Constraining the timing of shale detachment faulting: A geochemical approach

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ABSTRACT

K-Ar dating of illite in fault gouges is a useful tool for constraining the timing of brittle fault movement; however, this can be problematic in fault gouges hosted in clay-rich rocks due to the influence of host-rock material. Therefore, this study employs a multianalytical geochemical approach to unravel the influence of host-rock mineralogy, as well as fault zone development, on ages from fault-gouge samples in a shale detachment zone. K-Ar dating of the ≥2 µm fraction of 6 samples from the Sap Bon Formation detachment zone and associated fault zones in the Khao Khwang fold-thrust belt of central Thailand yielded an age range of 262 ± 5.4 to 208 ± 4.6 Ma. Carbon and oxygen stable isotope analysis along with X-ray diffraction mineralogy indicate that the samples with the youngest K-Ar ages are characterized by higher grade clay mineralogy, and hotter, orogenic fluid temperatures. Using these proxies and comparison to existing geochronology of the study area, we correlated K-Ar illite ages to one of three stages of fault zone evolution: detrital, diagenetic (burial), and authigenic (fault movement). The youngest K-Ar dates in the Sap Bon Formation are contemporaneous with recently published zircon province data indicating that faulting and detachment zone formation in the Sap Bon Formation were occurring by the mid-Late Triassic, with deformation continuing as late as the Rhaetian.

INTRODUCTION

Dating of fine-grained minerals such as clays can provide constraints on the timing of fault movement in the shallow crust (van der Pluijm et al., 2001; Zwingmann and Mancktelow, 2004; Pleuger et al., 2012). K-Ar dating is a reliable tool to constrain authigenic formation of fine-grained illite clay minerals in brittle faults (Torgersen et al., 2015). K-Ar ages for fine-grained illite clay fractions (< 10 µm) are frequently reported as inclined age spectra with respect to different grain-size fractions (e.g., Torgersen et al., 2015). K-Ar ages decrease with grain size of the fraction from which they are obtained and the relationship is interpreted to reflect the mixing of detrital ages and authigenic ages (Pevear, 1999; Viola et al., 2013). The percentage of 1M/1M0 to 2M0, illite polytypes (authigenic, 1M, versus detrital, 2M1) can be considered in relation to K-Ar age in an illite age analysis plot (Pevear, 1999). This technique can be used to determine the degree to which the mineralogy of fault host rock influences the mineralogy of dated fault-gouge material (van der Pluijm et al., 2006; Zwingmann et al., 2010; Yamasaki et al., 2013), or to quantify the influence of authigenic versus detrital component of the clay fraction (Elliott et al., 1991). Plots of K-Ar ages versus the percentage of total illite that is diagenetic give a linear correlation that can be extrapolated to 0% and 100% detrital illite end members to give the diagenetic and detrital ages, respectively (Pevear and Elliott, 1991). Complications arise if the fault host rock contains minerals that may contaminate clay fractions and influence the K-Ar ages (e.g., Torgersen et al., 2014, 2015). This is particularly true in shales, where it can be difficult to determine if ages are reflective of fault-gouge formation (authigenic), are detrital, or reflect the diagenetic formation of illite between deposition and fault activation.

K-Ar analysis of illite to determine the timing of brittle fault movement is not a technique typically used in clay-rich host rocks. For example, in igneous host rocks it can be confidently assumed that fault-gouge illite is authigenic, while shales have the potential to contaminate fault-gouge illite with detrital micas. Therefore, this study aims to illustrate how a range of geochemical data can be used to unravel meaningful information from K-Ar ages of <2 µm fraction clay separates from fault gouges in an exhumed shale detachment zone in the Khao Khwang fold-thrust belt (KKFTB) in central Thailand (Fig. 1).

GEOLOGICAL SETTING

The study area is a fault damage zone associated with an exhumed upper level detachment thrust in the Sap Bon Formation of the KKFTB of central Thailand (Fig. 1). The detachment zone is exposed in the Siam City cement quarry, in the Muak Lek District of Saraburi Province, Thailand.
Figure 1. Location of study area in the Khao Khwang fold-thrust belt, central Thailand. Alum shales are defined as black, organic-rich, pyrite-bearing shales. (A) Location within Thailand of the exposed Saraburi Group. (B) Simplified geology of the exposed Saraburi Group; the Siam City cement quarry is in white. (C) Simplified cross section through the Siam City cement quarry showing the locations of the mid-quarry ridge and shale quarry S study areas. Strat—stratigraphic. (D) Simplified cross section through the mid-quarry ridge illustrating sample locations. (E) Simplified cross section through shale quarry S illustrating sample locations.
The detachment zone is characterized by variably deformed shales and carbonate-cemented arenites deformed during the Triassic Indosinian orogeny above a detachment fault referred to as the Eagle thrust (Hansberry et al., 2014). Few studies have been carried out in this area; constraining the tectonic evolution of the KKFTB has been the focus of ongoing work (e.g., Morley et al., 2013; Arboit et al., 2014, 2015; Hansberry et al., 2015). Arboit et al. (2014, 2015, 2016) focused on revision of the Saraburi Group stratigraphy and improved constraints on the timing of Indosinian orogenesis. U-Pb detrital zircon ages indicate a middle Permian (275 ± 4 Ma, Kungurian) maximum depositional age for the Sap Bon Formation in the quarry. A maximum depositional age of 205 ± 6 Ma (Rhaetian) in a clastic unit interpreted to have been deposited in a thrusting-related piggyback basin north of the Siam City cement quarry indicates that the Indosinian orogeny was active into the latest Triassic (Arboit et al., 2015). Competency contrast within the Sap Bon Formation has influenced the formation of shear zones at strain rate discontinuities; these shear zones characterize the fault damage zone, which constitutes an upper level detachment zone (Hansberry et al., 2015). Within the fault damage zone, the most continuous thrusts are surrounded by well-developed shear zones and fault gouges, which we refer to as shear domains (Hansberry et al., 2014). These shear zones are characterized by well-developed foliations and C-S fabrics, and vary in thickness from a few millimeters around discrete fractures to ~50-cm-wide shear zones (Fig. 2).

**SAMPLING**

We collected 51 samples from the Sap Bon Formation in the Siam City cement quarry. From these samples, six were selected as being appropriate for illite K-Ar dating due to the quality of exposure of fault-gouge material. To avoid weathering contamination, samples were collected directly from the deformation zone ~30 cm below the surface, as recommended by Emery and Robinson (1993). Global positioning system sample locations are listed in Table 1. Samples were taken from five locations in the exposure of the Sap Bon Formation fault damage zone (here referred to as shale quarry S) and one from the thrust imbricate overlying it (here referred to as the mid-quarry thrust). Four of these samples come from shear zone material surrounding major faults (Fig. 2); the other two are from zones of discontinuously deformed rock, where sample material was collected immediately adjacent to discrete fault fractures (Fig. 2). These latter two samples (EAG12046, EAG12051) are therefore likely to contain host-rock material. In all cases, kinematic indicators from slickenfibers of exposed parts of slip surfaces indicate consistent movement senses, sympathetic to the Eagle thrust at the base of the Sap Bon Formation.
METHODS

The use of K-Ar dating of illite to determine the age of brittle fault movement is most commonly used in protoliths that are unlikely to contaminate the sample with material from the fault wall; its use in clay-rich rocks is problematic. Although the techniques to correct for the influence of nonauthigenic illites within a sample exist, this typically requires extensive dating of multiple size fractions in each sample. This study instead uses an array of geochemical methods to unravel the 6 K-Ar ages obtained from only the <2 µm fraction of each sample, to illustrate how meaningful results can be produced from such a data set.

Scanning Electron Microscope Petrography

Freshly broken surfaces of rock chips from samples EAG12014 and EAG12032 were carbon-coated and examined using an FEI Quanta 450 FESEM (field emission gun scanning electron microscope) with an EDAX EDS (energy dispersive spectrometer) at Adelaide Microscopy, University of Adelaide (Australia). The analyses were conducted on the CO2 gas produced by acidification with 105% orthophosphoric acid at 70 °C. The sample isotopic ratios are expressed in the conventional delta (δ) notation relative to the Vienna PeeDee belemnite (VPDB) scale, following normalization to an in-house Carrara Marble calcite standard (NEW1) previously calibrated against international standard reference materials NBS19 and NBS18. Analytical uncertainty on the carbon (δ13C) and oxygen (δ18O) are ±0.05‰ and ±0.10‰, respectively.

K-Ar Dating

The analytical method for separating and dating the illite in the samples was described in detail in Zwingmann and Mancktelow (2004). Approximately 20 mg of sample material was required for argon analysis. During the study four HD-B1 standards (Hess and Lippolt, 1994) and airshot contamination, which strikes northwest-southeast, dips 50°, and has a top-to-the-northeast transport direction (Fig. 2) (Hansberry et al., 2014). All the sampled faults exhibit calcite mineralization with slickenfibers and, less frequently, tension gashes in the adjacent, more competent rock packages (Fig. 2). An extended description of each sample can be found in Table 1.

X-Ray Diffraction Analysis

X-ray diffraction of both orientated preparations and randomly oriented powders was used to characterize the mineralogy of each sample (Table 2). Samples were prepared following the recommendations of Kisch (1991) and diffraction patterns were collected using a Bruker D8 Advance X-ray diffractometer at the following instrument settings: CuKα radiation at 40 kV/40 mA; 0.6 mm divergence slit; 0.05 (2θ) step size, 1.5 s counting time. Diffraction patterns were collected from 3.5° to 45° 2θ. Semiquantitative mineralogy for comparison between samples was calculated from the weighted basal-peak method of Poppe et al. (2001), giving the ubiquitous phyllosilicate mineral assemblage (quartz) + illite ± kaolinite ± chlorite ± smectite (Table 2). An error margin of 5% is here suggested for these data.

Stable Isotope Analysis

Three samples of calcite veins and slickenfibers were taken from the slip surfaces of each of the six faults (Fig. 2A), providing three data points for each fault sample (Fig. 3). Sample powders were extracted from vein cements using a dental drill. Carbonate mineralogy (calcite) was confirmed by thin-section analysis; no dolomite was observed. Each sample was analyzed in duplicate using an Analytical Precision AP2003 continuous-flow isotope ratio mass spectrometer at the University of Melbourne (Australia). The analyses were conducted on the CO2 gas produced by acidification with 105% orthophosphoric acid at 70 °C. The sample isotopic ratios are expressed in the conventional delta (δ) notation relative to the Vienna PeeDee belemnite (VPDB) scale, following normalization to an in-house Carrara Marble calcite standard (NEW1) previously calibrated against international standard reference materials NBS19 and NBS18. Analytical uncertainty on the carbon (δ13C) and oxygen (δ18O) are ±0.05‰ and ±0.10‰, respectively.

TABLE 1. SAMPLE LOCATIONS AND DESCRIPTIONS

<table>
<thead>
<tr>
<th>Sample</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Quarry location*</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAG12014</td>
<td>14°38’27.9″</td>
<td>101°05’24.9″</td>
<td>shale quarry S</td>
<td>fault-gouge material directly above the eagle thrust</td>
</tr>
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<td>EAG12032</td>
<td>14°38’26.4″</td>
<td>101°05’25.4″</td>
<td>shale quarry S</td>
<td>fault-gouge material in 30–50 cm shear zone surrounding large, continuous fault</td>
</tr>
<tr>
<td>EAG12046</td>
<td>14°38’25.0″</td>
<td>101°05’24.5″</td>
<td>shale quarry S</td>
<td>host-rock and minor gouge material from discrete fault with thin (1–2 cm) shear zone</td>
</tr>
<tr>
<td>EAG12047</td>
<td>14°38’25.0″</td>
<td>101°05’24.5″</td>
<td>shale quarry S</td>
<td>host-gouge material from ~10–20 cm shear zone around fault</td>
</tr>
<tr>
<td>EAG12051</td>
<td>14°38’24.1″</td>
<td>101°05’24.8″</td>
<td>shale quarry S</td>
<td>host-rock and fault-gouge material from discrete fault with thin (3–10 cm) shear zone</td>
</tr>
<tr>
<td>EAG12055</td>
<td>14°38’06.4″</td>
<td>101°05’04.0″</td>
<td>mid-quarry thrust</td>
<td>heavily sheared shale and fault-gouge material in broad (to 1 m) shear zone</td>
</tr>
</tbody>
</table>

Note: Sample locations by global positioning system (World Geodetic System 1984).
*Shale quarry S—taken from exposure of the Sap Bon Formation fault damage zone.

TABLE 2. XRD AND STABLE ISOTOPE RESULTS

<table>
<thead>
<tr>
<th>Sample</th>
<th>Smeectite (%)</th>
<th>Illite (%)</th>
<th>Kaolinite (%)</th>
<th>Chlorite (%)</th>
<th>Chlorite Fe/Mg ratio</th>
<th>δ18O (VPDB)</th>
<th>δ13C (VPDB)</th>
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</thead>
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<td>EAG12014</td>
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<td>86</td>
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<td>10</td>
<td>0.86</td>
<td>−13.51</td>
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<tr>
<td>EAG12032</td>
<td>1</td>
<td>83</td>
<td>t</td>
<td>14</td>
<td>0.83</td>
<td>−11.41</td>
<td>−11.98</td>
</tr>
<tr>
<td>EAG12046</td>
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<td>69</td>
<td>t</td>
<td>29</td>
<td>1.00</td>
<td>−10.18</td>
<td>−9.44</td>
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<tr>
<td>EAG12047</td>
<td>4</td>
<td>81</td>
<td>t</td>
<td>15</td>
<td>0.95</td>
<td>−10.88</td>
<td>−10.90</td>
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<tr>
<td>EAG12051</td>
<td>6</td>
<td>72</td>
<td>t</td>
<td>19</td>
<td>1.00</td>
<td>−9.93</td>
<td>−10.01</td>
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<tr>
<td>EAG12055</td>
<td>1</td>
<td>93</td>
<td>7</td>
<td>0</td>
<td>N.D.</td>
<td>N.D.</td>
<td>N.D.</td>
</tr>
</tbody>
</table>

Note: VPDB—Vienna Peedee belemnite; N.D. indicates no data acquired.
* Determined by the method of Poppe et al. (2001), intended as relative estimates only; t indicates trace amount (<3%).
Constraining the timing of shale detachment faulting

RESULTS

Scanning Electron Microscope Petrography

SEM images of representative clay mineral sample assemblages are summarized in Figure 4. Figures 4A and 4B highlight the morphology and clay mineral mélange comprising what is interpreted to be mainly platy illite and chlorite. Both illite and chlorite crystallites indicate a strong preferred orientation and exhibit regular, euhedral boundaries (Figs. 4A, 4C). The hexagonal and prismatic morphologies of the illite and chlorite plates suggest in situ neocrystallization. Euhedral particle outlines are typical of an authigenic (or diagenetic) origin (Figs. 4C, 4E), in contrast to the more irregular or diffuse outlines characteristic of a detrital origin. EDS spectra confirm illite and chlorite mineralogy. Due to the intimate mixture of illite and chlorite, Fe and K peaks were used to distinguish the clay mineral phases.

Mineralogical Characterization of Clay Fractions by X-Ray Diffraction

All of the samples from shale quarry S contain chlorite (10%–29%); the sample from the overlying thrust imbricate to the southeast does not. All samples contain illite, as well as trace (4%–7%) amounts of smectite and kaolinite (Table 2). Results of RockJock (Eberl, 2003) full pattern-fitting software indicated that the majority of chlorite present in the five samples from shale quarry S is Fe chlorite, although samples EAG12047, EAG12032, and EAG12014 exhibit increasing amounts for Mg chlorite, from 5% to 17% of the total chlorite in each sample (Table 2).

Stable Isotopes

The δ¹⁸O values from carbon and oxygen stable isotopes analysis were used as a proxy for the relative temperature at which syntectonic calcite mineralization occurred along the five sample faults in shale quarry S (i.e., Warren et al., 2014; Hansberry et al., 2015). Three samples were taken from each fault sampled for K-Ar dating of illite, with δ¹⁸O VPDB values ranging from −13.51‰ to −9.01‰, while δ¹³C VPDB values range from 4.93‰ to 1.20‰.

K-Ar Dating

Six samples were dated by K-Ar analysis (Table 3). Samples from shale quarry S yield ages ranging from 262.1 ± 5.4 Ma (Permian, i.e., Guadalupian) to 225.1 ± 4.6 Ma (Late Triassic, i.e., Carnian–Norian). The sample from the mid-quarry thrust yield an age of 208.5 ± 4.4 Ma (Norian–Rhaetian; ages are referred to the time scale of Cohen et al., 2013). Radiogenic ⁴⁰Ar contents range from 92.0% to 95.1%, indicating reliable analytical conditions for all analyses with no significant atmospheric interference.

Table 3. K-Ar Radiogenic Dating Results

<table>
<thead>
<tr>
<th>Sample (≤2 µm)</th>
<th>K (%)</th>
<th>Radiogenic ⁴⁰Ar (mol/g)</th>
<th>Radiogenic ⁴⁰Ar (%)</th>
<th>Age (Ma)</th>
<th>Error (Ma)</th>
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<tbody>
<tr>
<td>EAG12014</td>
<td>4.67</td>
<td>1.9870E-099</td>
<td>94.1</td>
<td>230.0</td>
<td>4.6</td>
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<tr>
<td>EAG12032</td>
<td>4.86</td>
<td>2.0207E-099</td>
<td>95.1</td>
<td>225.1</td>
<td>4.6</td>
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<tr>
<td>EAG12046</td>
<td>3.86</td>
<td>1.8883E-099</td>
<td>93.7</td>
<td>262.1</td>
<td>5.4</td>
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<tr>
<td>EAG12047</td>
<td>4.38</td>
<td>1.9050E-099</td>
<td>93.4</td>
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<td>4.9</td>
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<td>EAG12051</td>
<td>3.07</td>
<td>1.3789E-099</td>
<td>94.8</td>
<td>242.0</td>
<td>5.1</td>
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<tr>
<td>EAG12055</td>
<td>5.24</td>
<td>2.0088E-099</td>
<td>92.0</td>
<td>208.5</td>
<td>4.4</td>
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Argon standard data

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>K (%)</th>
<th>Radiogenic ⁴⁰Ar (mol/g)</th>
<th>Radiogenic ⁴⁰Ar (%)</th>
<th>Age (Ma)</th>
<th>Error (Ma)</th>
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<tbody>
<tr>
<td>HD-B1-112</td>
<td>7.96</td>
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<td>93.69</td>
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<td>3.3357E-10</td>
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<td>24.01</td>
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<td>HD-B1-122</td>
<td>7.96</td>
<td>3.3607E-10</td>
<td>92.17</td>
<td>24.19</td>
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<td>HD-B1-123</td>
<td>7.96</td>
<td>3.3590E-10</td>
<td>92.07</td>
<td>24.18</td>
<td>0.37</td>
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Airshot data

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<th>Airshot ID</th>
<th>⁴⁰Ar/³⁶Ar</th>
<th>±</th>
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<tbody>
<tr>
<td>AS108-AirS-1</td>
<td>297.59</td>
<td>0.51</td>
</tr>
<tr>
<td>AS109-AirS-1</td>
<td>294.57</td>
<td>0.27</td>
</tr>
<tr>
<td>AS119-AirS-1</td>
<td>296.36</td>
<td>0.34</td>
</tr>
<tr>
<td>AS119-AirS-2</td>
<td>294.76</td>
<td>0.30</td>
</tr>
</tbody>
</table>

*Error to reference (Hess and Lippolt, 1994).
Relating K-Ar Ages to Geochemistry

It is well established that illite in shales is a mixture of the detrital polytype (2M1) with diagenetic illite (1M/1Md) precipitated from pore fluids (Pevear, 1999). The relatively smaller grain size of diagenetic 1M illite means that finer grain-size fractions typically exhibit a greater abundance of diagenetic illite and yield correspondingly younger K-Ar ages. Conversely, coarser fractions contain more detrital 2M1 illite, yielding older ages (Bailey et al., 1962; Pevear, 1999). The finest particle separates (<0.1–2 µm) contain material derived from the ends of filamentous grains and should, theoretically, represent the most recently grown, authigenic illite in gouge rocks. This is confirmed by numerous inclined illite age–grain-size spectra that show that the finest grain size fractions contain a greater proportion of authigenic (i.e., fault related) illite (1M/1Md) and produce the youngest age (Zwingmann et al., 2010; Viola et al., 2013; Torgersen et al., 2015). The potential presence of these three classes of illite illustrates the critical importance of identifying the origin of illite in shale-hosted fault-gouge material used for K-Ar dating. The ages of bulk mixtures of detrital, diagenetic, and authigenic illites yield dates that are essentially meaningless, unless the origin and relative abundance of illite can be constrained. Here we have constrained the origin of the analyzed illites by combining stable oxygen thermometry and trends in clay species abundance relative to measured K-Ar dates with observations of field relationships to assess the geological significance of the measured K-Ar ages and infer the likely timing of fault activation.

The X-ray diffraction patterns from oriented preparations were run as both air-dried and treated with ethylene glycol to highlight the presence of expandable smectite layers (e.g., Lanson et al., 2009). The occurrence of peaks in the glycol treated samples at 4.9–5.3 °2θ identifies the presence of smectite layers in mixed layers in all but one of the samples (EAG12014; Fig. 5). The five samples from the Eagle thrust damage zone generally show a decreasing quantity of smectite, and a less prominent increase in abundance as age decreases and relative temperature increases.

Relating K-Ar Ages to Paleothermometry Proxies

All five samples from the Eagle thrust damage zone show a consistent decrease in chlorite content with increasing age, while the sample from the overlying thrust imbricate contains no chlorite (EAG12055; Table 2). The majority of chlorite present in the five samples from the shale quarry S is Fe chlorite; however, the ratio of Fe chlorite to Mg chlorite decreases with K-Ar age, as well as relative temperature as indicated by the δ18O results (Fig. 6). Generally, Fe chlorites are considered to form at relatively low (diagenetic) temperatures while Mg chlorites are considered to be indicative of higher temperatures, and have been variously reported to begin forming from 130–165 to 220–290 °C (Weaver, 1989). Given that the increase of Mg:Fe ions in the chlorites is well correlated with the δ18O temperature proxy (Fig. 6), we interpret that the majority of the chlorites in the samples from shale quarry S are diagenetic, and decrease in abundance as age decreases and relative temperature increases due to increased dilution by authigenic illite. Data from illite crystallinity indicate a maximum deformation temperature range of 160–210 ± 20 °C.

DISCUSSION

The assumptions and limitations of K-Ar dating of fault-gouge material to constrain fault timing have been discussed elsewhere (e.g., Zwingmann and Mancktelow, 2004; Haines and van der Pluijm, 2008; Torgersen et al., 2014; Mancktelow et al., 2015). The method is most reliable in areas where the host rock does not contain mineralogy similar to the authigenic fault-gouge mineralogy, so that it is most commonly applied to studying the timing of fault reactivation in metamorphic and igneous host rocks (Zwingmann et al., 2010; Torgersen et al., 2015). The application of this technique in shales is complicated by the fact that the clay size fraction of the host rock can be expected to contain phyllosilicates (I/S, illite, muscovite), which can contaminate the fault-gouge material. It is therefore important when interpreting the age data obtained in this study to consider the likely effect of detrital and diagenetic illite components (Pevear, 1999).

40Ar contamination. K contents range from 3.07% for sample EAG12051 to 5.24% for sample EAG12055 <2 µm. The relatively high K content of most illite fractions is consistent with an authigenic origin. Variable K concentrations in the size fractions are caused by mixture with other mineral phases, such as quartz and chlorite (Table 2).

Figure 4. Scanning electron microscope images of clay mineral assemblages. For each identified mineral a spot energy dispersive spectrometer (EDS) spectrum is shown. (A) Illite and illite/chlorite (possibly a spot overlap or mixed layer) in sample EAG12032. (B–E) Progressively zoomed views of illite in sample EAG12014.
based on Kübler Index values of 0.45–0.36 corrected to the Crystallinity Index Standard of Warr and Rice (1994). This is consistent with the development of Mg chlorites during orogenesis (Hansberry et al., 2015). As temperature increases (Fig. 3; Table 2), the percentage of illite in the <2 µm fraction increases, diluting the relative percentage of chlorite and of mixed layer chlorite-illite-smectite.

An understanding of fluid-rock matrix interaction history can be useful to constrain the development of a fold-thrust belt (Wittschcho et al., 2009; Lacroix et al., 2014). Carbon and oxygen stable isotope data have been used to investigate the relative temperatures at which carbonates and vein cements precipitated, and to characterize the stage of burial, diageneosis, and/or orogenesis recorded (Lacroix et al., 2014; Warren et al., 2014; Hansberry et al., 2015). Recent work in the Saraburi Province (Warren et al., 2014), and in the Sap Bon Formation in particular, has defined a fluid–rock matrix interaction history and model of the structural and fluid-flow evolution of the upper level detachment zone (Hansberry et al., 2015). Diagenetic to late orogenic isotopic signatures were defined and the large continuous faults (and associated shear zones) were found to have acted as conduits for high-temperature orogenic fluids once matrix permeability had ceased (Hansberry et al., 2015). Samples of syntectonic calcite vein fills along these fault planes and immediately adjacent to dated fault-gouge material are plotted against age in Figure 3. Both δ¹³C and δ¹⁸O show a trend of increasingly negative isotopic signature with decreasing age. The transition from burial to orogenic conditions is reported as exhibiting temperatures equivalent to −10.00 to −12.00 δ¹⁸O, signatures that come exclusively from slickenfibers and vein fills along large faults (Warren et al., 2014; Hansberry et al., 2015). This trend of younger ages associated with orogenic temperatures may indicate that the younger ages from samples EAG12032, EAG12014, and EAG12047 reflect the age of authigenic illite formed in fault gouges during orogenic movement and formation of these faults (Fig. 4). It is uncertain whether the observed correlation between age and δ¹⁸O represents a kinematic effect of increased temperature-driven authigenic illite formation, or alteration and/or precipitation due to direct interaction with an orogenic fluid. However, local heating along the high-strain zones would be generated by orogenic (hydrothermal) fluid advection; these processes are likely to reflect similar geological processes and timing. The older ages from samples EAG12051 and EAG12046 are interpreted to represent a bulk mixture age with a smaller contribution by authigenic illite.

In summary, a greater abundance of Fe chlorites, a greater abundance of smectite, a smaller percentage of illite, and a less negative (cooler) δ¹⁸O association indicates that K-Ar ages measured on samples EAG12051 and in particular EAG12046 largely reflect 262.1 ± 5.4 to 242.0 ± 5.1 Ma detrital ages, whereas K-Ar ages of 230.0 ± 4.6 to 225.1 ± 4.6 Ma measured on samples EAG12014, EAG12032, and EAG12047 are likely to be deformation and/or faulting ages with only a minor contribution of detrital and/or diagenetic illite. The recent dating of detrital zircons in the Saraburi Group discussed in the following is consistent with and provides independent support for our interpretation (Fig. 7).

Impact on Constraining Local and Regional Geochronology

Arboit et al. (2016) used U-Pb ages and Hf isotopes of detrital zircons to better constrain the stratigraphy of the Saraburi Group, and to identify deposition into syntectonic basins as a consequence of Indosinian orogenesis into the Late Triassic. The maximum depositional age of the Sap Bon Formation in the Siam City cement quarry is constrained as middle Permian (275 ± 4 Ma). This is consistent with the interpretation that the 262.1 ± 5.4 Ma age of illite in sample EAG12046 is largely influenced by detrital illite. The foredeep basin (or series of basins) containing the Sap Bon Formation was

![Figure 5. X-ray diffractograms from orientated preparations of the six samples from 3.5° to 10° 2θ. Air-dried preparations are in black; runs on samples treated with ethylene glycol are dashed red. Peaks for smectite (17.3 Å), chlorite (14.2 Å), and illite (10.1 Å) are highlighted. VPDB—Vienna Peedee belemnite.](https://example.com/image)

![Figure 6. Plot of sample chlorite mineralogy vs oxygen stable isotope results. Upper x-axis displays the percentage of chlorite in the <2 µm fraction of the sample and the lower x-axis displays the ratio of Fe/Mg chlorite in that percentage.](https://example.com/image)
incorporated into the KKFTB by 240 Ma, placing this as the earliest likely age of growth of authigenic illite in fault zones (Fig. 7) (Arboit et al., 2016).

Incorporating the Arboit et al. (2016) detrital zircon data, which provide maximum depositional ages for synorogenic sedimentary basins, and the authigenic illite ages from this study, the main age of thrusting in the KKFTB occurred from ca. 250–240 Ma to 225 Ma. However, the Indosinian orogeny is a protracted event that encompasses a number of episodes of subduction and collision (e.g., Sone and Metcalfe, 2008; Metcalfe, 2013). Superimposed structures observed at a large scale from maps and satellite images, and from smaller scale field relationships (e.g., Morley et al., 2013; Arboit et al., 2014), coupled with paleostress determinations (Arboit et al., 2015) indicate that a number of thrusting and folding events associated with different maximum horizontal stress orientations (north-south, northwest-southeast, northeast-southwest) have affected the area. The timing of these events remains uncertain, and further authigenic illite studies have the potential to help unravel this issue.

An example of a later deformation episode is found 11 km east-northwest of Muak Lek. This area contains platform carbonates with well-developed coral and algal build-ups, as well as fore-reef slope deposits, that pass abruptly to the north into a shale-sandstone sequence interpreted as the Pang Asok (Permian) Formation (see review in Ueno and Charoentitirat, 2011). Stratigraphic relationships exposed in a quarried area indicated that the carbonates are a large (at least 500 m wide) slide block into the area of deeper water. This interpretation represents a completely new facet to the geological evolution of the area, but was initially reliant on detrital zircon data alone. The 208.5 ± 4.6 Ma age of illite in sample EAG12055 from the Siam cement quarry provides important support for this interpretation, as out-of-sequence thrusting only 11 km from the carbonate slide can be documented. Therefore it can be inferred that the younger phase of thrusting west-southwest of Muak Lek triggered sliding of a well-lithified carbonate block into the Rhaetian basin.

Until recently our understanding of the timing of deformation affecting the Indochina block in Thailand was reliant on relationships observed in outcrop around the margins of the Khorat Plateau, seismic reflection data, and wells that provided data on a deformed Permian–Triassic section beneath the Khorat Group (Booth and Sattayarak, 2011). Following the history from this area, it was assumed that thrusting and folding in KKFTB occurred below the Indosinian 1 event (Morley et al., 2013). However, the likely range of the Indosinian 1 unconformity could only be loosely placed between Ladinian and early Norian (i.e., ca. 238–215 Ma). New results from detrital zircon data (Arboit et al., 2016) and from the dating of authigenic illites in this study indicate that the early phase of thrusting and folding lasted until at least 225 Ma and that there was an additional younger Rhaetian phase of deformation. Evidence is now emerging that the Saraburi area differs significantly from the Khorat Plateau area in the timing of deformation, which reflects the closer proximity of the Khao Kwang fold-thrust belt to the western and southwestern Indochina plate margin compared with the Khorat Plateau area.

**CONCLUSIONS**

By relating the association of the K-Ar dates produced in this study to proxies and indicators of the stage of development (detrital, to diagenesis,
to orogenesis) of the fault damage zone of the Eagle thrust, we can conclude the following.

The youngest ages in shale quarry S (230.7 ± 4.6 to 223.7 ± 4.6 Ma) reflect the age of fault movement and illite formation. These youngest ages are associated with hotter (relative to the rest of the fault damage zone) orogenic fluid, high-temperature chlorites, less diagenetic chlorite and mixed-layer phyllosilicates, and a higher percentage of neocrystalline illite, all suggestive of higher maturity of clay mineralogy (Figs. 3–6).

We are currently consistent with the accepted age at which the basin containing the Sap Bon Formation was incorporated into the KKFTB.

Older dates (between 262.1 ± 5.4 and 242.0 ± 5.1 Ma) are likely to represent a bulk mixture age of the Sap Bon Formation, potentially consisting of orogenic illites, but also influenced by a diagenetic and detrital component. In particular, the oldest age, from sample EAG12046, of largely host-rock material, is consistent with the ca. 268 Ma age of deposition of the Sap Bon Formation.

The 208 ± 4.6 Ma illite age from the mid-ridge thrust in the Siam City cement quarry (Figs. 1 and 7) is in agreement with the age of deposition in syntectonic basins in the mid-northern KKFTB, suggesting ongoing, potentially out-of-sequence deformation, brittle fault movement, and authigenic illite growth in the Sap Bon Formation as late as the latest Triassic.

REFERENCES CITED


cogenic illite growth in the Sap Bon Formation as late as the latest Triassic.


Erratum to this article

Constraining the timing of shale detachment faulting: A geochemical approach

When this article was originally published, one author was inadvertently left out of the author list. Christopher K. Morley and his affiliation have now been added to the author list on the first page of the paper.