Orogenic pulses in the Alberta Rocky Mountains: Radiometric dating of major faults and comparison with the regional tectono-stratigraphic record

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ABSTRACT

Radiometric ages from regionally distributed thrust-fault gouge show that the eastward propagation of the southern Rocky Mountain fold-and-thrust belt in Canada occurred in four orogenic pulses that correlate with tectonic events of the Cordilleran interior and with depositional patterns in the adjacent foreland. In the Main Ranges, the Pyramid (163.0 Ma), Simpson Pass (161.7 Ma), and Johnson Creek (145.7 Ma) thrusts were related to the initiation of thin-skinned deformation from Jurassic terrane accretion and were partly contemporaneous with development of the first clastic wedge in the foreland basin. In the Front Ranges, the emplacement of the Greenock thrust (103.1 Ma) and Broadview–Snake Indian thrust (99.2 Ma) was contemporaneous with development of Cenomanian deltaic deposits in the immediate foreland. Three thrusts in the Front Ranges, Rocky Pass (74.8 Ma), Sulfur Mountain (75.6 Ma), and Clearwater (74.2 Ma) thrusts, define a Campanian phase of tectonic loading that led to the last major transgression in the southern portion of the Alberta foreland. Along the eastern margin of the Front Ranges, the McConnell thrust (54.0 Ma), together with the Muskeg (52.4 Ma), Brule (53.9 Ma), and Nikanassin (52.1 Ma) thrusts in the Foothills, recorded the last phase of regional contraction. The Late Jurassic, mid-Cretaceous, Late Cretaceous, and early Eocene deformation pulses are separated by relatively long periods (>40 m.y., >20 m.y., and >10 m.y.) of tectonic quiescence. These spatially and temporally restricted fault motion pulses contrast with gradual, forward fault propagation, while regional eastward progression of deformation is preserved.

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INTRODUCTION

With its extensive and spectacular exposures, the Canadian Rocky Mountains have been the natural laboratory for detailed geological studies of orogeny, which include the development of today's paradigms of fault propagation and thin-skinned tectonic wedges (e.g., Dahlstrom, 1970; Price, 1981; Stockmal et al., 2007). Ever more detailed subsurface images of the Canadian Rocky Mountains Foothills and Front Ranges obtained from improved seismic techniques, coupled with an ever-expanding information base from deep wells, have resulted in a high level of understanding of the stratigraphy and three-dimensional configuration of the Canadian Rocky Mountain fold-and-thrust belt. Its temporal evolution, however, has remained more elusive, mainly due to the difficulty of absolute dating of near-surface faulting.

Deformation of the Rocky Mountain fold-and-thrust belt generally progressed from west to east and accommodated up to 200 km of horizontal shortening just north of the Canada-U.S. border and ~70 km in northeastern British Columbia (Bally et al., 1966; Price, 1981; Price and Fermor, 1985; Fermor and Moffat, 1992; McMechan and Thompson, 1992). The timing of thrusting has been inferred from field relationships, sedimentation patterns in the Alberta foreland basin, radiometrically dated crosscutting intrusions, and low-temperature cooling histories of rocks (e.g., Price, 1981; Arne and Zentilli, 1994; Feinstein et al., 2007). The only time constraints for the initiation of thrusting near the western, internal margin of the Foreland belt are the stitching of the Lussier River thrust by 108 Ma intrusions near 50°N (Larson et al., 2006) and Bear Foot thrust sheet cooling ages of 100–112 Ma near 53°N (McDonough and Simony, 1988) (Fig. 1). The deformation front to the east involves strata of late Paleocene age near 53°N (Demchuk, 1990), with contractional deformation inferred into the Eocene (Kalkreuth and McMechan, 1996; Stockmal et al., 1997).

The first reported radiometric ages obtained by direct dating of thrust-fault gouge from the Front Ranges of the southern Canadian Rockies identified two spatially and temporally restricted deformation episodes, which were called the "Rundle pulse" around 72 Ma and the "McConnell pulse" around 52 Ma (van der Pluijm et al., 2001, 2006). These findings challenged the traditional view of a fold-and-thrust belt that gradually progressed forward in a deformation continuum. Encouraged by the potential of direct dating of shallow fault rocks for better understanding upper-crustal kinematics and regional tectonics of the southern Canadian Cordillera, the present study significantly extends and tests the earlier geochronological work, both along strike to the northwest, and toward more internal thrusts to the west, in the Main Ranges of the Rocky Mountain fold-and-thrust belt. This study expands our understanding of the temporal evolution of the belt, along and across strike, and advances the concept of orogenic episodicity. Fault gouge was sampled along major faults in the area, and 12 faults were selected for dating (Table 1). The results are presented herein and discussed together with the previous six dates reported by van der Pluijm et al. (2006) from the southernmost Canadian Rocky Mountain fold-and-thrust belt. The regional data set in this paper highlights the relationships between tectonic events in the Omineca hinterland, orogenic pulses in the foreland fold-and-thrust belt and depositional changes documented in the foreland basin.

REGIONAL GEOLOGY

The Rocky Mountain fold-and-thrust belt is part of the Cordilleran Foreland belt of North America, and, in Canada, it is succeeded to the west by the Omineca, Intermontane, Coast, and Insular morphogeological belts (e.g., Gabrielse

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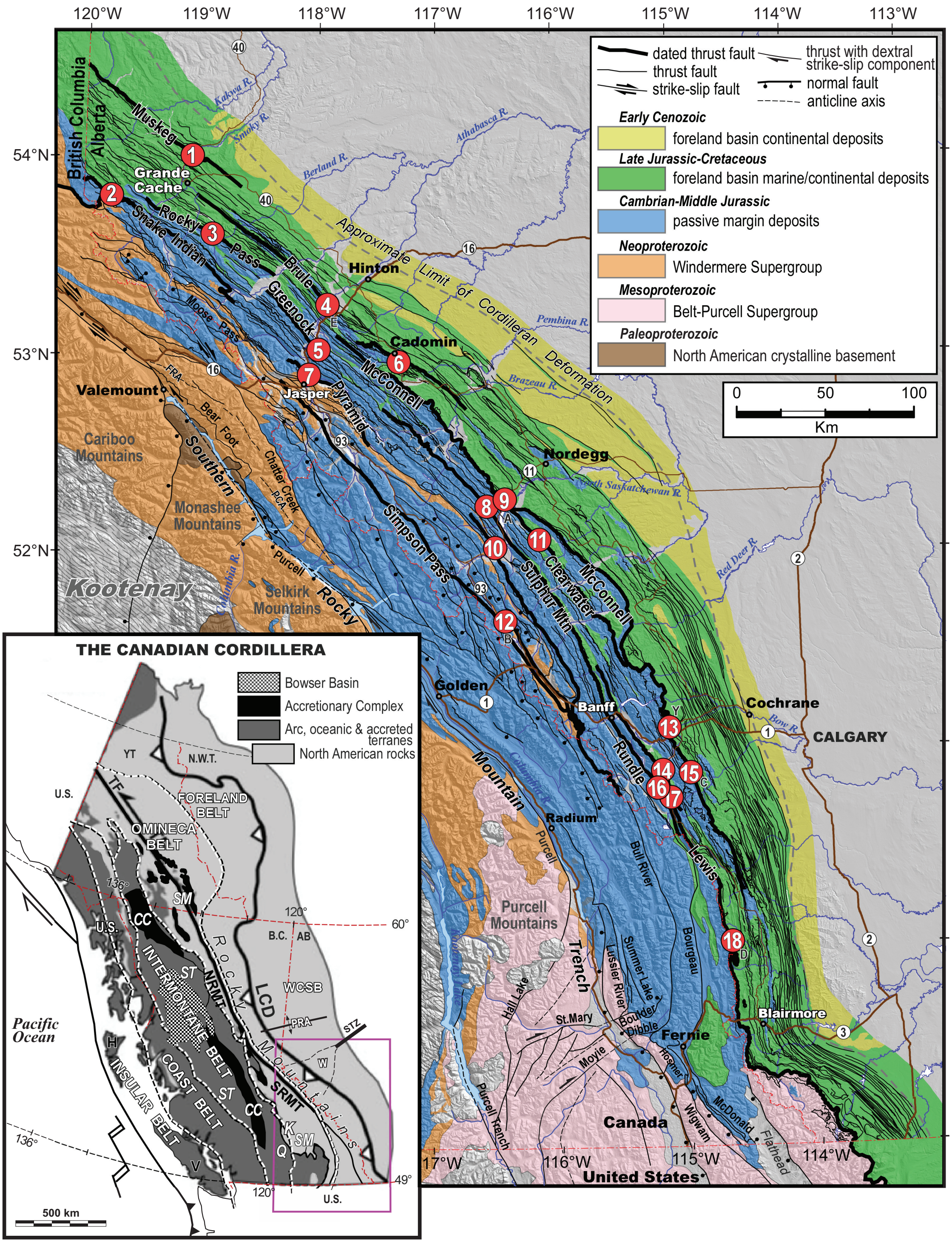


Figure 1. Structural sketch of the southern Rocky Mountains showing the distribution of faults and sample locations; numbered sample locations correspond to numbers in Table 1, and letters correspond to sites described in the text: E—Entrance, A—Abraham Lake, B—Bow Lake, Y—Mount Yamnuska, C—Compression Ridge, and D—Gould Dome; FRA—Fraser River anticlinorium; PCA—Porcupine Creek anticlinorium. Faults in Alberta are from Panǎ and Elgr (2013); faults in British Columbia are compiled from Craw (1978), Gal et al. (1989), Wheeler and McFeely (1991), and McDonough and Murphy (1994). Index map was compiled from McMechan and Thompson (1989) and Monger and Price (2002); only tectonic units discussed in text are represented. WCSB—Western Canada sedimentary basin; TF—Tintina fault; NRMT and SRMT—Northern and Southern Rocky Mountain Trench, respectively; PRA—Peace River Arc; W—Wabamun basement domain; STZ—Snowbird tectonic zone; LCD—approximate eastern limit of Cordilleran deformation; CC—Cache Creek and SM—Slide Mountain accretionary complex terranes; ST—Stikinia and Q—Quesnellia island-arc terranes; K—Kootenay terrane; V—Vancouver Island; H—Haida Gwaii Islands; YT—Yukon Territory; N.W.T.—Northwest Territories; AB—Alberta; B.C.—British Columbia.

TABLE 1. THRUST FAULT SAMPLE LOCATIONS AND ASSOCIATED ROCK UNITS IN HANGING WALL AND FOOTWALL AT EACH LOCATION

Label	Easting	Northing	Thrust name	Hanging wall	Footwall
1	365037	5987989	Muskeg	Gates sandstone (Lower Cretaceous)	Kaskapau shale/siltstone (Upper Cretaceous)
2	319160	5966245	Broadview	Whitehorse silty dolomite (Triassic)	Fernie shale (Jurassic)
3	376202	5943210	Rocky Pass	Rundle carbonate (Mississippian)	Nikanassin shale/siltstone (Upper Jurassic–Lower Cretaceous)
4	440700	5903844	Brule	Palliser carbonate (Upper Devonian)	Nikanassin shale/siltstone (Upper Jurassic–Lower Cretaceous)
5	435132	5878704	Greenock	Lower Rundle carbonate (Mississippian)	Fernie shale (Jurassic)
6	478985	5872820	Nikanassin	Palliser carbonate (Upper Devonian)	Nikanassin shale/siltstone (Upper Jurassic–Lower Cretaceous)
7	429180	5863668	Pyramid	Miette grit (Neoproterozoic)	Perdrix/Sassenach shale (Upper Devonian)
8	528458	5791917	Sulphur Mountain (at Abraham Lake)	Rundle carbonate (Mississippian)	Fernie shale (Jurassic)
9	541402	5791201	McConnell (at Abraham Lake)	Eldon carbonate (Middle Cambrian)	Luscar shale/siltstone (Lower Cretaceous)
10	533967	5766999	Johnston Creek	Miette sandstone/siltstone/grit (Neoproterozoic)	Eldon carbonate (Middle Cambrian)
11	563402	5767593	Clearwater	Banff carbonate (Mississippian)	Kootenay shale/siltstone (Upper Jurassic–Lower Cretaceous)
12	540109	5727078	Simpson Pass	Gog quartzite/quartz sandstone (Lower Cambrian)	Pika carbonate (Middle Cambrian)
13*	632225	5665355	McConnell (at Mount Yamnuska)	Eldon carbonate (Middle Cambrian)	Belly River shale/siltstone (Upper Cretaceous)
14*	628400	5640943	Rundle	Palliser carbonate (Upper Devonian)	Kootenay shale/siltstone (Upper Jurassic–Lower Cretaceous)
15*	644663	5640713	McConnell (at Compression Ridge)	Palliser carbonate (Upper Devonian)	Belly River shale/siltstone (Upper Cretaceous)
16*	626517	5630655	Sulphur Mountain (in Kananaskis)	Palliser carbonate (Upper Devonian)	Fernie shale (Jurassic)
17*	631919	5626896	Lewis (in Kananaskis)	Rundle carbonate (Mississippian)	Fernie shale (Jurassic)
18*	668634	5545208	Lewis (at Gould Dome)	Palliser carbonate (Upper Devonian)	Belly River shale/siltstone (Upper Cretaceous)

*Samples from van der Pluijm et al. (2006).

et al., 1992) (Fig. 1). The Canadian Rocky Mountain fold-and-thrust belt stretches from 49°N (Canada-U.S. border) to 60°N latitude (Liard River) in western Canada and consists of overlapping thrust sheets and detached folds in the eastern portion of the Cordilleran orogen. The eastern boundary of the Canadian Rocky Mountain fold-and-thrust belt is the elusive "eastern limit of Cordilleran deformation," arbitrarily traced east of the easternmost deformed strata known in outcrop and/or subsurface. The strata underlying the Alberta Plains to the east dip gently to the SSW, except near the edge of the Foothills, where Paleocene strata are gently folded upward on the east flank of a structural triangle zone, forming the western limb of the Alberta syncline (e.g., Stockmal et al., 2001). To the west, the Rocky Mountains are bounded by the Rocky Mountain Trench. This continental-scale physiographic feature is underlain by a major strike-slip fault zone north of 51°N latitude, whereas south of 50°N, the trench is interpreted to overlie the western, downdropped blocks of major normal faults that separate the southern Rocky Mountains from the Purcell Mountains to the west (e.g., Price, 1994). Our study area is in the Alberta portion of the Canadian Rocky Mountain fold-and-thrust belt, spanning several hundred kilometers, between 51°N and 54°N latitude (Fig. 1).

The Canadian Rocky Mountain fold-and-thrust belt formed between the Middle Jurassic and early Eocene within an easterly tapering wedge of Mesoproterozoic to early Cenozoic sedimentary rocks that were deposited in the Western Canada sedimentary basin. A profound unconformity separates the sedimentary cover from the normal thickness or attenuated Archean to Paleoproterozoic crystalline crust of ancestral North America (e.g., Price, 1994). The detached and displaced supracrustal rocks comprise several broad tectono-stratigraphic assemblages deposited over 1.4 b.y. within distinct tectonic settings (Fig. 1):

(1) The Mesoproterozoic Belt-Purcell Supergroup (ca. 1470–1370 Ma) was deposited in an intracontinental rift basin (Price, 1981; Höy, 1992; Evans et al., 2000; Lydon, 2007; Sears, 2007), or an extensional basin on the western edge of Laurentia with a tectonically active western side (Ross and Villeneuve, 2003).

(2) The Late Neoproterozoic (ca. 760–570 Ma) Windermere Supergroup was deposited on the initial rifted western margin of Laurentia toward the proto–Pacific Ocean basin (Arnott and Hein, 1986; Hein and McMechan, 1994; Ross and Arnott, 2006). The Miette Group, exposed in the western, internal ranges of the Rocky Mountains, is the only representative of this stage involved in the thrusts investigated in this study.

(3) The Cambrian to Middle Jurassic (ca. 540–165 Ma) assemblages that formed in a westward-prograding continental margin terrace wedge that faced the adjacent proto–Pacific Ocean basin and include (McMechan and Thompson, 1989): (a) the Lower Paleozoic sequence consisting of continental platform and shelf carbonates with subordinate shale that pass laterally into finer-grained, deeper-water facies; (b) the Middle and Upper Paleozoic platform and shelf carbonates and subordinate clastics that pass laterally into deeper-water facies; and (c) the Triassic to Middle Jurassic shale, siltstone, sandstone, and minor carbonate and chert units that are punctuated by several significant unconformities.

(4) The Late Jurassic to Eocene Cordilleran foreland basin sequence (ca. 155–50 Ma), which overlies the cratonic platform assemblage and accumulated in front of the northeastward-prograding accretionary wedge as the continental lithosphere subsided isostatically under the weight of the advancing wedge, was partly incorporated in, and cannibalized by, the encroaching fold-and-thrust belt (e.g., Price, 1973, 1981; Beaumont, 1981; McMechan and Thompson, 1989, 1992; Stockmal et al., 2007).

From late Proterozoic until Early Jurassic time, the continent-ocean boundary (marked by lithotectonic assemblages within and immediately west of the Omineca belt) was a passive margin, and the deposition occurred in mainly extensional settings (Monger, 1989; Murphy et al., 1995). Episodes of Paleozoic through Middle Jurassic plate convergence and consumption, demonstrated by the development of successive forearc and retro-arc basins, Mesozoic to Cenozoic batholith belts, accretion of oceanic island arcs, and subduction complexes, are limited to the accreted or "suspect" pericratonic terranes (e.g., Monger, 1984, 1989; Struik, 1988). Tectonic events did not markedly affect ancestral North American rocks in Canada until the Middle Jurassic; in the late Middle Jurassic, the region became a foreland basin in front of the growing orogen to the west (Monger and Price, 2002).

Between the Middle Jurassic and early Eocene, the Cordilleran realm was mainly under compression, accompanied at different times by sinistral and dextral transpression (Evenchick et al., 2007; Gervais et al., 2010). Events leading to Cordilleran mountain building started in Middle Jurassic time, as a result of breakup of Pangea and North American plate motion toward subduction zones at its western margin, followed by collisions with eastward and northeastward drifting island arcs on the proto-Pacific lithosphere (e.g., Monger et al., 1972, 1982; Monger, 1984, 1989; Gabrielse et al., 1992; Monger and Price, 2002). Most of today's Canadian Cordillera consists of a collage of tectonic elements of upper-crustal rocks detached from denser lower-crustal and proto-Pacific upper-mantle lithosphere that was subducted (e.g., Monger, 1984, 1989; Price, 1986, 1994). The upper-crustal tectonic elements (or allochthonous terranes) were juxtaposed over each other and over the western margin of the North American craton along a system of interleaved, northeast- and southwest-verging major thrust faults (Tempelman-Kluit, 1979; Monger et al., 1982; Struik, 1988). These allochthonous terranes are distinct from each other and from (par)autochthonous North American rocks (e.g., Monger et al., 1982). Some are coherent bodies comprising laterally persistent tectono-stratigraphic assemblages dominated by oceanic volcanic arc rocks (e.g., Quesnellia-Stikinia), separated by oceanic accretionary wedges marking the sites of former ocean basins, marginal seas, or back-arc basins (e.g., Slide Mountain, Cache Creek), which are dominated by deep-ocean-basin sedimentary rocks, basaltic volcanic rocks, and bodies of ultramafic rock (Monger and Price, 1979, 2002; Price, 1994) (Fig. 1).

The current version of the popular "back-arc" tectonic model (e.g., Monger and Price, 2002) envisions that the orogenic involvement of North American rocks in the southern Canadian Cordillera was a consequence of tectonic processes associated with long-lasting easterly directed subduction. Westward migration of North America toward the subduction zone resulted in the Jurassic consumption of the late Paleozoic–Early Jurassic (ca. 355–185) back-arc basin through westward underthrusting and obduction; the remnants of this basin are represented by the dismembered Slide Mountain deep-water assemblage with ophiolite-type rocks. Middle Jurassic and Early Cretaceous continental arcs were built both on the accreted material and parts of the ancient continental margin now exposed in the Intermontane and Omineca belts (Fig. 1). The easterly directed Cascadia subduction zone initiated at ca. 90 Ma near its present position west of Vancouver and Haida Gwaii (informally known as Queen Charlotte) islands, ~500 km oceanward from the position of the original margin of ancestral North America (Fig. 1). Late Cretaceous and younger continental arc rocks were emplaced across older, previously accreted island-arc rocks. The initiation of the mid-Cretaceous subduction zone roughly coincides with the initiation of dextral strike-slip faulting on the Northern Rocky Mountain Trench–Tintina fault system and dextral transpression along the northern segment of the Southern Rocky Mountain Trench, concurrent with most of the shortening in the Rocky Mountain fold-and-thrust belt (Eisbacher, 1985; Price and Carmichael, 1986; Van den Driessche and Maluski, 1986; Monger and Price, 2002).

Late Middle Jurassic to early Eocene deformation resulted in a thick stack of east-vergent, generally downward- and eastward-younging thrust slices in the Rocky Mountain fold-and-thrust belt. Proterozoic strata, locally overprinted by low- to medium-grade metamorphism, dominate in the western parts of the belt, unmetamorphosed Paleozoic strata in the central and eastern parts, and Mesozoic to Cenozoic rocks in the frontal parts (Monger, 1989). Contraction was succeeded by transtension and extension during the middle Eocene (Evenchick et al., 2007; Gervais et al., 2010; Gervais and Brown, 2011).

The tectonic setting and paleogeography of the western margin of North America and its interaction with offshore terranes remain controversial (e.g., Thompson et al., 2006). Alternative tectonic models highlight weaknesses and emphasize particular aspects of the traditional back-arc model to advocate for initial westward subduction and collision with a far-traveled northward ribbon continent having various names and boundaries; these include, Cordilleria (Chamberlain and Lambert, 1985; Lambert and Chamberlain, 1988), Baja British Columbia (Umhoefer, 1987), SAYBIA (Johnston, 2008), and Rubia (Hildebrand, 2009, 2013).

SAMPLING SITES

The helicopter-supported sample collection encompassed the Alberta portion of the Rocky Mountain fold-and-thrust belt between the Bow and Smoky Rivers (Fig. 1). Although, in most instances, the location of thrust faults is readily identifiable in the field, sampling of the appropriate gouge material is challenging. In spite of widespread exposures in the alpine zone of the Rocky Mountains, thrust faults are typically covered by rubble, whereas in the Foothills, thrust faults are commonly covered by vegetation on hills and by Quaternary sediments in river valleys. The sampled gouge material consists of variably foliated, variably cohesive, soft to hard, greenish gray to black, clay-rich material that commonly disaggregates in water. In our experience, the best preserved clay gouge is found between massive Paleozoic carbonate hanging walls (such as Palliser Formation limestone) and the Mesozoic shale-siltstone footwalls (such as Fernie Formation shale). Although limestone in the hanging wall is sheared and locally folded, most deformation appears to have been accommodated by thin layers of clay gouge, typically 15–30 cm thick. Mineral transformation and hydration, leading to the formation of low-friction clay minerals in clay gouge, facilitated low-angle fault slip in the elasto-frictional regime (e.g., Carpenter et al., 2011; Lockner et al., 2011; Haines and van der Pluijm, 2012). Previously, we showed that wall rocks are significantly older than zones of fault gouge (van der Pluijm et al., 2006; Solum and van der Pluijm, 2007). Similarly, for this study, we also sampled and dated four size fractions of the Lower Cretaceous Luscar shale from the footwall of the McConnell thrust, ~200 m below the thrust. This resulted in an authigenic age of 69.3 ± 6.0 Ma (sample A in Table 2), which is 15 m.y. older than nearby fault gouge at the hanging wall (see sample 9 in Table 2). These footwall tests and observed gouge ages, which vary systematically (described in the following), demonstrate that regional diagenesis is not the mechanism for fluid-driven clay mineralization in narrow fault gouge in this area (see also Vrolijk and van der Pluijm, 1999).

More than 20 locations have been examined and sampled, and 12 new thrusts have been dated for this regional study. Note that each fault age has been derived from four $^{40}Ar/^{39}Ar$ dates, resulting in a large data set. The extent of the major thrusts and the sample locations are shown in Figure 1. The names of sampled thrusts and the lithologies making up the immediate hanging wall and footwall at each sample location are listed in Table 1. We examine the new analytical results in this paper (samples 1–12) in conjunction with previously reported fault gouge ages (samples 13–18; van der Pluijm et al., 2006).

METHODS

Sample Preparation

Samples were disaggregated and allowed to settle in a large beaker in order to separate the clay-sized fraction. The suspension of deflocculated clays was decanted and allowed to dry slowly. Oriented clay slurry mounts of the clay-

TABLE 2. ILLITE POLYTYPE AND AGE OF GRAIN SIZE FRACTIONS OF CLAY GOUGE AND WALL ROCK, AND CALCULATED AUTHIGENIC (0% 2M1) AND DETRITAL (100% 2M1) ILLITE AGES WITH YORK REGRESSION ERRORS

Label	Sample	Thrust name		%2M1	±	TGA (Ma)	±	R^2	Age (Ma), 0% 2M1	Age (Ma), 100% 2M1
1	DP10-406C	Muskeg						0.981	52.4 ± 12.3 Ma	766.2 ± 65.9 Ma
			C	21	2	231.1	0.8			
			MC	16	2	182.8	0.8			
			M	10	2	130.1	0.5			
			F	6	2	112.9	0.5			
2	DP11-90	Broadview (Snake Indian)						0.972	99.2 ± 10.2 Ma	659.6 ± 65.9 Ma
			C	19	2	213.6	1.2			
			MC	14	2	197.7	1.5			
			M	9	2	155.2	1.3			
			F	5	2	131.5	1.5			
3	DP11-100	Rocky Pass						0.995	74.8 ± 2.1 Ma	224.8 ± 9.8 Ma
			C	36	2	129.4	2.3			
			MC	26	2	116.3	1.4			
			M	17	2	99.9	2.7			
			F	13	2	95.3	2.2			
4	DP10-166D	Brule						0.993	53.9 ± 5.5 Ma	559.4 ± 29.8 Ma
			C	24	2	187.6	0.8			
			MC	18	2	159.1	0.6			
			M	11	2	112.4	0.3			
			F	6	2	91.3	0.3			
5	DP10-140A	Greenock						0.994	103.1 ± 2.0 Ma	255.7 ± 9.8 Ma
			C	32	2	152.3	0.6			
			MC	30	2	151.7	0.4			
			M	9	2	115.4	0.4			
			F	2	2	108.0	0.4			
6	DP10-11	Nikanassin						0.919	52.1 ± 3.9	248.8 ± 19.5
			C	38	2	122.6	0.5			
			MC	19	2	102.0	0.6			
			M	11	2	74.0	0.3			
			F	6	2	61.4	0.3			
7	DP10-1	Pyramid (Jasper)						0.987	163.0 ± 7.6 Ma	526.9 ± 32.8 Ma
			C	28	2	272.1	1.0			
			MC	32	2	286.2	0.9			
			M	16	2	232.3	0.6			
			F	12	2	206.8	0.6			
8	DP11-104	Sulphur Mountain (Abraham Lake)						0.965	75.6 ± 3.7 Ma	260.9 ± 16.2 Ma
			C	42	2	149.7	1.1			
			MC	29	2	137.7	0.5			
			MC	11	2	99.9	0.4			
			F	7	2	85.6	0.4			
9	DP10-2	McConnell (Abraham Lake)						0.998	54.0 ± 0.7 Ma	483.0 ± 4.52 Ma
			C	20	2	148.0	0.4			
			MC	16	2	130.3	0.5			
			M	8	2	92.7	0.3			
			F	6	2	82.4	0.2			
10	DP11-107	Johnston Creek						0.959	145.7 ± 14.9 Ma	615.3 ± 50.3 Ma
			C	41	2	359.0	1.4			
			MC	31	2	295.8	1.3			
			M	22	4	239.7	1.5			
			F	11	2	212.2	1.3			
11	DP11-114	Clearwater						0.752	74.2 ± 6.7 Ma	334.7 ± 36.6 Ma
			C	32	2	145.1	0.4			
			MC	18	2	141.1	1.1			
			M	11	2	110.0	0.6			
			F	8	2	91.5	0.3			
12	DP11-112	Simpson Pass						0.582	161.7 ± 6.6 Ma	302.5 ± 21.1 Ma
			C	52	2	226.5	1.1			
			MC	33	2	217.8	1.1			
			M	11	5	209.7	1.1			
			F	7	5	157.4	1.1			
A	MTF-FW2	McConnell footwall						0.937	69.3 ± 6.0 Ma	363.0 ± 32.5 Ma
			C	32	2	160.2	1.0			
			MC	17	2	135.8	0.7			
			M	8	2	93.0	0.4			
			F	6	2	85.5	0.4			

Note: C—coarse, MC—medium-coarse, M—medium, F—fine grain size fraction; TGA is total gas age (in Ma), R^2 is correlation of York regression and 2M1 is the (detrital) illite polytype.

sized fraction were created to characterize the mineralogy of each gouge sample by scanning from 2° to 50° 2θ (Cu Kα) at a rate of 1° per minute under both air-dried and glycolated conditions, using a Scintag X-ray diffractometer (XRD). Samples with illite were separated into size fractions via centrifugation. The clay fraction was first placed in an ultrasonic bath for ~15 min to promote deflocculation and then was subsequently separated using centrifuge settling. Gouge samples were separated into multiple size fractions, all smaller than 2 µm. In cases where carbonate minerals obscured the peaks that are used for polytype quantification, size fractions of gouges containing carbonates were treated with a weak (~1 *N*) acetic acid solution after separating material for $^{40}Ar/^{39}Ar$ dating to avoid any effects of acid treatment on Ar and K retention.

Illite Characterization

For illite age analysis, we quantified the percentages of the two main polytypes of illite: higher-temperature, detrital 2M1 polytype, and lower-temperature, authigenic 1Md polytype. Oriented slurry mounts can obscure the 2M1-specific peaks, which all have nonbasal reflections. Therefore, random orientation of the illitic material was used to quantify illite polytypes. Near-random powder mounts were made using an end-packer device modeled after Moore and Reynolds (1997). Samples were step-scanned in a Scintag diffractometer from 16° to 44° 2θ with a step size of 0.05° and count time of 30 s per step.

Illite polytype quantification was accomplished by modeling diffraction patterns using program WILDFIRE-generated XRD patterns (Reynolds, 1993) and mixtures of illite polytype standards. A spreadsheet program was used for matching the measured XRD patterns to modeled XRD patterns. Typical precision for this method is on the order of ±2%–3% (Haines and van der Pluijm, 2008). More detailed description of the illite characterization and dating procedures can be found in a recent methods paper by van der Pluijm and Hall (2015).

$^{40}Ar/^{39}Ar$ Dating

Samples were dated using the $^{40}Ar/^{39}Ar$ encapsulation method at the University of Michigan; development of the method and its application to fault dating are described in Dong et al. (1995), Hall et al. (2000), and van der Pluijm et al. (2001). Along with the acquisition of both a total gas age and a retention age, $^{40}Ar/^{39}Ar$ simultaneously measures radiogenic ^{40}Ar and ^{39}Ar, resulting in high precision, and allowing small samples (<1 mg) that require minimal chemical treatment. Size fractions were first compacted into pellets using a high-speed centrifuge and placed into small quartz vials. They were subsequently evacuated to high vacuum and sealed prior to irradiation in order to retain any argon released during irradiation in the reactor. After irradiation, the fused vial was broken so any recoiled gas could be analyzed. The sample was then step heated by a defocused laser (Coherent Innova 5 W Ar-ion laser) until fusion of the sample. Ages were calculated relative to the 520.4 Ma age for the Mmhb-1 hornblende standard, also irradiated in the same package as the illite size fractions. For this study, total gas ages, which include the recoiled fraction, are plotted against percentage of 2M1 and subsequently extrapolated using York regression (York, 1968; Mahon, 1996) to determine authigenic (fault rock) and detrital ages for each sample along with 1σ errors. Because the range in %2M1 is so much smaller than the range in Ar ages for each size fraction, this leads to relatively large errors in York regression (the "unochron" effect). The data regression for each sample shows excellent correlation (R^2 is typically greater than 0.95; Table 2), so standard linear regression would produce age errors that are as much as an order of magnitude smaller for most samples, reflecting the small errors of individual ages. However, we have opted to use the statistically more rigorous York regression errors, reflecting our recent practices. The results in Figure 2 show the York regression analysis for each fault sample, representing at least four size fractions each, in addition to upper and lower errors. Additional description and examples of the various steps of Ar dating and clay characterization can be found in van der Pluijm and Hall (2015).

RESULTS

Argon spectra for all samples show the effect of ^{39}Ar recoil, and, given the diagenetic grade and smectite content in these samples, total gas ages were used to determine fault rock ages (e.g., Foland et al., 1992; Dong et al., 2000; van der Pluijm and Hall, 2015). We plot the total gas age (represented as $e^{\lambda t} - 1$) against the percentage detrital illite in four size fractions for each fault gouge sample. For each rock sample, York regression analysis of ages from the four grain-size fractions produces an intercept at 0% detrital material (i.e., 100% authigenic) that records clay neomineralization in fault rock. Estimates of the age error include the analytical precision of the Ar age and the proportionally larger error in mineralogic quantification, as mentioned already. The upper intercept (at 100% detrital) is a proxy of the age of mica growth or cooling in the source area of the sediments, which can be a mixture of different detrital ages. These upper age intercepts, at 100% detrital illite, vary significantly for the samples analyzed, reflecting the varied sources of detrital material.

The results of 12 samples analyzed for this study together with 6 previous fault gouge analyses (summarized in Tables 1 and 2) yield ages that fall into four spatio-temporal clusters, which we interpret as distinct orogenic pulses, Late Jurassic, mid-Cretaceous, Late Cretaceous, and early Eocene, as examined in detail next. XRD patterns and Ar stepwise degassing spectra for all samples are available on request.

Late Jurassic Ages

Fault gouge samples from the westernmost (internal) thrusts sampled (Fig. 1) yield Late Jurassic ages. The Pyramid thrust (7 in Table 1) sampled on Highway 16, just north of the town of Jasper, has an age of 163.0 ± 7.6 Ma (Fig. 2A). The Simpson Pass thrust (12), sampled in the glacier cirque east of Highway 93 near Bow Lake, yields an age of 161.7 ± 6.7 Ma (Fig. 2A), and the Johnston Creek thrust (10) yields an age of 145.7 ± 14.9 Ma (Fig. 2A). The relatively high-grade (subgreenschist) Simpson Pass thrust is west of the Pyramid thrust but has a slightly younger age. However, the data show considerable scatter for this particular fault, and the ages are the same within error.

The upper age intercepts of the Johnston Creek (ca. 615 Ma) and Pyramid (ca. 527 Ma) thrusts indicate a significant contribution of Precambrian phyllosilicates in the gouge, likely derived from the Neoproterozoic Miette protolith of the hanging wall (Table 1). The contribution of the carbonate-dominated footwall is minor, if any, in the gouge of the Johnston thrust. In contrast, the phyllosilicates in the Devonian shale of the footwall considerably shifted the age of the detrital mixture in the Pyramid thrust gouge. The ca. 303 Ma upper age intercept of the Simpson Pass thrust indicates a Pennsylvanian cooling age of the detrital component in the Middle Cambrian protolith of the analyzed gouge.

Mid-Cretaceous Ages

The fault gouge sample from the Greenock thrust (5), collected south of the Athabasca River, yields an age of 103.1 ± 2.0 Ma (late Albian according to Gradstein et al., 2012) (Fig. 2B). The upper intercept age of ca. 256 Ma probably reflects the Late Permian cooling age of detrital phyllosilicate in the Jurassic Fernie Formation footwall of the thrust. The sample collected from the Broadview thrust (2) farther north near the Alberta–British Columbia border (Fig. 1) yields

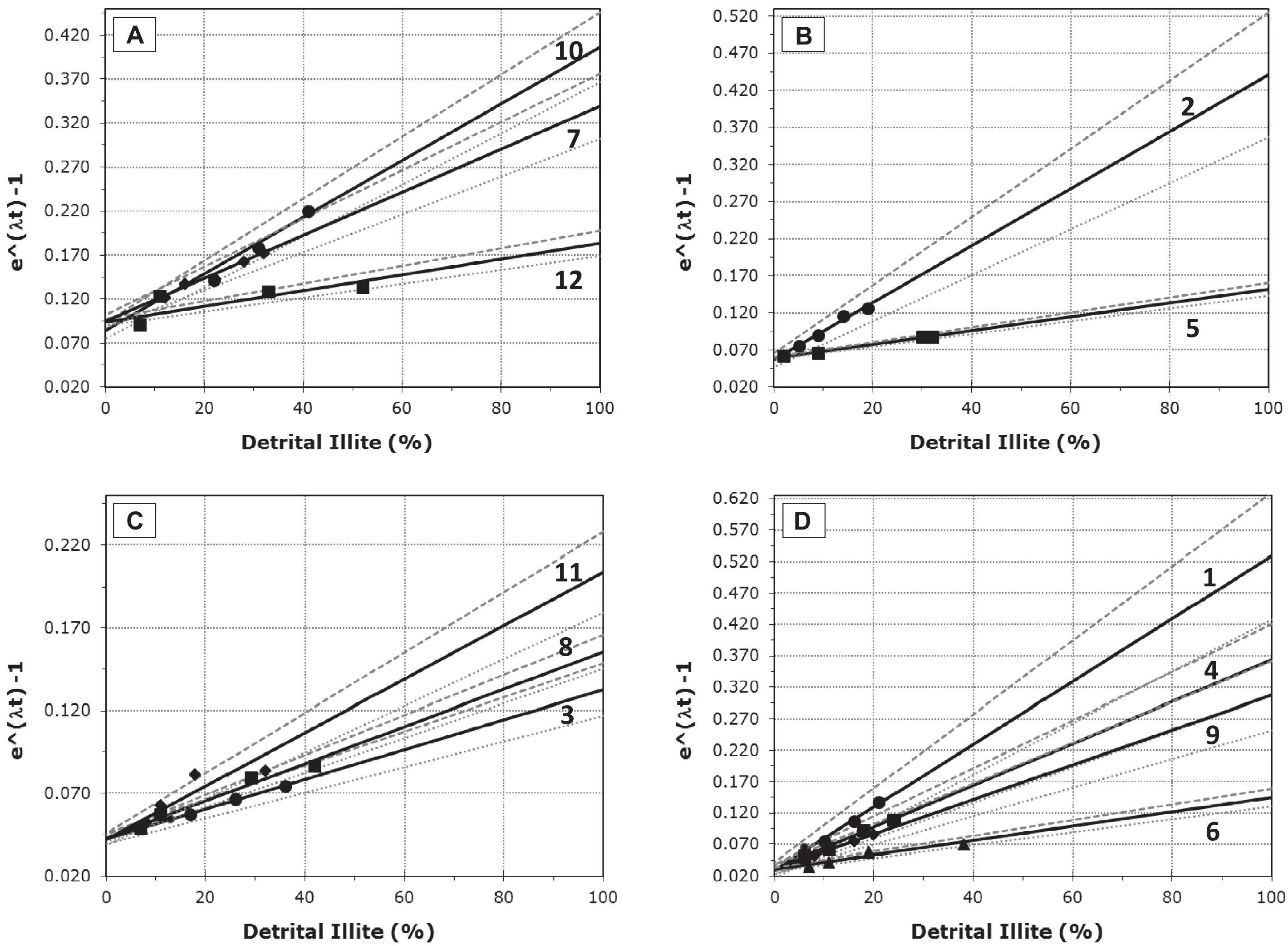


Figure 2. Illite age analysis (IAA) plots of percentages of detrital component and corresponding Ar ages of four fractions of clay gouge at each thrust. (A) Jurassic thrusts: 7—Pyramid thrust, 12—Simpson Pass thrust, 10—Johnson Creek thrust. (B) Mid-Cretaceous thrusts: 5—Greenock thrust, 2—Broadview thrust. (C) Late Cretaceous thrusts: 3—Rocky Pass thrust, 8—Sulfur Mountain thrust, 11—Clearwater thrust. (D) Early Cenozoic thrusts: 1—Muskeg thrust, 4—Brule thrust, 9—McConnell thrust, 6—Nikanassin thrust. The function $e^{\lambda t} - 1$ is linearly related to illite composition, where λ is decay constant, and *t* is time. Errors for each thrust were determined using York regression (see text) and are shown by dashed lines (upper error is long dash; lower error is short dash) surrounding the best-fit line in bold. The lower intercept at 0% detrital illite (i.e., 100% authigenic illite) corresponds to the fault rock age.

an age of 99.2 ± 10.2 Ma (Fig. 2B). The upper intercept of ca. 660 Ma likely reflects the local dominance of Proterozoic phyllosilicate to the gouge mixture derived from the Triassic Whitehorse Formation hanging wall and from the Jurassic Fernie Formation footwall.

Late Cretaceous Ages

Three fault gouge samples yielded well-clustered Campanian ages (Fig. 2C) that date the following thrusts from north to south: the Rocky Pass thrust (3), 74.8 ± 2.1 Ma; the Sulfur Mountain thrust at Abraham Lake (8), 75.6 ± 3.7 Ma; and the Clearwater thrust (11), 74.2 ± 6.7 Ma. The upper age intercepts of these fault rocks vary from ca. 225 Ma to 335 Ma, showing a larger contribution of younger mica (or younger cooling ages) to the detrital phase mixtures in the Jurassic footwall of these thrusts (Table 1).

Paleocene–Early Eocene Ages

Two thrusts in the northern portion of the Alberta Foothills yielded early Eocene ages: The Muskeg thrust (1), sampled along Highway 40, north of Grande Cache, yields an age of 52.4 ± 12.3 Ma (Fig. 2D), and the Brule thrust (4), sampled north of the Highway 16 "Entrance" into Jasper National Park, yields an age of 53.9 ± 5.5 Ma (Fig. 2D). Upper-intercept ages of ca. 766 Ma and 559 Ma, respectively, indicate a mixture of Precambrian detrital phases in the Lower Cretaceous Gates Formation and Upper Jurassic to lowermost Cretaceous Nikanassin protoliths at these two northern sample sites.

The McConnell thrust (9), sampled at Abraham Lake on the mountain slope just north of Highway 11, yields an age of 54.0 ± 0.7 Ma (Fig. 2D), and the Nikanassin thrust (6), sampled immediately south of the town of Cadomin, yields an age of 52.1 ± 3.9 Ma (Fig. 2D). The upper-intercept ages of ca. 483 Ma and 249 Ma reflect quite different mixtures of detrital phases in the Lower Cretaceous Luscar and the Upper

Jurassic to lowermost Cretaceous Nikanassin formations, respectively (Table 1).

The new $^{40}Ar/^{39}Ar$ illite ages for fault gouge presented here complement a smaller set of gouge ages previously reported from the southernmost Rocky Mountain fold-and-thrust belt in Alberta (van der Pluijm et al., 2006). Together, these gouge ages allow the recognition of temporal and spatial clustering of regional faulting that we interpret as four distinct tectonic pulses (Fig. 3). The relationship of these age clusters to sedimentation and regional tectonics is discussed in the next section.

DISCUSSION

The development and structural evolution of the Canadian Rocky Mountain fold-and-thrust belt is an intrinsic part of the tectonic assembly of the southern Canadian Cordillera (e.g., Monger, 1984, 1989; Price, 1994; Evenchick et al., 2007). Of particular interest to the tectonic evolution of the Foreland belt is the understanding of its kinematic links to various tectonic assemblages of the Omineca belt that bound the Foreland belt to the west (Fig. 1). In the traditional interpretation, the Omineca belt includes the most outboard lithotectonic assemblages with North American affiliation (Monger and Price, 2002): (1) Paleoproterozoic basement exposed in structural culminations of the Monashee complex and thrust slices of the Malton complex; and (2) Mesoproterozoic to Paleozoic supracrustal rocks deposited on the western margin of North America, as well as assemblages of the pericratonic Kootenay terrane (Lower Paleozoic sedimentary, volcanic, and igneous rocks) that formed on or adjacent to the North American continental margin. In addition, the Omineca belt comprises the oceanic suture (the Slide Mountain Permian volcanic and ultramafic rocks) between ancient North America and the Upper Devonian to Lower Jurassic volcanic and sedimentary arc–related rocks of Quesnellia (Monger, 1984, 1989; Price, 1994). Together, the lithotectonic assemblages marking the suture acted as a continental-scale snowplow, scraping off the rocks deposited on the continental margin of North America and, later, of the foreland basin. Rocks of the Omineca belt were polydeformed and metamorphosed during and following their Early to Middle Jurassic accretion (ca. 187–174 Ma), and some structural levels were reactivated and overprinted through the Jurassic, Cretaceous, Paleocene, and early Eocene (Evenchick et al., 2007).

Kinematic links between tectonic processes in the interior of the Canadian Cordillera and the foreland system (foreland fold-and-thrust belt and foreland basin) have been long discussed and are generally accepted today (Eisbacher et al., 1974; Beaumont, 1981; Beaumont et al., 1993; Price, 1981; Porter et al., 1982; Stott, 1984; Cant and Stockmal, 1989; Leckie and Smith, 1993; Stockmal et al., 1993, 2007). Moreover, contractional thin-skinned structures of the Foreland belt have been kinematically linked to deeper structures in the metamorphosed Omineca belt and, south of 53°N, are interpreted to be structurally continuous (McDonough and Simony, 1988; Kubli and Simony, 1994; Parrish, 1995; Price, 2007; Simony and Carr, 2011).

Our dating of major thrust faults in the southern Canadian Rockies offers new and independent constraints confirming that deformation of the foreland fold-and-thrust belt progressed from west to east as previously inferred. However, four age group clusters indicate that the eastward propagation of thrusting took place in distinct pulses that are separated by intervals of relative tectonic quiescence (Fig. 4). Flexural subsidence and uplift are the primary controls (relative to eustasy and local basement tectonics) on the creation or destruction of accommodation space in the foreland, thus controlling, to a large extent, the type of depositional system and the thickness of depositional sequences. The new radiometric fault ages allow, for the first time, a direct comparison between the timing of tectonism in the Omineca belt and the tectonic pulses identified in the Alberta portion of the Rocky Mountain fold-and-thrust belt, which are also related to changes in the depositional processes and sediment input in the foreland basin (Fig. 4). Next, we expand on the kinematic links among tectonic events recognized in the internal parts of the Cordillera, the thrusting pulses in the Alberta Rocky Mountain foreland fold-and-thrust belt, and the effects on depositional processes in the foreland basin.

Early Jurassic Pre-Orogenic Configuration of the Ancient North American Margin

During the Early Jurassic (Sinemurian to middle Toarcian), the western margin of North America south of 54°N consisted of a cherty carbonate platform that changed westward and northward into a narrow belt of organic-rich shale and carbonate sandstone, and farther west into a westward-thinning unit of starved-shelf, phosphatic mudstone and limestone (Asgar-Deen et al., 2004). Although, no margins or hinge line toward a deep basin west of the platform are preserved (Poulton, 1984), a western Early Jurassic North American continent-ocean margin is inferred based on intermittent phosphorite deposition since the Mississippian until the Early Jurassic, which required access to deep cold oceanic water to the west, either the open Pacific Ocean or a longitudinal trough connected with the ocean (Poulton and Aitken, 1989). According to Monger and Price (2002), outboard of cratonic North America, a region of marginal (Kootenay) or pericratonic (Quesnellia-Stikinia) terranes (Fig. 5) was followed westward by the last vestiges of the Cache Creek ocean (Fig. 1).

Early to Middle Jurassic Obduction and Westward Underthrusting of the Outer Margin of Ancestral North America

The Quesnellia and Slide Mountain terranes were imbricated and thrust eastward onto the western margin of North America between ca. 187 and 173 Ma (Nixon et al., 1993; Murphy et al., 1995). The Pliensbachian Nordegg Member depocenter in the Fernie Basin is roughly confined to the Wabamun domain of the Alberta basement, which is inferred to consist of Paleoproterozoic mylonitic rocks along the western segment of the Snowbird tectonic zone (Ross et al., 1994; McCartney, 2012) (index map in Fig. 1). McCartney (2012) proposed that this localized subsidence records the far-field, structurally controlled response of the basement to Early Jurassic tectonism at the western margin of North America.

Aalenian–Bajocian (ca. 173 and 168 Ma; Gradstein et al., 2012) shortening and crustal thickening up to 50–55 km in the Omineca belt were accompanied by low- to medium-grade regional metamorphism that reached its peak at ca. 169–165 Ma (Archibald et al., 1983; Price, 1986; Struik, 1988; Colpron et al., 1996). The western Omineca belt and eastern Intermontane belt have collectively defined an uplifted region concomitant with the onset of decoupling of supracrustal rocks from westward underthrusting North America (Price, 1986; Evenchick et al., 2007). Bathonian to early Oxfordian (ca. 168–161 Ma; Gradstein et al., 2012) rapid denudation exposed the northern Stikinia and Cache Creek terranes, as indicated by Cache Creek detritus shed to the west into the Bowser Basin (Eisbacher, 1981).

In spite of the structurally thickened crust, deep burial (20–25 km) of the outer margin of ancestral North America, and the emergence of the Omineca highland, the Middle Jurassic tectonism had little effect on the sedimentary record preserved in the Foreland belt over 350 km to the east. This has been explained by tectonic wedging of the Intermontane superterrane between the outboard part of the "miogeoclinal" strata and their North American crystalline basement, which does not require crustal thickening, uplift, and deep erosion in the Jurassic Fernie Basin to the east (Price, 1994), or by

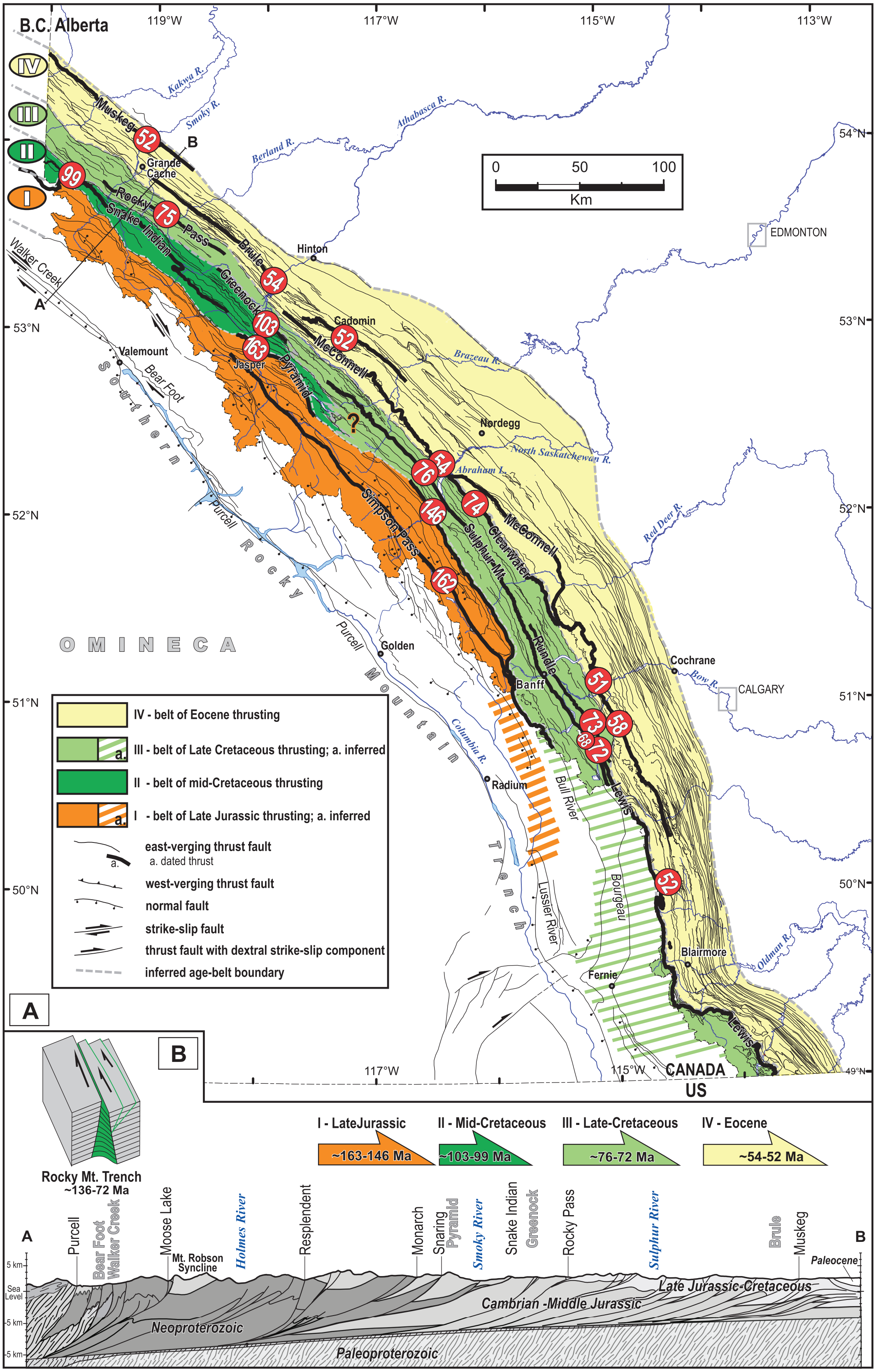


Figure 3. Summary of gouge illite ages obtained from the southern segment of the Rocky Mountains fold-and-thrust belt. (A) Twelve ages north of the town of Banff are from the present study, whereas six ages south of Banff are from van der Pluijm et al. (2006). Roman numbers in the top left part of the figure are the four, eastward-progressing orogenic pulses that are identified in this study. (B) Generalized cross section in the region north of Valemount-Jasper-Hinton, where all four generations of thrusts have been identified. The age intervals are based on nearby ages obtained in this study. Names of thrusts in black are for thrusts intersected by the cross section, whereas names in gray are for thrusts projected to the line of cross section (modified after Mountjoy, 1980).

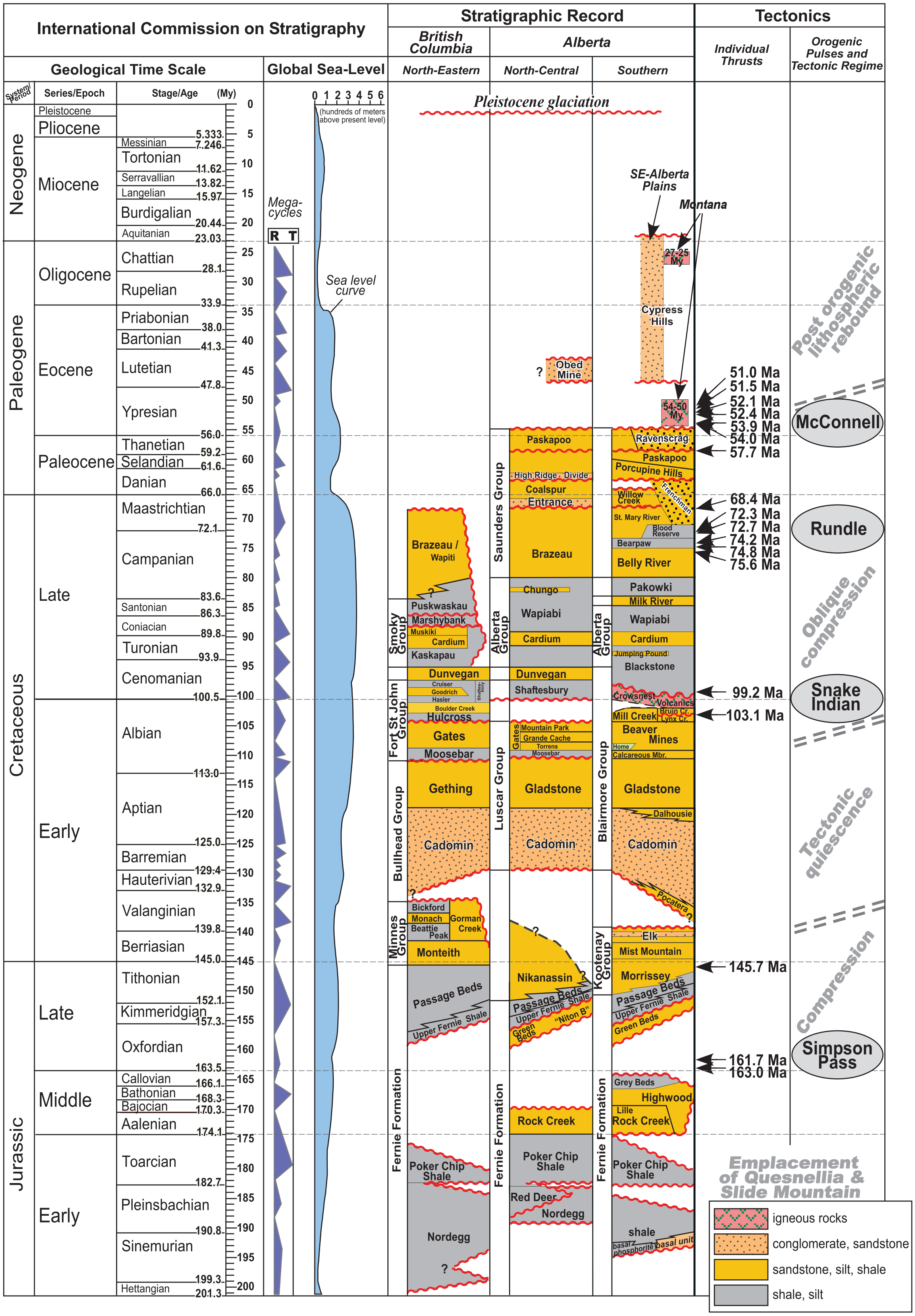


Figure 4. Summary of the stratigraphic and tectonic record in the southern Canadian Foreland belt and chronostratigraphic table with numerical ages of epoch/series and age/stage boundaries after the International Union of Geological Sciences–International Commission on Stratigraphy (2013); sea-level curve and megacycles of sea-level trends are from Gradstein et al. (2012); R—regression, T—transgression. For the detailed stratigraphy of the Rocky Mountains and Foothills, see Pană and Elgr (2013).

tectonic loading on weak lithosphere, too far to the west to have elastically depressed the thick craton to the east (Evenchick et al., 2007). The Aalenian–Bajocian deposits in the foreland consist of 30–90 m of shelf mudstone and sandstone, still of northeasterly derivation (Hall, 1984; Poulton et al., 1990). Ross et al. (2005) explained the lack of metamorphic detritus in the foreland basin strata by invoking a drainage divide between the Omineca belt and the river systems that drained the eastern side of the orogen, which consisted of thrust-imbricated unmetamorphosed miogeoclinal strata.

Several ash beds (188–165 Ma) in the Red Deer, Highwood, and Grey Beds members of the Fernie Formation in SW Alberta and SE British Columbia indicate igneous activity to the west (Hall et al., 2004). Significant differences in the units deposited and preserved in different areas, and the depth of erosion at unconformities, suggest that the Lower and Middle Jurassic western cratonic platform or shelf was not entirely stable, perhaps due to the initial Cordilleran orogenic events to the west (Poulton et al., 1994). McCartney (2012) used tectonic subsidence maps (as proxy for paleostructure maps), together with isopach patterns and sedimentological and geochemical indications of a restricted basin to argue for the deposition of the Lower Jurassic units (Nordegg, Poker Chip Shale, and Rock Creek members) in a backbulge region, distal to crustal loading. The pre-Toarcian unconformity (ca. 183 Ma; Gradstein et al., 2012) below the Poker Chip Shale Member and the pre-Aalenian unconformity (ca. 174 Ma) below the Rock Creek Member may represent far eastern expressions of the (proto)forebulge migration in the Early and Middle Jurassic Fernie Basin (Fig. 4). Increased subsidence is suggested by the local preservation of an 80-m-thick section of Bathonian (to early Callovian?) Grey Beds in the Fernie area (Poulton, 1984).

Late Middle Jurassic to Earliest Cretaceous Orogen Buildup and Development of the Rocky Mountain Foredeep

The Late Jurassic and Early Cretaceous convergence between North America and the Pacific oceanic lithosphere, with its embedded, buoyant oceanic volcanic arcs, plateaus, and seamount chains, was dominated by near-orthogonal and left-lateral oblique contraction (Engebretson et al., 1985; Price, 1994). The Cordilleran platformal deposits were scraped off their basement and accreted to the advancing front of the Intermontane superterrane (Fig. 1), where it formed the oldest part of the Rocky Mountain fold-and-thrust belt. The sub-Oxfordian unconformity represents the passage of the Jurassic forebulge through the area, and the Upper Fernie shale and sandstone strata are the first foredeep deposits (McCartney, 2012). As a result of the first widespread loading of the North American craton by accreted terranes and thickened western North American supracrustal rocks, the first pronounced flexural subsidence and development of a two-sided foredeep trough in the foreland began in about the Oxfordian.

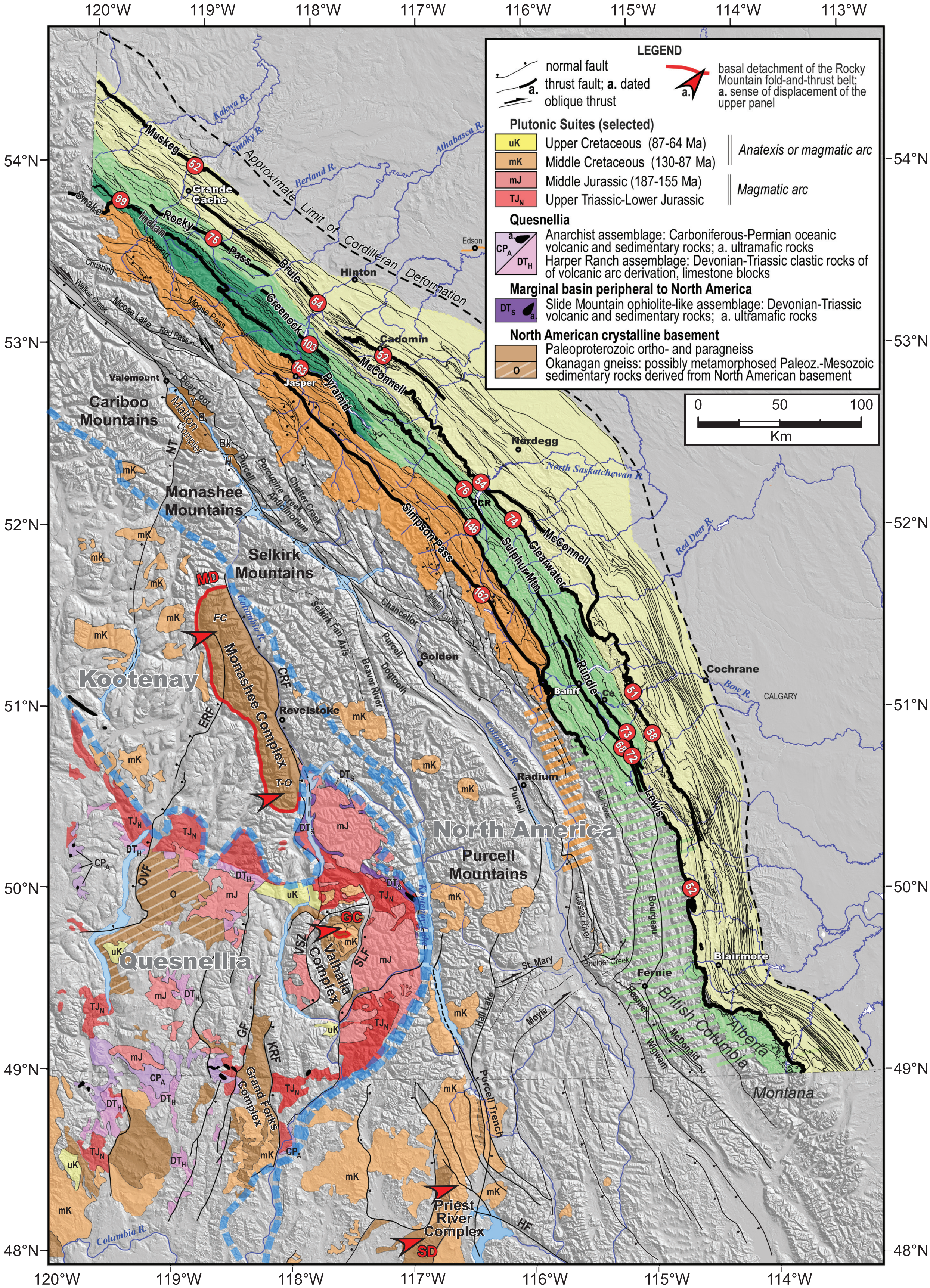
Post–early Oxfordian deposition of a thick west-derived coarsening- and shallowing-upward succession is considered to indicate the first regional subsidence, marking the transition from a continental margin to the succeeding Rocky Mountain foreland trough or foredeep superimposed on the same area (Bally et al., 1966; Poulton, 1984, 1989; Poulton et al., 1993, 1994; Stott, 1998). During the Kimmeridgian to Valanginian (ca. 156–136 Ma; Gradstein et al., 2012), the orogen contributed sediment to the oldest component of the foreland basin, the increasingly sandstone-dominated Passage Beds (upper Fernie Formation) through Morrissey–Nikanassin–Monteith formations (Fig. 4). Multiple transgressive and regressive events recognized in the 2200-m-thick Minnes Group indicate that subsidence was greater and continued later in the northern portion of the basin (Stott, 1984, 1998; Poulton et al., 1994). To the north, in the northern Yukon, the initial orogenic clastic wedge in the Foreland basin is of Cretaceous age (Poulton, 1984), suggesting northward-advancing tectonic loading during oblique collision in and west of the Omineca belt (Eisbacher, 1981, 1985).

In the Omineca belt, between latitudes 52°N and 53°N, a zone of medium-grade metamorphism that trends north-northwest across the Cariboo, Monashee, and Selkirk Mountains (Fig. 5) preserves evidence of penetrative shortening throughout the Late Jurassic to Paleocene (Currie, 1988; Ferguson, 1994; Digel et al., 1998; Reid, 2003; Ghent and Simony, 2005; Gibson et al., 2008). Continued growth of the Omineca highland, as it was translated inboard onto thicker, more rigid crust, loaded the lithosphere and affected the sedimentation patterns of the adjacent basin to the east.

Paleocurrent data, detrital zircon U-Pb ages, and the sedimentary characteristics of the Kimmeridgian to Valanginian strata in the southern Canadian Rocky Mountain fold-and-thrust belt suggest a dominant longitudinal depositional system with a main source in the Cordilleran and continental deposits of the United States, added by transverse river systems that would supply detritus from the adjacent Canadian Cordillera (Hamblin and Walker, 1979; Poulton et al., 1994; Raines et al., 2013; Kukulski et al., 2013) (Fig. 6).

In northeastern British Columbia, the thick Passage Beds through Minnes Group were ascribed to western sources (Stott, 1998), but the first more definitive evidence of western provenance is the presence of conglomerates in the late Tithonian–Berriasian Monteith Formation (McMechan, et al., 2006). In the Banff area, two turbidite lobes in the lower part of the Kimmeridgian Passage Beds, which show northeasterly paleocurrent directions (Hamblin and Walker, 1979), and zircon grains as old as 152 Ma and 147 Ma in the Tithonian sandstones of the lower Kootenay and Minnes Groups (Raines et al., 2013) indicate that detritus from contemporaneous Cordilleran igneous sources was shed into the foreland basin. Kimmeridgian strata also contain detrital muscovite that is unlikely to have survived long-distance transport (from the east or south), or episodes of sediment recycling. Moreover, in the exposed Canadian Shield, most rocks formed at pressures and temperatures higher than the quartz + muscovite stability

Figure 5 (*on following page*). Simplified geological map of the southern Canadian Foreland and Omineca belts (compiled from Journeay et al., 2000; Pană and Elgr, 2013). Thrust faults in the foreland fold-and-thrust belt are assigned to the four age belts defined in Figure 3, using the same color scheme. Gneiss bodies on east side of Rocky Mountain Trench near the Malton complex: Y—Yellowjacket; B—Bulldog; Bk—Blackman, and H—Hugh Allan. FC—Frenchman Cap and T-O—Thor-Odin areas of the Monashee Complex. Okanagan gneiss (O) with ages of ca. 2.2–2.0 Ga across multiple radiometric systems (Armstrong et al. 1991) was initially interpreted as the westernmost exposure of North American crystalline basement; Brown et al. (2012) interpreted the Okanagan gneiss to have formed by metamorphism of Paleozoic–Mesozoic sedimentary rocks derived from North American basement and intruded by 160 Ma mafic sheets. NT—North Thompson fault; CRF—Columbia River fault; ERF—Eagle River fault; OVF—Okanagan Valley fault; VSZ—Valkyr shear zone; SLF—Slocan Lake fault; GF—Grand Forks fault; HF—Hope fault; KRF—Kettle River fault. Inferred western exposures of the midcrustal structural level of the Rocky Mountain basal detachment: SD—Spokane Dome mylonite zone; GC—Gwillim Creek shear zone; MD—Monashee décollement; arrows indicate sense of hanging-wall displacement.



LEGEND
normal fault
thrust fault; a. dated
oblique thrust
basal detachment of the Rocky Mountain fold-and-thrust belt; a. sense of displacement of the upper panel
Plutonic Suites (selected)
uK Upper Cretaceous (87-64 Ma)
mK Middle Cretaceous (130-87 Ma)
Anatexis or magmatic arc
mJ Middle Jurassic (187-155 Ma)
TJN Upper Triassic-Lower Jurassic
Magmatic arc
Quesnellia
Anarchist assemblage: Carboniferous-Permian oceanic volcanic and sedimentary rocks; a. ultramafic rocks
Harper Ranch assemblage: Devonian-Triassic clastic rocks of of volcanic arc derivation, limestone blocks
Marginal basin peripheral to North America
Slide Mountain ophiolite-like assemblage: Devonian-Triassic volcanic and sedimentary rocks; a. ultramafic rocks
North American crystalline basement
Paleoproterozoic ortho- and paragneiss
Okanagan gneiss: possibly metamorphosed Paleoz.-Mesozoic sedimentary rocks derived from North American basement
0 50 100
Km
Approximate Limit of Cordilleran Deformation
Cariboo Mountains
Monashee Mountains
Selkirk Mountains
Kootenay
Monashee Complex
North America
Purcell Mountains
Quesnellia
Valhalla Complex
Grand Forks Complex
Priest River Complex
British Columbia
Alberta
Montana
Grande Cache
Hinton
Edson
Cadomin
Jasper
Valemount
Nordegg
Golden
Revelstoke
Banff
Cochrane
CALGARY
Radium
Fernie
Blairmore
Muskeg
Rocky Pass
Brule
Greenock
McConnell
Pyramid
Simpson Pass
Sulphur Mtn
Clearwater
Rundle
Lewis
Bourgeau
120°W 119°W 118°W 117°W 116°W 115°W 114°W 113°W
54°N 53°N 52°N 51°N 50°N 49°N 48°N

Figure 5.

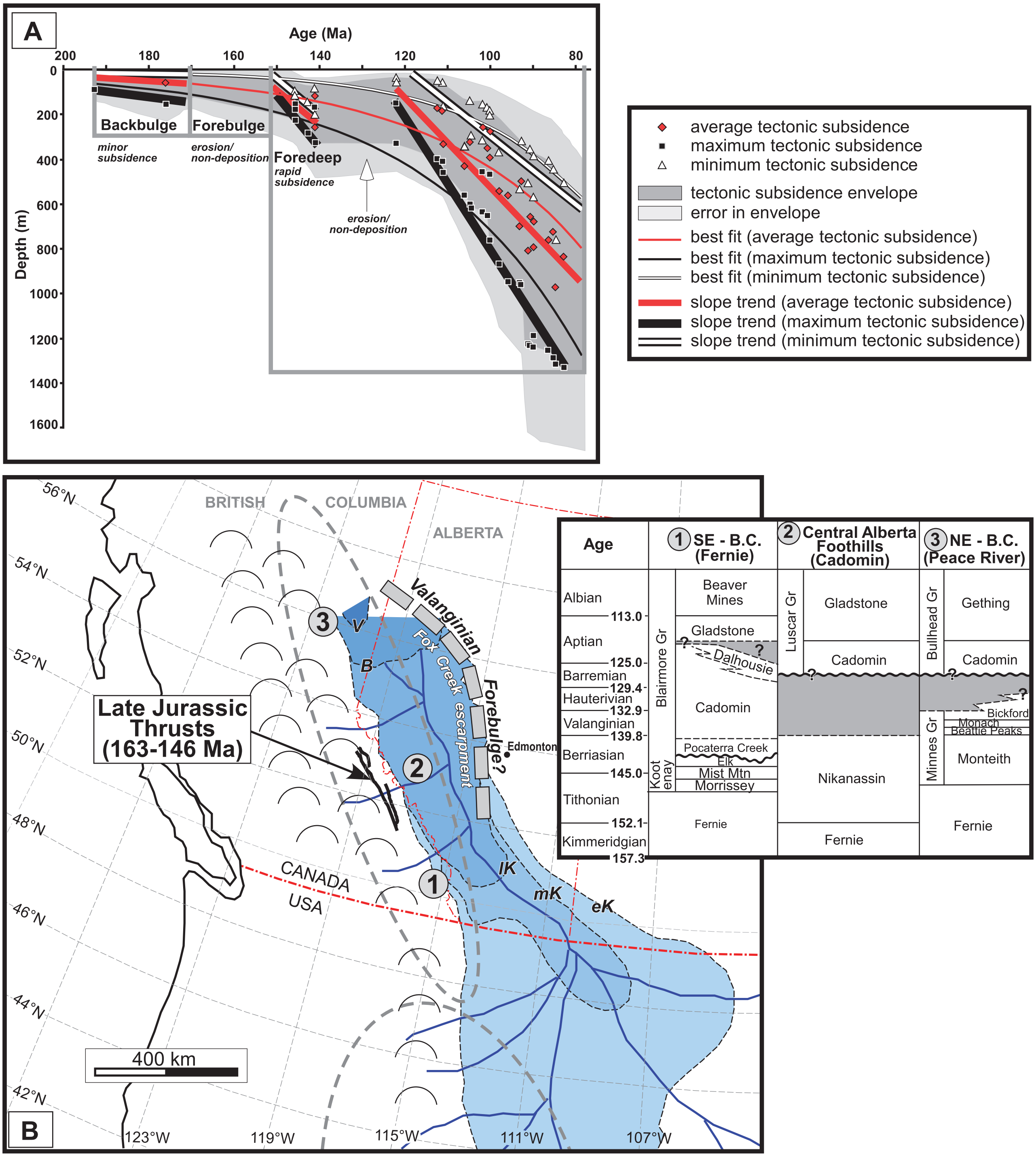


Figure 6. Initiation of the foreland basin stage in the Western Canada sedimentary basin and its Jurassic–Cretaceous evolution. (A) Tectonic subsidence envelope with regional subsidence trends for a reference well in west-central Alberta (modified from McCartney, 2012): The tectonic subsidence envelope shows the low subsidence rates expected in a back-bulge depozone (deposition of the Nordegg, Poker Chip Shale, and Rock Creek members of the lower Fernie Formation), the unconformity associated with the passage of a forebulge, and the rapid subsidence during deposition in the foredeep (upper Fernie Formation and Kootenay/Nikanassin/Minnes strata). (B) Evolution of the foreland depositional system during Kimmeridgian to Valanginian: The narrow northwest-trending basin was dominated by an axial river network (Hamblin and Walker, 1979; Stott, 1998); overall, the basin filled axially from the south with contribution from the rising orogen to the west (Raines et al., 2013); forebulge location is from Kukulski et al. (2013); northwestward prograding shorelines are eK, mK, and lK—early, middle, and late Kimmeridgian, respectively; B—Berriasian, V—Valanginian (after Raines et al., 2013); circled numbers on map correspond to columns in the correlation chart; correlation chart was compiled from Poulton et al. (1994), Stott (1998), and White and Leckie (1999).

field, and muscovite is only present in narrow low-grade shear zones and associated minor late- to postkinematic granite plugs (e.g., Berman and Bostock, 1997; Pană, 2010). Muscovite and the associated stretched quartz require western metamorphic sources of the exhumed terranes in the eastern Omineca highland (McMechan and Thompson, 1992; Ross et al., 2005).

Detrital mica from gouge samples derived from the Jurassic Fernie Formation yielded a Neoproterozoic age (ca. 660 Ma, Broadview thrust), as well as Mississippian (335 Ma, Clearwater thrust), Late Permian (256 Ma, Greenock thrust; and 261 Ma, Sulfur Mountain thrust), and Middle Triassic (225 Ma, Rocky Pass thrust) ages. These ages may indicate a dominant Neoproterozoic mica source in the northern part of the Fernie Basin and the influx of younger or later-cooled Paleozoic to Triassic mica to the south.

Because no eastern source of Neoproterozoic mica is obvious, we speculate that the initial source was at the ancient western margin of North America. The formation of Neoproterozoic mica could be related to the ca. 800–700 Ma prolonged and diachronous rift-drift events that resulted in the breakup of Rodinia and the establishment of Laurentia's west margin (Sears and Price, 2000; Millonig et al., 2012).

Upper-intercept ages of 660 Ma in the Fernie Formation gouge, together with 766 Ma and 556 Ma ages from Cretaceous Gates Formation gouge, and 615 Ma and 527 Ma ages from Miette gouge, indicate the presence of mica with Precambrian cooling ages. Such mica could have been recycled into strata of the Western Canada sedimentary basin through erosion of Precambrian rocks exposed in domal and arch structures developed during the early, middle (ca. 500 Ma, 360–340 Ma; Millonig et al., 2012), or late (McDonough and Parrish, 1991) Paleozoic tectonothermal events that affected the outboard side of the Western Canada sedimentary basin. For example, the Neoproterozoic Windermere Supergroup uplifted in the Peace River Arch (index map in Fig. 1) is truncated by the Cambrian Gog Group.

Mississippian, Permian, and Triassic ages associated with inferred tectonothermal events, albeit infrequent and scattered, have been reported from the Windermere Supergroup and basement rocks in southern Omineca (Mortensen et al., 1987; Murphy et al., 1995; Crowley et al., 2000; Millonig et al., 2012) and the adjacent western Rocky Mountain fold-and-thrust belt (McDonough and Parrish, 1991; McMechan and Roddick, 1991). Mica formed during these events could have been recycled in the Western Canada sedimentary basin from domes and arches during the "platformal" stage and from the orogen or forebulge during the "foreland" stage of basin evolution.

The ages of 163–162 Ma of the Pyramid and Simpson Pass thrusts and of 146 Ma of the Johnson Creek thrust from the western Rocky Mountain fold-and-thrust belt suggest a Late Jurassic tectonic pulse consistent with early Oxfordian to late Tithonian (ca. 163–146 Ma; Gradstein et al., 2012) flexural subsidence and deposition inferred from the stratigraphic record in the Alberta foreland belt.

The emplacement of the Simpson Pass and Pyramid thrust sheets coincides with the exhumation of the Middle Jurassic metamorphic core of the southeastern Omineca hinterland completed at 163 Ma (Colpron et al., 1996), and with the sub-Oxfordian time-transgressive erosive disconformity recorded by the depositional system of the Middle to Late Jurassic "Sundance Sea," a southward-extending arm of the Arctic Ocean (Marion, 1984) (Fig. 4). We speculate that the tectonic loading event dated here triggered the northeastward migration of the forebulge, inferred by Poulton (1984) and Poulton et al. (1993) from the removal of much of the Middle Jurassic stratigraphic record from the Foreland belt and adjacent craton.

The Oxfordian glauconite-rich, sandstone-dominated Green Beds in the Jasper area (Frebold et al., 1959) and the locally glauconitic "Niton B" sandstone in the subsurface to the east (Losert, 1990; Williams et al., 2013) were replaced by the regionally extensive, westerly thickening, upper Fernie shales during one of many Sundance Sea transgressions. This interval of thin, unconformably bound clastics at the base of the transgressive Kimmeridgian upper Fernie shale (Williams et al., 2012) probably records deposition between tectonic events of the long-lasting Late Jurassic tectonic pulse.

The emplacement of the east-vergent Johnston Creek thrust at 146 Ma was quasi-contemporaneous with the SW-vergent penetrative deformation and metamorphism recognized in the Cariboo Mountains of the Omineca belt (ca. 147 Ma; Reid, 2003) and with the youngest zircon grains identified in the lower Kootenay and Minnes sandstones (152–147 Ma; Raines et al., 2013). One noteworthy observation is that Late Jurassic thrust ages have been identified so far only in the north-central part of the study area (Fig. 3), where the Oxfordian and Kimmeridgian unconformities in the foreland are best developed (Poulton et al., 1994).

The long interval of apparent tectonic quiescence between the emplacement of the 146 Ma Johnston Creek thrust and the mid-Cretaceous thrusts (see next section) may be a consequence of the limited number of dated thrusts. On the other hand, this interval encompasses the continental-scale break in the Early Cretaceous Cordilleran foreland basin sedimentation, attributed to either isostatic uplift or the passage of a flexural forebulge (Heller and Paola, 1989; Hayes et al., 1994). In the foreland of the southern Canadian Rocky Mountain fold-and-thrust belt, palynological data from bounding strata indicate that this depositional hiatus, marked by the sub–Cadomin Formation low-angle unconformity, varies from minimal (if any) in southeastern and northeastern British Columbia, to the entire Hauterivian–early Aptian interval in west-central Alberta (Ricketts and Sweet, 1986; Stott and Aitken, 1993; Stott, 1998) (Fig. 4). In southeastern British Columbia and southwestern Alberta, deposition of the thin Cadomin Formation occurred over a long period of time, from Berriasian to Barremian (possibly early Aptian) time, with north-flowing rivers migrating laterally across the 50 km E-W extent of the braid plain, producing local diastems of varying duration (White and Leckie, 1999). Similarly, in northeastern British Columbia, the deposition was more continuous in the western Foothills, and the sub-Cadomin unconformity is less pronounced, with little, if any, depositional hiatus (Stott, 1998).

The region of longest nondeposition in the foreland is in front of the only Late Jurassic thrusts identified so far in the central Alberta segment of the Rocky Mountain fold-and-thrust belt (Fig. 6). This, and the almost continuous deposition toward the ends of this arcuate, 700-km-long segment in the southeastern and northeastern British Columbia portions of the Early Cretaceous foreland basin argue for regional causes triggered by tectonic loading rather than uniform continental-scale isostatic uplift. Moreover, in the immediate foreland, the Fox Creek Escarpment (Smith, 1994) limited eastward deposition of stratigraphic units that overlie the Monteith Formation and may be the expression of the forebulge in this region (Kukulski et al., 2013) (Fig. 6). The maximum depositional hiatus in front of the Late Jurassic thrusts may mark an area of Valanginian–Barremian isostatic rebound in front of these thrusts. Alternatively, and consistent with numerical models for foreland systems, it may simply record a decline in sediment supply from the orogen at the end of thrusting, accompanied by basin exhumation and generation of an unconformity (Tucker and van der Beek, 2013), which is more prominent in the region of maximum Late Jurassic tectonic loading.

Mid-Cretaceous Tectonic Pulse

A global mid-Cretaceous (105–100 Ma) plate reorganization event modified relative plate motions, tectonic regimes at major convergent margins, and far-field stress patterns at continent interiors (Matthews et al., 2012). In the Canadian Cordillera, it is the time of the Insular superterrane accretion (Monger, 1989). Starting in mid-Cretaceous up to early Eocene, the evolution of the Canadian Cordillera was dominated by a general pattern of oblique convergence, involving a combination of subduction of Pacific oceanic lithosphere (in the Cascadia subduction zone) beneath western North America, dextral strike slip, and thrusting (Tempelman-Kluit, 1979; Eisbacher, 1985; Van den Driessche and Maluski, 1986; Price and Carmichael, 1986). The mid-Cretaceous ages of thrusting identified in this study are consistent with the previously inferred kinematic link across the entire southern Canadian Cordillera between the Cascadia subduction zone and the Cordilleran Foreland belt (Price, 1994; Evenchick et al., 2007).

In the Omineca belt, the Late Jurassic tectonic phase was followed by an interval of apparent tectonic quiescence, until the mid-Cretaceous, when lower-structural-level rocks south of latitude 52°30′N were reactivated under amphibolite- to greenschist-facies metamorphic conditions (Sevigny et al., 1990; Scammell, 1993). Deeply exhumed rocks exhibit mid-Cretaceous to Eocene ductile strain, folding, and transposition, indicating that strain partitioning at deep structural levels in the Omineca belt was concomitant with northeastward propagation of deformation and thin-skinned shortening in the Foreland belt (Simony and Carr, 2011). The emplacement of the northeast-vergent Purcell–Hall Lake thrust system (sealed by the ca. 93 Ma intrusion of the Horsethief Creek batholith), as well as the Albian cooling of the Yellowjacket gneiss (ca. 112 Ma) are quasi-contemporaneous with the northeast-directed thrust faults in the Foreland belt (Archibald et al., 1983; Van Den Driessche and Maluski, 1986; McDonough and Simony, 1988; Digel et al., 1998) (Fig. 5).

The Greenock thrust yielded an age of 103.1 ± 2.0 Ma, which coincides with the unconformity at the base of the upper Fort St. John Group (the transgression of the "Hulcross Sea") in the immediate foreland (Fig. 4). The 99.2 ± 10.2 Ma age of the Broadview thrust, which is a frontal splay of the Snake Indian thrust, approximates the timing of emplacement of the regionally extensive and much larger Snake Indian thrust, which straddles the Alberta–British Columbia border (Fig. 7). The emplacement of this thrust system coincides with the development of the Cenomanian fluvio-deltaic system that drained the active mid-Cretaceous orogenic belt and led to the accumulation of the Dunvegan Formation (Bhattacharya, 1993). The facies distribution map shows coarse alluvial deposits shed from the orogen in northeastern British Columbia and facies boundaries oriented at high angle to the thrust faults, suggesting longitudinal depositional systems (Leckie and Smith, 1993) (Fig. 7). This may indicate more active mid-Cretaceous thrusting and orogen buildup in the northern Canadian Rockies linked to the mid-Cretaceous dextral transcurrent tectonics along the Teslin–Northern Rocky Mountain Trench fault network, accompanied by voluminous ca. 115–100 Ma granitic plutonism (Gabrielse et al., 2006). Thus, the dated thrusts could represent the southernmost expression of a mid-Cretaceous thrust front in the northern Rocky Mountain fold-and-thrust belt (Fig. 7).

The Dunvegan allomembers (A–G in Fig. 7) are separated by several regional transgressive flooding surfaces (Bhattacharya and MacEachern, 2009). Relative to their K1 marker datum, the westward-dipping Fish Scale marker suggests ongoing Cenomanian downward flexing of the foreland basin floor. The timing of subsidence, associated with numerous growth faults (Plint, 2000), is constrained by the Fish Scale marker, the base of which coincides with the 100.5 Ma Albian-Cenomanian boundary (according to Gradstein et al., 2012), and by the almost flat lying 95.9 ± 0.1 Ma "X" bentonite (Barker et al., 2011). These depositional and structural features are consistent with the incremental propagation and erosion of Cenomanian thrusts, which triggered fault-assisted subsidence in the foredeep, and individual flooding events of the Cenomanian Western Interior Seaway of North America.

The 110–90 Ma granitoid magmatism documented in the southern Canadian Cordillera represents a magmatic arc on the mid-Cretaceous margin of North America (Fig. 5). It extends eastward into the Rocky Mountain fold-and-thrust belt with the ca. 102 Ma pyroclastic deposits of the Crowsnest Formation west of Blairmore and their hypabyssal feeders, exposed to the south in the Lewis thrust sheet (Pană and Elgr, 2013). Some Albian strata in the Alberta foreland basin have clasts of Intermontane belt volcanic and intrusive rocks indicating long river systems cutting across the rising orogen (McMechan and Thompson, 1992; Ross et al., 2005).

Late Cretaceous Tectonic Pulse

In the Omineca belt, south of latitude 52°N, intense Late Cretaceous–Paleocene tectonism is recorded by penetrative polydeformation and metamorphism (e.g., eastern Selkirk fan, Selkirk allochthon north of Monashee complex), development of zones of high strain, ductile shear zones, and crystalline nappes (e.g., mid-crustal deformation zone south of Thor-Odin; the Monashee décollement in Frenchman Cap dome; Gwillim Creek shear zone in Valhalla complex; Carr, 1992; Scammell and Parrish, 1993; Crowley, 1997, 1999; Crowley and Parrish, 1999; Gibson et al., 1999; Crowley et al., 2001; Gibson, 2003; Kuiper, 2004; Williams and Jiang, 2005; Brown and Gibson, 2006; Carr and Simony, 2006; Simony and Carr, 2011). Igneous activity during Late Cretaceous tectonism retreated westward in the Omineca belt (Fig. 5). Active tectonism in the Omineca belt was contemporaneous with significant sediment accumulation and basin subsidence in the Alberta foreland basin over a broad area during the Campanian through Paleocene.

The deformation front migrated eastward across the Front Ranges, accompanied by rapid, coarse clastic sedimentation dominantly sourced from the Foreland belt (Price and Mountjoy, 1970; Price, 1981; McMechan and Thompson, 1992; Stott and Aitken, 1993; Ross et al., 2005). Most of the shortening of the southern Rocky Mountain fold-and-thrust belt was inferred to have occurred after the Turonian (younger than 89 Ma), concurrent and kinematically linked with strike-slip faulting on the northern Rocky Mountain–Tintina fault system (Price, 1994; Gabrielse et al., 2006).

Clustered Late Cretaceous gouge ages previously identified in the southern Canadian Rockies from Sulfur Mountain (68.4 ± 13.0 Ma), Rundle (72.7 ± 6.1 Ma), and Lewis (72.3 ± 2.3 Ma) thrusts were assigned to the 72 Ma "Rundle pulse" (van der Pluijm et al., 2006). Three more fault gouge samples from major thrusts presented here yielded Campanian ages: the Rocky Pass thrust, 74.8 ± 2.1 Ma; the Sulfur Mountain thrust (at Abraham Lake), 75.6 ± 3.7 Ma; and the Clearwater thrust, 74.2 ± 6.7 Ma. The six Late Cretaceous (five Campanian and one, less constrained, Maastrichtian) thrust ages identified in the southern Canadian Rocky Mountain fold-and-thrust belt range from 75.6 Ma to 68.4 Ma. The gouge age of 72.3 ± 2.3 Ma yielded by the Lewis thrust overlaps, within error, with the 75 ± 5 Ma emplacement age previously inferred for this thrust from fission-track and vitrinite reflectance data combined with stratigraphic data (Feinstein et al., 2007).

In the Banff region at the latitude of the Trans-Canada Highway 1 (Fig. 1), the Rundle, Bourgeau, and Sulfur Mountain thrust faults formed as an interlinked system (Price, 2001). To the south, the Bourgeau and Lewis thrusts are indirectly linked with the Hosmer-Wigwam-McDonald thrust system (Figs. 1 and 5), and all together are believed to represent the upper structural level of a Late Cretaceous to Paleocene Rocky Mountain basal décollement (Price, 2007; Simony and Carr, 2011). The basal décollement is inferred to extend westward under the Purcell and Selkirk Mountains as a

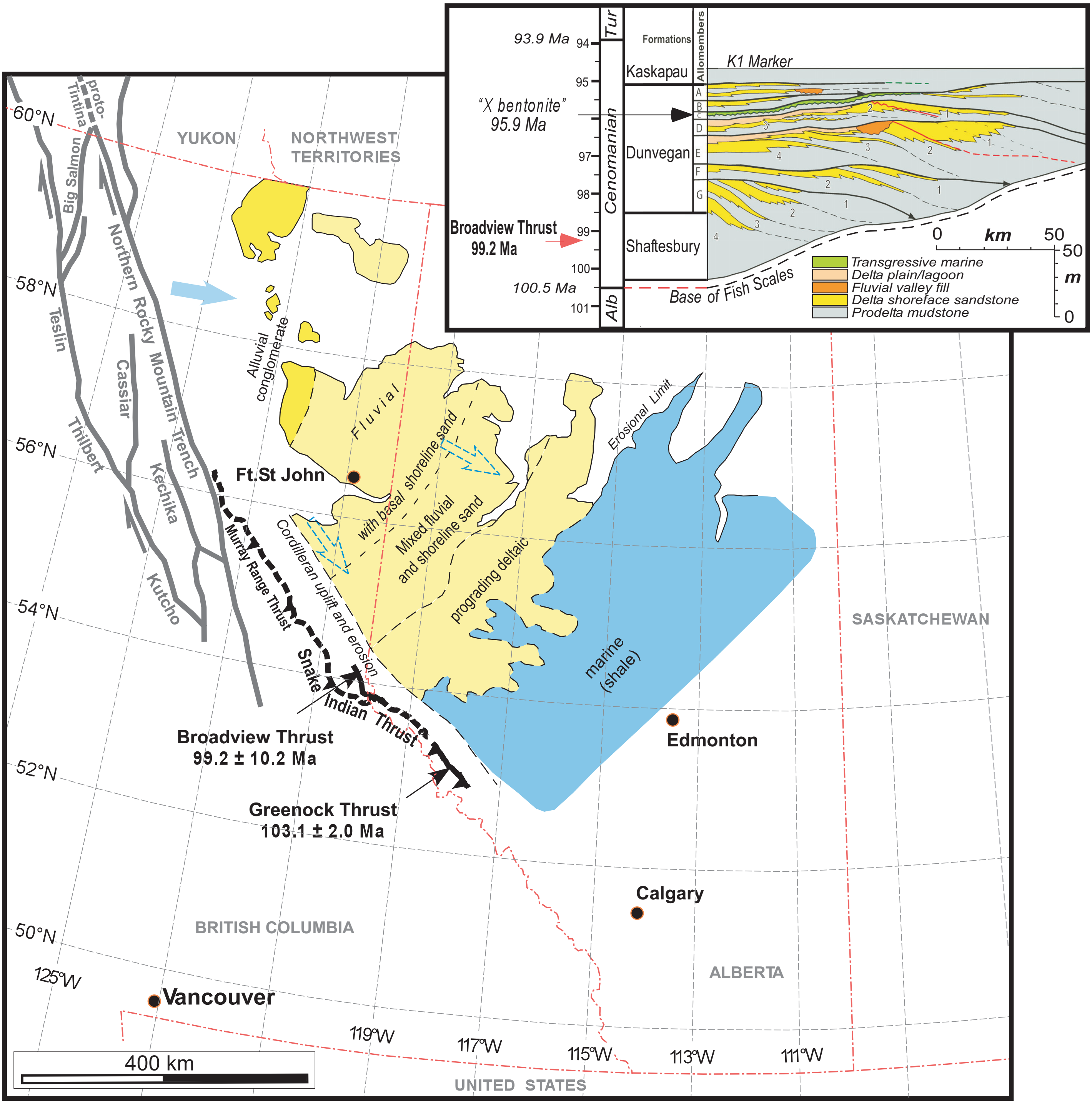


Figure 7. Evolution of the foreland system in northeastern British Columbia and west-central Alberta during mid-Cretaceous: Thrusting and orogenic buildup may have triggered lithospheric downflexing, followed by the development of the areally extensive Dunvegan fluvio-deltaic system. The extent of the Snake Indian thrust in British Columbia (as Murray Range thrust) is after McMechan and Thompson (1989) and McMechan (2000); Northern Rocky Mountain Trench and related major structures to the west are restored to their late Early Cretaceous position (after Gabrielse et al., 2006); the paleogeography during Dunvegan deposition is from Leckie and Smith (1993); diagram with the sequence stratigraphic interpretation of the Dunvegan Formation is modified after Bhattacharya and MacEachern (2009). See text for discussion.

mylonite zone located within the base of the Belt-Purcell Supergroup and exposed within tectonic windows (Price and Fermor, 1985; Colpron et al., 1998; Doughty and Price, 1999; Simony and Carr, 2011).

The deeper portion of the basal detachment is interpreted to be exposed in northern Idaho and Washington as the mylonite zone above Archean basement in the Priest River complex of the Spokane dome (Doughty et al., 1998) (Fig. 5). Monazite and xenotime from the deeper part of the Spokane dome mylonite zone indicate peak metamorphism during deformation at ca. 72 Ma (Doughty et al., 1998). This is consistent with a coherent shear zone at depth and a fan of quasi-contemporaneous eastward-verging thrusts at shallower structural level, including the 72.3 Ma Lewis and the 72.7 Ma Rundle thrusts, and possibly, yet undated, spatially related thrusts.

To the north, the Spokane dome mylonite zone was linked to the top-to-the-east Gwillim Creek thrust shear zone presumably lying at the base of the Quesnell and Kootenay terranes (and merging at depth with the Valkyr shear zone) in the Valhalla complex (Simony and Carr, 2011) (Fig. 5). Based on relationships between sheared rocks and dated plutons and pegmatites, Carr and Simony (2006) concluded that the Gwillim Creek shear zone in the Valhalla complex was activated in the Late Cretaceous at 85 Ma. Doughty et al. (1998) and Schaubs et al. (2002) documented its reactivation between 75 and 60 Ma, a time interval that encompasses all Late Cretaceous ages obtained to date from the southern Canadian Rocky Mountain fold-and-thrust belt. Simony and Carr (2011) proposed that the Gwillim Creek shear zone re-emerges on the southern and western flanks of the Monashee complex as the Monashee décollement (Fig. 5), where top-to-the-northeast ductile structures formed during Late Cretaceous and/or Paleocene metamorphism (Brown et al., 1992; Carr, 1991, 1992, 1995; McNicoll and Brown, 1995; Parrish, 1995; Gibson et al., 1999; Crowley et al., 2000; Kuiper, 2004; Williams and Jiang, 2005; Hinchey et al., 2006; Glombick et al., 2006; Lemieux, 2006). These ages span the time interval of the last major Western Interior Seaway transgression in southern Alberta and Montana and the subsequent deposition of most of the upper Campanian–Maastrichtian clastic wedge (Figs. 4 and 8).

We infer that the Campanian tectonic loading, documented by our dating of thrust faults in the Canadian Rocky Mountain fold-and-thrust belt, triggered the crustal downwarping and Bearpaw transgression in the immediate foreland and that the associated orogenic buildup provided the high topographic relief for Late Cretaceous–Paleocene erosion and deposition of the enormous volumes of clastic deposits of the upper Brazeau–Wapiti Formation–Edmonton Group and equivalents in the foreland. These sequences form a set of strongly asymmetrical clastic wedges infilling the Alberta Basin from the west (Jerzykiewicz, 1997). In the northern Alberta Basin, a major change from dominantly marine shale with pulses of westerly derived deltaic sand to dominantly nonmarine coarse clastics occurred during the late Campanian (Dawson et al., 1994). Variable accommodation conditions along the axis of the foredeep, which reflect differential flexural subsidence and the southeasterly tilt, are consistent with syndepositional strike variability in orogenic loading, with the maximum subsidence in front of the major Lewis thrust (Fig. 8). Paleotemperatures and geothermal gradients indicate that the Lewis thrust sheet was ~12–13.5 km thick when thrusting commenced (Feinstein et al., 2007). However, flexural tectonism of the foreland was also recorded inland into the fluvial realm, over 250 km to the northwest (Fanti and Cătuneanu, 2010): a regional subaerial unconformity in the alluvial Wapiti Formation could be traced into the major Bearpaw marine maximum flooding surface, and subsequent less extensive maximum flooding surfaces (marine transgressions) appear to extend into the fluvial realm, where they are marked by major coal seams (e.g., Drumheller marine tongue). Tectonically induced changes in the basin architecture were accompanied by volcanism (bentonite layers in upper Brazeau Formation and its equivalents) and profound changes in climate and biota (Jerzykiewicz and Sweet, 1988).

Early Cenozoic Tectonic Pulse

The 52.4 ± 12.3 Ma Muskeg, the 53.9 ± 5.5 Ma Brule, the 54.0 ± 0.7 Ma McConnell, and the 52.1 ± 3.9 Ma Nikanassin thrusts indicate Eocene shortening in the eastern Front Ranges and Foothills of central Alberta. These ages are within the range previously reported from the McConnell thrust, 51.0 ± 3.5 Ma (at Mount Yamnuska) and 57.7 ± 1.2 Ma (at Compression Ridge), and they are similar to the 51.5 ± 2.2 Ma age from the Lewis thrust at Gould Dome in the southern Alberta Front Ranges. The 58–51 Ma time interval includes the ages assigned by van der Pluijm et al. (2006) to the "McConnell pulse" and appears to define the final late Paleocene–early Eocene period of thrusting in the Rocky Mountain fold-and-thrust belt.

The latest Paleocene–early Eocene gouge ages are slightly younger and partly overlap with existing apatite fission-track ages and vitrinite reflectance data in the Alberta Foothills. In the northern Hinton–Grand Cache area, calculated burial histories show maximum burial at ca. 60 Ma for sites in the Foothills, and between 60 and 55 Ma at sites in the Plains (Kalkreuth and McMechan, 1996). To the south, apatite fission-track data from Aptian–Albian strata suggest tectonic uplift of the most frontal Brazeau thrust sheet at ca. 65–60 Ma (Donelick and Beaumont, 1990), and further south at the latitude of Calgary, integrated apatite fission-track thermochronology and vitrinite reflectance data from the area of the Burnt Timber thrust were interpreted as thrusting-related cooling at 59 ± 0.5 Ma (Arne and Zentilli, 1994). In the outer Foothills of southern Alberta, apatite fission-track data have been interpreted to indicate early to middle Eocene thrusting (Stockmal et al., 1997). We propose that the latest tectonic pulse in the Rocky Mountain fold-and-thrust belt started with the emplacement of late Paleocene thrusts, such as the 58 Ma McConnell (south segment) thrust, and continued with early Eocene along-strike propagation of the 54.0 Ma (Abraham Lake) and 51.0 Ma (Yamnuska) segments of McConnell thrust, the 51.5 Ma Lewis thrust at Gould Dome, and the emplacement of thrusts in the Foothills, such as the 53.9 Ma Brule, 52.1 Ma Nikanassin, and 52.4 Ma Muskeg thrusts.

Most of the latest Cretaceous to Paleocene sediments were derived from the foreland highlands and from volcanic air-fall material (Ross et al., 2005). The late Maastrichtian Entrance, and the middle Paleocene High Divide conglomerates near Hinton (Fig. 1), contain a few andesitic pebbles, which indicate that the drainage divide locally extended into the Intermontane belt (Jerzykiewicz, 1985; 1997).

In the southern Omineca belt (south of lat 52°N), Late Cretaceous penetrative polydeformation and metamorphism (e.g., eastern Selkirk fan, Selkirk allochthon north of Monashee complex), and the northeastward translation of the belt on midcrustal zones of high ductile strain (e.g., Gwillim Creek shear zone in Valhalla complex, and its equivalents south of Thor-Odin, and the Monashee décollement in Frenchman Cap dome) continued through the Paleocene into the early Eocene (Evenchick et al., 2007, and references therein). The early Eocene corresponds to the timing of final contraction. Based on U-Pb titanite from the Bourne gray granite dike suite, Gervais et al. (2010) dated the penetrative easterly verging Cordilleran shear strain in the upper carapace of the Frenchman Cap gneiss dome of the Monashee complex (on both the west-dipping and the east-dipping flanks of the dome) at ca. 53 and 49 Ma. This suggests that the Rocky Mountain basal detachment was reactivated in the early Cenozoic as a coherent shear zone at depth in the Cordilleran interior, whereas in the Front Ranges and Foothills, the

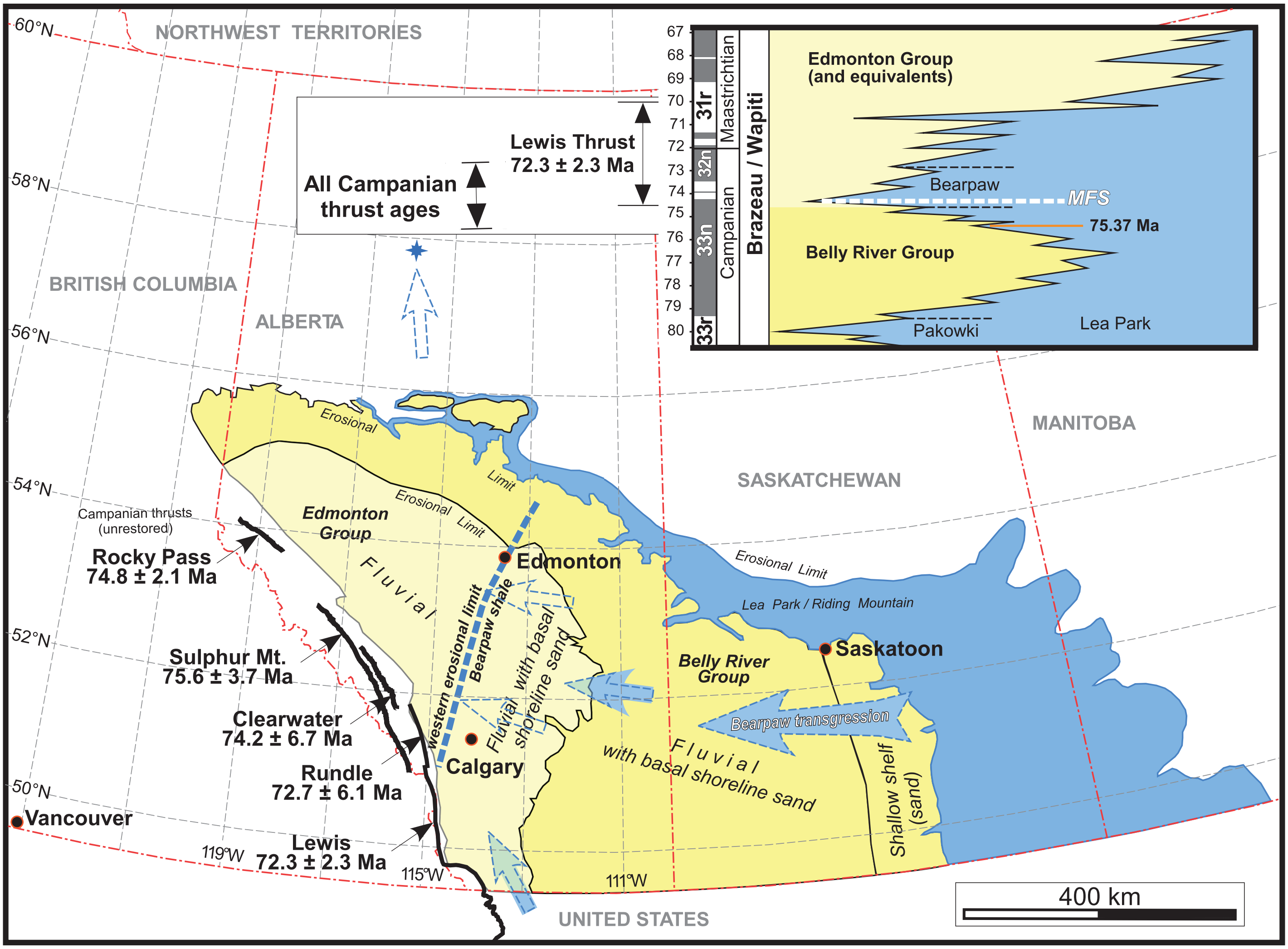


Figure 8. Evolution of the foreland system during the Late Cretaceous: Tectonic loading in the fold-and-thrust belt may have triggered lithospheric downflexing in the foreland basin. Five Campanian thrust ages identified in the southern Canadian Rocky Mountain fold-and-thrust belt span the time interval of the last major Western Interior Seaway transgression in southern Alberta and the subsequent deposition of the uppermost Cretaceous clastic wedge. The Campanian paleogeographic evolution of the foreland basin before and after "the Bearpaw transgression" is modified from Leckie and Smith (1993); time scale is from Gradstein et al. (2012); bentonite (75.37 Ma) in Bearpaw shale in Montana is from Obradovich (1993), and Bearpaw maximum flooding surfaces (MFS) is after Fanti and Cătuneanu (2010); blue star in north-central Alberta is the northernmost occurrence of Bearpaw shale, from Wall and Singh (1975).

strain was accommodated either by segments of existing thrusts such as Lewis thrust at Gould Dome (51.5 Ma) or by new thrusts propagating eastward in front of the mid-Cretaceous thrusts, such as the McConnell (54.0 Ma and 51.0 Ma), Brule (53.9 Ma), Muskeg (52.4 Ma), and Nikanassin (52.1 Ma) thrusts. The leading edge of the thrust system progressed eastward, resulting in exhumation, erosion, and cannibalization of the Alberta foreland basin wedge, including strata of Paleogene age (e.g., Price and Mountjoy, 1970; Price, 1981; McMechan and Thompson, 1992). The early Eocene cessation of contractional deformation ended subsidence in the Alberta foreland basin.

At the end of early Eocene contraction, the Front Ranges–Foothills formed a topographic high perhaps 4–5 km above the modern, deeply eroded Foothills surface (Price and Fermor, 1985; Osborn et al., 2006). At the eastern edge of the Foreland belt south of 54°N latitude, a 2–2.5-km-thick Paleocene and Eocene clastic succession, no longer preserved, has been inferred from coal reflectance data (Nurkowski, 1984; Kalkreuth and McMechan, 1996). The final phase of shortening, dated in the southern Canadian Rocky Mountain fold-and-thrust belt at 54–51 Ma, triggered the deposition of the last clastic wedge, which appears to have started with southerly and westerly derived quartzite-cobble gravel sheets. These gravels (of uncertain Cenozoic age) now cap topographic highs with elevations well over the surrounding areas throughout Alberta. At Obed Mountain, close to the "deformation front," such gravel deposits overlie a thin succession of sandstone above the 57.1 Ma Paleocene-Eocene boundary in the Paskapoo Formation (Lerbekmo et al., 2008).

Following Late Cretaceous–early Eocene dextral transpression, middle Eocene Cordilleran tectonics in northwest North America changed to large-scale transtension, accompanied by regional cooling and extension, and redistribution of the orogenic load (Parrish et al., 1988; Constenius, 1996; Gibson et al., 1999; Crowley et al., 2000; Hinchey et al., 2006). Dextral transtension on intracontinental strike-slip faults in northeastern and southwestern British Columbia culminated with mid-Eocene extensional exhumation of midcrustal metamorphic core complexes (Evenchick et al., 2007, and references therein). The cessation of compressional tectonics in the Rocky Mountains and the beginning of extensional tectonics in the Cordilleran interior are marked by early Oligocene graben-fill fanglomerates of the Flathead Formation in the Lewis thrust sheet in the southern Rocky Mountains (McMechan and Price, 1980).

The Oligocene extension in the Rocky Mountains coincided with the beginning of lithospheric rebound accompanied by more than 1500 m of uplift of many areas in the Rockies (Cook, 1960) and deposition of extensive fluvial sheets in the Alberta Plains and beyond, as well as episodes of alkalic intrusion emplacement (stocks, laccoliths, sills, and dikes) in the Sweetgrass Arch (ca. 54–50 Ma) and the central Montana Alkalic Province (27–25 Ma) (Fig. 4). Phases of isostatic rebound of the foreland system are recorded by individual erosional surfaces and depositional episodes of the Oligocene–Miocene succession preserved in the Cypress Hills of southeastern Alberta (e.g., Leckie, 2006).

CONCLUSIONS

The eastward-propagating Rocky Mountain fold-and-thrust belt of the southern Canadian Cordillera transported continental terrace and foreland basin strata onto the western margin of North America during Late Jurassic to early Eocene contraction. A new set of ages has been obtained from clay-rich fault gouge that was collected from major thrust faults located in the Rocky Mountains and Foothills of Alberta. The age of each fault gouge sample was obtained by extrapolating $^{40}Ar/^{39}Ar$ total gas ages of multiple grain-size fractions with varying ratios of detrital (2M1) and authigenic (1Md) illite polytypes.

The upper age intercept of each fault rock represents a (mixed) age of detrital phase(s), varying from 225 to 766 Ma, and it provides some insight for regional provenance studies. Each fault data set provides detrital results that are in accord with late Proterozoic–Mesozoic (cooling) ages of regional source areas to the west. Neoproterozoic phyllosilicates have been found in gouge derived from the Neoproterozoic Miette Group (615 Ma, Johnston Creek thrust), but also recycled into Jurassic Fernie (660 Ma, Broadview thrust), earliest Cretaceous Nikanassin (559 Ma, Brule thrust), and Albian Gates (762 Ma, Muskeg thrust) clastic strata. The preservation of Neoproterozoic ages suggests that the thrust sheets in the Rocky Mountain fold-and-thrust belt were never buried below the ~350 °C isotherm; the younger mica originates in the accreted terranes and Mesozoic collision-related metamorphism.

Our regional $^{40}Ar/^{39}Ar$ dates from 18 samples of thrust fault gouge indicate that the southern Canadian Rocky Mountain fold-and-thrust belt formed through a series of forward-propagating deformation pulses in the late Jurassic (163–146 Ma), middle Cretaceous (103–99 Ma), latest Cretaceous (76–68 Ma), and late Paleocene–early Eocene (57–51 Ma), separated by relatively long periods (>40 m.y., >20 m.y., and >10 m.y., respectively) of tectonic quiescence. These pulses correlate well with ages of tectonism in the interior and western Cordillera, and especially well with significant depositional and stratigraphic changes in the adjacent foreland basin in Alberta.

To the west, in the Main Ranges, a sample of gouge from the Pyramid thrust (northeast of Jasper) produced an age of 163.0 ± 7.6 Ma, which coincides, within analytical error, with a widespread and well-defined pre-Oxfordian unconformity in the upper Fernie Formation. This age is likely related to an early phase of thin-skinned deformation during the widespread tectonic loading of the western edge of the North American craton, and the establishment of a well-defined foreland basin. Ages obtained from the Simpson Pass (161.7 ± 6.6 Ma) and Johnson Creek (145.7 ± 14.9 Ma) thrusts indicate that the initial phase of contraction lasted at least throughout the Late Jurassic deposition of the Kootenay-Nikanassin-Minnes clastic wedge.

In the Front Ranges, the Greenock thrust yielded an age of 103.1 ± 2.0 Ma, which coincides with the unconformity at the base of the upper Fort St. John Group (the transgression of the "Hulcross Sea") in the immediate foreland; to the northwest, the Broadview thrust, a splay of the Snake Indian thrust, yielded an age of 99.2 ± 10.2 Ma, contemporaneous with the development of the Cenomanian Dunvegan delta in the immediate foreland of the Snake Indian thrust. Three other thrusts in the Front Ranges yielded Late Cretaceous ages of 74.8 ± 2.1 Ma, the Rocky Pass thrust; 75.6 ± 3.7 Ma, the Sulfur Mountain thrust; and 74.2 ± 6.7 Ma, the Clearwater thrust. These ages are similar to previously reported ages of ca. 72 Ma from the Rundle and Lewis thrusts to the south and may represent the shallow expression of the Cretaceous basal detachment of the Rocky Mountain fold-and-thrust belt, the western, deep-seated structural level of which is exposed atop metamorphic core complexes of the Omineca belt. This Late Cretaceous phase of tectonic loading led to new accommodation space and the last major transgression (the "Bearpaw Sea") in the Alberta portion of the foreland.

Along the eastern margin of the Front Ranges and western Foothills, gouge samples from four major thrust faults yielded early Eocene ages. The McConnell thrust, which defines the eastern boundary of the Rocky Mountains with the Alberta Foothills, yielded an age of 54.0 ± 0.7 Ma, similar to previous ages obtained from the same thrust farther south. In the Foothills, from north to south, the Muskeg, Brule, and Nikanassin thrusts yielded ages of 52.4 ± 12.3 Ma, 53.9 ± 5.5 Ma, and 52.1 ± 3.9 Ma, respectively. These early Eocene ages record the last phase of contraction within the Rocky Mountains fold-and-thrust belt of southern Canada, which triggered the accumulation of large volumes of entirely continental deposits in the foreland basin, which were later reworked and deposited farther east.

Dating of fault rocks in the Rocky Mountains, which provides new, and perhaps controversial, perspectives on the regional geology and evolution of the Canadian Cordillera, highlights the value of direct dating of deformation in orogenic systems. Deformation dating of faults constrains the spatio-temporal dimensions of continents, young and ancient, as well as continental margins around the world, and it is a key to our understanding of the geometries, timing, and rates of crustal deformation.

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