Supplemental Appendices

New zircon radiometric U/Pb ages and Lu-Hf isotopic data from the ultramafic-mafic sequences of Ranau and Telupid (Sabah, east Malaysia): Time to reconsider the geological evolution of SE Asia?

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APPENDIX S1: PETROGRAPHIC INFORMATION

The Ranau peridotites show granular and less frequently cataclastic textures. They comprise mainly spinel- and garnet-lherzolites, as well as subordinate clinopyroxene-bearing harzburgites, transitional harzburgites, and replacive dunites. Frequent impregnation phenomena are observed as veins of variable size with fine grained unstrained olivine and rare spinel crosscutting the rocks. Coarse intergranular Al-spinels ($\text{Cr\#} [100 \times \text{Cr}/(\text{Cr} + \text{Al})] = 3-11$, $\text{Mg\#} [100 \times \text{Mg}/(\text{Mg} + \text{Fe}^{2+})] = 72-88$) are euhedral to subhedral whereas smaller droplet-shaped (with one or two pointy edges) Al-spinels ($\text{Cr\#} = 3-38$, $\text{Mg} = 55-82$) occur in the impregnating veins together with olivine. Infrequent Cr-spinel ($\text{Cr\#} = 21-32$, $\text{Mg\#} = 62-70$) with lobate boundaries exist in harzburgite. Pargasitic amphibole is a common accessory phase together with zircon, apatite, titanite and ilmenite. The samples show low to moderate degrees of serpentinization with serpentine, chlorite, ferrian chromite and magnetite as secondary phases.

The ophiolitic peridotites of Telupid show porphyroclastic textures and include lherzolites, harzburgites and subordinate replacive dunites. Ortho- and clinopyroxenes and olivine are

strained with undulose extinction and kink-bands, typical features of upper mantle phases. A second generation of finer grained and mostly unstrained olivine impregnates the peridotites. Euhedral to subhedral Al-spinel ($\text{Cr\#} = 11-18$, $\text{Mg\#} = 73-79$) and subhedral Cr-spinel ($\text{Cr\#} = 70-75$, $\text{Mg\#} = 72-74$) with lobate boundaries occur in the lherzolite and the harzburgite, respectively. Replacive olivines after orthopyroxene denote peritectic reactions, thus together with the lobate boundaries of the spinels supporting the interpretation that the peridotites have undergone partial melting phenomena. Extreme replacement of orthopyroxene from olivine have resulted in local dunites. The podiform dunite shows significant serpentinization and typical relics of cumulate texture in line with their geological position.

The diabase shows a typical subophitic texture with plagioclase laths intergrown with clinopyroxene. The basalts show intergranular, intersertal and porphyritic textures. Both of these mafic lithologies have similar assemblages with plagioclase and clinopyroxene as primary phases. Local orthopyroxene and opaque phases, as well as rare olivine, are observed. Accessory phases are titanite, zircon and apatite whereas secondary phases include amphiboles, chlorite, albite, quartz and epidote.

APPENDIX S2: GEOCHEMICAL FEATURES

The Ranau lherzolites are fertile having nearly chondritic REE abundances and enriched incompatible elements nature. This is explained well from the fact that they are impregnated and hence refertilized. In contrast, the harzburgite show a highly depleted nature due to partial melting events (Fig. A1-A). The analyzed lherzolites show high Cr (2546-2694 ppm) and Ni (1836-1884 ppm) abundances, whereas the depleted harzburgite displays Cr = 2668 ppm and Ni = 3937 ppm (Table A1).

Figure A1. Geochemical characteristics of the dated samples from Sabah: A) Chondrite normalized REE spiderdiagrams (normalizing values after McDonough and Sun, 1995); B), C) and D) Plot of the basalts and the diabase on selected discrimination diagrams. Fields are after: B: Meschede (1986), C: Cabanis and Lecolle (1989), and D: Pearce (2008). Field for the Okinawa BABB after Shinjo et al. (1999).

The Telupid ophiolitic diabase and basalt have trace element contents typical for mid-ocean ridge basalts (MORB) and back-arc basin basalt (BABB) affinities (Fig. A1). Their REE profiles lie at around 10x the chondritic values supporting this hypothesis. These mafic rocks display rather low MgO (4.15-8.54 wt.%), Cr (up to 270 ppm), Ni (90-122 ppm) and Mg# ($100 \times \text{MgO}/(\text{MgO} + \text{FeO})$) indicating their relatively fractionated nature (Table A1). They are rather depleted in high-field

strength elements and their incompatible element ratios are similar to depleted mantle, consistent with the hypothesis that they have been derived from a depleted mantle reservoir. Particularly, their $\text{Nb/Th} > 8$ and their $\text{Zr/Nb} > 20$ (Table A1) are analogous to depleted mantle ratios (Condie and Shearer, 2017). In addition to this, their Nb/Y and Zr/Y ratios are similar to those from depleted mantle ($\text{Nb/Y} = 0.05$ and $\text{Zr/Y} = 1.95$; data from Salters and Stracke, 2004).

APPENDIX S3: METHODS

Sample preparation

A total of five samples were zircon U-Pb-Hf isotope analyzed in this study, including lherzolites (SB 120A and SB 120B), basalts (SB 125 and SB 130C) and a diabase dike (SB 127). Zircon grains were separated from ~5 kg of crushed sample using conventional magnetic and heavy liquids separation technique, followed by hand-picking under a binocular microscope. The zircon grains were then mounted in epoxy resin and polished down to expose their core. Reflected light petrographic observation and cathodoluminescence (CL) imaging (Fig. A2) were performed to select suitable grains and sites for the U-Pb and Lu-Hf isotope analyses. CL imaging was carried out on a scanning electron microscope (SEM) equipped with X-MAX020 energy-dispersive spectrometer (EDS) at the School of Earth Science and Engineering, Sun Yat-Sen University.

Whole-rock geochemical analysis

For the characterization of the dated rocks we performed whole-rock geochemical analyses on samples devoid of weathering and cleaned, at Activation Laboratories, Ancaster, Ontario. Major elements were analyzed by fusion-ICP, whereas trace elements were analyzed by ICP/MS. Detection limit for major elements is 0.01%, except for TiO_2 and MnO which is 0.001%. The

analytical precision calculated from replicate analyses is better than 3% for most major elements and better than 5% for most trace elements including REE.

LA-ICP-MS zircon U-Pb dating

The analysis was performed at the Key Laboratory of Mineralogy and Metallogeny, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIGCAS), on a Resonetics RESolution S-155 laser ablation system coupled with an Agilent 7900 ICP-MS and the detailed results are listed in Table A2. Squid smoothing device was installed to reduce statistical error induced by laser-ablation pulses and to improve the data quality. A spot size of 29 μm was used (Fig. A2). The helium carrier gas carrying the ablated sample aerosol was mixed with argon to enhance sensitivity before entering the ICP. Before the analysis, the LA-ICP-MS system was optimized with NIST610 (ablated with 29 μm spot size and 5 $\mu\text{m/s}$ scan speed) to achieve maximum signal intensity and low oxide rate. Each analysis comprises a 20–30 s background signal acquisition (laser-off) followed by 50 s sample data acquisition (laser-on). The 91500 (Wiedenbeck et al., 1995) and Plesovice (Sláma et al., 2008) zircon were used as the primary and secondary standards, respectively (Fig. A3). When 91500 was used as the primary standard, analysis of the Plesovice zircon yielded a concordia age of 346.1 ± 2.9 Ma, within $< 3\%$ error of the recommended value (ID-TIMS: 337.13 ± 0.37 Ma; Sláma et al., 2008). For LA-ICP-MS, the analytical precision for zircon U-Pb dating is commonly around 4% (Li et al., 2015). The reference material (NIST 610) was used as the external calibration reference and Si was used as the internal standard to quantify elemental concentrations of the samples. The standards were analyzed between every five unknowns. The off-line selection and integration of the background and analyte signals, time-drift correction, and quantitative calibration, were performed using

Figure A2. Cathodoluminescent images of the dated (concordant) euhedral to subhedral zircons from the Ranau peridotite (RP) and Telupid Ophiolite (TO), Sabah. Red circles show the spots from which U-Pb data were acquired whereas yellow circles indicate the spots where additional Lu-Hf isotopic data were obtained (numbers in brackets are ϵ_{Hf}): A) SB 120A (RP) includes a group of zircons with consistent Late Miocene ages and a sole Neoproterozoic crystal; B) SB 120B (RP) shows three age groups of Late Miocene, Cenomanian and a single Lower-Middle Devonian (2 spots) zircons; C) and D) each of SB 127 (TO diabase) and SB 125 (TO basalt) contain a group of exclusively Late Miocene zircons; E) SB 130 (TO basalt) includes a group of Late Miocene and a single Middle Triassic (2 spots) zircons.

ICPMSDataCal (Lin et al., 2016). Zircon spots with concordant or nearly concordant ages, with less than 15% discordance, were only considered (Fig. A4). Detailed instrumentation, analytical and data reduction procedures are as described in Yang et al. (2020) and references therein.

Figure A3. Conventional concordia diagrams for the Plesovice zircons, when reducing the data using 91500 as the primary standard.

LA-MC-ICP-MS zircon Hf isotope analysis

Zircon Hf isotope analysis was conducted on the U-Pb dated zircons, close to the U-Pb spot in the same age domain (Fig. A4, Table A2). The analysis was performed at the State key Laboratory of Isotope Geochemistry, GIGCAS on a Neptune Plus MC-ICP-MS (Thermo Scientific), coupled with a RESolution M-50 193 nm laser ablation system (Resonetics). An X skimmer cone in the interface and a small N₂ flow (2ml L⁻¹) were used to improve the instrumental

sensitivity. All isotope signals were detected with Faraday cups under static mode. Analytical parameters include 4 J cm^{-2} energy density, 6 Hz repetition rate, $45 \mu\text{m}$ beam size, and helium as the carrier gas (800 ml min^{-1}). A “squid” smoothing device was used on the ICP gas line to give a smooth signal. Each analysis consists of 400 cycles with an integration time of 0.131 s per cycle. Zircon Hf isotope analysis was performed on the previous U-Pb dating spots. CL imaging shows that the zircons are highly homogenous (without inherited core or growth rim), thus overlapping of two spots should not pose any analytical issues. To ensure that Hf spot was ablated on a level smooth surface, we have re-polished the sample after the U-Pb analysis. Each analysis comprises 28 s of gas blank background measurement (laser-off), followed by 30 s sample signal collection (laser-on). During our analysis, the gas blank of ^{180}Hf was below 0.2 mv. ^{173}Yb and ^{175}Lu were used to correct the isobaric interference of ^{176}Yb and ^{176}Lu on ^{176}Hf . The natural $^{176}\text{Yb}/^{173}\text{Yb}$ and $^{176}\text{Lu}/^{175}\text{Lu}$ ratios used in the correction are 0.79381 and 0.02656, respectively (Segal et al., 2003). The mass bias factor of Yb is calculated from the measured $^{173}\text{Yb}/^{171}\text{Yb}$ and the natural ratio of 1.13268, whilst the mass bias factors of Lu and Yb are assumed to be the same. The mass bias of $^{176}\text{Hf}/^{177}\text{Hf}$ was normalized to $^{179}\text{Hf}/^{177}\text{Hf} = 0.7325$ with an exponential law. 40 analyses of the Plešovice zircon (measured between every five unknowns) during the course of this study yielded a weighted mean of $^{176}\text{Hf}/^{177}\text{Hf} = 0.282484 \pm 0.000011$ (2SD), consistent (within errors) with the recommended value (0.282482 ± 0.000013 (2SD); Sláma et al., 2008). Detailed instrumentation, analytical and data reduction procedures are as described in Xu et al. (2019) and references therein.

Figure A4. Conventional concordia diagrams for zircons from the dated samples from Sabah. All results are plotted using ISOPLOT (Ludwig, 2003).

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