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Kinematics and timing of brittle–ductile shearing of Mylonites along the Bok Bak fault, Peninsular Malaysia

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Study on the Bok Bak fault in Peninsular Malaysia reveals it to be a predominantly dextral brittle–ductile strike slip fault zone. This fault zone is characterized by gentle to sub-horizontal NE stretching lineation. The deformation occurred in a brittle–ductile domain. ^{40}Ar/^{39}Ar radiometric dating of biotite from the mylonite assigns an age of 136.1 ± 1.4 Ma. This age is the first reported radiometric dating of the Bok Bak fault, suggesting that the fault affected Sundaland prior to the collision between India and Asia, and therefore indicates an early faulting in the Malay Peninsula.

Keywords: ^{40}Ar–^{39}Ar dating, Bok Bak fault, Peninsular Malaysia, Sundaland, strike slip.

CONTINENTAL core of SE Asia (Sundaland) is dominated by Cenozoic tectonics, which include the genesis of large-scale faults such as the Khlong–Marui fault, Ranong fault, Three Pagoda fault, Sagaing fault and Ailao-Shan Red River fault. These Cenozoic faults have been linked to either the slab pull of the Proto-South China Sea, or escape tectonics[1]. In Peninsular Malaysia, the fault systems which encompasses the Bok Bak fault, Kuala Lumpur fault, Bukit Tinggi fault, Mersing fault, and Lebir fault show trends parallel to the large-scale faults of SE Asia such as the Three Pagoda fault, Mae Ping fault and Ailao Shan–Red–River fault. The faults of Peninsular Malaysia are considered to have pre-dated the India–Asia collision event[2–10], although information on kinematics and dating of these faults is lacking. As such, their implication to the regional tectonics is inconclusive. Here we examine the kinematics of the Bok Bak fault, and date its timing by the ^{40}Ar/^{39}Ar method.

The Bok Bak fault is classified as one of the terrane crossing faults of Peninsular Malaysia[3]. It is visible as NNW and NW trending of en echelon tectonic lineaments sets spanning of ~200 km (Figure 1). A structural study was carried out in the study area, NW of Peninsular Malaysia, near the border of Kedah-Perak state, where mylonite and sheared granite along the Bok Bak fault zone are well exposed. Several kinematic studies of mylonite of other faults in Peninsular Malaysia[11,12] and

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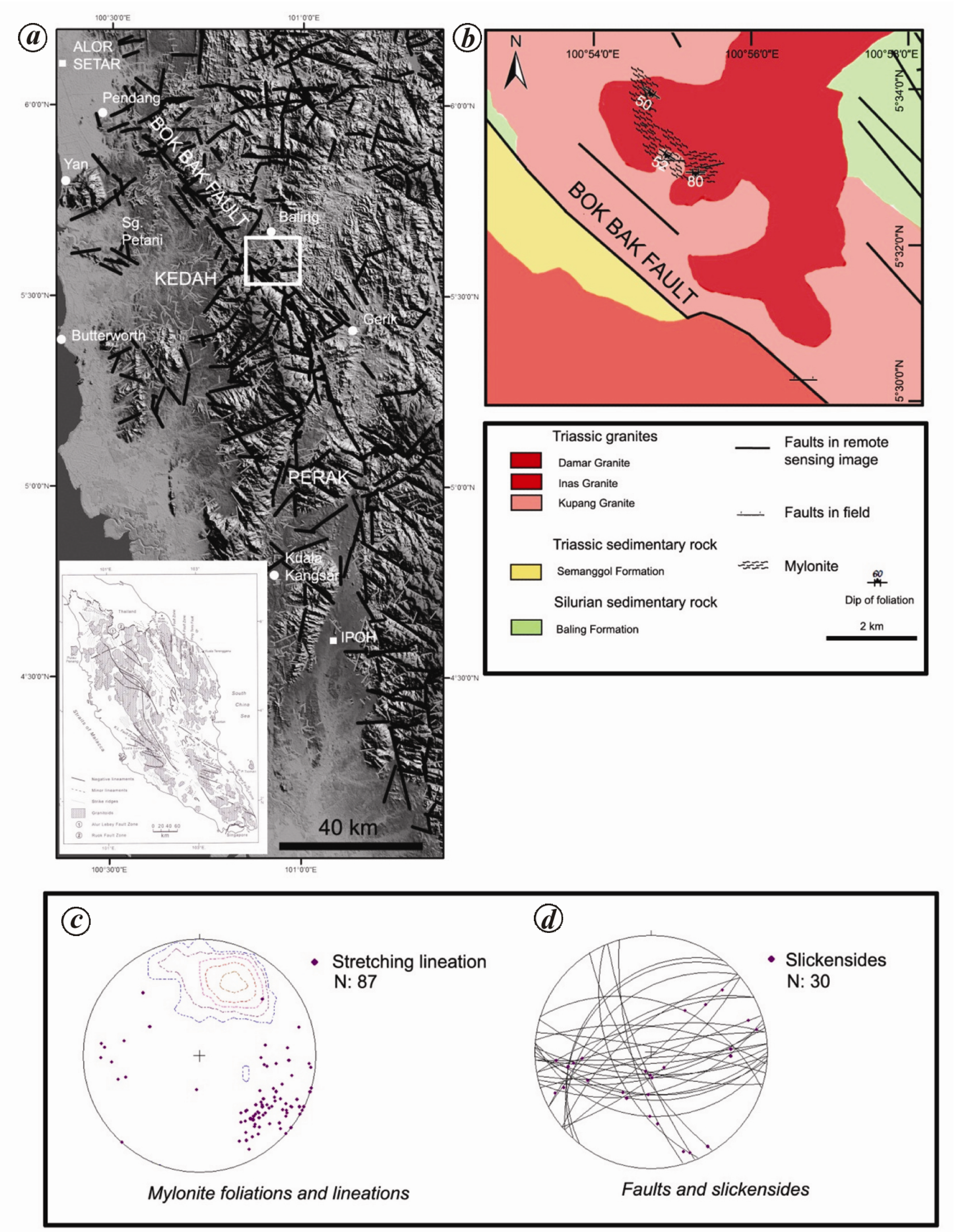

Figure 1. ***a***, Shaded relief map generated from Shuttle Radar Topography Mission (SRTM) data showing trace of Bok Bak Fault Zone lineaments in Kedah-Perak state, NW Peninsular Malaysia. White border refers to study area shown in ***b***. Inset: Fault zones of Peninsular Malaysia[49]. ***b***, Geological map of the Baling-Gerik area in Kedah-Perak state. Geology modified from Burton[18]. Fault in remote sensing image is plotted from SRTM. Note the main Bok Bak Fault trace that separates the Triassic sediment with granites. Plotted mylonite and fault readings are representative of readings from the field. ***c***, Lower hemisphere equal area projection for mylonite foliation and stretching lineation. ***d***, Lower hemisphere equal area projection for fault plane and slickenside.

radiometric dating of faults[12] are used for interpretation of tectonic history of Peninsular Malaysia faults. Previous kinematic studies on the Bok Bak fault focused on the brittle deformation exhibited in the field by remote sensing[12–16]. However, only few references to ductile deformation along the fault zone are available[17].

A structural study was carried out at in the study area, NW of Peninsular Malaysia, near the border of Kedah Perak state, where mylonite and sheared granite along the Bok Bak fault zone are well exposed (Figure 1). The fault zone passes through the main range granite. The granite shows locally primary magmatic foliation with visible

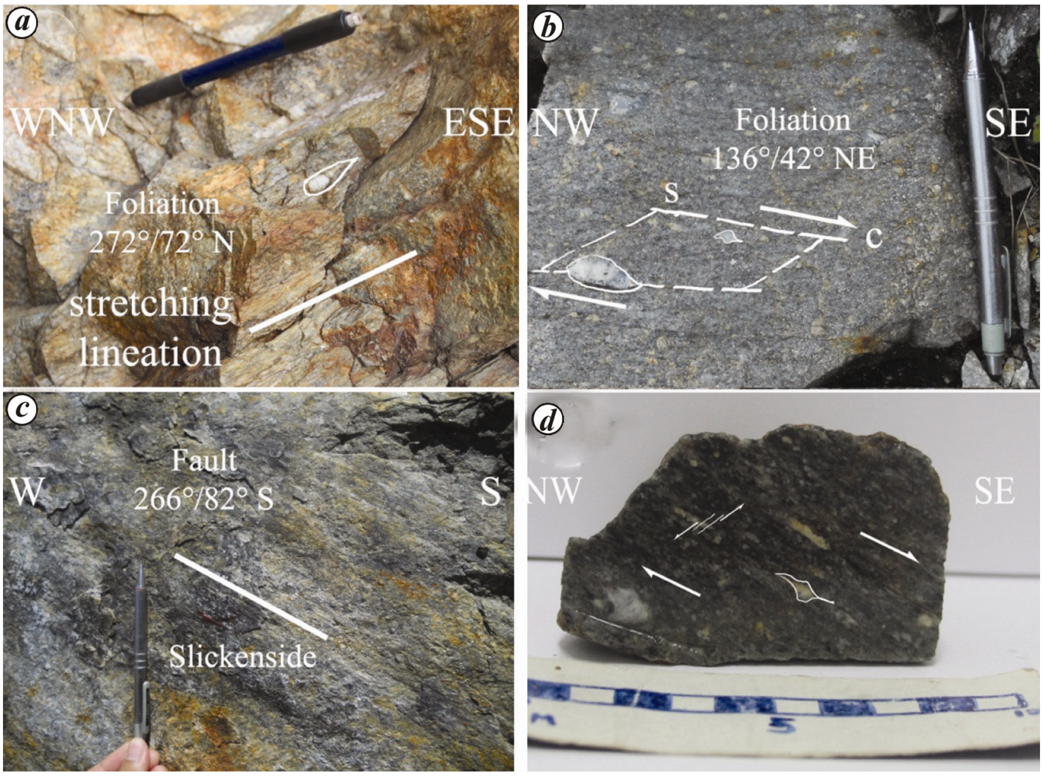

Figure 2. Deformation structures in granite along Bok Bak Fault: ***a***, Narrow mylonite zone in granite with strong stretching lineations formation and large porphyroclast set in foliation. View parallel to stretching lineations; ***b***, S–C structure and rotated clast in mylonite. View parallel to stretching lineations; ***c***, slickenside on fault plane cutting the mylonite, showing normal movement; ***d***, Oriented hand specimen of mylonite,showing mantled feldspar porphyroclast, and antithetic (sinistral) shearing in feldspar clast. Sample cut parallel to stretching lineations.

feldspar phenocrysts, with the matrix consisting of quartz, mica, and other accessories minerals. The granites of the area have been subdivided based on texture and mineralogy[18]. In this study we have classified the different granite groups as a part of the Main Range Granite.

Granites deformed to mylonite formed protomylonite – with some occurrence of orthomylonite – which show foliation formed by layers of recrystallized quartz grains alternating with mica-rich layers[19–21]. The S–C structure is visible in most of the mylonite, and this, along with feldspar porphyroclasts in the mylonite, indicates shear sense reliably[22–24]. In several localities, mylonites were found to be overprinted by brittle structures, such as cataclastic fault zone rocks, shear planes and veins. Further north of the study area, brittle deformation is more ubiquitous with NW–SE/NNW–SSE, NE–SW and E–W sets of faults and brittle fault rocks cross-cutting each other. The mylonite foliation generally strikes NW, dipping either towards S or N, with gentle plunging to sub-horizontal lineations. As high values of plunge is not observed, the mylonite along the fault zone is considered to record oblique slip movements with dominant strike slip movements. S–C fabric and rigid clasts of mylonite in the field connote dextral shear (Figure 2).

Microstructural studies were carried out on oriented thin sections of the mylonite for best results of kinematic indicators[25]. The mylonite contains abundant recrystallized mica layers with quartz ribbons. Evidence of crystal plastic deformation in quartz is abundant, with formation of sub-grains, deformation bands, and σ-type mantled feldspar porphyroclast. Recrystallized quartz grains have undergone bulging recrystallization (BLG) and subgrain rotation recrystallization (SGR), which would be initiated at 300°C and 400°C respectively[26]. Alkali feldspars and plagioclase form the porphyroclasts, which commonly fracture into smaller grains between quartz ribbons. The S–C fabric is well developed in mylonite, with the S-fabric defined by obliquely arranged quartz and feldspar arrangement, while thin bands of recrystallized mica and quartz ribbons form the shear bands of the C-fabric. Mica fish structure is observed in all the mylonites. σ-type mantled feldspar porphyroclasts are also observed in some of the mylonites. No evidences of shear heating were deciphered from these thin sections[27–30].

The NW–SE foliated mylonite shows dextral shear with top-to-NW movement (Figure 2), and few reverse top-to-NE dip-slip movements. The mylonite shows brittle–ductile deformation as is evident from mineral microstructures (Figure 3). Feldspars show brittle deformation through fracturing, and exhibit micro- and macroscopic antithetic sinistral displacements[21]. Recystallized quartz show consistent clear dextral stair-stepping microstructural

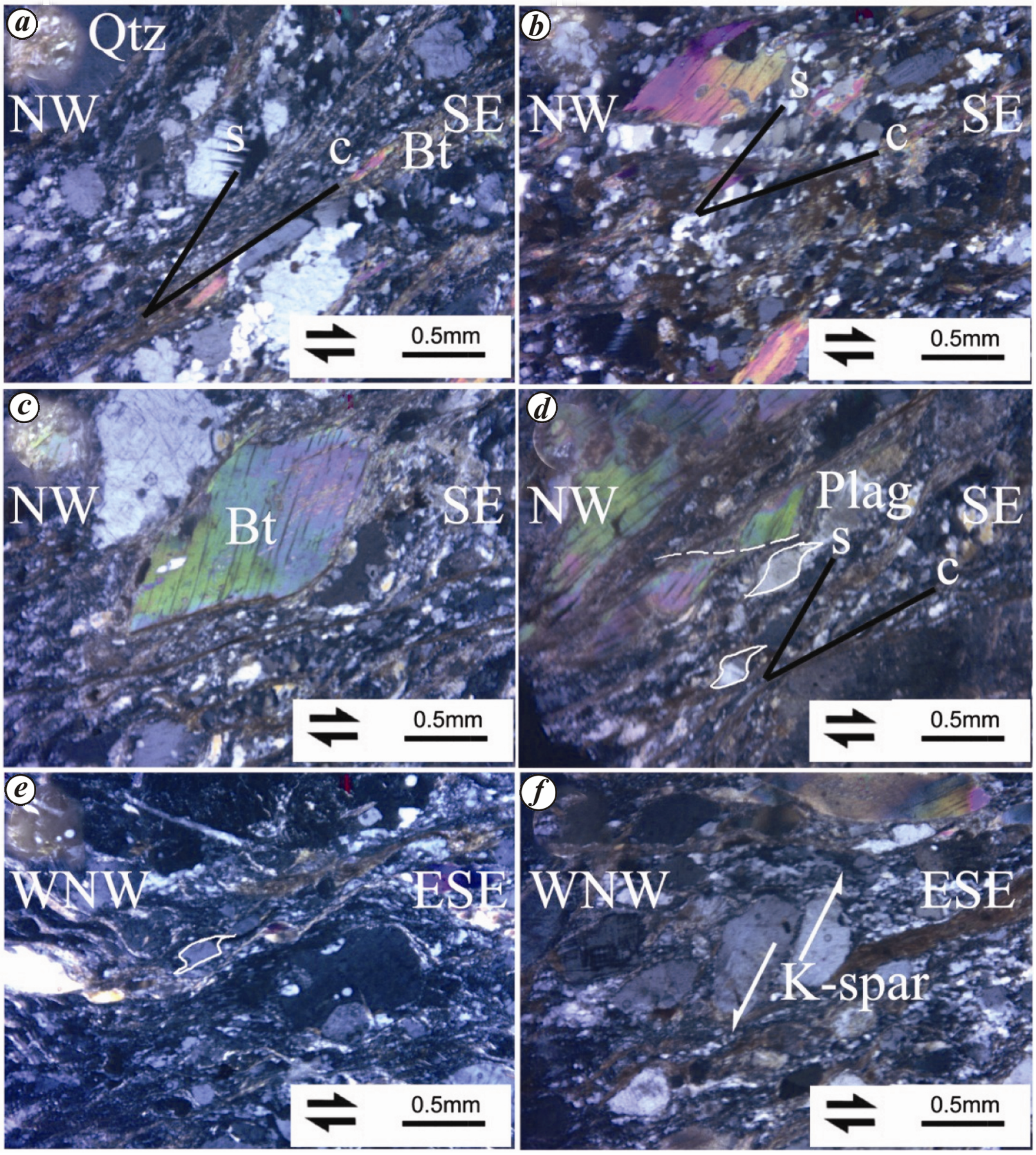

Figure 3. Microstructures from Bok Bak Fault indicating WNW–ESE to NW–SE dextral shearing: ***a***, S–C structure in mylonite. Note the trend of mica fish and feldspar porphyroclast in between C shear band; ***b***, oblique foliation; ***c***, Mica fish and shear bands; ***d***, σ-type mantled feldspar porphyroclast bordered by mica fish and shear band. Note the mica fish in the centre of view being offset by shear band; ***e***, σ-type mantled feldspar porphyroclast in mylonite; ***f***, Antithetic fracture in K-feldspar: movement of fracture (sinistral) is opposite of the sense of shear in mylonite. Qtz: Quartz, Plag: Plagioclase, K-spar: Alkali feldspar, Bt: Biotite. All images under crossed nicol.

geometry. The predominance of ductile phase in quartz would indicate a temperature condition that is not below ~300°C and with the presence of BLG and SGR recrystallization, the temperature is between 300°C and 400°C (ref. 26). These structures were overprinted by faults with steeply plunging slickensides trending mostly E–W to WSW–ENE, suggesting that the strike slip in mylonite were overprinted by normal faults. The faults indicate reactivation of the shear zone.

A mylonite sample was sent for a ^{40}Ar/^{39}Ar dating at the Activation Laboratories Limited (Canada). The sample had exhibited dextral shearing microstructures, and the recystallized biotiteneocrysts in the mylonite was separated for dating. The biotite sample showed age spectrum with five steps plateau characterized by 83.8% of ^{39}Ar, with weighted mean plateau age (WMPA) of 136.1 ± 1.4 Ma (Figure 4). On the inverse isochrone plot, the points do not show a significant linear trend. The deformation temperature of the dated mylonite is near the closure temperature of biotite (300 ± 50°C)[31,32]. It is possible that the Ar system in the biotite could have been reset, and the age obtained would represent cooling age associated with deformation event, rather than the age of deformation itself. The variable age spectra of the mylonite sample connote spartial resetting, possibly due to subsequent uplift experienced by the fault.

Although no other radiometric dating of mylonite along the Bok Bak Fault is available, there are several other radiometric dating of granites in areas close to the fault zone. The age of the dated mylonite in this study is close to other Early Cretaceous age for dated granites along the fault zone (Figure 5). These younger ages, as opposed to the older age achieved through Rb–Sr and U–Pb dating of the Main Range Granite of Malay Peninsula[33,34], were attributed to argon loss in the granite as a result of Late Triassic intrusions and young fault related disturbances[35]. An age of 150 Ma (Late Jurassic) was achieved by K–Ar dating[36] for a rock unit that was then referred to as Kupang Gneiss (Figure 5) – later mapped to be part of the Main Range Granite. The age was believed to be related to faulting events rather than metamorphic events, as the rock unit is bounded by faults[37].

As several other Early Cretaceous ages have been reported for granites close to trace of the fault zone (Figure 5), it is likely that this age represents the cooling age for the Bok Bak fault. The $^{40}Ar/^{39}Ar$ dating in this study that was carried out on the recrystallized biotiteneocryst in the mylonite assigns the age as one related to faulting events, rather than metamorphic events. By compiling the radiometric dating ages of granitic rocks, the Early Cretaceous age is considered to represent the lower age constraint of the ductile shear of the Bok Bak Fault, while the Late Jurassic age represents an upper age constraint of the ductile shear. The constraint would place the timing of ductile shear between 150 ± 8 Ma and 136.1 ± 1.4 Ma. In the absence of other thermochronological studies for minerals along the fault zone, we propose this as the period of ductile deformation of the Bok Bak fault.

In Sumatra and Myanmar, a Jurassic to Early Cretaceous subduction event has been reported[2,38–42], followed by island arc collision in Middle Cretaceous forming the Woyla Terrane and possibly the Mawgyi Nappe[43]. The Jurassic to Early Cretaceous is a time when Sundaland became cratonized and major strike-slip and block faults developed[44]. The NW–SE and NE–SW faults of Peninsular Malaysia activated presumably during the period of collision of the Burma Arc to the East Asian Continent during Cretaceous[45]. The Late Cretaceous to Paleogene period represents a critical time of faulting and deformation in Sundaland as observed in Thailand, Burma and Malaysia[42,46]. Extensive thermochronological work on the

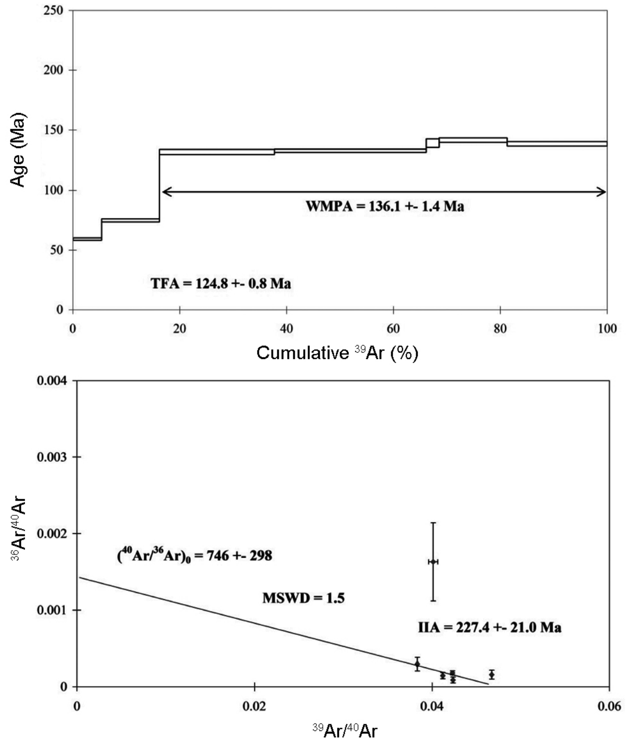

Figure 4. $^{40}Ar/^{39}Ar$ gas release spectrum and inverse isochron plot for mylonite from Bok Bak Fault.

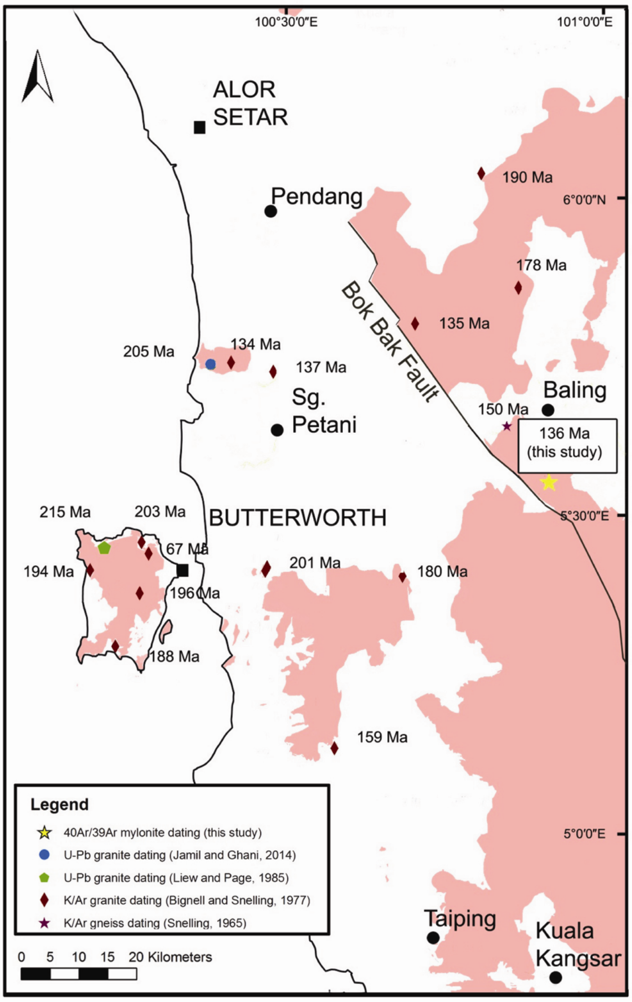

Figure 5. Ages of various dated granite in NW Peninsular Malaysia (ages in figure from: this study and refs 35–37, 55). Granite distribution modified from Mineral and Geoscience Department[56]).

Malay Peninsula using ^{40}Ar/^{39}Ar, (U–Th–Sm)/He, and fission track data[45,47] indicate that the peninsula underwent significant tectonism during Late Cretaceous and Eocene. Similar tectonic events have been proposed for Thailand based on thermochronological studies of the Ranong and Khlong Marui faults[48].

The Bok Bak fault is modelled as having been initiated after Upper Triassic[49], and reactivated through transpresive movement in Late Cretaceous[13]. Evidence of sinistral and dextral brittle kinematic indicators indicates subsequent reactivations of the fault, which were most likely plausible linked to the India-Asia collision event[12,16,50]. Thermochronological analysis of granitic rocks of the Malay Peninsula shows several periods of exhumation, during Late Cretaceous to early Paleogene and Eocene[45,47]. The Late Eocene to Oligocene rapid exhumation coincides with significant subsidence in offshore areas[47], during the time when sinistral transtensional movement along pre-existing NW–SE fault zones formed the Tertiary offshore and onshore basins[51–53].

From this study, it is shown that the Bok Bak fault underwent an early brittle-ductile dextral strike-slip, possibly initiated as early as Late Jurassic, with the fault undergoing cooling during Early Cretaceous. The brittle–ductile deformation of the Bok Bak Fault would post-date the Late Permian to Middle Triassic orogenic event of Peninsular Malaysia and the intrusion of Main Range Granite[54]. Studies of other faults of the peninsular have reported an age of Late Cretaceous and Eocene for the mylonite[5]. The older age of the mylonite in this study could represent an earlier tectonics that precedes the Late Cretaceous reactivation of the faults of Peninsular Malaysia.

Our study provides a tentative age for the ductile deformation age of the Bok Bak fault, which has so far not been dated with certainty. The Late Jurassic to Early Cretaceous age corresponds to a period when the Bok Bak fault had undergone dextral strike slip, which was overprinted by subsequent brittle deformations which were reported as NW sinistral and NE dextral strike slip movements[13,15]. However, the result of dating from this study could only serve as a preliminary fault deformation age range, and more detailed work is needed for a more accurate interpretation of the timing of deformation event along the fault. Several other factors such as deformation conditions of the fault and timing of subsequent brittle reactivations of the fault are yet to be investigated. Further kinematic and thermochronological studies are required for a better understanding of the evolution of faults of Peninsular Malaysia, and in effect, the tectonic history of the region.

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