Pulsed emplacement of the Mount Kinabalu granite, northern Borneo

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Abstract: High-precision U–Pb ion microprobe analyses provide new constraints on the emplacement and origin of the Kinabalu granite in Sabah, northern Borneo. The granite is a sheeted laccolith-like body comprising dyke-fed granitic units that young downwards, each emplaced beneath the previous sheet. Analyses of concentric growth zones in zircons indicate crystallization between 7.85 ± 0.08 and 7.22 ± 0.07 Ma, and show that the entire pluton was emplaced and crystallized within less than 800 ka. Several pulses of magmatism are recognized, each lasting for a maximum of 250 ka, and possibly as briefly as 30 ka. The oldest ages coincide with the highest elevations whereas the youngest ages are found at lower elevations around the edge of the body. Based on these new age data and field observations we identify the biotite granodiorite, hornblende granite and porphyritic facies as the Upper, Middle and Lower Units respectively. Inherited zircon ages indicate different protoliths for the Upper and Middle Units. The Upper Unit is derived from attenuated continental crust of the South China margin subducted beneath Sabah. The Middle Unit is sourced from melting of the crystalline basement in Sabah with little or no contribution from South China crust.

Supplementary material: Full U–Pb ion microprobe analytical data, and modal and major element composition data are available at http://www.geolsoc.org.uk/SUP18385.

Granite magmatism plays a fundamental role in the growth and differentiation of the continental crust but there is still significant controversy about the generation and intrusion of granitic magmas in the crust. In particular, the physical processes of magma ascent and emplacement have been the subjects of considerable recent debate (e.g. McCaffrey & Petford 1997; Petford & Clemens 2000; Petford et al. 2000). Early ideas of granite diapirism (e.g. Mrazec 1915; Nicolesco 1929) are being substantially revised by studies employing present-day geophysical and geochronological techniques (e.g. Evans et al. 1993; Michel et al. 2008). A growing body of evidence suggests that many plutons are emplaced at shallow levels as tabular laccoliths (e.g. Vigneresse 1990; Evans et al. 1993; McCaffrey & Petford 1997) that grow incrementally in a number of discrete magmatic pulses over a range of time scales (e.g. Coleman et al. 2004; Matzel et al. 2006; Michel et al. 2008). Single pulses are interpreted to be injected either as dyke-fed horizontal sheets (e.g. Evans et al. 1993; Michel et al. 2008) or as subvertical dykes (e.g. Glazner et al. 2004) that subsequently inflate.

The Kinabalu pluton provides an opportunity to test models of granite emplacement. It is exposed over an area of c. 120 km² and forms the peak of Mt Kinabalu (c. 4100 m), situated at the northern end of the Crocker Ranges in the Malaysian state of Sabah (Fig. 1). This collisional mountain range results from the Eocene to Early Miocene subduction of the proto-South China Sea beneath northern Borneo (Hall & Wilson 2000; Hutchison et al. 2000). The Mt Kinabalu granite is the only pluton to intrude the deformed rocks of the Crocker Ranges. Most of the granite body is extremely well exposed on the relatively flat western and eastern summit plateaux of Mt Kinabalu (both c. 4000 m), well above the regional tree line at c. 2500 m. Rainforest cover and steep topography restrict geological observations below 3000 m. The northeastern area of the pluton remains extremely inaccessible because of thick rainforest cover, lack of roads and trails, and difficulty of the terrain (Connaughton 1996).

Controversy still surrounds the origin and emplacement of the Kinabalu Pluton. Amphibole geobarometry suggests intrusion at depths of between 3 and 10 km (Vogt & Flower 1989). Previous workers have proposed various models related to southward subduction of the proto-South China Sea beneath Borneo (Vogt & Flower 1989), melting during Miocene isostatic rebound after subduction (Swauger et al. 2000), or crustal anatexis during post-subduction relaxation (Hutchison et al. 2000; Chiang 2002). Evaluating such models depends in part on the exact age of the body. Jacobson (1970) first estimated the age of the Kinabalu granite to be c. 9 Ma, based on K–Ar dating of biotite and hornblende. Subsequent K–Ar dating produced a wider spread of ages, ranging from 13.7 to 1.3 Ma (e.g. Rangin et al. 1990; Bellon & Rangin 1991; Hutchison et al. 2000; Swauger et al. 2000). Swauger et al. (2000) suggested that the granite was formed by a tectonic event at 15 Ma that also led to the formation of the important offshore unconformity known as the Deep Regional Unconformity (e.g. Hutchison 1996; Sandal 1996). Similar U–Pb ages (13–15 Ma) from the Capoas granite along-strike in Palawan (Encarnacion & Mukasa 1997) may indicate that melting was more widespread and linked to a regional tectonic event.

This study presents the results of secondary ionization mass spectrometry (SIMS) U–Pb analyses on zircons from nine samples of the Kinabalu granite. Based on these new data we suggest that the entire Kinabalu pluton was emplaced in less than 800 ka as a series of dyke-fed subhorizontal granite sheets between 8 and 7 Ma, intruded in several pulses.
Geological background

Country rocks

The Kinabalu granite is intruded into Mesozoic igneous and metamorphic rocks and their Cenozoic sedimentary cover (Fig. 2). Basement rocks in the Kinabalu area include variably serpentinized peridotites and small exposures of rocks described as crystalline basement (Reinhard & Wenk 1951). The ultrabasic rocks form part of a Middle Jurassic to Early Cretaceous ophiolite (Hutchison 2005) emplaced in the Late Cretaceous or Early Palaeogene (Newton-Smith 1967; Omang & Barber 1996). Crystalline basement rocks are Triassic to Cretaceous in age (Reinhard & Wenk 1951; Djonau & Hutchison 1966; Koopmans 1967; Kirk 1968; Leong 1974), and most resemble deformed...
ophiolitic rocks intruded by arc plutonic rocks, suggesting an origin in a Mesozoic intra-oceanic arc (Hall & Wilson 2000). Imai & Ozawa (1991) described unusual peridotites that are exposed close to Mt Kinabalu and suggested that they represent subcontinental mantle.

Throughout Sabah basement rocks are observed in faulted contact with steeply dipping sedimentary cover sequences, predominantly deep-water turbidites and related deposits assigned to the Eocene to Lower Miocene Trusmadi and Crocker Formations (Collenette 1965). All of these rocks were folded and faulted during the Early Miocene Sabah orogeny (Hutchison 1996) when the extended passive continental margin of South China collided with north Borneo (Hall & Wilson 2000; Hutchison et al. 2000) and subduction terminated. Much of the area then became emergent but most of present-day Sabah subsided again below sea level in the Late Early Miocene (Hall et al. 2008). Neogene sedimentary rocks rest unconformably on folded Eocene to Early Miocene rocks across Sabah. Fluvialite and marginal marine sediments were deposited across large areas of south Sabah (Balaguru et al. 2003; Balaguru & Nichols 2004) during the Middle and Late Miocene. Offshore of northern Sabah shelf sequences pass northwards into deep marine sediments (Ingram et al. 2004; Franke et al. 2008), and the shelf edge moved progressively north from the Middle Miocene (e.g. Hazebroek & Tan 1993; Sandal 1996). Onland in northern Sabah marine clastic sediments are interpreted to have been deposited, but have now been removed by erosion after the region became emergent once more in the Late Miocene or Early Pliocene (Hall 2002; Balaguru et al. 2003; Tongkul & Chang 2003; Morley & Back 2008). No younger sedimentary rocks are known from the Kinabalu area except Pleistocene glacial tills of the Pinosuk Gravels (Collenette 1958).

The Kinabalu granite

The Kinabalu pluton has a roughly elliptical shape with a long axis oriented approximately NE–SW. The major axis is about 16 km and the minor axis about 10 km (Fig. 2). The igneous rocks of the Kinabalu pluton have been described at different times as quartz monzonite, adamellite, granodiorite and granite reflecting changes in classification and nomenclature, and different observations (Reinhard & Wenk 1951; Kirk 1968; Jacobson 1970; Kasama et al. 1970; Vogt & Flower 1989). We recognize three distinct granitic lithologies: a biotite granodiorite, a hornblende granite and a porphyritic hornblende granite. Based on new age data and field observations we term these the Upper, Middle and Lower Units respectively.

Reinhard & Wenk (1951) gave the first detailed petrological account with a small number of chemical and modal analyses and reported that the rocks belonged to ‘the family of quartz-monzonites’. Kirk (1968) preferred the term adamellite from Nockolds’ (1954) classification scheme. Jacobson (1970) completed the most extensive study of Mt Kinabalu and considered the dominant lithology to be hornblende adamellite using the classification of Bateman et al. (1963) based on visual estimates of modes. Vogt & Flower (1989) carried out a mineralogical and chemical study using Jacobson’s samples. They described Kinabalu as a batholith that ‘comprises variably phric hornblende quartz monzonite and biotite quartz monzodiorite’ without specifying their classification scheme, and presented modes for 26 samples. Kasama et al. (1970) presented modes for 15 samples described as granites, granodiorites and porphyritic adamellites.

In this study point counting was carried out on 36 granitoid samples and six aplites, and 22 of the samples were stained for potassium feldspar (Sperber 2009). Five porphyritic rocks contain phenocrysts of K-feldspar that are very large compared with the thin-section size. For two of these samples the modal proportion of K-feldspar was corrected based on an estimate from the hand specimen. According to our study, the Upper Unit samples are biotite granodiorites or biotite tonalites, whereas the Middle and Lower Unit samples are almost all granites with a few samples plotting as quartz monzonites or quartz syenite (Fig. 3c) using the classification scheme of Le Maitre (1989). Our modal plots are similar to those of Reinhard & Wenk (1951), Kirk (1968) and Kasama et al. (1970) (Fig. 3b) whereas the Vogt samples are not.

Fig. 3. QAP diagram (Le Maitre 1989) of the Kinabalu granite. (a) According to the data of Vogt & Flower (1989); (b) as proposed by Reinhard & Wenk (1951), Kirk (1968) and Kasama et al. (1970); (c) according to this study.
& Flower (1989) modes appear to be more plagioclase-rich (Fig. 3a), and although several would now be classified (Le Maitre 1989) as granites or granodiorites many plot as quartz monzonites, quartz monzodiorites or quartz diorites.

To investigate the differences we compared rock compositions reported by Reinhard & Wenk (1951), Kirk (1968) and Vogt & Flower (1989) with bulk-rock compositions calculated from their modes using mineral composition data from Vogt & Flower (1989). We repeated this exercise for our own samples using our own rock and mineral analyses. Vogt & Flower (1989) reported 18 samples for which there are modes and major element compositions and we have 11 samples. The comparisons are shown for SiO₂ and K₂O in Figure 4. The Vogt & Flower (1989) observed and calculated compositions show a great deal of scatter (e.g. Fig. 4a and c), in contrast to our compositions, which show very good agreement for all major elements (e.g. Fig. 4b and d). The observed and calculated compositions for the small number of samples from Reinhard & Wenk (1951) and Kirk (1968) are also very similar; Kasama et al. (1970) provided no chemical analyses. Vogt & Flower (1989) did not report their methods but we suspect that they did not stain the sections, may have misidentified K-feldspars and quartz, and may not have corrected their modes for the very large size of the phenocrysts in the porphyritic granites. The major lithologies are granites not monzonites according to current classification schemes (Le Maitre 1989).

The Upper Unit is referred to here as a biotite granodiorite, although it varies from biotite–hornblende tonalite to granodiorite. It is exposed in a small area (about 2 km²) coinciding with the highest elevations of the western plateau. It contains abundant biotite, which appears texturally to be in equilibrium with less common hornblende, although in some samples hornblende is replaced by biotite. The Middle Unit forms most of the exposed body and is a hornblende granite. Hornblende occurs as small phenocrysts texturally in equilibrium with minor biotite and potassium feldspar, plagioclase feldspar and quartz. The colour varies from darker to lighter grey, which corresponds to the abundance of hornblende. The Lower Unit is a porphyritic hornblende granite that is megacrystic in places. It is chemically similar to the Middle Unit but contains large potassium feldspar phenocrysts (2–3 cm in length) and megacryst-rich zones. The Lower Unit is exposed in a band running along the southern and western edges of the pluton, varying in width from 0.5 to 1.7 km (Fig. 2).

Each of the three units is intruded by dykes and the number of dykes varies from place to place. Field observations indicate there are two broad types: abundant aplites and a range of microgranites including porphyritic and pyroxene-bearing varieties (Jacobson 1970).

Based on observations of steeply dipping contacts (Jacobson 1970) and apparent geochemical zonation (Vogt & Flower 1989), previous workers have interpreted the granite as a compositionally zoned, steep-sided pluton consistent with diapiric models (e.g. Mrazec 1915; Nicolesco 1929). The relationships of the various granites are unusual. The Lower Unit has previously been interpreted as a ‘shell’ or marginal facies surrounding the pluton’s ‘main body’ of hornblende granite (e.g. Jacobson 1970; Vogt & Flower 1989) despite the fact that it contains the largest crystals. We regard the ‘main body’ as the Middle Unit. Intrusive and/or chilled contacts are observable on steep cliff sections within the Middle Unit, identified by contrasts between light and dark hornblende granites. The nature of the contact of the biotite granodiorite (our Upper Unit) with the hornblende granites (Middle Unit) is not clear. Jacobson (1970) reported a narrow (c. 1 m) gradational contact between the Upper and Middle Units on the western summit plateau without interpreting any relative age relationship between them. Vogt & Flower (1989) made no new field observations but interpreted the observations of Jacobson of a narrow gradational contact and flow structures to suggest that the magmas were only partially crystallized during intrusion. Based on a geochemical model they concluded that the biotite granodiorite was the youngest part of the body. However, we crossed the boundary in several places and saw no clear margin.

The Middle and Lower Unit hornblende granites are magnesian, predominantly calc-alkaline and metaluminous (e.g. Frost et al. 2001). Upper Unit biotite granodiorite samples are peraluminous. All resemble most closely the Cordilleran granitoids of Frost et al. (2001). The Upper Unit rocks have been termed volcanic arc granites (Pearce et al. 1984), island arc and continental arc granitoids (Maniar & Piccoli 1989), or amphibole-bearing calc-alkaline granites (Barbarin 1999). Samples plot as volcanic arc granites on the Y, Nb and Rb plots of Pearce et al. (1984); the evolved samples (aplices and some porphyritic samples) plot in the synvolcanic granite field. Several workers have suggested that trace element classifications reflect the melt protolith rather than the tectonic setting in which melting occurred (Arculus 1987; Twist & Harmer 1987; Roberts & Clemens 1993; Frost et al. 2001). Least-squares modelling confirms the suggestion (Vogt & Flower 1989) that the upper biotite granodiorite cannot be derived from the hornblende granite by closed-system fractional crystallization alone. The other granites can be related by fractional crystallization involving K-feldspar, plagioclase, quartz, hornblende, magnetite and biotite.

![Fig. 4. Comparison of observed and calculated values for SiO₂ and K₂O for Kinabalu granites using data reported by Vogt & Flower (1989) and this study. The major element compositions for the rocks were calculated from the modes and mineral analyses.](image-url)
Analytical methods

Zircon separates from nine samples were analysed by sensitive high-resolution ion microprobe (SHRIMP) on the SHRIMP II (at the Australian National University: one sample from the Upper Unit, five from the Middle Unit, and three from the Lower Unit; Table 1). Three of the five Middle Unit samples were collected from the western summit plateau (two hornblende granites and an aplite dyke), and two from the eastern plateau. The three Lower Unit samples include two megacrystic samples and an associated pyroxene microgranite dyke. Samples were crushed and graded using disposable nylon cloth sieves in a brass holder. Zircon separates were prepared from the resulting 100–250 μm fraction using standard heavy liquid and Frantz isodynamic separation techniques. High-purity zircon separates were then hand picked and the grains were mounted in epoxy resin, alongside the Temora zircon standard (Black et al. 2003) and the SL13 standard (Claoué-Long et al. 1995) of the Research School of Earth Sciences, The Australian National University. The grains were then sectioned and polished until exposed through their midsections and Au coated. The internal zonation and structure of single grains were mapped using cathodoluminescence and reflected light images, allowing spot analyses to be targeted on grain areas free of cracks and inclusions.

U–Pb analyses were performed following the analytical procedures outlined by Williams (1998). Data reduction and all age calculations were achieved using the SQUID 1.03 and Isoplot/Ex 2.29 programs of Ludwig (2001a,b). Uranium and thorium concentrations were calibrated against the SL-13 standard. Young ages are assumed to be concordant, and were determined solely using the 238U/206Pb ratio; common Pb was estimated using the 206Pb/207Pb ratio. This method has been shown to be very reliable for analyses that have low inherent common Pb and lie close to the concordia (e.g. Muir et al. 1994), as is the case here. Rare Precambrian crystals and cores were corrected for common Pb using the 206Pb/207Pb ratio, and the age was based on the 206Pb/207Pb ratio. Uncertainties in isotopic ratios and ages (including data tables and error bars for plotted data) are reported at the 1σ level. Final, weighted mean ages are reported as 95% confidence limits.

Magmatic ages

Analyses of concentric growth zones from all nine samples reveal tightly clustered Late Miocene ages. These ages are interpreted to represent the magmatic age of the zircons and thus the crystallization age of the Kinabalu pluton. The results of these analyses are plotted as isotopic compositions, uncorrected for common Pb, in the form of Tera–Wasserburg concordia diagrams (Tera & Wasserburg 1972) in Figs 5 and 6. Mean sample ages (Table 1) were calculated using the SQUID 1.03 and Isoplot/Ex 2.29 programs of Ludwig (2001a,b). Data points plotting off a regression line from common lead are not included in mean age calculations.

Upper Unit: biotite granodiorite

Thirty-one spot analyses were made on 24 grains from a biotite granodiorite sample CS-021. Twenty-five analyses form a coherent group interpreted as reflecting the magmatic age. Six analyses yield ages that are clearly inherited, being more than twice the mean magmatic age. Twenty-four of the magmatic ages plot close to concordia, elongated along the mixing line to common Pb. This group defines a mean magmatic age of 7.85 ± 0.08 Ma (Fig. 5a). A single analysis with an abnormal uranium content plots off the common lead mixing line and is not included in magmatic age calculations.

Middle Unit: hornblende granite, Western plateau

The two hornblende granite samples from the western plateau (CS-018 and CS-020) and an aplite dyke (CS-059) were collected close to the mapped contact with the Upper Unit. Thirty-one spot analyses on 23 grains from CS-018 yield 20 coherent magmatic ages. Excluding an outlier that plots off the common Pb mixing line (Fig. 5b), and one analysis rejected on the basis of an anomalously high uranium content, 18 data points define a mean magmatic age of 7.64 ± 0.11 Ma. There are 11 inherited ages. Nineteen analyses from CS-020, sampling 17 crystals, yield 17 coherent magmatic ages. Two analyses yield inherited ages. Discarding a single analysis with abnormally high uranium, the remaining 16 magmatic analyses are tightly clustered (Fig. 5c), defining a mean age of 7.69 ± 0.07 Ma. Twenty-six grains were analysed from the aplite dyke (CS-059). Two analyses were discarded because they have abnormal uranium contents. The 24 remaining analyses yield a mean magmatic age of 7.58 ± 0.07 Ma (Fig. 5d). No inherited ages were observed for sample CS-059.

Table 1. Sample locations, descriptions and mean magmatic ages

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Longitude (decimal degrees)</th>
<th>Latitude (decimal degrees)</th>
<th>Elevation (m)</th>
<th>Lithology</th>
<th>Spot analyses*</th>
<th>Magmatic analyses†</th>
<th>Age (Ma)‡</th>
<th>Error ± (Ma)§</th>
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<tbody>
<tr>
<td>Upper Unit</td>
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<tr>
<td>CS-021</td>
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<td>N 6.078</td>
<td>3827</td>
<td>Biotite granodiorite</td>
<td>31</td>
<td>25</td>
<td>7.85</td>
<td>0.08</td>
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<td>Middle Unit</td>
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<td>N 6.068</td>
<td>3847</td>
<td>Hornblende granite</td>
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<td>16</td>
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<td>Lower Unit</td>
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<td>N 6.048</td>
<td>2888</td>
<td>Microgranite dyke</td>
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<td>13</td>
<td>7.38</td>
<td>0.08</td>
</tr>
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</table>

* Total number of spot analyses made on sample.
† Number of analyses giving magmatic ages.
‡ Mean age of all accepted magmatic analyses.
§ Errors are 1σ.

Longitude and latitude data are based on global positioning system (GPS) measurements. Altitude data are based on position within a detailed digital elevation model (DEM).
Middle Unit: hornblende granite, Eastern plateau

Two hornblende granite samples (CS-070 and CS-072) were collected from the mountain’s eastern plateau. Eighteen spot analyses from different grains yield exclusively magmatic ages for sample CS-070. The data form a coherent group (Fig. 5e) close to concordia, with a single analysis that plots further along the mixing line with common lead. These analyses have a mean age of 7.44 ± 0.09 Ma. Twenty-seven spot analyses on 22 zircons from sample CS-072 give 23 magmatic ages. Twenty-one analyses define a continuous array towards common Pb (Fig. 5f) that yields a mean age of 7.46 ± 0.08 Ma. Two data points with anomalously high uranium contents are not included in age calculations. Four analyses yield inherited ages.

Lower Unit: porphyritic hornblende granite

Three samples from the Lower Unit were dated. Two are porphyritic hornblende granites (CS-027 and CS-054) and the third is a microgranite dyke (CS-007) intruding country rock close to the south margin of the pluton. Twenty-one spot analyses on 20 crystals from sample CS-027 all yield coherent magmatic age data (Fig. 6a) giving a mean age of 7.32 ± 0.09 Ma. No inherited ages were observed. Twenty-three spot analyses on a total of 20 zircons from the second sample, CS-054, give 17 magmatic ages and yield a mean age of 7.22 ± 0.07 Ma (Fig. 6b). There are six inherited ages. Eighteen spot analyses were made on 11 grains from a microgranite dyke (CS-007). Two analyses yield inherited ages. Sixteen analyses form a coherent group of magmatic ages. Two analyses plot off the mixing line to common Pb; a third has anomalously high uranium content. These analyses are not included in calculations of mean magmatic age. The remaining 13 data points give a mean age of 7.38 ± 0.08 Ma (Fig. 6c).

Crustal inheritance patterns: ages of zircon cores

All three lithological units contain inherited zircon that forms a small but significant age population (Table 2). Thirty-one of the 214 spot analyses give ages that are unquestionably inherited, being greater than twice the magmatic age. All represent analyses of crystal cores. The small number is a true reflection of the proportion of older cores. Overall, there is a strong peak
of Mesozoic ages, accounting for 67% of all inherited ages, dominated by 16 Early Cretaceous ages.

**Upper Unit: biotite granodiorite**

The Upper Unit biotite granodiorite (CS-021) contains the oldest inherited ages found in any of the Kinabalu samples (Table 2) and they are very different from those for the Middle and Lower Units. This sample contains two zircons with Palaeoproterozoic ages (1658 ± 18 and 1896 ± 20 Ma). There is one Permian (289 ± 4 Ma), one Early Triassic (242 ± 3 Ma) and one Early Jurassic age (179 ± 3 Ma). There are no Early Cretaceous ages. A single sector-zoned grain has an Eocene (49 ± 1 Ma) core with a younger magmatic rim.

**Middle Unit: hornblende granite, Western plateau**

The two hornblende granites from the western plateau (CS-018 and CS-020) and the aplite dyke (CS-059) contain 15 inherited ages (Table 2). There are two Jurassic (186 ± 2 Ma, 173 ± 2 Ma) ages, eight Early Cretaceous (138 ± 2 to 102 ± 1 Ma) one Late Cretaceous (68 ± 1 Ma), and two Cenozoic ages (41 ± 1 and 25 ± 1 Ma). There are no ages older than Jurassic.

**Middle Unit: hornblende granite, Eastern plateau**

Only one of the two hornblende granite samples from the mountain’s eastern plateau yielded inherited cores (CS-072); CS-070 was not examined for inherited grains because of limitations on the machine time available. There are four ages from CS-072: three are Early Cretaceous (142 ± 1 to 114 ± 1 Ma) and one is Eocene (43 ± 1 Ma) (Table 2). Again, there are no ages older than Jurassic.

**Lower Unit: porphyritic hornblende granite**

Because of time constraints, only one sample from the Lower Unit was searched for inherited cores. The porphyritic hornblende granite (CS-054) contains six inherited ages (Table 2). There is a single Neoproterozoic (970 ± 11 Ma) age, one Ordovician (469 ± 7 Ma), one Jurassic (182 ± 2 Ma), and three Early Cretaceous ages (130 ± 2 to 105 ± 1 Ma).

**Discussion**

The U–Pb age data from zircons reported here record the emplacement of the Kinabalu pluton and provide information on the crust beneath Kinabalu that was the source of the melt.

**Age of the Kinabalu granite**

It has always been difficult to interpret the previous K–Ar ages obtained from the Kinabalu granite, which range between 13.7 and 1.3 Ma (e.g. Jacobson 1970; Rangin et al. 1990; Bellon & Rangin 1991; Hutchison et al. 2000; Swauger et al. 2000). The new ages presented here provide a precise age for the Kinabalu pluton. They show that the entire body was intruded in a narrow time interval between c. 7.85 and c. 7.22 Ma, and that there were several separate pulses of magmatism.

The Upper Unit is not the youngest part of the pluton as suggested by Vogt & Flower (1989) but is in fact the oldest lithology with a mean magmatic age of 7.85 ± 0.08 Ma. This is the first recorded magmatic episode (Pulse 1). Zircons from the Middle Unit range in age from 7.69 ± 0.07
to 7.44 ± 0.09 Ma. The two hornblende granite samples from the western plateau have crystallization ages of 7.69 ± 0.07 and 7.64 ± 0.11 Ma. An aplite dyke that intruded these granites yields an age of 7.58 ± 0.07 Ma. These ages are interpreted to record one complete intrusive pulse terminating with a fractionated aplite end product (Pulse 2). Less than 3 km away, the two hornblende granite samples from the eastern plateau yield younger ages of 7.46 ± 0.08 to 7.44 ± 0.09 Ma. These ages may represent a second intrusive pulse within the Middle Unit (Pulse 3). However, given the uncertainties associated with these mean ages (1–1.5%) it is not possible to distinguish these two pulses based solely on age data. Recent studies have shown that zircon growth in silicic magmas may predate eruption by several 100 ka, biasing U–Pb mean ages towards older ages (Simon et al. 2008). For the young ages reported here, even relatively short zircon residence times of c. 200 ka would significantly increase errors associated with U–Pb mean ages and further preclude distinction between pulses.

Field observations suggest that further dating, with an increased spatial resolution and precision, would probably identify additional intrusive pulses within the Middle Unit. Observations of a chilled contact between light and dark hornblende granite within the Middle Unit (Jacobson 1970; this study) support multiple intrusive pulses. Complex cross-cutting dyke sets may reflect the fractionated end products of several intrusive pulses. The porphyritic Lower Unit yields ages of 7.32 ± 0.09 and 7.22 ± 0.07 Ma. The microgranite dyke intruding country rock gives an age of 7.38 ± 0.08 Ma, within error of the two Lower Unit ages. These three ages represent a further magmatic episode (Pulse 4). The younger ages of the Lower Unit rule out the suggestion that it was emplaced first, as a shell into which the Middle and Upper Units were intruded (Jacobson 1970). Field observations of porphyritic granite intruded locally as dykes within the Middle Unit (Jacobson 1970) are entirely consistent with its younger age.

### Duration and rates of emplacement

These data show that the Kinabalu granite was incrementally assembled by several discrete episodes of magmatism. The entire pluton was emplaced and crystallized within a period of less than 800 ka. The ages from the Middle Unit provide some constraint on the duration of an individual magma pulse. The oldest hornblende granite on the western plateau has an age of 7.69 ± 0.07 Ma and the fractionated aplite intruding it has an age of 7.58 ± 0.07 Ma. Considering the associated errors, these ages constrain the duration of this pulse to less than 250 ka, and it could possibly have been as brief as 30 ka.

Such time scales necessitate rapid magma ascent and emplacement via fracture propagation and dyking (e.g. Clemens &

### Table 2. Ion microprobe U–Pb zircon analyses of inherited zircons

<table>
<thead>
<tr>
<th>Sample spot</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>204/206 % error</th>
<th>206Pb/238U % error</th>
<th>Age (Ma)*</th>
<th>Error ± (Ma)†</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Upper Unit</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CS021-1.2</td>
<td>282</td>
<td>146</td>
<td>0.000199</td>
<td>39.5</td>
<td>0.050394</td>
<td>1.8</td>
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<tr>
<td>CS021-2.2</td>
<td>257</td>
<td>254</td>
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<td>43.2</td>
<td>0.124594</td>
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</tr>
<tr>
<td>CS021-13.1</td>
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<td>–</td>
<td>0.045264</td>
<td>6.2</td>
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<tr>
<td>CS021-17.2</td>
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<td>0.000076</td>
<td>99.0</td>
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</tr>
<tr>
<td>CS021-19.1</td>
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<td>25</td>
<td>0.001091</td>
<td>41.6</td>
<td>0.061051</td>
<td>3.3</td>
</tr>
<tr>
<td>CS021-23.1</td>
<td>184</td>
<td>110</td>
<td>–</td>
<td>–</td>
<td>0.112315</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Middle Unit (western plateau)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CS018-2.1</td>
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<td>0.047755</td>
<td>3.5</td>
<td>0.034497</td>
<td>1.1</td>
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<tr>
<td>CS018-3.1</td>
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<td>184</td>
<td>0.000217</td>
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</tr>
<tr>
<td>CS018-4.1</td>
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<td>0.000634</td>
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<td>CS018-6.2</td>
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<tr>
<td>CS018-7.2</td>
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<td>–</td>
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<td>111</td>
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<td>1.1</td>
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<tr>
<td>CS072-19.2</td>
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<td>2.7</td>
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<tr>
<td><strong>Middle Unit (eastern plateau)</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CS021-23.1</td>
<td>184</td>
<td>110</td>
<td>–</td>
<td>–</td>
<td>0.112315</td>
<td>1.1</td>
</tr>
<tr>
<td>CS072-19.2</td>
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<td>382</td>
<td>0.000039</td>
<td>99.0</td>
<td>0.049354</td>
<td>1.1</td>
</tr>
<tr>
<td>CS072-20.2</td>
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<td>CS020-6.1</td>
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<td>234</td>
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<tr>
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<td>–0.000626</td>
<td>60.9</td>
<td>0.049565</td>
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</tbody>
</table>

* Based on 207Pb-corrected 206Pb/238U age.
† Errors are 1σ.

<table>
<thead>
<tr>
<th>Sample spot</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>204/206 % error</th>
<th>206Pb/238U % error</th>
<th>Age (Ma)*</th>
<th>Error ± (Ma)†</th>
</tr>
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<tbody>
<tr>
<td><strong>Aplite dyke</strong></td>
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<td>CS007-6.2</td>
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<td>0.000210</td>
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<td>84</td>
<td>0.000599</td>
<td>78.6</td>
<td>0.047903</td>
<td>4.6</td>
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</table>
Mawer 1992; Petford 1996) rather than slower diapiric ascent (Miller & Paterson 1999). Field observations of sharp magmatic contacts suggest minimal interaction between the products of each pulse, implying that each was fully crystallized prior to subsequent pulses.

**Morphology and internal structure**

The new data presented here are inconsistent with earlier interpretations (Fig. 7) of the Kinabalu granite as a compositionally zoned, steep-sided diapir-like pluton (e.g. Jacobson 1970; Vogt & Flower 1989). The oldest ages of the Upper Unit coincide with the highest elevations of the western plateau, and the youngest ages of the Lower Unit are found at the edges of the body at lower elevations. The age and field relationships can be explained if the Kinabalu pluton is a subhorizontally layered body comprising multiple granite sheets (Fig. 7). This is consistent with recent models of plutons (e.g. Evans et al. 1993; McCaffrey & Petford 1997; Petford & Clemens 2000), which have been shown to grow incrementally as a number of dyke-fed horizontal sheets (e.g. Petford et al. 2000) that become younger downwards (Michel et al. 2008).

Recent geophysical studies have shown that many small granite plutons are emplaced at shallow levels as tabular laccoliths (e.g. Vigneresse 1990; Evans et al. 1993; McCaffrey & Petford 1997; Ameglio & Vigneresse 1999; Vigneresse et al. 1999; Petford & Clemens 2000; Petford et al. 2000). Their dimensions may follow a power-law relationship (McCaffrey & Petford 1997). With a major axis of c. 16 km and a minor axis of c. 10 km the power-law relationship predicts a maximum thickness for the Kinabalu granite of 1.82 km. Based on the observed height difference between the Kinabalu summit and the bottom of Low’s Gully, the deep chasm that cuts through the pluton, the Kinabalu granite is at least 2 km thick. However, neither the roof nor the base of the Kinabalu body is seen. Low’s Gully remains dangerous and almost unvisited (Connaughton 1996) and it is not known if the bottom of the granite is exposed in it. Tilting and post-intrusive extensional faulting (Fig. 7) may have increased the apparent vertical thickness of the pluton. If the roof of the granite were just above the present summit of the mountain, and the body is assumed to extend no deeper than the lowest observed outcrop on the flanks, the granite would have a thickness broadly consistent with the power-law prediction.

**Melt protoliths**

The inherited zircons in the Middle Unit are predominantly Early Cretaceous and have no ages greater than Jurassic. In contrast, the Upper Unit contains the oldest zircon ages, which are Proterozoic, and there are no Cretaceous zircon cores. The different crustal inheritance patterns suggest a number of different sources.

The Proterozoic zircons within the Upper Unit necessitate an extremely old protolith. The thinned South China continental crust subducted beneath northern Borneo during the Early Miocene collision (Hall & Wilson 2000; Hutchison et al. 2000) is a potential source. Little is known of the basement age of this crust. It must have formed part of the South China margin before Oligocene to Miocene opening of the South China Sea, and consequently is part of the Cathaysian South China block. A Proterozoic basement is probable (Sewell et al. 2000; Li et al. 2001). Gravity data indicate that the Kinabalu pluton was intruded directly above the position of maximum crustal thickness in northern Borneo, reflecting the subduction of South China continental crust and collisional thickening (Hutchison et al. 2000; Milsom & Holt 2001). Therefore we suggest that the Upper Unit represents the melting of the thinned South China continental crust deep beneath Kinabalu.

There are two possible sources for the Mesozoic zircons that dominate inheritance within the Middle Unit (Table 2). The subducted South China continental crust beneath Sabah is a potential source. A belt of granitic rocks of Jurassic and Early

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**Fig. 7.** Simplified cross-sections of the Mt Kinabalu region drawn along the line X–Y shown in Figure 2. (a) Redrawn from Jacobson (1970) based on original plutonic interpretations. (b) New interpretation of the Kinabalu granite as a sheeted laccolith-like body.
The Cenozoic ages in the Upper and Middle Units are consistent with the observation that these two units cannot be linked by closed-system fractional crystallization (Vogt & Flower 1989). The Upper Unit represents an older and distinct intrusive pulse (Pulse I) derived by melting of a different source. In contrast, the Middle and Lower Units can be linked by fractionation. Therefore, the Neoproterozoic and Palaeozoic ages suggest that the Lower Unit has a similar source to the Middle Unit. The Neoproterozoic and Palaeozoic ages hint at the involvement of older crustal material, possibly as a result of mixing with previously intruded material or mixing of melts at depth. There are too few data to speculate further.

The different crystallization ages and sources for the Upper and Middle Units are consistent with the observation that these two units cannot be linked by closed-system fractional crystallization (Vogt & Flower 1989). The Upper Unit represents an older and distinct intrusive pulse (Pulse I) derived by melting of a different source. In contrast, the Middle and Lower Units can be linked by fractionation.

Finally, the Cenozoic ages in the Upper and Middle Units suggest melting of arc rocks formed during Eocene to Early Miocene subduction of the proto-South China Sea.

Emplacement model

The new data provide compelling evidence to reinterpret the Kinabalu granite as a sheeted laccolith (Fig. 7), comprising multiple dyke-fed sheets. The Upper Unit was emplaced first, sourced by melting of the deep continental crust thrust beneath Sabah following orogenic thickening. Intrusion of the Upper Unit may have heated the middle crust, leading to further melting. The intra-oceanic arc crystalline basement at this level provided the source for the hornblende granites of the Middle and Lower Units, which were intruded sequentially beneath the Upper Unit. The porphyritic nature of the Lower Unit is attributed here to textural coarsening of feldspar crystals (e.g. Vernon 1986; Higgins 1999); large crystals coarsening at the expense of dissolved smaller crystals. This phenomenon suggests that the Lower Unit was intruded before the Middle Unit had fully cooled, with the remaining heat from the latter buffering the magma’s temperature at the K-feldspar liquidus for a substantial time (Higgins 1999). Migration of interstitial melt during this period, enhancing coarsening along fluid flow channels, may explain field observations of megacryst-rich zones within the Lower Unit exposed near Mesilau (Fig. 1). Conversely, the absence of megacrysts within the Middle Unit suggests that the Upper Unit was fully cooled before subsequent emplacement.

Sills and laccoliths emplaced at shallow depths have been widely reported to preferentially intrude along shale horizons (e.g. Corry 1988). The ductile response of such layers limits the ability of the feeder dykes to propagate upwards via vertical fracturing, forcing the magma to intrude sideways (Thomson & Schofield 2008). Such effects may be enhanced by the volatilization of pore fluids upon contact with the magma, dramatically increasing pore fluid pressures (Bjorlykke 1993), reducing the effective strength of the rock and thus aiding horizontal intrusion (Thomson & Schofield 2008).

Regional mapping demonstrates that the Kinabalu granite is in contact with serpentinitized ultrabasic basement rocks along its western margin (Jacobson 1970). We suggest that the relatively weak serpentinitized rocks may have acted in a similar fashion to shales, with ductile deformation restricting upward propagation of feeder dykes and forcing lateral emplacement. Dehydration of serpentinites and the associated increase in pore fluid pressures could aid this process. Contact metamorphism at the Kinabalu contact has been observed in both ultrabasic and Crocker Formation rocks. This may imply that the level at which the granite was emplaced was influenced by the thrust contact between the serpentinite and the Crocker Formation.

Summary

The U–Pb age data reported here provide important constraints on the emplacement and origin of the Kinabalu granite. Several separate pulses of intrusion can be recognized between 7.85 ± 0.08 and 7.22 ± 0.07 Ma. Magmatic pulses lasted no longer than 250 ka but could possibly be as short as 30 ka. The oldest ages coincide with the highest elevations; the youngest ages are found at lower elevations around the edge of the body. Based on these age data and field observations the units previously regarded as the central biotite granodiorite, main hornblende granite and marginal porphyritic facies are renamed the Upper, Middle and Lower Units respectively.

Our data suggest that the Kinabalu pluton is a sheeted laccolith (Fig. 7) incrementally assembled over a period of less than 800 ka. These data add to a growing body of evidence that small granitic plutons are incrementally assembled over relatively short time scales by the intrusion of multiple granitic sheets that young downwards (e.g. McCaffrey & Petchford 1997; Petchford & Clemens 2000; Michel et al. 2008).

The Upper Unit biotite granodiorite is the oldest part of the pluton and requires a source that includes old zircons, which is most likely to be subducted attenuated continental crust of the South China margin. Inherited zircon ages from the Middle and Lower Units imply melting of the crystalline basement exposed today in part of Sabah with little or no contribution from South China crust. Cenozoic inherited zircon ages probably indicate some contribution of arc material formed during subduction of the Proto-South China Sea.

The Late Miocene age of the Kinabalu pluton indicates that it is not a subduction product (compare Vogt & Flower 1989), as subduction terminated in the Early Miocene (Hall & Wilson 2000; Hutchison et al. 2000; Hall 2002). The granite melting occurred more than 10 Ma after the Early Miocene collision.

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