Fault gouge dating in the Southern Appalachians, USA

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ABSTRACT

Illite age analysis (IAA), the method of comparing radiometric ages of successive size fractions with varying percentages of detrital illite, has been successfully applied to several rock types, including fault gouge, shales and argillaceous limestones. IAA results are presented for five fault rocks, including four clay gouges and one cataclasite, from the exhumed Southern Appalachian foreland fold-thrust belt (eastern United States). Determining detrital versus authigenic illite is now an established procedure, utilizing X-ray analysis to quantify illite polytypes. Less established, however, is how to interpret ^{40}Ar/^{39}Ar ages as a function of diagenetic grade. Both a total gas age, incorporating the recoiled argon fraction after irradiation, and a retention age (omitting the recoiled fraction) are obtained for a sample. We relate their respective use to diagenetic grade and, specifically, the crystallite thickness of illite. When measured crystallite sizes are equal to or smaller than that calculated from Ar recoil we use total gas ages (here ~5 nm), while for crystallites greater than ~10 nm we use retention ages.

The four clay gouge ages are all the same within error and much younger than that of the cataclasite. We conclude that a major period of frontal Appalachian fault activity occurred during the early Permian (Cisuralian, 276–280 Ma) and that these foreland faults were active simultaneously as part of an internally deforming, regional thrust wedge.

INTRODUCTION

It has long been established that the potassium-rich clay mineral illite can be directly dated in shales, slates and clay-rich fault rocks (Hower et al., 1963; Aronson and Hower, 1976; Lyons and Snellenburg, 1971; Kralik et al., 1987; Clauer et al., 1997). Early studies of clay minerals in shales have shown that decreasing grain sizes of illite have an increased percentage of the low-temperature, authigenic $1M/1M_d$ polytype, coincident with decreasing K-Ar ages (Hower et al., 1963). Until recently, these ages were not easily interpreted, because the absolute age represents a mixture of the younger, low-temperature authigenic $1M_d$ illite and the older, high-temperature detrital $2M_1$ illite polytypes. The development of illite age analysis (IAA) has provided a means to determine both authigenic and detrital ages by quantifying the amount of each polytype for multiple grain sizes of illite-rich material and their respective radiometric ages (Pevear, 1992; van der Pluijm et al., 2001; Haines and van der Pluijm, 2008). Recent applications have benefited from further development of the IAA method, including studies of shale diagenesis (Pevear, 1992; Grathoff et al., 1998, 2001) and clay-rich gouges from shallow faults (e.g., van der Pluijm et al., 2006; Solum and van der Pluijm, 2007).

Many studies involving radiometric dating of illite have employed conventional K-Ar dating (e.g., Aronson and Hower, 1976; Pevear, 1992; Grathoff et al., 2001; Clauer et al., 2012). K-Ar dating has been successful in several areas, especially when a single phase could be concentrated (e.g., Clauer et al., 1997; Zwingmann et al., 2010). In the ^{40}Ar/^{39}Ar method, neutron irradiation applied to clay-sized material releases significant amounts of ^{39}Ar gas, recoiled during the transmutation from ^{39}K. Encapsulation of the sample prior to irradiation allows the recoiled gas to be included in the analysis, resulting in two ages per sample (Foland et al., 1992; Dong et al., 1995). Including the recoiled ^{39}Ar gas during the calculation of an age gives a "total gas age," which is equivalent to a conventional K-Ar age, while omitting the recoiled fraction results in an "argon retention age" that only uses the argon retained in the crystalline structure after irradiation (Dong et al., 1995, 1997).

Earlier work has noted that interpretation of ^{40}Ar/^{39}Ar ages from illite is related to diagenetic grade, as the presence of smectite (which commonly contains abundant crystalline defects; Merriman and Peacor, 1999) appears to affect ^{40}Ar retention (Dong et al., 1995, 1997, 2000; Hall et al., 2000). Indeed, total gas ages have been found to be geologically reasonable in low-grade diagenetic settings, typically with interlayered smectite (Dong et al., 2000), while retention ages have been shown to be more suitable to higher-grade diagenetic, anchizonal and epizonal illite (Dong et al., 1995, 1997; Hall et al., 2000). However, these studies primarily focused on rocks with purely neomineralized illite, requiring no adjustment for the contribution of a detrital component that characterizes many fault rocks. The common presence of such mixtures is the foundation of the IAA approach to fault dating. Secondly, our prior work on clay gouge dating using the IAA method has involved relatively young (<100 Ma) faults, where illite was formed in low-grade settings with or without smectite interlayers (van der Pluijm et al., 2001, 2006; Solum et al., 2005; Haines and van der Pluijm, 2008). The low diagenetic grade of these rocks reflects exhumation from relatively shallow depths (several kilometers) and only the total gas age model was applicable for their interpretation.

Here, we study fault rocks from the late Paleozoic, Southern Appalachian foreland fold-thrust belt (eastern United States) to constrain the ages of faulting in a more deeply buried, older fold-thrust belt and to address the effect of a range of diagenetic grades on the interpretation of polytype-based illite ages (Fig. 1). Our analysis of several main faults in this orogenic belt also provides insights into regional fault progression and wedge dynamics of the frontal Appalachians.

GEOLOGIC BACKGROUND

The Southern Appalachians orogen is a classic, thin-skinned fold-thrust belt that formed during the late Paleozoic Alleghanian orogeny. The belt consists of a west-verging stack of thin-skinned thrusts that share a basal décollement within Cambrian shales, including a mechanically strong unit of thick Cambro-Ordovician carbonates (Milici, 1975; Woodward and Beets, 1988; Hatcher et al., 1989, 2007). The structural

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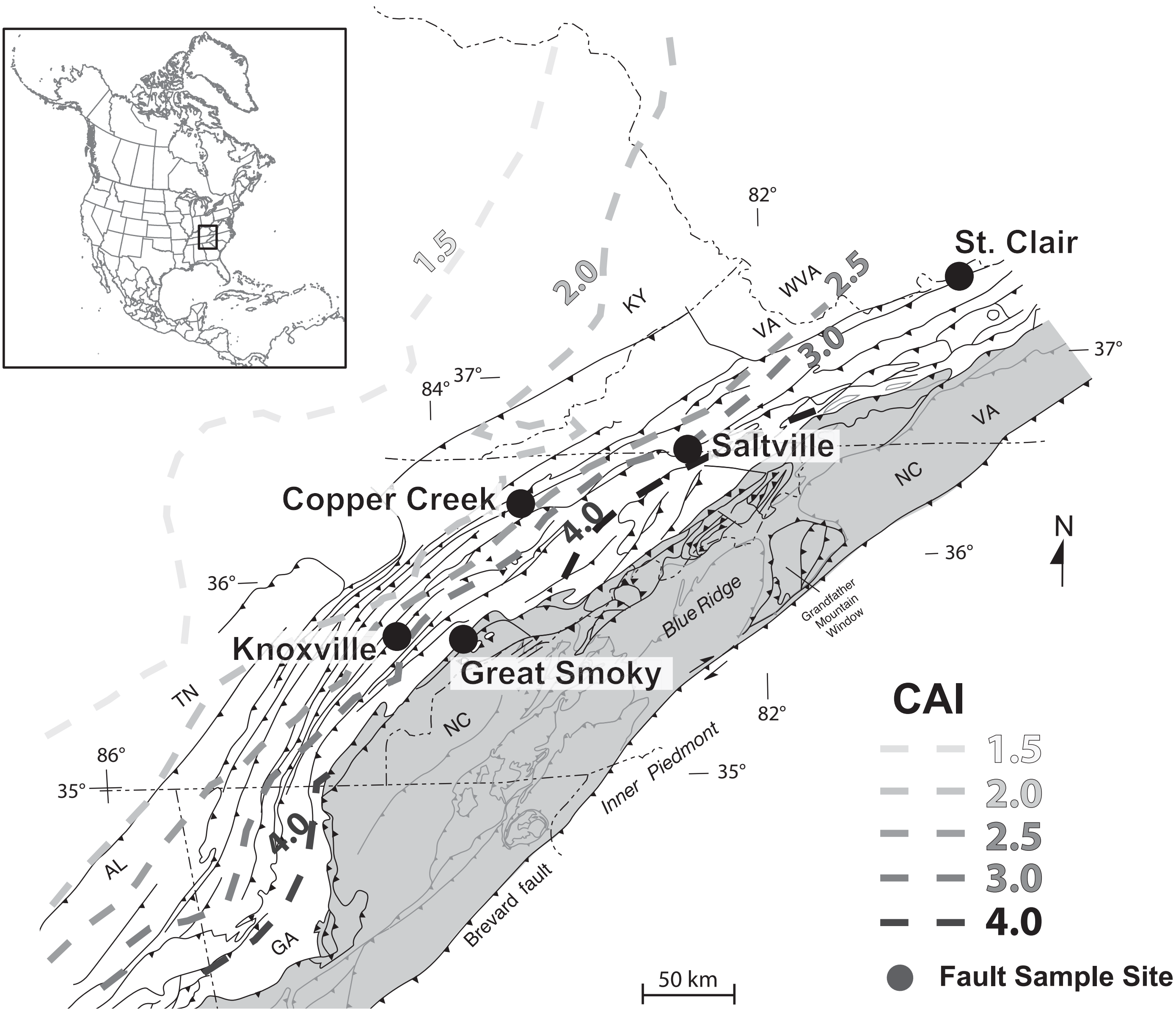

Figure 1. Inset showing the location of the study area and map with the location of sampled faults in the Southern Appalachian fold-thrust belt (after Hatcher et al., 2007). Conodont alteration index (CAI) contours represent thermal maturity (from Harris et al., 1978). AL—Alabama; GA—Georgia; KY—Kentucky; NC—North Carolina; TN—Tennessee; VA—Virginia; WVA—West Virginia.

style of the fold-thrust belt reflects the controlling nature of the thick carbonates, with southeast-dipping thrust faults dominating, instead of a fold-dominated system like the central Appalachians to the north (Hardeman, 1966; Harris and Milici, 1977; Hatcher et al., 1989).

Timing of deformation in fold-thrust belts can be constrained by tectono-stratigraphy, and the age of synorogenic sedimentary units in particular. However, given that the Appalachians have been tectonically quiet for more than 200 million years, much of this evidence has been eroded, leaving only older, pre-orogenic sedimentary rocks in most places. Therefore, the absolute age of deformation is difficult to constrain. Currently, the youngest age of thrusting comes from the central Appalachians, where timing is based on deformation of the youngest unit, the lower Permian Dunkard Group, in the foreland-most portion of the belt in West Virginia. The age of the Dunkard Group, as determined from paleontological evidence, ranges from 285 to 265 Ma (Hatcher et al., 1989). In the Southern Appalachians, the youngest sedimentary units involved in thrusting are Pennsylvanian clastic rocks, which are deformed along the Pine Mountain thrust as well as the Cumberland Plateau detachment.

Radiometric dating in the Southern Appalachians is generally limited to metamorphic provinces in the hinterland. However, Elliott and Haynes (2002) previously described K-Ar ages from illite in Devonian and Ordovician potassium bentonites exposed in the Southern Appalachian thrust belt that ranged from 260 to 310 Ma. These ages, along with supporting evidence from oxygen isotopes and K/Rb ratios, were interpreted to reflect diagenesis associated with the migration of warm saline fluids during the Alleghanian orogeny, as proposed by previous workers (Oliver, 1986; Schedl et al., 1992; Bethke and Marshak, 1990).

In the hinterland, ages from the crystalline Blue Ridge province range from Precambrian to Permian, representing tectonic events during the Grenville, Taconic, Neoacadian and Alleghanian orogenies (Hatcher et al., 1989; Goldberg and Dallmeyer, 1997). Initial assembly of the crystalline thrust sheets during the Alleghanian within the Blue Ridge province has been dated as ca. 325 Ma, with progression into the foreland during later Pennsylvanian into Permian times (Goldberg and Dallmeyer, 1997). Results from the metamorphic Piedmont province have shown that Alleghanian deformation advanced during many stages, with the final stage occurring in the Permian, ca. 265–290 Ma (Dallmeyer et al., 1986; Secor et al., 1986; Hadizadeh et al., 1991; Steltenpohl et al., 1992; Steltenpohl and Kunk, 1993). In particular, the Brevard fault zone, representing the boundary between the Blue Ridge and the Piedmont provinces, records a whole rock Rb-Sr date of 273 Ma from an ultramylonite (Hatcher et al., 1988) that signifies the final stage of motion along this long-lived fault zone.

In addition to the absolute ages of deformation in the foreland fold-thrust belt, the sequence of thrust imbrication has also remained a controversial topic in the Southern Appalachians. Previous workers have shown evidence for both a forward-propagating thrust belt (Woodward, 1985; Woodward and Beets, 1988), which is considered typical of fold-thrust belt development, as well as backward-breaking thrusting (Harris and Milici, 1977; Milici, 1986), with the frontal thrust being the first to break and gradual progression toward the hinterland. Determining the absolute age of thrusts through radiometric dating of fault gouge would resolve these conflicting scenarios.

SAMPLING AND METHODS

Despite deep weathering in the southeastern U.S., fault exposures for major thrusts were identified within the foreland fold-thrust belt of the Southern Appalachians (Fig. 1). Clay gouge was collected at outcrops of the St. Clair, Copper Creek, Knoxville and Great Smoky thrusts; in addition, a cataclasite from the Saltville thrust was collected to compare the results of clay gouge dating with fault rock processes that are primarily mechanical in origin. Samples were collected after digging into the exposures to reduce the effects of recent surface weathering.

Sample Preparation

Samples were disaggregated in an ultrasonic bath 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-sized fraction were created to characterize the mineralogy of each gouge 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. 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 subsequently separated using centrifuge settling. Gouge samples were typically separated into coarse (2.0–0.5 µm), medium (0.5–0.05 µm) and fine (<0.05 µm) fractions. Samples from the St. Clair thrust were separated into medium (0.5–0.1 µm), medium-fine (0.1–0.05 µm) and fine (<0.05 µm) fractions in order to avoid contamination by K-feldspar in the coarse fraction. Because carbonate minerals can obscure peaks 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 the effects acid treatment on Ar and K retention. More details of the preparation steps and methods are in van der Pluijm and Hall (2014).

Illite Characterization

To characterize the diagenetic grade, oriented slurry samples of the bulk clay-sized fraction as well as each size fraction were scanned from 2 to 20 °2Θ with a step size of 0.05° under both air-dried and glycolated conditions, using a Scintag diffractometer. The percent illite in illite-smectite (I-S) was estimated based on the method of Środoń (1980) and verified for representative samples by comparing to modeled diffraction patterns using the program NEWMOD (Reynolds and Reynolds, 1996). Illite crystallinity (IC) was determined by measuring the full width at half maximum (FWHM) of the 001 illite peak in °2Θ, which is essentially a measure of sharpness (Kübler, 1964; Kisch, 1983; Warr and Rice, 1994; Kübler and Jaboyedoff, 2000; Verdel et al., 2011). FWHM reflects the thickness distribution of the illite crystallites, with each illite layer being 1 nm. Crystallite thickness was calculated using the Scherrer equation, which relates thickness to FWHM (Drits et al., 1997).

The IAA method that we use requires quantifying the percentage of the two main polytypes of illite using X-ray diffraction (XRD): the higher-temperature, detrital $2M_1$ polytype, and the lower-temperature, authigenic $1M_d$ polytype. Oriented slurry mounts tend to obscure the $2M_1$ specific peaks, which all have nonbasal reflections. Therefore, random orientation of the illitic material is key to quantify the illite polytypes. Near-random powder mounts were made using an end-packer device modeled after Moore and Reynolds (1997). Samples were step-scanned from 16 to 44 °2Θ with a step size of 0.05° and a count time of 30 s/step. The relative intensity of the (002) and (020) peaks was used to determine whether randomness was achieved (Grathoff and Moore, 1996).

Illite polytype quantification was accomplished by modeling diffraction patterns using XRD patterns generated by the WILDFIRE program (Reynolds, 1993). WILDFIRE allows the user to apply different properties for $2M_1$ and $1M_d$ illite, and to vary such parameters as randomness of the sample ("Dollase" factor), hydration state, percentage cis- and trans-vacant interlayers, as well as smectite interlayers. A spreadsheet program was used to match the measured XRD patterns to the synthetic XRD patterns. In most cases, the lowest variance between the WILDFIRE-generated pattern and the powder pattern was used to constrain the best match except in instances where other minerals (e.g., quartz, plagioclase, carbonate) were present and obscured some of the illite peaks in the pattern. Typical precision for this method is ±2–3 %$2M_1$ (Haines and van der Pluijm, 2008).

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

Samples were dated at the University of Michigan using the ^{40}Ar/^{39}Ar encapsulation method; details of the theory and method are described in Dong et al. (1995) and van der Pluijm and Hall (2014). Along with the acquisition of both a total gas age and a retention age, the main advantages of ^{40}Ar/^{39}Ar dating over traditional K-Ar dating are the simultaneous measurement of radiogenic ^{40}Ar and ^{39}Ar, resulting in higher precision for the analysis, and, especially, 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 that is recoiled. After irradiation, the fused vial was broken so any recoiled gas could be analyzed first. 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. Both total gas ages (including the recoiled fraction) and retention ages (omitting the recoiled fraction) are plotted against percentage of $2M_1$

and subsequently extrapolated using York regression (York, 1968; with improvements by Mahon, 1996) to determine authigenic and detrital ages for each sample along with 1σ errors. While the error of Ar ages for each grain-size fraction is very small (<1%), the error in mineralogic quantification is comparatively large (±2–3 %2M1). As a consequence, the extrapolated ages of authigenic and detrital end-member components in mixtures primarily reflect the %2M1 error, resulting in intercept ages with errors that can be as much as an order of magnitude greater than individual ages, regardless of an excellent correlation coefficient for the data sets and regardless of the dating method (e.g., Ar-Ar, K/Ar).

RESULTS

Radiometric ages have been acquired for four faults that contained clay gouge and one cataclasite (Table 1). Results for each fault are discussed, starting with the Great Smoky thrust and moving progressively westward toward the foreland. Ar-release spectra display between 10% and 35% recoil, and do not have plateaus due to the mixture of authigenic and detrital phases. Modeling of illite polytypes for all samples shows a systematic decrease in the amount of the detrital (2M$_1$) illite with decreasing grain size. Of the samples, three faults (Great Smoky, Copper Creek and St. Clair) contain more than 70% 1M$_d$ illite (i.e., the authigenic polytype) in any size fraction, while two samples (Saltville and Knoxville) contain more detrital illite.

Great Smoky Thrust

The Great Smoky thrust is the fault with largest displacement (>300 km) in the Southern Appalachians (Hatcher et al., 2007), separating the mostly crystalline Blue Ridge province, which acted as the indenter (Hnat and van der Pluijm, 2011), from foreland sediments in the thin-skinned fold-thrust belt. An exposure of the fault along U.S. Route 321 that places lower Cambrian Chilhowee Group quartzite on upper Cambrian Conasauga Group shales was sampled for this study (Fig. 2). The fault contact is marked by coherent gouge that gradually progresses into the footwall shales.

The percentage of smectite interlayers in the samples is negligible (<5%) and the crystallinity reveals a relatively high diagenetic grade (FWHM of fine fraction = 0.567 °2Θ). Polytype quantification gives a high percentage (>75%) of authigenic 1M$_d$ illite for the gouge (Table 1). The polytype-derived authigenic age using total gas ages is 150.5 ± 41.0 Ma, and the retention age is 277.2 ± 29.6 Ma. The relatively large errors are a statistical effect of a small range in %2M1 values and a large age difference between detrital and authigenic illite.

Knoxville Thrust

The Knoxville thrust is a major fault in the Southern Appalachians, with an approximate maximum displacement of 18 km (Hatcher et al., 2007; Fig. 3). The sampled exposure lies along the Tennessee River, near Lenoir City, Tennessee, with a Cambro-Ordovician Knox Group dolostone in the hanging wall and nodular Lenoir Limestone of the mid-Ordovician Chickamauga Group. The fault contact is a gouge with a number of calcite-filled veins subparallel to the fault plane.

Glycolation reveals little smectite (<5%) and the illite crystallinity of the fine fraction (0.875 °2Θ) suggests a much lower diagenetic grade than at the Great Smoky (Table 1), which is consistent with thermal maturity (Fig. 1). The authigenic illite component is consistently below 35% and the extrapolated authigenic age from total gas ages is 280.2 ± 23.3 Ma, whereas the retention age is 431.8 ± 26.9 Ma. As before, the relatively large errors reflect a small range in %2M1 values and a large age difference between detrital and authigenic illite.

TABLE 1. RADIOMETRIC AGES FOR FOUR FAULTS THAT CONTAINED CLAY GOUGE AND ONE CATACLASITE

Great Smoky thrust	%2M$_1$	FWHM	Scherrer thickness	Total gas age	Retention age
Coarse fraction	22.0% ± 2.0%	0.376 °2θ	21 nm	374.5 ± 1.3 Ma	448.0 ± 1.5 Ma
Medium fraction	16.0% ± 2.0%	0.419 °2θ	19 nm	314.8 ± 1.0 Ma	385.5 ± 1.2 Ma
Fine fraction	9.0% ± 2.0%	0.567 °2θ	14 nm	245.6 ± 0.7 Ma	357.3 ± 1.0 Ma
Authigenic total gas age 150.5 ± 41.0 Ma				Detrital total gas age 996.1 ± 161.8 Ma	
Authigenic retention age 277.2 ± 29.6 Ma				Detrital retention age 931.6 ± 143.7 Ma	
Knoxville thrust	%2M$_1$	FWHM	Scherrer thickness	Total gas age	Retention age
Coarse fraction	33.0% ± 2.0%	0.371 °2θ	22 nm	468.4 ± 1.1 Ma	542.1 ± 1.2 Ma
Medium fraction	17.0% ± 2.0%	0.538 °2θ	15 nm	406.4 ± 0.8 Ma	500.2 ±1.0 Ma
Fine fraction	7.0% ± 3.0%	0.875 °2θ	9 nm	305.5 ± 0.7 Ma	448.1 ±1.0 Ma
Authigenic total gas age 280.2 ± 23.3 Ma				Detrital total gas age 829.8 ± 75.8 Ma	
Authigenic retention age 431.8 ± 26.9 Ma				Detrital retention age 759.4 ± 92.3 Ma	
Saltville thrust (cataclasite)	%2M$_1$	FWHM	Scherrer thickness	Total gas age	Retention age
Coarse fraction	40.0% ± 4.0%	0.296 °2θ	27 nm	323.3 ± 0.6 Ma	400.0 ± 0.8 Ma
Medium fraction	35.0% ± 3.0%	0.373 °2θ	21 nm	331.5 ± 0.5 Ma	395.9 ± 0.6 Ma
Fine fraction	15.0% ± 4.0%	0.514 °2θ	16 nm	264.6 ± 0.7 Ma	371.7 ± 0.9 Ma
Authigenic total gas age 215.7 ± 25.1 Ma				Detrital total gas age 510.4 ± 77.2 Ma	
Authigenic retention age 354.2 ± 9.9 Ma				Detrital retention age 469.0 ± 31.0 Ma	
Copper Creek thrust	%2M$_1$	FWHM	Scherrer thickness	Total gas age	Retention age
Coarse fraction	18.0% ± 2.0%	0.739 °2θ	11 nm	344.9 ± 0.5 Ma	457.9 ± 0.6 Ma
Medium fraction	12.0% ± 2.0%	0.837 °2θ	10 nm	326.8 ± 0.8 Ma	462.6 ± 1.1 Ma
Fine fraction	4.0% ± 2.0%	1.149 °2θ	7 nm	293.7 ± 0.6 Ma	410.7 ± 0.8 Ma
Authigenic total gas age 279.5 ± 11.3 Ma				Detrital total gas age 623.2 ± 70.5 Ma	
Authigenic retention age 390.0 ± 17.2 Ma				Detrital retention age 817.6 ± 89.0 Ma	
St. Clair thrust	%2M$_1$	FWHM	Scherrer thickness	Total gas age	Retention age
Medium fraction	27.0% ± 3.0%	0.372 °2θ	21 nm	259.5 ± 0.8 Ma	300.4 ± 0.9 Ma
Medium-fine fraction	19.0% ± 2.0%	0.453 °2θ	18 nm	253.3 ± 0.7 Ma	294.0 ± 0.8 Ma
Fine fraction	16.0% ± 2.0%	0.582 °2θ	14 nm	226.6 ± 0.3 Ma	290.7 ± 0.4 Ma
Authigenic total gas age153.8 ± 41.0 Ma				Detrital total gas age 579.8 ± 178.0 Ma	
Authigenic retention age 276.6 ± 6.8 Ma				Detrital retention age 364.2 ± 34.8 Ma	

Note: Ages in bold—representative ages based on crystallite thickness. %2M$_1$—Percentage of detrital illite determined from polytype quantification. FWHM—Measure of illite crystallinity using the full width at half maximum of the 001 peak in °2θ.

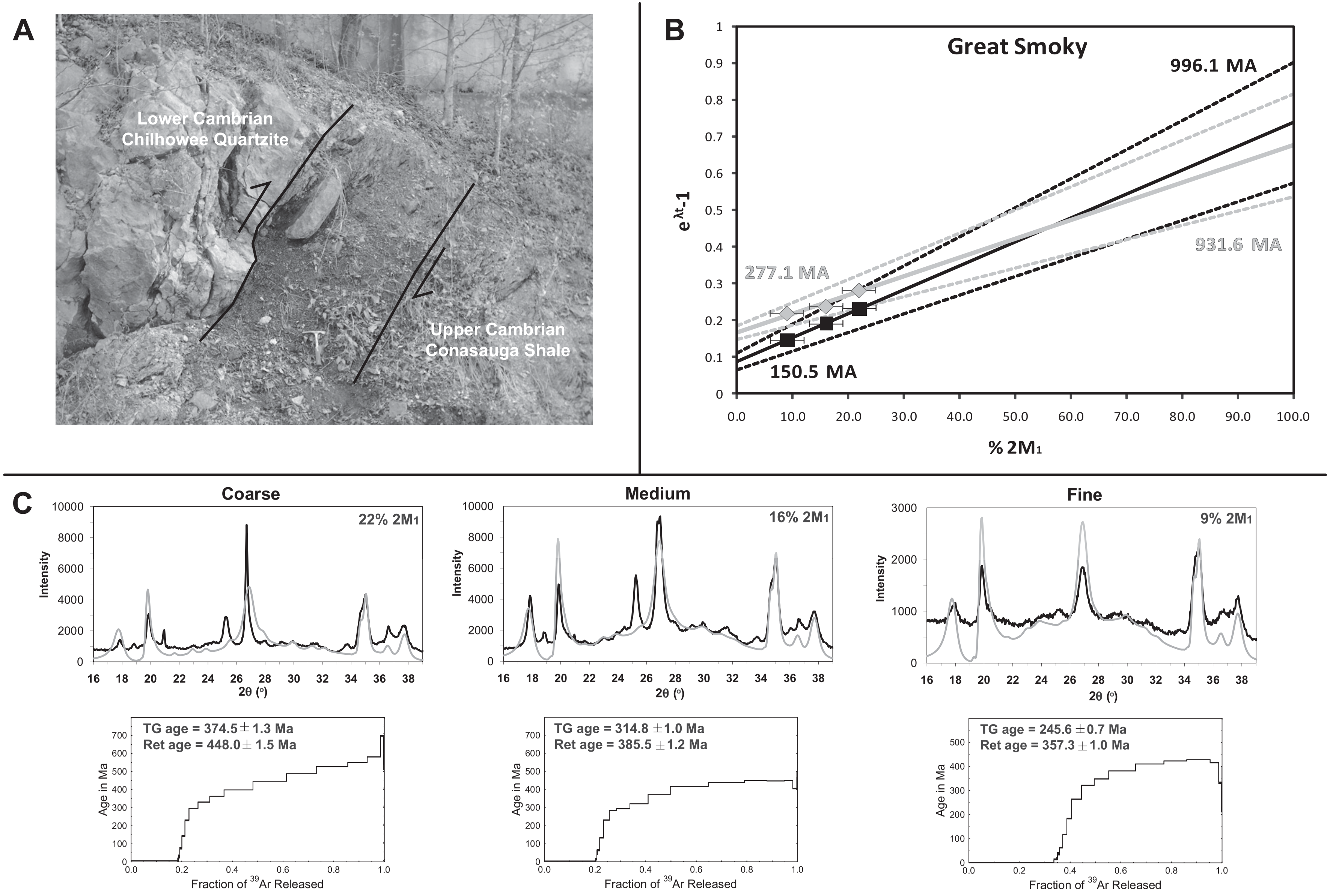

Figure 2. (A) Photograph of Great Smoky fault exposure. (B) Illite age analysis (IAA) plot, showing percent detrital ($2M_1$) illite versus age (expressed as $e^{\lambda t} - 1$; λ—decay constant, t—time). Gray symbols and lines represent retention (Ret) ages while black symbols and lines represent total gas (TG) ages. Dashed lines represent errors based on York regression of the data, which is a version of reduced major axis analysis that incorporates errors for independent X and Y values. Because the clay quantification error is an order of magnitude greater than individual Ar dates, the extrapolated ages that combine the two data sets are an order of magnitude greater than typical Ar age errors. 100% $2M_1$ ages, on the right side of the IAA plot, represent detrital ages, while 0% $2M_1$ illite, on the left side of the IAA plot, represents authigenic ages. (C) Modeled X-ray diffraction (XRD) patterns compared to measured XRD patterns and corresponding argon release diagrams for the Great Smoky thrust with decreasing grain size.

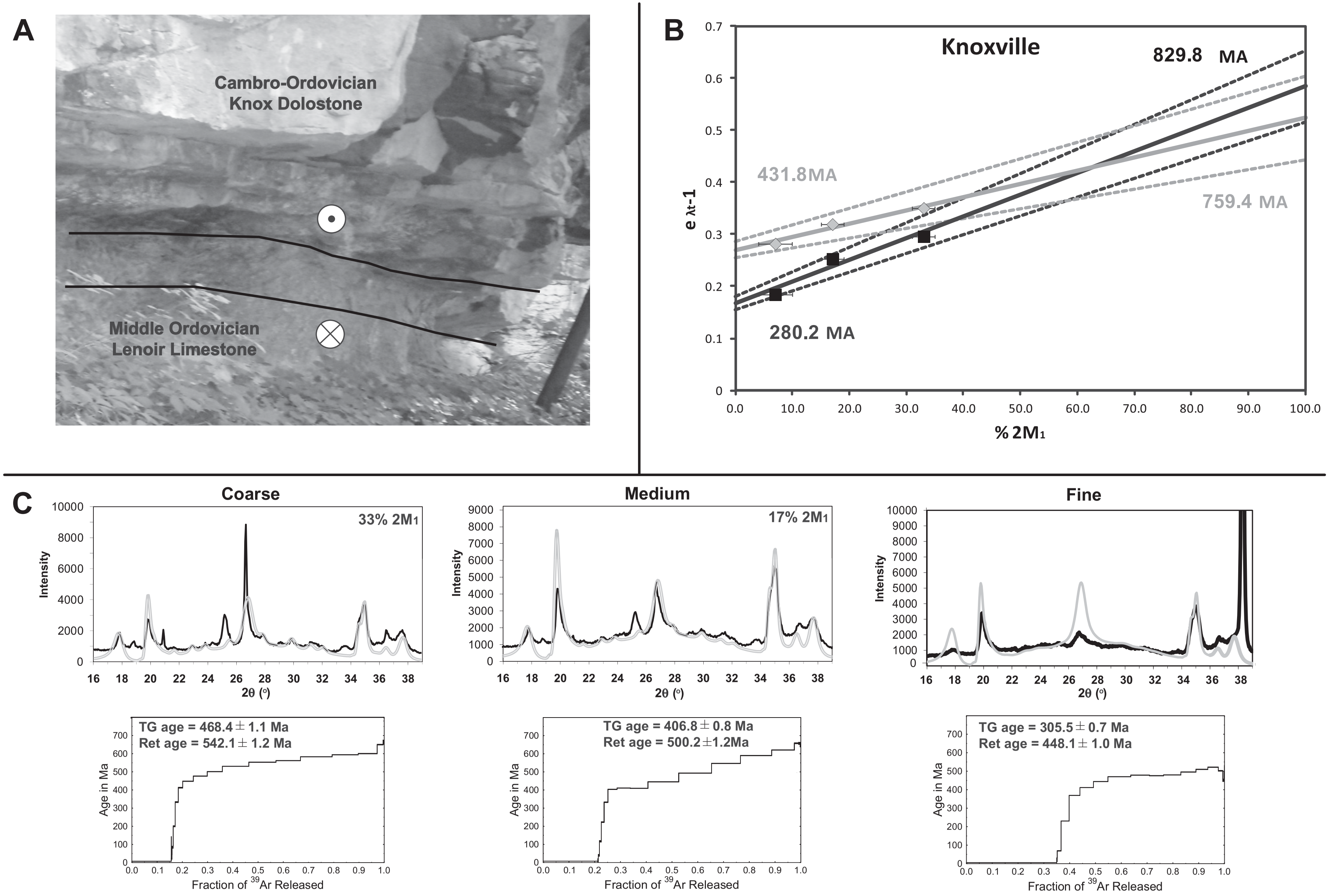

Figure 3. (A) Photograph of Knoxville fault exposure. (B) Illite age analysis. (C) X-ray diffraction patterns and Ar spectra. See Figure 2 and text for explanation.

Saltville Thrust

The Saltville thrust represents the thrust with second-largest displacement in the Southern Appalachian fold-thrust belt, separating a zone of major folding toward the hinterland and a zone of dominant faulting toward the foreland (Woodward et al., 1988; Fig. 4). Displacement estimates based on facies changes in mid-Ordovician sediments and strike length are ~100 km (Hatcher et al., 2007). The sampled exposure of the Saltville thrust is located along U.S. Route 23 at the Virginia-Tennessee border. The fault places middle Cambrian Rome Formation onto a large dolomite horse of unknown age, which is in turn thrust onto Devonian black shales of the Chattanooga Formation. In contrast to the other sampling sites, clay gouge was not present; instead, shale cataclasite with polished surfaces was collected.

The FWHM value of the fine fraction (0.514 °2Θ) and the lack of smectite interlayers (<2%) for the Saltville thrust indicate a relatively high diagenetic grade. While still dominated by $1M_d$ illite in the fine fraction, the Saltville fault contains considerably more detrital $2M_1$ illite than the other fault rocks analyzed. The authigenic age derived using total gas ages yields an age of 215.7 ± 25.1 Ma, while the retention ages yield an age of 354.2 ± 9.9 Ma.

Copper Creek Thrust

The Copper Creek thrust is a major fault in the Southern Appalachians, with a displacement of ~50 km (Hatcher et al., 2007). Although exposed at a number of locations, the one sampled is located along U.S. Route 25-E, at the "Thorn Hill section," a popular locality of well-exposed Paleozoic stratigraphy in the Appalachians (Fig. 5). Here, dolomites of the middle Cambrian Rome Formation are thrust onto red siltstones of the Middle Ordovician Moccasin Formation (Fig. 5). The gouge zone is ~0.5 m thick and is mostly clay, with zones of reddish and gray gouge.

The percentage of illite in I-S is ~95%, given that no peak shift occurred after glycolation, but only some peak broadening. The crystallinity is low, with the FWHM value of the fine fraction being 1.149 °2Θ, suggesting low-grade diagenetic conditions. The gouge has very high authigenic illite content, with <20% detrital $2M_1$ illite in the coarse fraction and less in finer fractions. The authigenic ages derived from the polytype analysis yield a total gas age of 279.5 ± 11.3 Ma and a retention age of 390.0 ± 17.2 Ma.

St. Clair Thrust

The St. Clair thrust is the northwestern-most major fault sampled in the Appalachian fold-thrust belt of southwestern Virginia (Fig. 1). Displacement is on the order of 30 km (Whisonant and Schultz, 1986; Perry et al., 1979). The sampled exposure lies along U.S. Route 460 south of Rich Creek, Virginia, placing Cambro-Ordovician Knox Group (Beekmantown dolostones) onto upper Devonian–lower Mississippian shales (Fig. 6).

The ~0.25-m-wide fault zone contains a carbonate-rich, clayey gouge with small horses of brecciated dolomite. Smectite interlayers are virtually nonexistent in analysis of the bulk sample or of individual grain sizes. Crystallinity is high for all size fractions (fine fraction FWHM = 0.582 °2Θ), indicating a relatively high diagenetic grade. The percentage detrital illite is less than 30% in all size fractions. The authigenic age derived from polytype quantification using the argon total gas ages yields an age of 153.8 ± 41.0 Ma. Using the retention ages produces an authigenic age of 276.6 ± 6.8 Ma for this fault.

DISCUSSION

Interpreting the ages of Appalachian fault rocks requires a brief examination of the use of total gas ages versus retention ages to date faults, which is linked to the crystallite size of illite. Subsequently, the implications of these ages for regional tectonics and thrust belt propagation are explored.

Total Gas Ages versus Retention Ages

In a series of papers, Dong et al. (1995, 1997, 2000) and Hall et al. (1997, 2000) have described the theory and application of total gas ages and retention ages in illitic clays using $^{40}Ar/^{39}Ar$ dating. These studies showed that the age of large illite crystallites, such as anchizonal shales, is measured by retention ages, while small illite crystallites, formed at lower temperatures, are dated by total gas ages. Total gas ages combine Ar that is released during sample irradiation (trapped in a glass vial) and step-heating of the sample, and is therefore analogous to traditional K-Ar dating. Retention ages use Ar retained in the illite structure and released during step-heating, but excludes Ar that is released during irradiation, as it overcorrects for naturally produced radiogenic Ar. Details of K and Ar systematics are already explored in the studies referenced above and elsewhere (Clauer et al., 2012; van der Pluijm and Hall, 2014). In this study we propose a straightforward application that utilizes the recoil fraction and crystallite size to distinguish between the application of total gas ages and retention ages.

It is well established that layer stacking increases with increasing diagenetic grade, resulting in thicker illite crystallites, as well as sharper basal 00l reflections in XRD patterns (Kübler, 1964; Eberl and Velde, 1989; Kübler and Jaboyedoff, 2000). Dong et al. (1995) showed that the recoil fraction is a proxy of the illite layer stacking, such that the percentage of recoil correlates to the number of illite layers (*n*); specifically, recoil % = 1/*n* *100. Our finer-grained samples, containing the greatest amount of authigenic illite, show recoil percentages in the range of 20%–35%. Based on the relationship above this would reflect Ar-illite model thicknesses of 3–5 illite layers, i.e., a crystallite thickness of 3–5 nm. The age of illite crystallites with sizes on this order and below, therefore, is represented by total gas ages. Warr and Nieto (1998) showed, based on a transmission electron microscopy (TEM) study, that diagenetic illite typically has an average defect-free distance up to 10 nm, limiting the release of radiogenic argon through diffusion (Hames and Bowring, 1994; Hall et al., 2000). Thus, we use a cutoff for crystallite sizes up to ~5 nm for total gas ages and >10 nm for retention ages, but recognize that a transitional range must exist. For the future, we are planning to develop a model that is based on crystal characterization and age spectrum analysis using these and other samples.

Table 1 shows the average crystallite thickness for each size fraction, calculated using the Scherrer equation (Drits et al., 1997) applied to the FWHM. The Scherrer equation calculates crystallite thickness based on the peak breadth of the 001 peak by the function:

$$\beta_{001} = \frac{K\lambda}{T\cos\theta_{001}}, \qquad (1)$$

where β_{001} is the FWHM of the 001 peak, K is a constant, λ is the wavelength of the incident X-rays, θ_{001} is the center angle of the 001 peak and *T* is the crystallite thickness. The difference in the broadness of the 001 illite peak is illustrated by comparing the patterns of the Copper Creek and St. Clair samples (Fig. 7). The finest fraction for each sample is used for this analysis, because the coarser grain sizes are disproportionally affected by detrital illite that has muscovite-like crystallite thicknesses.

Based on measured crystallite thicknesses (Table 1), we therefore use retention ages for samples from the Great Smoky, Saltville and St. Clair thrusts and total gas ages for samples from the Copper Creek and Knoxville faults.

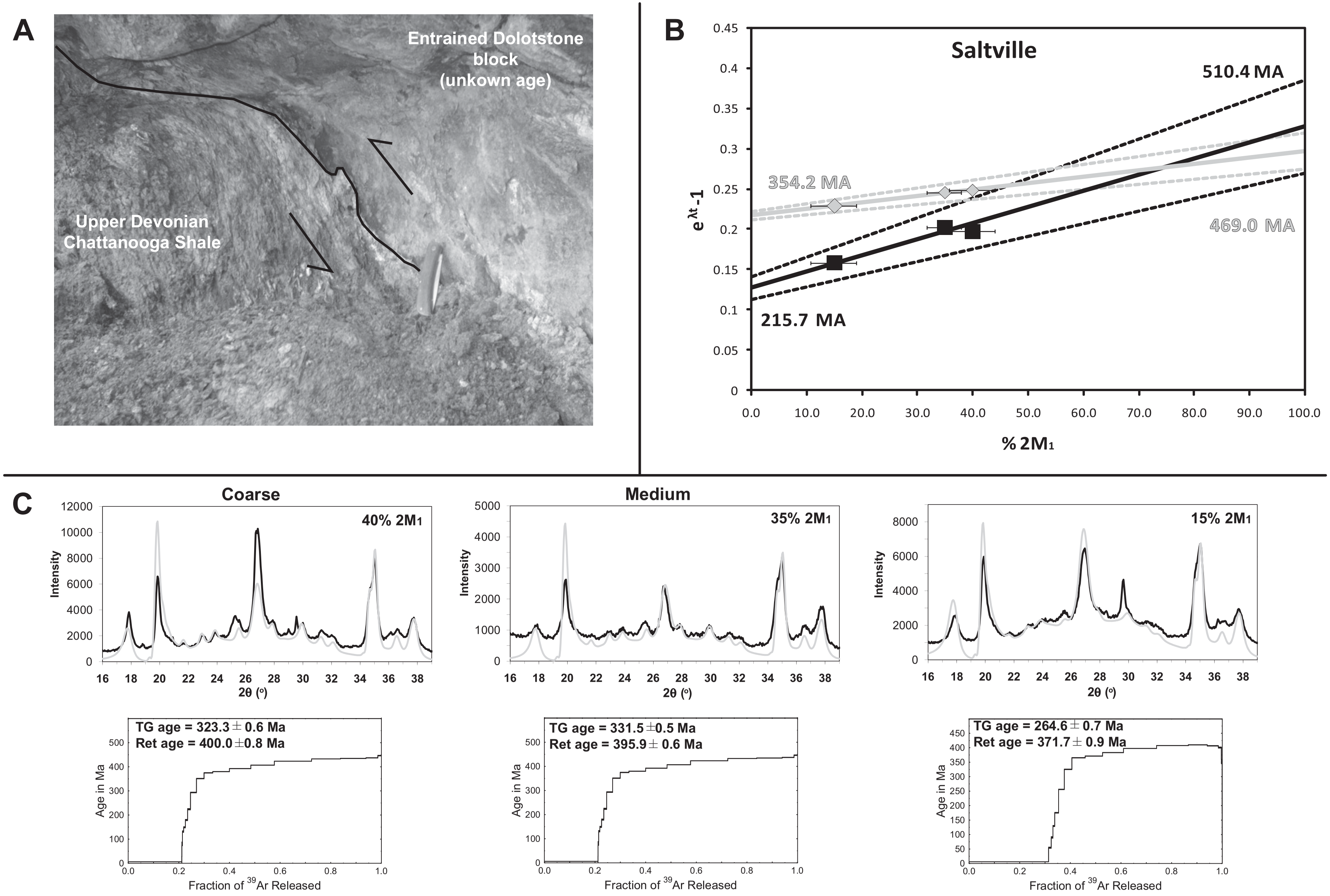

Figure 4. (A) Photograph of Saltville thrust exposure. (B) Illite age analysis. (C) X-ray diffraction patterns and Ar spectra. See Figure 2 and text for explanation.

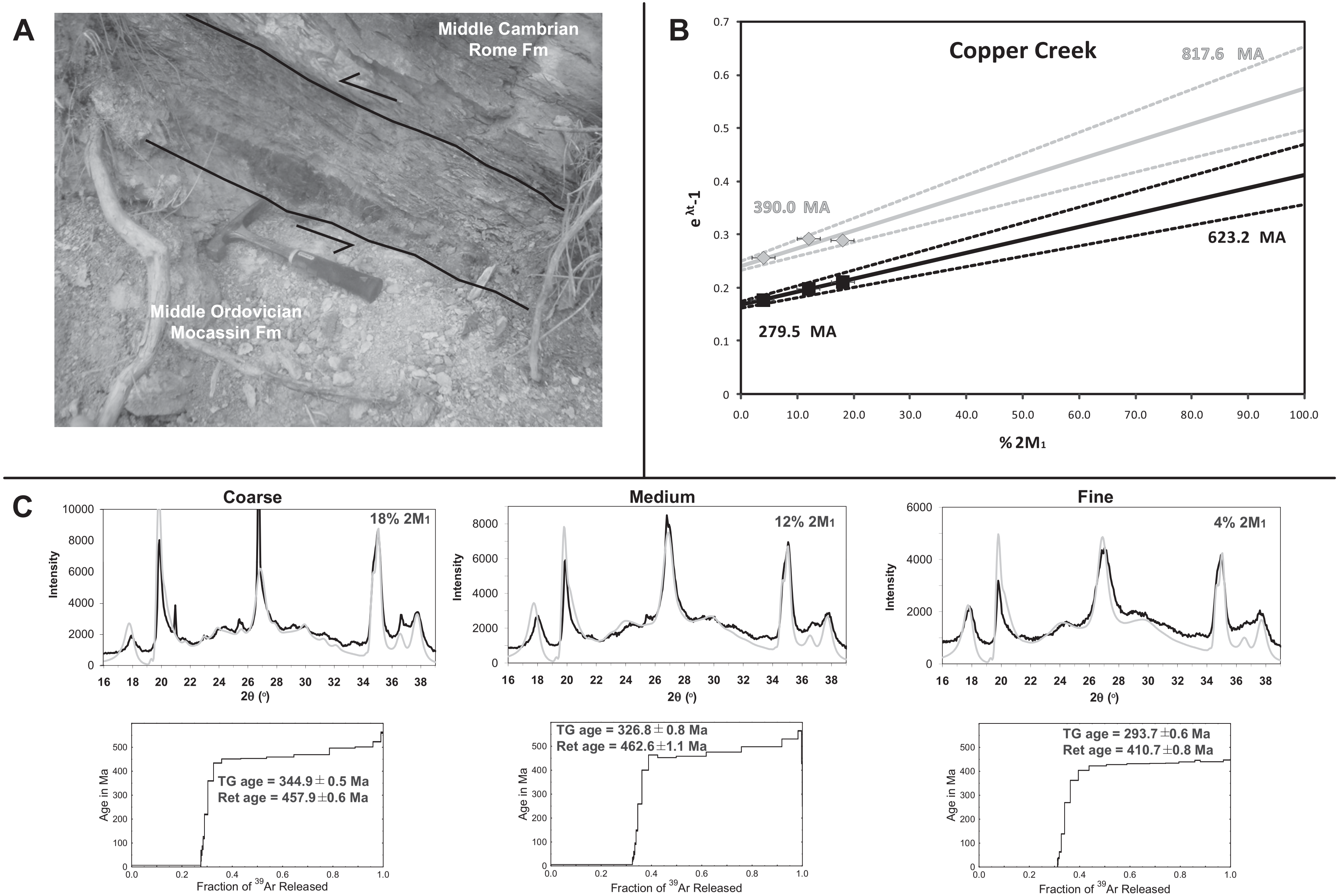

Figure 5. (A) Photograph of Copper Creek thrust exposure. (B) Illite age analysis. (C) X-ray diffraction patterns and Ar spectra. See Figure 2 and text for explanation.

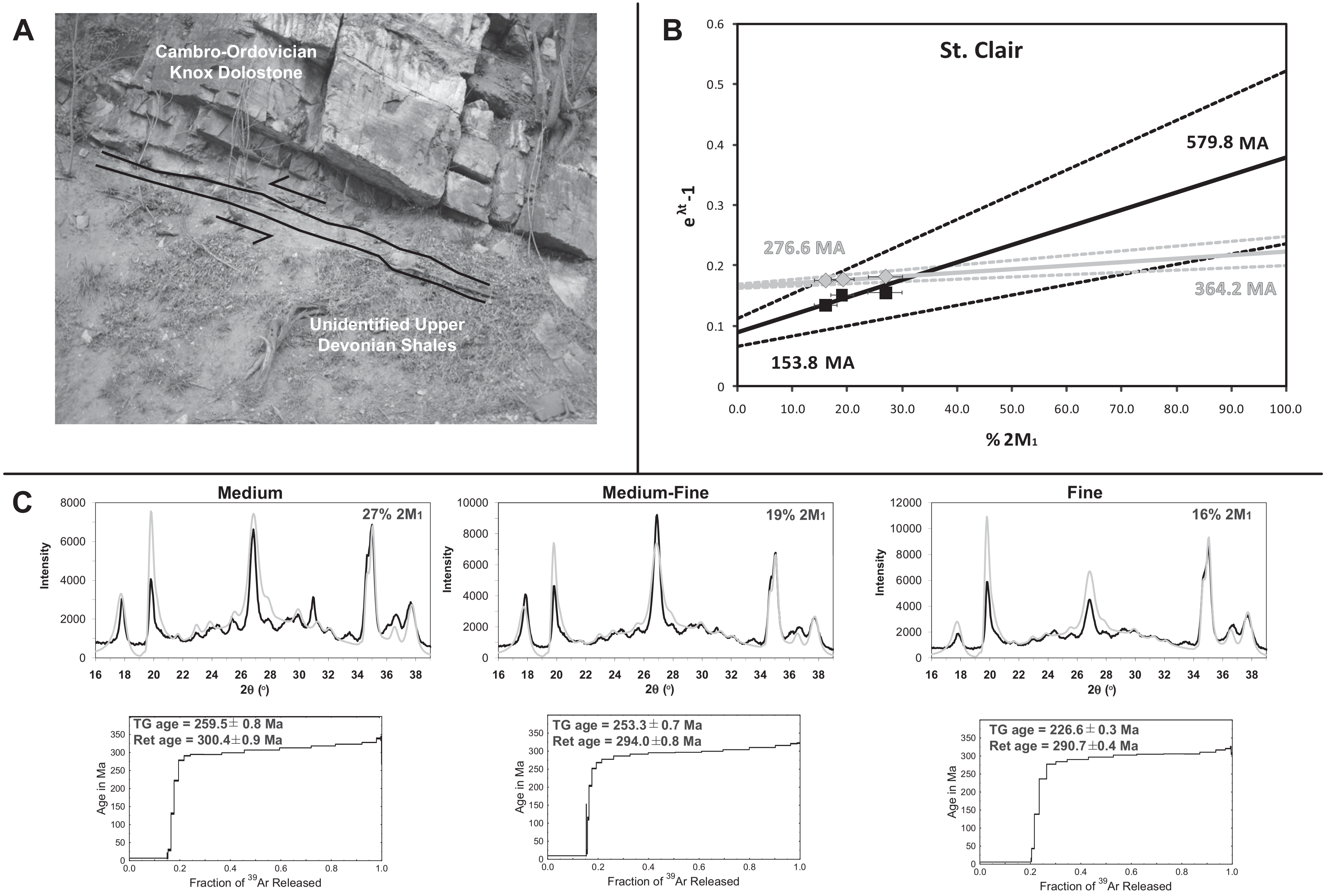

Figure 6. (A) Photograph of St. Clair fault exposure. (B) Illite age analysis. (C) X-ray diffraction patterns and Ar spectra. See Figure 2 and text for explanation.

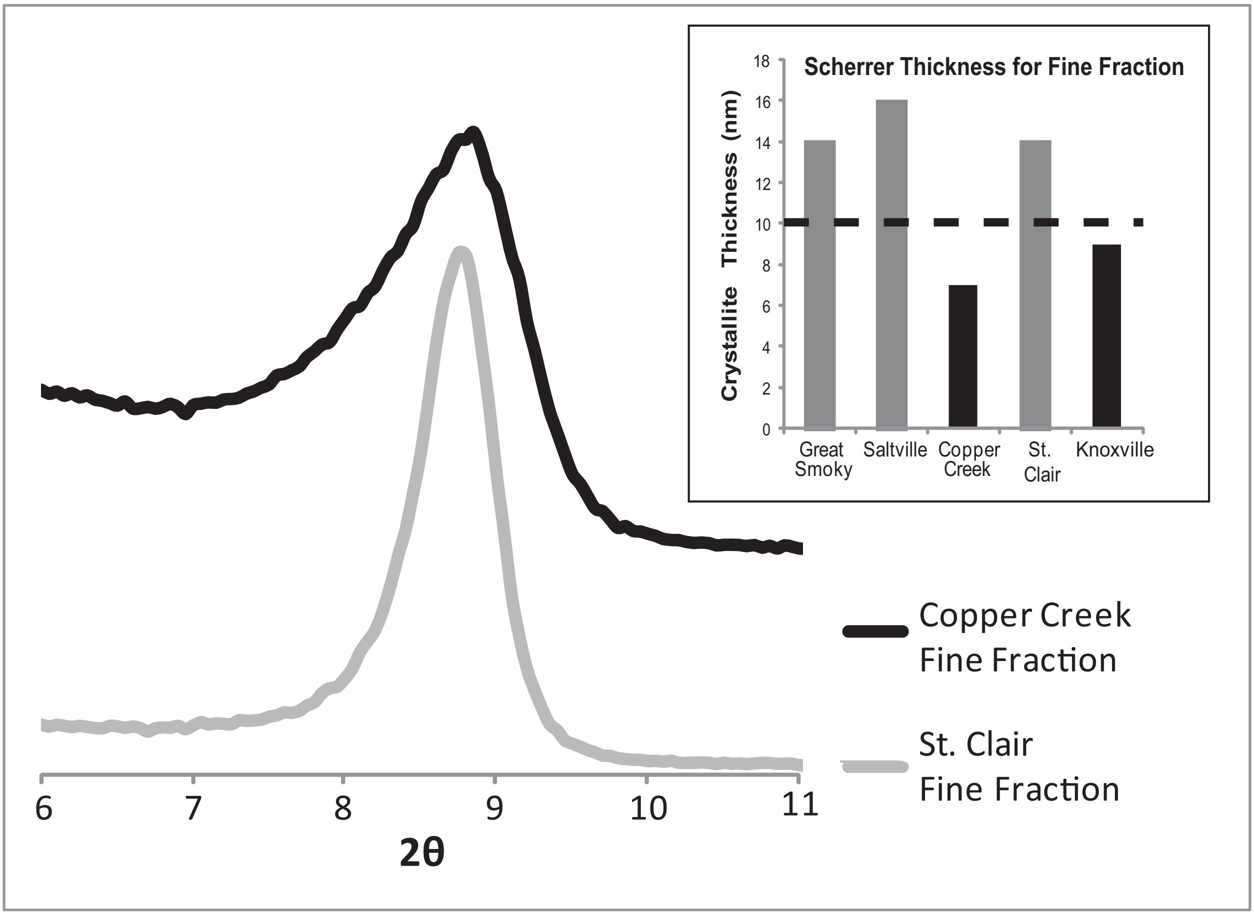

Figure 7. X-ray diffraction patterns of the illite 001 peak, displaying the contrast between the broad peak of the finest fraction from the Copper Creek thrust (low diagenetic grade) and the sharp peak of the finest fraction of the St. Clair thrust (high diagenetic grade). Insert shows Scherrer thickness of each fine fraction relative to the 10 nm cutoff. Gray bars represent sites where retention ages were used; black bars represent sites where total gas ages were used.

Implications for Regional Tectonics

Authigenic illite dominates in four of the sampled fault rocks. The Copper Creek and Knoxville faults are of lower diagenetic grade than the Great Smoky, Saltville and St. Clair thrusts, based on crystallinity measurements. Therefore, total gas ages are used for the Copper Creek and Knoxville faults, while retention ages are used for the others. The higher grade of the Great Smoky, Saltville and St. Clair thrusts can be attributed to the greater depth at which they were active and from which they were subsequently exhumed. Indeed, studies using the conodont alteration index (Fig. 1), apatite fission-track thermochronology and geodynamic modeling all suggest that the Copper Creek and Knoxville sites have been exhumed from shallower depths than those of the Great Smoky, Saltville and St. Clair thrusts (Epstein et al., 1977; Beaumont et al., 1987; Roden, 1991).

Based on our results, the clay gouge–bearing Great Smoky, Knoxville, Copper Creek and St. Clair thrusts all have respective ages in the range of 276–280 Ma (Table 1), indicating that, within analytical error, they were simultaneously active during early Permian (Cisuralian) time. These ages fall within the previously constrained stratigraphic range, and significantly narrow the time window of major displacement. In contrast to these four faults, the Saltville fault sample is a shale cataclasite that recorded the age of illitization (354 ± 9.9 Ma) of the Upper Devonian–Lower Mississippian Chattanooga shale in the footwall. This age cannot correspond to activity along the fault, because the Saltville thrust cuts younger Mississippian sediments in its footwall. The result from reworked host rock at the Saltville thrust also illustrates that regional resetting is not responsible for the ages of the other four faults; instead the latter represent local, fault-related illitization during the early Permian.

As also observed in the Rocky Mountain forelands of Alberta (Canada) and Wyoming (United States) (van der Pluijm et al., 2006; Solum and van der Pluijm, 2007), fault gouge ages from the Southern Appalachians indicate that a belt of several tens of kilometers along the orogen's frontal wedge was simultaneously active during the early Permian (Fig. 8). The contemporaneous displacement on several major Appalachian faults reconciles conflicting studies on the progression of thrusting, with both foreland and hinterland proposed. Based on radiometric ages for major faults in the foreland segment of the Southern Appalachians we conclude that they were active simultaneously.

CONCLUSIONS

IAA has been applied to clay gouge–bearing fault rocks and one cataclasite from the Southern Appalachians to determine timing of major movement. Results from this study also highlight

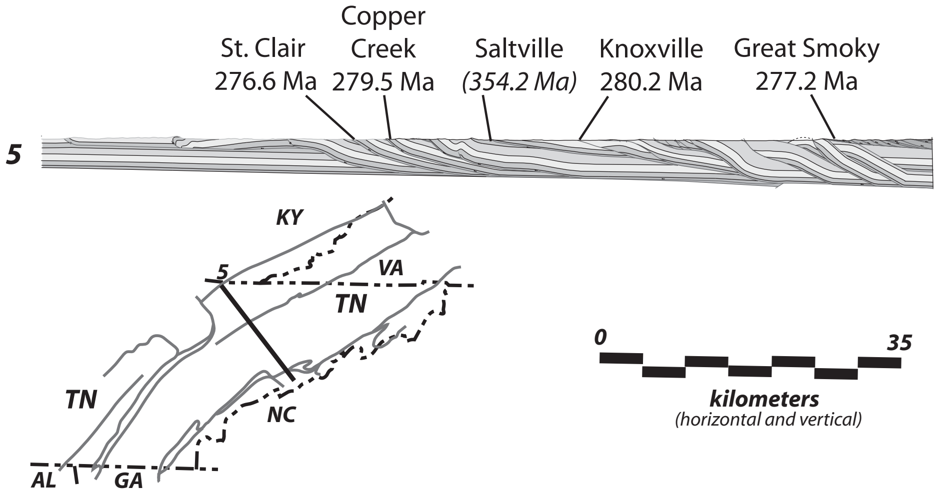

Figure 8. Representative cross-section across the Tennessee salient of the Southern Appalachians (section 5; courtesy Hatcher et al., 2007), showing the relative positions of major faults dated in this study and their ages. See Figure 1 for state abbreviations.

the role of varied diagenetic grades, and particularly the use of total gas and retention ages, when applying IAA to fault dating. Crystallites from low-grade diagenetic regimes are on the order of or less than the average recoil thickness of illites, requiring the use of total gas ages; larger crystallites in higher-grade, anchizonal rocks require the use of retention model ages. This distinction is particularly important for the application of ^{40}Ar/^{39}Ar dating to clay gouge in areas of higher diagenetic grades, as failure to recognize the role of large crystallites can lead to misinterpreted results. The present study constrains the use of total gas ages and retention ages for each sample based on average crystallite size as measured by XRD, with the cutoff at 5–10 nm.

Ages in the Southern Appalachian foreland fold-thrust belt have been obtained from clay gouge of four major faults along and across the belt: the Great Smoky, Knoxville, Copper Creek and St Clair thrusts. A reworked host rock cataclasite from the Saltville fault, where clay gouge did not develop, was analyzed for comparison and reveals earlier diagenetic alteration in the area. Illite ages from the Great Smoky, Knoxville, Copper Creek and St. Clair thrusts in the Appalachian foreland all show a period of significant motion ca. 276–280 Ma, supporting the interpretation that several major faults were active contemporaneously in the frontal segment of the orogenic wedge of the Southern Appalachians and that the area was part of an internally deforming, regional-scale foreland wedge.

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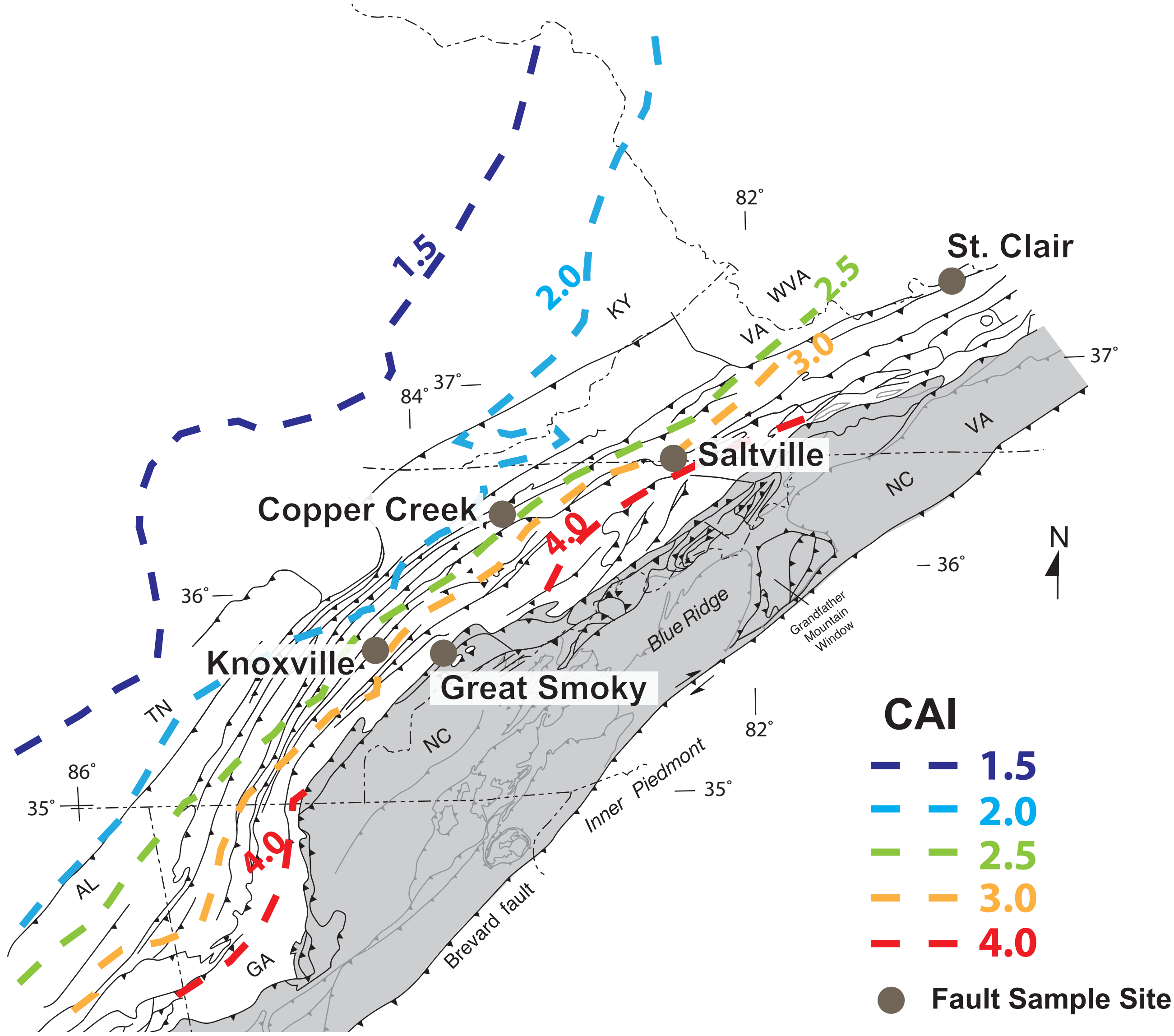
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2.5
WVA
KY
2.0
1.5
VA
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37°
37°
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VA
Saltville
Copper Creek
NC
4.0
N
36°
36°
Blue Ridge
Grandfather Mountain Window
Knoxville
Great Smoky
TN
82°
NC
86°
Inner Piedmont
35°
35°
AL
4.0
Brevard fault
GA
CAI
1.5
2.0
2.5
3.0
4.0
Fault Sample Site