interpreted

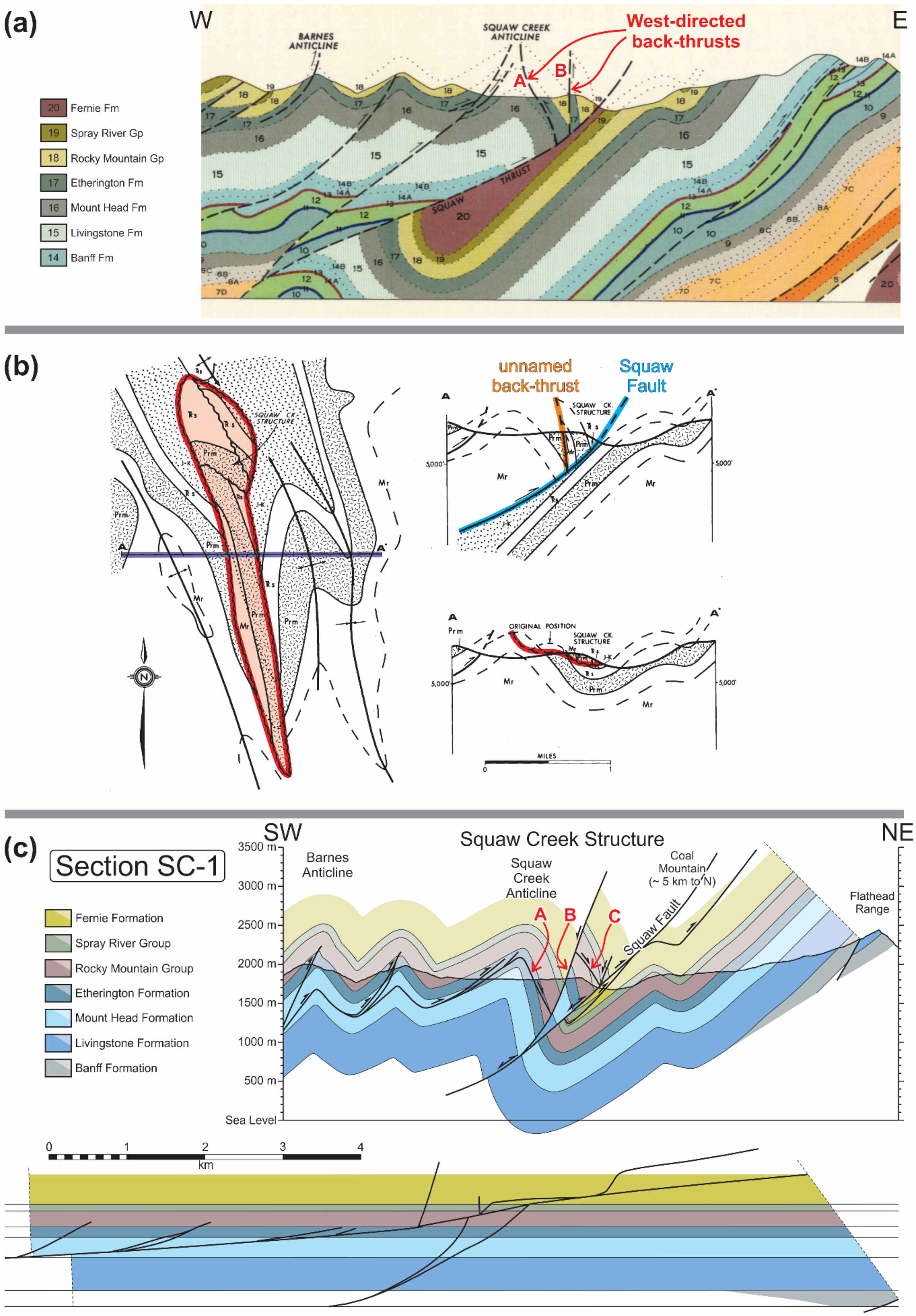

(a)
W
E
BARNES ANTICLINE
SQUAW CREEK ANTICLINE
West-directed back-thrusts
A
B
SQUAW THRUST
20 Fernie Fm
19 Spray River Gp
18 Rocky Mountain Gp
17 Etherington Fm
16 Mount Head Fm
15 Livingstone Fm
14 Banff Fm
(b)
unnamed back-thrust
Squaw Fault
SQUAW CK. STRUCTURE
ORIGINAL POSITION
A
A'
5,000'
MILES
(c)
Section SC-1
SW
NE
Squaw Creek Structure
Barnes Anticline
Squaw Creek Anticline
Coal Mountain (~ 5 km to N)
Flathead Range
Squaw Fault
A
B
C
3500 m
3000 m
2500 m
2000 m
1500 m
1000 m
500 m
Sea Level
Fernie Formation
Spray River Group
Rocky Mountain Group
Etherington Formation
Mount Head Formation
Livingstone Formation
Banff Formation
0
1
2
3
4
km

Figure 25 (previous page): *Cross-sectional interpretations of the Squaw Creek structure, all at the same scale and aligned on the trace of the Squaw Fault; locations shown in Figure 24. (a) Annotated reproduction of a portion of section C–D of Price (1965a). West-directed back-thrusts "A" and "B", on east limb of the Squaw Creek Anticline, lie in the hanging wall of the Squaw Thrust. (b) Annotated reproduction of figure 7 of Jones (1977). Map and upper cross-section were redrawn and simplified after Price (1965a). Interpreted gravitational slide highlighted in red. (c) Balanced structure section SC-1 and palinspastic reconstruction. Squaw Fault is interpreted as a normal-sense reactivated thrust fault. Faults labeled "A" and "B" correspond to those in part (a) of this figure. See text for discussion.*

as a normal fault that merges down-dip with the reactivated Squaw Fault (see corresponding faults labeled in Figure 24). Fault "C" in Figure 24 is shown as mapped by Price (1965a), who symbolized it as a northeast-dipping thrust with a dextral strike-slip component, but he did not project this fault into his section C–D (see Figure 25a). As shown in Figure 25c, fault "C" is interpreted as a folded east-directed thrust that corresponds to fault "A", offset by the normal fault "B". The interpretation at depth of the folded thrust west of Squaw Creek Anticline is purely conjectural, but constructed assuming it formed in Rundle Group strata at a low angle to bedding prior to folding (Figure 25c, bottom).

Discussion

The original interpretation of the Howell Creek structure by Price (1958) and subsequent variants (Price, 1959, 1962, 1965a, 1965b, 2013), as a window through the Lewis Thrust sheet, is highly unlikely for reasons explained above. As also detailed above, the alternative interpretations of Oswald (1964), Jones (1964, 1966, 1977), and Dahlstrom (1970) are either highly unlikely or simply not permissible. The Howell Fault is best interpreted as a normal fault, as argued by Labrecque and Shaw (1973), and adapted by Fermor and Moffat (1992) and Legun (1993). However, the new interpretation presented here addresses a number of shortcomings of Labrecque and Shaw (1973), as well as implications not explicitly considered by any previous authors, which ultimately bear on the relative timing of motion on the principal normal faults.

The interpretation of Labrecque and Shaw (1973; Figure 15) implies normal-sense motions of the Howell and Harvey faults that are closely related, that post-dated deposition of the basal portion of the Kishenehn Formation, and that were broadly contemporaneous with motion on the Flathead Fault. Although the smooth merger of the Howell and Harvey faults mapped by these authors (Figure 13e, marked by yellow oval) suggests both faults developed in the same extensional event, as implied by their restored cross-section (Figure 15, bottom), the available constraints (e.g., Price, 1965b; p. 107) indicate the Harvey Fault strikes 315°, parallel to its trace, and dips approximately 45° SW, whereas the Howell Fault strikes 020° and dips 30° W. This implies that the Harvey Fault cuts and offsets the Howell Fault, as mapped by Price (1958, 1959, 1962, 1965) and Jones (1966), and shown in the new interpretation (figures 17, 19, 20, and 21).

One of the most important features of the Labrecque and Shaw (1973) reconstructed cross-section is the unconformity underlying the Kishenehn Formation prior to extension (orange-highlighted surface; Figure 15, bottom). Although they did not explicitly discuss this feature, they cite Jones (1969), who mapped isolated exposures of Kishenehn Formation across Macdonald Dome, and they likely used these critical constraints to show unconformable deposition above Mississippian strata a few kilometres east of the Harvey Fault (yellow star; Figure 15, bottom). The very shallowly dipping unconformity shown east of this low point was likely estimated knowing that Kishenehn Formation is deposited in the Flathead Valley half-graben (Figure 15, top). To the west, Labrecque and Shaw may have recognized a physiographic challenge: the Upper Cretaceous strata now exposed in the Howell Creek structure obviously could not have been removed by sub-Kishenehn erosion prior to normal-sense motion on the Howell and Harvey faults. This required them to infer a very steeply dipping (~50°) erosion surface across Mesozoic clastic rocks that was >3 km high (labeled angle; Figure 15, bottom).

As unlikely as such a large and steeply dipping erosional feature may be, the geometry shown in Figure 15 (bottom) was constructed assuming a thickness of Jurassic through Lower Cretaceous strata (Fernie Formation and Kootenay and Blairmore groups) of approximately 1500 m (see labeled thickness; Figure 15, bottom). However, the total thickness of these units, compiled from McMechan (1981) and Price (1962, 1965b), is conservatively estimated as 2510 m (Figure 2). If this corrected thickness is incorporated into the interpretation of Labrecque and Shaw (1973), the reconstructed sub-Kishenehn erosion surface dips nearly 60° and is >4 km high. To make matters even worse, Labrecque and Shaw (1973) show Kishenehn Formation overlying Mississippian strata ~5 km east of the Harvey Fault (yellow star, Figure 15, bottom), but this unconformable relationship occurs <2 km from this fault (Figure 17). Incorporating this constraint into their interpretation would imply a >4 km high vertical to overturned erosion surface! The assumption of Labrecque and Shaw (1973) that normal-sense motions on the Howell and Harvey faults were contemporaneous must be incorrect.

TIMING OF DEFORMATION

The Twentynine Mile Creek Fault and other faults southeast of the Howell Creek structure clearly cut the Flathead intrusions (figures 3, 4, 8, 17, and 18), which must predate the faults. Brown and Cameron (1999, p. 183) considered the unpublished U-Pb zircon age of 98.5 ± 5 Ma (2σ) reported by Skupinski and Legun (1989) to be the best available at that time. This date was determined by Don Murphy of the GSC, from a drill-core sample of syenite from west of Trachyte Ridge (see southeast corner of Figure 4) collected by Dave Grieve (B.C. Geological Survey). More recently, Barnes (2002) reported $^{40}Ar/^{39}Ar$ apparent cooling ages of orthoclase of 102.5 ± 1.0 Ma (2σ) for megacrystic syenite and 101.3 ± 1.0 Ma (2σ) for foid syenite.

As implied by map relationships and illustrated in Figure 22, the Twentynine Mile Creek Fault is folded across the transverse North Kootenay Pass Monocline (Figure 26). The coincidence of the monocline with the lateral ramp through Mesoproterozoic strata in the hanging wall of the Lewis Thrust implies that the monocline formed as a consequence of displacement on the Lewis Thrust. Therefore, thrusting of the Twentynine Mile Creek Fault probably predated motion on the Lewis Thrust, which began at ca. 75 Ma as noted above. However, as outlined below, normal-sense motion of the compound Twentynine Mile Creek–Howell Fault may have postdated displacement on the Lewis Thrust, segments of which to the north apparently record motion as young as ca. 52 Ma (van der Pluijm et al, 2006).

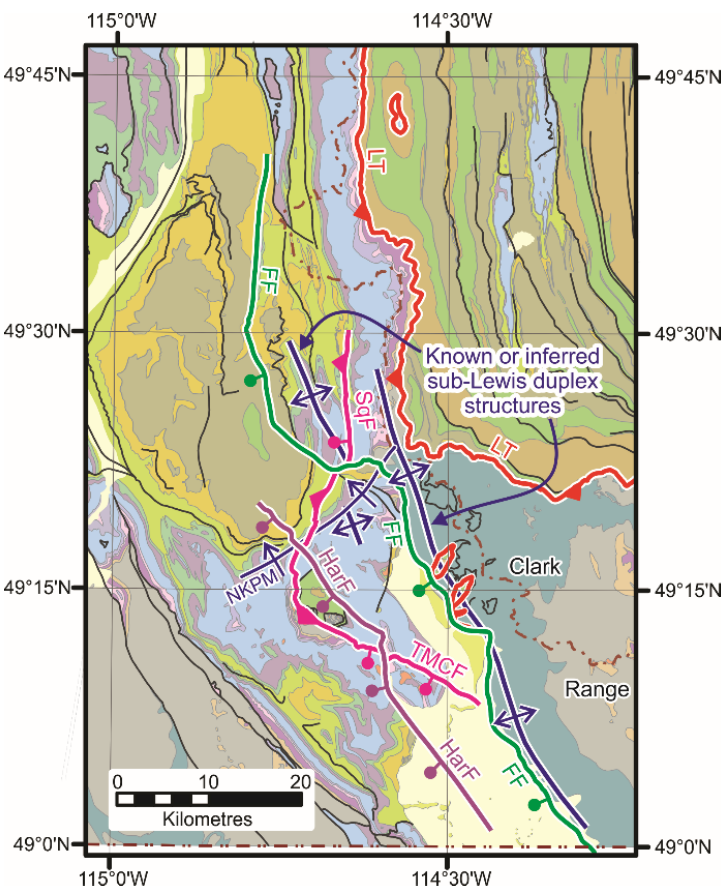


Figure 26: *Trends and offsetting relationships of major fault traces. The Harvey Fault is approximately parallel to, and may slightly post-date, the Flathead Fault. Both the Harvey and Flathead faults offset and therefore post-date the formerly continuous Twentynine Mile Creek and Squaw faults, which are oblique to the former, in part because the Twentynine Mile Creek Fault is folded across the North Kootenay Pass Monocline. Known or inferred sub-Lewis duplex structures are indicated as anticlines (from Monahan, 2000). Unit colours as defined in Figure 1. See figures 1 and 3 captions for fault and fold abbreviations.*

Relative timing of faulting can also be gleaned from overprinting relationships. As seen in Figure 26, the formerly continuous Twentynine Mile Creek and Squaw faults are cut and offset by the Flathead Fault (and, in detail, the Shepp Fault, which is part of the Flathead Fault system; see Figure 3). The Harvey Fault, which is subparallel to that portion of the Flathead Fault south of North Kootenay Pass, cuts and offsets the Twentynine Mile Creek Fault in two places, due in part to folding of the latter across the North Kootenay Pass Monocline (Figure 26). The Harvey Fault also truncates the Howell Fault (figures 8 and 17). Therefore, the Twentynine Mile Creek, Squaw, and Howell faults all predated the Flathead and Harvey faults.

Figure 27 illustrates the evolution of the Howell Creek structure implied by the new interpretation and the above timing constraints. Thrust displacement on the Twentynine Mile Creek Fault postdated the mid-Cretaceous Flathead intrusions (Figure 27a), but probably predated initial motion on the Lewis Thrust (Figure 27b) because it is folded across the North Kootenay Pass Monocline, which formed as a consequence of motion on the Lewis Thrust. The maximum depth of erosion prior to normal faulting on the compound Twentynine Mile Creek–Howell Fault (Figure 27b) is constrained by the strata preserved in and west of the Howell Creek structure. The reconstructed configuration of the Twentynine Mile Creek–Howell Fault, prior to motion on the Flathead Fault (Figure 27c), is constrained by the observed cut-off angles through strata in the footwalls and hanging walls of the Twentynine Mile Creek and Howell faults (figures 17 through 21). Figure 27c shows this compound fault as folded in concert with the Lewis Thrust above a sub-Lewis duplex structure (Bally et al, 1966; Fermor and Moffat, 1992). This folded geometry, with a reconstructed nearly horizontal kilometres-wide trajectory, suggests that extension along this compound fault either predated or was possibly partly concurrent with the growth of the underlying duplex, which carried and folded the Lewis Thrust sheet. The duplex structure elevated the top of the sub-Lewis Paleozoic succession ~4.0 km above its regional level, which is comparable to the

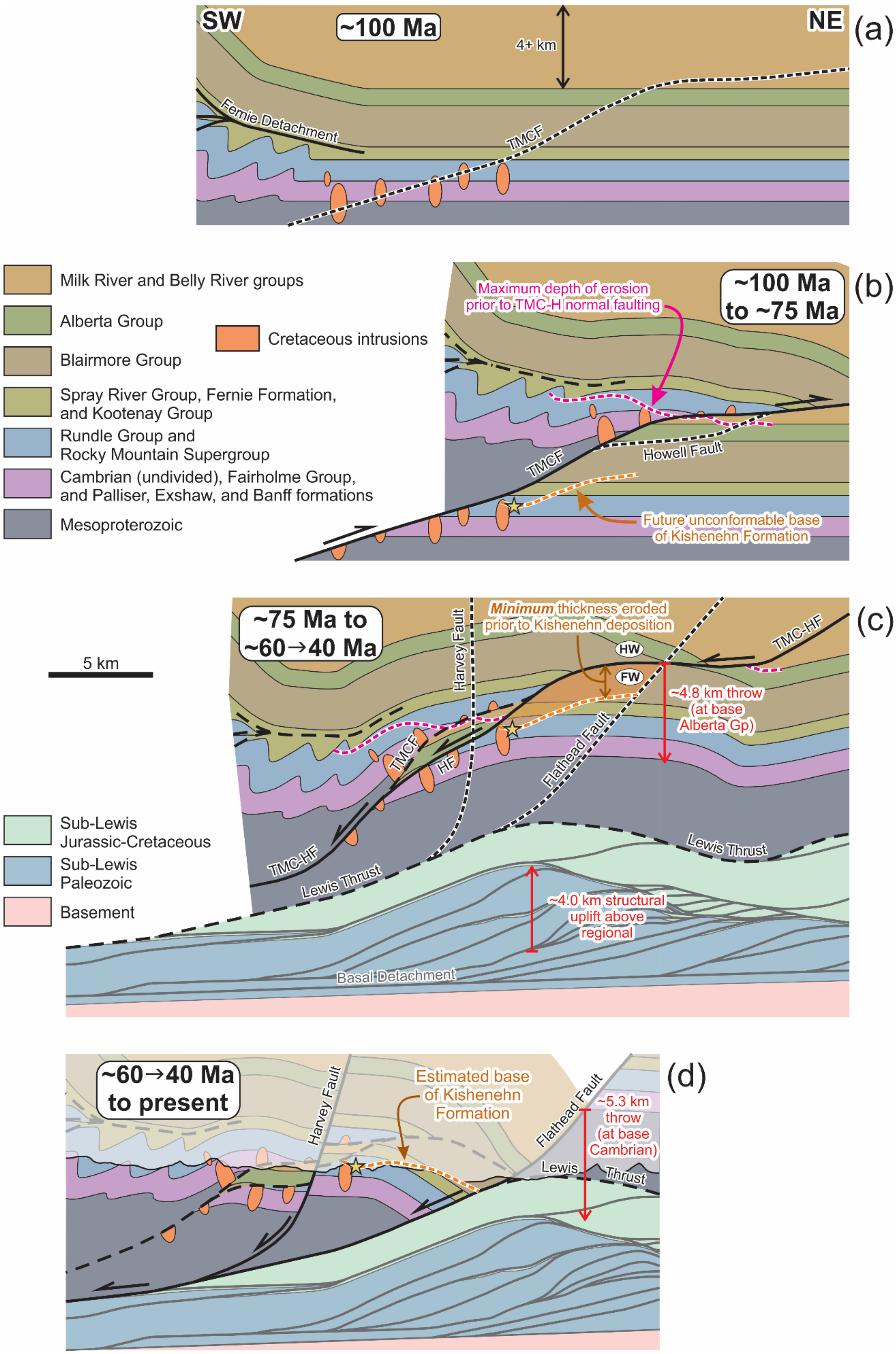

SW
~100 Ma
NE
(a)
4+ km
Fernie Detachment
TMCF
Milk River and Belly River groups
Alberta Group
Blairmore Group
Spray River Group, Fernie Formation, and Kootenay Group
Rundle Group and Rocky Mountain Supergroup
Cambrian (undivided), Fairholme Group, and Palliser, Exshaw, and Banff formations
Mesoproterozoic
Cretaceous intrusions
Maximum depth of erosion prior to TMC-H normal faulting
~100 Ma to ~75 Ma
(b)
Howell Fault
TMCF
Future unconformable base of Kishenehn Formation
~75 Ma to ~60→40 Ma
Harvey Fault
Minimum thickness eroded prior to Kishenehn deposition
HW
FW
TMC-HF
(c)
5 km
~4.8 km throw (at base Alberta Gp)
TMCF
HF
Flathead Fault
Lewis Thrust
TMC-HF
Lewis Thrust
Sub-Lewis Jurassic-Cretaceous
Sub-Lewis Paleozoic
Basement
~4.0 km structural uplift above regional
Basal Detachment
~60→40 Ma to present
Harvey Fault
Estimated base of Kishenehn Formation
Flathead Fault
(d)
~5.3 km throw (at base Cambrian)
Lewis
Thrust

Figure 27 (previous page): *Generalized, but scaled and area balanced, inferred cross-sectional evolution of the Howell Creek structure. Unit thicknesses assumed constant for simplicity.*

(a) Nascent position of the Twentynine Mile Creek Fault (TMCF; black short-dashed line) through an essentially undeformed sedimentary succession. The Flathead intrusions (ca. 100 Ma) predate development of the fault. Fold train shown west of the Howell Creek structure includes the Bighorn Anticline (middle of three anticlines; see figures 1 and 3); these are shown as detached from overlying Jurassic and Cretaceous strata by the Fernie Detachment (to be discussed elsewhere). Fold geometry at depth is purely schematic. These folds may predate or have formed concurrently with the TMCF. Probable thickness of the Milk River and Belly River groups overlying the Lewis Thrust sheet was 4 to 5.5 km (Osadetz et al, 2004; Feinstein et al, 2007). Position of underlying nascent Lewis Thrust is not shown at this or the next stage.

(b) Thrust motion on the TMCF juxtaposed Paleozoic and Mesoproterozoic strata above Upper Cretaceous strata. The position of the nascent Howell Fault (black short-dashed line) suggests it could have formed as a footwall cutoff with either thrust-sense or normal-sense initial motion. Strata preserved within and surrounding the Howell Creek structure constrains the absolute maximum depth of erosion (magenta short-dashed line) prior to normal-sense motion on the Twentynine Mile Creek–Howell (TMC-H) compound fault. Positions of the future unconformable base of the Kishenehn Formation, and the projected position of mapped Kishenehn strata east of the Harvey Fault (see figures 17 and 19), shown by orange short-dashed line and yellow star, respectively. Pre-existing and probably inactive faults are shown as black long-dashed lines. Underlying Lewis Thrust (not shown) was probably not yet active at this stage (see text for discussion).

(c) Configuration following normal-sense motion on the TMC-H compound fault, which resulted in ~4.8 km of throw (measured at the base of the Alberta Group), and also following folding of the Lewis Thrust sheet above the Clarke Range duplex structure. The folded Lewis Thrust and the generalized sub-Lewis structure, which uplifted the top of the Paleozoic succession ~4.0 km above its regional level, are from Fermor and Moffat (1992; see Figure 19). Reconstructed positions and attitudes of the Flathead and Harvey faults

(black short-dashed lines) suggest that the Harvey Fault slightly post-dated the Flathead Fault. Yellow star and orange short-dashed line defined in (b), above. Minimum thickness and cross-sectional area of material in the footwall of the TMC-F compound fault that was eroded prior to deposition of the Kishenehn Formation is indicated and shaded orange, respectively. General areas of required footwall and probable hanging wall erosion are indicated by "FW" and "HW", respectively.

(d) Present-day configuration, combining generalized elements of cross-sections in figures 19, 20, and 21. Yellow star and orange short-dashed line defined in (b), above.

~4.8 km of throw on the Twentynine Mile Creek–Howell Fault, measured at the base of the Alberta Group (Figure 27c). Oligocene extension along the Flathead and Harvey faults, with ~5.3 km and ~0.9 km of throw, respectively, rotated and dissected the Howell Creek structure, resulting in its preserved configuration (Figure 27d).

As discussed above, Labrecque and Shaw (1973) interpreted extension on the Flathead, Harvey, and Howell faults to be broadly concurrent, with the Harvey and Howell faults merging smoothly (figures 13e and 15), rather than the former cross-cutting and offsetting the latter (figures 17, 19, 20, 21, and 27). This led them to infer a sub-Kishenehn Formation erosion surface that was unrealistically (or impossibly) high and steep (Figure 15, bottom), as noted above. Alternatively, a rigorous palinspastic reconstruction using known thickness constraints (Figure 19), in conjunction with known occurrences of Kishenehn Formation adjacent to and within the Howell Creek structure (figures 17, 18, and 19), implies that normal-sense motion on the compound Twentynine Mile Creek–Howell Fault significantly predated Kishenehn deposition (Figure 27). At a minimum, the intervening period of time must have been sufficient to erode strata from the footwall (Figure 27c) and most likely also the hanging wall of the compound fault. Estimating this time interval requires reasonable bounds on the erosion rate and the thickness of strata eroded.

On the basis of the stratigraphic range and positions of Cretaceous through Mesoproterozoic phenoclasts preserved within the Kishenehn Formation, McMechan (1981; p. 147) estimated that average Oligocene denudation rate across the Clark Range, in the footwall of the Flathead Fault (Figure 26), was 0.5 mm/year. It is reasonable to infer that prior to extension on the Flathead Fault, and the consequent creation of high relief due to motion on this steep fault, the erosion rates across both its nascent footwall and hanging wall were significantly lower, perhaps even by an order of magnitude or more.

Following and/or concurrent with normal-sense motion on the Twentynine Mile Creek–Howell Fault, but prior to Kishenehn Formation deposition, erosion removed at least 1.5 km of strata in the footwall of the fault and an unknown thickness in the hanging wall (Figure 27c). Assuming that the average erosion rate was lower, by a factor ranging from 2 to 10, than that estimated by McMechan (1981) during Oligocene extension, then erosion of 1.5 km of strata (the minimum value) could represent a time interval of anywhere from 6 to 30 m.y. McMechan (1981; p. 146) indicated the age range of the Kishenehn Formation as “earliest (?) Early Oligocene to at least early Late Oligocene”, which places its base at ca. 33 Ma. Therefore, normal-sense motion on the Twentynine Mile Creek–Howell Fault, sufficient to preserve the Upper Cretaceous strata at Howell Creek from the effects of ongoing erosion, is crudely estimated to have occurred between 39 and 63 Ma.

The substantial period of erosion between the times of extension on the Twentynine Mile Creek–Howell Flathead faults, coupled with cross-cutting map relationships (Figure 26), strongly suggest each belongs to a different extensional event. In addition, palinspastic reconstruction (Figure 27) suggests that initial normal-sense motion on the Twentynine Mile Creek–Howell Fault predated, or was possible broadly concurrent with, the growth of a sub-Lewis Thrust duplex structure. Together, these suggest that at least locally there was a significant period of extension within the southernmost Canadian Cordillera prior to or overlapping with the terminal phase of regional contractional deformation in the early Eocene (Constenius, 1996; van der Pluijm et al, 2006).

An episode of contractional deformation following extensional deformation may have occurred within the Howell Creek structure itself. The west-dipping, thrust-sense Outlier Fault (figures 17 and 18) cross-cuts and offsets the Twentynine Mile Creek Fault, resulting in the isolated map exposures of the two inliers discussed above. In cross-sectional view (Figure 19), the Outlier Fault is interpreted to be a relatively small-displacement thrust that splayed upward from the Howell Fault. Although this contractional structure could have formed prior to extensional motion on the compound Twentynine Mile Creek–Howell Fault, its occurrence where the Twentynine Mile Creek Fault is folded above the Howell Fault suggests that it is a relatively late-stage feature.

POSITION OF THE HOWELL CREEK STRUCTURE

The unique Howell Creek structure is located immediately adjacent to the North Kootenay Pass Monocline (Figure 1), which is also a unique feature. A reasonable conjecture is that this coincidence reflects a kinematic or mechanical linkage. As illustrated in Figure 22, the Twentynine Mile Creek Fault and, to a lesser degree, the Howell Fault, are folded across the monocline suggesting that they predated it to some degree. The nature of the monocline at depth and its growth history are unknown, but the large magnitude of displacement on the Lewis Thrust (~55-60 km; see above) coupled with the known hanging wall lateral ramp suggests that it could have had a complicated and protracted development. The formation of the Howell Fault as a footwall cut-off fault beneath the Twentynine Mile Creek Fault in the initial stage of normal-sense motion (Figure 27b), could have resulted from a change in the shape or curvature of the monocline. If so, then early motion on the compound Twentynine Mile Creek–Howell Fault would have overlapped in time with late motion on the Lewis Thrust, prior to significant folding by the sub-Lewis duplex structure (Figure 27c).

CONCLUSIONS

A new interpretation of the Howell Creek structure accommodates all available known constraints, reconciles a variety of conflicts between previous interpretations of this “enigmatic” feature, and helps explain the associated Squaw Creek structure. In addition, new balanced cross-sections and palinspastic restorations coupled with timing constraints suggest that thrusting on the Twentynine Mile Creek and Squaw faults predated motion on the underlying Lewis Thrust, and that normal-sense motion on the Twentynine Mile Creek and Howell faults significantly predated motion on the cross-cutting Flathead and Harvey faults.

The existence of the Howell Creek structure indicates a more complicated deformation history for the southeastern Canadian Cordillera than previously recognized, which included alternating or possibly overlapping periods of local contraction and extension prior to the terminal phase of regional contractional deformation. The fortuitous erosional preservation of the Upper Cretaceous strata in the Howell Creek structure is the essential element that points to this conclusion. As seen in the detailed structure sections (figures 19, 20, 21, and 22) and in Figure 27, roughly 2 km more or 2 km less erosion would have either entirely removed or concealed the Howell Creek structure. Perhaps other faults that show evidence of being normal-sense reactivated thrusts, such as the McEvoy Fault (Figure 3, on the east flank of the Fernie Synclinorium) that was mapped originally by Price (1958, 1959, 1962, 1965a) as the Flathead Fault, also underwent extension well in advance of normal faulting on the Flathead Fault and associated structures.

ACKNOWLEDGEMENTS

I sincerely thank Kirk Osadetz for numerous extensive discussions regarding the Howell Creek structure and for his viewpoints and insights into the structural geology of the southeastern Canadian Cordillera in general. I thank Karen Fallas and Margot McMechan, my co-authors on the Chinook map compilation series, for lengthy discussions, joint field work, and internal GSC reviews of this manuscript. Peter Jones very kindly loaned me an original copy of his D.Sc. thesis, and allowed me to scan the map and cross-section enclosures as well as selected figures. I also thank Mark Cooper, an anonymous reviewer, and associate editor John Waldron for comments on a withdrawn submission to the Bulletin of Canadian Petroleum Geology.

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