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Late Eocene-Oligocene granulite facies garnet-sillimanite migmatites from the Mogok Metamorphic belt, Myanmar, and implications for timing of slip along the Sagaing Fault.

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Key Words: Granulite facies migmatites, Biotite dehydration melting, Petrological Modelling, U–Pb Monazite geochronology, Mogok Metamorphic belt, Sagaing Fault.

Key Points:

1. Mogok Metamorphic belt reached granulite facies conditions of ~ 0.9 GPa and 870–970 °C and was followed by an extensive amphibolite facies overprint.
2. Granulite facies metamorphism occurred at 43–32 Ma, and a later upper amphibolite facies sillimanite-grade event peaking at 23–20 Ma.
3. Monazite U–Pb dates constrain the oldest age of initiation of the eastern branch of the cross-cutting Sagaing dextral strike-slip fault at <20 –18 Ma.

ABSTRACT

The Mogok Metamorphic Belt (MMB) in Myanmar is a polymetamorphic, mainly Paleogene granulite-uppermost amphibolite facies terrane consisting mainly of marbles and calc-silicates hosting spinel, ruby and sapphire. Jurassic charnockite-syenite intrusions, as well as Eocene-Miocene leucogranite intrusions are also present. Pelitic rocks are

uncommon, and where present, have sillimanite, both as primary inclusions in garnet and as secondary Bt+Sil coronas around garnet. Core samples from the Kyi-Tauk-Pauk gold mine at Thabeikkiyin, north of Mandalay, are mostly Grt+Bt+Sill gneisses and migmatites with uncommon interbanded Opx+Grt+Bt gneisses. Pseudosection modelling suggests prograde garnet growth occurred by biotite-dehydration melting that reached peak P – T conditions of 870–970 °C and ~0.9 GPa, and was followed by garnet breakdown forming coarse retrograde Bt + Sil coronas. U–Pb monazite data show an early high-grade granulite event at 43–32 Ma, and a later upper amphibolite sillimanite-grade event peaking at 23–20 Ma, with a change in monazite chemistry after c. 22 Ma that is consistent with fluid/(melt) interaction and garnet breakdown. Elevated Th/U ratios from ~35 to 22 Ma, and at ~18 Ma are compatible with melt influx at that time, timing that is similar to the age of the regional Kabaing leucogranite in the Mogok valley area. Our data show that peak granulite facies metamorphism along the Mogok Metamorphic belt was mainly Middle Eocene–Early Oligocene, with upper amphibolite facies metamorphism extending to earliest Miocene. The MMB is cut abruptly by the Sagaing fault, a large-scale dextral fault that extends from the Andaman Sea north to the East Himalayan syntaxis. Our new U–Pb monazite data constrain the oldest age of initiation of the eastern branch of the cross-cutting Sagaing dextral strike-slip fault at <20–18 Ma.

1. Introduction

The Mogok Metamorphic Belt (MMB) in central Burma (Myanmar) is a granulite–upper amphibolite facies belt that runs the length of Myanmar from the Andaman Sea in the south to the East Himalayan syntaxis in the north (Chhibber, 1934; D.L. Searle and Haq, 1964; M.P. Searle et al., 2007, 2017, 2020; Myanmar Geosciences Society, 2012). The MMB forms the western margin of the Shan–Thai plateau, part of the Sibumasu (Asia) plate, east of various Neo-Tethyan ophiolite zones interpreted as the eastern extension of the main Indus (Yarlung Tsangpo) suture zone along the Himalaya (Searle and Morley, 2011; Liu et al., 2016; Searle et al. 2017). The MMB is truncated abruptly to the west by the Sagaing fault, a large-scale dextral strike-slip fault that stretches for ~1400 km from the Andaman Sea in the south to the east Himalayan syntaxis (Fig. 1). Present day fault slip rates are estimated at ~1.8 cm/yr (Vigny et al., 2003; Maurin et al., 2010; Sloan et al., 2017). In the south the initiation of the Sagaing fault has been interpreted as related to the opening of the Andaman Sea spreading center (Curry et al., 1979; Curry, 2005; Morley and Alvey, 2013; Rangin et al., 2013; Searle and Morley, 2011). Total dextral displacements are estimated from geological

offsets at ~400–430 km (Mitchell, 1981, 1993; Morley, 2016; Morley and Searle, 2017), although Bertrand and Rangin (2003) suggested a lower offset of only ~100 km, and a later timing of initiation. The offsets and timing of slip along the northern extension of the fault remain speculative, as does its connection to the East Himalayan Syntaxis. In northern Myanmar the fault splays into several strands with intervening syn-kinematic basins. The West Sagaing fault splay bounds the western margin of the North Minwun basin which has detrital zircon ages as young as 28–27 Ma (Morley and Arboit, 2019). These authors proposed that these ages date the onset of strike-slip motion along the West Sagaing fault. The East Sagaing fault bounds the western margin of the transpressionally uplifted Katha-Gangaw range, composed of low-grade metamorphic rocks of unknown age, and extends northwards at least as far as the Myanmar-China border (Fig. 2). The timing of motion, amount of slip and tectonic evolution of the northern part of the Sagaing fault remains poorly constrained.

The MMB is composed dominantly of marbles and calc-silicates that host the World's best ruby, sapphire and spinel (amongst many others) gemstones, Jurassic charnockite-syenite intrusions, and Miocene leucogranites (D.L. Searle & Haq, 1964; M.P. Searle et al. 2007, 2017, 2020). Pelitic rocks are extremely rare, and thus precise pressure and temperature (P – T) conditions of metamorphism are difficult to obtain. The age of Mogok metamorphism has been controversial with suggestions ranging from Precambrian (Fermor, 1931; Chhibber 1934; Iyer, 1953), through early Permian to early Jurassic (Mitchell et al., 2007, 2012). However, U-Pb geochronology has suggested latest Cretaceous to early Miocene age of granulite metamorphism (Earley et al., 2003; Searle et al., 2007, 2020; Maw Maw Win et al., 2016; Sutherland et al., 2019). Yonemura et al. (2013) reported U–Th–Pb monazite ages of ~30 Ma from Grt + Sill, neisses in the Mandalay area, with older Cretaceous age spikes at ~80 Ma and 110 Ma. Maw Maw Win et al. (2016) reported equilibrium P – T conditions of ~0.6–1.0 GPa and 780–850°C for a Grt + Pl + Bt + Sil + Qtz assemblage, with Th–Pb monazite ages indicating a range of ages from ~49–23 Ma. Recently, Searle et al. (2020) published a map, field relationships, and U–Pb zircon, monazite and titanite ages from igneous and metamorphic rocks in the Mogok valley area. U–Pb zircon ages of the charnockite-syenite intrusions are 170–168 Ma, with younger ages grouped at ~68–63 Ma, and 44–21 Ma. Age of metamorphism of the MMB in the Mogok valley is constrained by U–Pb zircon, monazite and titanite ages ranging from ~68–21 Ma with garnet-present melting between ~45–21 Ma (Searle et al., 2020).

The general lack of pelitic rocks along the MMB has inhibited both precise P – T constraints and U–Pb dating. This paper describes some spectacular garnet-biotite-sillimanite migmatites interbanded with orthopyroxene-bearing granulite facies gneisses in core samples from the Kyi-Tauk-Pauk gold mine at Thabeikkyin, ~100 km north of Mandalay, ~30 km west of Mogok (Fig. 2) (N22° 42' 05.13, E96° 02' 55.15, elevation 242 meters). The gneisses and migmatites have an intrusive network of younger epithermal to mesothermal gold-bearing quartz veins, which also contain sphalerite, galena, chalcopyrite and arsenopyrite (Oo et al., 2016; Zar et al., 2017). We here provide P – T conditions of amphibolite-granulite facies migmatites by conventional thermobarometry and THERMOCALC pseudosection modelling of two metapelite samples, and report new U-Pb zircon, monazite and titanite ages from three samples of these unusual granulite facies migmatites. These data provide further information on the age of initiation of the Sagaing fault.

2. Petrography of the Kyi-Tauk-Pauk migmatites

Garnet-biotite-sillimanite migmatites from the Kyi-Tauk-Pauk gold mine (N22° 42' 05.13, E96° 02' 55.15, elevation 242 meters), are stromatic in nature and characterized by distinct cross-cutting, garnet-bearing leucocratic regions (neosome) with a garnet + sillimanite + K-feldspar + plagioclase + quartz anhydrous mineral assemblage, that are surrounded by selvages of foliated biotite + sillimanite + quartz that define the metamorphic fabric (palaeosome). Within the neosome, leucosomes consist of plagioclase + quartz + garnet with minor K-feldspar that display magmatic textures, with minor irregular schollen and schilern of biotite + sillimanite (Fig. 3). In a few semi pelitic samples, orthopyroxene and cordierite bearing assemblages are preserved and these will be fully described and investigated in a future contribution. In sample KP10, garnet forms euhedral crystals that reach up to 2 cm in diameter and shows straight faces, interpreted to have represent crystallization from melt. Melanosomes contain coarse (up to >0.5 cm in diameter) garnets, wrapped by a partially preserved anhydrous coronae of plagioclase, K-feldspar and sillimanite (Fig. 3). This is strongly overprinted by extensive intergrowth of biotite and sillimanite that can be very coarse-grained. Large garnets within both leucosomes and melanosomes are commonly rimmed by coarse biotite and mats of fibrolitic sillimanite. Domains of coarse discordant hydrous minerals completely truncate unfoliated anhydrous segregations and are interpreted to represent local retrograde replacement of anhydrous phases by breakdown of garnet during retrogression (Spear et al., 1997; 1990; Brown, 2002). Sample KP11 displays similar textures to KP10, however KP11 has a more pervasive

stromatic fabric with cm sized segregations. Leucosomes and melanosomes that both contain smaller garnets (~0.5 cm in diameter), and melanosomes are defined by finer grained intergrowths of biotite and sillimanite that wrap garnet with interstitial quartz, plagioclase, K-feldspar. Coarser grained biotite (Bt II) does occur around some garnet, which is interpreted to have formed by retrograde replacement (Fig. 3g).

The complete absence of muscovite in all samples suggest that metamorphic conditions surpassed the muscovite dehydration melting reaction. During the muscovite dehydration melting reaction, biotite is a peritectic product due to the incongruent breakdown of muscovite, and the biotite produced may partly account for the larger biotite crystals forming selvages at the edges of leucosomes in stromatic migmatite (Brown, 2002). In contrast, the biotite dehydration melting reaction commonly form Grt + a peritectic phase from a Bt + Sill + Qz assemblage (paleosome) in a metapelite. Whereas in a greywacke or semi pelite protolith, orthopyroxene may also be a product, consistent with observed orthopyroxene in some samples. The lack of cordierite in samples KP10 and KP11 suggests that pressures were high enough to preserve garnet and sillimanite in most bulk compositions.

2.1. Mineral Chemistry

The compositions of phases in stromatic Grt + Bt + Sill migmatite samples KP10 and KP11 were derived from a CAMECA SX5-FE (field emission) electron microprobe at the Department of Earth Sciences, University of Oxford. Operating conditions involved an accelerating voltage of 15.0 keV corresponding to a current of 20 nA, a range of primary and secondary standards were used including andradite (Fe, Mg, Ca), TiO₂ (Ti), Mn metal (Mn), labradorite (Na, Al, Si) and smidrine (K) for major elements and synthetic standards for (from the University of Edinburgh) for the rare earth elements (REE's). Garnet line profiles were collected using a 10-micron step size across all garnets corresponding to between 100 and 200 analyses. Mineral abbreviations follow the guidelines of Whitney and Evans (2010) and migmatite terminology after Ashworth (1975). Anhydrous phase compositions were calculated to standard numbers of oxygen per formula unit (Deer et al., 1992), micas were recalculated to 11 oxygens, and chlorite to 28 oxygens. Where present, H₂O content was assumed to occur in stoichiometric amounts. The proportion of Fe³⁺/Fe^{total} was calculated using AX (Holland, 2009) and amphibole exchange vectors were calculated using the method of Holland and Blundy, (1994) (see supplementary material for further details), the complete electron probe micro-analyses are presented in Supplementary Table S1.

During prograde metamorphism in a pelitic bulk composition, garnet preferentially fractionates Mn into core regions, and therefore spessartine content decreases toward rims as a result of progressive Mn depletion followed by the reacting matrix (Hollister, 1966). However, in the Kyi-Tauk-Pauk migmatites (Fig. 4) garnet contains spessartine (Spss) [X_{Mn}] profiles that are homogeneous or concave upward from core to rim, with a sharp inflexion towards the outer rim indicative of retrograde net transfer reactions. Pyrope (Prp) [X_{Mg}] displays convex down trends from core to rim, whereas grossular (Grs) [X_{Ca}] increases towards the inner rim followed by minor decrease to the outermost rim. Almandine (Alm) [X_{Fe}]. Sample KP10 is characterized by core to rim zonation of Prp = 0.41–0.32, Grs = 0.035–0.050, Alm = 0.54–0.60, Spss = 0.010–0.015, whereas sample KP11 displays core to rim zonation Prp = 0.37–0.30, Grs = 0.065–0.040, Alm = 0.56–0.72, Spss = 0.010–0.030. The length scale of Mn (and Mg, Fe, and Ca) zonation within the garnets is more than the diffusional length scale (up to 3 mm) suggested by >5 m.y. residence time at peak temperatures >650 °C (Caddick et al., 2010), indicating that preservation of the prograde growth history has been modified by diffusion; therefore only peak metamorphic conditions will be preserved in garnet cores due to thermal re-equilibration (Woodsworth, 1977; Spear, 1993), whereas garnet rims are affected by retrograde net transfer reactions (Kohn and Spear, 2000). Biotites in KP10 and KP11 are characterised by Ti 0.5–0.15 atoms per formula unit (apfu) and XMg [$XMg = (Mg/(Mg+Fe^{2+}))$] = 0.52–0.42 and interpreted to be dominantly retrograde (Bt II). Plagioclase occurring in both leucosomes and melanosomes have anorthite [$XCa = (Ca/(Ca+Na+K))$] contents ranging from 0.39–0.27.

3. Thermobarometry and Equilibrium Phase Diagram Modelling

P-T conditions were determined using Ti-in-biotite thermometer of Henry et al. (2005), the garnet–aluminium silicate–plagioclase–quartz (GASP) barometer, the garnet–biotite thermobarometer (Spear, 1993; Bhattacharya et al., 1992; Holdaway, 2000), and AvPT (Powell et al., 1998) using THERMOCALC version 3.40i. Calculated *P-T* results for garnet cores span from 0.86 GPa and 923 °C (GASP) (KP10) to 0.91 GPa and 861 °C (KP11), whereas titanium in biotite thermometry yield temperatures between ca. 770–670 °C which are interpreted to be retrograde. Garnet rims are consistently associated with slightly elevated spessartine and lower pyrope and yield calculated *P-T* results of 0.91 GPa and 831 °C (GASP) (KP10) to 0.68 GPa and 777 °C (KP11) that span to lower temperatures towards their outer most rims, that is consistent with retrograde net transfer reactions. The complete

results are displayed in Figures 5-7 and Table 1. Activities of solid-solution end members were calculated using AX (Holland, 2009) and displayed in the supplemental information. However, conventional thermobarometry is largely ineffective at constraining peak P - T conditions in high-grade and/or partially melted rocks (e.g., Halpin et al., 2007; Indares et al., 2008; Palin et al., 2013) owing to changing mineral compositions due to retrograde diffusion (Kohn and Spear, 2000; Pattison and Begin, 1994, 2003), and it has large associated uncertainties (typically ± 50 °C and ± 0.1 GPa at 1 standard deviation; Powell and Holland, 2008; Palin et al., 2016). Due to these reasons, phase diagram modelling (pseudosection construction) was employed herein as the main tool to constrain P - T information, and has significantly smaller uncertainties.

As such, pseudosections of samples KP10 and KP1 were calculated using THERMOCALC version 3.40i and internally consistent thermodynamic dataset ds-62 (Powell and Holland, 1988; Holland and Powell, 2011). Modelling of KP10 was performed in the $\text{MnO}-\text{Na}_2\text{O}-\text{CaO}-\text{K}_2\text{O}-\text{FeO}-\text{MgO}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}-\text{TiO}_2-\text{O}$ (MnNCKFMASHTO) system using the activity-composition relations of White et al., (2014a,b). The pure phases andalusite, kyanite, sillimanite, rutile, quartz, and H_2O were considered in all cases. The bulk-rock composition was derived by point counting phases from thin section combined with average EPMA derived analyses following the method of Carson, (1999). The bulk rock water content was fixed based on the proportion of high-grade biotite and its associated water content. Investigation into the peak and retrograde conditions were achieved by investigating compositional isopleths for pyrope and grossular content in garnet and garnet mode. The intersections of isopleths representing measured compositions are represented by shaded boxes indicating uncertainty at the 1σ level calculated by THERMOCALC.

A pseudosection of sample KP10 (Fig. 5) shows a solidus with a negative slope between 750 and 800°C and 0.4–1.4 GPa. The preserved assemblage of Grt–Bt–Ilm–Sill–Pl–Qtz–Kfs–L occurs up to P - T conditions of ~ 0.6 – 1.0 GPa and ~ 820 – 845 °C. A field matching this assemblage is delimited on the calculated pseudosection at higher temperature by the loss of biotite and at higher pressure by the stabilization of kyanite in place of sillimanite, and at lower pressure by the appearance of cordierite, both of which are not present in the sample. Where assemblage fields span wide ranges in P - T conditions, tighter constraints on the conditions of peak metamorphism can typically be provided by correlating observed and predicted proportions of key temperature- or pressure-dependent phases (Powell and Holland, 2008). Although the modal proportion of biotite, which is shown to be highly temperature sensitive, can provide an uppermost limit of this peak assemblage field

(e.g., 820–840 °C and 0.6–1.0 GPa), extensive back-reaction and secondary biotite limit this use. Tighter constraints on equilibrated P – T conditions are provided by estimates of garnet volume and pyrope and grossular end-member intersections. Extensive diffusion driven homogenization associated with high-grade conditions, has affected the core of garnet garnet porphyroblasts, and therefore cores provide a lower bound on peak metamorphic conditions (Caddick et al., 2010), whereas garnet rims. Intersection of isopleths for garnet core compositions (40% pyrope and 3%–4% grossular) indicate peak metamorphism occurred in the Grt–Bt–Sil–Kfs–Ilm–L assemblage field at ~0.7–1.1 GPa and ~970 °C. Spessartine isopleths of ~1% also match the observed garnet core and inner rim compositions, although elevated spessartine at the outer rim is predicted at much lower temperatures, consistent with a retrograde origin. However, the uncertainty in bulk composition, given the large proportion of garnet in the sample leads to subsequent uncertainty in peak isopleth results (e.g. Palin et al., 2016). This is a particularly important consideration in this case due to the insensitivity of compositional isopleths at such conditions (e.g. ~50 °C temperature interval between individual 1% pyrope isopleths). As such, the 970 °C as suggested by 40% pyrope isopleths likely represents an absolute maximum peak temperature, and this cannot be strongly resolved from a range of peak temperatures between 870–970 °C across the Grt–Bt–Sil–Kfs–Ilm–L field. Across this temperature range, the isopleth intersections lie almost directly on the biotite dehydration melting reaction, consistent with the preserved anhydrous textures. Garnet rim isopleths (30–34% pyrope and 5 % grossular) plot in the current observed assemblage phase field, Grt–Bt–Sil–Pl–Kfs–Qtz–Ilm–L at ~0.9 GPa and 820–840 °C. Rutile occurs within thin-section which is not predicted by the model, possibly due to more biotite predicted than observed during the retrograde path consuming Ti.

A pseudosection of sample KP11 (Fig. 6) shows a similar phase topology to KP10 with a solidus associated with an isothermal slope also between 750 and 800 °C and 0.4–1.4 GPa. Like sample KP10, KP11 preserves the assemblage of Grt–Bt–Ilm–Sill–Pl–Qtz–Kfs–L which occurs up to P – T conditions of ~0.65–1.05 GPa and ~790–845 °C. A field matching this assemblage occurs on the calculated pseudosection at higher temperature by the loss of biotite and at higher pressure by the stabilization of kyanite in place of sillimanite, and at lower pressure by the appearance of cordierite. KP11 display minimal garnet zoning from core to rim and is mainly homogenous associated with ~36–37% pyrope and ~6% grossular and ~1% spessartine, which corresponds to garnet isopleths plotting in the observed Grt–Pl–Kfs–Bt–Ilm–Qtz–Sill–L field corresponds to a P – T condition of ~0.95 GPa and 840 °C, lying almost directly on the biotite out reaction line and corresponds well with observed

garnet modal proportion derived from thin section point counting of ~28%. Partially preserved anhydrous textures around garnets also suggest the rock may have crossed the biotite out reaction, and therefore this P - T constraint should be treated as minimum as it lies on the biotite out reaction line and may have been affected by chemical homogenisation following the thermal peak as demonstrated by the flat garnet zoning profiles with an increase in spessartine towards the outer rim to ~3%. Increased spessartine in the garnet outer rim is predicted at lower temperatures (<600 °C) on the pseudosection, consistent with retrograde replacement of garnet by biotite at sub solidus conditions.

In summary, thermobarometric calculations suggest the Kyi-Tauk-Pauk migmatites experienced biotite dehydration melting at peak conditions of ~0.9 GPa and ~870–970 °C, followed by isobaric cooling and extensive retrogression and back-reaction to produce secondary biotite, suggesting the melt may have remained *in situ* to P - T conditions of ~9 kbar and 820–840 °C (Fig. 7). The lack of cordierite or kyanite in the assemblage of samples KP10 and KP11 suggest that cooling was mainly isobaric in nature at elevated pressure, or slightly decreasing in pressure, which is consistent with the lack of decompression-related coronae features (Brown, 2002).

4. U–Pb Geochronology

We conducted LASS (laser-ablation split-stream inductively coupled plasma mass spectrometry) measurements on zircon, monazite, and titanite. Mineral zoning was qualitatively assessed with cathodoluminescence (CL) or X-ray maps (created by EPMA), and U–Pb dates and trace elements were measured quantitatively during LASS. The LASS analytical protocols and data reduction strategies have been presented in earlier papers (e.g., Kylander-Clark et al., 2013). In summary, a Photon Machines 193 nm excimer laser and HelEx sample cell were used, and data were collected on a Nu Plasma or Plasma 3D multicollector ICP-MS coupled to an Agilent 7700S quadrupole ICP-MS. Analyses of NIST 612 glass and the basalt standard BHVO-2 (Jochum et al., 2005) were interleaved with the unknowns as trace-element reference materials, and well-characterized zircon, monazite, and titanite were interleaved as U–Th–Pb reference materials. Data were processed using Iolite (Paton et al., 2011), which corrects for machine drift and downhole inter-element fractionation using reference material. Most analyses were standard LASS analyses in which all data from a single hole were interpreted as a single date–trace element pair.

We interpret changes in mineral trace-element signatures in the following ways: 1) an increase/decrease in Lu/Gd ratio indicates garnet breakdown/growth; 2) an increase/decrease in Eu/Eu* ratio is compatible with plagioclase-rich melt injection/extraction or plagioclase breakdown/growth; 3) an increase/decrease in Th/U reflects recrystallization in the presence of a silicate melt/hydrous fluid. Unless otherwise noted, all dates quoted here for zircon are $^{207}\text{Pb}/^{206}\text{Pb}$ -corrected $^{238}\text{U}/^{206}\text{Pb}$ intercept dates, and all monazite dates are concordant $^{232}\text{Th}/^{208}\text{Pb}$ – $^{238}\text{U}/^{206}\text{Pb}$ dates. Many of the monazite analyses have a concordant spread in U/Pb–Th/Pb ratios that could be the result of Pb loss, mixing during laser ablation, long-term recrystallization, or spatially heterogeneous short-term recrystallization.

We dated monazite from three samples; all of the grains are 20–200 μm , subhedral, and associated with biotite and feldspar; none are included in garnet. The U–Pb dates are variably affected by thorogenic ^{206}Pb , so we focus on Th–Pb dates. Typical of metamorphic monazite, the individual samples have large ranges of dates that, fortunately, are correlated with changes in elemental composition. The complete U–(Th)–Pb results are presented in Figure 8 and Supplementary Table S2.

4.1. KP5 monazite

The Th–Pb spot dates range from 39 Ma to 17 Ma, and the Th–Pb – U–Pb data define a distinct cluster at ~37 Ma and a continuum of dates from 22–17 Ma: whether this continuum reflects analytical mixing of domains of different age or long-term recrystallization is not resolved by the data (see, e.g., Hacker et al., 2015). There are marked secular changes in Th/U, Lu/Gd, and Eu/Eu*, compatible with melting at ~37 Ma, and metamorphism with garnet breakdown at 22–17 Ma.

4.2. KP15 monazite

The Th–Pb spot dates range from 77 Ma to 22 Ma, with a continuum of concordant dates from ~48 Ma to 22 Ma. There is considerable variance in the Th/U, Lu/Gd, and Eu/Eu*. Decreases in Eu/Eu* and Lu/Gd from 77 Ma to 45 Ma are compatible with garnet growth at 45 Ma; the presence of elevated Th/U from ~35 to 22 Ma is compatible with melt influx at that time.

4.3. KP17 monazite

The Th–Pb spot dates range from 42 Ma to 18 Ma, with a continuum of concordant dates from ~40 Ma to 32 Ma, plus a younger cluster at ~18 Ma. A distinct decrease in Th/U is compatible with melting at ~18 Ma.

5. Discussion

5.1 Petrogenesis of the Kyi-tauk-Pauk migmatites

The Kyi-Tauk-Pauk migmatites experienced granulite facies metamorphism at peak P – T conditions of ~0.9 GPa, 870–970 °C followed by approximately isobaric cooling to 0.8–0.9 GPa and 820–840 °C producing an extensive amphibolite facies hydrous overprint. The lack of muscovite in all samples suggest conditions exceeded the muscovite dehydration melting reaction. The partially preserved anhydrous garnet-sillimanite-K-feldspar-plagioclase-quartz segregations are consistent with the hypothesis that they are the solid and liquid products of the following prograde biotite dehydration melting reaction producing peritectic garnet and K-feldspar (Waters, 1988):

During this reaction, melting progress is mainly controlled by the thermodynamic and chemical properties of the melt (White et al., 2001, 2005; White and Powell, 2002). The large entropy of the melt and its strong preference for K, Na and H₂O cause continuous biotite (+Sil + Pl) dehydration-melting (1) with increasing temperature as reflected by decreasing biotite mode across the pseudosections of KP10 and KP11. Since biotite is consumed during this melting reaction, selvages are not expected to form if the biotite dehydration melting was completed. Although it has been argued that biotite-sillimanite selvages will form by retrograde reaction reversal (Kriegsman and Hensen, 1998; Kriegsman, 2001; Spear et al., 1999) which may explain the observed biotite in rocks where melt remained in contact with the source rock and the strong amphibolite facies overprint (White and Powell, 2002). It has also been shown that the presence of K-feldspar may also be expected as a product of biotite dehydration melting under high $a(\text{H}_2\text{O})$ conditions. However, it is acknowledged that in many other granulite terranes with low $a(\text{H}_2\text{O})$ commonly prevailing in the middle crust during biotite dehydration melting, K-feldspar is absent as a reaction product (Carrington and Watt, 1995, Brown, 2002). Growth of partially preserved anhydrous haloes around garnet-sillimanite-K-feldspar bearing segregations maybe consistent with local gradients in water activity during prograde and peak metamorphism, and that individual segregations and bodies of partially melted rock acted as sinks for soluble volatiles (Waters, 1988). However, the

widespread distribution of late cross-cutting coarse biotite, sillimanite and chlorite around garnet, and concave upward garnet core to rim profiles suggest that extensive retrograde reaction between hydrous melt and solids occurred in all samples by the following retrograde reaction the reverse of the biotite dehydration melting reaction.

Garnet outer rims are replaced by coarse biotite grains and are truncated, surrounded, and replaced by mats of fibrolitic sillimanite, which is consistent with this retrograde interpretation and suggests that melt formed via prograde biotite dehydration melting remained largely in situ and did not escape the rock (Spear et al., 1990; 1999). Resorption of garnet outer rims by retrograde biotite caused an inflexion in Mn and Ca towards the rim of the garnet implying retrograde net transfer reactions (Kohn and Spear, 2000), by back diffusion due to the incompatibility of Ca and Mn to substitute into the structure biotite. The length scale of the inflexion of Ca towards the outer rim of garnet in KP10 of >5 mm is indicative of diffusion at temperatures >800 °C for timescales of >5 Myrs (Caddick, 2010), suggesting high grade conditions were prolonged. The fibrolitic sillimanite clots observed along leucosome margins may have formed by this retrograde reaction, rather than by the prograde reaction. Leucosomes formed during prograde metamorphism subsequently cooled to produce a retrograde quartz, plagioclase and biotite assemblage via retrograde reaction 2 at *P–T* conditions of 820–840 °C and 0.6–0.9 GPa as reproduced by the pseudosection results of samples KP10 and KP11.

5.2 Tectonic Implications

5.2.1. Age and PT conditions of Mogok metamorphism

Knowledge of the age of Mogok metamorphism is crucial for the development of tectonic models relating to the India-Asia (Sibumasu) collision in SE Asia. Previous suggestions that metamorphism along the Mogok belt was Precambrian (Fermor, 1931; Chhibber 1934; Iyer, 1953), or early Permian to early Jurassic (Mitchell et al., 2007, 2012) can be discounted through recent U–Pb geochronology. U–Pb geochronology suggest that peak granulite to upper amphibolite facies metamorphism spanned latest Cretaceous to early Miocene (Searle et al., 2007, 2017, 2020; Yonemura et al., 2013; Maw Maw Win et al., 2016; Sutherland et al., 2019). Recently, new U-Pb zircon, monazite and titanite dates suggest that the charnockite-syenite intrusions in the Mogok valley intruded during the Jurassic (170–168 Ma), and that peak granulite facies metamorphism was latest Cretaceous – early Paleocene

(~68–63 Ma), and late Eocene to Oligocene (44–21 Ma; Searle et al., 2020). Protoliths of the Mogok marbles are probably Middle – Late Permian massive limestones that overlie the Carboniferous – Lower Permian glacial diamictites of the Mergui Group (Oo et al. 2002). The MMB also contains pre-collision, subduction-related I-type hornblende-bearing diorites and granites (Barley et al., 2003; Searle et al., 2007; Mitchell et al., 2012), similar to the Lhasa Block of south Tibet (Gangdese granites). Late Cretaceous – Early Oligocene U–Pb zircon and monazite ages (71–50 Ma and 44–33 Ma) from kyanite- and sillimanite-bearing gneisses near the East Himalayan Syntaxis (Palin et al., 2013) are also compatible with ages of peak metamorphism along the MMB, suggesting a possible link northwest to the lower crust of the Lhasa Block.

The northern margin of the Indian plate along the Himalaya records a long period of tectonic stability following the late Carboniferous-Permian rifting of Gondwana up until the late Cretaceous. Obduction of ophiolites onto the Indian plate preceded closing of Neo-Tethys and collision of India with Asia. Major crustal thickening, regional Barrovian facies metamorphism and crustal melting is ubiquitous along the Himalaya from ~50 Ma onwards (Searle, 2015, for a review). The peak of sillimanite grade partial melting and formation of leucogranites was early Miocene when the entire Greater Himalayan slab was extruded southwards above the Main Central Thrust ductile shear zone, and bounded along the top by the normal sense low-angle normal fault, the South Tibetan detachment. Along the Asian continental margin, extensive pre-collision I-type granite intrusions are related to northward subduction of Tethyan oceanic lithosphere spanned at least early Cretaceous to early Miocene (Searle et al., 2011). Regional kyanite-sillimanite grade metamorphic rocks are uncommon along the Asian margin but are present around the East Himalayan (Namche Barwa) syntaxis (Zeitler et al., 2001; Booth et al., 2004; Zhang et al., 2014). In situ U–(Th)–Pb monazite ages show that partial melting occurred at ~71 and 50 Ma with later kyanite-grade migmatization at ~44–33 Ma (Palin et al., 2013). Exhumation of the Namche Barwa (Himalaya) deep crustal gneisses in the syntaxis occurred structurally beneath a large-scale ductile shear (Donjiu-Milin shear zone) around the northwest flank of Namche Barwa. Peak staurolite grade metamorphism in these rocks occurred at 23.4 ± 0.7 Ma (Palin et al., 2015).

Rocks along the Mogok belt show higher temperatures (granulite facies) and less partial melting than the rocks in SE Tibet, but show temporal similarities of peak metamorphism during latest Cretaceous to Paleocene time. The MMB appears unique and different from metamorphic rocks along the Tibet segment to the north and the Thailand sector to the south in two main respects. One is the presence of extensive charnockite-syenite

intrusions in the central Mogok valley region, and the other is in the very high grade of granulite facies metamorphism (Searle et al., 2020; this paper). Whereas pelitic rocks dominate in SE Tibet, the Mogok rocks are mainly marbles and calc-silicates with few pelites. The garnet migmatites and biotite dehydration melts described in this paper provide a unique opportunity to determine P – T conditions and timing of partial melting, and our results have a direct bearing on the interpretation of the evolution of the Sagaing dextral strike-slip fault which abruptly cuts the MMB along the west.

5.2.2. Nature and timing of initiation of the Sagaing Fault

In the Mogok-Mandalay area, the Mogok Metamorphic rocks, intrusive granites and syenites and Palaeozoic rocks on the west side of the Shan Plateau are affected by, and exhumed along, a complex region of faulting called the Shan Scarp Fault zone, which comprises NNW-SSE to N-S trending strike-slip and transpressional faults, and ENE-WSW extensional faults (Bertrand and Rangin, 2003; Fig. 2A). Rocks adjacent to this fault zone have Early Miocene mica cooling ages (c. 20–15 Ma; Bertrand et al., 2001). To the north E-W to NE-SW trending major strike-slip faults (Ruili, Momeik faults), related to the Oligocene-Neogene strike-slip fault system in Yunnan cut through the Mogok Metamorphic belt (e.g. Socquet and Pubellier, 2005). In this region high grade metamorphic rocks occur as uplifted cores to major strike-slip zones, with overlying detached Neoproterozoic to Palaeozoic sedimentary and metasedimentary cover and unconformable or detached Cenozoic sedimentary cover (Socquet and Pubellier, 2005). In the region of the study area the Sagaing Fault is a relatively low-lying feature on the west side of the Shan Plateau, located to the west of the fault systems above. Although the Sagaing Fault may truncate these faults, there is no clear evidence for this.

Regional lower and middle crust amphibolite-granulite grade Mogok Metamorphics are widespread along the eastern side of the Sagaing Fault. The high-grade Mogok Metamorphic rocks are unconformably overlain by the Late Miocene-Pliocene Irrawaddy Formation, to the east. The western margin of the metamorphics is abruptly truncated by the north-south Sagaing Fault. Figure 9B, shows a mapped example of the Sagaing Fault obliquely truncating generally steeply dipping and folded foliations of the MMB near the town of Sagaing. The Sagaing Fault lacks the strong ductile strike-slip fabrics that have been exhumed and exposed along Cenozoic strike-slip fault zones further east (e.g. the Mae Ping fault, Osterle et al., 2019; Red River fault, Palin et al., 2012; and Ranong fault, Watkinson et al., 2012). Instead, the truncation of older non-strike slip metamorphic fabrics means that our

new U-Pb ages provide a robust maximum age limit on the initiation of the Sagaing Fault, between 22 °N – 23 °N, to $<\sim 20$ Ma.

On the west side of the fault lie Cenozoic sedimentary rocks of the Central Basin, but in some areas there is a narrow belt of metamorphic rocks adjacent to the fault zone, called the Minwun Metamorphics (Fig. 9B). These rocks comprise garnet-muscovite/biotite schists, and actinolite schists (Maung Maung, 1980). Due to their lower grade, they are likely different from the Mogok Metamorphic rocks. Permian limestones occur in small outcrops on the west side of the Sagaing Fault. The limestones are commonly mylonitised, but a few with a Cathaysian fauna are suggestive of a link with south Sumatra (Barber and Crow, 2009; Ueno et al., 2016).

Assuming approximately 400 km of dextral offset has occurred along the Sagaing Fault since ~ 20 Ma, then long-term slip rates are of the order of 1.8–2 mm/yr. These high slip rates explain the highly seismogenic nature of the fault (Vigny et al., 2003; Maurin et al., 2010; Sloan et al., 2017). There is a short time interval between the end of high-grade metamorphism discussed here, and the onset of Early Miocene exhumation of the Mogok Metamorphics along the Shan Scarp Fault zone trend (Bertrand et al., 2003), followed by exhumation on the east side of the Sagaing Fault zone. Further north, where the Sagaing Fault splays into at least three branches (Fig. 10), the Western branch has been constrained as younger than 28–27 Ma (Morley and Arboit, 2019) based on detrital zircon ages from the North Minwun basin. It is possible that this western branch represents older activity than is surmised for the Mogok-Mandalay area. The Mogok Metamorphic rocks continue northwards towards the East Himalayan Syntaxis but this region is extremely poorly known geologically. Future work will attempt to map out the northward continuation of the Mogok belt and the various faults associated with the Sagaing fault in order to link north to Himalayan structures in more detail.

6. Conclusions

Granulite and upper amphibolite facies marbles, calc-silicates and rare pelitic rocks along the MMB are the southeastern continuation of the Lhasa block (Asian plate) lower crustal rocks exposed around the Eastern (Namche Barwa) syntaxis. Grt + Bt + Sill gneisses and migmatites from the Kyi-Tauk-Pauk gold mine at Thabeikkyin, north of Mandalay, are interbanded with Opx + Grt + Bt gneisses and orthopyroxene-bearing charnockites-syenites. Pseudosection modelling suggests prograde garnet growth occurred at granulite facies conditions during biotite-dehydration melting at peak P – T conditions of 870–970°C and ~ 0.9

GPa, followed by garnet breakdown forming coarse Bt + Sil coronas and an inflexion in grossular garnet contents towards the outer garnet rim, due to retrograde replacement of garnet by biotite. Our U–Pb monazite data show an early high-grade granulite event at 43–32 Ma, and a later upper amphibolite sillimanite-grade event, peaking at 23–20 Ma, with a change in monazite chemistry after c. 22 Ma that is consistent with fluid/(melt) interaction and garnet breakdown. These data confirm that peak granulite facies metamorphism along the Mogok Metamorphic belt was mainly Middle Eocene-Early Oligocene (Searle et al., 2007, 2020) and may have been long lived, extending to Earliest Miocene in the upper amphibolite facies associated with the strong retrograde overprint. Mesothermal-epithermal gold-bearing quartz veins intrude the gneisses and migmatites, so must be younger than 22–20 Ma. The Mogok metamorphic rocks are also cut abruptly by the eastern strand of the right-lateral Sagaing strike-slip fault west of Thabeikkyin, constraining the oldest age of initiation of dextral shear along the Sagaing fault in this region.

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References

- Ashworth, J.R., 1975, The sillimanite zones of the Huntly Portsoy area in the north-east Dalradian, Scotland: *Geological Magazine*, v. 112, p. 113–136, <https://doi.org/10.1017/S0016756800045817>.
- Barber, A. J., & Crow, M. J. 2009. Structure of Sumatra and its implications for the tectonic assembly of Southeast Asia and the destruction of Paleotethys. *Island Arc*, 18(1), 3-20.
- Barley, M.E., Pickard, A.L., Khin Zaw, Rak, P., Doyle, M.G. 2003. Jurassic to Miocene magmatism and metamorphism in the Mogok Metamorphic Belt and the India-Asia collision in Myanmar. *Tectonics*, 22, <https://doi.org/10.1029/2002TC001398>

- Bertrand, G., Rangin, C., Maluski, H., Bellon, H. & GIAC Scientific-Party, 2001, Diachronous cooling along the Mogok Metamorphic Belt (Shan Scarp, Myanmar): the trace of the northward migration of the Indian syntaxis. *Journal of Asian Earth Sciences*, 19, 649-659.
- Bertrand, G., and Rangin, C. 2003. Tectonics of the western margin of the Shan plateau (central Myanmar): implication for the India–Indochina oblique convergence since the Oligocene. *Journal of Asian Earth Sciences*, 21(10), 1139-1157.
- Bhattacharya, L., Mohanty, L., Maji, A., Sen, S.K., and Raith, M., 1992, Non-ideal mixing in the phlogopite- annite binary: Constraints from experimental data on Mg-Fe partitioning and a reformulation of the biotite-garnet geothermometer: *Contributions to Mineralogy and Petrology*, v. 111, p. 87–93, <https://doi.org/10.1007/BF00296580>.
- Brown, M. (2002), Retrograde processes in migmatites and granulites revisited. *Journal of Metamorphic Geology*, 20: 25-40. doi:10.1046/j.0263-4929.2001.00362.x
- Caddick, M. J., Konopásek, J., Thompson, A. B., 2010. Preservation of Garnet Growth Zoning and the Duration of Prograde Metamorphism, *Journal of Petrology*, Volume 51, Issue 11, November 2010, Pages 2327–2347, <https://doi.org/10.1093/petrology/egq059>
- Carrington, D. P. & Watt, G. R., 1995. A geochemical and experimental study of the role of K-feldspar during water-undersaturated melting of metapelites. *Chemical Geology*, 122, 59–76.
- Carson, C.J., 1999. Calculated mineral equilibria for eclogites in CaO-Na₂O-FeO-MgO-Al₂O₃-SiO₂-H₂O: application to the Pouébo Terrane, Pam Peninsula, New Caledonia. *Jour. Metam. Geol.*, 17, pp.9-24.
- Clegg, E.L.G. 1941. The Crystalline and associated rocks of Burma. Geological Survey of India Memoirs, 74, 101p.
- Fermor, L.L. 1934. Mogok Stone Tract. Records of the Geological Survey of India, 68, 50-58.
- Chhibber, H.L. 1934a. *The Geology of Burma*. McMillan and co. London. 538p.
- Chhibber, H.L. 1934b. *The Mineral Resources of Burma*. Macmillan, London, 320p.
- Clegg, E.L.G., Iyer, L.A.N. 1953. Geological Map of the Mogok Stone Tract.
- Curry, J.R., 2005. Tectonics and history of the Andaman Sea region. *Journal of Asian Earth Sciences*, 25, 187-232.
- Curry, J.R., Moore, D.G., Lawver, L.A., Emmel, F.J., Raitt, R.W., Henry, M., Kieckhefer, R., 1979. Tectonics of the Andaman Sea and Burma. In: Watkins, J., Montadert, I.,

- Dickerson, P.W. (eds.), Geological and Geophysical Investigations of Continental Margins, American Association of Petroleum Geologists, Memoir 29, pp. 189-198.
- Deer, W.A., Howie, R.A., and Zussman, J., 1992, An Introduction to the Rock Forming Minerals (2nd ed.): Harlow, Essex, UK Longman Scientific & Technical, 528 p.
- Gardiner, N.J., Searle, M.P., Robb, L.J. 2014. The Metallogenic provinces of Myanmar. Applied Earth Sciences (Transactions of the Institute of Mineralogy and Metallurgy B), 123.1. doi: 10.1179/1743275814Y.0000000049
- Gardiner, N.J., Searle, M.P., Morley, C.K., Whitehouse, M.J., Spencer, C.J., Robb, L.J. 2015a. The Closure of Palaeo-Tethys in Eastern Myanmar and Northern Thailand: New Insights from Zircon U-Pb and Hf Isotope Data. Gondwana Research 39, 401-422. doi:10.1016/j.gr.2015.03.001
- Gardiner, N.J., Searle, M.P., Robb, L.J., Morley, C.K. 2015b. Neo-Tethyan Magmatism and Metallogeny in Myanmar – an Andean Analogue? Journal of Asian Earth Sciences 106, 197-215. doi:10.1016/j.jseas.2015.03.015
- Gardiner, N.J., Robb, L.J., Morley, C.K., Searle, M.P., Cawood, P.A., Whitehouse, M.J., Kirkland, C.L., Roberts, N.M.W., Tin Aung Myint. 2016. The Tectonic and Metallogenic Framework of Myanmar: A Tethyan Mineral System. Ore Geology Reviews 79, 26-45. doi:10.1016/j.oregeorev.2016.04.02
- Halpin, J.A., Clarke, G.L., White, R.W., and Kelsey, D.E., 2007, Contrasting P–T–t paths for Neoproterozoic metamorphism in macrobertson and Kemp Lands, east Antarctica: Journal of Metamorphic Geology, v. 25, p. 683–701, <https://doi.org/10.1111/j.1525-1314.2007.00723.x>.
- Henry, D.J., Guidotti, C.V., and Thomson, J.A., 2005, The Ti-saturation surface for low-to-medium pressure metapelitic biotite: Implications for geothermometry and Ti-substitution mechanisms: The American Mineralogist, v. 90, p. 316–328, <https://doi.org/10.2138/am.2005.1498>.
- Holdaway, M.J., 2000, Application of new experimental and garnet Margules data to the garnet-biotite geothermometer: The American Mineralogist, v. 85, p. 881–892, <https://doi.org/10.2138/am-2000-0701>.
- Holland, T.J.B., 2009, AX: A program to calculate activities of mineral end-members from chemical analyses: <http://www.esc.cam.ac.uk/research/research-groups/holland/ax> (accessed July 2016).
- Holland, T.J.B., and Powell, R., 2011, An improved and extended internally consistent thermodynamic dataset for phases of petrological interest, involving a new equation of

- state for solids: *Journal of Metamorphic Geology*, v. 29, p. 333–383, <https://doi.org/10.1111/j.1525-1314.2010.00923.x>.
- Hollister, L.S., 1966, Garnet zoning: an interpretation based on the Rayleigh fractionation model: *Science*, v. 154, p. 1647–1651.
- Indares, A., White, R.W., and Powell, R., 2008, Phase equilibria modelling of kyanite-bearing anatectic paragneiss from the central Grenville Province: *Journal of Metamorphic Geology*, v. 26, p. 815–836, <https://doi.org/10.1111/j.1525-1314.2008.00788.x>.
- Iyer, L.A.N. 1953. *Geology and Gemstones of the Mogok Stone Tract*. Memoirs of the Geological Survey of India, 82, 100p.
- Jochum K.P., Willbold, M., Raczek, I., Stol, B., Herwig, K. 2005 Chemical Characterisation of the USGS Reference Glasses GSA-1G, GSC-1G, GSD-1G, GSE-1G, BCR-2G, BHVO-2G and BIR-1G Using EPMA, ID-TIMS, ID-ICP-MS and LA-ICP-MS. *Geostandards and Geoanalytical Research* 20(3), 285-302 doi:10.1111/j.1751-908X.2005.tb00901.x
- Kaung Sithu and Saw Ngwe Khaing, 2017. Structural deformation along the active Sagaing Fault zone between Sagaing and Mungun area, Central Myanmar. Asia Oceania Geosciences Conference, Singapore, poster presentation.
- Kohn, M. J., and Spear, F. 2000. Retrograde net transfer reaction insurance for pressure-temperature estimates. *Geology*, 28(12), 1127-1130.
- Kriegsman, L. M., 2001. Partial melting, partial melt extraction and partial back reaction in anatectic migmatites. *Lithos* 56,75–96.
- Kriegsman, L. M. & Heisen, B. J., 1998. Back reaction between restite and melt: Implications for geothermobarometry and pressure-temperature paths. *Geology*, 26, 1111–1114.
- Kylander-Clark, A.R.C., Hacker, B.R., Cottle, J.M. 2013. Laser-ablation split-stream ICP petrochronology. *Chemical Geology* 345, 99-112. Doi: <http://dx.doi.org/10.1016/j.chemgeo.2013.02.019>
- Lin, T-H., Mitchell, A.H.G., Chung, S-L., Tan, X-B., Tang, J-T., Oo, T., Wu, F-Y. 2019. Two parallel magmatic belts with contrasting isotopic characteristics from southern Tibet to Myanmar: zircon U-Pb and Hf isotopic constraints. *Journal of Geological Society, London*, <https://doi.org/10.1144/jgs2018-072>
- Maung Maung, 1980. *Geology of the Kyaukta-Yega Area*. University of Mandalay, unpublished report.

- Maurin, T., Masson, F., Rangin, C., U Than Min, Collard, P. 2010. First Global Position system results in northern Myanmar: constant and localised slip rate along the Sagaing Fault. *Geology* 38(7), 591-4.
- Mitchell, A.H.G., Htay, M.T., Htun, K.M., Win, M.N., Oo, T., Hlaing, T. 2007. Rock relationships in the Mogok metamorphic belt, Tatkon to Mandalay, central Myanmar. *Journal of Asian Earth Sciences*, 29, 891-910.
- Mitchell, A., Chung, S-L., Oo, T., Lin, T-H., Hung, C-H. 2012. Zircon U-Pb ages in Myanmar: Magmatic-metamorphic events and the closure of a neo-Tethys ocean? *Journal of Asian Earth Sciences*, 56, 1-23.
- Mitchell, A. 2018. *Geological Belts, Plate Boundaries and Mineral Deposits in Myanmar*. Elsevier, 509p.
- Morley, C.K. 2016. Syn-kinematic sedimentation at a releasing splay in the northern Minwun Range, Sagaing Fault zone, Myanmar: significance for fault timing and displacement. *Basin Research*, 1-17 doi: 10.1111/bre.12201
- Morley, C.K., Arboit, F. 2019. Dating the onset of motion on the Sagaing fault: Evidence from detrital zircon and titanite U-Pb geochronology from the North Minwin basin, Myanmar. *Geology*, 47, 581-5, <https://doi.org/10.1130/G46321>
- Myanmar Geosciences Society, 2012. *Geological Map of Myanmar*.
- Osterle, J.E., Klotzli, U., Stockli, D.F., Palzer-Khomenko, M. and Kanjanapayont, P., 2019. New age constraints on the Lan Tang gneiss complex, Thailand, and the timing of activity of the Mae Ping shear zone from in-situ and depth-profile zircon and monazite U-Th-Pb geochronology. *Journal of Asian Earth Sciences*, 181, 102886.
- Oo, T.N., Setijadji, L.D., Warmada, I.W., Oo, T.T. 2016. Geochemistry, hydrothermal alteration and ore mineralogy of Skarn mineralization at Wethey-Pheshey area, Thabeikkyin township, Mandalay region, Myanmar. *Journal of Applied Geology*, 1(2) 53-62.
- Palin, R.M., Searle, M.P., Waters, D.J., Parrish, R.R., Roberts, N.M.W., Horstwood, M.S.A., Yeh, M.-W., Chung, S.-L., and Anh, T.T., 2012. A geochronological and petrological study of anatectic paragneiss and associated granite dykes from the Day Nui Con Voi metamorphic core complex, North Vietnam: constraints on the timing of metamorphism within the Red River shear zone. *Journal of Metamorphic Geology*, 31, 359-387.
- Palin, R.M., Searle, M.P., St-Onge, M.R., Waters, D.J., Roberts, N.M.W., Horstwood, M.S.A., Parrish, R.R., Weller, O.M., Chen, S., Yang, J. 2014. Monazite geochronology

- and petrology of kyanite- and sillimanite-grade migmatites from the northwestern flank of the Eastern Himalayan syntaxis. *Gondwana Research*, doi:org.10/1016/j.gr.2013.06.022
- Palin, R.M., Searle, M.P., Morley, C.K., Charusiri, P., Horstwood, M.S.A., Roberts, N.M.W. 2013. Timing of metamorphism of the Lansang gneiss and implications for left-lateral motion along the Mae Ping (Wang Chao) strike-slip fault, Thailand. *Journal of Asian Earth Sciences*, 76, 120-136, doi: org/10.1016/j.seaes.2013.01.0121
- Palin, R.M., Weller, O.M., Waters, D.J. and Dyck, B., 2016. Quantifying geological uncertainty in metamorphic phase equilibria modelling; a Monte Carlo assessment and implications for tectonic interpretations. *Geoscience Frontiers*, 7(4), pp.591-607.
- Paton, C., Hellstrom, J.B, Woodhead, J., Hergt, J. 2011. Iolite: Freeware for the visualisation and processing of mass spectrometric data. *Journal of Analytical Atomic Spectrometry* 26(12), 2508-2518 doi:10.1039/C1JA10172B
- Powell, R., Holland, T.J.B., and Worley, B., 1998, Calculating phase diagrams involving solid solutions via non-linear equations, with examples using THERMOCALC: *Journal of Metamorphic Geology*, v. 16, p. 577-588, [https:// doi.org/10.1111/j.1525-1314.1998.00157.x](https://doi.org/10.1111/j.1525-1314.1998.00157.x).
- Powell, R. and Holland, T.J.B. (2000) On thermobarometry. *Journal of Metamorphic Geology*, 26: 155-179. doi:10.1111/j.1525-1314.2007.00756.x
- Ridd, M.F., Crow, M.J., Morley, C.K. 2019. The role of strike-slip faulting in the history of the Hukawng Block and Jade Mines Uplift, Myanmar. *Proceedings of the Geologists Association*, <https://doi.org/10.1016/j.pgeola.2019.01.002>
- Rupasinghe, M.S., Dissanayake, C.B. 1985. Charnockites and the genesis of gem minerals. *Chemical Geology*, 43, 1-16.
- Searle, D.L., Haq, B. 1964. The Mogok belt of Burma and its relationship to the Himalayan Orogeny. *Proceedings of International Geological Congress, Delhi*, 22, 132-161.
- Searle, M.P. 2015. Mountain Building, Tectonic Evolution, Rheology, and Crustal Flow in the Himalaya, Karakoram, and Tibet. Ch. 6-11. In: Shubert, G. (Editor), *Treatise on Geophysics*, 2nd edition, vol. 6. 469-511. <http://dx.doi.org/10.1016/B978-0-444-53802-4.00121-4>
- Searle, M.P., Morley, C.K. 2011. Tectonic and thermal evolution of Thailand in the regional context of SE Asia. In: RIDD, M.F., BARBER, A.J. & CROW, M.J. (eds.). *The Geology of Thailand*. Geological Society, London, 539-571.

- Searle, M.P., Cottle, J.M., Streule, M.J., Waters, D.J. 2010b. Crustal melt granites and migmatites along the Himalaya: melt source, segregation, transport and granite emplacement mechanisms. *Transactions of the Royal Society of Edinburgh*, 100, 219-233. Doi:10.1017/S175569100901617X
- Searle, M.P., Elliott, J.R., Phillips, R.J., Chung, S-L. 2011. Crustal-lithospheric structure and continental extrusion of Tibet. *Journal of the Geological Society, London*, 168, 633-672, doi: 10.1144/0016-76492010-139.
- Searle, M.P., Noble, S.R., Cottle, J.M., Mitchell, A.H.G., Hlaing, T., Horstwood, M.S.A. 2007. Tectonic evolution of the Mogok metamorphic belt, Burma (Myanmar) constrained by U-Th-Pb dating of metamorphic and magmatic rocks. *Tectonics*, 26, TC3014, doi: 10.1029/2006TC002083.
- Searle M.P., Morley, C.K., Waters, D.J., Gardiner, N.J., Kyi Htun, Than Than Nu, Robb, L.J. 2017. Ch.12. Tectonic and metamorphic evolution of the Mogok Metamorphic and Jade Mines belts and ophiolite terranes of Burma (Myanmar). In: Barber, A.J., Khin Zaw & Crow, M.J. (Eds) *Myanmar: Geology, Resources and Tectonics*. Geological Society of London, Memoir, 48, 261-293 <https://doi.org/10.1144/M48.12>
- Searle, M.P., Garber, J.M., Hacker, B.R., Kyi Htun, Gardiner, N.J., Waters, D.J., Robb, L.J. 2020. Timing of Syenite-Charnokite magmatism and ruby and sapphire metamorphism in the Mogok valley region, Myanmar. *Tectonics*, 39, e2019TC005998. <https://doi.org/10.1029/2019TC005998>
- Sloan, R.A., Elliott, J.R., Searle, M.P. & Morley, C.K. 2017. Ch.2. Active tectonics of Myanmar and the Andaman Sea. In: Barber, A.J., Khin Zaw & Crow, M.J. (Eds) *Myanmar: Geology, Resources and Tectonics*. Geological Society of London, Memoir, 48, 19-52 <https://doi.org/10.1144/M48.2>
- Soquet A., & Pubellier M., 2005. Cenozoic deformation in western Yunnan (China-Myanmar border), *Journal of Asian Earth Sciences* 24, 495-515.
- Spear, F. S., Kohn, M. J. & Cheney, J. T., 1999. P-T paths from a tectonic pelites. *Contributions to Mineralogy and Petrology*, 134, 17±32.
- Spear, F. J., Kohn, M. J., Florence, F. P. & Menard, T., 1990. A model for garnet and plagioclase growth in pelitic schists: implications for thermobarometry and P-T path determinations. *Journal of Metamorphic Geology*, 8, 683-696.
- Spear, F.S., 1993, *Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths*: Mineralogical Society of America Monograph 1, 799 p.

- Sutherland, F.L., Khin Zaw, et al. 2019. Diversity in Ruby geochemistry and its inclusions: Intra- and Inter-continental comparisons from Myanmar and Eastern Australia. *Minerals*, 9, 28, doi:10.3390/min9010028
- Thein, M.L., Myint, O., Kyi, S., Win, H.N. 1990. Geology and stratigraphy of the metamorphosed early Paleozoic rocks of the Mogok-Thabeikkyin-Singu-Madaya areas. Yangon.
- Thu, Ye Kyaw, Enami, M., Kato, T., Tsiboi, M. 2017. Granulite facies paragneisses from the middle segment of the Mogok metamorphic belt, central Myanmar. *Journal of Mineralogical and Petrological Sciences*, 112, 1-19.
- Thu, Ye Kyaw, Enami, M. 2017. Evolution of metamorphic fluid recorded in granulite facies metacarbonate rocks from the middle segment of the Mogok metamorphic belt in central Myanmar. *Journal of Metamorphic Geology*, 36, 905-931, doi:10.1111/jmg.12419
- Thu, Kyaw, Khin Zaw, 2017. Ch. 23. Gem deposits of Myanmar. In: Barber, A.J., Khin Zaw & Crow, M.J. (Eds) *Myanmar: Geology, Resources and Tectonics*. Geological Society of London, Memoir 48, 497-529 <https://doi.org/10.1144/M48.23>
- Ueno, K., Thein, M., & Barber, A. J., 2016. Permian fusuline fauna from the Minwun Range, Central Myanmar. In 5th Symposium of the International Geosciences Programme (IGCP) 589, 27-28.
- Vigny, C., Socquet, A., Rangin, C., Chamot-Rouke, N., Pubellier, M., Bouin, M.N., Bertrand, G., & Becker, M. 2003. Present-day crustal deformation around the Sagaing fault, Myanmar, *Journal of Geophysical Research, Solid Earth*, 108, 25-33.
- Waters, D. J., 1988. Partial melting and the formation of granulite facies assemblages in Namaqualand, South Africa. *Journal of Metamorphic Geology*, 6, 387-404.
- Watkinson, C., Elders, C., Blatt, G., Jourdan, F., Hall, R., McNaughton, N.J., 2011. The timing of strike-slip shear along the Ranong and Khlong Marui faults, Thailand. *Journal of Geophysical Research, Solid Earth*, 116, 1-26.
- White, R.W. and Powell, R. 2002. Melt loss and the preservation of granulite facies mineral assemblages. *Journal of Metamorphic Geology*, 20, 621-632. doi:10.1046/j.1525-1314.2002.00206_20_7.x
- White, R. W., Powell, R. & Holland, T. J. B., 2001. Calculation of partial melting equilibria in the system Na₂O-CaO-K₂O-FeO-MgO-Al₂O₃-SiO₂-H₂O (NCKFMASH). *Journal of Metamorphic Geology*, 19, 139 – 153.

- White, R. W., Pomroy, N. E. & Powell, R., 2005. An in-situ metatexite–diatexite transition in upper amphibolite facies rocks from Broken Hill, Australia. *Journal of Metamorphic Geology*, 23, 579– 602.
- White, R.W., Powell, R. and Johnson, T.E., 2014. The effect of Mn on mineral stability in metapelites revisited: New a–x relations for manganese-bearing minerals. *Journal of Metamorphic Geology*, 32, 809-828.
- White, R.W., Powell, R., Holland, T.J.B., Johnson, T.E. and Green, E.C.R. (2014), New mineral activity–composition relations for thermodynamic calculations in metapelitic systems. *Journal of Metamorphic Geology*, 32, 261-286. doi:10.1111/jmg.12071
- Whitney, D.L., and Evans, B.W., 2010, Abbreviations for names of rock-forming minerals: The American Mineralogist, v. 95, p. 185–187, <https://doi.org/10.2138/am.2010.3371>.
- Win, Maw Maw, Enamai, M., Kato, T. 2016. Metamorphic conditions and CHIME monazite ages of Late Eocene to Late Oligocene high-temperature Mogok metamorphic rocks in central Myanmar. *Journal of Asian Earth Sciences*, 117, 304-316.
- Woodsworth, G.J., 1977, Homogenization of zoned garnets from pelitic schists: Canadian Mineralogist, v. 15, p. 230–242.
- Yonemura, K., Osanai, Y., Nakano, N., Ando, T., Charusiri, P., Zaw, T.N. 2013. EPMA U-Th-Pb monazite dating of metamorphic rocks from the Mogok Metamorphic belt, central Myanmar. *Journal of Mineralogical and Petrological Sciences*, 198, 184-8.
- Yui, T-F., Khin Zaw, Wu, C-M 2008. A preliminary stable isotope study on Mogok ruby, Myanmar. *Ore Geology Reviews*, 34, 192-199.
- Zar, A.T., Warmada, I.W., Setjadji, L.D., Watanabe, K. 2017. Fluid inclusion studies of marble hosted quartz veins at Onzon area Mandalay region, Central Myanmar. *International Journal of Geophysics and Geochemistry*, 4(4), 30-38.
- Zaw, Khin. 1998. Geological evolution of selected granite pegmatites in Myanmar (Burma): constraints from regional setting, lithology and fluid inclusion studies. *International Geological Reviews*, 40, 647-662.
- Zhang, P., Mei, L., Hu, X., Li, R., Wu, L., Zhou, Z., Qiu, H. 2017. Structures, uplift, and magmatism of the Western Myanmar Arc: Constraints to mid-Cretaceous-Paleogene tectonic evolution of the western Myanmar continental margin. *Gondwana Research*, 52, 18-38.

Figure Captions

Figure 1. Regional geological map of Myanmar, from Mitchell et al. (2007), Searle et al. (2007, 2020), Myanmar Geosciences Society, (2012), Gardiner et al. (2015).

Figure 2. Geological overlay map on DEM of the area around the Kyi-Tauk-Pauk gold mine, western part of the Mogok Metamorphic belt, after Thein et al. (1990), Zar et al. (2017), Thu and Enami (2017), and Thu et al. (2017).

Figure 3. Textural relationships of the Kyi-Tauk-Pauk Grt + Bt + Sil migmatites. Core showing core hand specimen photographs and photomicrographs of samples KP10 and KP11. (a) Hand specimen, core photograph of KP10, with 2-3 cm garnet rimmed by biotite and sillimanite and green retrograde chlorite. (b) Cross-Polarised full thin section photomicrograph of KP 10 showing the position of line profile A-A' and overprinting relationship of garnet by biotite and sillimanite. (c) Mesosome cross-polarised photomicrograph of KP10 showing biotite, sillimanite intergrowths with interstitial k-feldspar and garnet. (d) Leucosome plane polarised photomicrograph with dominantly plagioclase and quartz with interstitial prismatic sillimanite and k-feldspar and garnet. (e) Garnet rim from sample KP10 showing biotite-sillimanite-plagioclase rim between large biotite flakes (Bt II), interpreted to be retrograde from garnet breakdown. (f) Hand specimen core photograph of KP11, stromatic migmatite. (g) Full thin section photomicrograph of KP11 showing leucosome and mesosome and the position of garnet line scan B-B'. (h) Cross-polarised photomicrograph of a leucosome from KP11 with quartz, plagioclase, K-feldspar porphyroblasts and minor biotite. I) KP10 cross-polarised photomicrograph showing coarse biotite, with inclusions of plagioclase.

Figure 4: Garnet line profiles and Ti in Biotite thermometry results. (a) KP10 garnet line profile A-A' showing uniformly high Pyrope across the core and inner rim, decreasing towards the outer rim, with an increase in grossular towards the inner rim. (b) KP11 garnet line profile B-B' showing garnet homogenisation to the outer rim, followed by decreasing pyrope and grossular to the outermost rim, with increasing spessartine. (c) Titanium in biotite thermometry (Henry et al., 2005) results for samples KP10 and KP11.

Figure 5: Calculated equilibrium phase diagram for sample KP10 and thermobarometry results. (a) P - T Pseudosection of sample KP10 showing the stable assemblage fields observed phase field in red text. (b) Pseudosection of KP10 showing contoured isopleths of garnet pyrope and grossular contents with observed rim and core compositions in coloured polygons. (c) Pseudosection of KP10 showing contoured isopleths of garnet

mode and spessartine contents with observed rim and core compositions in coloured polygons.

Figure 6: Calculated phase diagram for sample KP11 showing tightly constrained P – T constraints (a) Pseudosection of KP11 showing the stable assemblage fields observed phase field in red text. (b) Pseudosection of KP11 showing contoured isopleths of garnet pyrope and grossular contents with observed garnet core and rim compositions in coloured polygons. (c) Pseudosection of KP11 showing contoured isopleths of garnet mode and spessartine contents with observed garnet compositions in coloured polygons.

Figure 7. Summary P – T diagram for Kyi-Tauk-Pauk migmatites showing pseudosection results, average P – T results of KP10 and KP11, Grt + Bt + Als geothermobarometry results and Titanium in biotite thermometry, with interpreted P – T path.

Figure 8. Concordia diagrams for U–Pb–Th–Pb data, REE–date data, $^{208}\text{Pb}/^{232}\text{Th}$ dates, and trace-element–date data. Left column: cited dates are either concordia ages (sensu Ludwig) or “207-corrected” $^{206}\text{Pb}/^{238}\text{U}$ intercepts. Center column: REE changes are shown as a function of date. Right column: Tr/U , Eu/Eu^* , and Lu/Gd changes over time may result from recrystallization in the presence of a silicate melt/hydrous fluid, melt injection/extraction or plagioclase breakdown/growth, and garnet breakdown/growth, respectively.

Figure 9. A) Regional map of the Sagaing Fault and adjacent fault trends in Northern Myanmar (Shan Scarp Fault zone from Bertrand and Rangin, 2003). B) Detail of the Sagaing Fault zone west of Mandalay (see A for location). Showing highly variable foliation trends in the Sagaing Fault, that are typically oblique to, and cross-cut by the fault, modified from Kaung Sithu and Saw Ngwe Khaing (2017).

Figure 10. Digital Elevation model for the Mogok Metamorphic belt and northern part of the Sagaing Fault zone and surrounding region, after Morley (2016).

Tables Captions

Table 1. Summary of P – T results for samples KP10 and KP11.

Supplementary Information

S1. Table of LASS data for samples KP-5, KP-15 and KP-17.

Declaration of interests

☒ 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.

☒ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Journal Pre-proof

Titanium in Biotite Thermometry

KP10 MnNCKFMASHTO
SiO2 TiO2 Al2O3 FeO MnO MgO CaO Na2O K2O O H2O
48.264 1.239 14.162 15.609 0.264 11.649 1.306 0.935 2.100 1.178 3.559
All Assemblages +Grt ilm

Kyi-Tauk Migmatites Summary P-T

Strike-slip to transpressional fault
 Extensional fault

- Pliocene Irrawaddy Formation
- Miocene Kyaukta Formation
- Mylonitized limestone
- Minwun Metamorphics (low to medium grade schists)
- Sagaing Metamorphics
- Serpentine
- Strike and dip direction of metamorphic foliation

Sample	Method	Conventi			
		Grt Stage	End members included	Temperature (° C)	SD (° C)
KP10	AvPT	Grt Core	an-san-phl-ann-py-gr-q-ilm-H2O-sill-ru	856	101
		Grt Rim	san-phl-ann-east-py-alm-qz-ilm-sill-ru-H2O	868	83
	Grt-Bt-Als-Pl	Grt Core	-	923 (Grt-Bt)	50
		Grt Rim	-	831 (Grt Bt)	50
	Pesudosection	Grt Core	-	-	-
		Grt Rim	-	-	-
KP11	AvPT	Grt Core	phl-ann-east-san-py-q-ilm-ru-ky-sill-H2O	901	81
		Grt Rim	phl-ann-east-an-san-py-gr-alm-q-ilm-ru-sil-H2O	857	79
	Grt-Bt-Als-Pl	Grt Core	-	861 (Grt-Bt)	50
		Grt Rim	-	777 (Grt-Bt)	50

onal Thermobarometry					THERMOCA
Pressure (GPa)	SD (Gpa)	Corr	Sig Fit	Ti in Bt	Prssure (Gpa)
1.1	0.22	0.984	2.86	553-704	-
0.55	0.16	0.43	2.04		
0.86 (GASP); 0.86 (GPMB-MG); 0.61(GPMB-FE)	0.13	-	-		
0.91 (GASP); 0.81 (GPMB-MG); 0.64 (GPMB-FE)	0.13	-	-		
-	-	-	-	-	0.8-1.0
-	-	-	-	-	0.8-0.9
1.2	0.18	0.989	1.88	565-706	-
0.66	0.14	0.505	1.9		
0.91 (GASP)	0.13	-	-		
0.68 (GASP); 0.52 (GPMB-MG); 0.34 (GPMB-FE)	0.13	-	-		

LC Pseudosection
Temperature (° C)
-
870-970
820-845
-