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Reconstructing the Snake River–Hoback River Canyon section of the Wyoming thrust belt through direct dating of clay-rich fault rocks

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ABSTRACT

Quantification of fault-related illite neomineralization in clay gouge allows periods of fault activity to be directly dated, complementing indirect fault dating techniques such as dating synorogenic sedimentation. Detrital "contamination" of gouge is accounted for through the use of illite age analysis, where gouge samples are separated into at least three size fractions, and the proportions of detrital and authigenic illite are determined using illite polytypism ($1M_d$ = neoformed, $2M_1$ = detrital). Size fractions are dated using the $^{40}Ar/^{39}Ar$ method, representing a significant improvement over earlier methods that relied on K-Ar dating. The percentages of detrital illite are then plotted against the age of individual size fractions, and the age of fault-related neoformed material (i.e., 0% detrital/100% neoformed illite) is extrapolated.

The sampled faults and their ages are the Absaroka thrust (47 ± 9 Ma), the Darby thrust (46 ± 10 Ma), and the Bear thrust (50 ± 12 Ma). Altered host rock along the frontal Prospect thrust gives an age of 85 ± 12 Ma, indicating that the 46–50 Ma ages are not related to a regional fluid-flow event. These ages indicate that the faults in the Snake River–Hoback River Canyon section of the Wyoming thrust belt were active at the same time, indicating that a significant segment of the thrust belt (100 km^2+) was active and therefore critically stressed in Eocene time.

Keywords: illite, clay gouge, $^{40}Ar/^{39}Ar$ dating, Sevier orogeny, Wyoming thrust belt.

INTRODUCTION AND GEOLOGIC SETTING

Wyoming Thrust Belt

The Wyoming thrust belt (Royse et al., 1975; Dixon, 1982; Wiltschko and Dorr, 1983) (Figs. 1 and 2) formed during the Late Cretaceous to Eocene Sevier orogeny, which affected western North America from Canada to Mexico (Armstrong 1968; Wiltschko and Dorr, 1983; Price, 1986; Burchfiel et al., 1992; Miller, 2004). The orogeny occurred as the result of the subduction of the Kula and Farallon plates beneath the North American plate (Livaccari and Perry, 1993; Bird, 1998). The deformation style is generally characterized by east-verging, shallowly dipping thrusts with detachments in Mesozoic and Paleozoic shale-rich horizons (DeCelles, 1994).

It has long been proposed that the generally foreland-younging sequence of faults in thrust belts ("in-sequence" faults),

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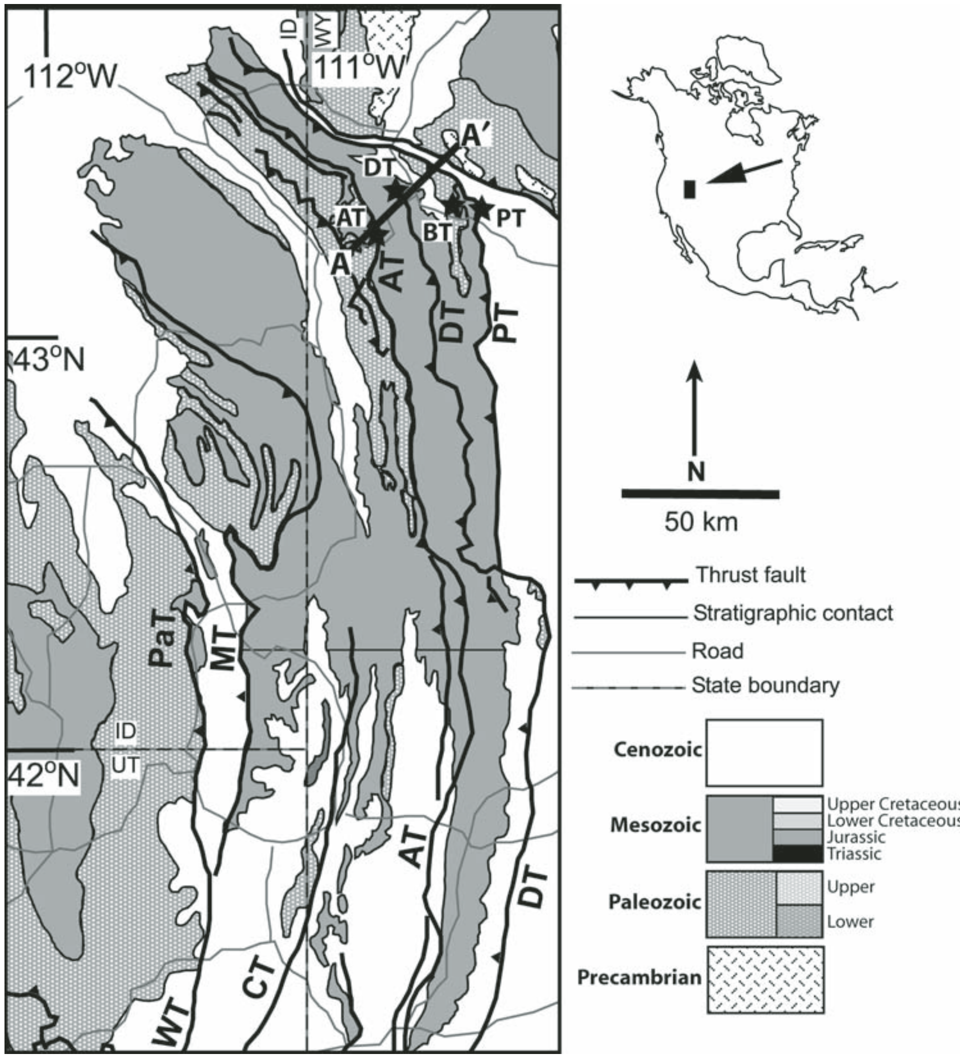

Figure 1. Simplified geologic map of the Idaho-Wyoming thrust belt (after Mitra et al., 1988). Sampling locations are shown with stars. AT—Absaroka thrust; BT—Bear thrust; CT—Crawford thrust; DT—Darby thrust; GCT—Game Creek thrust; HF—Hoback normal fault; MT—Meade thrust; PaT—Paris thrust; PT—Prospect thrust; WT—Willard thrust. Details of sampling locations are described in the text.

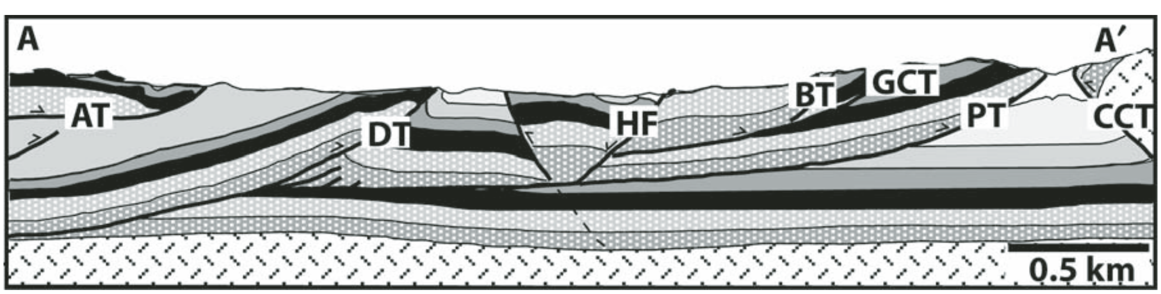

Figure 2. Cross section through the Snake River–Hoback River Canyon section of the Wyoming thrust belt (after Craddock et al., 1988). Reconstructions of this section that are based on timings inferred from synorogenic sedimentation suggest that most of the shortening occurred prior to the Eocene. The results presented in this paper suggest that Eocene shortening was more important than has previously been thought. Fault labels and lithologies are defined in Figure 1.

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and faults that violate this trend ("out-of-sequence" faults) can be explained by progressive wedge evolution (Price, 1981; Dahlen, 1984). In order to reconstruct wedge evolution, it is critical to determine the ages of the involved faults. Thick sequences of synorogenic sediments shed from the Sevier thrust belt are preserved in Utah, Idaho, and Wyoming, which have allowed the deformation history of associated faults to be determined (Dorr, 1958; Royse et al., 1975; Wiltschko and Dorr, 1983; DeCelles, 1994; DeCelles and Mitra, 1995). Based on histories inferred from this sedimentation, it is thought that the evolution of the Utah-Idaho-Wyoming thrust belt was controlled by maintenance of critical wedge taper (Wiltschko and Dorr, 1983; DeCelles, 1994; DeCelles and Mitra, 1995). However, in addition to uncertainties in stratigraphic correlation, this type of reconstruction cannot be applied to fault systems where no record of synorogenic sedimentation is preserved. It is therefore desirable to directly date fault rocks whenever possible. The considerations, complications, limitations, and techniques necessary to directly date clay-rich fault rocks are discussed in this contribution using new results from the Wyoming segment of the Sevier thrust, followed by the implications of results from the study area.

Character of Illite and Illite-Smectite Neomineralization

It has long been recognized that the clay fraction of a sample is composed of a mixture of clays with multiple origins (i.e., detrital and authigenic). Velde and Hower (1963) noted that the <1 µm fraction of illite-bearing samples was relatively enriched in $1M_d$ illite. Using the phase relations of Smith and Yoder (1956), which indicate that $2M_1$ illite is stable at higher temperatures than 1M and $1M_d$, they concluded that the $1M_d$ fraction of their samples formed at a lower temperature than the $2M_1$ fraction, likely during diagenesis. They similarly inferred that the $2M_1$ component of their samples was detrital in origin. Hower et al. (1963) noted that the K-Ar ages of size fractions from shale samples decreased with decreasing grain size and that the finer size fractions contained more $1M_d$ illite than the coarser fractions. They concluded that the finer material formed some time after deposition of the shale, but that the age was difficult to interpret because the ages of all size fractions reflected mixtures of clays with different origins. More recent studies (Pevear et al., 1997; Clauer et al., 1997; Pevear, 1999; Srodon, 2002) have shown that finer fractions of shales tend to be more enriched in mixed-layer illite-smectite (I-S) than coarser fractions, and therefore that I-S is authigenic and that discrete illite is detrital. The ability to extract geologically meaningful ages from clay-rich rocks requires additional characterization of the clay populations in a sample. Whereas the fine fraction of a shale or gouge may be dominated by authigenic material, it still generally contains some detrital material, and therefore the age of that fraction will be a mixing age. Quantification of the amounts of detrital and authigenic phases is therefore required to extract the neoformation age.

Originally the amounts of detrital and authigenic illite were quantified by measuring the amounts of discrete illite and interlayered illite-smectite (Pevear, 1994; van der Pluijm et al., 2001), a procedure called illite age analysis. Additionally, illite age analysis can also incorporate changes in illite polytypism to quantify the detrital and authigenic components, based on the observation that the $2M_1$ polytype is detrital, while the $1M_d$ is authigenic (Grathoff and Moore, 1996; Grathoff et al., 1998, 2001; Solum et al., 2005). This study of Wyoming thrust fault rocks principally uses changes in polytypism to quantify the proportions of detrital and neoformed clays in fault rocks.

Direct Dating of Fault Rocks

The age of a shallow-crustal fault is usually constrained by bracketing, relying on the age of features that are cut by the fault, or by dating synorogenic sedimentation. Although minerals suitable for radiometric dating are common in many fault rocks (the K-bearing clay mineral illite), direct dating of fault rocks is complicated by the observation that such rocks are a mixture of detrital and neoformed fault-related phases. The occurrence of multiple illite polytypes in clay-bearing samples, and, as discussed already, variations between polytype composition and age, has long been recognized (e.g., Hower et al., 1963; Velde and Hower, 1963), but the use of detailed polytype quantification and some form of illite age analysis has been used sparingly to date fault rocks (Vrolijk and van der Pluijm, 1999; Ylagan et al., 2002; Solum et al., 2005) and undeformed shales and mudstones (Grathoff et al., 2001).

Multiple gouge (or shale) size fractions coupled with clay characterizations have been used previously for dating (Hower et al., 1963; Lyons and Snellenburg, 1971; Chen et al., 1988; Wang et al., 1990; Parry et al., 2001; Zwingmann et al., 2004; Zwingmann and Mancktelow, 2004). However, these studies did not use the illite age analysis technique to extrapolate an age for neoformed clays (Pevear et al., 1997; van der Pluijm et al., 2001, 2006; Solum et al., 2005). The finest size fraction in shales and clay gouges contains the least amount of detrital illite, so its age is closest to the age of authigenic mineralization. However, even the finest fraction contains some detrital material, so the age of the finest fraction is only the maximum possible age of authigenic mineralization. In some special circumstances, detailed characterizations of the clay fractions may not be necessary. If the age of all three size fractions is the same, that age is the age of faulting, as this phenomenon indicates that all of the illite has been reset (Parry et al., 2001). Such age relations, however, are rarely observed.

Few studies have simultaneously used both quantifications of $2M_1/1M_d$ illite and discrete illite/mixed-layer I-S to quantify detrital and authigenic material, but, based on such studies, it appears that polytype quantification is the more generally applicable of the two approaches. Pevear (1999) conducted a study using both approaches on shales. Ylagan et al. (2002) conducted a study for the Canadian Rockies in Alberta and British Columbia, and Solum et al. (2005) studied the Moab normal fault in east-central Utah. As pointed out by Ylagan

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et al. (2002), use of polytypism quantification instead of discrete illite/mixed-layer I-S has the advantage of making use of the entire three-dimensional crystal structure, and not just relying on 001 reflections. In addition, it is not possible to use discrete illite/mixed-layer I-S quantification if a sample contains little or no I-S, and the use of discrete illite/mixed-layer I-S dating may also be complicated by fault-related neoformation of illite. For example, gouge along the Lewis thrust (Vrolijk and van der Pluijm, 1999; Yan et al., 2001) and the Moab fault (Solum et al., 2005) is enriched in illite relative to protolith, indicating that when I-S–bearing material is deformed, discrete illite may form. Note that this contradicts the assumption that all discrete illite in a sample is detrital. The formation of illite from smectite during burial is also well-documented (Ahn and Peacor, 1986; Freed and Peacor, 1989, 1992; Lindgreen et al., 1991; Buatier et al., 1992). Moreover, in order to use discrete illite/mixed-layer I-S quantification to extrapolate authigenic ages, the detrital/authigenic ratios must be normalized based on the percentage of illite interlayers in the mixed-layer I-S (Ylagan et al., 2002), which accounts for the general lack of potassium in the smectite in I-S (not including exchangeable cation sites). Therefore, the smectite interlayers should not be included in age-related calculations. If this renormalization is not conducted, the proportion of the detrital phase is underestimated, resulting in invalid extrapolations (Srodon, 1999), although with illite-rich I-S, this renormalization results in only minor adjustments. For these reasons, polytype quantification may be preferred over discrete illite/mixed-layer I-S quantification when dating fault rocks in most settings.

METHODS

Sampling Locations

Fault rock samples were collected along the Snake River and Hoback River sections of the Wyoming segment of the Idaho-Wyoming thrust belts (Dorr et al., 1987; Coogan, 1992) (Figs. 1 and 2). A generalized stratigraphic section of the region is shown in Figure 3. The Absaroka thrust was sampled ~22.5 km (14 mi) west of Hoback Junction, Wyoming, in the Snake River Canyon along the north side of Highway 26. At this location, the Mississippian Madison limestone (intensely fractured with abundant calcite veins within 2–4 m of the fault) is faulted against the Cretaceous Bear River Formation. Small outcrops of limestone in the hanging wall and sandstone in the footwall make the location of the fault easy to determine; however, clay gouge is not well-exposed. We sampled a footwall outcrop of faulted clay-rich gouge, with abundant slickenlines and polished surfaces, ~5 m from the main fault.

The Darby thrust was sampled along Fall Creek Canyon, ~1 km (0.6 mi) along a dirt road that forms off from Fall Creek Road, ~5.1 km (3.2 mi) from the intersection of Fall Creek Road and Highway 26 (~6.8 km [4.2 mi] west of Hoback Junction, Wyoming). The Jurassic Nugget sandstone, brecciated for a distance of 5–7 m from the fault, is in fault contact with a Mesozoic carbonate, which is similarly intensely fractured near the fault. The gouge is up to 0.3 m wide, well-consolidated, and composed of a red/yellow sandy clay and carbonate with anastomosing foliations.

The Bear thrust was sampled at Red Creek, along Highway 191, ~4.8 km (3 mi) east of the mouth of the Hoback River Canyon. Here, the Pennsylvanian Tensleep Formation was emplaced over the Triassic Chugwater Formation. Gouge along the main fault is not exposed, but many small thrusts with displacements from ~1–3 m are exposed in the Chugwater Formation along the banks of the Hoback River, below the main thrust.

No suitable exposures of gouge along the Prospect thrust were found on the west side of Granite Creek, ~1.4 km (0.9 mi) from the junction of Granite Creek with the Hoback River, ~18 km (11.2 mi) east of Hoback Junction in the Hoback River Canyon, where the Jurassic Nugget and Triassic Chugwater Formations are emplaced over the late Paleocene Hoback Formation. For comparison with fault rock samples, a clay-rich rock ~10 m from the fault contact in the hanging wall of the fault within the Chugwater Formation was collected. At this location, detrital muscovite grains were common and visible to the naked eye.

Sample Preparation

Unconsolidated samples were placed in beakers filled with distilled water and allowed to disaggregate for approximately one week. Consolidated samples were crushed using a jaw crusher and then treated in the same manner as unconsolidated samples. After initial soaking, the samples were suspended and allowed to settle multiple (three or more) times. After each settling, the remaining clear liquid was decanted to remove dissolved salts. Samples were treated with a small amount of powdered sodium carbonate to aid deflocculation. Following rinsing, the <4 µm fraction was separated using gravity settling (hereafter referred to as the "clay fraction"). The settling was repeated approximately three times to increase the volume of the fraction. The <2 µm fraction was separated from samples in which the <4 µm fraction contained K-feldspar, as indicated by X-ray diffraction (XRD). The clay fraction was then placed in multiple 50 mL plastic centrifuge aliquots, each of which was treated with an ultrasonic probe for 5 min. Following this treatment, the <0.5 µm fraction was separated using centrifugal settling. A similar procedure was used to extract the <0.05 µm fraction from the sample. In this fashion, a gouge sample was separated into coarse (4–0.5 µm), intermediate (2–0.5 µm), medium (0.5–0.05 µm), and fine (<0.05 µm) fractions.

During extraction, clay samples are commonly treated with weak acids and organic solvents to remove carbonates, iron oxides, and organic matter. Moore and Reynolds (1997) cautioned that possible effects of each of these treatments on mixed-layer clays, such as illite-smectite, have not been quantitatively evaluated, and so we did not apply these treatments to our samples. Moreover, while the presence of these phases can

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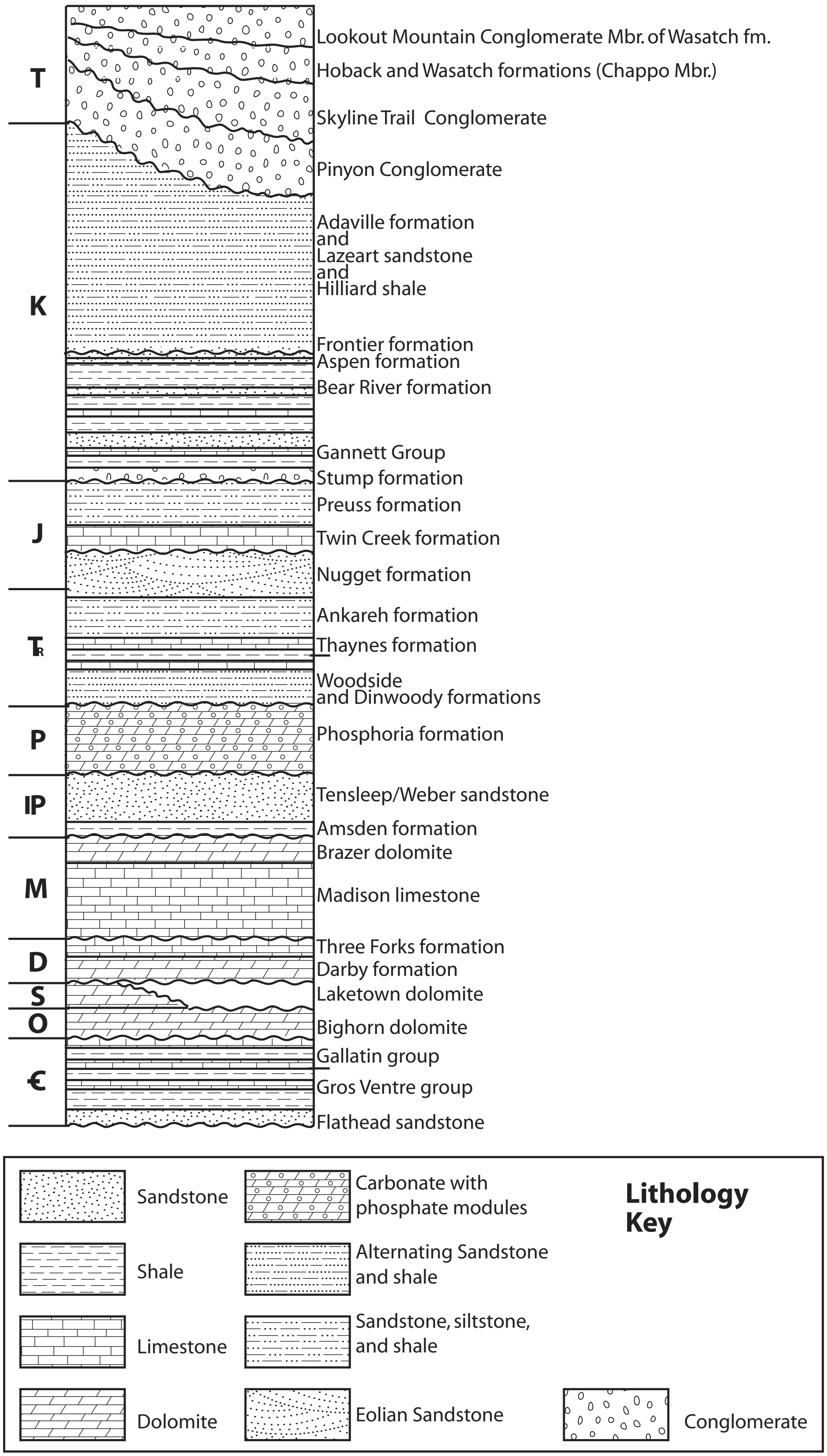

Figure 3. Simplified stratigraphic section for the general area of the Wyoming thrust belt (modified from Dixon, 1982; Wiltschko and Dorr, 1983). T—Tertiary; K—Cretaceous; J—Jurassic; TR—Triassic; P—Permian; IP—Pennsylvanian; M—Mississippian; D—Devonian; S—Silurian; O—Ordovician; €—Cambrian.

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impair sample preparation or mineral identification, the small grain-size fractions limited the concentration of these contaminating phases in our medium and fine fractions.

Clay Characterizations

Samples for polytypism analysis required additional sample preparation. The $2M_1$-specific peaks all have non-(001) indices, and so will not be visible on an X-ray diffractogram from a sample with a strong preferred orientation. Consequently, it is necessary to prepare a sample with a random orientation, which can be difficult in the case of clay minerals due to their platy habit. A near-random preparation was achieved by using an end-packer device (Moore and Reynolds, 1997), in which a dried, powdered sample was loosely tamped into a milled plate of aluminum covered with a glass slide. Once tamping was complete, the glass slide was removed, and the aluminum holder was placed in the diffractometer. Care was taken to compact the powder as loosely as possible, as it was found through trial and error that strong tamping increased the preferred orientation in the sample. Grathoff and Moore (1996) noted that it is possible to evaluate the effectiveness of the random sample preparation by comparing the relative intensity of the (020) and (002) peaks on random and oriented samples. If the relative intensity of the (002) peak is reduced, then the powder pattern may be used for polytype quantification. If the relative intensity is not reduced, then the sample must be repacked and rescanned.

Similar to analyses of discrete illite and interlayered I-S (Solum et al., 2005), illite polytypism was quantified by modeling X-ray powder diffraction patterns. The program WILDFIRE (Reynolds, 1993a, 1993b) was used to generate synthetic patterns of various types of $2M_1$ and $1M_d$ illite (detailed in the following). WILDFIRE allows the number of continuous interlayers to be varied, as well as allowing for some degree of preferred orientation in the sample through the use of an orientation factor (the "Dollase factor"). There are several more parameters that can be varied in the case of $1M_d$, such as the proportion of cis- and trans-vacant interlayers, the number of smectite interlayers, and the degree of ordering in the stacking sequence (i.e., it is not assumed that stacking is completely random). WILDFIRE was used to calculate patterns of $1M_d$ with ordering that varied from random to complete (i.e., classic $1M_d$ to classic 1M). Patterns for $2M_1$ illite were generated assuming a minimum number of continuous interlayers of 5, and maximum numbers of 10–30 in increments of 5, using Dollase factors of 1, 0.9, and 0.8 (15 patterns). Patterns for $1M_d$ illite were calculated using a probability of a zero rotation of 0.33–1.0 (0.33 = pure $1M_d$; 1.0 = pure 1M) in increments of 0.1, using Dollase factors of 1, 0.9, and 0.8. The ratio of trans-vacant to cis-vacant interlayers was set at 0, 0.5, and 1, and the fraction of expandable interlayers was set to 0.1, 0.3, 0.5, 0.7, and 0.9, and interlayer rotations of multiples of 60° were used (360 patterns).

Spreadsheets using the WILDFIRE-generated reference libraries were used to quantify the concentrations of the $2M_1$ and $1M_d$ polytypes in a sample. Patterns of each of the possible types of $2M_1$ illite were mixed with each of the types of $1M_d$ illite from 100% to 0% in increments of 10% of $2M_1$. The variance between the synthetic mixtures and the gouge sample and the synthetic mixture was calculated, and mixtures with the lowest variance were further refined by creating patterns from 100% to 0% of $2M_1$ in increments of 1%. The sample with the lowest variance was selected as the best match. Quartz, carbonate, plagioclase, and hematite peaks in the sample were excluded. Representative XRD powder patterns for $2M_1$ and $1M_d$ illites with WILDFIRE-generated overlays are shown in Figure 4, and examples of best matches for gouge size fractions are shown in Figure 5. Extrapolated illite ages were calculated using a York regression (York, 1968), which takes into account uncertainties in both variables.

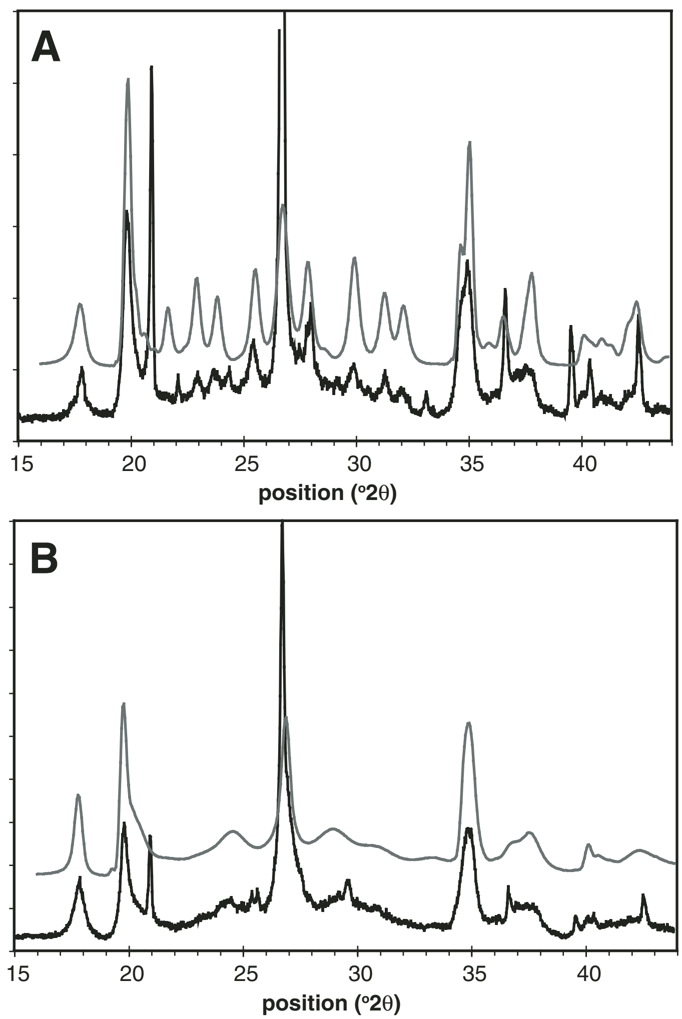

Figure 4. Illite polytype standards overlain with WILDFIRE synthetic patterns. (A) $2M_1$ illite and (B) $1M_d$ illite. Unmatched peaks in X-ray diffraction (XRD) patterns are quartz and feldspars. Note the greater number of peaks for the $2M_1$ illite as a result of coherent stacking of clay interlayers. The matching technique described in this paper matches mixtures of these standards to ~2%.

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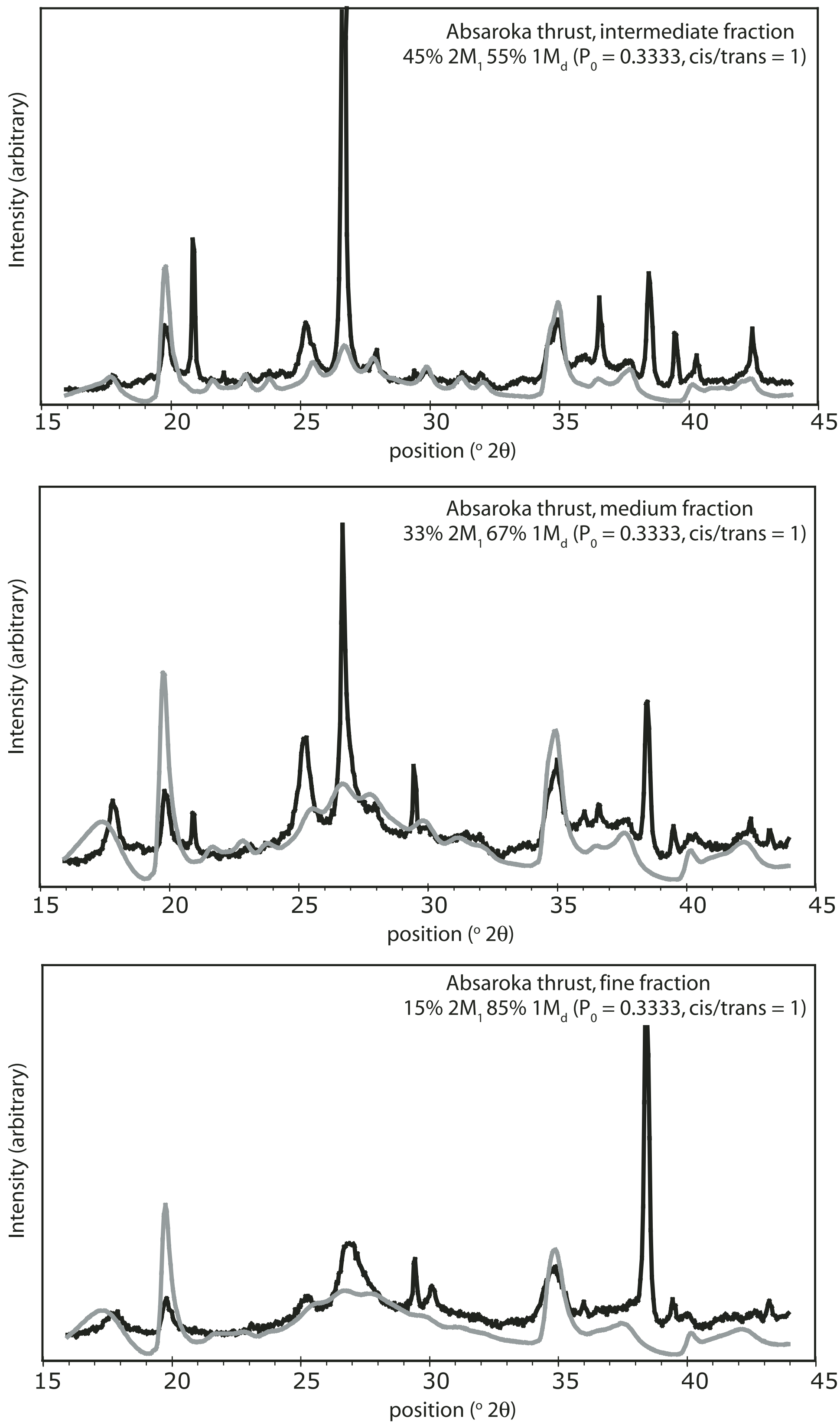

Figure 5. Best-fit WILDFIRE-generated powder patterns for X-ray diffraction (XRD) patterns of size fractions for a representative fault gouge sample from the Absaroka thrust. Synthetic patterns are based on varying proportions and crystal structures of $2M_1$ and $1M_d$ illite. The crystallographic parameters of the $1M_d$ illite are given in parentheses. As discussed in the text, unmatched peaks are quartz, feldspars, and non-illite clays.

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It is also possible to determine the concentration of the $2M_1$ polytype by measuring the area of peaks that are unique to the $2M_1$ polytype and finding the ratio of them against the area of a peak at ~0.258 nm (2.58 Å)/35 °2θ (Cu Kα), which is common to both polytypes (Grathoff and Moore, 1996; Grathoff et al., 1998). This technique has been successfully used to generate quantifications in dating fault rocks (Solum et al., 2005) and hydrothermal events (Grathoff et al., 2001); however, the quantification approach used in this paper offers the advantage of matching an entire powder pattern instead of separate, isolated peaks.

In contrast to earlier studies, we do not include classic 1M illite in our analyses (cf. Grathoff and Moore, 1996; Grathoff et al., 1998), because transmission emission microscopy (TEM) investigations of shales, mudstones, and slates inferred to contain 1M illite based on XRD analysis have almost exclusively been unable to find that polytype (Peacor et al., 2002). This is also in agreement with the work of Zoller and Brockamp (1997), who concluded that $2M_1$ and 1M illite differ in composition and therefore are not polytypes in a strict sense. Therefore, instead of modeling gouge as a mixture of $2M_1$, 1M, and $1M_d$ illite, we model gouge as a mixture of $2M_1$ and $1M_d$ illite with varying probabilities of a 0° rotation, as discussed already.

Errors of ±2% absolute were assigned for each of the polytype characterizations. The magnitude of this error was based on the characterization of a 50/50 mixture of $2M_1$ illite from an unknown site in Illinois and $1M_d$ illite (Illite from Silver Hill, Montana, Clay Minerals Society Source Clay IMt-1) using the approach described already. Our quantification of this standard yielded a result of 52% $2M_1$/48% $1M_d$.

RESULTS

The Absaroka, Darby, and Bear thrusts are located along the Snake River and Hoback River Canyons, reflecting a geographical progression from west to east. A sample from wall rock in the most frontal segment of the belt, in the hanging wall of the Prospect fault, is also shown for comparison with fault rock. Age spectra for all samples are shown in Figures 6 and 7. The extrapolated ages and statistical parameters of our analyses are shown in Figure 8 and in Table 1. Individual faults are discussed next here.

Absaroka Thrust

Based on the record of synorogenic sedimentation, the Absaroka thrust was initiated with a period of activity in the Late Cretaceous (the "Early Absaroka" of Royse et al., 1975), it experienced a period of major activity in the late Paleocene, and it underwent a final period of activity in the Eocene (DeCelles and Mitra, 1995). The earlier episodes have been inferred to be major displacements (Wiltschko and Dorr, 1983; DeCelles and Mitra, 1995), whereas the latter two have been inferred to be relatively minor (DeCelles and Mitra, 1995). The illite age for fault rock of the Absaroka thrust in the Snake River Canyon is 47 ± 9 Ma, indicating a significant period of activity at that location in the lowermost middle Eocene.

Darby Thrust

The age of the Darby thrust is poorly defined due to a lack of well-constrained synorogenic sedimentation, but it is considered to be the youngest thrust in the belt. Wiltschko and Dorr (1983) concluded that the Darby thrust was active around the middle Paleocene to the early Eocene, and perhaps involved multiple periods of motion. The polytype-derived authigenic age of fault rock of the Darby thrust along Fall Creek is 46 ± 10 Ma, indicating a period of activity along the fault at that location in the middle Eocene.

Bear Thrust

The Bear thrust outcrops along the Hoback River and is an imbricate splay from the frontal Prospect thrust (e.g., Craddock et al., 1988) and must, therefore, be younger than earliest Eocene on stratigraphic grounds (Wiltschko and Dorr, 1983; Dorr and Steidtmann, 1977). Indeed, the illite age for subsidiary faults in the footwall of the Bear thrust along Red Creek gives an early to middle Eocene age of 50 ± 12 Ma for the fault rocks.

Wall Rock at the Prospect Thrust

The similarity in ages from fault rocks as discussed here may indicate regional resetting of the Ar clock in illite and not fault-related neomineralization, so we also examined a sample of host rock for comparison. If fault rock ages reflect regional resetting, through fluid and/or thermal activity, nearby host rock ages of similar composition should give the same age range as fault rocks. The age of the Prospect thrust (the Cliff Creek thrust of Dorr et al., 1977) was constrained to be early Eocene by Wiltschko and Dorr (1983), as the fault cuts the late Paleocene Skyline trail conglomerate and is overlapped by the early Eocene Lookout Mountain conglomerate. This constraint is supported by our radiometric age of the Bear fault splay (see previous). In contrast, the polytype-derived authigenic age for host rock near the Prospect thrust is 85 ± 12 Ma. This older illite age supports a non–fault related alteration of Late Cretaceous age.

DISCUSSION

The illite ages from the Snake River–Hoback River thrusts show that all of the main faults (Absaroka, Darby, and Bear faults), combined with the stratigraphically constrained Eocene age of the Prospect thrust in the most easterly segment of the

Figure 6. Argon age spectra for individual size fractions from clay gouge samples. Extrapolated ages of fault-related authigenesis are shown in Figure 8. All size fractions are composed of a mixture of clays with multiple origins (detrital and authigenic), and so plateaus are not expected.

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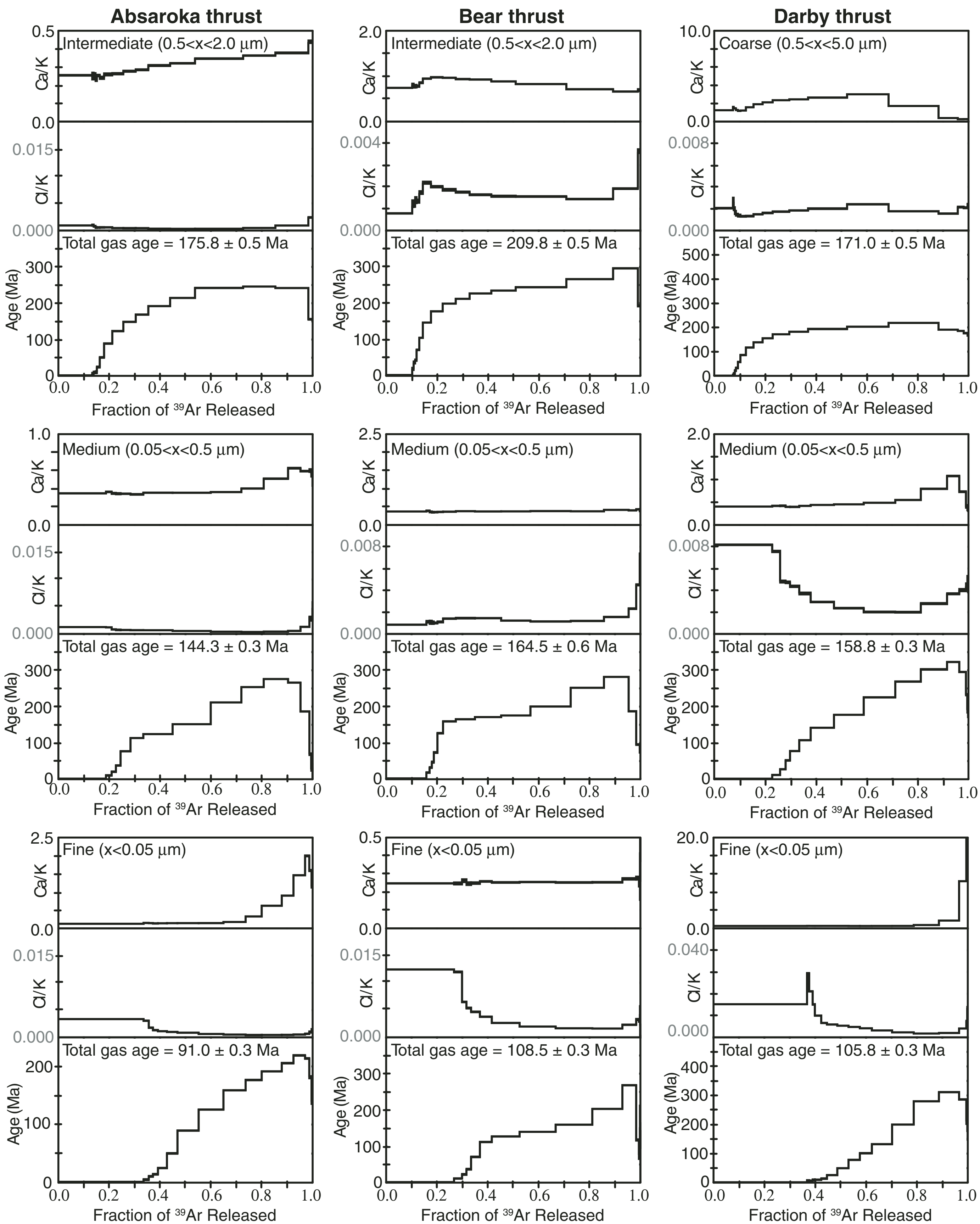

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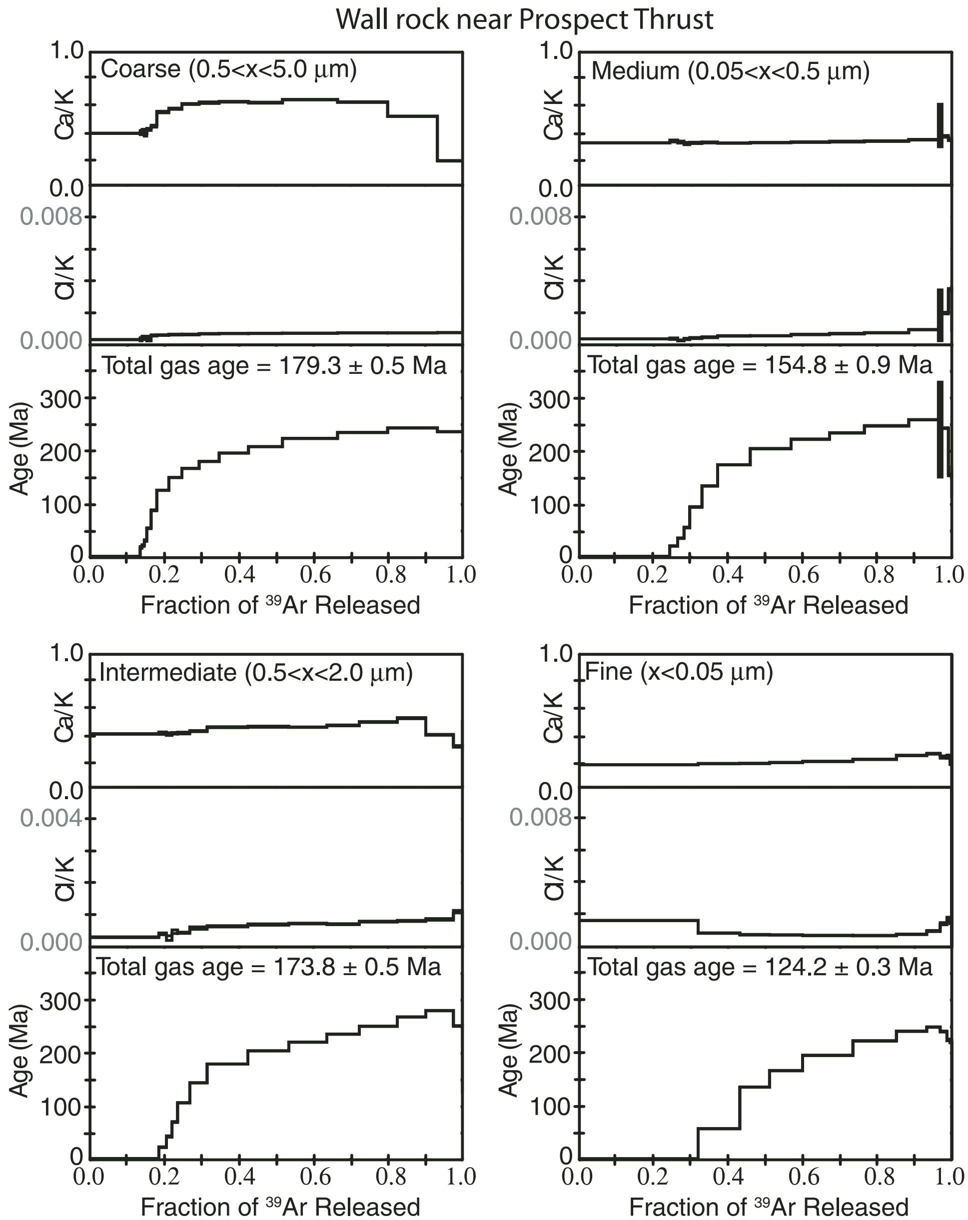

Figure 7. Argon age spectra for individual size fractions from samples of wall rock near the Prospect thrust. Extrapolated ages of fault-related authigenesis are shown in Figure 8. All size fractions are composed of a mixture of clays with multiple origins, so plateaus are not expected.

section, representing a section of 30+ km, were active at the same time in the Eocene. This section was shortened by >15% from the Cretaceous to the Eocene, representing approximately one-third of the total shortening of the thrust belt (Royse et al., 1975, their plate IV). Within our error estimates, this implies that thrusts were not progressively abandoned as the belt propagated into the foreland; rather, this segment of the thrust belt was active during the same period in the early to middle Eocene. Our results suggest that more shortening occurred in the Eocene than has previously been thought.

As noted previously, Cretaceous activity, as well as an Eocene period of activity, are inferred for the Absaroka thrust based on synorogenic sedimentation near the town of Kemmerer (Royse et al., 1975), located ~180 km south of the Snake River Canyon. DeCelles and Mitra (1995) concluded that in southern Wyoming, the Cretaceous periods of activity were major, while the Eocene period was minor. Since no record of Cretaceous activity is shown by the fault rock ages along the Snake River Canyon section of the Absaroka thrust, this indicates that either the fault was active in the Eocene, or that clays that were formed

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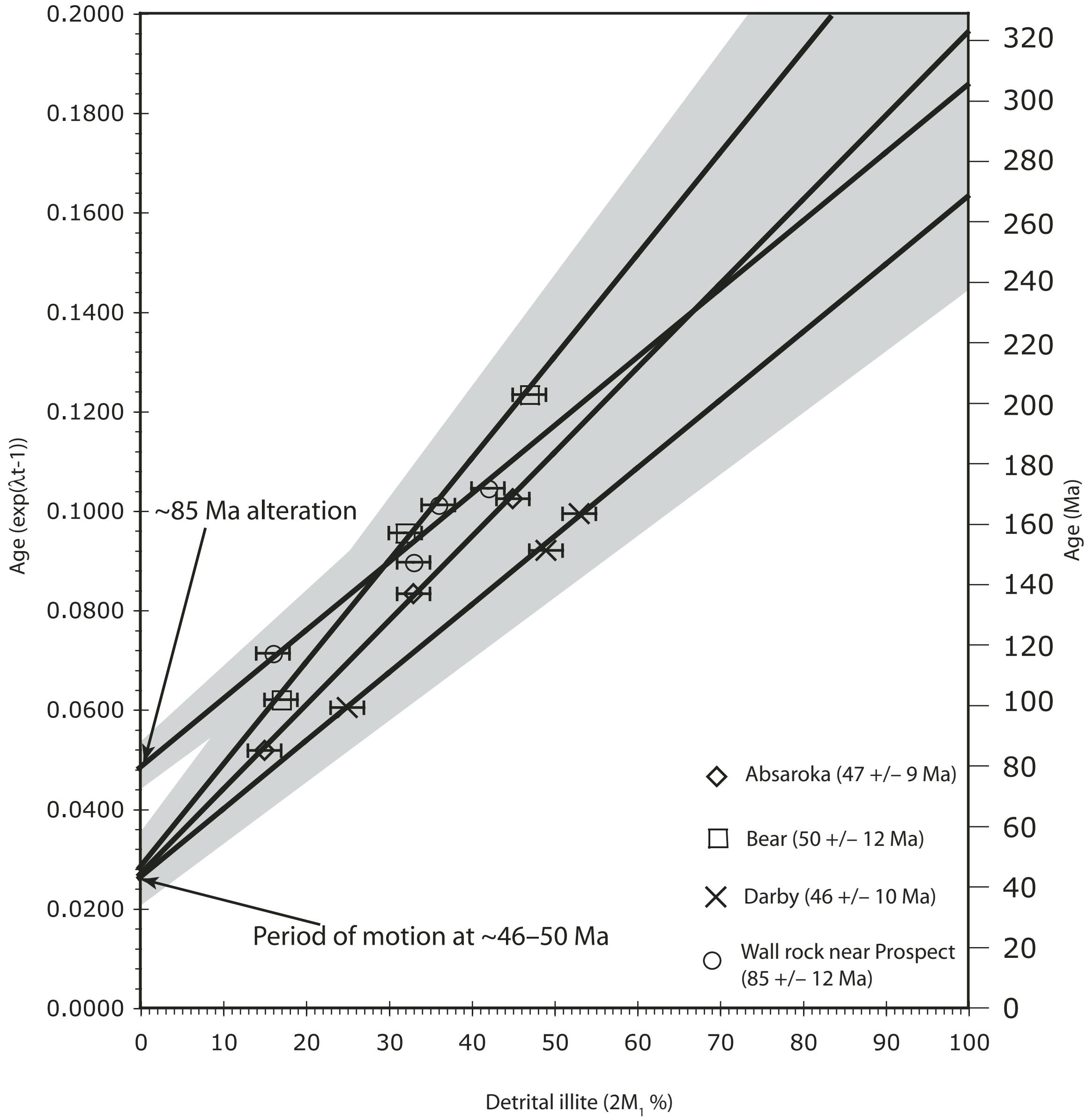

Figure 8. Illite age analysis plot for three fault rock samples and one host rock sample. The errors are shows by the gray bands surrounding best-fit lines to the data. The relationships of these results to ages derived from the record of synorogenic sedimentation are discussed in the text.

during the inferred Cretaceous events were reworked, causing the fault rock ages to be reset. Regardless of resetting, the early to middle Eocene must have been a period of major fault activity in this segment of the thrust belt.

Coeval periods of activity along multiple thrusts have been proposed as a means by which critical taper of a thrust wedge can be maintained (Boyer, 1992; Jordan et al., 1993). This scenario has been inferred for the thrust belt in northeast Utah and southwest Wyoming (DeCelles, 1994), although DeCelles (1994) noted that more internal deformation, including reactivation along existing faults, is required than has previously been recognized. The illite ages reported in this study suggest that internal deformation may be more widespread than previously thought, increasing the applicability of critical taper models to the Sevier thrust belt.

The observation that the 46–50 Ma ages occur in fault rocks from several different faults, and not in adjacent protolith, is a strong indication that those ages reflect a period of regional fault activity. The age of ca. 85 Ma from clay-rich alteration in the Chugwater Formation in the hanging wall of

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TABLE 1. MINERALOGIC QUANTIFICATIONS AND ASSOCIATED ILLITE AGE ANALYSES FOR SAMPLES ALONG THE SNAKE RIVER–HOBACK RIVER SECTION OF THE WYOMING SEGMENT OF THE SEVIER THRUST BELT

	Detrital illite ($2M_1$%)	Error	Total gas age (Ma)	Error	Age [exp(λt) – 1]
Absaroka thrust					
Size fraction					
Intermediate	45.00	2.00	175.80	0.50	0.10
Medium	33.00	2.00	144.30	0.30	0.08
Fine	15.00	2.00	91.00	0.30	0.05
Slope	0.00169	0.00016			
Intercept	0.02662	0.00530			
Authigenic age	47 ± 9				
Bear thrust					
Size fraction					
Intermediate	38.00	2.00	209.80	0.50	0.12
Medium	22.00	2.00	164.50	0.60	0.10
Fine	17.00	2.00	108.50	0.30	0.06
Slope	0.00205	0.00019			
Intercept	0.02798	0.00664			
Authigenic age	50 ±12				
Darby thrust					
Size fraction					
Coarse	53.00	2.00	171.00	0.50	0.10
Medium	49.00	2.00	158.80	0.30	0.09
Fine	25.00	2.00	105.80	0.30	0.06
Slope	0.00137	0.00013			
Intercept	0.02595	0.00566			
Authigenic age	46 ±10				
Wall rock near the Prospect thrust					
Size fraction					
Coarse	42.00	2.00	179.30	0.50	0.10
Intermediate	36.00	2.00	173.80	0.50	0.10
Medium	33.00	2.00	154.80	0.90	0.09
Fine	16.00	2.00	124.20	0.30	0.07
Slope	0.00137	0.00015			
Intercept	0.04805	0.00485			
Authigenic age	85 ±12				

the Prospect thrust is clearly unrelated to the timing of motion along that fault, which is well-constrained to be Eocene in age based on dating of synorogenic sediments. This highlights the importance of obtaining samples directly from gouge zones in order to date fault rocks, since even clay-rich samples close to the gouge zone may not record fault-related mineralization. Most importantly, this age demonstrates that the 46–50 Ma ages from fault rocks are not related to a regional diagenetic event. If this were the case, then protolith as well as fault rocks would exhibit the same authigenic age. It is possible that the ca. 85 Ma age of host rock may represent neomineralization associated with fluids migrating toward the foreland during Cretaceous motion along more inboard thrusts, such as the Paris, Meade, or Crawford thrusts, which produced synorogenic conglomerate of Late Cretaceous age (Gannet Group; e.g., DeCelles and Mitra, 1995).

SUMMARY AND CONCLUSIONS

Illite ages using $2M_1/1M_d$ polytype quantification of clay-rich rocks provide a reliable means of directly dating periods of activity along shallow faults. The illite ages obtained in the area and the record of synorogenic sedimentation are generally compatible; however, the illite ages indicate that motion may occur along a fault without leaving a record of synorogenic sedimentation or that some stratigraphic ages are incompletely constrained. Moreover, the ages suggest that Eocene shortening in this section of the Wyoming thrust belt may have been more substantial than has previously been suspected. The illite ages indicate that the faults in the Snake River–Hoback River Canyon section of the thrust belt were simultaneously active at ca. 48 Ma. The Absaroka, Darby, and Bear/Prospect thrusts are presently separated by 30+ km, and, when restored, were separated by 45 or more kilometers. These

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ages therefore indicate that a considerable segment of the Wyoming thrust belt was pervasively active in early to middle Eocene times. The coeval period of faulting in this segment of the thrust belt supports experiments and theoretical models (e.g., Dahlen, 1984; Dahlen et al., 1984; Wiltschko and Dorr, 1983; DeCelles and Mitra, 1995) of a critically stressed thrust belt, where frontal deformation of the Sevier thrust belt was controlled by the maintenance of a critical taper (e.g., DeCelles, 1994).

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