1 **Direct dating of folding events by $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of**
2 **synkinematic muscovite from flexural-slip planes**

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22 **Abstract**

23 Timing of folding is usually dated indirectly, with limited isotopic dating studies reported in
24 the literature. The present study investigated the timing of intracontinental, multi-stage folding in
25 Upper Proterozoic sandstone, limestone, and marble near Beijing, North China, and adjacent
26 regions. Detailed field investigations with microstructural, backscattered electron (BSE) images
27 and electron microprobe analyses indicate that authigenic muscovite and sericite crystallized

parallel to stretching lineations/striations or along thin flexural-slip surfaces, both developed during the complex deformation history of the study area, involving repeated compressional, extensional and strike-slip episodes. Muscovite/sericite separates from interlayer-slip surfaces along the limbs and from dilatant sites in the hinges of folded sandstones yield muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of ~158–159 Ma, whereas those from folded marble and limestone samples yield ages of 156 ± 1 Ma. Muscovite from thin flexural-slip planes on fold limbs and hinges yields ages within analytical error of ~155–165 Ma. Further muscovite samples collected from extensionally folded limestone and strike-slip drag folds yield younger ages of 128–125 Ma with well-defined plateaus. To assess the potential influence of the detrital mica component of the host rock on the age data, two additional muscovite samples were investigated, one from a folded upper Proterozoic–Cambrian sandstone outside the Western Hills of Beijing and one from a folded sandstone sampled 20 cm from folding-related slip planes. Muscovite separates from these samples yield significantly older ages of 575 ± 2 Ma and 587 ± 2 Ma, suggesting that the timing of folding can be directly determined using the $^{40}\text{Ar}/^{39}\text{Ar}$ method. This approach enables the identification and dating of distinct deformation events that occur during multi-stage regional folding. $^{40}\text{Ar}/^{39}\text{Ar}$ dating can be used to constrain the timing of muscovite and sericite growth at moderate to low temperatures (<400 °C) during folding, yielding well-defined plateau ages and thereby the age of deformation in the upper crust.

Keywords: Folding, muscovite, $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age, direct isotopic dating

1. Introduction

Folding is a common deformation mechanism whose effects can be observed at multiple scales (Fig.1). Folds typically develop in ductile environments and affect most rock types (Hudleston and Treagus, 2010). Direct dating of folding can assist the unraveling of complex strain paths within highly deformed regions. Various methods are thus routinely used to constrain

indirectly the age of folding, including the constraints provided by the age of the folded lithological sequences and the dating of igneous intrusions that cross-cut folded rocks of a known age, thereby bracketing the timing of folding (e.g. Fleet, 2003). These approaches, however, are often limited by significant uncertainties and become less applicable, because they depend on complete stratigraphic exposures or clear cross-cutting relationships that are often obscured or missing.

Several studies have shown that direct age constraints can be successfully obtained for deformation events by using a range of isotopic systems (e.g. Reddy and Potts, 1999; van der Pluijm et al., 2001; Zwingmann et al., 2010; Fitz-Díaz and van der Pluijm, 2013; Viola et al., 2013; Torgersen et al., 2015). Synkinematic minerals of the mica group are commonly the target of these isotopic analyses (e.g. Kligfield et al., 1986; Dunlap et al., 1991; West Jr and Lux, 1993; Sherlock et al., 2003). Ductile shear zones and brittle faults, for instance, have been dated by $^{40}\text{Ar}/^{39}\text{Ar}$ or K-Ar analyses of muscovite, biotite and K-feldspar (e.g. Dunlap et al., 1991; West Jr and Lux, 1993; Reddy and Potts, 1999; Torgersen et al., 2015), or by Rb/Sr dating of increments of fibrous strain fringes (Müller et al., 2000). However, depending on the closure temperature of the dated mineral and the temperature at the time of deformation (Dodson, 1973; McDougall and Harrison, 1999), the results may, in fact, be cooling ages (Dunlap, 1997), that can be significantly younger than the actual age of deformation.

In the case of folding, recent studies have dated directly fold formation by $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of neocrystallized minerals (illite and mica/sericite) formed authigenically along axial planar cleavage planes (Fig. 1B; e.g. Sherlock et al., 2003), and by dating illite grown within shale sheared parallel to bedding during flexural-slip folding (Fitz-Díaz and van der Pluijm, 2013; Fitz-Díaz et al., 2014a, b). This approach is challenging due primarily to the very fine grain size of the newly formed mica/sericite on the cleavage surfaces, and the possible overprint of later low-grade metamorphism due to younger deformation events (e.g. Kirschner et al., 1996; Clauer et al., 2012; Clauer et al., 2013).

Prior efforts have been made to use single mica grains to date cleavage formation, but this study proposes a different approach to constrain the timing of folding by dating synkinematic micas crystallized in situ along rock bed interfaces during flexural-slip folding of carbonaceous and sandy rocks or within dilational cracks formed in the outermost layers of the folds at the hinge zone (Fig. 1). Strain accommodation by slip along individual interlayers (Fig. 1A) is typical of flexural-slip folds developed at shallow levels in the upper to middle crust (van der Pluijm and Marshak, 2004) at temperatures of 200–350 °C (Fleet, 2003; Passchier and Trouw, 2005) or even as low as 80°C (Fitz-Díaz et al., 2014b and references therein), that is, at temperatures lower than the muscovite closure temperature of 400 ± 50 °C (Hames and Bowring, 1994) or 420 ± 50 °C, as refined by Harrison et al. (2009) for the $^{40}\text{Ar}/^{39}\text{Ar}$ system. However the closure temperature can be lower for grains smaller than 100 μm as discussed by Sherlock et al. (2003).

The folds analyzed in this study, located in North China (Fig. 2A and 2B), affect limestone and sandstone beds and formed at shallow crustal levels (depths of $< \sim 10$ km; Wang et al., 2011). The main phases of regional deformation, especially of compressional and extensional deformation, have been previously investigated by Wang et al. (2011).

In the present study, we carried out detailed structural mapping and microstructural analysis of the folded sequences (Fig. 2C and 2D) and subsequently analyzed synkinematic muscovite from flexural-slip surfaces between folded layers and from the hinges of folds that are kinematically linked to contractional, extensional, and strike-slip episodes (Figs 3 and 4). The results reported by Wang et al. (2011) summarize an initial overview of the regional tectonics of the study area. In contrast, the present study investigates selected fault zones to constrain the timing of folding in more detail. Therefore, we have integrated the new results with $^{40}\text{Ar}/^{39}\text{Ar}$ data from a previously published database (Wang et al., 2011) to further decipher and constrain the ages of the extension and compression in the study area.

2. Geological setting of the study area

The North China tectonic domain is part of the Sino-Korean craton (Ren et al., 1990) (Fig. 2A). On the north the craton is surrounded by the Central Asian orogenic belt and Qinling-Dabie orogenic belt on the south (Fig. 2A). Since 1.8 Ga, the craton has remained largely stable until the Triassic, when intense deformation along its margins started (Davis et al., 2001; Ratschbacher et al., 2003; Wang et al., 2013). The initial intracontinental deformation has been overprinted as a result of changes in the tectonic setting. The Yanshan tectonic belt and the Taihang tectono-magmatic belt in North China (Fig. 2A) are typical of E–W, NE–SW, and NNE–SSW-trending structural zones that have been overprinted by later tectonic events (Wang and Li, 2008; Wang et al., 2011) (Fig. 2B). In these regions, Archean to early Proterozoic crystalline basement and overlying middle–late Proterozoic to Ordovician sedimentary rocks (<10 km thick) have been intensively deformed, forming folds, thrusts, and strike-slip faults. In this study, we investigate and extend the timing and significance of these folds based on previous studies by Wang et al. (2011).

During the Triassic, the northern margin of the domain was reactivated (Zhou and Wang, 2012; Wang et al., 2013) and the southern margin was subducted beneath the Yangtze plate (Ratschbacher et al., 2003), forming the E–W-trending Qinling-Dabie orogenic belt (Fig. 2A). Subduction of the Paleo-Pacific plate beneath the eastern Asian continental margin began in the Middle to Late Jurassic (e.g., Bartolini and Larson, 2001; Wang and Li, 2008; Wang et al., 2011; Liu S. F. et al., 2013) and this tectonism formed basins, strike-slip faults, and extensional structures in the continental margin and interior of eastern China. These features have NE to NNE tectonic trends and record NW-vergent contraction, NW–SE extension, and later E–W extension. The structures vary between the eastern margin and the interior of the continent, although the kinematics are similar in both regions.

The investigated folded rocks in the study area comprise middle–late Proterozoic and Cambrian sandstone, limestone, dolomite, and claystone in the Western Hills of Beijing (Fig. 2C), North China. The rocks experienced an early N–S contractional phase (D1), present in pre-Upper

Triassic strata. Regional- to outcrop scale E-W trending folds are well exposed throughout the area and are associated with a steeply N-dipping axial plane cleavage. Small N-dipping thrusts commonly accompany the folds. D1 structures are overprinted by D2 NE-NNE-trending and WNW-verging folds and top-to-the-WNW thrusts. D3 inclined folds with axial planes dipping to ESE deform D2 folds and thrusts (Fig. 2C and 2D), and their kinematic analysis indicates a top-to-the-ESE extensional sense of shear, as constrained by asymmetries associated with an ESE-stretching lineation. Renewed compression was accommodated by a D4 shortening episode, which generated N-S-trending folds and W-vergent thrusts (Fig. 2C). Finally, D5-related high-angle brittle normal faults formed with a 45–55° dip to the ESE during the Mesozoic-Cenozoic (see Wang et al., 2011, for a detailed description of the deformation history).

3. Microstructural and textural features of synkinematic muscovite in flexural-slip folds

3.1. Context of synkinematic muscovite in the study area

In this study, selected folds document important regional tectonic features and can be clearly distinguished in the field. Constraining the timing of fold formation has significant regional geological implications, particularly with respect to determining absolute time differences between many different deformation phases. This study focuses mainly on recumbent and inclined asymmetric folds in the hanging wall and footwall of D2 NE-NNE-trending and WNW-vergent thrusts, as well as D3 folds (Fig. 2D). D2 folds generally have axial planes that dip to the SE or are sub-horizontal (Fig. 4A and 4C). A D2-related WNW-vergent fold (Fig. 3A) contains mica in the hinge area (Fig. 3B), with a crystal preferential alignment parallel to striations on the fold limbs, that track the interlayer flexural-slip direction perpendicular to the fold axis (Fig. 3C and 3D). The sampled D3-related ESE-directed extensional- (Fig. 4E) and strike-slip-related folds (Fig. 4G) deform sandstone, limestone, and marble beds, and contain abundant mica along the flexural-slip planes (Fig. 4F and 4H).

The muscovite mica has two possible origins: (a) detrital and (b) deformational. Detrital muscovite within the folded sandstone and shale sequences of the Western Hills area is generally fine grained ($<3\text{--}20\text{ }\mu\text{m}$). As the muscovite grains are deformed and large ($>100\text{ }\mu\text{m}$), they are interpreted to be of synkinematic and authigenic origin formed during folding. Synkinematic mica was observed along discrete flexural-slip planes, generally thinner than $0.3\text{--}5.0\text{ mm}$, where muscovite is aligned parallel to the stretching lineation/striation (Fig. 3C–E) along with quartz and phlogopite. The corresponding foliation planes are defined by the phyllosilicates including the muscovite, creating a continuous schistosity at the thin-section scale.

3.2. *Microstructures of muscovite and sericite*

Despite occurring in different tectonic regimes, contractional (D2), extensional (D3), and strike-slip-related folds (D3) contain authigenic muscovite, sericite, and phlogopite (Figs 3 and 4). Recrystallized calcite is oriented parallel to bedding along with muscovite, sericite, and phlogopite (Fig. 5A, 5C, and 5E). Locally, quartz and muscovite are formed together (Fig. 5A and 5D). Quartz forms the background matrix to parallel muscovite grains (e.g. Figs 3E and 5B). Micas show no evidence of dynamic recrystallization. Quartz shows in some thin sections polygonal textures (Figs 5–6), which may indicate annealing during static recrystallization at middle to lower temperature range. Thin-section analysis indicate that muscovite and phlogopite grains are orientated along the flexural-slip planes of folds, and also parallel to the foliation and stretching lineation, suggesting that these minerals formed at the same time during deformation.

Muscovite, sericite and kaolinite typically formed at the interface between deformed limestone and sandstone facies (Fig. 5B). Noteworthy also is that some sedimentary layers are deformed and metamorphosed, showing no signs of muscovite or quartz recrystallization (Fig. 5F). Very fine-grained and irregularly shaped muscovite crystals occur locally in some folded sandstone and shale layers (oriented perpendicular to flexural slip planes), but are unrelated to folding (Fig. 5G and 5H).

The grains that were utilized for $^{40}\text{Ar}/^{39}\text{Ar}$ dating were sampled by gentle crushing in an agate mortar and hand-picking under a binocular microscope. We interpreted that muscovite grains within the sandstone layers, along fracture zones and between syndepositional quartz and feldspar grains with sizes $<10\text{--}15\text{ }\mu\text{m}$ were not formed during folding and hence, were not considered for analysis. Two criteria were used to verify that muscovite grains from sampled folds are synkinematic and could therefore be used to constrain the timing of folding by $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating analysis: (1) muscovite flakes are parallel to the local stretching direction, which tracks the slip between contiguous beds, at a high or orthogonal angle to the fold axis, and were located within planes of flexural slip (see Fig. 3C-D, Fig. 4E-G and Fig. 7); and (2) muscovite flakes are larger than $100\text{--}120\text{ }\mu\text{m}$ and located in thin planes of flexural slip ($<0.3\text{--}5.0\text{ mm}$).

3.3. Back-scattered electron images

Microstructural analyses using backscattered electron (BSE) images indicate that the synkinematic muscovite occurs as generally undeformed sheets or platelets without kinks (Wilson and Bell, 1979), fractures, or pervasive undulose extinction. Petrographic investigation by optical microscopy and BSE indicate that muscovite grains form thin layers ($>20\text{--}30\text{ }\mu\text{m}$) along the gliding plane between adjacent bedding layers.

BSE images showed a variety of muscovite types with slaby, flaky and fine-flaky structures (Fig. 6). Most muscovite flakes are parallel to the foliation (Fig. 6A, 6C, 6G and 6H), but some are also found mixed with calcite or quartz grains with no preferred orientation (Fig. 6E and 6F).

3.4. Mica composition: analytical methods and results

Quantitative analysis of rock-forming minerals was conducted (Table 1, Fig. 6) using an electron microprobe (EMP) with a 15 kV accelerating voltage, a 10 nA beam current and a $1\text{ }\mu\text{m}$ beam size at the China University of Geosciences (Beijing), China. Data about muscovite and phlogopite Al^{IV} (Table 1), along with Si of $\sim 2.9\text{--}3.3$, indicate that no phengite is present. In

addition, the EMP analyses indicate presence of K_2O and Al_2O_3 in clay minerals within the marbles. The presence of K_2O and Al_2O_3 -rich clays represent important precursor mineral sources for synkinematic muscovite.

3.5. Sampling synkinematic muscovite in folds

Muscovite is generally not affected by weathering processes, but its anisotropy allows it to be easily dissolved and reprecipitated above 400 °C during deformation (Passchier and Trouw, 2005). Thus, muscovite is found commonly in rocks that have experienced deformation at temperatures greater than 400 °C. In such rocks, muscovites are commonly deformed by micro-folds and kinks. Muscovite dated in this study shows no evidence of kinking (Fig. 4B, 4D, 4F, 4H, Fig. 5A-D, Fig. 6B), undulose extinction resulting from deformation, or subgrain formation in SEM and BSE images (Fig. 5, Fig. 6A-F). In addition, there are no broken grains or fine grains of muscovite, quartz or calcite that would be expected to have formed during late-stage deformation. The presence of superimposed folds deforming older structures in some of the investigated outcrops required careful sampling based on field relationships and microstructural observations (SEM, BSE, and X-ray or electron-probe analyses) to identify the suitable mineral phases for ^{40}Ar - ^{39}Ar age dating.

4. Temperature during deformation and authigenesis of white mica

Temperature-sensitive quartz and calcite microstructures can constrain temperature ranges during rock deformation (Ferrill, 1991; Kruhl, 1996; Stipp et al., 2002; Passchier and Trouw, 2005). Calcite twins are commonly reported in the literature to assess the extent of deformation or the metamorphic temperature (e.g. Ferrill et al., 2004; Bucher and Grapes, 2011; Molli et al., 2011). Calcite twinning occurs at relatively low temperatures (<300 °C) during deformation (Passchier and Trouw, 2005). At elevated temperatures, twin boundaries can bulge, except where they are confined by grain boundaries or other crosscutting twins. Calcite twins can, therefore, be

used as indicators of temperature, strain and stress (e.g. Ferrill, 1991; Weber et al., 2001; Ferrill et al., 2004; Craddock et al., 2007). We applied calcite-twin morphology as an independent control to evaluate temperatures during deformation, in particular the temperature range at which muscovite, sericite and phlogopite formed in the deformed host rocks.

Three types of deformation twins were observed. Along deformed grain margins, narrow (<1 μm wide) straight twins occur in calcite (Fig. 8A), indicating temperatures of <200 $^{\circ}\text{C}$, mainly <170 $^{\circ}\text{C}$ (Rowe and Rutter, 1990; Evans and Dunne, 1991; Ferrill et al., 2004). Wider twins also occur (>1 μm ; Fig. 8A–C), indicating temperatures of >200 $^{\circ}\text{C}$, even up to 300 $^{\circ}\text{C}$ (Groshong Jr et al., 1984; Rowe and Rutter, 1990; Evans and Dunne, 1991). Deformed and recrystallized calcite indicates temperatures of >200 $^{\circ}\text{C}$ where intersecting and bent twins are present (Fig. 8D and 8E). At temperatures >250 $^{\circ}\text{C}$, twins develop serrated boundaries due to twin boundary migration as a result of recrystallization (Fig. 8F). Some samples contain calcite grains with distinct tabular twins, indicating temperatures of 200–300 $^{\circ}\text{C}$ (Fig. 8A–E) but most grains contain common wider twins, suggesting temperatures of <300 $^{\circ}\text{C}$. Complete dynamic recrystallization of calcite may occur at temperatures above 300 $^{\circ}\text{C}$ (Evans and Dunne, 1991; Weber et al., 2001). No high temperature >400 $^{\circ}\text{C}$ twins with dynamic recrystallization features as discussed by Ferrill et al. (2004) could be identified in the investigated samples indicating temperature during deformation to be <300 $^{\circ}\text{C}$.

Calcite twin thermometry is not a definitive indicator of temperature, especially at the low temperatures proposed in this study. In addition to the use of calcite twins as temperature gauges, we investigated quartz microfabrics as a supplementary microstructural criteria. In the study region, only a few samples with appropriate quartz microfabrics (Schmid and Casey, 1986; Passchier and Trouw, 2005) were observed. Samples that contain recrystallized quartz consist of a finely layered matrix with muscovite grains (Fig. 7E and 7F).

Six samples containing recrystallized quartz displaying irregular grain boundaries and undulose extinction patterns were analyzed by Electron Backscattered Diffraction (EBSD). XZ

sections (i.e., oriented parallel to the lineation and normal to the foliation) were prepared from the samples. EBSD analysis was conducted at the China University of Geosciences (Beijing), China. The analytical procedures are described by Liu et al. (2012). Two types of quartz c-axes fabric were observed: samples wys-152 and wys-153 display point maxima between the X and Z axes (Fig. 9A-B), while samples wys-142, ys-108, wys-154 and wys-360-1 display quadrant maxima between the X and Z axes (Fig. 9C-F). Both of the fabric types are indicative of basal <a> slip at low temperatures (<400 °C) and non-coaxial deformation (Schmid and Casey, 1986; Kruhl, 1996; Stipp et al., 2002). Consequently, the available calcite and quartz microfabrics are consistent with deformation-related microstructural suites forming at less than 400 °C.

5. Dating Method and Analytical Results

The $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating technique was applied in this study to date synkinematic muscovite separates from 11 samples. Within this study four new muscovite data (ym-68, ym-71, wys-408 and wys-409) were obtained and reported in combination with previous data obtained by Wang et al. (2011). Nine samples were analyzed using a MM-5400 micromass spectrometer at the China University of Geosciences (Beijing), China. The ages were calculated using the ISOPLOT 2.31 program (Ludwig, 2000). Two samples (ym-68 and ym-71) from this study were analyzed at the National Taiwan University, Taipei, using a VG 1200S mass spectrometer equipped with a double vacuum Mo furnace, and age data were calculated using the ArArCALC program (Koppers, 2002). Details of the analytical procedures are in Lo et al. (2002), Wang and Li (2008) and Wang et al. (2011). Analytical results of the $^{40}\text{Ar}/^{39}\text{Ar}$ measurements completed here (Table 2 and data repository) are plotted as age spectra and in isotope correlation diagrams (Fig. 10).

Three muscovite/sericite separates (ys-107, ys-108 and wys-94) were previously collected from interlayer-slip surfaces along the limbs and within the hinge areas of D2 recumbently folded sandstone layers (Table 2; Figs 2C, 2D, 3 and 4; Wang and Li, 2008; Wang et al., 2011). Two samples yielded muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of ~158–159 Ma, similar to their isochron ages,

with a $^{40}\text{Ar}/^{36}\text{Ar}$ intercept of ~ 295.5 Ma, indicating no ^{40}Ar loss or excess. The K/Ca ratios and plots are flat, and the K/Ca ratios do not fluctuate at lower- or higher-temperature steps. Two further muscovite samples (wys-146 and wys-153) from flexural-slip surfaces along the D2 limbs and hinges of folded marble and limestone layers (Fig. 4A and 4C, respectively), yield a similar $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of 156 ± 1 Ma (Wang et al., 2011). The $^{40}\text{Ar}/^{36}\text{Ar}$ intercept and K/Ca ratios show no ^{40}Ar loss or excess. In summary, muscovite previously collected from thin planes of flexural-slip surfaces on folds limbs and hinges yields homogenous age data.

Two muscovite samples (ys-104 and wys-92) were collected from a D3 folded limestone layer affected by extension along low-angle detachment faults. Both yield similar $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of 128–125 Ma (Wang et al., 2011) (Table 2). They are well-defined plateaus lacking saddle- or hump-shaped spectra, with no ^{40}Ar loss or excess. These ages are well within the established ages of this regional extensional event for this part of China (Lin et al., 2011; Wang et al., 2011; Liu J. L. et al., 2013).

Two muscovite samples (ym-68 and ym-71) collected for this study from folded marble in a strike-slip belt (Fig. 2B) yield $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of 128 ± 1 and 134 ± 2 Ma, respectively (Table 2 and data repository 2). Sample ym-68, which is located closer (~ 20 cm) to the strike-slip fault zone, yields the younger age. The $^{40}\text{Ar}/^{36}\text{Ar}$ intercept and K/Ca ratios likewise show no signs of ^{40}Ar loss or excess (Fig. 10C and 10D).

For further comparison, two additional muscovite samples (wys-408 and wys-409; Table 2 and data repository 1) were collected from an upper Proterozoic–Cambrian sandstone located outside the northeastern extension of the Western Hills of Beijing (Fig. 2B). These samples are affected by the ~ 155 – 160 Ma NW-vergent inclined folding (D2) event and were investigated to complement the previous age data set within a regional geological context (Figs. 2B, 5G-H). These muscovite separates are from folded sandstone layers rather than from slip planes and yield older ages of 575 ± 2 Ma and 587 ± 2 Ma, probably indicating a detrital component in the sediment.

6. Discussion

6.1. Factors controlling authigenesis of mica during folding

Grain dissolution can occur along interlayer gliding planes or planes of flexural slip, and by plastic deformation of individual mineral grains during fold formation, provided the environmental conditions are suitable for crystal plasticity (Fleet, 2003; van der Pluijm and Marshak, 2004). Interlayer strain, inter-grain sliding and dissolution, especially linked to fluid-assisted processes in clay-rich rocks (Mares and Kronenberg, 1993; Fleet, 2003), can lead to muscovite/sericite formation along flexural-slip planes.

6.1.1. Controls of tectonic stress and strain during folding

Authigenesis of muscovite, sericite and phlogopite occurs in low- to medium-temperature host rocks below the closure temperature of muscovite/phengite (~420 °C; Harrison et al., 2009). Orientation of these minerals parallel to the lineation or foliation indicates that their crystallization takes place under dynamic conditions and associated with fluid flow (Evans and Elmore, 2006; Evans and Fischer, 2012). In this study, strain accommodation resulted in localized dilation (Figs 3, 4, and 6A, C, F, H), allowing new phases to form parallel to the lineations/striations along flexural-slip planes and in fold hinges. Crystallization temperatures for muscovite and sericite were similar to the blocking temperature of the $^{40}\text{Ar}/^{39}\text{Ar}$ system.

Thin section observations suggest variable thickness of synkinematic growth of muscovite, phlogopite, sericite, calcite and quartz within the deformed layers (Figs 5A-E and 8). However, no textural evidence is found for the formation of synkinematic micas away from flexural-slip planes, irrespective of the thickness of the sedimentary layers (Fig. 5F-H). As muscovite crystals were separated by hand-picking fine-grained K-rich clay mineral phases such as illite in the separates were absent and did not induce ^{40}Ar recoil during irradiation for the $^{40}\text{Ar}/^{39}\text{Ar}$ dating procedure, which would have resulted in older or mixed ages caused by mixtures of authigenic and detrital minerals (Fitz-Díaz and van der Pluijm, 2013).

6.1.2. Fluid flow during deformation

Fluids play a key role in the deformation of carbonate sequences, both physically and chemically, as well as in the transformation of mudstone to slate with the accompanying deformation (Evans and Elmore, 2006; Sherlock et al., 2008; Fitz-Díaz et al., 2011; Molli et al., 2011; Evans and Fischer, 2012). During the formation of muscovite that accompanies the deformation of carbonate, sandstone, and claystone, fluids are important for the transfer of K^+ , Si^{4+} , Al^{3+} , and other ions.

In this study, calcite veins but no quartz veins could be observed, suggesting that limited, medium to high temperature thermal fluids entered the rock system. With temperature and tectonic regime being the main drivers of coupled fluid flow and water–rock interactions, low temperatures during deformation suggest that the authigenic muscovite and sericite formation does not relate to the classical cooling model of $^{40}Ar/^{39}Ar$ dating. Ages of minerals that form at medium–high temperatures (i.e., exceeding the $^{40}Ar/^{39}Ar$ closure temperature) are interpreted as cooling ages (Forster and Lister, 2004; Beltrando et al., 2009; Harrison et al., 2009; Warren et al., 2012a, b). Furthermore, evidence of feldspar or phengite authigenesis during folding is lacking, which implies that deformation temperature was low to moderate ($<350\text{ }^{\circ}C$) for the D2 and D3 fold-related deformation with the concomitant formation of slip-related muscovite grains in this study.

6.2. Tectonic implications

Synkinematic muscovite grains can date folding events if the following conditions are met: (a) the muscovite grains occur in structural locations such as flexural-slip surfaces or in fold hinges; (b) temperatures during folding were equal to or lower than the closure temperature of the $^{40}Ar/^{39}Ar$ system in K-white mica; and (c) the muscovite grains show a textural relationship to the deformation kinematics and are unrelated to diagenesis. All of these conditions were met in the

present study enabling us to constrain the timing of folds from two different deformation phases that met these conditions. This approach to dating fold events is applicable to other orogenic belts and intracontinental tectonic domains where these three conditions are met and synkinematic muscovites are present in the targeted folds.

The $^{40}\text{Ar}/^{39}\text{Ar}$ ages of the NW-vergent folding phase (D2) of ~155–165 Ma constrained here by new muscovite and sericite $^{40}\text{Ar}/^{39}\text{Ar}$ ages from kinematically and geometrically associated NW-vergent thrust faults are consistent with independent regional geological constraints (Davis et al., 2001; Wang et al., 2011; Liu S. F. et al., 2013; Figs 2D and 11). In the regional geological context, syn-tectonic granitic and diabase dykes oriented parallel to fold axial planes and axial planar cleavage yield zircon U–Pb ages of 160–163 Ma that are similar to the $^{40}\text{Ar}/^{39}\text{Ar}$ ages obtained in this study for muscovite separates of folds related to D2 (Fig. 11). The later extensional episode (D3) affecting the Western Hills of Beijing is in an age range similar to zircon U–Pb ages of 128–130 Ma in granite dykes (Wang et al., 2011; Figs 2 and 11).

Multi-stage folding can be investigated by examining fold hinges, slip layers, and fold limbs, regardless of whether the fold is developing in a contractional, extensional or strike-slip setting. The isotopic dating of folding offers a new approach to constrain the timing of regional tectonic events, as low-temperature minerals that grow during folding in shallow crustal deformation environments, including multiple phases of deformation. At shallow crustal levels (<10 km), cooling ages can be obtained for plutons and dykes, and cooling generally occurs at lower temperatures than folding or thermal events, which can disturb or reset the $^{40}\text{Ar}/^{39}\text{Ar}$ systematics of muscovite and sericite minerals (Forster and Lister, 2004). However, the direct dating of folds yields the timing of deformation and offers an additional approach to constrain the age of tectonic events.

7. Conclusion

$^{40}\text{Ar}/^{39}\text{Ar}$ dating of synkinematic muscovite sampled along discrete flexural-slip surfaces

can be applied to constrain the age of folding. The method can be applied if the following conditions are met: (1) Careful separation and analysis of authigenic muscovite grown during folding, regardless of rock type; (2) Muscovite crystals sampled from flexural slip surfaces that extend parallel to the local striation/stretching lineation, that is perpendicular or at high angle to the fold axis; and (3) Deformation temperature is lower than or equal to the Ar-closure temperature of muscovite. Provided these prerequisites are met, the $^{40}\text{Ar}/^{39}\text{Ar}$ method offers a suitable method for unraveling complex deformation histories.

In this case study, muscovite/sericite samples from interlayer-slip surfaces along the limbs and within the hinge areas of folded sandstones at the Western Hills of Beijing in North China yield muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of ~158–159 Ma, whereas those of the folded marble and limestone yield ages of 156 ± 1 Ma. In the same region, muscovite samples collected from extensional folds within limestones generally assigned to a later extensional phase, yield younger ages of 128–125 Ma with well-defined plateaus. Muscovite grains from unfolded equivalent rocks yield older $^{40}\text{Ar}/^{39}\text{Ar}$ ages of about 580 Ma. $^{40}\text{Ar}/^{39}\text{Ar}$ fold dating offers a new approach to constrain the timing of events in areas affected by multi-stage folding low-temperature deformation, and where the growth of authigenic muscovite and sericite grains occurred during folding. Such age data provide precise information on the timing of tectonic events in intracontinental and orogenic belts.

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586

Figure Captions

Figure 1. Fold formed by flexural slip during muscovite growth in the cleavage and fractured regions of the fold hinge. Along a flexural-slip surface, muscovite is oriented parallel to the stretching lineation. (A) Flexural-slip planes and fractures in the hinge area with muscovite/sericite formation. (B) Cleavage parallel to fold axial planes and formation of sericite or illite.

Figure 2. Simplified regional geology of the study area. (A) Tectonic provinces and major faults of eastern part of North China, (B) Geology of northern part of eastern China, (C) Fault and fold distributions in the Western Hills of Beijing (after Wang et al., 2011), and (D) a simplified structural cross-section. Also shown are muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages, interpreted to represent the timing of folding. X-C– Xiayunling–Changcao Thrust Fault; H– Huangshandian Thrust Fault; CAO– Central Asian orogenic belt; NCC– North China Craton. Locations of Figures 3A, 4A, 4C, 4E and 4G are shown. In the figure, D1-D5 indicates deformation events.

Figure 3. Muscovite collected from fold limbs and hinge areas of a D2 contractional recumbent fold in the Western Hills of Beijing. The fold is WNW-vergent with a sub-horizontal axial plane (A) and deformed a Proterozoic sandstone. Also shown are deformation in the hinge area (B), flexural-slip structures on a fold limb with a stretching lineation (C), muscovite-oriented parallel to the stretching lineation (D), and a photomicrograph (E) and BSE images (F) of muscovite along a flexural-slip surface. Age data are from Wang et al. (2011). The thin section was cut parallel to the lineation and normal to the foliation. Ms– muscovite; Qz– quartz. Inset equal-area lower hemisphere stereonet shows: (1) the stretching lineation on the flexural-slip surface of the WNW-vergent recumbent fold, and (2) foliation associated with the WNW-vergent recumbent fold.

Figure 4. Typical contractional inclined folds developed in limestone–marble (sample wys-146)

(A) and marble (sample wys-153) (C), with accompanying photomicrographs (B and D). (E) extensional fold developed in schist-marble (sample wys-92) with accompanying photomicrographs (F), and (G) a drag fold in a strike-slip zone in limestone-marble (samples ym-68 and ym-71) with accompanying photomicrographs (H). All thin sections are parallel to the aggregate lineation and normal to the foliation. Age data in Figure A, C, and E are from Wang et al. (2011) and in Figure G from this study. Cal- calcite; Ms- muscovite; Qz- quartz; R. Qz- recrystallized quartz. Inset equal-area lower hemisphere stereonet show (1) a foliation related to NW-vergent contraction, and (2) a lineation related to NW-SE extension.

Figure 5. Photomicrographs of microstructures in muscovite, sericite, and phlogopite. The thin section is parallel to an aggregate lineation and normal to the foliation. (A) New-growth muscovite is oriented parallel to the quartz grains. Some areas contain calcite with no quartz or muscovite (top left corner). The boundary between deformed and undeformed layers is sharp. (B) Muscovite and sericite formed between layers of limestone and sandstone. (C) Muscovite formed along a zone where larger calcite grains also formed together with quartz. (D) Muscovite formed along the foliation. (E) Muscovite formed between calcite clusters. (F) Deformed marble lacking muscovite. (G) Detrital muscovite in sandstone (sample wys-408). (H) Detrital muscovite in sandstone (sample wys-409). Cal- calcite; Ms- muscovite; Qz- quartz; R. Qz- recrystallized quartz.

Figure 6. BSE images showing different types of muscovite that formed during folding. (A) Slabby muscovite. (B) Deformed calcite layers lacking any muscovite, with the growth of muscovite restricted to thin deformed layers. (C) Muscovite grains parallel to the foliation. (D) Large grains of muscovite that formed together with quartz. (E) Muscovite grains without preferred orientation. (F) Parallel muscovite grains with other muscovite grains with a variety of orientations. (G) Very fine-grained muscovite parallel to the foliation. (H) Muscovite that parallel and sub-parallel to the foliation. (I) Deformed muscovite, showing the late-stage overprinting

deformation. Cal– calcite; Lm– limonite; Ms– muscovite; Qz– quartz.

Figure 7. Photomicrographs showing the various minerals in limestone, dolomite, and sandstone. (A) Limestone adjacent to flexural-slip plane containing muscovite, calcite, and recrystallized quartz. Clear boundary between limestone (calcite) and deformed layers that contain muscovite. (B) Muscovite together with quartz, calcite, chlorite, etc. (C) Muscovite and sericite formed between sandstone and clay-rich areas and limestone. (D) Sandstone with calcite and clay minerals. Muscovite also formed in this type of deformed sandstone. (E) Recrystallized quartz formed together with calcite. Muscovite also formed parallel to the foliation. (F) Muscovite formed together with recrystallized quartz. Cal– calcite; Ms– muscovite; Qz– quartz; R. Qz– recrystallized quartz.

Figure 8. Photomicrographs of calcite deformation twins that formed during folding. Thin sections are parallel to the slip direction for flexural slip and normal to the foliation. (A) Thin (I-type) and wider (II-type) calcite twins and deformed calcite. (B) Wider calcite twins that formed together with new growths of muscovite and quartz. (C) Wider calcite twins and their deformational features, and quartz and muscovite that formed together. (D) Wider tabular calcite twins (III-type). (E) Wider and slightly curved calcite twins. (F) Deformed calcite grains and calcite twins. No large grains of muscovite are present. Ms– muscovite, I– thin calcite twins, II– wider calcite twins, III– wider tabular calcite twins.

Figure 9. Quartz c-axis fabrics. (A–B) Fabrics defined by point maxima near Z between the X and Z axes. (C–F) Fabrics defined by quadrant maxima between the X and Z axes. Sample wys-360-1 was collected from a strike-slip drag fold. Other samples were collected from NW-vergent contraction folds. Samples were cut parallel to the slip direction and normal to the foliation.

Figure 10. Six muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ spectra and isochron plots. (A) Sample wys-94 was collected from a contractional recumbent fold on the hanging wall of the Huangshandian thrust fault (D2) (Wang et al., 2011). (B) Sample ys-104 was collected from an extensional fold (D3) on the hanging wall of the Xiayunling–Changcao thrust fault (Wang et al., 2011). (C and D) Samples ym-68 and ym-71 were collected from a strike-slip-related drag fold (D3; dating in this study). (E and F) Samples wys-408 and wys-409 were collected from within folded sandstone layers, away from slip planes (dating in this study). Other spectra and isochron plots are provided in the data repository in Wang et al. (2011). Ms – muscovite.

Figure 11. Summary figure and comparison of all age data from the host rocks and earlier deformation ages from the literature, and new data with the fold ages. Host rock ages and collected deformation/cooling/synkinematic intrusion age data are from 1) Wang et al., 2011; 2) Wang et al., 2013; and 3) Beijing Institute of Geological Survey, 2001. Ages derived from folds associated kinematically with the later extensional episode range from 128 to 130 Ma (U–Pb zircon dating of granite dykes). Fold dating data in this study are also shown as error bars. D1-D3 deformation stages are marked.

Figure 1

Figure 2A-B

Figure 2C-D

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

(A) contractional fold (D2)

(B) extensional fold (D3)

(C) strike-slip dragged fold

(D) strike-slip dragged fold

(E) sandstone layers (detrital muscovite)

(F) sandstone layers (detrital muscovite)

Figure 10

Figure 11

Table 1

Table 1 Electron probe analysis on the samples collected from the folded limestone, sandstone and marble

Sample numbers	Minerals	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	F	Total	Si	Al ^{IV}
wys-154-1-1	Phl	43.38	0.46	14.43	0.68	0.03	26.12	0.19	0.24	10.47	2.32	98.32	2.9225	1.0775
wys-154-1-2	Phl	42.62	0.57	13.92	0.53	0.02	25.91	0.02	0.28	10.12	2.66	96.65	2.9165	1.0835
wys-154-1-3	Ms	51.17	1.22	27.41	0.15	-	4.74	0.30	0.35	11.21	-	96.55	3.3577	0.6423
wys-154-1-4	Ms	50.13	1.44	28.25	0.16	-	4.34	0.36	0.38	11.13	-	96.19	3.3054	0.6946
wys-154-2-1	Phl	43.41	0.53	13.84	0.62	0.04	25.94	0.07	0.25	9.83	2.24	96.77	2.9579	1.0421
wys-154-2-2	Phl	42.61	0.62	14.08	0.74	0.11	25.36	0.27	0.21	10.15	2.41	96.56	2.9232	1.0768
wys-154-2-3	Ms	50.76	1.17	27.69	0.12	-	4.56	0.33	0.31	9.56	-	94.50	3.3660	0.6340
wys-154-2-4	Ms	50.33	1.17	27.12	0.04	0.05	4.65	0.34	0.36	11.02	-	95.08	3.3530	0.6470
wys-154-2-5	Ms	50.20	1.37	27.59	0.16	0.03	4.54	0.32	0.38	10.96	-	95.55	3.3292	0.6708
ys-1-1-1	Ms	49.39	1.24	27.36	2.23	0.01	3.42	0.59	0.42	9.79	-	94.45	3.3276	0.6724
ys-1-1-2	Ms	49.05	1.27	28.48	2.14	0.01	3.21	0.55	0.58	10.11	-	95.40	3.2791	0.7209
ys-1-1-3	Ms	50.24	0.98	26.86	2.41	0.00	3.56	0.35	0.42	10.07	-	94.89	3.3704	0.6296
ys-1-2-1	Ms	48.70	1.28	27.75	2.33	0.15	3.29	0.42	0.44	9.94	-	94.30	3.2950	0.7050
ys-1-2-3	Ms	49.07	1.15	28.23	1.99	0.06	3.28	0.53	0.49	9.74	-	94.54	3.2986	0.7014
wys-142-1-1	Ms	48.47	1.17	31.77	0.21	-	3.12	0.04	1.02	10.02	-	95.82	3.1904	0.8096
wys-142-1-2	Ms	48.03	1.16	33.29	0.08	-	1.95		1.20	10.06	-	95.77	3.1597	0.8403
wys-142-1-3	Ms	48.02	1.10	32.07	0.22	-	2.31	0.09	1.03	10.46	-	95.30	3.1862	0.8138
wys-142-1-5	Phl	42.15	0.49	16.04	1.05	-	25.10	0.07	0.57	9.46	1.43	96.36	2.8868	1.1132
wys-149-1-2	Ms	47.33	0.39	34.03	1.00	0.04	0.77	-	1.05	10.25	-	94.86	3.1557	0.8443
wys-149-1-3	Ms	47.49	0.29	34.81	0.95	0.01	0.61	-	1.27	10.00	-	95.43	3.1417	0.8583
wys-149-1-5	Ms	54.44	0.33	29.80	0.79	-	0.66	0.00	0.99	8.84	-	95.85	3.5163	0.4837
wys153-1-1	Phl	42.15	1.13	12.98	0.52	0.05	26.09	0.20	0.42	8.68	3.43	95.65	2.8996	1.0524

Extensional
fold
deformation
(D3)

wys153-1-2	Phl	42.58	1.16	13.18	0.39	0.04	26.40	0.20	0.50	8.84	3.66	96.95	2.8904	1.0544	Compressional fold deformation (D2)
wys153-1-3	Phl	43.25	1.29	12.89	0.53	0.03	26.66	0.39	0.52	8.78	3.54	97.88	2.9087	1.0217	
wys153-2-1	Phl	42.78	1.24	13.27	0.40	0.18	26.57	0.20	0.47	9.13	3.17	97.41	2.8961	1.0588	
wys153-2-2	Phl	43.75	1.09	13.05	0.48	0.11	26.96	0.08	0.35	9.05	3.43	98.35	2.9252	1.0284	
wys153-2-3	Phl	43.54	1.13	12.83	0.58	0.10	26.64	0.07	0.32	9.19	3.7	98.10	2.9232	1.0152	
ys-48-1-1	Ms	49.55	0.46	32.23	0.09	0.05	2.17	0.09	0.42	10.57	-	95.63	3.2566	0.7434	
ys-48-1-2	Ms	48.44	0.52	31.50	0.15	0.01	2.02	0.33	0.50	10.59	-	94.06	3.2473	0.7527	
ys-48-1-3	Ms	49.43	0.57	32.67	0.44	0.02	1.96	0.43	0.49	10.78	-	96.79	3.2251	0.7749	
ys-83-1-1	Ms	48.53	0.42	27.10	5.17	0.01	3.79	0.08	0.46	10.48	-	96.04	3.2791	0.7209	
ys-83-1-2	Ms	49.27	0.32	26.95	4.67	-	2.99	0.04	0.43	10.93	-	95.60	3.3360	0.6640	
ys-83-1-5	Ms	48.24	0.49	27.21	4.80	-	2.79	0.13	0.45	10.86	-	94.97	3.2960	0.7040	
ys-83-2-1	Ms	48.81	0.40	27.55	4.06	-	2.62	0.12	0.44	10.83	-	94.83	3.3206	0.6794	
ys-83-2-2	Ms	50.10	0.45	26.97	4.34	0.07	3.07	0.03	0.38	9.90	-	95.31	3.3699	0.6301	
ys-83-2-3	Ms	45.05	0.41	26.88	7.74	0.09	6.48	0.23	0.49	8.04	-	95.41	3.0915	0.9085	
ys-106-1-1	Phl	45.17	1.03	11.62	0.12	0.06	26.57	0.40	0.83	8.16	5.51	99.47	2.9692	0.9002	
ys-106-1-2	Phl	44.64	1.08	11.40	0.00	0.06	26.15	0.38	0.75	8.24	5.34	98.04	2.9773	0.8961	
ys-108-1-1	Phl	45.79	0.10	11.63	0.08	-	26.74	0.05	0.87	8.40	5.75	99.41	3.0059	0.8998	
ys-108-1-2	Phl	45.39	0.25	11.88	0.16	0.40	26.58	0.12	0.98	8.24	5.23	99.23	2.9923	0.9230	
wys-360-1	Phl	45.44	0.52	10.47	0.12	0.04	28.12	0.08	0.16	9.32	4.37	98.64	3.0234	0.8210	
wys-360-1-2	Phl	46.03	0.61	10.05	0.25	-	27.94	0.07	0.21	9.23	4.82	99.21	3.0430	0.7830	
wys-360-1-3	Phl	46.87	0.46	8.90	0.24	-	27.47	0.09	0.23	8.84	4.74	97.84	3.1290	0.7003	
wys-360-1-5	Phl	45.27	0.61	10.53	0.14	0.06	28.03	0.12	0.20	9.11	4.48	98.55	3.0135	0.8261	
wys-360-2-2	Cpx	55.27	0.12	0.01	0.20	-	20.50	22.98	0.16	-	-	99.24			
ym-68-1-1	Phl	42.56	0.64	14.12	0.47	-	24.89	0.26	0.21	10.75	2.5	96.40	2.9290	1.0710	sheared fold deformation
ym-68-1-2	Phl	43.85	0.65	12.93	0.48	-	24.95	0.07	0.24	10.74	3.17	97.08	2.9903	1.0097	

ym-68-1-3	Ms	48.82	1.36	30.91	0.14	0.02	2.80	0.15	0.31	9.97		94.48	3.2456	0.7544	(D3)
ym-68-1-4	Phl	42.50	0.58	14.45	0.59	0.04	25.34	0.16	0.28	10.77	3.15	97.86	2.8855	1.1145	
ym-68-2-1	Ms	47.47	1.39	32.10	0.06	0.05	2.22	0.24	0.35	11.21	-	95.09	3.1660	0.8340	
ym-68-2-2	Ms	48.00	0.47	33.26	0.23	-	2.36	0.21	0.35	11.04	-	95.92	3.1650	0.8350	
ym-68-2-3	Ms	47.64	0.50	32.38	0.08	-	2.44	0.23	0.31	11.21	-	94.79	3.1822	0.8178	(D3)
ym-68-2-4	Phl	42.93	0.71	14.15	0.58	-	25.01	0.36	0.29	10.76	2.84	97.63	2.9198	1.0802	
ym-69-1-1	Phl	42.30	0.77	15.30	1.55	-	25.57	0.57	0.54	9.52	0.52	96.64	2.9036	1.0964	
ym-69-1-2	Phl	42.40	0.82	14.59	1.48	0.13	25.14	0.59	0.63	9.19	0.37	95.34	2.9455	1.0545	
ym-69-1-3	Phl	42.98	0.68	15.26	1.55	0.11	25.34	0.32	0.51	9.45	0.41	96.61	2.9431	1.0569	(D3)
ym-69-2-1	Phl	42.74	0.68	16.09	1.33	-	24.78	0.21	0.34	9.46	0.42	96.05	2.9337	1.0663	
ym-69-2-2	Phl	42.92	0.81	14.87	1.60	-	25.52	0.17	0.31	9.60	0.43	96.23	2.9505	1.0495	
ym-71-1-1	Phl	42.30	0.82	15.93	2.41	0.00	23.88	0.36	0.38	9.38	0.28	95.74	2.9303	1.0697	
ym-71-1-2	Phl	43.15	0.79	15.06	2.34	0.05	23.57	0.38	0.65	8.52	0.62	95.13	2.9908	1.0092	(D3)
ym-71-1-3	Phl	41.85	0.76	15.74	2.13	-	24.06	1.58	0.45	9.11	0.4	96.08	2.8973	1.1027	
ym-71-2-1	Phl	41.82	0.69	16.31	2.17	0.07	24.40	0.86	0.35	8.75	0.02	95.44	2.8999	1.1001	
ym-71-2-2	Phl	42.49	0.68	15.50	2.28	-	24.44	0.92	0.40	8.95	0.32	95.98	2.9334	1.0666	
ym-71-2-3	Phl	42.66	0.71	15.76	2.33	-	24.69	0.50	0.48	8.81	0.48	96.42	2.9258	1.0742	(D3)

In the table, abbreviations are: Cpx-clinopyroxene, Ms-muscovite, Phl-phlogopite, D2-D3-two-stage deformations.

Table 2

Table 2 Samples description and ages data

Fold type	Sampled Number	Litho-petrology	Sampled Site	Fold positions	Determined Minerals	J-value	Isochron Age (Ma) and $^{40}\text{Ar}/^{36}\text{Ar}$ Initial Ratio	WMPA or PA (Ma)	references
Contractional recumbent fold (D2)	ys-107	Deformed limestone	N39° 38' 51", E115° 49' 28"	limb	muscovite	0.005240	159 ± 2, 232 ± 49	158 ± 1 (PA)	Wang et al. (2011)
	wys-94	Deformed sandstone	N39° 38' 51", E115° 49' 55"	limb	muscovite	0.002091	157 ± 3, 310 ± 18	159 ± 1 (PA)	Wang et al. (2011)
	ys-108	Deformed sandstone	N39° 38' 51", E115° 49' 28"	hinge	sericite	0.005243	170 ± 5, 295 ± 98	173 ± 2 (PA)	Wang and Li (2008)
Contractional inclined fold (D2)	wys-146	Deformed limestone	N39° 43' 18", E115° 46' 08"	limb	muscovite	0.002011	159 ± 6, 270 ± 51	156 ± 1 (PA)	Wang et al. (2011)
Contractional inclined fold (D2)	wys-153	Deformed sandstone	N39° 43' 14", E115° 43' 36"	hinge	muscovite	0.002044	156 ± 4, 319 ± 59	156 ± 1 (WMPA)	Wang et al. (2011)
Extensional fold (D3)	wys-92	Deformed limestone	N39° 43' 22", E115° 50' 26"	hinge	muscovite	0.001991	125 ± 5, 302 ± 44	125 ± 1 (WMPA)	Wang et al. (2011)
	ys-104	Deformed limestone	N39° 49' 08", E115° 59' 09"	limb	muscovite	0.005228	126 ± 9, 474 ± 1000	128 ± 1 (PA)	Wang et al. (2011)
Dragged fold in strike-slip zone	ym-68	Deformed limestone	N40° 44' 54", E116° 52' 49"	limb	muscovite	0.007753	129 ± 2, 271 ± 26	128 ± 1 (WMPA)	This study
	ym-71	Deformed limestone	N40° 44' 54", E116° 52' 49"	hinge	muscovite	0.007753	133 ± 5, 302 ± 31	134 ± 2 (WMPA)	This study
Folded Cambrian sandstone	wys-408	sandstone	N40° 43' 39", E118° 09' 46"	within layers	muscovite	0.002059	587 ± 3, 218 ± 170	587 ± 2 (WMPA)	This study
Folded Cambrian sandstone	wys-409	sandstone	N40° 43' 39", E118° 09' 46"	within layers	muscovite	0.002052	574 ± 3, 291 ± 190	575 ± 2 (WMPA)	This study

In the table, WMPA-weighted mean plateau age, PA-preferred age. Weighted mean plateau ages (WMPA) are reported where >50% of the ^{39}Ar released in contiguous steps is within 1 σ error. For disturbed spectra, preferred ages (PA) are reported where the spectrum is relatively flat but does not meet the strict criterion for a WMPA. In the table, ys-104 has much larger error of the $^{40}\text{Ar}/^{36}\text{Ar}$ initial ratio because of plotted data scatter, that the isochron age should be used carefully. D2-D3 deformation stages are shown.

Fold formed by flexural slip

Contractional recumbent fold

Photomicrograph

BSE image of muscovite

Ar-Ar plateau age