

Review

Geochemical and Age Constraints on Devonian Black Shales and Limestones in Myanmar: Insights into Gold Source Rocks

Charles Makoundi^{1,*}, Jordan Sheppard¹, Khin Zaw¹, Tin Aung Myint², and Naing Win³

¹ Centre for Ore Deposit and Earth Sciences (CODES), University of Tasmania, Hobart, Tasmania, Australia

² Department of Geology, Magway University, Magway, Myanmar

³ Geology Department, Mandalay University, Mandalay, Myanmar

* Correspondence: c.makoundi@utas.edu.au

ABSTRACT

Pyrite trace element chemistry, lithogeochemistry, and U–Pb dating of detrital zircon were carried out on the Devonian black shales and limestones, Northern Shan State, Myanmar. The findings indicate that the Upper to Middle Devonian Padaukpin Formation is enriched in CaO and show a similar content in SiO₂, TiO₂, Al₂O₃, Fe₂O₃, and K₂O compared to Post-Archean Australian Shale (PAAS). The Middle Devonian Wetwun Formation is depleted in SiO₂, TiO₂, Al₂O₃, Fe₂O₃, and K₂O but enriched in CaO relative to PAAS. The Lower Devonian Zebingyi Formation is enriched in CaO and strongly depleted in SiO₂, TiO₂, Al₂O₃, Fe₂O₃, and K₂O compared to PAAS. Total organic carbon (TOC) remains high in the Lower Devonian between 5% and 9.7% (mean = 8%) but drops in the Middle Devonian to value of 2.5% to 3.2% (mean = 2.9%), only to rise again in the Middle to Upper Devonian to 9.7%. Using trace element (TE) and TOC%, the contents of trace elements Mo, As, Zn, Cu, V, and Ni are inversely proportional to the TOC content in the Upper and Middle Devonian. Pyrite trace element chemistry shows that the beginning of the Middle Devonian, in the Lower Wetwun black shale, is marked by elevated levels of the gold (up to 1.1 ppm Au), which corresponding to a peak in oxygen content in the atmosphere (up to 28.7 wt% O₂) in oxic to anoxic redox conditions. The evidence suggests that the Wetwun shales are likely gold source rocks. The research outcome indicates a limited dataset of age dating pointing to three maximum depositional ages of 399, 480, and 537 Ma. There are a few zircon age peaks ranging from over 400 Ma up to 2500 Ma, suggesting a discernible connection with Gondwana; however, further work is required to confirm this relationship.

ARTICLE INFO

History:

Received: 23 June 2026

Revised: 09 August 2026

Accepted: 23 September 2026

Published: 29 September 2026

Keywords:

Devonian;
black shales;
pyrite;
zircon;
gold;
Myanmar

Citation:

Makoundi, C.; Sheppard, J.; Zaw, K.; et al. Geochemical and Age Constraints on Devonian Black Shales and Limestones in Myanmar: Insights into Gold Source Rocks. *Habitable Planet* **2026**, *2*(2), 468–489. <https://doi.org/10.63335/j.hp.2026.0049>

Research Highlights

- The Lower Wetwun black shales are gold source rocks (up to 1.1 ppm Au).
- Elevated gold content corresponds to a peak in oxygen content (up to 28.7 wt% O₂).
- Zircon age peaks range between 400 Ma and 2500 Ma.
- Discernible connection with Gondwana is likely.

1. Introduction

The geological and stratigraphic setting of Paleozoic sequence of Northern Shan State, Myanmar have been documented by La Touche prior to World War II as landmark memoirs of Geological Society of India during the British colonial period [1]. Modern geological works were followed by overseas projects including foreign and Myanmar geologists though limited in scope, occurring periodically throughout time [2–7]. During the Late Palaeozoic, Myanmar region has been fragmented as part of the Paleo-Tethys Ocean of the Northern Gondwana which was in the southern hemisphere at the time and the Greater Gondwana was later drifted and rotated counterclockwise [8, 9]. This counterclockwise rotation also opened and separated off several crustal slivers from Gondwana such as North and South China, Tarim, Indochina, East Malaya, West Myanmar and Sumatra terranes and the Paleoclosure of the Tethys Ocean resulted in Proto-Myanmar region to form into what Myanmar region is today. In Southeast Asia, black shales are known to be host rocks in many orogenic gold deposits [10, 11]. In Myanmar, the Devonian black shale and limestone formations have not been studied to determine their trace element contents, let alone assess whether they present characteristics of gold source rocks. They also have limited detrital zircon age data. To address this knowledge gap, this research documents the major and trace element composition of Devonian black shales and limestones and the redox conditions during deposition. Additionally, the trace element content of sedimentary pyrite is documented with emphasis on gold content across the Wetwun, Padaukpin and Zebingyi Devonian formations and how it all relates to the variation of other trace elements on the seafloor.

2. Tectonic and Geological Setting

The district-scale geology and stratigraphic setting of the area between Mandalay and Pyin Oo Lwin Township was documented by previous researchers and the authors own observations and field studies [1, 2, 4, 6, 12]. Pyin Oo Lwin Township is situated 67 km east of Mandalay, nestled in the mountainous region of the Shan Scarp in Northern Shan State. Tectonically, the study area lies within the

Sibumasu Terrane (Figure 1), locally referred to as the Sino-Burman Ranges of the Shan Scarp.

The Sibumasu Terrane encompasses western Thailand, western Peninsular Malaysia, eastern Myanmar, and northeastern Sumatra [13–16] and is bordered by the Sagaing Fault and Mogok Metamorphic Belt in the west in Myanmar and the Inthanon Terrane to the east in Thailand. In the last thirty or so years, researchers such as [17, 18] and most Thai geologists have used the term Shan-Thai Terrane in the same sense as Sibumasu, although [17] did not include Baoshan or Sumatra in his original usage.

To the north, Sibumasu is generally considered to include the Baoshan and/or Tengchong terranes in western Yunnan [19]. Based on detrital zircon studies in the Malay Peninsula, the Sibumasu Terrane basement has been suggested to be primarily Palaeoproterozoic (1.9–2.0 Ga) [20, 21].

Recent studies have found that the detrital zircon population of the Late Cambrian–Early Ordovician Tarutao Sandstone in Sibumasu has a strong statistical resemblance to that of the Ordovician Tumblagooda Sandstone in Western Australia [9].

The Nan-Uttaradit-Sra Kaeo Suture zone separates the Sukhothai Fold Belt from Indochina. In Malaysia, the Sibumasu Terrane is separated from the Indochina/East Malaya Terranes by the Bentong-Raub Suture Zone (BRSZ). The terranes moved away from the northwest Gondwana margin during the Phanerozoic and resulted in the opening and closure of the Palaeo-, Meso- and Neotethyan (or Cenotethys) Oceans.

The drive from Mandalay to Pyin Oo Lwin Township passed through a well-defined sequence of Paleozoic geological formations, showcasing outcrops ranging from the Cambrian to the Silurian, which are actively quarried for limestone from the Nyangbaw Formation. The Lower to Upper Devonian succession is represented by the Zebingyi and Wetwun Formations, respectively, while Permian-aged rocks are present within the Shan Plateau Limestones. These stratigraphic units have been well-constrained through fossil-based biostratigraphic dating, providing a reliable framework for understanding the geological history of Northern Shan State. The geological map is presented in Figure 2.

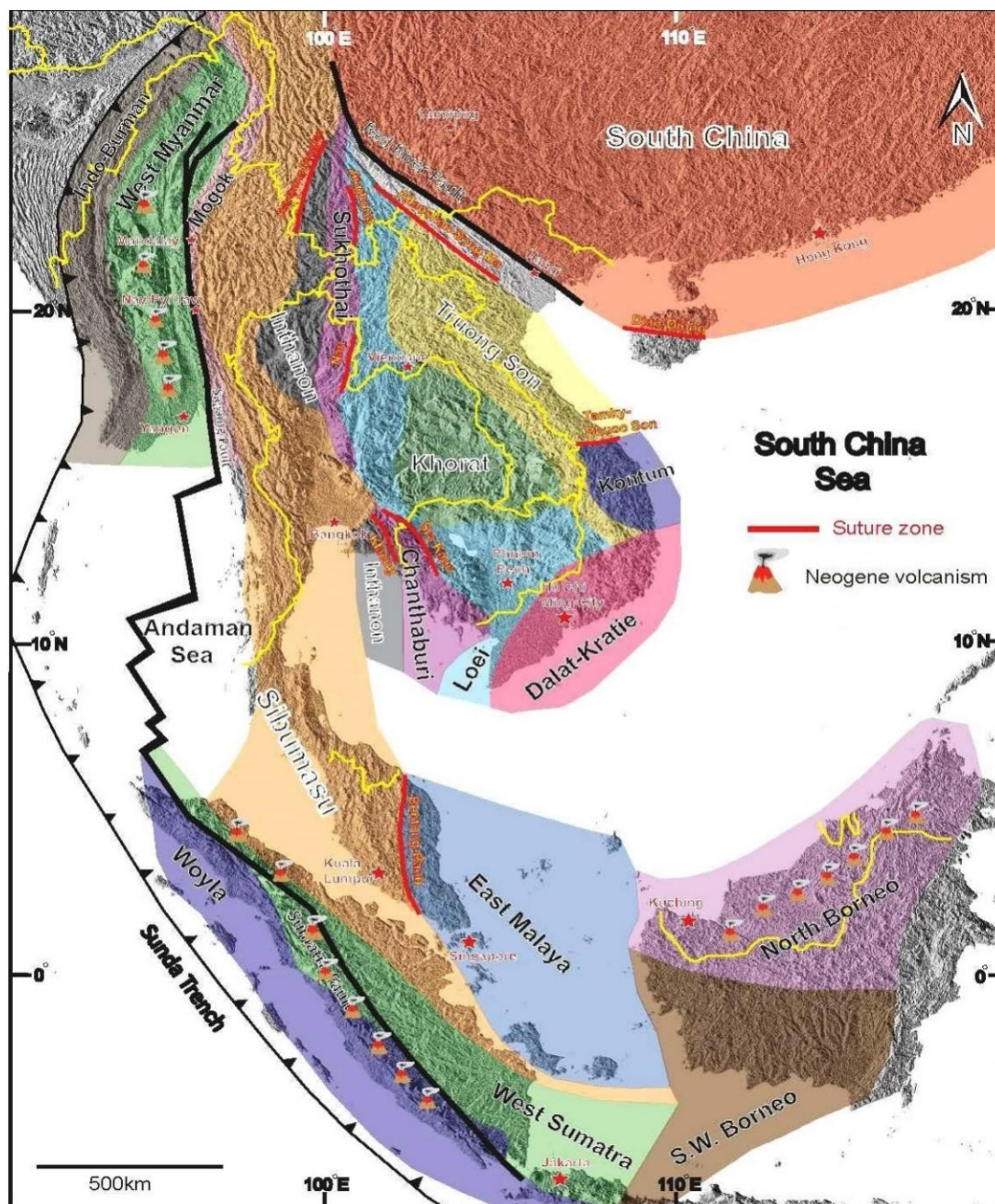


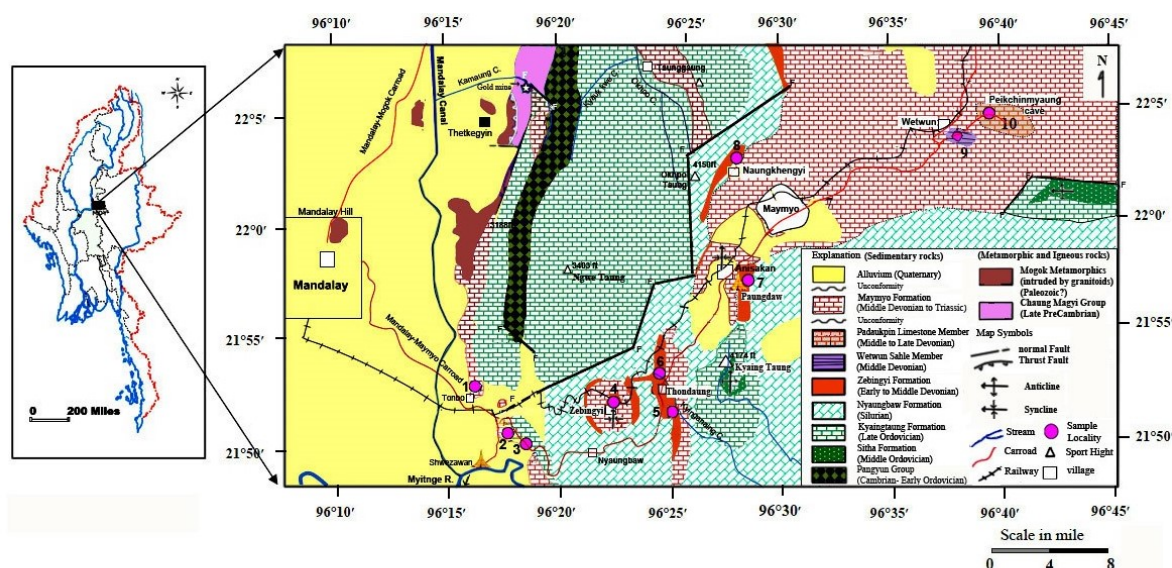
Figure 1. Tectonic setting of SE Asian region modified from [5, 7, 22]. Location of the studied area is shown in yellow rectangle in the top hand corner and the geology is presented in Figure 2.

2.1. The Cambrian Ngwetaung Group

This Group is a sandstone bed which has been dated due to the presence of Late Cambrian sauikiid trilobites [4, 6]. The Bawdwin Volcanic formation is a 1000 m thick [22] is the equivalent to the Ngwetaung Group or possibly ranges to Lower Ordovician and is a massive, hard, reddish grey dense rhyolite tuff with other volcanoclastic sediments. This unit is hosting the Bawdwin Lead-Zinc-Silver (Pb–Zn–Ag) deposit, which appears to be a mixed SEDEX-VHMS deposit [7].

2.2. The Naung Kangyi Group

The most prominent outcrops of Ordovician age occur between the city of Mandalay and the Township of Pyin Oo Lwin (Figure 2). This group is called the Naung Kangyi Group which has the “Lokepyin Formation (Early Ordovician) and the Sitha Formation (Middle Ordovician) which conformably lies in between the Lokepin Formation (Lower Ordovician) and underlies the Kunlein formation (Late Ordovician). The uppermost unit is the Khun Lein Formation, and the Hwemaung purple shale member, dated as Late Ordovician [4, 6].



1 – Tonbo quarry, 2- AAA cement factory, 3- chlorite schist, 4- Zebingyi village, 5- Kyinganaing, 6-Tondaung, 7- Paungdaw Pagoda, 8- Sinlan Dam near Naungkhangyi, 9- Wetwun shale at Kyuntabin village near Wet wun and 10- Padaupin Limestone near Pyeichinmyaung Cave

Figure 2. Geological map of the Northern Shan State, Myanmar, and location of samples in this study, after [23].

2.2.1. The Lokeyin Formation

This Formation of Early Ordovician age consists of well-defined beds of blueish limestone interbedded with thin layers of silts, with other yellowish to brown siltstone sequences contained within. There are also fossils found within the sequence such as small brachiopods *Nanorthis* ssp., and trilobites *Aulacoraria* sp. which indicated that the rock formations are early Ordovician [4, 6].

2.2.2. The Sitha Formation

The Middle Ordovician Sitha Formation is made up of a limestone unit, which consists of medium to thickly bedded grey to dark grey/blueish, reddish limestone [4, 6]. The formation is bioturbated locally and this unit is known as the Burrow Limestone. There is also oolitic limestone encountered in specific outcrops in the area. Fossil nautiloids (*Actinoceras sithaensis* sp., *Ormoceras* sp.) as well as the well-known bryozoan *Diplotrypa*, indicated a depositional age of Middle Ordovician [4, 6]. The limestones are interbedded with brown to yellowish brown siltstone units.

2.2.3. The Khun Lein Formation

The Khun Lein Formation of Late Ordovician age consists of thin to medium bedded calcareous mudstones with minor silt laminations and buff coloured siltstone and claystone [4, 6]. There is a layer of calcareous shale which is 120 cm thick, also found within the unit. The sequence also contains fossils such as bryozoan, crinoids, brachiopods, and cystoids. These fossils are more abundant in the yellow siltstone beds.

2.3. Nyangbaw Formation and the Namhsim Sandstone

These units of Silurian in age are represented by Nyangbaw Formation and the Namhsim Sandstone. These overlays the Hwemaung Purple Shale of Late Ordovician age [4]. The Nyangbaw Formation consists of limestones with prominent phacoidal texture formed due to differential weathering of silty layers, which are medium to thick bedded reddish grey colour, and sometimes interbedded with bands of red clays.

2.4. Devonian Formations

The Devonian Formations appear to have formed in a pelagic environment, with slow sedimentation, in both shallow and deep waters in a low energy environment below the wave base. This was affected by storm events. The ocean sea level continues to drop throughout the Devonian [4, 6, 24]. The stratigraphic sequence and lithologic characteristics are shown in Figures 3 and 4.

2.4.1. Zebingyi Formation

The Zebingyi Formation consists of three stratigraphic units, the Doganaing Chaung Orthoquartzite members, the In-ni Chaung limestone member and the Khinzo Chaung limestone [4, 6, 24]. The Khinzo Chaung limestone consists of blackish limestones, which are separated with layers of black shales and buff coloured siltstone with their base marked by a change of lighter coloured calcareous mudstone darkening to a grey with wavy calcareous silty bands in the unit. The In-ni Chaung limestone is marked by a light grey, thinly bedded partly dolomitised unit [4, 6]. There is then the Doganaing Chaung Quartzose sandstone unit which is a clast-supported monomict conglomerates, associated with light grey calcareous mudstone, and a pink-brown siltstone [4, 6, 24].

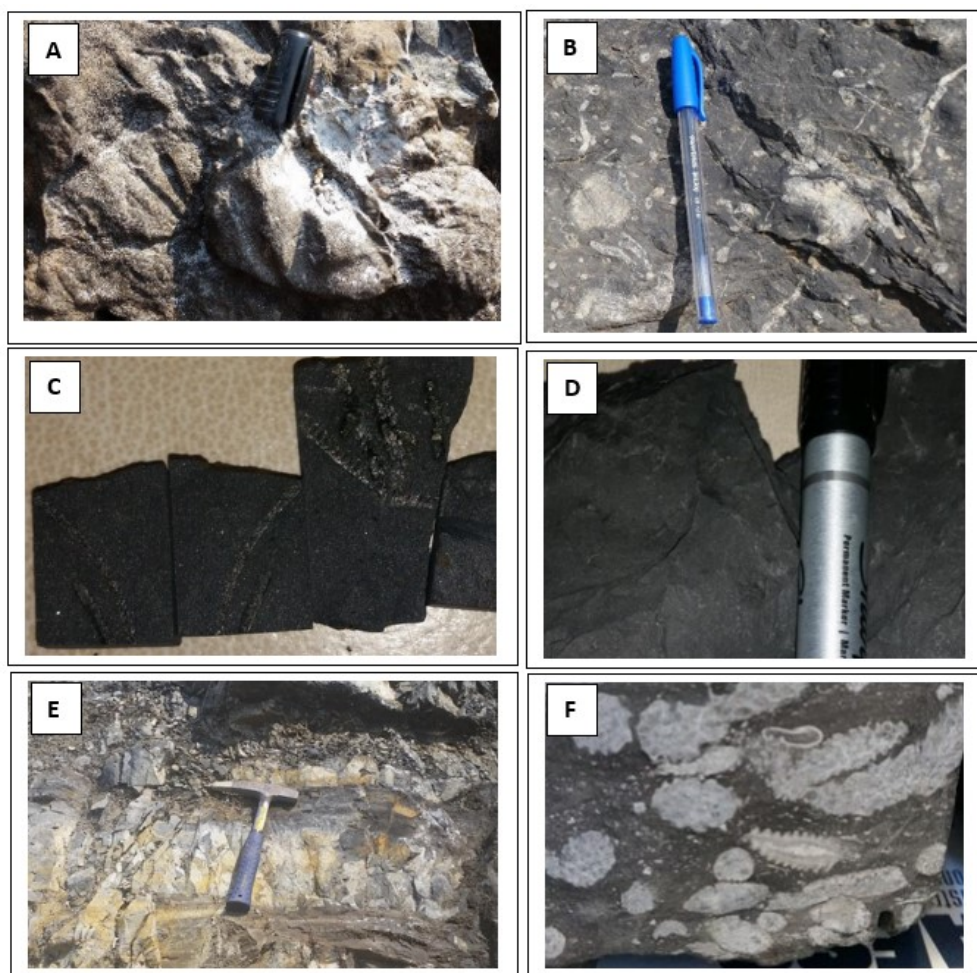


Figure 3. Outcrops and hand samples of the selected units. (A) Outcrop of Maymyo Formation of the Upper Devonian. (B) Padaukpin limestone outcrop overlying the Wetwun shales. (C) Pyritized graptolites in the Padaukpin limestone. (D) Wetwun black shales of the lower part of the Upper Devonian. (E) Black shales of Lower Devonian Zebingyi Formation found near the Indha Village. (F) Padaukpin limestone consists of medium bedded dolomitic limestones containing fossils such as Bryozoa and Corals.

2.4.2. Middle Devonian Maymyo Formation

The Maymyo Formation runs through the Middle and Upper Devonian. In the Middle Devonian, the two distinct units found are the Wetwun shale and the Padaukpin limestone Formation.

The Wetwun shale is a black shale that contains fossils of brachiopods, bivalves, bryozoan, graptolites, tenaculites, and trilobites [4]. From field observations, it is believed that the Padaukpin limestone was deposited on top of the Wetwun Shale [3]. The limestones would also form in shallow marine waters as coral formation requires shallow seas for the organisms to survive. The lithology of the Padaukpin limestone consists of medium bedded Mg-rich dolomitic limestones containing fossils such as Bryozoa and Tabulate corals. It is also interbedded with black shaley limestones and dark grey shales. There are localised thin layers of black shales interbedded with the limestones [4, 6].

2.4.3. Upper Devonian Formations

The Maymyo Formation stratigraphically appears at the beginning of the Upper Devonian and occurring in the Northern Shan State [3, 4] (Figure 4). The lithology of the Maymyo Formation is purple to red calcareous limestones that contain ammonoids, nautiloids, and gastropods [4]. The depositional environment is interpreted to be a pelagic setting [4, 6].

In this study sedimentary pyrites show a variety of textures (Figure 5). The Lower Devonian Zebingyi Formation pyrite size from 18 μm to 22 μm ; the Middle Devonian Wetwun Shale pyrite size varies from 8 μm to 25 μm and the Middle to Upper Devonian Padaukpin Limestone average pyrite size ranges from 9 μm to 15 μm . Any pyrites that may have been either massive euhedral pyrites or pyrites cutting across the bedding were not selected. The detection of zonation in pyrite has been done by etching with nitric acid (HNO_3).

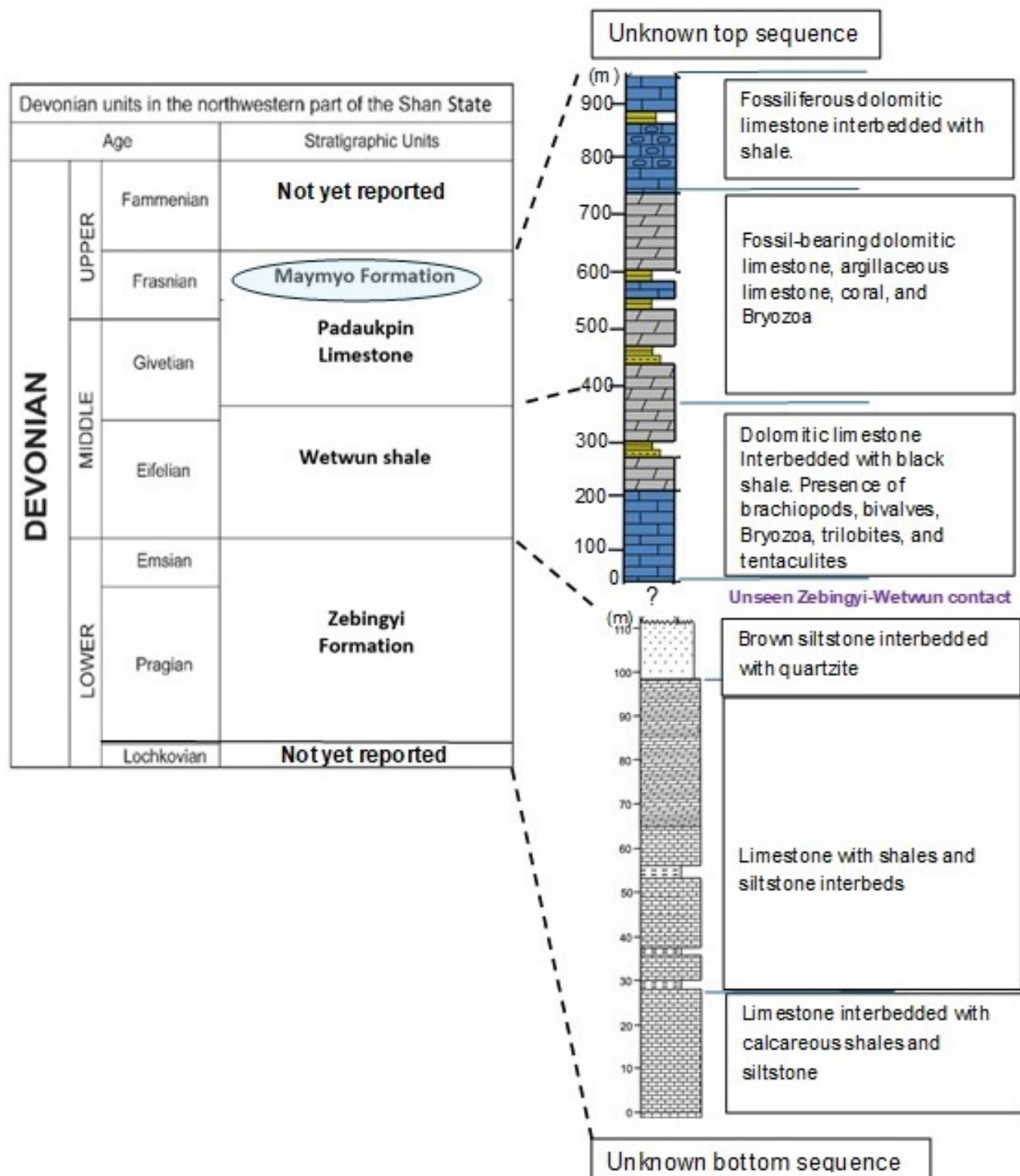


Figure 4. Interpretative Devonian lithostratigraphy in the northwestern part of the Shan State, Myanmar (modified after [3, 4, 6]).

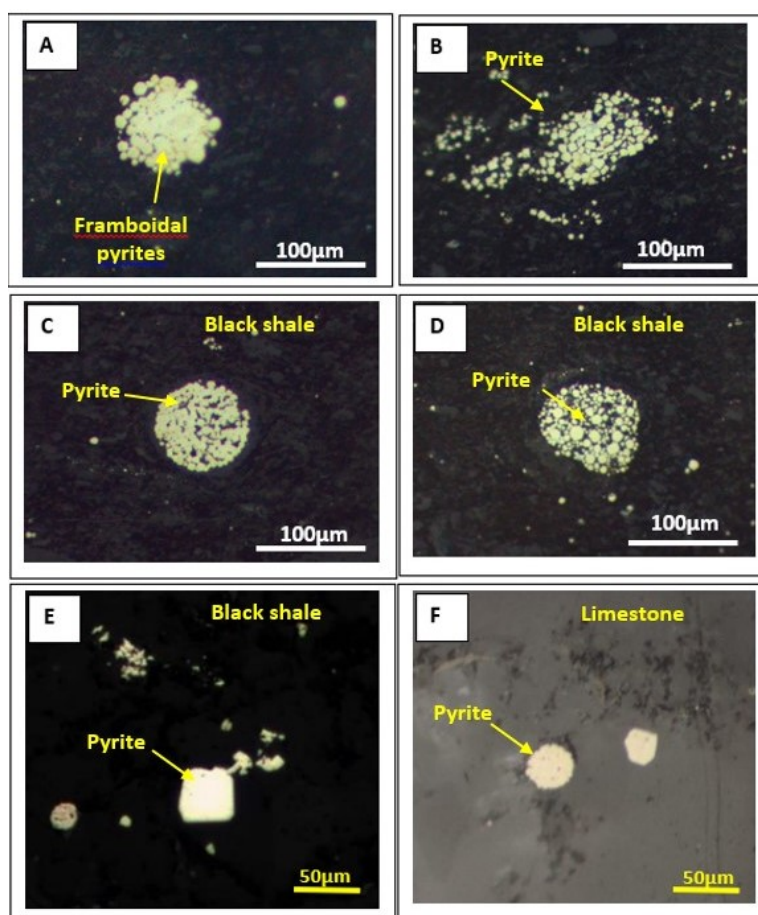


Figure 5. Textural features of sedimentary pyrite from the Devonian shales and limestones, Myanmar. (A) Pyrite framboids found from the Wetwun Formation. (B) Disseminated microcrystals of sedimentary pyrite from the Wetwun Formation. (C) Pyrite framboids from the Wetwun Formation. (D) Framboidal pyrites from Zebingyi Formation. (E) Euhedral clean pyrite and disseminated framboids from the Zebingyi Formation. (F) Pyrite framboid and subhedral pyrite from Padaukpin Formation.

3. Methodology

3.1. U–Pb Detrital Zircon Dating

The Zircon mounts are used for dating using the LA-ICP-MS technique. Zircons are ideal for dating because they are very robust (physically and chemically), making them ideal for extraction out of whole rock sample. Zircon readily incorporates uranium into its crystal structure, while lead does not readily incorporate into the zircon crystal lattice. This means when the Zircons form and grow, there is no little to no lead in the structure of the zircons. However, as the zircons age, radioactive decay of U occurs, which turns into Pb. These elements and their isotopes remain trapped in the zircon allowing for their ratios to be analysed [25]. These ratios are then compared to datasets, allowing for accurate and precise ages to be calculated. Alpha decay will damage the crystal lattice of Zircons, leading to lead-loss, as the fission tracks act as a conduit within the crystal lattice, transporting and allowing the lead isotopes to leach from the zircon [25]. Undamaged zircons retain the lead formed from radioactive decay of U [25].

U–Pb isotope dating of three samples was conducted using LA-ICP-MS, by measuring the uranium isotopes and the lead isotopes of Zircons (ZrSiO_4) to provide first order interpretation for the provenance. This method is one of the oldest and most refined dating methods, and is highly accurate, usually within ± 10 million years. Zircons are also excellent for measuring U–Pb because they are rigid, not breaking easily during diagenesis, they can withstand high temperatures (900 °C) before they melt and are chemically inert. This gives certainty of less contamination of foreign U and Pb, making U–Pb dating an accurate dating method [26].

Zircon measurements were conducted on an Agilent 7900 quadrupole ICPMS resonetics resolutions system, which is equipped with a Coherent COMPex Pro Ar-F Excimer using a laser wavelength of 193nm, specific for silicate and U–Pb geochronology. This is coupled with a Resonetics S155 ablation cell. All the analyses were conducted at the University of Tasmania. Corrections for instrument drift, mass bias correction factors and downhole fractionation, were calculated through the utilisation of the primary standard for Pb/U ratios, 91,500, and on a sec-

ondary standard called Tremora [27]. The standards were analysed at the beginning of the session and after every 15 zircons unknowns (or 30 min; whichever comes first). Using the same spot size (32 μm and the laser energy of 5 Hz was used for all analyses).

The corrections done on the $^{207}\text{Pb}/^{206}\text{Pb}$ were calculated using spots on NIST610 which the standard is used. These are analysed after every 30 zircons which had been analysed using values from [28]. Each unknown was analysed first for 30 s to measure background before the laser was switched on, and then for another 30 s of analysis. The samples that were analysed had spot sizes of 32 μm using the laser at 5 Hz. He (Helium) gas carries the ablated particles from the sample chamber where it mixes Ar (Argon) gas to a plasma torch and passes through to the mass spectrometer. Where the isotopes ^{49}Ti , ^{56}Fe , ^{90}Zr , ^{178}Hf , ^{202}Hg , ^{204}Pb , ^{206}Pb , ^{207}Pb , ^{208}Pb , ^{232}Th , ^{235}U and ^{238}U are measured. Each element is measured for 0.17 s intervals although Pb isotopes are measured longer (0.35 s intervals). The data is calculated using methods outlined by [29].

Zircons also give relative probability of zircon age peaks, which is useful at determining the provenance of not only the detrital zircons found in each sample, but also the source of the sediment. These can be compared to well-defined terranes, which can be used to help determine the source of sediments for a terrane.

3.2. X-ray Fluorescence Analysis (XRF)

Seven samples were analysed: four samples from the Lower Devonian, two samples from the Middle Devonian and one sample from the Middle–Upper Devonian. The Olympus Delta Premium handheld XRF was used to measure the whole rock geochemical makeup of the samples. This is a non-destructive rapid analytical. The whole rock samples had a clean face cut using the rock saw as to get the most accurate and precise results from the handheld XRF. The drawback being high detection limits compared with other analytical techniques. This was set up in a special mount that put the optics in a confined X-ray proof space, allowing for measurements to be made consistent. Using the geochemical function, the handheld XRF would take a 160 s measurement per sample using just two beams of X-rays. The standards used were Blank SiO_2 which was pure quartz sand, TAS Dior which is Tasmanian Diorite, TAS GRAN which is Tasmanian granite, TAS BAS which is Tasmania Basalt and GXR5 539. The XRF also calibrates itself to Fe using a steel instrument monitor (a round metal disc). Samples that were considered homogenous were only analysed with the XRF device once. Samples such as JS-27, which contained a lot of coral in the matrix were analysed in an area with mixed coral and matrix.

The handheld XRF measured 8 major elements in oxides weight percent (wt%), with SiO_2 (Silicon dioxide), TiO_2 (Titanium dioxide), Al_2O_3 (Aluminium oxide), Fe_2O_3 (Iron oxide), MgO (Magnesium oxide), CaO (Calcium oxide), K_2O (Potassium oxide), SO_3 (Sulphur trioxide).

The handheld XRF analysed 25 Trace elements which were Mn (Manganese), P (Phosphorus), Cr (Chromium), Ni (Nickel), V (Vanadium), Cu (Copper), Zn (Zinc), Mo (Molybdenum), Cd (Cadmium), W (Tungsten), Pb (Lead), Se (Selenium), Rb (Rubidium), Sr (Strontium), Hg (Mercury), Th (Thorium) and U (Uranium). Certain elements like Cl (Chlorine), Co (Cobalt), Ag (Silver), Sn (Tin), Sb (Antimony), Bi (Bismuth) were analysed; however, these elements were below the limit of detection (LOD) for all samples. Phosphorus (P) had detection limits of 1000 ppm; however, phosphorus levels were below the limit of detection (LOD). The phosphorus was detected in the whole rock analysis of the standard. The Arsenic (As) data was not reliable. This was because the standard has a known value of 0.5 ppm, yet the handheld XRF was giving values of 18 ppm. This would give inaccurate results when analysing for As in the samples. The data was reduced into wt% for major elements, and ppm for trace elements. The element Al_2O_3 was converted into Al% by multiplying the $\text{Al}_2\text{O}_3 \times 0.52926$. This is then converted into Al ppm by multiplying $\text{Al}\% \times 10,000$.

We use the results of trace element composition to estimate redox conditions that prevailed in the Devonian time. Based on previous work, the proxies V/Cr, $\text{V}/(\text{V} + \text{Ni})$, and U/Th are put together to interpret the redox conditions [30, 31]. The ratio $\text{V}/\text{Cr} < 2$ indicates oxic conditions, ranging from 2 to 4.5 implies dysoxic, and >4.5 points to anoxic conditions. The ratio $\text{V}/(\text{V} + \text{Ni}) < 0.46$ points to oxic environment, ranging from 0.46 to 0.60 indicates dysoxic, between 0.54 and 0.82 characterizes anoxic and >0.84 implies euxinic conditions. The ratio $\text{U}/\text{Th} < 0.75$ points to oxic conditions, ranging between 0.75 and 1.25 is associated with dysoxic conditions, and >1.25 indicates anoxic conditions.

3.3. Trace Element Geochemistry of Pyrite

Trace element geochemistry of pyrite was undertaken using LA ICP-MS facilities at Centre for Ore Deposit and Earth Sciences (CODES), University of Tasmania, Hobart, Tasmania. Analyses were carried out using a Newwave UP213 laser ablation microprobe coupled with an Agilent 7500 or 7700 ICP-MS. Samples were ablated in He and mixed with Ar before reaching the ICP-MS. The standard was analysed at regular intervals during analysis to correct for drift and mass bias. To minimize surface contamination, sulphides were pre-ablated with laser pulses. The background gas levels were monitored for 30 s before analysis. The laser shutter was then opened, and the pyrite grains were ablated for about 60–70 s at a firing rate (frequency) of 5 Hz and a laser fluence of 3.5 J/cm^2 . The pyrite spot sizes used were 10, 15, 20 and 22 μm .

Statistically, there were 10 grains per sample and 8–12 spots per grains. The standards were analysed first, before the samples. These were preprogrammed, allowing for the standards to be analysed in the same location, and to be reanalysed after each sample had been analysed to work out how much the LA-ICPMS drifts. This was programmed that way so, the laser would analyse the stan-

dards before and after a sample, to account for any drift that might occur. This was repeated, throughout the session. The standards used were STDGL2b2 and GSD-1G to quantify chalcophile and lithophile elements, respectively. The standard STDGL2b2 and GSD-1G were set up at the beginning and the end of each analysis run [32]. The in-house Peru Pyrite standard (Peru Pyrite) was used for quantification of sulphur. The spots sizes for the standards were 80 μm for STDGL2b2, 50 μm for GSD-1G and 20 μm for Peru Pyrite. The standard value for iron concentration was set at 465,000 ppm based on the stoichiometry of pyrite.

4. Results

4.1. U–Pb Zircon Dating

To determine the U–Pb zircon ages of detrital grains, 45 zircon grains were analysed. Using Th/U ratio suggested by [33, 34], the zircon grains in this study mostly have $\text{Th/U} > 0.1$. Samples JS-18 had 91% of zircons above 0.1, with values ranging from 0.07 to 1.08. Sample JS-22 had 90% of zircon values above 0.1, with a range from 0.08 to 2.18. Sample JS-25 had 96% of zircons with values about 0.1, with values between 0.07 and 1.78. The LA-ICP-MS, U–Pb zircon dating results of the 45 zircon grains analysed are presented in Table 1 and the Concordia diagram and probability plots are shown in Figure 6.

The age of sample JS-18, a limestone, was determined to be 399 Ma, which corresponds to the Middle Devonian fossil age of the Maymyo Formation. This age was estimated from one young detrital zircon and maybe considered unreliable.

The sandstone unit (sample JS-22) gave a Lower Ordovician Lokeypin Formation age of 480.3 Ma. The age of sample JS-25, a black shale, is 537 Ma. Peaks in limestone zircon data are found around 500, 1000, and 1500 Ma (Figure 6). Peaks in the sandstone zircon dataset are located around 500, 1000, 1500, and 2500 Ma (Figure 6). In addition, peak ages for black shale are 500, 1000, 1500, 2000, and 2500 Ma (Figure 6). The data is documented in supplementary datasets (see supplementary files S1 and S2). Probability plots and Cathodolumines-

cence (CL) imaging of zircon grains are shown below (Figures 7 and 8).

4.2. Major and Trace Element Composition

Seven black shale samples were analysed using X-ray fluorescence technique. The major and trace element composition is normalised to Post-Archean Australian Shales (PAAS) [35] and are shown in Figure 9.

The Upper-Middle Devonian Padaukpin shales are enriched in CaO and show a similar content in SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 , and K_2O compared to PAAS. The Middle Devonian Wetwun shales are depleted in SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 , and K_2O but enriched in CaO relative to PAAS. The Lower Devonian Zebingyi shales are enriched in CaO and strongly depleted in SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 , and K_2O compared to PAAS. Total organic carbon (2.5–9.7 wt%); and sulfur (0.03–1.4 wt%). Wetwun black shale sample (JS-28) has the lowest TOC content. The Zebingyi black shale samples (JS-4, 8, 20 and 21) have elevated sulfur content with values ranging from 0.04 to 1.4 wt% (Table 2).

Trace elements (TE) such as As, Pb, Se, Mo, Ni, Cu, Zn, Mn, U, and V including TOC have been selected to assess their distribution through the Devonian. The trends of their occurrences are displayed in Figures 11–13 (Section 5). Paleoredox conditions are summarised in Table 3.

4.3. Pyrite Trace Element Composition

The texture and As/Ni ratio (between 0.1 and 10) was used as a proxy for pyrite of sedimentary origin [36]. Using this ratio, the data shows that 100% of Zebingyi pyrites are of sedimentary origin. The Wetwun shale pyrites are all sedimentary origin, with 95% of the pyrites having As/Ni between 0.1 and 10. In addition, 89% of the Padaukpin pyrites are of sedimentary origin.

Ninety-nine spot analyses were performed on selected sedimentary pyrite grains found in black shale and limestone from the Padaukpin, Wetwun, and Zebingyi formations. The results of pyrite trace element chemistry are documented in Table 4 (see supplementary dataset).

Table 1. Maximum depositional age of selected rock samples.

Sample ID	Rock Type	Age (Ma)	$\pm$	Error	Zr Grains
JS - 18	Limestone	399	$\pm$	–	$n = 11$
JS - 22	Sandstone	480	$\pm$	9.9	$n = 10$
JS - 25	Black shale	537	$\pm$	12	$n = 24$

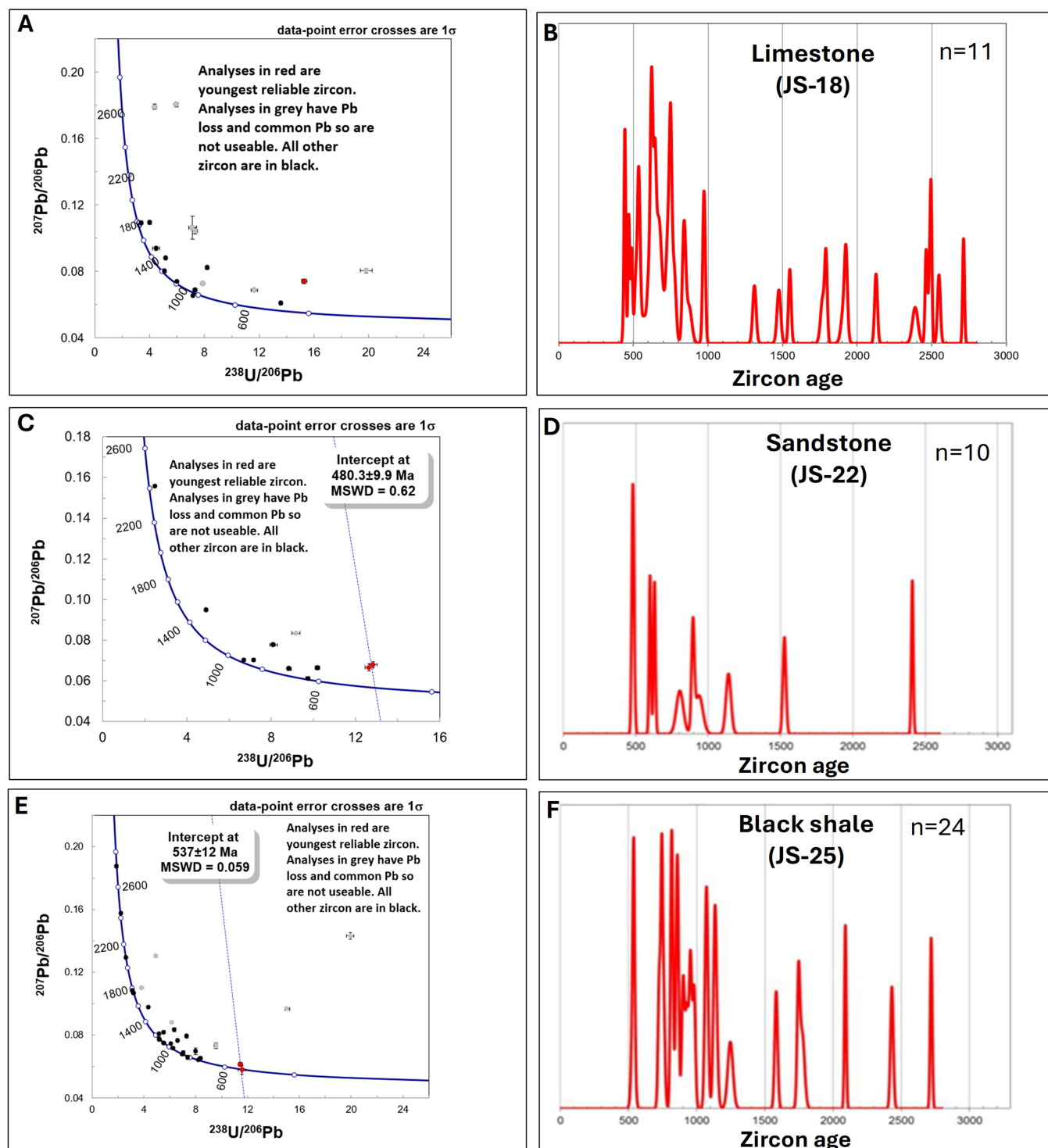


Figure 6. Concordia and probability plots for $^{207}\text{Pb}/^{206}\text{Pb}$ versus $^{238}\text{U}/^{206}\text{Pb}$. (A) Silty limestone from Middle Devonian Maymyo Formation (Sample JS-18). (B) Probability plot of sample JS-18. (C) Concordia plot of JS-22 sandstone from the Lower Ordovician Loekpyin Formation (Sample No. JS-22). (D) Probability plot of JS-22. (E) Concordia plot of black shale, sample JS-25. (F) Probability plot of JS-25.

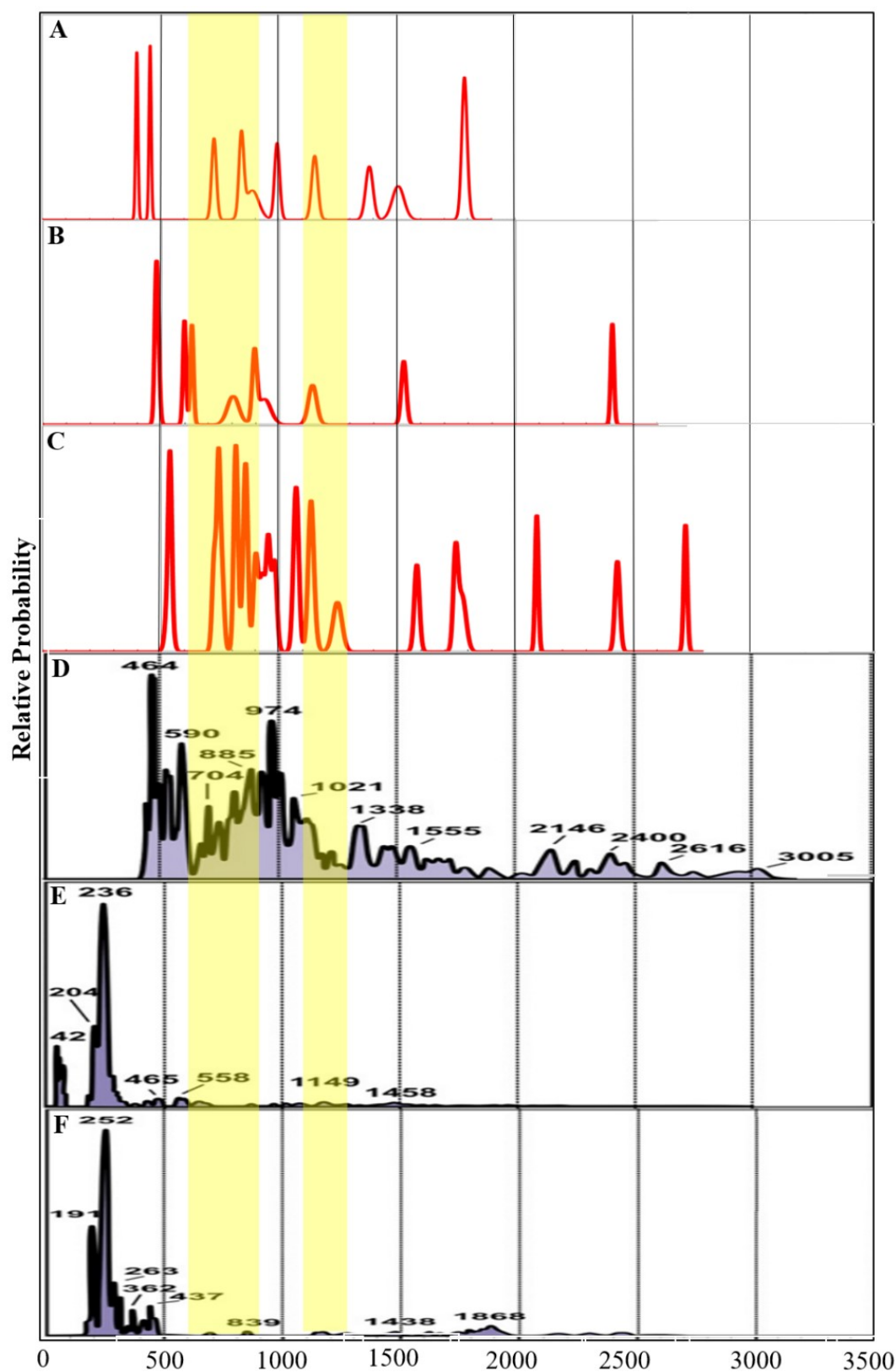


Figure 7. Relative probability plots of zircon grains in the rock samples. (A) JS-18 silty limestone from Middle Devonian Maymyo Formation. (B) JS-22 sandstone from the Lower Ordovician Lokepyin Formation. (C) JS-25 Black Shale, ages at Lower Cambrian. (D) Sibumasu Terrane. (E) Sukhothai Terrane. (F) Indochina Terrane. D, E and F are from [9]. The main peaks are highlighted in yellow.

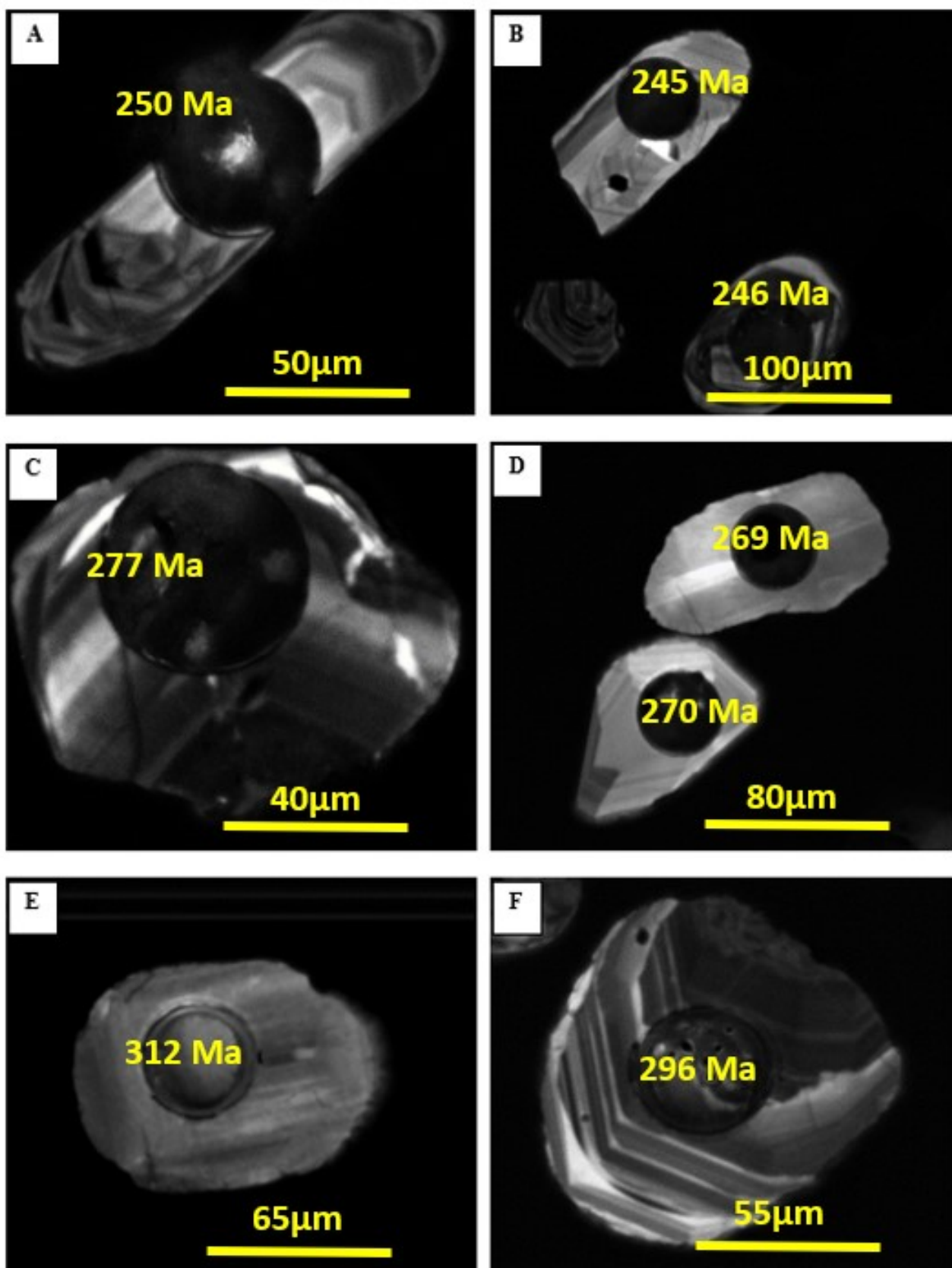


Figure 8. Zircon images photographed using cathodoluminescence, a technique that is useful to visualize the interior of the crystals with the help of a scanning electron microscope. Dark circles on the zircons are the pits left by the laser that was used to analyse the age of the zircons. (A) Zircon from sample JS-18. (B) Zircons from sample JS-18. (C) Zircon from Sample JS-22. (D) Zircons from Sample JS-22. (E) Zircon from Sample JS-25. (F) Zircon from Sample JS-25.

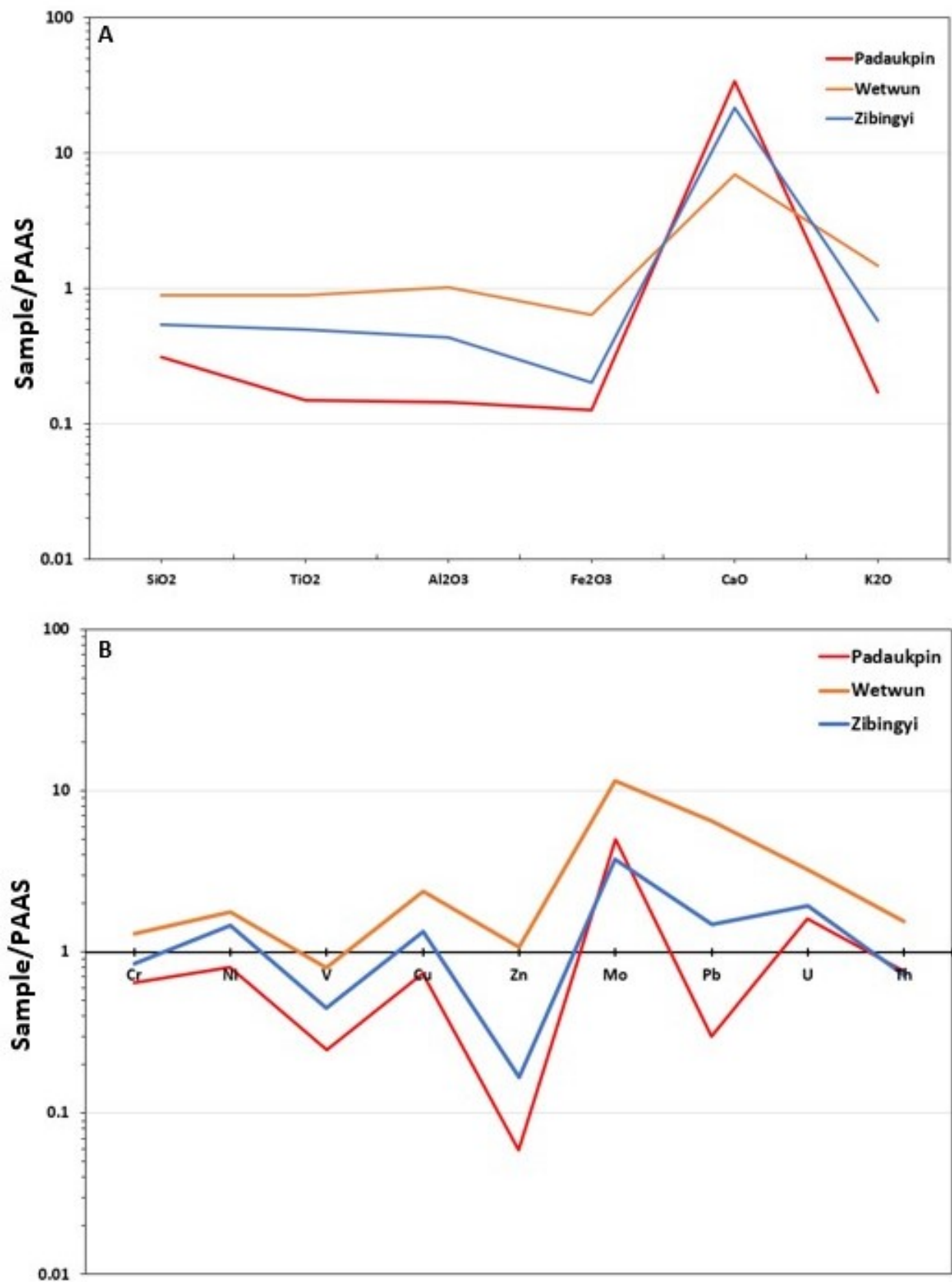


Figure 9. Major and trace element composition normalised to PAAS. **(A)** Major element composition relative to PAAS. **(B)** Minor element composition compared to PAAS.

Table 2. Major and minor element compositions of the black shale and limestone samples.

ID	JS-27	JS-6	JS-28	JS-21	JS-8	JS-4	JS-20	PAAS
(wt%)								
SiO ₂	19.38	50.71	61.36	20.09	56.63	37.44	20.25	62.8
TiO ₂	0.15	0.72	1.05	0.18	1	0.52	0.28	1
Al ₂ O ₃	2.74	19.89	18.7	3.99	16.95	7.86	3.93	18.9
Fe ₂ O ₃	0.91	5.57	3.56	0.82	2.53	1.31	1.19	7.22
CaO	44.21	9.01	<LOD	29.63	6.73	31.08	44.37	1.3
K ₂ O	0.63	4.52	6.39	1.21	3.54	2.68	1.12	3.7
TOC	9.7	3.2	2.5	9.6	7.7	5.5	9	–
S	0.7	0.6	1.3	0.9	1.4	0.03	0.04	–
(ppm)								
Cr	71	144	142	65	131	97	80	110
Ni	44	96	100	55	139	64	62	55
V	37	77	162	47	99	57	65	150
Cu	37	77	162	47	99	57	65	50
Zn	5	68	115	5	25	11	16	85
As	5	9	34	8	36	5	6	–
Mo	5	5	18	3	3	5	4	1
Pb	6	28	233	26	64	11	17	20
Se	2	1	1	5	3	1	2	–
U	5	5	15	4	10	6	4	3.1
Th	11	21	24	7	14	12	9	14.6
Mn	99	440	94	200	171	233	548	–
V/Cr	0.52	0.53	1.14	0.72	0.76	0.59	0.81	–
V/(V + Ni)	0.46	0.45	0.62	0.46	0.42	0.47	0.51	–
U/Th	0.71	0.24	0.63	0.57	0.71	0.50	0.44	–

Table 3. Paleoredox conditions from the Devonian limestone and black shales.

Formation	V/Cr	V/(V + Ni)	U/Th	Likely Conditions
JS-27	0.52	0.46	0.71	Oxic to Dysoxic
Padaukpin	Oxic	Dysoxic	Oxic	
JS-6	0.53	0.45	0.24	Oxic
Wetwun	Oxic	Oxic	Oxic	
JS-28	1.14	0.62	0.63	Oxic to Anoxic
Wetwun	Oxic	Anoxic	Oxic	
JS-21	0.72	0.46	0.57	Oxic to Dysoxic
Zebingyi	Oxic	Dysoxic	Oxic	
JS-8	0.76	0.42	0.71	Oxic
Zebingyi	Oxic	Oxic	Oxic	
JS-20	0.81	0.51	0.44	Oxic to Dysoxic
Zebingyi	Oxic	Dysoxic	Oxic	
JS-4	0.59	0.47	0.50	Oxic to Dysoxic
Zebingyi	Oxic	Dysoxic	Oxic	

5. Discussion

5.1. Detrital Zircon Dating

CL imaging shows that the zircon grains display oscillatory zoning. The ratio $\text{Th}/\text{U} < 0.1$ is mostly below 0.1 with seven analyses indicating values above 0.1. The results likely point to a metamorphic origin of the zircon grains with some igneous parental source [37, 38]. Zircon grains with Th/U ratios below 0.1 imply that they may have grown or recrystallized during metamorphic events.

The findings on U–Pb zircon ages do not rely on a robust dataset. Therefore, the interpretation does not rely on a robust dataset. The maximum depositional age for silty limestone (JS-18) show that the youngest zircon age was 399 Ma placing this sample in the Upper part of the Lower Devonian right on the boundary of the Emsian and Eifelianin (Middle Devonian 399 Ma). However, this date is not reliable as only one young zircon of 399 Ma was used for age calculation. In addition, the ages for sandstone sample (JS-22) are $480 \text{ Ma} \pm 9.9 \text{ Ma}$ which places the sample in the ages of Lower Ordovician, with the two youngest zircons found ages at 477 Ma and 485 Ma. JS-25 are $537 \pm 12 \text{ Ma}$, which places the sample as Lower Cambrian, with the two youngest zircons found ages at 534 Ma and 538 Ma.

The relative probability plots back up that the field area is in Sibumasu Terrane, with zircon provenance, especially when comparing relative plots from silty limestone (JS-18), JS-22 and JS25 to known Sibumasu Terrane, Indochina Terrane and Sukhothai Terrane zircon relative probability plots from [9]. The sample JS-18 (Maymyo Formation) has peaks at 399 Ma, 455 Ma, 723 Ma, 840 Ma, and 1784 Ma. The sample JS-22 has peaks at 478 Ma, 597 Ma, 893 Ma, 2409 Ma. In addition, the sample JS-25 has peaks at 536 Ma, 743 Ma, 815 Ma, 827 Ma, 1070 Ma, 1133 Ma, 1579 Ma, and 1746 Ma. In this study, the zircon dataset is not robust. Nevertheless, these peaks correspond to the Sibumasu Terrane zircon peaks [9] indicating that the detrital zircons may have originated from the Sibumasu Terrane. This probably indicate an affinity with Gondwana, when in the Late Carbonaceous, Sibumasu was still part of Gondwana, and then split off in Early to Middle Permian forming the Mesotethys [39]. We consider this interpretation less convincing given a limited zircon age dataset. In addition, field observation shows that the Wetwun shales contain brachiopods, which make them comparable to the Late Middle-Devonian (Givetian) siliclastic deposits in southwestern China [40].

5.2. Whole Rock Composition and Seafloor Redox Conditions

Ratios proposed by previous researchers can be used to determine paleo-redox conditions in the Devonian units [41, 42]. Three paleo-redox ratios were used V/Cr , $\text{V}/(\text{V} + \text{Ni})$ and U/Th . The ratios such as V/Cr and U/Th showed the ocean redox conditions to be oxic consistently with

each sample from the Lower Devonian to the Upper Middle Devonian. Ratio $\text{V}/(\text{V} + \text{Ni})$ has values showing the Lower Devonian to be oxic to dysoxic seafloor conditions. The Middle Devonian had anoxic to oxic oceanic redox condition. The Upper Devonian appears to be oxic to dysoxic. In this study, there is a drop of Se in between the Middle Devonian Wetwun and Upper Devonian Padaukpin. The Padaukpin redox conditions were oxic to dysoxic in the Upper Devonian.

Total organic carbon (TOC) varies in the black shales, through time. The TOC remains high in the Lower Devonian between 5% and 9.7% (mean = 8%) but drops in the Middle Devonian to value of 2.5% to 3.2% (mean = 2.9%), only to rise again in the Middle to Upper Devonian to 9.7%. Using trace element (TE) and TOC weight per cent, the trace element (Mn, U, Zn, Mo, As, Zn, Cu, V, and Ni) contents are much lower compared to TOC content by three orders of magnitude (Figure 10).

Ref. [30] proposed that the metals are absorbed in the stratified water column, into the organic matter, which gets transported down into the sediment. Under oxic conditions, the decomposition of organic matter releases trace elements which get released into the water column or trapped in the formation of sulphide minerals. This redox condition of the ocean appears to be oxic to dysoxic, in the Lower Devonian and the beginning of the Middle Devonian, probably explaining the depletion of Mo, Ni, U, V and Cu. Ref. [43] suggests that U and V enrichment, without Mo being enriched then you can infer a suboxic/anoxic environment without any free H_2S . The Mo levels in whole rocks (1–5 wt%) are low in the Lower Devonian Zebingyi Formation, and Middle Devonian Wetwun Formation.

The contents of Zn and Mn are not simultaneously elevated with TOC in the Lower Devonian Zebingyi, indicating that Zn and Mn were remobilized or scavenged by the bacteria, especially if in an event the sediment source slows down, limiting trace element nutrients. The Zn content drops at the end of the Wetwun, which could indicate the lack of trace element nutrients entering the basin. The redox sensitive trace elements U, V and Mo become soluble under oxidative state, but much less soluble under reducing conditions, which results in enrichment in oxygen depleted sediment.

Ref. [44] suggests that pyrite in oxic to dysoxic sea water conditions are $>5 \mu\text{m}$ and pyrite from euxinic environments is $<5 \mu\text{m}$. The Lower Devonian Zebingyi formation pyrite sizes were between $18 \mu\text{m}$ – $22 \mu\text{m}$, the Middle Devonian Wetwun Shale pyrite sizes were between $8 \mu\text{m}$ – $25 \mu\text{m}$ and the Middle to Upper Devonian Padaukpin Limestone average pyrite size was $9 \mu\text{m}$ – $15 \mu\text{m}$. The evidence based on the pyrite size suggests that the Middle Devonian Wetwun black shale deposited under oxic seawater conditions. Similarly, the Upper Devonian Padaukpin deposited under oxic seawater conditions.

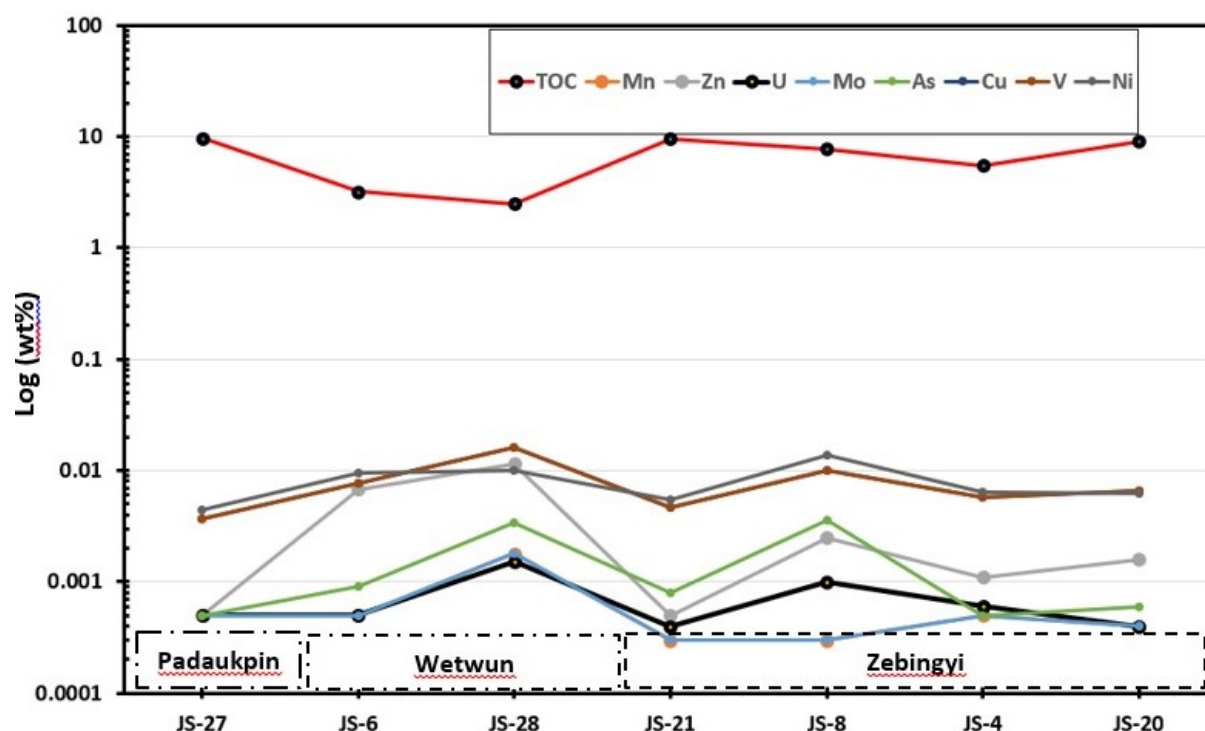


Figure 10. Variation of Total Organic Carbon (TOC) content relative to Mn, Zn, U, Mo, As, Cu, V, and Ni in the shale and limestone of Devonian age.

5.3. Pyrite Trace Element Composition

The trace elements in pyrite show four trends: (1) As, Ni, Cd, Co, Tl, Bi, Se, Cu, Te, Sb, and Ag do not show consistent patterns during the Devonian. (2) The Padaukpin, Zebingyi, and the upper Wetwun units have the lowest Au content; however, the lower Wetwun unit has the highest Au content. (3) Zn concentration is consistently low throughout the Devonian. (4) Mo concentration is high in the upper Wetwun unit and has remained relatively high in the Zebingyi Formation. The trace element variation is shown in Figures 11 and 12.

The Lower Devonian begins with high levels of Se, Ni, Zn, Cu but begins to drop towards the end of the Lower Devonian except for Mo which rises (Figures 11 and 12). Cobalt (Co) also rises briefly and then drops. This drop continues through to the Middle Devonian crash to low levels. Mo rises in the Middle Devonian, until it significantly drops towards the end of the Middle Devonian. Cobalt (Co) rises in the Middle Devonian, doing the opposite to Se, which is to be expected. Se, Ni, Mo, Cu, Zn are at their lowest levels that in both the Lower, Middle and Upper Devonian. Towards the end at the Upper part of the Middle Devonian, Se, Ni, Mo, Cu, Zn begins to rise again. Cobalt (Co) begins to drop.

The beginning of the Lower Devonian is enriched in Se. The TE concentrations of Cu, Ni, Mo, Zn follow Se concentration. These trace elements start to drop as we progress through the Lower Devonian. Co is depleted in the beginning, but the TE starts to rise. The beginning of the Middle Devonian is still enriched in Se, Cu, Ni, Mo, Zn

but in lower concentration than the Lower Devonian. Then the trace elements are depleted but Co in the Middle Devonian becomes enriched. The TE levels are the opposite of the Lower Devonian. The Upper Devonian Padaukpin Limestone TE levels of Se begin to rise again, with other TE following Se, such as Cu, Ni, Mo, Zn. The Upper Devonian Padaukpin is depleted in Co, which is to be expected.

5.4. Relationship between Selenium and Cobalt Contents in Pyrite

The Selenium content in sedimentary pyrite has been used as a proxy to estimate atmospheric oxygen levels [45]. The theory behind this is that high oxygen levels corresponding with higher rates of continental collision and uplift which increase a high nutrient flux, causing plankton productivity to increase, which in turn releases oxygen [46]. High oxygen in the atmosphere can drive oxidative weathering. This process releases more trace elements into the ocean, making the oceans increase productivity within the surface ocean. Considering this study, the cobalt content increased in the Lower Devonian within the upper and lower Zebingyi black shales (Figure 13A). It reached a maximum level in the Middle Devonian and decreased in the Upper Devonian. The selenium content in pyrite remained stable throughout the Lower Devonian and dropped in the Middle Devonian and to remain unchanged up to the Upper Devonian (Figure 13B). The Se/Co ratio reach its maximum and minimum values both in the Middle Devonian (Figure 13C) corresponding to a similar trend in the atmospheric oxygen levels (Figure 13D).

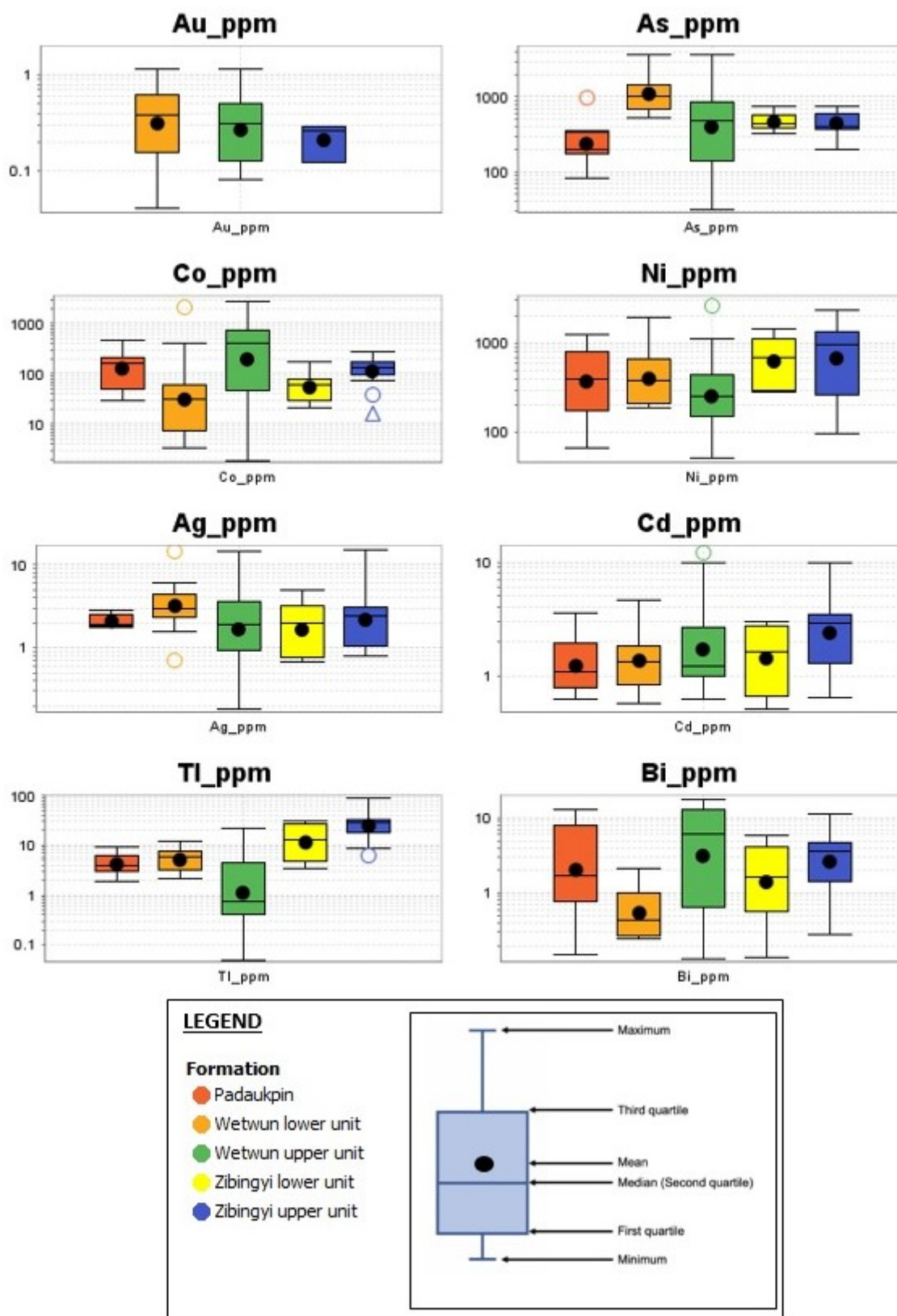


Figure 11. Tukey box plot of trace elements Au, As, Co, Ni, Ag, Cd, Tl, and Bi from pyrite in the black shales and limestones.

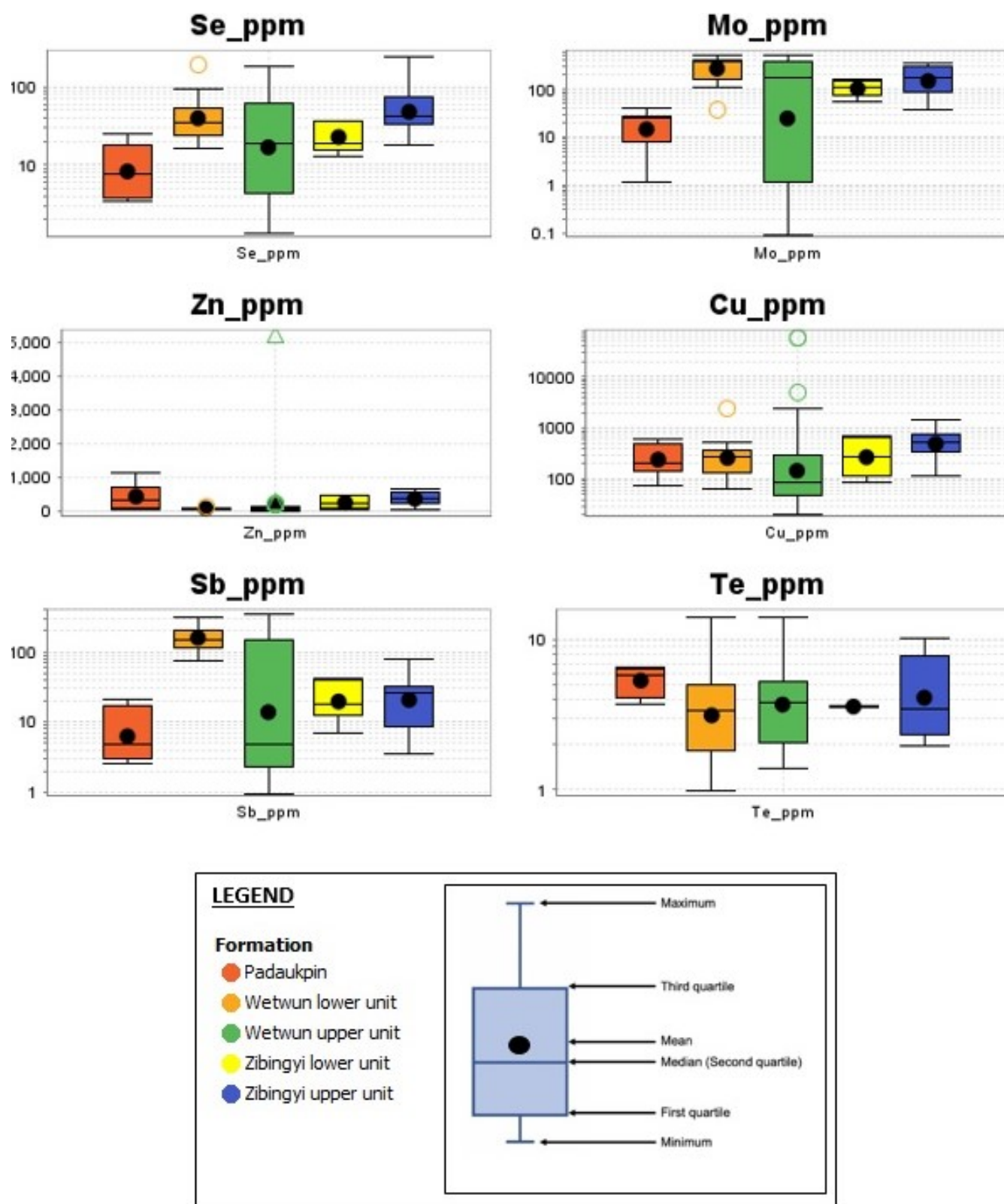


Figure 12. Tukey box plot of trace elements Se, Mo, Zn, Cu, Sb, and Te from pyrite in the black shales and limestones.

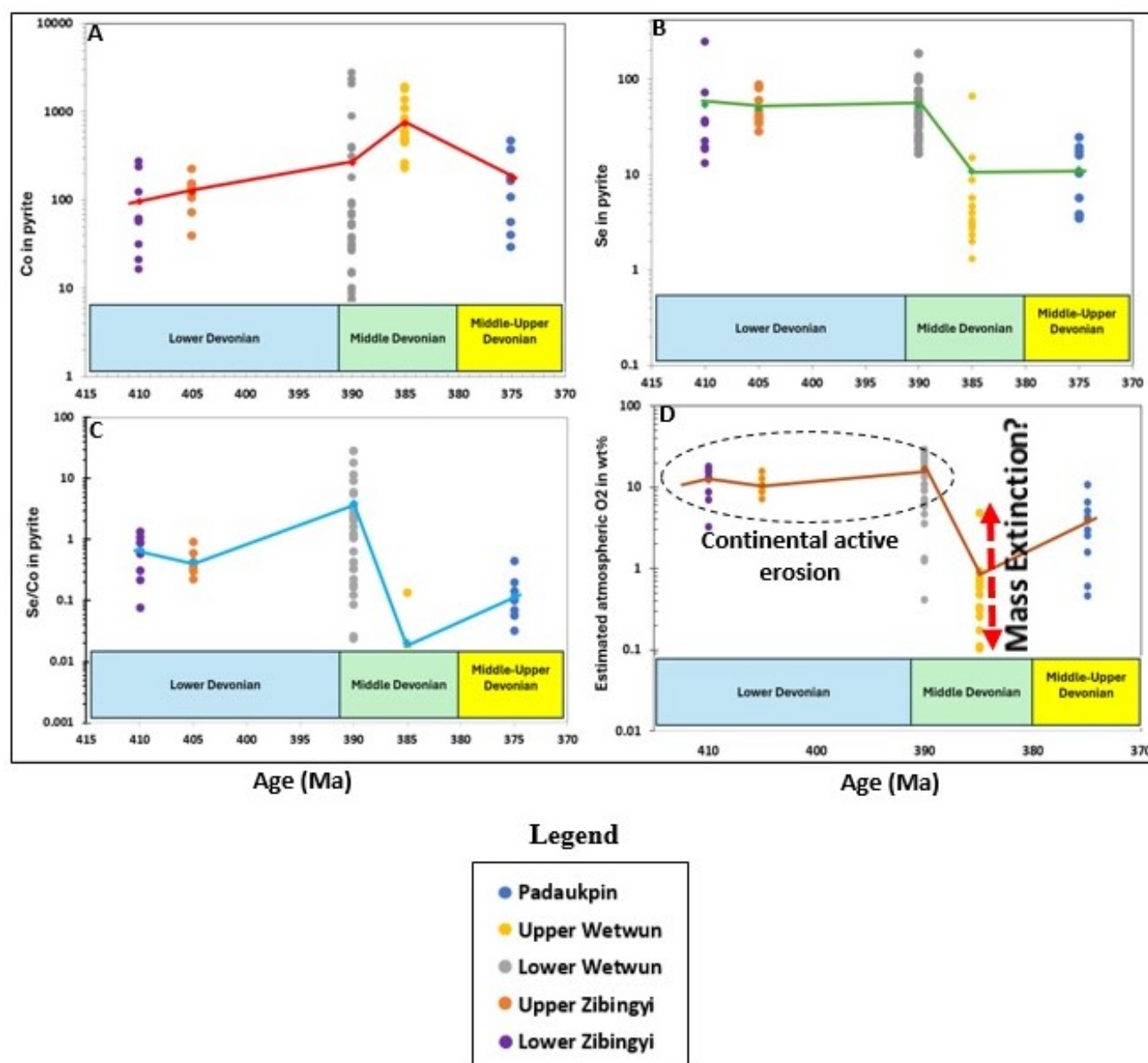


Figure 13. Variation of cobalt, selenium contents in pyrite, and atmospheric oxygen levels through the Devonian. The coloured lines across represent the mean values for each dataset. (A) Cobalt concentration in pyrite. (B) Selenium concentration in pyrite. (C) The Se/Co ratio in pyrite. (D) The estimated atmospheric oxygen level across the Devonian units. The relationship between estimated atmospheric oxygen and Se/Co ratio in sedimentary pyrite is from [47]: $\text{wt\% O}_2 = 30 P/1 + P$, where $P = 10^{(0.89 \times \log(\text{Se/Co}) + 0.07)}$.

The high Se/Co ratio and atmospheric oxygen in the beginning of the Middle Devonian (Figures 13C,D) coincides with the elevated gold contents in sedimentary pyrite which can be explained by an active continental erosion and an increase of nutrient supply including gold into the ocean. Compared to Lower Devonian, the content of Selenium from Middle Devonian to Upper Devonian is low (up to 25 ppm) in the sedimentary pyrite samples analysed, which indicates selenium deficiency in the oceans (Figure 13B). That significant decrease in selenium corresponds to low levels of atmospheric oxygen (up to 6.5 wt%) which may be related to the late Devonian mass ex-

tingtion. Comparatively, in the Lower Devonian, the level of atmospheric oxygen became high (Figure 13D) up to 28.7 wt%. The high oxygen in the atmosphere triggered an active continental erosion which increased the amount of nutrients going into oceans. That resulted in nutrient supply into the ocean leading to eutrophication (excessive amount of nutrients derived from the land, which causes a dense growth of plant life) creating an anoxic event (low oxygen), which ultimately leads to mass extinction. The relationship between Late Devonian Mass Extinction, oceanic anoxia and climate swings have also been documented in previous research [48].

5.5. Implication for gold source rocks

Fine-grained sedimentary rocks such as shales or mudstones can host several trace elements, including Zn, Pb, Cu, Mo, Se, V, U, Ni, As, Ag, Sb, Cr, and Au [49, 50]. Some shales are source rocks when the contents of these elements are abnormally high. In this study, gold concentration (up to 1.1 ppm) in sedimentary pyrite is elevated in the Lower Wetwun sequences. However, gold content is very low or below detection limit (up to 0.3 ppm) in other formations such as Zebingyi and Padaukpin. The evidence shows that the black shales of the Lower Wetwun sequences are gold source rocks in the region for their elevated gold content in sedimentary pyrites being a prerequisite to form sediment-hosted gold deposits in Sibumasu Terrane in Myanmar following gold released from sedimentary pyrite to metamorphic fluids.

6. Conclusions

Dating of detrital zircon returned three maximum depositional ages of 399, 480 and 537 Ma, with multi-age spectrum peaks over 500 Ma indicating a possible connection with Gondwana.

This present research has revealed occurrences of graptolites, bryozoans, and corals in the limestones indicating a Middle to Upper Devonian age for the Padaukpin Formation.

Major and trace element compositions show that the Middle to Upper Devonian Padaukpin Formation has elevated CaO content compared to PAAS. It shows a similar content in SiO₂, TiO₂, Al₂O₃, Fe₂O₃, and K₂O compared to PAAS. The Middle Devonian Wetwun Formation is depleted in SiO₂, TiO₂, Al₂O₃, Fe₂O₃, and K₂O but enriched in CaO relative to PAAS. The Lower Devonian Zebingyi Formation is enriched in CaO and strongly depleted in SiO₂, TiO₂, Al₂O₃, Fe₂O₃, and K₂O compared to PAAS.

Pyrite chemistry shows that the beginning of the Middle Devonian (the Wetwun shale) is marked by elevated levels of gold (up to 1.1 ppm Au) corresponding to a peak in oxygen content in the atmosphere (up to 28.7 wt% O₂). However, the gold content plummeted in the Late Devonian coinciding with low levels of oxygen content in the atmosphere (up to 6.5 wt% O₂).

The decrease in selenium contents corresponds to low levels of atmospheric oxygen (up to 6.5 wt%) which may be related to the Late Devonian mass extinction. The elevated gold concentration (up to 1.1 ppm) in sedimentary pyrite makes the Wetwun shale likely to be gold source rocks.

Supplementary Materials

The supporting information can be downloaded at: <https://doi.org/10.63335/j.hp.2026.0049>.

Author Contributions

C.M.: Data curation; Validation, review and editing original manuscript. J.S.: Conceptualization, Validation,

Field and Laboratory work, Writing—original draft. K.Z.: Conceptualization, Validation, Writing—review and editing. T.A.M.: Field work, Writing—review and editing. N.W.: Field work, Writing—review and editing.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

All data used in this work are presented in the paper.

Acknowledgements

The authors would like to thank support from the Project “Ore Deposits of SE Asia Project” led by Khin Zaw, University of Tasmania. Many thanks also go to Christine Cook, Catherine McGoldrick, and Ian Little for their assistance on the X-ray fluorescence at CODES geochemical laboratory. Authors would like to thank Sarah Gilbert for her immense contribution to the LA-ICP-MS work. Ross Large, Jeff Steadman and Sean Johnson are also thanked for their helpful reviews of the earlier versions of the manuscript. The authors are deeply indebted to the two anonymous journal reviewers and the editors for their insightful and useful comments to improve the manuscript.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI and AI-assisted Technologies

No AI assisted tools were used over the preparation of this paper.

References

1. La Touche, T.H.D. *Geology of the Northern Shan States*; Part 2 of Memoirs of the Geological Survey of India; Office of the Geological Survey: Kolkata, India, 1913; Volume 39, 379p.
2. Chhibber, H.L. *The Geology of Burma*; Macmillan & Co., Ltd: London, UK, 1934; p. 538.
3. Khaing, K.S.; Ko, K.G. The Black Shale Unit in the Maymyo Formation, Pyin Oo Lwin Township. *Universities Res. J.* **2011**, *4*, 101–116.
4. Aye, K.A. The Palaeozoic stratigraphy of Shan Plateau, Myanmar – An Updated Version. *J. Myanmar Geosci. Soc.* **2012**, *5*, 1–73.
5. Khin, Z.; Meffre, S.; Lai, C.-K.; et al. Tectonics and metallogeny of mainland SE Asia – A review and contribution. Special Issue on Tectonics and Metallogeny of Mainland SE Asia. *Gondwana Res.* **2014**, *26*, 5–30. <https://doi.org/10.1016/j.gr.2013.10.010>
6. Aye, K.A.; Cocks, L.R.M. Cambrian–Devonian stratigraphy of the

- Shan Plateau, Myanmar (Burma). In *Myanmar: Geology, Resources and Tectonics*; Barber, A.J., Khin, Z., Crow, M.J., Eds.; Memoirs, 48; Geological Society: London, UK, 2017; pp. 317–342. <https://doi.org/10.1144/M48.14>
7. Khin, Z. Overview of mineralization styles, tectonic, and metallogenic setting in Myanmar. In *Myanmar: Geology, Resources and Tectonics*; Barber, A.J., Khin, Z., Crow, M.J., Eds.; Memoirs, 48; Geological Society: London, UK, 2017; pp. 531–556. <https://doi.org/10.1144/M48.24>
 8. Metcalfe, I. Paleozoic and Mesozoic tectonic evolution and palaeogeography of East Asian crustal fragments: The Korean Peninsula in context. *Gondwana Res.* **2006**, *9*, 24–26. <https://doi.org/10.1016/j.gr.2005.04.002>
 9. Burrett, C.; Khin, Z.; Meffre, S.; et al. The configuration of Greater Gondwana – Evidence from LA ICPMS, U-Pb geochronology of detrital zircons from the Palaeozoic and Mesozoic of Southeast Asia and China. *Gondwana Res.* **2014**, *26*, 31–51. <https://doi.org/10.1016/j.gr.2013.05.020>
 10. Cromie, P.; Makoundi, C.; Khin, Z.; et al. Geochemistry of Au-bearing pyrite from the sepon mineral district, Laos DPR, Southeast Asia: Implications for ore genesis. *J. Asian Earth Sci.* **2018**, *164*, 194–218. <https://doi.org/10.1016/j.jseaes.2018.06.014>
 11. Makoundi, C.; Endut, Z.; Large, R.R.; et al. Geochemistry of pyritic mudstones from the Singa Formation, Malaysia: Insights into gold potential, source of sulfur and organic matter. *Geosciences* **2021**, *11*, 279. <https://doi.org/10.3390/geosciences11070279>
 12. Khaing, K.S. Middle Devonian Rugose Corals of the Padaukpin Limestone, Pyin Oo Lwin Township, Mandalay Division. Unpublished Ph.D. Thesis, University of Mandalay, 2005; p. 282.
 13. Metcalfe, I. Stratigraphy, palaeontology, and palaeogeography of the Carboniferous of Southeast Asia. *Mém. Soc. Géol. Fr.* **1984**, *147*, 107–118.
 14. Metcalfe, I. Pre-Cretaceous evolution of SE Asian terranes. *Geol. Soc. Spec. Publ.* **1996**, *106*, 97–122. <https://doi.org/10.1144/GSL.SP.1996.106.01.09>
 15. Ridd, M.F. Geological history of the Sibumasu Block in Peninsular Thailand: Report of a Geologists' Association Field Meeting in 2007. *Proc. Geol. Assoc.* **2009**, *120*, 163–174. <https://doi.org/10.1016/j.pgeola.2009.09.002>
 16. Ridd, M.F. The Phuket Terrane: A Late Palaeozoic rift at the margin of Sibumasu. *J. Asian Earth Sci.* **2009**, *36*, 238–251. <https://doi.org/10.1016/j.jseaes.2009.06.006>
 17. Bunopas, S. *Palaeogeographic History of Western Thailand and Adjacent Parts of Southeast Asia: A Plate Tectonic Interpretation*; Geological Survey Special Paper, Issue, 5; Department of Mineral Resources: Bangkok, Thailand, 1982.
 18. Ferrari, O.M.; Hochard, C.; Stampfli, G.M. An alternative plate tectonic model for the Palaeozoic–Early Mesozoic Palaeotethyan evolution of Southeast Asia (Northern Thailand–Burma). *Tectonophysics* **2008**, *451*, 346–365. <https://doi.org/10.1016/j.tecto.2007.11.065>
 19. Ueno, K. The Permian fusulinoidean faunas of the Sibumasu and Baoshan blocks: Their implications for the palaeogeographic and palaeoclimatologic reconstruction of the Cimmerian Continent. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2003**, *193*, 1–24. [https://doi.org/10.1016/S0031-0182\(02\)00708-3](https://doi.org/10.1016/S0031-0182(02)00708-3)
 20. Sevastjanova, I.; Clements, B.; Hall, R.; et al. Granitic magmatism, basement ages, and provenance indicators in the Malay Peninsula: Insights from detrital zircon U–Pb and Hf-isotope data. *Gondwana Res.* **2011**, *19*, 1024–1039. <https://doi.org/10.1016/j.gr.2010.10.010>
 21. Hall, R.; Sevastjanova, I. Australian crust in Indonesia. *Aust. J. Earth Sci.* **2012**, *59*, 827–844. <https://doi.org/10.1080/08120099.2012.692335>
 22. Bender, F. Geology of Burma. In *Beiträge zur Regionalen Geologie der Erde, Band 16*; Bannert, D., Ed.; Gebrüder Borntraeger: Berlin, Germany, 1983; Volume VIII, p. 293.
 23. Tin, A.M.; Mi, M.K. Origin of iron ore deposits in Maymyo Formation exposed around Baw village, Pyinoolwin Township, Mandalay Region, Myanmar. *J. Myanmar Acad. Arts Sci.* **2020**, *xviii*, 137–148.
 24. Aye, K.A.; Kyaw, M. Stratigraphy of the Lower Devonian sediments in the northwestern Shan Plateau, Myanmar. *Bull. Geol. Soc. Malays.* **2011**, *57*, 55–67. <https://doi.org/10.7186/bgsm57201108>
 25. Sack P.J.; Berry R.F.; Meffre S.; et al. In situ location and U-Pb dating of small zircon grains in igneous rocks using laser ablation-inductively coupled plasma-quadrupole mass spectrometry. *Geochem. Geophys. Geosyst.* **2011**, *12*, Q0AA1.4. <https://doi.org/10.1029/2010GC003405>
 26. Satyabala, S.P. Subduction in the Indo-Burman region: Is it still active? *Geophys. Res. Lett.* **1998**, *16*, 3189–3192. <https://doi.org/10.1029/98GL02256>
 27. Meffre, S.; Large, R.R.; Scott, R.; et al. Age and pyrite Pb-isotopic composition of the giant Sukhoi Log sediment-hosted gold deposit, Russia. *Geochim. Cosmochim. Acta* **2008**, *72*, 2377–2391. <https://doi.org/10.1016/j.gca.2008.03.005>
 28. Black, L.P.; Kamos, L.; Allen, C.M.; et al. TEMORA 1: A new zircon standard for Phanerozoic U–Pb geochronology. *Chem. Geol.* **2003**, *200*, 155–170. [https://doi.org/10.1016/S0009-2541\(03\)00165-7](https://doi.org/10.1016/S0009-2541(03)00165-7)
 29. Baker, J.; Peate, D.; Waight, T.; et al. Pb isotopic analysis of standards and samples using a Pb-207-Pb-204 double spike and thallium to correct for mass bias with a double-focusing MC-ICP-MS. *Chem. Geol.* **2004**, *217*, 275–303. <https://doi.org/10.1016/j.chemgeo.2004.06.030>
 30. Hatch, J.R.; Leventhal, J.S. Relationship between inferred redox potential of the deposition environment and geochemistry of the Upper Pennsylvanian (Missourian) Stank Shale Member of the Dennis Limestone, Wabaunsee County, Kansas, U.S.A. *Chem. Geol.* **1992**, *99*, 65–82. [https://doi.org/10.1016/0009-2541\(92\)90031-Y](https://doi.org/10.1016/0009-2541(92)90031-Y)
 31. Jones, B.; Manning, D.A.C. Comparison of geochemical indices used for the interpretation of palaeoredox conditions in ancient mudstones. *Chem. Geol.* **1994**, *111*, 111–129. [https://doi.org/10.1016/0009-2541\(94\)90085-X](https://doi.org/10.1016/0009-2541(94)90085-X)
 32. Danyushevsky, L.V.; Robinson, P.; Gilbert, S.; et al. Routine quantitative multi-element analysis of sulfide minerals by laser ablation ICP-MS: Standard development and consideration of matrix effects. *Geochem.: Explor. Environ. Anal.* **2011**, *11*, 51–60. <https://doi.org/10.1144/1467-7873/09-244>
 33. Hoskin, P.W.O.; Schaltegger, U. The composition of zircon and igneous and metamorphic petrogenesis, In *Zircon Review in Mineralogy and Geochemistry*; Hanchar, J.M.; Hoskin, P.W.O., Eds.; Mineralogical Society of America: Chantilly, VA, 2003; Volume 53, pp. 27–62. <https://doi.org/10.2113/0530027>
 34. Rubatto, D. Zircon trace element geochemistry: Partitioning with garnet and the growth of metamorphic zircon overgrowths. *Chem. Geol.* **2002**, *184*, 123–138. [https://doi.org/10.1016/S0009-2541\(01\)00355-2](https://doi.org/10.1016/S0009-2541(01)00355-2)
 35. Taylor, S.R.; McLennan, S.M. *The Continental Crust: Its Composition and Evolution*; Blackwell: Oxford, UK, 1985; p. 312.
 36. Large, R.R.; Mukhin, P.; Gregory, D.; et al. Ocean and atmosphere geochemical proxies derived from trace elements in marine pyrite: Implications for ore genesis in sedimentary basins. *Econ. Geol.* **2017**, *112*, 423–450. <https://doi.org/10.2113/econgeo.112.2.423>
 37. Belousova, E.; Griffin, W.; O'Reilly, S.Y.; et al. Igneous zircon: Trace element composition as an indicator of source rock type. *Contrib. Mineral. Petrol.* **2002**, *143*, 602–622. <https://doi.org/10.1007/s00410-002-0364-7>
 38. Yakymchuk, C.; Kirkland, C.L.; Clark, C. Th/U ratios in metamorphic zircon. *J. Metamorph. Geol.* **2018**, *36*, 715–737. <https://doi.org/10.1111/jmg.12307>
 39. Ridd, M.F. Should Sibumasu be renamed Sibuma? The case for a discrete Gondwana-derived block embracing western Myanmar, upper Peninsular Thailand, and NE Sumatra. *J. Geol. Soc.* **2016**, *173*, 249–264. <https://doi.org/10.1144/jgs2015-065>
 40. Wang, J.; Mi, Y.; Ma, X.; et al. Stratigraphic correlation of the Give-

- tian (late Middle Devonian) deposits in Qujing, Yunnan, southwestern China and the paleogeographic implications. *Turk. J. Earth Sci.* **2022**, *31*, 3. <https://journals.tubitak.gov.tr/earth/vol31/iss3/9/>
41. Rimmer, S.M. Geochemical paleoredox indicators in Devonian–Mississippian black shale, Central Appalachian Basin (USA). *Chem. Geol.* **2004**, *206*, 373–391. <https://doi.org/10.1016/j.chemgeo.2003.12.029>
 42. Riquier, L.; Tribouillard, N.; Averbuch, O.; et al. Productivity and bottom water redox conditions at the Frasnian–Famennian boundary on both sides of the Eovariscan Belt constraints from trace element geochemistry. In *Understanding Late Devonian and Permian–Triassic Biotic and Climatic Events: Towards an Integrated Approach: Developments in Palaeontology and Stratigraphy*; Over, D.J., Morrow, J.R., Wignall, P.B., Eds.; Elsevier: Amsterdam, Netherlands, 2005; Volume 20, pp. 199–224. [https://doi.org/10.1016/S0920-5446\(05\)80008-1](https://doi.org/10.1016/S0920-5446(05)80008-1)
 43. Tribouillard, N.; Algeo, T.J.; Lyons, T.; et al. Trace metals as Paleoredox and paleoproductivity proxies: An update. *Chem. Geol.* **2006**, *232*, 12–32. <https://doi.org/10.1016/j.chemgeo.2006.02.012>
 44. Wilkin, R.T.; Barnes, H.L.; Brantley, S.L. The size distribution of framboidal pyrite in modern sediments: An indicator of redox conditions. *Geochim. Cosmochim. Acta* **1996**, *60*, 3897–3912. [https://doi.org/10.1016/0016-7037\(96\)00209-8](https://doi.org/10.1016/0016-7037(96)00209-8)
 45. Cannell, A.; Blamey, N.; Brand, U.; et al. A revised sedimentary pyrite proxy for atmospheric oxygen in the Paleozoic: Evaluation for the Silurian–Devonian–Carboniferous period and the relationship of the results to the observed biosphere record. *Earth-Sci. Rev.* **2022**, *231*, 104062. <https://doi.org/10.1016/j.earscirev.2022.104062>
 46. Large, R.R.; Halpin, J.A.; Lounejeva, E.; et al. Cycles of nutrient trace elements in Phanerozoic Ocean. *Gondwana Res.* **2015**, *28*, 1282–1293. <https://doi.org/10.1016/j.gr.2015.06.004>
 47. Steadman, J.A.; Large, R.R.; Blamey, N.J.; et al. Evidence for elevated and variable atmospheric oxygen in the Precambrian. *Precambrian Res.* **2020**, *343*, 105722. <https://doi.org/10.1016/j.precamres.2020.105722>
 48. McGhee, G.R.; Grzegorz, R. Extinction: Late Devonian mass extinction. In *Encyclopedia of Life Sciences (eLS)*; Wiley: Chichester, UK, 2021; Volume 2, pp. 1–8. <https://doi.org/10.1002/9780470015902.a0029301>
 49. Pašava, J.; Sulovsky, P.; Kovalova, M. Geochemistry and mineralogy of Proterozoic metal-rich black shales from the Bohemian massif Czech Republic with a description of possible new Molybdenum selenide and Telluride phases. *Can. Mineral.* **1993**, *31*, 745–754.
 50. Gregory, D.; Large, R.R.; Halpin, J.A.; et al. Trace elements content in sedimentary pyrite in black shales. *Econ. Geol.* **2015**, *110*, 1389–1410. <https://doi.org/10.2113/econgeo.110.6.1389>