Absolute age evidence of Early to Middle Ordovician volcanism in Peninsular Malaysia

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Evidence of Early Palaeozoic volcanism in Peninsular Malaysia is largely represented by felsic Gerik–Dinding meta-volcanic rocks; however, reliable absolute ages for the meta-volcanic rocks are still lacking. This restricts correlation of these meta-volcanic rocks with other Early Palaeozoic East Gondwana Proto-Tethys margin tectonic elements identified in the evolution of Southeast Asia. Here, we report petrographic data and zircon U–Pb age of the Gerik–Dinding meta-volcanic rocks. Zircons from three Gerik–Dinding meta-volcanic rock samples yield Early to Middle Ordovician weighted mean $^{206}Pb/^{238}U$ ages between 480 and 460 Ma.

The formation age of the meta-volcanic rocks coincides with the post-collision stage from the final amalgamation of Asian micro-continental fragments with the East Gondwana Proto-Tethys margin. Tectonic processes such as lithospheric delamination during the post-collision period could have induced the hot asthenosphere to underplate the continental crust and trigger crustal anatexis. With these findings, the Early Palaeozoic tectonic history of Peninsular Malaysia needs careful review.

Keywords: Absolute age, meta-volcanic rocks, petrographic data, tectonic elements.

THE Sibumasu Terrane (Figure 1 *a*) is one of the main terranes along the East Gondwana Proto-Tethys margin during the Early Palaeozoic, and comprises Western Peninsular Malaysia, Western Yunnan, the Shan States of Burma, Northwest Thailand, Peninsular Burma and Thailand and Northwest Sumatra. Widespread Early Palaeozoic magmatism discovered along the East Gondwana Proto-Tethys margin is suggested to be related to the subduction of the Proto-Tethys Ocean, and the subsequent collision and accretion of outboard Asian micro-continental fragments onto the margin[1–7]. This has led to a proposed subduction zone at the East Gondwana Proto-Tethys margin during the Early Palaeozoic (Figure 2). The absence of good exposures mainly due to heavy weathering, dense vegetation and also strong overprinting of older Mesozoic crustal-forming orogeny in these terranes has resulted in limited studies on reliable age data of the Early Palaeozoic magmatic rocks. Although there have been field reports describing probable Early Palaeozoic meta-volcanic rocks in Western Peninsular Malaysia[8–10], reliable isotope date for the meta-volcanic rocks are still lacking. The absence of absolute age restricts correlation of these volcanics with other Early Palaeozoic East Gondwana Proto-Tethys margin tectonic elements identified in the evolution of Southeast Asia. In this study, we report zircon U–Pb age data for Early Palaeozoic meta-volcanic rocks in Western Peninsular Malaysia.

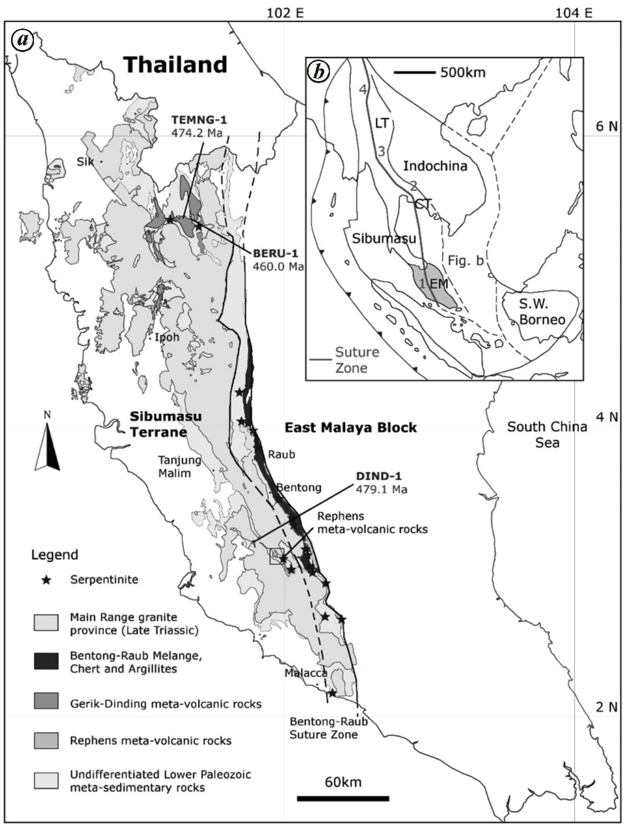

Figure 1. ***a***, Distribution of continental blocks, fragments and terranes of mainland Southeast Asia[12]. EM, East Malaya Block; CT, Chanthaburi Arc Terrane and LT, Lincang Arc Terrane. Suture zones: 1. Bentong–Raub suture zone, 2. Chanthaburi suture zone, 3. Chiang Mai-Inthanon suture zone, and 4. Changning-Menglian suture zone. ***b***, Geological sketch map of Peninsular Malaysia showing granitoids of the Main Range granite province, Bentong–Raub suture rocks, Gerik–Dinding meta-volcanic rocks, Rephens meta-volcanic rocks and undifferentiated Lower Palaeozoic meta-sedimentary rocks[10].

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Peninsular Malaysia comprises two distinct tectonic blocks derived from Gondwana; the Sibumasu Terrane and the Indochina–East Malaya Block[11,12] (Figure 1 *b*). Western Peninsular Malaysia represents part of the Sibumasu Terrane and Eastern Peninsular Malaysia represents part of the Indochina–East Malaya Block. The two tectonic blocks are separated by the Bentong–Raub suture zone, which is interpreted to contain a segment of the closed Eastern Palaeo-Tethys Ocean[11–13]. The suture zone is for the most part composed of mélange with sheared mud/silt framework containing an assortment of clasts, comprising oceanic ribbon-bedded cherts, metamorphosed mudstones and rhythmites, limestone, sandstone, conglomerate and volcaniclastic rocks, and several isolated and small bodies of serpentinite[11–14]. The closing of the Eastern Palaeo-Tethys Ocean was due to the Late Palaeozoic to Early Mesozoic subduction under the Indochina–East Malaya Block and subsequent collision with Sibumasu Terrane[11,12,15,16]. The collision formed the Late Triassic (201–227 Ma) Main Range Granite Province, which covers most of Western Peninsular Malaysia[16–23].

Western Peninsular Malaysia volcanic rocks belong to three age groups: Late Triassic, Early Palaeozoic and Middle Palaeozoic[8–10,24]. The Late Triassic volcanic rocks are represented by the Genting Sempah volcanic rocks[25,26] (~226 Ma), which are associated with the Late Triassic Main Range Granite Province[16,20]. The two main rock types found in Genting Sempah volcanic rocks are rhyolite and orthopyroxene rhyodacite[25,26]. The Early Palaeozoic volcanic rocks are represented by the Gerik–Dinding meta-volcanic rocks[8,9] and the Middle Palaeozoic volcanic rocks are represented by the Rephens meta-volcanic rocks[24]. These two groups of meta-volcanic rocks are commonly described as metamorphosed felsic to intermediate volcanic rocks with sub-schistose to schistose texture imposed by regional metamorphism of varying degree which post-dates the volcanism[10]. Minor volcaniclastic rocks have been reported in the Cambrian to Early Ordovician Machinchang Formation located to the west of the volcanic rocks (which is equivalent to Tarutao Formation at Thailand)[27]. Data on the Early Palaeozoic and Middle Palaeozoic volcanic rocks are limited and no absolute age is available for the Early Palaeozoic and Middle Palaeozoic volcanic rocks. Based on relative stratigraphic position, the age of the Gerik–Dinding meta-volcanic rocks is suggested to be Ordovician[8,9], while the relative age for Rephens meta-volcanic rocks is suggested to be somewhere between Devonian and Carboniferous[24].

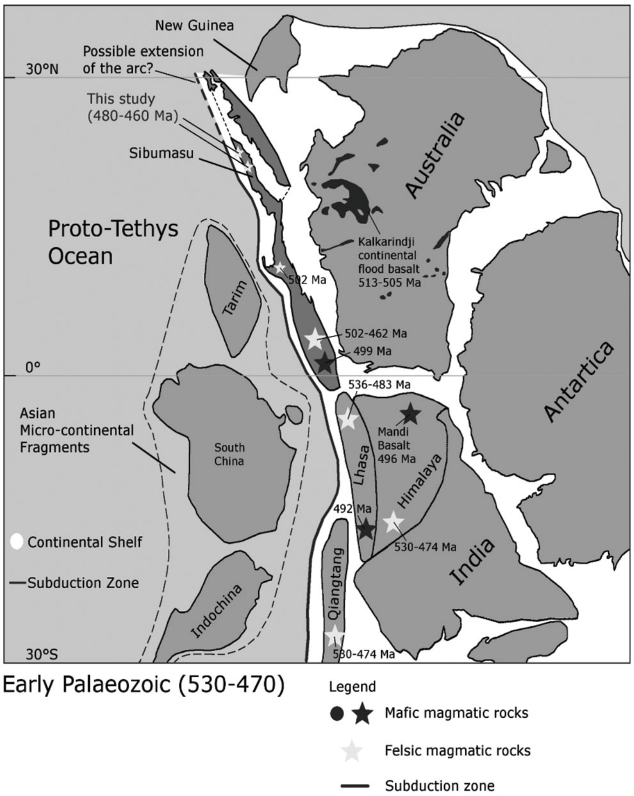

Figure 2. Reconstruction of Gondwana showing the palaeogeographic locations of Gondwana-derived terranes and Asian microcontinental fragments[5,6].

The outcrops of the Gerik–Dinding meta-volcanic rocks are situated towards the west of the Bentong–Raub suture zone, at the foothills of the Main Range Granite Province granitoid (Figure 1 *b*). The maximum thickness of the Gerik–Dinding meta-volcanic strata is estimated to be around 1830 m (ref. 8). Meta-sedimentary rocks deposited contemporaneously with the Gerik–Dinding meta-volcanic rocks and metamorphosed lithic-tuff indicate that the volcanic rocks were formed by explosive volcanism under sub-aerial to marine conditions[8,9]. No lava flows have been documented with certainty in the northern part of Peninsular Malaysia, but fragments of scoriaceous rhyolite resembling flow material and metamorphosed rocks strongly resembling a rhyolite have been recognized[8]. Overall, the metamorphic grade of the Gerik–Dinding meta-volcanic rocks is no higher than greenschist facies, although higher-temperature metamorphic minerals (e.g. garnet and andalusite) have developed as a result of contact metamorphism induced by younger Late Triassic Main Range Granite Province granitoid[8]. The Gerik–Dinding meta-volcanic rocks consist of meta-lithic tuff, meta-rhyolite and meta-crystal tuff[8]. Figure 1 *b* shows the locations of the Gerik–Dinding meta-volcanic rocks sampled for this study.

The meta-lithic tuff was excluded from this study as it contains a significant quantity of terrigenous material. The meta-rhyolite is a fine-grained porphyritic volcanic rock dominated by phenocrysts of quartz (50%), perthitic K-feldspar (45%) and plagioclase (5%) in a fine-grained groundmass dominated by quartz, chlorite, muscovite, feldspar and biotite. The groundmass is strongly sheared and constitutes 75–80% of the rock. Embayments (Figure

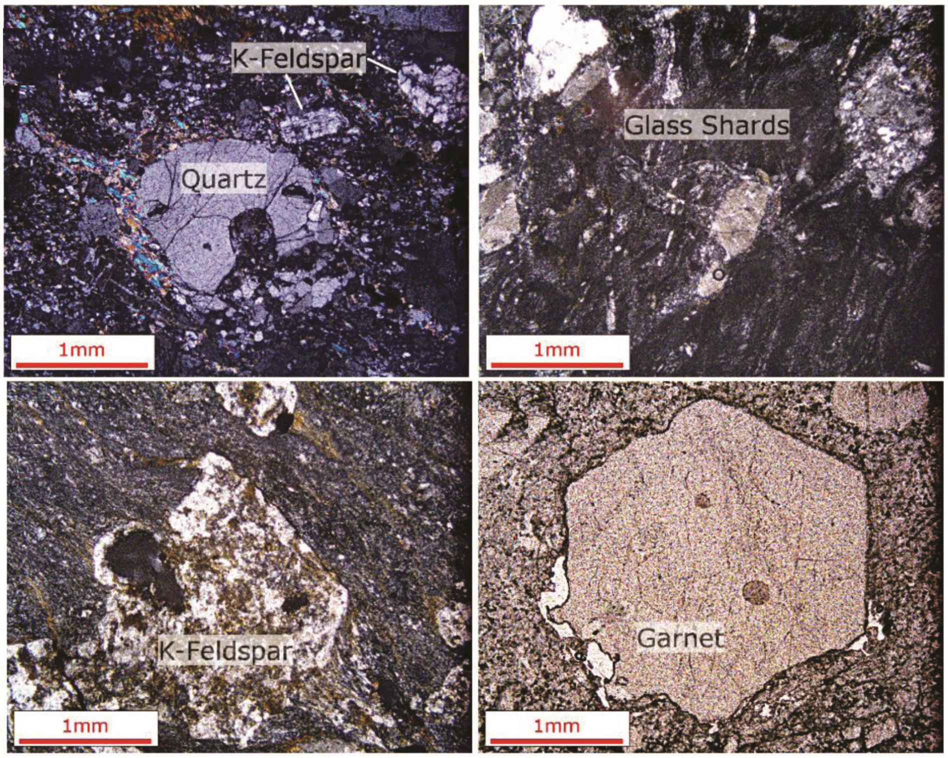

Figure 3. Photomicrographs showing textures and mineral constituents of the Gerik–Dinding meta-volcanic rocks.

3 *a*) and 'corroded' margins are observed in some quartz phenocrysts. Alteration of some feldspar grains to calcite suggests the presence of calcic feldspar. Accessory minerals are zircon, apatite and leucoxene. The meta-crystal tuff has higher phenocryst content and is more varied in phenocryst mineral composition compared to the meta-rhyolite. K-feldspar, quartz, plagioclase, amphibole, orthopyroxene and epidote have been found as the phenocrysts in the meta-crystal tuff. Most of the collected meta-crystal tuff samples have a heavily chloritized, fine-grained groundmass without any unique rock fabrics. Only a small quantity of meta-crystal tuff is observed to preserve its original non-welded (Figure 3 *b*) and welded texture (Figure 3 *c*). In rare instances, garnet (Figure 3 *d*) and chlorite pseudomorphs after garnet are found as accessory minerals within the meta-crystal tuff.

Zircon grains were separated from three Gerik–Dinding meta-volcanic rock samples weighing about ~3 kg each. Conventional heavy liquid and magnetic separation techniques followed by hand-picking under a binocular microscope were used to get pure zircon fraction. After mounting the zircon grains in epoxy, polishing and carbon-coating, they were examined using cathodoluminescence (CL) imaging. The CL images of zircon grains were acquired using a JEOL JSM-6360LV scanning electron microscope (SEM) at the Institute of Earth Sciences, Academia Sinica, Taiwan. The U–Pb isotope analysis of zircon grains from rest of the four samples was done at the Department of Geosciences, National Taiwan University, Taiwan, using a New Wave UP-213 laser ablation system coupled with Agilent 7500s inductively coupled plasma-mass spectrometer (ICP-MS), following analytical procedures described in Chiu *et al.*[28]. The U–Pb age determination was made in 35 μm diameter areas within single zircon grains using laser ablation at an energy output of 41% with densities of 6.36 J/cm^2 and 5 Hz repetition rate. Data acquisition time for each spot was about 100 s (50 s gas blank followed by 50 s ablation). The GJ-1 zircons were used as a standard for instrumental drift correction, which yielded an average ^{207}Pb/^{206}Pb age of 607.5 Ma during experimental runs. This value close to the standard age of 608.5 Ma by thermal ionization mass spectrometry (TIMS) analyses by Jackson *et al.*[29]. All U–Pb isotopic concentrations were calculated using the GLITTER 4.4.4 data reduction software for laser ablation microprobe developed by the ARC National Key Centre for Geochemical Evolution and Metallogeny of Continents (GEMOC). Common lead correction was done using the procedure suggested by Andersen[30]. The calculation of weighted mean U–Pb ages and drawing of concordia plots were carried out using Isoplot version 4.15 (ref. 31).

The zircon grains extracted from the Gerik–Dinding meta-volcanic rock samples in this study are characteristically yellowish-brown to colourless, transparent, euhedral and display long to short prismatic forms. The zircon

Table 1. GPS coordinates of sample localities, rock types and summary of the age results

Sample	GPS coordinates	Rock type	Age (Ma) (2σ)	Mean square weighted deviation
TEMNG-1	5.408730°N, 101.299290°E	Meta-rhyolite	474.2 ± 2.9	2.3
BERU-1	5.393630°N, 101.339990°E	Meta-rhyolite	460.0 ± 2.4	1.4
DIND-1	3.204780°N, 101.777505°E	Meta-crystal tuff	479.1 ± 3.3	2.2

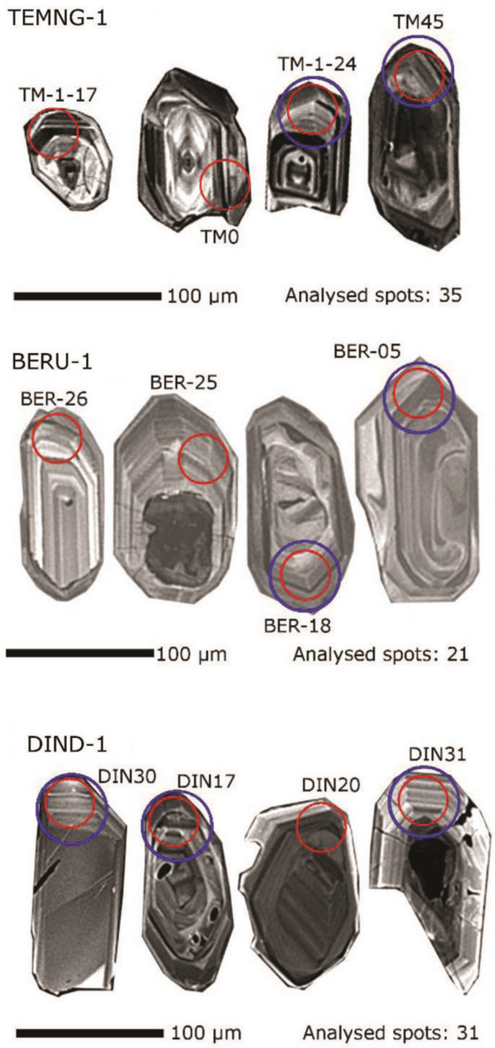

Figure 4. Cathodoluminescence (CL) images of representative zircon grains from Gerik–Dinding meta-volcanic rocks. Red and blue circles show the locations of U–Pb dating and Hf analyses respectively. Scale bar on the CL images is 100 μm.

crystals normally have lengths of 100–250 μm. In CL images (Figure 4), almost all of the zircons show oscillatory zoning indicative of magmatic growth[32,33]. As reported by Rubatto and Gebauer[34], bands rich in U and Y appear dark in CL images, and brighter areas are relatively poor in those trace elements. Zircons with rounded or oval shapes and complex internal textures are rare. The U–Pb age results are plotted in concordia diagrams and weighted mean diagrams (Figure 5). Most of the zircon U–Pb data are concordant and form consistent populations. All the age errors are given at the 2σ level. Table 1 summarizes the coordinates of sample localities, rock types and age results. The older zircon ages from the meta-volcanic rock samples (~1650 and ~1850 Ma) are significant in the compilation of Australian igneous events[35]. Although few in numbers, they may suggest that Western Peninsular Malaysia has been contiguous with Northern Australia during the Early Palaeozoic[36].

According to paleogeographic reconstruction, during the Early Palaeozoic, Sibumasu Terrane (Western Peninsular Malaysia) was located in the north of the East Gondwanan Proto-Tethys margin (Figure 2). Based on Early Palaeozoic tectonic model in Baoshan (Southern Sibumasu) from previous studies[6,7,37], an Andean-type magmatism was almost certainly present along the East Gondwanan proto-Tethyan margin by ca. 530 Ma, and ended after the collision with Asian micro-continental fragments ca. 510 Ma. After the collision, slab break-off is considered to have taken place at ca. 500–490 Ma and was followed by lithospheric thickening ca. 490–475 Ma (ref. 38). The subsequent lithospheric delamination ca. 475–460 Ma triggered an extensive magmatism which finally waned off ca. 450 Ma (ref. 39). Although Cambrian arc-related volcanic rocks are not well exposed in the Northern Sibumasu Terrane (Western Peninsular Malaysia), reports of the Bawdwin Volcanics in the Burmese (Myanmar) Early Palaeozoic succession[9] and the discovery of Cambrian Khao Tao orthogneiss in Peninsular Thailand (Central Sibumasu)[40] suggest that the Early Palaeozoic Andean-type subduction of East Gondwana Proto-Tethys margin and the associated orogenic event can be reasonably extended to this region.

Zircon U–Pb dating indicates that the Gerik–Dinding meta-volcanic rocks in Western Peninsular Malaysia were formed between 480 and 460 Ma, hence revealing the first robust evidence for the presence of Early to Middle Ordovician volcanism. The formation age of the Gerik–Dinding meta-volcanic rocks (480–460 Ma) is synchronous with the post-collision stage of the final amalgamation of Asian micro-continental fragments to the East Gondwana Proto-Tethys margin. We suggest the formation of the parent magma of meta-volcanic rocks may have been related to the post-collision lithospheric delamination following the lithospheric thickening from the collisional accretion of Asian micro-continental fragments to the East Gondwana Proto-Tethys margin. Tectonic processes such as lithospheric delamination during the

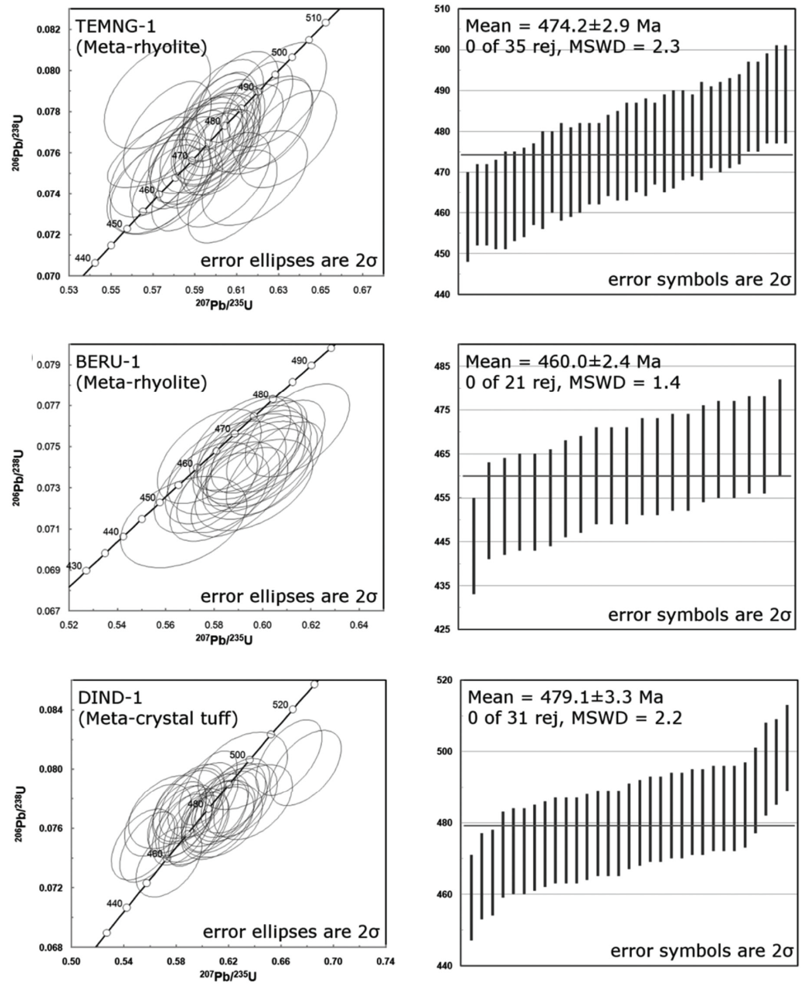

Figure 5. Zircon U–Pb age concordia and weighted average plots.

post-collision period would have induced the hot asthenosphere to underplate continental crust and trigger crustal anataxis to generate the parent magma for volcanic protoliths which have given rise to the meta-volcanic rocks.

However, the discussion is generally based on the current data in relation to the Early Palaeozoic geology of the terranes along the Gondwana Proto-Tethys margin. An appropriate explanation for tectonic setting of Gerik–Dinding meta-volcanic rocks should be supported by further geochemical and isotope evidence. With these new findings, the tectonic history of Peninsular Malaysia, especially of the Early Palaeozoic period needs to be carefully revised, to work out the geochronological continuity of Early Palaeozoic East Gondwana Proto-Tethys margin magmatic belt from Peninsular Malaysia to Southwest China.

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