Fault dating in the Canadian Rocky Mountains: Evidence for late Cretaceous and early Eocene orogenic pulses

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ABSTRACT

Fault rocks from the classic Rocky Mountain foreland fold-and-thrust belt in southwestern Canada were dated by Ar analysis of clay grain-size fractions. Using X-ray diffraction quantification of the detrital and authigenic component of each fraction, these determinations give ages for individual faults in the area (illite age analysis). The resulting ages cluster around 72 and 52 Ma (here called the Rundle and McConnell pulses, respectively), challenging the traditional view of gradual forward progression of faulting and thrust-belt history of the area. The recognition of spatially and temporally restricted deformation episodes offers field support for theoretical models of critically stressed wedges, which result in geologically reasonable strain rates for the area. In addition to regional considerations, this study highlights the potential of direct dating of shallow fault rocks for our understanding of upper-crustal kinematics and regional tectonic analysis of ancient orogens.

Keywords: Rocky Mountains, Canada, faults, orogeny, geochronology, gouge.

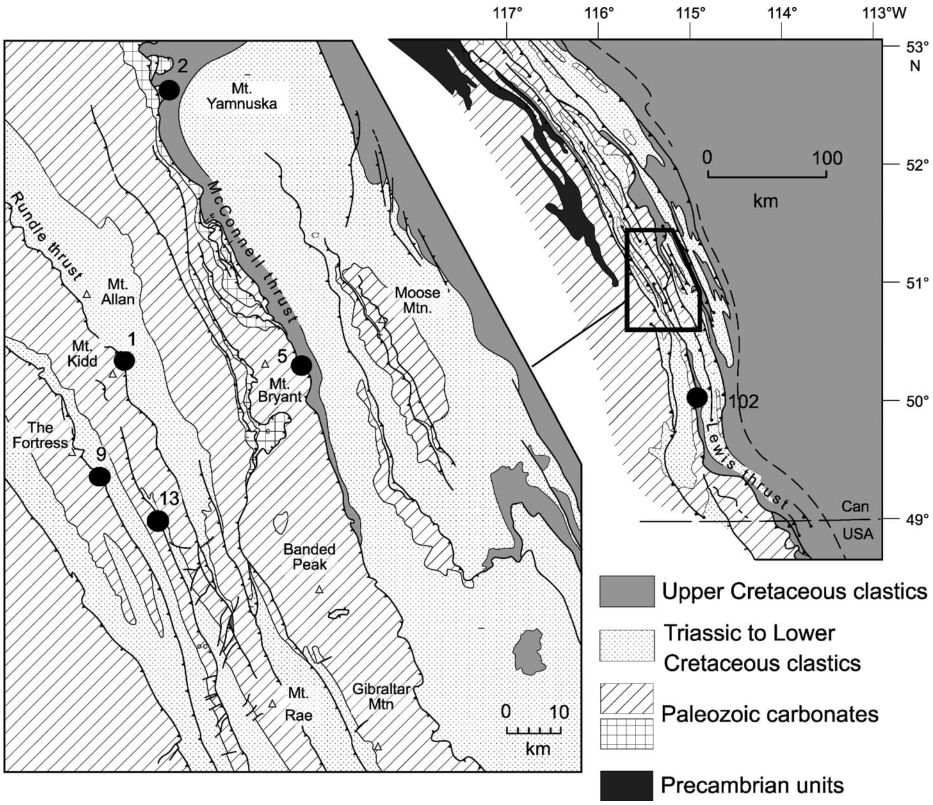

Figure 1. Location map of gouge samples in Canadian Rockies analyzed in this study. Details of sites are presented in Table 1.

INTRODUCTION

The Rocky Mountains of southern Canada are a classic area for the study of fold-and-thrust belt development. Spatial and temporal concepts such as piggyback (or foreland progression) thrusting, flat-ramp fault architecture, and cross-section balancing were pioneered in this region (e.g., Dahlstrom, 1970; Price, 1981), which is characterized by excellent lateral and vertical outcrop and is well known for its stunning vistas. In addition to understanding geometric constraints, unraveling the temporal evolution of fold-and-thrust belts provides critical information on the regional processes that drive tectonics, and potentially on the mechanics of thrust wedges. Information on the timing of near-surface faulting in fold-and-thrust belts is critical in this analysis, but previous estimates have mostly been determined from sedimentation patterns or from radiometric dating of associated features (such as veins and plutons). The relative lack of direct dating of near-surface fault rocks severely limits our understanding of the history of exhumed orogens, which is addressed by the approach in this paper. The recent development of isotopic dating of clay-bearing gouge, which is a common near-surface fault rock, offers new potential for radiometric ages of ‘‘brittle’’ faulting (Pevear, 1999; van der Pluijm et al., 2001; Ylagan et al., 2002; Solum et al., 2005), which can test and reexamine established concepts in thrust belts and offer a more tightly constrained temporal perspective on orogenic evolution in the upper crust.

The study area is located in the Canadian portion of the Rocky Mountains (e.g., Price, 1981; Fermor, 1999; Ross et al., 2005). Fault gouge was sampled along several major faults in the area, with six selected for Ar dating (Fig. 1). The analyzed sites include the McConnell thrust at Compression Ridge and at Mt. Yamnuska, the Lewis thrust at Grizzly Peak, the Sulfur Mountain thrust, and the Rundle thrust. These results are complemented by a radiometric age determination of the

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Geology; October 2006; v. 34; no. 10; p. 837–840; doi: 10.1130/G22610.1; 3 figures; 1 table.

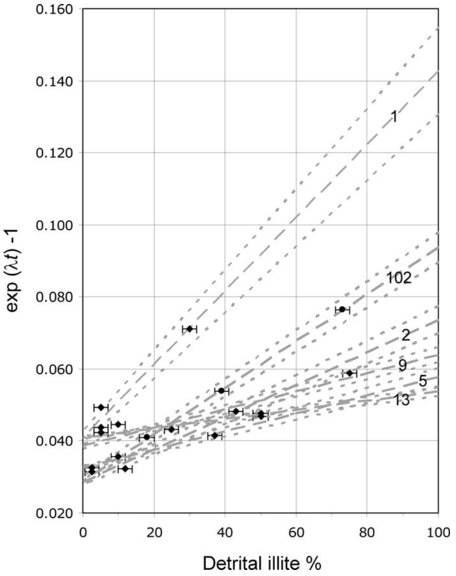

Figure 2. Illite age analysis plot of percentage detrital component and age of three fractions of six samples. Function $e^{\lambda t} - 1$ is linearly related to detrital illite, where λ is decay constant, and *t* is time. Errors for each sample are indicated by dashed lines surrounding best-fit line. Lower intercept at 0% detrital mica corresponds to age of faulting, which shows two clusters around 72 and 52 Ma.

TABLE 1. AR DATING OF GRAIN SIZE FRACTIONS OF FAULT ROCKS WITH EXTRAPOLATED AUTHIGENIC AND (MIXED) DETRITAL AGES

SAMPLE	Detr I (%)	Ar/Ar (tot)	exp (λt) −1
Lewis-Gould Dome			
HW: Devonian Palliser Carbonate			
FW: U Cretaceous Belly River Shale			
102E-coarse	73	133.0	0.076507
102E-medium	39	94.6	0.053836
102E-fine	18	72.15	0.040803
Authigenic Age (Ma)			**51.5 ± 2.2**
Detrital Age (Ma)			**162.0**
McConnell-Yamnuska			
HW: Cambrian Eldon Carbonate			
FW: U Cretaceous Belly River Shale			
2b coarse	43	84.9	0.048185
2b medium	12	57.6	0.032443
2b fine	2.5	55.7	0.031356
Authigenic Age (Ma)			**51.0 ± 3.5**
Detrital Age (Ma)			**126.7**
McConnell-Compression Ridge			
HW: Devonian Palliser Carbonate			
FW: U Cretaceous Belly River Shale			
5b coarse	37	73.6	0.041640
5b medium	10	63.2	0.035653
5b fine	2.5	58.1	0.032729
Authigenic Age (Ma)			**57.7 ± 1.2**
Detrital Age (Ma)			**100.7**
Lewis-Grizzly Creek			
HW: Mississippian Rundle Carbonate			
FW: Jurassic Fernie Shale			
13d coarse	57	83.8	0.047546
13d medium	37	76.2	0.043142
13d fine	6	74.8	0.042333
Authigenic Age (Ma)			**72.3 ± 2.3**
Detrital Age (Ma)			**89.3**
Sulphur Mountain			
HW: Devonian Palliser Carbonate			
FW: Jurassic Fernie Shale			
9a coarse	75	103.0	0.058754
9a medium	50	82.5	0.046791
9a fine	10	78.7	0.044589
Authigenic Age (Ma)			**68.4 ± 13.0**
Detrital Age (Ma)			**107.2**
Rundle-Mt Kidd			
HW: Devonian Palliser Carbonate			
FW: Jurassic Kooteneay Shale			
1a coarse	30	123.8	0.071032
1a medium	5	86.8	0.049289
1a fine	5	77.3	0.043779
Authigenic Age (Ma)			**72.7 ± 6.1**
Detrital Age (Ma)			**235.8**

Note: Hanging wall (HW) and footwall (FW) units are indicated for each thrust; c—coarse; m—medium; f—fine.

Lewis thrust at Gould Dome that was initially used to demonstrate the illite age analysis (IAA) application to shallow fault rocks (van der Pluijm et al., 2001). Collectively, these chronologic determinations provide a new interpretation for the area's history that also fits modern views of the evolution of mountain ranges.

METHOD

Using standard mineral settling techniques, we separated the gouge samples into grain-size fractions of 2–0.2 μm, 0.2–0.02 μm, and <0.02 μm, from which we determined the authigenic/detrital ratio through X-ray analysis of the clay fraction. In low-grade shales and mudstones, the detrital mica component is characterized by $2M_1$ polytype, whereas the authigenic form is $1M/1M_d$ polytype (typically mixed-layer illite-smectite [I-S]; e.g., Velde and Hower, 1963). $2M_1$ mica is considered to be the detrital phase because its crystallization temperature exceeds ~280 °C (Srodon and Eberl, 1984). The authigenic/detrital ratio is obtained through iterative modeling of the X-ray diffraction patterns of powdered samples using a version of the program NEWMOD, which generates synthetic diffractograms for discrete illite (assumed to be $2M_1$) and mixed-layer illite-smectite (assumed to be $1M_d$) (Moore and Reynolds, 1997).

For Ar vacuum-encapsulation dating, the sample was placed in a sealed silica vial that was then evacuated to $\sim 1 \times 10^{-5}$ Pa. As a consequence, all recoiled Ar isotopes were retained within the capsule during neutron irradiation and were released in our extraction system when the vial was cracked open. The samples were subsequently step-heated until fusion under a defocused laser beam occurred. The advantages of our vacuum-encapsulated ^{40}Ar/^{39}Ar dating approach over the traditional K-Ar method include small sample size (<1 mg), the simultaneous measurement of both radiogenic ^{40}Ar and ^{39}Ar (a proxy for K), and the high precision of analysis.

If samples consist of different mixtures between two end members, pure authigenic and detrital clay minerals, then the radiogenic ^{40}Ar/K ratio of each mixture should fall on a mixing line between the two end-member ratios. The function $e^{\lambda t} - 1$, where λ is the total K decay constant, is proportional to the radiogenic ^{40}Ar/K ratio, which we plot as a function of the percentage of detrital clay for differing grain-size fractions. A fitted line through a fault rock samples' data points from multiple mixtures can be extrapolated to 0% detrital illite to obtain an estimate for the age of the authigenic component, which represents the timing of faulting for gouge (see van der Pluijm et al., 2001, for additional details). Errors on the age determination are small compared to those for the mineralogic quantification. Based on prior work, we estimate the detrital quantification error to be within 2%–3%, and we used a value of 2.5% (1σ) for our calculations of the gouge age.

RESULTS

The Ar spectra for the samples all show the effect of ^{39}Ar recoil, and, given the significant smectite content in these samples, total gas ages were used to determine extrapolated authigenic ages (e.g., Foland et al., 1992; Dong et al., 2000). The results from three size fractions of each fault gouge sample are shown in Figure 2, which plots the percent detrital illite against the total gas age (represented as $e^{\lambda t} - 1$). Regression analysis of ages from three grain-size fractions of each sample produces an intercept at 0% detrital material (that is, 100% authigenic). Estimates on the error include the analytical precision of the Ar age and the error in the mineralogic quantification, as mentioned earlier. Note that the upper intercept (at 100% detrital) is a proxy of the (cooling) age of the source area, which may be a mixture of detrital ages.

Whereas the upper age intercept, at 100% detrital clay material, of gouge samples varies significantly, the lower intercepts, representing the authigenic ages, cluster into two populations. Fault gouge of the Sulfur Mountain thrust, Lewis thrust at Grizzly Creek, and Rundle thrust at Mt. Kidd all give ages in the range of 68–73 Ma. The McConnell thrust at Mt. Yamnuska and the Lewis thrust at Gould Dome are in the range ca. 51 Ma, while the McConnell thrust at Compression Ridge is ca. 58 Ma. Given the uncertainties in ages, we interpret these results as two age populations, at ca. 52 Ma and ca. 72 Ma, with estimated errors of ±3–5 m.y. for each fault. The upper age intercept of each fault rock, representing the age of the detrital phase(s), varies from 80 to 235 Ma. These results show no obvious local pattern, but are ages that are fully in accord with the Mesozoic (cooling) age of regional source areas to the west. In contrast to the proposal in van der Pluijm et al. (van der Pluijm et al., 2001), we conclude that the method's potential for provenance study is diminished by our inability to constrain detrital mixtures, leading to large variations. This latter application therefore awaits more regionally extensive data. Details of the lithologies at the sampling locations and analytical results are listed in Table 1.

DISCUSSION

The results of direct dating of gouge from six thrust faults in the Canadian Rockies show a regionally systematic chronology that offers a reinterpretation of current models of foreland evolution in this region. We present the two observed age clusters, ca. 72 and ca. 52 Ma, in the context of a generalized, balanced cross section of the area, which was modified from (Price, 1981) (Fig. 3). Our results show that a pulse of contractional activity resulted in the formation of a frontal range by ca. 72 Ma (the Rundle episode). This is further supported by similar overlap in ages among thrusts in the area based on geometric arguments, which was recently proposed by Price (2001). Because thrust faults in front (east) of this range did not form until much later, this range became a new source area for latest Cretaceous to Paleocene basin deposits in the foreland. This temporal pattern also seems to be supported by recent isotopic data of foreland basin deposits in the region (Ross et al., 2005). Thrusts in the area to the east of this late Cretaceous range became active around 52 Ma. The geographic location of these faults in the restored section (Fig. 3) shows that faulting in a large area was simultaneously active around that time, resulting in the formation of a second frontal range in early Eocene times, the McConnell episode, which occurred $\sim$20 m.y. after the Rundle episode. The recognition of temporally discrete episodes, each lasting a few million years, has important implications for the regional evolution of the southern Canadian Rockies and neighboring areas in the Rocky Mountains, and for the dynamics of fold-and-thrust belts in general.

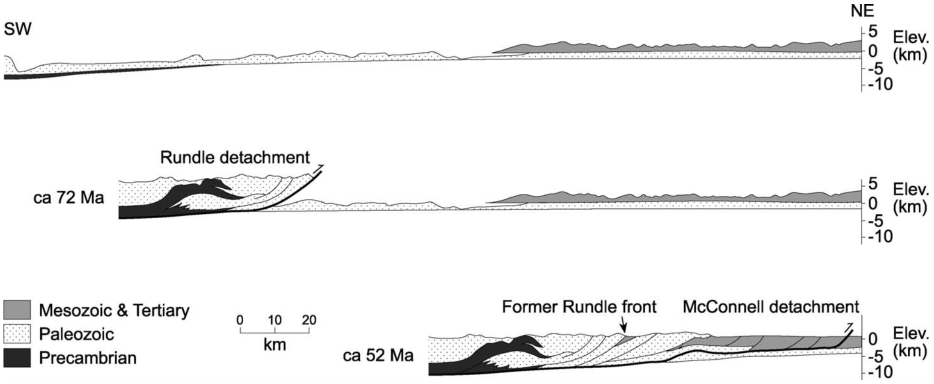

Figure 3. Regional cross sections showing spatial-temporal evolution of southern Canadian Rockies, based on ages of main faults in frontal segment of belt. Interpretation of two age clusters for faulting has been applied to a prior cross section (Price, 1981) that was modified to show proposed two-stage evolution of belt, with deformation pulses in late Cretaceous and early Eocene time.

Within the errors of our age determinations, we cannot recognize, with certainty, any forward progression within a thrust episode, but it is clear that clustered movement on fault groups characterizes the region's history. The possibility of later resetting of fault rocks from regional fluid movement would not explain the preservation of differences in ages of faults that were in close proximity, nor the presence of older radiometric ages in similar lithologies away from the fault zones, so this hypothesis is rejected. Rather, our results are interpreted as thrusting that was not gradual across the belt, but episodic in nature, resulting in spatially and temporally distinct front ranges. Regional shortening in the area is on the order of 50% (Price, 1981; Fermor, 1999), so a 25 m.y. or more time span of progressive deformation from west to east would represent very slow geologic strain rates. Rather, episodic movements as proposed here, each lasting a few million years, would result in strain rates on the order of 10^{-14} s^{-1} for each episode, which are geologically more reasonable. Our preliminary efforts in the foreland of the Rocky Mountains fold-and-thrust belt in Wyoming, $\sim$900 km south of the study area, show similar clustering of Eocene ages in the frontal segment of the orogen, supporting the view of orogenic pulses in the Rocky Mountain foreland (Solum, 2005). In addition to fault kinematics, the episodic formation of front ranges has implications for the erosional and thermal history of the area (e.g., Issler et al., 1999), which must be addressed in future studies.

The age clusters proposed in this study offer new support for modern views of critically stressed thrust wedges, which originated from analog models and theory (e.g., Davis et al., 1983; Dahlen et al., 1984). Modeling of thrust belts as critically stressed wedges, which require that the entire wedge be active, has been very successful in describing their evolution and some key properties, and is therefore widely adopted, but limited field support exists for these models from the study of natural orogenic systems (e.g., Willett et al., 2003). Our results from spatially separated, but temporally overlapping faults in the orogenic wedge of the Canadian Rockies show that a large region underwent contraction at about the same time, offering additional field support for the theoretical tenets of regional thrust-wedge dynamics.

Finally, the chronologic results presented in this work necessitate regional dynamic drivers for orogenic episodes at late Cretaceous and early Eocene times. Traditionally, Cretaceous-Tertiary ages have been lumped together as the Sevier-Laramide orogeny (e.g., Dickinson, 2004), but distinct, relatively short-lived thrust episodes indicate that hinterland activity, perhaps related to terrane accretion, occurred in latest Cretaceous and in earliest Eocene times, respectively. The regional dynamics radically changed soon after the final (McConnell) deformation episode, when the area became dominated by extension, possibly in response to regional plate reorganization (as suggested in the northern Rockies of the United States by Constenius [1996]). Besides regional implications, the application of illite age analysis to clay-rich fault rocks shows that direct dating of shallow fault rock offers a fertile topic for research in an area that has thus far mostly relied on indirect information.

ACKNOWLEDGMENTS

We thank the National Science Foundation and ExxonMobil Upstream Research Co. for support of our fault gouge research. We also thank Donald Peacor for discussions on clay mineralogy, Jeff Rahl for discussions on wedge evolution, and Jonathan Patchett and an anonymous journal reviewer for constructive comments.

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Manuscript received 17 January 2006
Revised manuscript received 2 May 2006
Manuscript accepted 9 May 2006

Printed in USA

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(Required by Title 39 U.S.C. 4369)

Geology (Publication No. 0091-7613) is published monthly by The Geological Society of America, Inc., (GSA) with headquarters and offices at 3300 Penrose Place, Boulder, Colorado 80301, U.S.A., and mailing address of Post Office Box 9140, Boulder, Colorado 80301-9140, U.S.A. The Publisher is Jon Olsen; the Managing Editor is Lyne Yohe; their offices and mailing addresses are the same as above. The annual subscription prices are: GSA Members $82; GSA Associate-Student Members $40; non-members $600. The publication is wholly owned by The Geological Society of America, Inc., a not-for-profit, charitable corporation. No known stockholder holds 1-percent or more of the total stock. CEDE & Company, 55 Water Street, New York, New York 10041, holds all outstanding bonds; there are no known mortgagees or holders of other securities. The purpose, function, and non-profit status of The Geological Society of America, Inc., has not changed during the preceding twelve months. The average number of copies of each issue during the preceding twelve months and the actual number of copies published nearest to the filing date (September 2006 issue) are noted at right.

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