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Key Points:

- Rubies and sapphires in granulite-facies marbles from the Mogok metamorphic belt, Myanmar, are spatially associated with charnockite-syenite sill-like intrusions and surrounding skarns
- U-Th-Pb LA-ICPMS dating of zircon, monazite, and titanite shows that there were two groups of charnockite-syenite dates, one Jurassic in age (170–168 Ma) and one latest Cretaceous to early Miocene (~68–21 Ma)
- Regional granulite-facies metamorphism along the Mogok metamorphic belt is Late Cretaceous to Oligocene or early Miocene in age (~68–21 Ma), peaking with garnet-present melting between 45 and 21 Ma

Supporting Information:

- Supporting Information S1

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Timing of Syenite-Charnockite Magmatism and Ruby and Sapphire Metamorphism in the Mogok Valley Region, Myanmar

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Abstract The Mogok metamorphic belt (MMB) extends for over 1,000 km along central Burma from the Andaman Sea to the East Himalayan syntaxis and represents exhumed lower and middle crustal metamorphic rocks of the Sibumasu plate. In the Mogok valley region, the MMB consists of regional high-grade marbles containing calcite + phlogopite + spinel + apatite ± diopside ± olivine and hosts world class ruby and sapphire gemstones. The coarse-grained marbles have been intruded by orthopyroxene- and clinopyroxene-bearing charnockite-syenite sheet-like intrusions that have skarns around the margins. Syenites range from hornblende- to quartz-bearing and frequently show layering that could be a primary igneous texture or a later metamorphic overprint. Calc-silicate skarns contain both rubies and blue sapphires with large biotites. Rubies occur in marbles with scapolite, phlogopite, graphite, occasional diopside, and blue apatite. Both marbles and syenites have been intruded by the Miocene Kabaing garnet-muscovite-biotite peraluminous leucogranite. New mapping and structural observations combined with U-Th-Pb zircon, monazite, and titanite geochronology from syenites, charnockites, leucogranites, meta-rhyolite-tuffs, and skarns have revealed a complex multiphase igneous and metamorphic history for the MMB. U-Pb zircon ages of the charnockite-syenites fall into three categories, Jurassic (170–168 Ma), latest Cretaceous to early Paleocene (~68–63 Ma), and late Eocene–Oligocene (44–21 Ma). New ages from five samples suggest that metamorphism in the presence of garnet and melt occurred between ~45 and 24 Ma. U-Pb titanite ages from the ruby marbles and meta-skarns at Le Oo mine in the Mogok valley are 21 Ma, similar to titanite ages from an adjacent syenite (22 Ma). U-Th-Pb dating shows that all the metamorphic ages are Late Cretaceous–early Miocene and related to the India-Sibumasu collision.

1. Introduction

High-grade granulite- and upper amphibolite-facies marbles form a major part of the Mogok metamorphic belt (MMB), Myanmar (Burma), stretching the length of northern Myanmar from the East Himalayan syntaxis south through the eastern Kachin state and the Mogok region to Mandalay (Figure 1). The Mogok valley in northern Burma (Myanmar) contains some of world's best examples of gem-quality spinel, ruby and sapphire, extracted from upper amphibolite- to granulite-facies marbles in the MMB (Chhibber, 1934a, 1934b; Fermor, 1931; Gordon, 1888; LaTouche, 1913; Middlemiss, 1899–1900; Myanmar Geosciences Society, 2012; O'Connor, 1888; Searle & Haq, 1964; Searle et al., 2007, 2017). The marbles are white, coarse-grained, and contain calcite, phlogopite, graphite, red spinel, diopside, and forsterite. Rare metapelitic rocks contain sillimanite and garnet, and some leucogneisses of possible metavolcanic origin are also present. The marbles have been intruded by a series of charnockite and syenite intrusions that have sill-like structures and calc-silicate skarns around the margins. Rare garnet- and tourmaline-bearing leucogranites intrude the marbles and are probably related to the 16.8 Ma Kabaing granite intrusion west of Mogok (Gardiner et al., 2016, 2014; Gardiner, Searle, Robb, et al., 2015).

The age of metamorphism and formation of the rubies and sapphires in Mogok has long been debated. Prior to any geochronology, the Mogok granulite-facies rocks were thought to be part of the Precambrian basement (Fermor, 1931; Barley et al., 2003; Chhibber, 1934a, 1934b; Mitchell, 2018). Mitchell et al. (2007) proposed two metamorphic events, one early Permian and the second Early Jurassic, based on field

Figure 1. Regional geological map of Myanmar from Searle et al. (2007).

relationships in the region south of Mandalay. Mitchell et al. (2012) published U-Pb zircon ages from a variety of igneous rocks along the MMB south of Mandalay and proposed an Early Cretaceous age of metamorphism, with the main fabric-forming metamorphic event predating the India-Asia collision. However, these ages were mainly from diorites and granites and may not date timing of regional metamorphism. The MMB has a range of biotite- and hornblende-bearing granites, granodiorites, and diorites that are thought to be related to the precollision, subduction-related Gangdese-type plutons along the southern margin of Asia, which range in age from Late Jurassic to early Eocene (Lhasa block; Chung et al., 2005; Gardiner, Searle, Morley, et al., 2015).

D.L. Searle and Haq (1964) first suggested that metamorphism along the MMB was related to the Cenozoic Himalayan orogeny. A Himalayan connection was confirmed by preliminary U-Th-Pb ID-TIMS and LA-ICPMS dating of metamorphic monazite, zircon, xenotime, and thorite by M.P. Searle et al. (2007). These data suggested two main periods of high-grade metamorphism in the MMB around Mandalay: (a) a Late Cretaceous–Paleocene event that ended with intrusion of 59 Ma biotite granite dykes, which cut metamorphic fabrics at Belin quarry and (b) a late Eocene–Oligocene main event (at least 37–29 Ma, possibly extending from 47 Ma to 25 Ma), when monazite grew at high temperature, sillimanite + muscovite replaced andalusite, zircon rims grew at 47–43 Ma, and tourmaline-bearing leucogranites formed at 45.5 ± 0.6 Ma and 25.5 ± 0.7 Ma (Searle et al., 2007). Metamorphic monazites from rare sillimanite- and andalusite-bearing pelites from Kyaushu ($600\text{--}650^\circ\text{C}$; $4.4\text{--}4.9$ kbar) revealed a peak-metamorphic age of 29.3 ± 0.5 Ma, and garnet + tourmaline leucogranite dykes cutting all earlier fabrics were dated at 24.5 ± 0.3 Ma (Searle

et al., 2007). Until recently, the age of crystallization of the spinel-, ruby-, and sapphire-bearing marbles around the Mogok valley has not been directly dated. These gems are common in the Mogok valley and hills to the north but rarely occur along the MMB south and north of Mogok. Thus, the two metamorphic episodes, pre-57 Ma (Paleocene) and 47–29 Ma (late Eocene–Oligocene), proposed by Searle et al. (2007, 2017) apply to the MMB around Mandalay but not necessarily to the ruby- and sapphire-bearing marbles in the gems fields of the Mogok valley farther north. Another question of direct relevance to the genesis of the MMB is why gem quality ruby and sapphire are localized in the Mogok Valley north of Mandalay and not widely distributed throughout the belt.

Recently Win et al. (2016) and Thu and Zaw (2017) and Sutherland et al. (2019) reported some preliminary U-Pb age data from Mogok rubies. A titanite inclusion in ruby from Thurein Taung gave a U-Pb date of 32.4 Ma, and subordinate nepheline was also noted as inclusions in the ruby. The adjacent syenite gave a U-Pb zircon date of 25 Ma (Thu, 2007; quoted in Sutherland et al., 2019). Also reported is a U-Pb date of 16.1 Ma in an extremely rare painite ($\text{CaZrAl}_9\text{O}_{15}(\text{BO}_3)$) overgrowth on ruby from Wet Loo mine (Thu, 2007). A zircon inclusion from a ruby collected at Mong Hsu gave a U-Pb date of 23.9 Ma (Sutherland et al., 2019) and is interpreted as the age of regional metamorphism. The geological and geochronological evidence seems to suggest that the MMB was the site of Jurassic–Paleocene Andean-type granitoid-diorite intrusions and localized low-pressure metamorphism, but the main high-temperature metamorphic event was Eocene–Oligocene and related to the Himalayan orogenic event.

The major ruby and sapphire mines are located mainly in the Mogok valley and the hills to the north (Fermor, 1934; Chhibber, 1934a, 1934b; Clegg & Iyer, 1953; Searle & Haq, 1964; Themelis, 2008) and are uncommon to the south of Mogok (Figure 2). Over 1,000 mines in the Mogok valley region produce spinel, ruby, sapphire, and numerous other gems. The Mogok valley has been closed to foreigners for decades but reopened in 2012. It remains sporadically closed due to local insurgencies, now from the TNLA (Palaung-armed ethnic group). Many of the larger ruby and sapphire mines remain off-limits to foreigners, but smaller locally owned mines are accessible. Recent changes in mining law in Myanmar have released the significant acreage to local artisanal miners, resulting in a gem rush of exploration in the Mogok valley area.

Since 2014, we have carried out extensive field investigations around the Mogok valley and surrounding hills and visited many of the ruby and sapphire mines in the region. A new geological map of the Mogok valley area is presented in Figure 3. Dense tropical jungle and thick red laterite soil make geological mapping difficult, and almost all critical contacts are not exposed. We were able to access underground shafts in several ruby and sapphire mines where continuous exposures made key structural observations possible. This paper presents new mapping and structural relationships together with new U-Th-Pb LA-ICPMS dating of zircon, monazite, and titanite that constrain timing of intrusion of the syenite-charnockite intrusions and the age of metamorphism in the Mogok valley. Field relationships clearly suggest that the distribution of ruby and sapphire in the Mogok valley is spatially related to the syenite and charnockite intrusions, but our data suggest a complex relationship between pluton emplacement, skarn formation, and ruby and sapphire crystallization.

2. Geology of the Mogok Region

The geology of the Mogok valley region was first mapped and studied by Gordon (1888), O'Connor (1888), LaTouche (1913), Fermor (1931, Fermor, 1934), Barrington-Brown (1933), Barrington-Brown & Judd (1896), Kane & Kammerling (1992), and Keller (1983). The most detailed descriptions were made by Chhibber (1934a, 1934b), and a geological map was published by Clegg and Iyer (1953) and Iyer (1953). In the days before radiometric age dating, these authors presumed that the high-grade metamorphic rocks in Mogok were Archean in age. They also suggested that the rubies in Mogok were formed by contact metamorphism around large granites such as the Kabaing pluton. However, metamorphism in the Mogok region is of regional extent (Searle et al., 2007, 2017; Searle & Haq, 1964) and not restricted to contact aureoles around granites.

The Mogok valley area is dominated by an ~10 km wide central zone of thick, coarse-grained calcite + phlogopite + graphite + spinel $\pm$ apatite-bearing marble that hosts many spinel, ruby, and sapphire mines (Figure 3). Marbles also contain scapolite, wollastonite, clinopyroxene (diopside), and olivine (forsterite) indicating granulite-facies conditions of formation. The marbles have been intruded by a large syenite-charnockite intrusion (Taung-met syenite) with several offshoots, mainly aligned as large sills (Figure 4a). On Taung-met mountain, the syenites commonly show interlayered felsic and mafic bands

Figure 2. (a) Digital elevation model for the Mogok area and (b) geological overlay showing the main structures. Box shows outline of the Mogok valley region in Figure 3.

(Figure 4b) with small veins of felsic syenite cross-cutting the igneous layering (Figure 4c,d). Coarse-grained orthopyroxene-bearing charnockites have igneous textures but are usually interpreted as granulite-facies rocks (Figure 4e). The Taung-met syenite intrusion is approximately 400 meters thick and may extend west as far as the Baw-lon-gyi area north of Kyat-pyin (Figure 5f), making this one of the largest alkaline igneous intrusions in Myanmar.

In the western part of the Mogok region around the Htay-pying ruby mine, small dykes of orthopyroxene charnockite intrude Mogok marbles (Figure 5a,b). The surrounding marbles are rich in high-quality rubies and have sapphire-bearing skarns around the dyke margins. Further west at Yadarnar kaday kadar mine next to Kyauk-pya-that pagoda hill, a variety of clinopyroxene syenites and orthopyroxene-bearing charnockites intrude Mogok marble (Figure 5c). The marbles are laden with both rubies and sapphires, and the margins have extensive metasomatic veining with large biotites (Figure 5d). East of Mogok the syenite-marble contact is well exposed at Nga Yant (Figure 5e). The syenite shows strong magmatic layering with interbanded felsic and mafic syenites (Figure 5f).

The Le Oo mine site east of Mogok town shows clear field relationships with a sharp contact between the Mogok marbles and syenite-charnockite intrusions (Figure 6a). The intrusions vary compositionally

Figure 3. Simplified geological map of the Mogok valley region, also showing locations of samples dated in this study.

between two pyroxene-charnockites and quartz syenites (Figure 6b). Some show perthitic textures with K-feldspar and quartz and a mafic constituent consisting of both clinopyroxene and amphibole. Calc-silicate skarns around the intrusion margins are rich in ruby (Figure 6c,d) and sapphire (Figure 6e). Individual ruby crystals can reach up to 4–5 cm (Figure 6f). Pale blue apatites are common across the Mogok marbles and can reach up to 5 cm length (Figure 6g). Extensive metasomatism along the marble contacts is evident from large biotites and hydrothermal minerals such as sodalite (Figure 5h).

High-grade regional metamorphic rocks comprising garnet + sillimanite gneisses and migmatites crop out to the SE of the Mogok valley but are poorly mapped. The surrounding rocks to the east comprise the Neoproterozoic-Cambrian Chaung Magyi Group (Dew et al., 2019), although the nature of its contact with the Mogok metamorphic rocks is not known. Overlying the Chaung Magyi Group are the Cambrian-Early Ordovician Pangyun Formation quartzites, sandstones, and siltstones and the Bawdwin volcanic series, which host the large Pb-Zn-(Cu-Ag-Ni) deposits at Bawdwin mine (Gardiner et al., 2017). To the west of the Mogok valley, a large leucogranite intrusion, the Kabaing granite, dated at 16.8 ± 0.5 Ma (U-Pb zircon) intrudes the Mogok marbles and syenites (Gardiner et al., 2016). To the north in the Pyang-yuang area (Bernardmyo; Figures 2 and 3), a large mass of peridotite, including dunite, harzburgite, and hornblende-bearing peridotite, was thought to represent an ophiolitic mantle rock (Searle et al., 2017) but may instead be a layered ultramafic intrusion, possibly related to the adjacent syenite intrusion at Taung-met (Figure 2). No gabbros, sheeted dykes, or pillow lavas are present at Pyang-yuang. Gem-quality peridot (olivine) and enstatite were mined from this massif. Marbles containing abundant rubies and sapphires crop out in the hills immediately north of the peridotite ridge at Ah Chauk and Htin-Shu Taung mines (Figure 3). The northern boundary of the Mogok region is a prominent north-dipping fault showing both normal and dextral fabrics, along the Momeik valley.

The structure of the Mogok valley is difficult to ascertain in detail due to the heavy jungle cover, but regional marble layers seem to dip consistently at steep angles, 45–60° SE. Thus, the garnet + sillimanite gneisses to the SE are structurally higher, above the Mogok marbles, and the Pyang-yuang ultramafic intrusion in the north is structurally beneath the Mogok marbles (Figure 2). It is possible that the entire Mogok massif represents a giant metamorphic core complex structurally below overlying Neoproterozoic and Paleozoic sedimentary rocks (Figure 2), although this is speculative since the whole area was covered in dense forest and in need of detailed mapping.

Figure 4. Field relations of the Chaungyi, Taung-met region. (a) View of Mogok town and hills to the north showing the Taung-met syenite sill and Pyang-yuang peridotites in distance. (b) Layered clinopyroxene-bearing syenite from Chaungyi (sample MY 215). (c) Layered mafic syenites at Chaungyi (sample MY216). (d) Perthitic feldspathic vein intruding mafic syenite, Chaungyi. (e) Coarse-grained enstatite crystals in charnockite, Chaungyi. (f). Outcrops of syenite at Baw-lon gyi, north of Kyat-pyin.

2.1. Spinel-, Ruby-, and Sapphire-Bearing Marbles

Red spinel (MgAl_2O_4) is the most common gem mineral in Mogok marbles, frequently forming euhedral octahedra within coarse-grained marble. Ruby and sapphire (corundum Al_2O_3) differ in color only as defined by their trace contents of iron, titanium, vanadium, and chromium; these phases both occur in Mogok marbles, with sapphires possibly more abundant in skarns. The presence of diopside and forsterite in marble requires amphibolite or granulite-facies metamorphic conditions (Bowen, 1940). The highest grade olivine (forsterite)-bearing marbles have the paragenesis $\text{Cal} + \text{Dol} + \text{Fo} + \text{Spl} + \text{Phl} + \text{Amp} + \text{Grt}$ and contain gem-quality rubies and sapphires; spinel is not present with ruby or sapphire. Impure marbles may contain micas (phengite, biotite, and fuchsite), graphite from organic debris, feldspars, and garnet. Pale blue apatite crystals that reach 5 cm or more in size are present in many Mogok marbles. Calc-silicate rocks contain $\text{Scp} + \text{Di} + \text{Cal} + \text{Qtz} + \text{Kfs} + \text{Grt} + \text{Ttn}$. Clinohumite- and scapolite-bearing assemblages yield high metamorphic grades at $>780\text{--}810^\circ\text{C}$ and 0.8 GPa (Thu & Enami, 2018). The calcite-dolomite

Figure 5. (a) Syenite dyke intruding Mogok marble, Htay-pying quarry, north of Kyat-pyin. (b) Sharp intrusive contact of syenite with Mogok marble, Htay-pying. (c) Coarse-grained clinopyroxene + amphibole syenite, Yadarney kadey kadar. (d) Hydrothermal metasomatic biotites along the intrusive contact of syenite in marble, Yadarnar kaday kadar. (e) Sharp intrusive contact of layered syenite with Mogok marble, Nga Yant, east of Mogok. (f) Layered felsic and mafic syenites, Nga Yant, east of Mogok.

geothermometer also suggests a minimum temperature of 720–765° C and a possible equilibrium temperature up to 780–860° C (Thu & Enami, 2018). These temperatures are consistent with granulite-facies metamorphic conditions, in which decarbonation of buried carbonate-rich rocks released CO₂-rich fluids, while some H₂O fluids may also have been associated with acidic igneous melts (Yui et al., 2008). The presence of uncommon wollastonite (CaSiO₃) in some skarns in Mogok indicates high temperature–low pressure breakdown of calcite + quartz with the release of CO₂.

Potential protoliths of the Mogok marbles are the thick Permian *Fusulinid*-bearing limestones (Chhibber, 1934a), which are widespread across SE Asia or the mid-Cretaceous *Orbitolina*-bearing limestones (Clegg, 1941). The Neoproterozoic–Early Cambrian Chaung Magyi Group and the Ordovician–Devonian argillaceous limestones of the Shan Plateau are probably too muddy to be suitable protoliths for the purer marbles in Mogok. Elevated aluminum content could be a result of specific aluminum-rich, silica-poor source rocks, such as laterites or evaporites. MgO combined with Al₂O₃ to

Figure 6. (a) Syenite-marble contact above Le Oo mine, east of Mogok. (b) Clinopyroxene-bearing syenite at Le Oo ruby mine. (c) Ruby-bearing calc-silicate skarn, Le Oo mine. (d) Rubies mined from Le Oo marbles. (e) Large euhedral sapphire crystals from Le Oo mine. (f) Large ruby hosted in Mogok marble. (g) Large pale blue apatite and small red spinel in Mogok marble. (h) Blue sodalite, a metasomatic product of fluids along the syenite-marble contact.

form spinel at low SiO_2 and CaO activities and corundum formed locally (Sutherland et al., 2019). Spinel is generally not found together with ruby or sapphire in the field, suggesting that variable Mg activity in the marbles may have controlled the occurrence of corundum. High-temperature fluids (CO_2 and H_2O) were driven off from surrounding skarns and infiltrated the marbles possibly during intrusion of the hot, dry charnockitic magmas. Metasomatic phases such as sodalite and lapis lazuli are common in several Mogok localities. The close association of charnockites with gem minerals (notably ruby, sapphire, spinel, cordierite, and sapphirine) has also been noted in the Proterozoic Highland Group of Sri Lanka, where

the gems have been related to contact metamorphism around ultra-high temperature charnockite intrusions (Rupasinghe & Dissanayake, 1985).

2.2. Pelites

Pelitic rocks containing the assemblage $\text{Grt} + \text{Bt} + \text{Pl} + \text{Sil} + \text{Qtz} \pm \text{Crd} \pm \text{Spl}$ are present but uncommon along the MMB, making precise PT conditions difficult to ascertain. The metamorphosed pelites, now garnet + sillimanite gneisses, are called khondalites in the older literature (Chhibber, 1934a, 1934b). Rare pelites containing garnet and sillimanite at Kyaushe, south of Mandalay, revealed PT conditions of 600–650 °C and 4.4–4.9 kbar, and a peak-metamorphic U-Pb monazite age of 29.3 ± 0.5 Ma (Searle et al., 2007). Kyanite is uncommon but occurs in the Kyaushe region. Yonemura et al. (2013) obtained PT conditions of 6.5–8.7 kbar and 800–950 °C from granulite-facies gneisses and also published imprecise U-Th-Pb ages of <50 Ma. Core samples from the Letpanhla-Kyitauk Pauk gold mine in the western part of the Mogok area, adjacent to the Sagaing fault, show extensive garnet + sillimanite migmatites with late cordierite, rock types that are not exposed in the Mogok valley or in the many quarries south of Mandalay along the MMB.

2.3. Charnockites and Syenites

2.3.1. Definitions

Syenites are defined as coarse-grained, intrusive igneous rocks with essential K-feldspar, frequently with perthitic textures and ferromagnesian minerals (biotite, hornblende, clinopyroxene, and orthopyroxene). A few syenite bodies have the full range from ultramafic jacupirangites (amphibole, pyroxene, and biotite rocks) to quartz syenites. Syenites are generally associated with anorogenic intraplate intrusions or along rifted continental margins such as along the East Africa rift system. It is unusual that the differentiated sequence from alkaline ultramafic to quartz syenite occurs in one intrusion, but one example, the Borralan intrusion in the Moine thrust zone, NW Scotland (Parsons, 1999; Searle, Law, et al., 2010), shows a similar compositional range. The Borralan intrusion includes an early suite of pyroxenites, nepheline syenites, and pseudoleucite-bearing syenites, and a later suite of feldspathic and quartz syenites. It was intruded into Cambrian sedimentary rocks and Ordovician marbles forming a high-grade contact metamorphic aureole of yellowish brucite and pyroxene marble. The dolomites were metasomatized and intruded as carbonatite sheets. The Borralan syenite intrusion thus has many similarities with the Mogok syenites.

Charnockites were originally defined as orthopyroxene-bearing (A-type) granite-granodiorites (opdalites), tonalites (enderbites), or monzogranites (mangerites; Howie, 1955; LeMaitre et al., 2005). They were named from the tombstone rock on Col. Job Charnock's grave in Calcutta, India (Holland, 1893). Charnockites are hot (~1,000 °C), dry, granulite-facies quartzofeldspathic rocks with orthopyroxene that can be either igneous or metamorphic in origin (Frost et al., 2000; Frost & Frost, 2008, 2000; Bhattacharya, 2010). Frost and Frost (2008) defined charnockite as “an Opx- (or Fay-) bearing granitic rock that is clearly of igneous origin or that is present as an orthogneiss within a granulite terrane” (Frost & Frost, 1987). Charnockites can form by differentiation from anhydrous tholeiitic rocks with low water activity and enriched levels of CO_2 . The process of charnockitization may be associated with several processes including high-temperature dehydration melting of mafic to intermediate protoliths, infiltration of CO_2 from deep crust levels, and magmatic differentiation above mantle anomalies such as rift zones or continental hot spots. Charnockites, despite having an igneous origin in many cases, are invariably associated with high-temperature granulite-facies terranes (Bhattacharya, 2010). Most charnockites are Precambrian in age, with classic examples from south India and Sri Lanka (Highland Group). Although granulites are widespread in Phanerozoic rocks from a variety of lower crust tectonic settings (deep levels of calc-alkaline batholiths, island arcs, or thickened continental plateau regions like Tibet), there are only a few possible examples of Phanerozoic charnockites, for example, in the Coast Ranges of British Columbia, the Variscan Bohemian massif, Czech Republic, and the Variscan Aracena belt, Spain (Windley, 1981).

Skarns are calcium-magnesium-iron-manganese aluminum silicate rocks that may also be referred to as calc-silicate rocks. They are typically formed by metasomatic or hydrothermal alteration of country rocks by fluids, usually only locally around igneous intrusions (contact metamorphism), but in Mogok, the skarn effects could be of more regional extent.

2.3.2. Mogok Charnockites and Syenites

The Mogok valley shows three or four major charnockite-syenite sill-like intrusions into the marble; the largest, the Taung-met intrusion, forms the high mountain ridge north of Mogok town (Figure 4a). At least two

further sills to the south have been mapped around Dattaw, and at least three sills have been mapped in the west, north of Kyat-pyin (Figure 3). It is not clear from the limited exposures whether these sills are all part of one major intrusion or whether separate sills have intruded in the same general area. A wide range of alkali granites, syenites, and charnockites has intruded the MMB. These include hornblende-rich melanocratic syenite, orthopyroxene-bearing charnockite, clinopyroxene + hornblende-bearing K-feldspar + plagioclase syenite, and quartz syenite. Some show compositional layering that may be an original igneous texture; others also show a tectonic foliation with aligned hornblende indicating a high-temperature fabric superimposed on the original igneous rock. In this study, most of the samples from larger sheets are charnockitic, whereas syenites are dominant in associations with marble and skarn at the mine localities. Rare alkaline ultramafic rocks consisting of amphibole + clinopyroxene + biotite jacupirangites (called “urtite” in older literature; Chhibber, 1934a, 1934b) with no feldspar are associated with the deepest levels of the syenite intrusions. Chhibber (1934a, p. 123) described nepheline in syenites from Chaunggyi; silica undersaturated melting could result in feldspathoids, such as nepheline replacing albite and leucite replacing orthoclase, but none of our samples contain nepheline. The map of Clegg and Iyer (1953) also shows several outcrops of nepheline syenites, but we were unable to confirm this at several localities around Pingu Taung and Kyauk pya-that (Figure 3).

2.4. Granites and pegmatites

Uncommon leucogranites containing garnet, sillimanite, and tourmaline intrude the marbles and may be related to the large Kabaing granite intrusion, west of the Mogok valley. The Kabaing leucogranite appears to be a large-scale midcrustal intrusion and differs from the Himalayan leucogranites that are sill-like intrusions emanating from a thick sillimanite $\pm$ cordierite migmatite terrane (Searle, Cottle, et al., 2010). One possible source could be the sillimanite migmatites known from drill cores in the Letpanhla-Kyitauk Pauk gold mine in the western part of the Mogok area (Figure 2), but other pelitic rocks are extremely rare along the MMB. A suite of pegmatites associated with the Kabaing granite contains gem-quality topaz, quartz, tourmaline, lepidolite, and aquamarine (e.g., at Sakangyi mine). K-feldspar augen gneisses are present in the area south of Mogok (e.g., Kyanikan and Nattaung quarries) and are associated with in situ partial melting to form tourmaline $\pm$ garnet leucogranites (Searle et al., 2007, 2017).

3. Field Relations and U-Th-Pb Geochronology

We present U-Th-Pb zircon, monazite, and titanite dates and trace elements for 13 samples tied to structural mapping from across the Mogok valley. These samples are described from three main regions (Figure 3): (a) the Mogok valley and region to the east, including the Le Oo, Dattaw, and Pein Pyit (Gorkha, Nepali) ruby-sapphire mines; (b) the Chaunggyi valley and Taung-met hill, north of the Mogok valley; and (c) the western part of Mogok, including Baw Lon Ley, Baw Mar, and Yadarnar kaday kaday ruby-sapphire mines around Kyat-pyin village. Figure 7 is a summary diagram showing the full range of dates and minerals dated (titanite, zircon, and monazite) from 13 samples across the Mogok region.

3.1. Methodology

We conducted laser-ablation split-stream inductively coupled plasma mass spectrometry (LASS) measurements on zircon, monazite, and titanite. Mineral zoning was qualitatively assessed in select samples with cathodoluminescence or X-ray maps (measured by EPMA), and U-Pb dates and trace elements (Table S1 in the supporting information) were measured quantitatively on all samples 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 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 interelement 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. Two samples, MY83 and MY164, were also evaluated using depth profiling, in which the downhole variation in date-element data was treated as spatially significant.

Figure 7. Summary and geologic interpretation of zircon, monazite, and titanite dates presented in this study. Gray bands emphasize geological events recorded in multiple samples and/or known from elsewhere in the orogen. “mmm,” metamorphism; “xln,” crystallization; “w.,” with; “w/o,” without. Solid colors indicate clusters of dates, and faded colors indicate ranges of concordant dates.

We interpret changes in mineral trace-element signatures in the following ways: (a) an increase/decrease in Lu/Gd ratio indicates garnet breakdown/growth; (b) an increase/decrease in Eu/Eu* ratio is compatible with plagioclase-rich melt injection/extraction or plagioclase breakdown/growth; (c) 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.

3.2. Mogok Valley and Region to the East

The Mogok valley runs NE-SW between high mountain ridges of Taung-met to the north and the more subdued jungle-clad hills toward Pyin Oo Lwin to the south. The valley shows at least 2 km thickness of coarse-grained, upper amphibolite, or granulite-facies marble that is host to at least six major ruby-sapphire mining districts extracting gems from bedrock as well as alluvial deposits (Bawpadan, Yebu, Le Oo, Dattaw, Onbin, and Pein Pyit). The marbles are intruded by several charnockite-syenite intrusions that appear to form sill-like structures. Skarns are present around the margins with a concentration of sapphires as well as large biotite flakes. Sample MY-Le Oo is from a ruby-bearing marble from the Le Oo mine, MY-228 is from a coarse-grained clinopyroxene-bearing syenite collected in situ immediately above the alluvial washing pits. Sample MY-229 is from a skarn along the syenite-marble contact from the same mine; it consists of 50% clinopyroxene with K-feldspar and around 5% quartz. Two further samples (MY-142 and MY-144) were collected from the Pein Pyit (also called Nepali Gorkha) ruby-sapphire mine east of Le Oo and Mogok. MY-142 is a leucocratic rock interbedded within marbles and contains lilac-colored garnet + plagioclase + K-feldspar + biotite + apatite. MY-144 is a graphitic garnet + biotite + plagioclase rock, inferred to represent a residual assemblage after loss of partial melt from a metapelite, interbanded within marbles, one of the more aluminous samples we found in the Mogok valley.

We dated zircon, monazite, and titanite from these samples (Figure 8). Zircon in MY142 comprise tiny euhedral grains, of which the oldest are 111 Ma; this sample could be a tuff that erupted at 111 Ma or a metasediment deposited after that time. Monazite from this rock is mostly younger and shows a distinct drop in Eu/Eu* and Lu/Gd from ~78 to 24 Ma, compatible with melt extraction and the crystallization of garnet. Zircon from MY144 has a large range in concordant dates—1.2 Ga to Cretaceous—typical of a

Figure 8. Concordia diagrams for U-Pb and Th-Pb data, REE-date data, and trace-element-date data from the central and eastern Mogok valley. (left column) cited dates are either concordia ages (sensu Ludwig) or “ $^{207}\text{Pb}/^{206}\text{Pb}$ -corrected” $^{238}\text{U}/^{206}\text{Pb}$ intercepts. (center column) REE changes are shown as a function of date. (right column) Th/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.

metasedimentary rock that might have a Cretaceous depositional age. Most of the zircon analyses are 74–24 Ma, compatible with metamorphism ending by 24 Ma. Monazite from MY144 mirrors the younger zircon, with a range from 80 Ma (high-Y and low-Th cores) to 35 Ma (low-Y and high-Th rims; Figure S1). Both zircon and monazite have weak decreases in Eu/Eu^* and increases in Th/U compatible with melting; the reduction seen in zircon Lu/Gd is suggestive of the growth of garnet, but this signature is absent from monazite. Zircon from MY-228 is entirely Cenozoic and of constant composition, compatible with either igneous or metamorphic parentage. The youngest titanite in MY229 and MY-Le Oo is ~22 Ma and certainly metamorphic in origin.

3.3. Chaunggyi Valley and Taung-Met Hill

This region lies north of the Mogok valley and is dominated by a long, high ridge leading up to Taung-met summit. The high ridge is composed of a large charnockite intrusion nearly concordant with the foliation in the surrounding marbles. The southwestern (Injauk valley) and southeastern (Chaunggyi valley) margins of the charnockite-syenite are intrusive into marbles, with numerous mines along the contact. The northern contact of the Taung-met charnockite-syenite intrusion is close to the layered ultramafic rocks of the Pyang-yaung (Bernard-myo) region. Samples MY-215, MY-216, and MY-164 were all collected from the Taung-met intrusion north of the Chaunggyi valley (Figure 3). MY-164 is a clinopyroxene charnockite with perthite and titanite. MY-215 is a felsic syenite consisting of K-feldspar + quartz + clinopyroxene. MY-216 is a mafic syenite (Figure 4b,c). Sample MY-83 was collected from a layered charnockite containing K-feldspar + plagioclase + quartz + orthopyroxene at the coffee plantation estate NE of the Injauk road junction (Figure 3). Sample MY-138 is a diopside + plagioclase + K-feldspar + phlogopite calc-silicate skarn from Chaunggyi collected from the southern margin of the Taung-met charnockite-syenite intrusion.

The simplest zircon sample is MY138, which gave a range of U-Pb dates from 44 to 28 Ma and shows minimal variation in Th/U , Lu/Gd , and Eu/Eu^* over that time span (Figure 9). These dates are definitively metamorphic because the rock is a skarn. The zircon data from the rest of the samples are not as simple to interpret. All four (MY83, MY164, MY215, and MY216) give broad ranges in U-Pb dates from ~170 to 22 Ma, with possible clusters of intermediate dates from 68 to 20 Ma (Figures 7 and 9). Most of the dates are concordant, or nearly so, indicating either small amounts of common Pb, partial resetting, or mechanical (laser) mixing of zones with distinct dates. That all four samples have a cluster of oldest analyses of ~170 Ma—observed exclusively in oscillatory to sector-zoned zircon cores (Figures S2 and S3)—indicates that the dated rocks are of roughly the same age and crystallized at the same time; there might be a range of crystallization ages from 170 to 163 Ma, but dispersion in the data makes this difficult to assess. Th/U decreases monotonically until ~60 Ma in MY83 and MY164, compatible with metamorphism at that time and then increases markedly after ~40 Ma, compatible with melting. Some U-Pb dates arrayed between ~170 and 60 Ma occur in obviously metamict zircon cores (Figures S2 and S3), although many do not; in contrast, Late Cretaceous (~68 Ma) to Miocene dates (~20 Ma) typically occur in distinct zircon overgrowths. The youngest dates from each sample always occur in cathodoluminescence-bright rims, and the range of measured dates from these rims (~40–20 Ma) are reproducible between spot and depth-profiling methods applied to the same samples. Eu/Eu^* is relatively invariant in all samples except for MY215, in which a peak at 60–40 Ma is compatible with plagioclase-rich melt injection. Titanite from MY216 gives a simple intercept date of 19.8 ± 0.4 Ma. In summary, and when considered in light of the geochronology data presented below, this data set is compatible with ~170 Ma igneous crystallization of the charnockite-syenite intrusions, metamorphism beginning at 65–40 Ma, and sustained high temperatures through to 20 Ma.

3.4. Kyat-Pyin and Western Mogok Region

This region lies west of Mogok and is centered around the town of Kyat-pyin and the Kyauk-pya-that golden pagodas (Figure 3). Numerous ruby and sapphire mines in this region are either within the marble or along skarn contacts with several syenite sills. We found no corundum gems in the syenite itself, although sapphires have been found in syenite elsewhere in the Mogok region (Themelis, 2008). Three main charnockite-syenite sills are mapped along the transect from Kyat-pyin north to Baw-mar. The main ruby-sapphire mines are at Kyat-pyin, Wet Loo, Baw-lon-lay, Baw-lon-gyi, and Bawmar. Farther west, the mines at Thurein Taung and Yadarnar kaday kaday (Burmese for “millions and billions”) produce gem star sapphires and rubies. Sample MY-227 is a syenite from a dyke intruding marble, north of Kyat-pyin

Figure 9. Concordia diagrams for U-Pb and Th-Pb data, REE-date data, and trace-element-date data from the Chaunggyi valley and Taung-met hill (cf. Figure 8 caption for additional figure details).

(Figure 5a). Sample MY-122 is a garnet + biotite leucogneiss adjacent to a clinopyroxene-olivine bearing calc-silicate or skarn, collected from Baw-lon-lay mine. Sample MY-94 is a garnet + sillimanite + biotite paragneiss that contains K-feldspar-rich leucosomes attributable to partial melting and is one of the few metapelite rocks seen in the Mogok valley.

Figure 10. Concordia diagrams for U-Pb and Th-Pb data, REE-date data, and trace-element-date data from Kyat-pyin and the western Mogok region (cf. Figure 8 caption for additional figure details).

We analyzed zircon from MY-227 and monazite and zircon from MY-94 and MY-122 (Figure 10). Zircon in MY-227 is 66.6 ± 1.2 Ma and invariant in REE composition. The Cretaceous date could be an intrusion age, and the few younger analyses are compatible with subsequent Pb mobilization. Zircon in MY-122 gave chiefly concordant dates from 151 to ~90 Ma, with a cluster at 124 Ma and little variation in REE composition. The Jurassic date is likely an intrusion age, and the few younger analyses are compatible with subsequent Pb mobilization. Monazite from the same sample is significantly younger, with concordant dates from ~101 to 21 Ma and a clear decrease in Th/U, Eu/Eu*, and Lu/Gd until ~60 Ma. These data are compatible with metamorphism without garnet prior to 60 Ma and metamorphism in the presence of garnet since. Monazite from MY-94 is similar, with high-Y cores mantled by low-Y rims (Figure S4), and warrants the same interpretation; however, thin, young, Th-rich rims on several grains suggest a late (~25 Ma) melting event. For this sample, the outermost zircon rim dates have U-Pb dates similar to the youngest monazite, revealing that the zircon underwent late metamorphism-related recrystallization or rim growth.

Figure 11. Model for the crustal structure of the Mogok metamorphic belt. Mantle rocks are the Pyang-yuang peridotites (dunites, harzburgites, etc.). Lower crustal rocks comprise the large layered syenite intrusion of Taung-met, Chaungyi, and several other sills exposed around Dattaw, Le Oo, and Bawpadan, intrusive into Mogok marbles. Ruby (R) and sapphire (S) mines are spatially associated with the syenite sills and their surrounding skarns. The garnet + sillimanite gneisses exposed in the mountains south of Mogok structurally overlie the marbles. West of Mogok, a large intrusive leucogranite, the Kabaing granite, intrudes the ruby marbles and gneisses. Gem-bearing pegmatites (e.g., Sakangyi topaz-quartz pegmatite) emanate from the roof of the Kabaing granite.

4. Model for Formation of Spinel, Ruby, and Sapphires in Mogok

Figure 11 is a simplified model showing the structural relationships of the lower and middle crustal rocks exposed in the Mogok region. Abundant charnockite-syenite magmas intruded from a hot lower crustal source. Alkaline ultramafic rocks (jacupirangites) associated with mafic syenites reflect an unusual and extreme alkaline source from the upper mantle. The charnockite-syenites intruded to midcrust levels where they became sill-like intrusions. Heat from the intrusion of hot (>1,000–1,200 °C) charnockite-syenites would likely have produced a contact metamorphic aureole and skarns around the margins. Magmatic-metasomatic fluids desilicified the surrounding country rock forming first spinel and then corundum. Both rubies and sapphires are regionally distributed and are almost always found close to (within 1–2 km structural thickness) the major syenite intrusions north of the Mogok valley. Sapphire mines appear to correlate mainly with skarns around the margins of the intrusions.

Although the large Taung-met charnockite-syenite is probably Jurassic in age (170–168 Ma), other charnockite-syenite intrusions around Thurein Taung, Kyauk Pya-that, and Bawmar in the west may be latest Cretaceous to early Miocene (~68 Ma and 44–21 Ma). One syenite along the northern margin of the Le Oo mine, east of Mogok has a U-Pb zircon crystallization age of 37 Ma (MY228), and a titanite crystallization age of 21.6 Ma (MY229), similar to the calc-silicate ruby-bearing skarns at Le Oo mine (22 Ma). U-Pb geochronology shows that all the metamorphic ages are latest Cretaceous through to Oligocene—earliest Miocene. The ages from the syenites and charnockites in Mogok are more difficult to interpret, and several possible scenarios are proposed (see section 5).

Garnet- and melt-present metamorphism occurred between ~45 and 24 Ma in Mogok and is coeval with previous U-Th-Pb metamorphic ages from MMB rocks near Mandalay (Searle et al., 2007, 2017). Systematic

Figure 12. Metamorphic peak P - T conditions for gneisses in the Mogok valley area based on calculated phase diagrams (pseudosections) showing stability fields for assemblages in Grt-Bt leucogneiss (Kfs-Pl-Qz-Bt-Grt-Ilm) and felsic Grt-Bt-Sil paragneiss (Kfs-Qz-Pl-Grt-Bt-Sil-Ilm). Area of overlap is centered on 775 ± 50 °C, 7.5 ± 1 kbar. Diagram calculated with Theriak/Domino software (De Capitani & Petrakakis, 2010), using the thermochemical database DS6 of Holland and Powell (2011) and activity models from White et al. (2007), White, Powell, Holland, et al., 2014, White, Powell, & Johnson, 2014). Mineral abbreviations follow Whitney and Evans (2010).

thermobarometry on the high-variance assemblages sampled in the Mogok valley area is problematic and has not been attempted. Moreover, there is very little evidence in the metamorphic assemblages for multiple events, despite the apparently complex history revealed in the zircon and monazite ages. Nevertheless, broad constraints can be placed on the maximum conditions (Figures 12) by phase equilibrium modelling of bulk compositions for Grt-Bt leucogneiss (e.g., MY-122 and MY-142) and Grt-Bt-Sil paragneiss (e.g., MY-94), based on observed mineral proportions in the samples. The location of the solidus places an important constraint on the peak temperature, given that MY-94 is a migmatitic gneiss and that MY-142 shows textural evidence for dehydration melting of biotite. The solidus curve is calculated for a bulk H_2O content that is defined by the volume proportion of biotite, the only hydrous mineral in the samples. A further constraint on the Grt-Bt leucogneiss is the absence of orthopyroxene, which is predicted to occur at lower pressure and also in melt-bearing assemblages through further dehydration melting of biotite. For the Grt-Bt-Sil paragneiss, cordierite is predicted to occur at lower pressure, and the high- P limit is given by the Ky-Sil curve. The extent of each field also takes into account uncertainty on the estimated bulk composition (cf. Palin et al., 2016). The area of overlap for the two rock compositions is centered on 7.5 kbar and 750–800 °C conditions that are comparable to those determined in granulite-facies paragneisses by Thu et al. (2017) at localities c. 45 km WSW of the Mogok valley.

Late garnet + tourmaline leucogranites resulted from widespread Miocene midcrustal anatexis and intrusion of the Miocene Kabaing granite with its gem-bearing pegmatites, and appear to cut fabrics in all surrounding metamorphic rocks. The age of the Kabaing granite (16.8 ± 0.5 Ma; Gardiner et al., 2016) reflects the final phase of metamorphism

and melting in the Mogok region. The relative lack of large-scale fold-nappe structures and absence of evidence for Himalayan-scale crustal thickening in the MMB may suggest a heat source other than orogenic thickening and radiogenic heating for the observed upper amphibolite-granulite metamorphism and the formation of corundum-bearing marbles. It could be argued that the close spatial association between ruby and sapphire-bearing marbles and the syenite-charnockite intrusions suggest a temporal connection, but the geochronological data presented here are more complicated and suggest that the alkaline magmatic intrusions are only indirectly related to the ruby and sapphire formation.

5. Discussion

Field structural relationships, metamorphism, and U-Pb geochronology from the Mogok area suggest three possible tectonic scenarios:

Model 1. All charnockite-syenites in the Mogok region are Jurassic, but only the large Taung-met-Chaunggyi intrusion preserves the original intrusion ages (170–163 Ma). The Kyat-pyin and Le Oo syenites and meta-skarns do not have Jurassic ages from our data, but later regional granulite-facies metamorphism during Late Cretaceous–Paleocene time could have overprinted an earlier intrusion event. Skarns formed around the syenite intrusions at ~170 Ma but did not necessarily contain ruby or sapphire at that time. Regional Mogok metamorphism was a Late Cretaceous–Miocene granulite-amphibolite facies event, and rubies and sapphires were formed from burial and metamorphism of meta-skarns and surrounding marbles.

Model 2. Two or three episodes of charnockite-syenite intrusion could be interpreted from our new U-Th-Pb geochronology data, the Jurassic Taung-met intrusion (170–163 Ma), the Kyat-pyin syenite (MY227; 67 Ma), and the Le Oo syenite (MY228; 37–28 Ma) with adjacent meta-skarns (MY229; 22 Ma). It is quite likely that there was some chemical-metasomatic effect of intrusion of these hot magmas into a regional, long-lasting

(ca. 45 m.y.) granulite-facies terrane, such that the occurrence of rubies and sapphires was directly related to multiple, distinct episodes of skarn formation.

Model 3. The charnockite-syenites were all intruded during the latest Cretaceous-Oligocene-early Miocene (between ~68 and 22 Ma) concomitant with regional metamorphic ages from zircon, monazite, and titanite dates. In this model, the older Jurassic zircon ages from Taung-met to Chaunggyi (170–163 Ma) are interpreted as inherited from the source and escaped overprinting during later granulite-facies metamorphism. The exclusively young zircon ages reported by Thu (2007) and Sutherland et al. (2019) support this model.

The Jurassic dates appear to be restricted to the large intrusion at Taung-met and Chaunggyi (MY 83, MY-164, MY-215, and MY-216). One sample, the Taung-met charnockite (MY 216), has zircon ages at 168, 63, and 26 Ma. The Cretaceous igneous rocks may be part of the trans-Himalayan Gangdese batholith in south Tibet and its proposed extension south into Myanmar (Lin et al., 2019; Zhang et al., 2017). All these samples have younger zircons, reflecting subsequent high-temperature metamorphism. One syenite sample from a dyke intruding marble (Figure 5a) at Kyat-pyin (MY-227) has only younger zircon dates ranging of 44–38 Ma. Zircon has a high closure temperature, but in charnockites and syenites, it may not preserve older inheritance ages due to a combination of diffusive Pb resetting and zircon resorption. If so, the oldest zircon ages should reflect the timing of intrusion.

The main pulse of metamorphism recorded by rocks in the Mogok valley appears to have begun around 60 Ma and extended until titanite crystallization or diffusive Pb closure at 22 Ma. This timing is similar to that from the MMB to the south around Mandalay (Searle et al., 2007, 2017). The oldest dates may reflect regional contact metamorphism around the trans-Himalayan batholith. Most of the metamorphic dates and particularly those with trace-element characteristics suggestive of melting, garnet growth, and granulite-facies conditions in the ruby- and sapphire-bearing skarns around the margins of the charnockite intrusions begin around ~45 Ma and extend to ~24 Ma. We suggest that this timing records the crystallization of the gem spinels, rubies, and sapphires in Mogok. The thick marble bands around the Dattaw mine north of Mogok have produced some of the best quality gem rubies and are located between the upper Taung-met charnockite-syenite intrusion and the lower Le Oo syenite intrusion (Figure 3).

High temperatures were maintained until as late as 16.8 Ma when the Kabaing leucogranite was intruded into the MMB to the west (Gardiner et al., 2016). Abundant garnet + sillimanite $\pm$ cordierite migmatites are known from drill core samples in the Kyi Tauk Pauk gold mine west of Mogok. At this location, numerous mesothermal gold-bearing quartz veins intrude the garnet-sillimanite migmatites. These migmatitic rocks must reflect a different, more pelitic source than the Mogok valley region and are of unknown age. Similar migmatites may be present SE of the Mogok valley (on the road to Mandalay and Pyin Oo Lwin), but the ages of these rocks are also unknown. Further research combining field structural mapping with detailed U-Th-Pb geochronology is required to unravel the complex metamorphic and magmatic history of the region.

6. Conclusions

Granulite- and upper amphibolite-facies marbles occur throughout the MMB that runs for >700 km north-south through central Burma. Spinel, ruby, and sapphire gemstones are common in the Mogok valley region but are rare outside this area. The ruby and sapphire in the Mogok valley are spatially related to a series of charnockite-syenite sill-like intrusions around the Mogok valley. Gem-quality sapphires are related to the metasomatic calc-silicate skarns around the margins of these charnockite-syenites. The composition range of charnockites and syenites is broad with both mafic and felsic varieties, ranging from ultramafic hornblende-pyroxene-biotite rocks through orthopyroxene and clinopyroxene-bearing charnockites to quartz syenites. Four charnockites and syenites from Taung-met and the Chaunggyi valley have U-Pb zircon dates spanning 170–163 Ma, indicating an earlier Jurassic phase of alkali igneous intrusion in the protolith rocks. U-Th-Pb zircon dates on six charnockite-syenites span 67–22 Ma, including four samples from the Taung-met charnockites that have Jurassic dates, and one (MY-227), together with a skarn rock (MY-138), that do not have any Jurassic dates. A single U-Pb titanite date from a syenite at Le Oo mine in Mogok is 22 Ma similar to a U-Pb titanite date of 21 Ma from an adjacent ruby-bearing calc-silicate skarn-marble. These are broadly coeval with monazite and zircon dates from metasedimentary rocks along the MMB in the Mandalay-Kyausha area to the south. A cluster of U-Pb monazite ages from 97 to 75 Ma are thought

to reflect the thermal influence of precollision subduction-related granite-granodiorite intrusions along the MMB. U-Th-Pb ages of the Mogok metamorphic rocks are all latest Cretaceous to early Miocene, related to the India-Asia (Sibumasu) collision. The MMB continues northward, east of the Putao region along the Myanmar-China border, toward the East Himalayan syntaxis and beyond, possibly to the basement units of the Northern Lhasa terrane on SE Tibet (Palin et al., 2014; Searle et al., 2011).

The unusual mineralogy and richness of ruby and sapphire gems in the Mogok area are spatially related to the ultrahigh temperature dry charnockites, alkali granites, and syenites in the lower crust. U-Pb geochronology, however, suggests three possible models, (a) that all the charnockites and syenites were Jurassic, but only the Taung-met-Chaunggyi intrusion has preserved Jurassic zircons; Late Cretaceous–Oligocene zircon and monazite ages reflect a regional metamorphic overprint that was synchronous with ruby and sapphire formation. (b) Three phases of charnockite-syenite intrusion are recorded in the Middle Jurassic (170–163 Ma), latest Cretaceous–Paleocene (68–63 Ma), and early Eocene–early Miocene (~47–22 Ma), each of which was associated with ruby and sapphire formation in adjacent skarns. However, only the second and third phases of intrusion during Late Cretaceous–Oligocene or earliest Miocene time were concomitant with granulite-facies metamorphism during the later period of intrusion. (c) The charnockites and syenites were Late Cretaceous–early Miocene in age and related to regional granulite-facies metamorphism. Older Jurassic zircon ages in the Taung-met syenite would have been inherited from the source or from contamination during magmatic transport.

Phanerozoic granulite terranes with charnockites are not common in the world, and multiple phases of charnockite-syenite intrusion in the same locality seem improbable. Further, because of the high temperatures of intrusion of charnockites (~1,000–1,200 °C), zircons are unlikely to preserve any older ages; thus, the oldest zircon ages from a given sample are probably either intrusive or metamorphic dates but are unlikely to be inherited. We suggest that the most likely model is that of Jurassic (~170–163 Ma) intrusion of syenites and charnockites that were affected by a regional granulite-facies metamorphism lasting from ~68 to 21 Ma. Rubies and sapphires were formed during this regional metamorphic episode by granulite-facies metamorphism of meta-skarns and thick marbles.

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