



Dating blueschist-facies metamorphism within the Naga ophiolite, Northeast India, using sheared carbonate veins

Journal:	<i>International Geology Review</i>
Manuscript ID	TIGR-2021-0265.R3
Manuscript Type:	Data Article
Date Submitted by the Author:	n/a
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Keywords:	blueschist, dynamic recrystallisation, exhumation, petrological modelling, U-Pb carbonate geochronology

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4 1 **Dating blueschist-facies metamorphism within the Naga ophiolite,**
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7 2 **Northeast India, using sheared carbonate veins**
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19 **Keywords:** blueschist; dynamic recrystallisation; exhumation; petrological modelling; U–Pb
20 carbonate geochronology
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22 **ABSTRACT**

23 The tectonic significance of blueschist-facies rocks associated with the Indo-Myanmar
24 ophiolite belt is uncertain, given lack of detailed petrological study and the paucity of reliable

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3 25 age data for different stages in their geological evolution. Here, we present new integrated
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5 26 petrological and geochronological data for samples from the Nagaland complex of the Indo-
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7 27 Myanmar ophiolite belt, northeastern India, which constrains the pressure–temperature
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9 28 conditions and absolute ages of peak and retrograde metamorphism. Several samples of
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11 29 blueschist were collected from the region, which have been variably deformed and subjected
12
13 30 to shear recrystallization. Based on microstructural constraints and mineral geochemistry,
14
15 31 garnet, omphacite, barroisite, chlorite and muscovite are interpreted to represent a high-
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17 32 pressure prograde-to-peak metamorphic assemblage, and omphacite, actinolite, hornblende
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19 33 and albite represent a lower-pressure retrograde metamorphic assemblage that formed during
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21 34 shear-related exhumation. Petrological modelling and thermobarometry indicates that
22
23 35 unsheared samples equilibrated at ~1.9 GPa and ~480–520 °C at peak metamorphism,
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25 36 indicating subduction to ~60 km depth, whereas sheared and recrystallised samples re-
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27 37 equilibrated at ~0.6 GPa and ~470 °C during retrograde metamorphism associated with
28
29 38 obduction of the Naga ophiolite onto the Indian foreland. U–Pb *in-situ* analysis of carbonate
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31 39 grains (aragonite–calcite) and associated silicate phases (epidote, prehnite, amphibole etc.) in
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33 40 different microstructural positions, including within dynamically recrystallised shear bands
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35 41 that cross-cut older metamorphic fabrics and cogenetic silicate phases, constrains the age of
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37 42 peak metamorphism to be c. 95 Ma and retrograde metamorphism to be c. 90 Ma. Based on
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39 43 the overall progression of ages in the sheared and unsheared samples, we interpret that the
40
41 44 area experienced exhumation at a time-averaged rate of ~1 cm/year in the order of
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43 45 Phanerozoic period plate tectonic rate. which is in the order of rates of plate tectonic
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45 46 processes on the Phanerozoic Earth
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1. Introduction

High-pressure metamorphic belts provide a critical record of the geological evolution of paleo-plate boundaries, and provide valuable constraints on tectonothermal models of both modern and ancient orogeneses (e.g. Ernst 1973; Carswell 1990). Blueschist-facies rocks form at high-pressure–low-temperature (HP–LT) metamorphic conditions characteristic of subduction zones (Miyashiro 1961; Cloos 1985; Palin and White 2016) or ephemerally in the embryonic stages of collisional orogeny (Wang and Foley, 2020), where they may subsequently recrystallize to greenschists or amphibolites under higher temperatures and/or lower pressures (Ernst 1973). Combining mineral equilibria constraints on the thermobarometric conditions under which sequential assemblages formed with absolute ages obtained via *in-situ* geochronology, can elucidate the timing and timescales of geodynamic processes that control the subduction–exhumation cycle (e.g. Terry *et al.* 2000; Rubatto and Hermann 2001; St-Onge *et al.* 2013).

The power of this integrated technique is demonstrated here in the case of the Indo-Myanmar ophiolite belt, a part of the Indo-Myanmar Range that extends to the east and southeast of the Himalayan orogen. The geological history and tectonic evolution of this belt is currently poorly understood, such that more precise constraints on the pressure–temperature–time (P – T – t) path of key lithologies are necessary to improving our geological understanding of this part of southeast Asia. Much of the current uncertainty concerning the tectonic evolution and significance of these Indian-plate ophiolitic rocks stems from a lack of reliable petrochronological data. In particular, the timing and P – T conditions of high-pressure metamorphism in the Indo-Myanmar belt is poorly constrained due to the general absence of datable mineral phases in mafic igneous rocks that are reactive at subsolidus subduction-zone HP–LT metamorphic conditions. Zircon from jadeitites in this region have previously yielded U–Pb ages ranging from Late Jurassic (c. 147 Ma: Shi *et al.* 2008) to Late Cretaceous (c. 77

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3 73 Ma: Yui *et al.* 2013), although all of these data show significant scatter due to incomplete
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5 74 recrystallization of magmatic grains and metasomatic/hydrothermal activity during
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7 75 subduction and exhumation, which can partially reset isotope systems (Wang and Griffin
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9 76 2004). Furthermore, these former studies performed geochronology on zircon grains
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11 77 separated from the host rocks, which inhibits direct correlation of age data with P – T
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13 78 conditions derived from metamorphic assemblages and microstructures, leading to potentially
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15 79 unreliable geological interpretations.

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19 80 The zircon U–Pb isotope system is widely applied for dating the crystallization and re-
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21 81 crystallization of mineral assemblages during high-temperature metamorphic events (e.g.
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23 82 Williams and Claesson, 1987; Parrish, 1990; Robb *et al.* 1999, Rubatto *et al.*, 2001). However,
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25 83 some lithologies and/or geological processes often cannot be dated directly by this technique
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27 84 due to the absence of appropriate minerals that incorporate measurable amounts of radiogenic
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29 85 nuclides. Examples of such rocks can be found in shear zones, but this issue also extends to
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31 86 HP – LT metamorphic rocks, ore mineralisations, diagenetic minerals and cements, some
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33 87 sedimentary rocks, and some alteration assemblages (e.g. Gilley *et al.* 2003). Recent studies
34
35 88 have focused on the application of *in-situ* U–Pb isotope analyses of low-U minerals in thin
36
37 89 section by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) for
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39 90 geochronological study (Millonig *et al.* 2012; Coogan *et al.* 2016; Ring and Gerdes 2016;
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41 91 Roberts and Walker 2016; Li *et al.* 2014). Thus, instead of dating single accessory mineral
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43 92 domains, millimetre-sized minerals and mineral assemblages (e.g., carbonate, epidote,
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45 93 amphibole etc.) that recrystallised and equilibrated during a single tectonic event and which
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47 94 contain measurable amounts of U and Pb can be used to determine crystallization ages (e.g.
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49 95 Burisch *et al.* 2017; Ring and Gerdes 2016).

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56 96 Here we apply the isochron method to dynamically recrystallised carbonate veins and
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58 97 selected mineral assemblages in blueschists within the Kiphire District of the Nagaland
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3 98 ophiolite belt and integrate these ages with thermobarometric data to produce new constraints
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5 99 on the timing and rates of subduction and exhumation of Neo-Tethyan crust in the Indo-
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8 100 Myanmar region.

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12 102 **2. Geological background**

14 103 The Indo-Myanmar Range is thought to represent a relict eastward-dipping subduction zone
15
16 104 that runs from the eastern edge of the Himalayan Range in southeast Tibet to the island of
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18 105 Sumatra in the south (Allen *et al.* 2008; Fig. 1). The Eastern Himalayas, about 700 km long,
19
20 106 trends ENE-WSW. Broadly N-S trending to sigmoid IMR has subdivided into three sectors
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22 107 from north to south of about 400 km length each e.g., Naga Hills, Chin Hills and Arakan
23
24 108 Yoma (Acharyya 2015). The belt continues as the Anadaman Nicobar island arc in the south.
25
26 109 Belts of narrow tectonised but nearly continuous, late Mesozoic-Eocene ophiolite and
27
28 110 associated sediments skirt along the northern margin of the Himalayas (Indus-Tsangpo
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30 111 Ophiolite-ITO) and the eastern margin of the Himalayas IMR. Structural relationships show
31
32 112 that Indian-plate oceanic crust was overridden by units of the West Burma Block (e.g. Holt *et*
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34 113 *al.* 1991; Mitchell *et al.* 2007; Searle *et al.* 2007), although its age of formation and the
35
36 114 timing of its obduction are poorly known. The Indo-Myanmar ophiolite belt separates
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38 115 subducted Indian-plate oceanic lithosphere to the west from a closely associated high-
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40 116 pressure metamorphic belt and Jurassic to Cretaceous magmatic arc–forearc complex of the
41
42 117 Burmese plate to the east (Mitchell *et al.* 2012). The Naga Hills ophiolite is represented by
43
44 118 peridotite, cumulate mafic-ultramafic, mafic volcanics, eclogite, glaucophane schist,
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46 119 amphibolite and late felsic intrusives. The ophiolite sequence has an east-dipping thrust
47
48 120 contact with the underlying flysch-like sediments of the Disang and Barail Formations
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50 121 exposed to the west, and are overthrust from the east by continental metamorphic rocks of the
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52 122 Naga Metamorphics consisting of quartz mica-schist, garnet mica-schist, quartzite, and
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3 123 granitic gneiss (Brunnschweiler, 1966). The mid-Cretaceous, fossil-bearing Nimi Formation
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5 124 occurs at the contact between the ophiolite and the Naga Metamorphics (Chatterjee and
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7 125 Ghose, 2010). Within this belt, blueschist- and eclogite-facies mafic rocks occur as tectonic
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9 126 slices (or detached layers and lenses) intercalated with unmetamorphosed mafic and
10
11 127 ultramafic units. Basement lithologies underlie Palaeogene sediments in the ophiolite belt,
12
13 128 although their geological history and lithological constitution are uncertain (Acharyya 2015).
14
15 129 Ophiolitic rocks within the Indo-Myanmar belt have been subdivided into two parallel
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17 130 groups: the 'Eastern' and 'Western' belts (Mitchell 1993), although both show similar
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19 131 structural and petrological characteristics. Accretion of the Eastern Belt, which contains
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21 132 metamorphosed ultramafic rocks in northern Myanmar that host world-famous jadeitites, is
22
23 133 thought to have occurred sometime after the Mesozoic (Gansser 1980; Mitchell 1993; Shi *et*
24
25 134 *al.* 2008). The Western Belt along the Naga and Manipur hills, which forms part of the Indo-
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27 135 Myanmar Range, formed due to collision between India and the Burmese microplate during
28
29 136 the late Oligocene (Sengupta *et al.* 1990).
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35 137 There is still controversy about emplacement ages of ophiolites in these two belts: the
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37 138 'Eastern Belt' is inferred to mark the locus of the subduction zone into which the ophiolites
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39 139 were accreted since Mesozoic, whilst the 'Western Belt' was inferred to have been caused by
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41 140 a late Oligocene terminal collision between the Indian and the Burmese continental blocks
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43 141 (Shit *et al.*, 2014 and references therein). In the 'Western Belt' a combination of radiolarian
44
45 142 biostratigraphy and whole-rock K–Ar geochronology suggests an Upper Jurassic age
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47 143 (Kimmeridgian–Lower Tithonian) for marine sedimentation and volcanism in the Nagaland
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49 144 ophiolite belt (Sarkar *et al.* 1996; Baxter *et al.* 2011). The mid-Cretaceous, fossiliferous Nimi
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51 145 Formation occurs at the contact between the ophiolite and the Naga metamorphic units, and
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53 146 so gives a maximum age constraint on the initiation of obduction. Recently, Singh *et al.*
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55 147 (2017) reported U–Pb zircon ages ranging between 116 and 119 Ma from the plagiogranite of
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3 148 the studied ophiolite. In the 'Eastern Belt' falling in the Mynamar Shi *et al.* (2008) reported a
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5 149 sensitive high-resolution ion microprobe (SHRIMP) U–Pb zircon age of 146.5 ± 3.4 Ma for
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8 150 jadeitites of the Jade Mines area, Myanmar, and proposed that subduction may have begun
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10 151 during the Late Jurassic. Mitchell (1993) suggested that the Manipur ophiolitic nappe was
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12 152 emplaced along the Indo-Myanmar ranges during the Mid-Eocene and was followed by a
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15 153 switch to east-dipping subduction from the mid-Miocene onwards. Recently, Liu *et al.* (2016)
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17 154 reported a c. 125 Ma U–Pb zircon crystallisation age for rodingite associated with formation
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19 155 of the ophiolite, and a c. 115 Ma age for garnet amphibolites within the Kalaymo ophiolite
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21 156 belt, which lies adjacent to the Indo-Myanmar ophiolite belt. Shi *et al.* (2014) reported
22
23 157 superimposed tectono-metamorphic ages of phengitic mica Ar–Ar ages from blueschist-facies
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25 158 rocks in the Tagaung-Myitkyina Belt. They interpreted a Jurassic age (152.4 ± 1.5 Ma)
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27 159 obtained from glaucophane as the lower limit of the subduction age and suggested that
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29 160 Eocene (45.0 ± 1.3 Ma) ages recorded an intra-continental shearing deformation event.
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33 161 Chatterjee and Ghose (2010) documented eclogite- and blueschist-facies rocks present
34
35 162 as thrust slices and lenses within the volcanic and ultramafic rocks of the Naga ophiolite belt.
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37 163 Ao and Bhowmik (2014) deduced the thermal history of the eclogite and blueschist rocks
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39 164 ranging from ~ 1.15 GPa and ~ 340 °C to 0.6 GPa and 335 °C. Despite an improved
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41 165 understanding of the tectonic evolution of the Indian ophiolite belt, a paucity of reliable
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43 166 geochronological age data has hindered the correlation of sutures and collisional deformation
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45 167 episodes within the region.
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51 169 **3. Analytical methods**

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53 170 The eclogites and blueschists rocks of Naga Hills occur as NE–SW to N–S oriented, steeply
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55 171 east-dipping shear fault-bound tectonic slices or detached layers and lenses intercalated with
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57 172 basaltic and ultramafic units parallel to the shear faults in the Naga Hills ophiolite of Phek
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3 173 district, Nagaland (Chatterjee and Ghose, 2010). In the area eclogite constitutes the core of
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5 174 some lenses, which are surrounded by successive layers of garnet-blueschist, glaucophanite
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7
8 175 and greenschist. Twenty metamorphosed samples were collected between Longkhimong and
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10 176 Moya villages, after systematic petrographic study six samples were selected for detailed
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12 177 study. Mineral compositional data for all samples were obtained on a JEOL JXA-8200
13
14 178 electron microprobe housed at the Institute of Geosciences, Johannes-Gutenberg University
15
16 179 of Mainz, Germany. Operating conditions included an acceleration voltage of 15 kV, a beam
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18 180 current of 12 nA, and a 2 μm spot size. A matrix correction for atomic number (Z),
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20 181 absorption (A), and fluorescence (F) was automatically applied to all analyses. For the data
21
22 182 presented below, mineral compositions were recalculated to standard numbers of oxygens per
23
24 183 formula unit (pfu) using the software AX (Holland 2009), with OH assumed to be present in
25
26 184 stoichiometric amounts. The proportion of ferric iron in different mineral species was also
27
28 185 calculated using AX. Mineral proportions for each sample were determined using the
29
30 186 software JmicroVision (Roduit 2010), with each individual count consisting of five hundred
31
32 187 points randomly distributed over a digitally scanned thin-section image. Calculated volume
33
34 188 proportions of minerals in each sample are given below. These bulk compositions are given
35
36 189 in Supplementary Table 3. Mineral abbreviations are after Kretz (1983). Representative
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38 190 compositions of major minerals for all samples are given in Supplementary Table 2 and
39
40 191 photomicrographs of microstructural features and assemblages are shown in Figures 2 and 3.

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42 192 Bulk-rock compositions for use in petrological modelling were obtained from X-ray
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44 193 fluorescence (XRF) via the production of glass beads in order to guarantee standardised and
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46 194 reproducible analyses. Powdered rock samples were initially dried overnight at 105 °C.
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48 195 Approximately 5.2 g of lithium tetraborate ($\text{Li}_2\text{B}_4\text{O}_7$) flux and 0.4 g of powdered rock sample
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50 196 were then weighed, homogenized, and melted in a Vulcan AMA melting device to produce
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52 197 each glass beads. These beads were then analyzed in a Philips MagXPRO spectrometer with
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3 198 a rhenium X-ray tube housed in the Institute of Geoscience, Johannes Gutenberg University
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5 199 of Mainz, Germany. Detection limits are estimated to be $100 \mu\text{g g}^{-1}$ for light elements (Na,
6
7 200 Mg, Al) and $10 \mu\text{g g}^{-1}$ for heavy elements (K to U). Analysed major oxides comprised SiO_2 ,
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9 201 Al_2O_3 , total Fe_2O_3 , MnO, MgO, CaO, Na_2O , K_2O , TiO_2 , P_2O_5 , SO_3 , Cr_2O_3 , and NiO.

12 202 All U–Pb ages for the analysed carbonate grains and silicate phases were acquired *in*
13
14 203 *situ* from polished thin sections by laser ablation-inductively coupled plasma-mass
15
16 204 spectrometry (LA-ICP-MS) at the Goethe University Frankfurt (GUF), using a Element2
17
18 205 (Thermo-Scientific) sector field ICP-MS coupled to a RESOLUTION ArF Excimer laser
19
20 206 (Compex Pro 102). The applied method was similar as described in Ring and Gerdes (2016),
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22 207 Burisch *et al.* (2017), Hansman *et al.* (2018) and Salih *et al.* (2019). Ablation spot size was
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24 208 $213 \mu\text{m}$ and crater depth was $\sim 20 \mu\text{m}$. Samples were screened by LA-ICP-MS for suitable Pb
25
26 209 and U concentration and variability, and selected spots were subsequently analysed in fully
27
28 210 automated mode. Spot analyses consisted of 20 s background acquisition followed by 20 s
29
30 211 sample ablation. Surface contamination was removed prior to each spot analysis via a 3-s pre-
31
32 212 ablation. Soda-lime glass SRM-NIST 614 was used as a reference material together with two
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34 213 carbonate reference materials – WC-1 and a Zechstein dolomite – to bracket sample analysis.
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36 214 SRM-NIST 614 yielded a depth penetration of about $0.5 \mu\text{m s}^{-1}$ and an average sensitivity of
37
38 215 $280,000 \text{ cps}/\mu\text{g g}^{-1}$ for ^{238}U . The detection limits for ^{206}Pb and ^{238}U were ~ 0.1 and 0.05 ng
39
40 216 g^{-1} , respectively. All data were corrected using an MS Excel spreadsheet program (Gerdes
41
42 217 and Zeh, 2006, 2009). NIST 614 was used as a standard for the analysis of silicate phases.
43
44 218 The possible offset related to sample matrix is within the analytical uncertainty of the quoted
45
46 219 ages.

53 220 The $^{207}\text{Pb}/^{206}\text{Pb}$ ratio was corrected for mass bias (0.3%) and the $^{206}\text{Pb}/^{238}\text{U}$ ratio for
54
55 221 inter-element fraction (ca. 5%) using SRM-NIST 614. An additional correction of 4% was
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57 222 applied on the $^{206}\text{Pb}/^{238}\text{U}$ to correct for difference in the fractionation due to the carbonate
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3 223 matrix. This resulted in a lower intercept age of 23 WC-1 spot analyses of 254.1 ± 1.5
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5 224 (MSWD = 1.5; anchored at $^{207}\text{Pb}/^{206}\text{Pb}$ of 0.851) and 253.9 ± 3.4 (MSWD = 1.5; $n = 17$) for
6
7 225 the Zechstein dolomite used as an in-house reference material in Frankfurt. Data were plotted
8
9 226 on a Tera-Wasserburg diagram and ages calculated as lower intercepts using Isoplot 3.71
10
11
12 227 (Ludwig 2007). All uncertainties are reported at the 2 sigma level.

13
14 228 According to Rasbury and Cole (2009), a linear regression taken through a group of
15
16 229 samples from the same system produces a slope from which an age can be calculated using
17
18 230 the accepted decay rate for the parent isotope. If the system being analysed has no initial
19
20 231 heterogeneity, and it remained closed throughout the duration of the decay process, all scatter
21
22 232 of data points about the isochron can be explained by analytical uncertainties. Closed isotopic
23
24 233 systems will plot as a line, giving a precise age and low mean squared weighted deviate
25
26 234 (MSWD) of ~ 1 , while systems that have not remained closed will show scatter and have a
27
28 235 high MSWD ($\gg 1$).

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34 237 **4. Sample petrology**

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36 238 Out of the twenty collected samples we have selected four metabasite samples for systematic
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38 239 study and thermobarometry Six metabasite samples were collected from. Locality
39
40 240 information and GPS co-ordinates for each outcrop are given in Supplementary Table 1 and
41
42 241 location map is presented in Figure 1C. Field photographs of the studied samples are
43
44 242 presented in Figure 1D. The samples occur as meter-sized boulder blocks, which occur
45
46 243 individually and in clusters (Figures 1 D1, D3) within serpentinites. Samples are thus
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48 244 classified as either sheared or unsheared based on the occurrence of key deformational
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50 245 features present at the field, hand sample, and microscopic scale. Samples N5 and 14 lack
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52 246 evidence of post-peak shear-driven recrystallization and likely represent relics of
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247 undeformed, peak metamorphic blueschists. By contrast, samples 7c, 13, 3b, and 11 are
248 strongly sheared and represent subsequently deformed equivalents of these older units.

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250 4.1. Sample description

251 4.1.1. Unsheared samples N5 and 14

252 Unsheared samples N5 and 14 exhibit a largely unfoliated microstructure and show no
253 evidence of pervasive retrogression following peak blueschist-facies metamorphism during
254 subduction, though localised retrogression does occur. Sample N5 is a blueschist that
255 contains abundant sodic amphibole (38%) and epidote (37%), with minor quartz (9%), garnet
256 (6%), sodic-calcic amphibole (4%), phengite (3%), and rutile (2%). Accessory pyrite, zircon,
257 and apatite also occur. Garnet porphyroblasts are between 0.5 and 2 mm in diameter (Figures
258 2a–b) and exhibit no substantial major element compositional zoning, with core compositions
259 of $\text{Alm}_{56-58}\text{Prp}_{12-14}\text{Grs}_{21-22}\text{Sps}_{7-8}$ and rim compositions of $\text{Alm}_{60-61}\text{Prp}_{15-16}\text{Grs}_{22-23}\text{Sps}_{3-4}$
260 (Supplementary Table 2 and Fig. 4). Core regions contain inclusions of pumpellyite,
261 phengite, epidote, barroisite, actinolite, and quartz, and rims contain inclusions of phengite,
262 epidote, actinolite, rutile, and quartz. Some grains show replacement by chlorite at their
263 outermost rims. Matrix phengite has $\text{Si} = 3.34\text{--}3.38$ pfu (on a 11 O basis; Supplementary
264 Table 2) and grains included in the outer rims of garnet has $\text{Si} = 3.32\text{--}3.35$ pfu. Epidote
265 shows no significant compositional zoning from core to rim, with a minor range in pistacite
266 content [$\text{XPs} = \text{Fe}^{3+}/(\text{Al}^{3+} + \text{Fe}^{3+})$] of 0.18–0.21 (Supplementary Table 2). According to the
267 classification scheme of Hawthorne *et al.* (2012), sodic and sodic-calcic amphiboles in the
268 matrix are glaucophane and winchite–katophorite, respectively (Figure 5).

269 Sample 14 is modally dominated by epidote (50%) and quartz (35%), with lesser garnet
270 (1%), sodic-calcic amphibole (10%), phengite (2%), rutile (0.5%), titanite (0.5%), and
271 carbonate (1%). Accessory minerals include chlorite, apatite, and zircon (all $\ll 1\%$).

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3 272 Although sample 14 displays no foliation, it is mildly anisotropic, with alternating
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5 273 centimetre-scale quartz- and epidote-rich domains. In contrast to the large porphyroblasts
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7 274 present in sample N5, garnet forms <0.1 mm diameter grains that are restricted to quartz-rich
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9 275 regions (Figure 2). These garnet grains have no inclusions and are compositionally
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11 276 homogeneous ($\text{Alm}_{36-39}\text{Prp}_{10-13}\text{GrS}_{31-36}\text{Sps}_{36-39}$). Epidote shows no significant zoning, with
12
13 277 core and rim compositions both having similar pistacite contents of 0.20–0.24
14
15 278 (Supplementary Table 2). Matrix rutile is partially or fully replaced by titanite (Figure 2),
16
17 279 though rare inclusions in sodic-calcic amphibole lack such pseudomorph textures. Phengite
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19 280 contains $\text{Si} = 3.34\text{--}3.35$ pfu (Supplementary Table 2) and in places is intimately intergrown
20
21 281 with chlorite, though the extremely fine-grained nature of these intergrowths prohibited
22
23 282 reliable compositional analysis of either phase. Sodic-calcic amphibole in the matrix is
24
25 283 barroisite–winchite–katophorite (Hawthorne *et al.* 2012; Figure 5), with rare tremolite, likely
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27 284 representing minor post-peak retrograde mineralogical transformation.
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33 285 34 35 286 *4.1.2. Sheared samples 11 and 7c*

36
37 287 In contrast to N5 and 14, sheared samples 11 and 7c contain distinct spaced foliations that are
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39 288 truncated by carbonate- and quartz-filled veins. These crosscutting veins commonly form
40
41 289 shear bands (Figures 3e–f) and locally deflect the main metamorphic foliations at their
42
43 290 boundaries (Figure 3b), indicating that shearing and vein formation post-dated subduction
44
45 291 metamorphism. The host rock domains in sample 7c are dominated by epidote (39%), calcic
46
47 292 amphibole (32%), and sodic–calcic amphibole (18%), with minor phengite (4%), albite (2%),
48
49 293 K-feldspar (2%), titanite (1%), and quartz (2%). Apatite and zircon occur as accessory
50
51 294 phases. The main metamorphic foliation is defined by elongate and aligned crystals of
52
53 295 epidote and amphibole (Figure 3a). Large green calcic amphibole is mostly pargasite with
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55 296 thin magnesiohornblende outer rims, and sodic-calcic amphibole is winchite (Figure 5).
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3 297 Matrix phengite has Si = 3.39–3.43 pfu and epidote cores have X_{Ps} = 0.19–0.25 and rims
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5 298 have X_{Ps} = 0.26–0.33 (Supplementary Table 2). Quartz- and carbonate -filled veins crosscut
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7
8 299 and offset this epidote- and amphibole-defined metamorphic foliation (Figure 3b).

9
10 300 Sample 11 contains abundant sodic amphibole (33%), quartz (34%), carbonate (14%),
11
12 301 and sodic pyroxene (11%), with subsidiary sodic–calcic amphibole (2%), phengite (1%),
13
14 302 garnet (2%), and albite (1%). Accessory pyrite, titanite, apatite, and zircon (all <<1%) also
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16
17 303 occur. Alternating sodic amphibole (glaucophane) and quartz-rich bands define a spaced
18
19 304 foliation that wraps around porphyroblasts of pyroxene and garnet (Figure 3c). Grains of the
20
21 305 latter are commonly less than 1 mm in diameter and are variably replaced by aggregates of
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23 306 carbonate, albite and/or quartz (Figure 3d). Though individual grains lack any significant
24
25 307 major-element compositional zoning from core to rim, compositions vary significantly
26
27
28 308 between grains; the majority are spessartine-rich ($Alm_{19-24}Prp_{10-14}Grs_{17-20}Sps_{45-51}$), while
29
30 309 others are richer in almandine and grossular ($Alm_{26-29}Prp_{12}Grs_{23-32}Sps_{28-37}$). Minor sodic-
31
32 310 calcic amphibole in the matrix is winchite, and sodic pyroxene porphyroblasts are
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34
35 311 compositionally classified as aegirine–augite (X_{Jd} = 0.04–0.23) (Morimoto *et al.* 1988).

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39 313 **5. Phase equilibria modelling**

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41
42 314 Constraints on the P – T conditions of peak subduction-zone metamorphism were obtained
43
44 315 from unsheared samples N5 and 14, whereas constraints on the P – T conditions of subsequent
45
46 316 ductile shearing were obtained from sheared sample 7c. Preliminary investigation of phase
47
48 317 equilibria stability in sample 11 did not allow for reliable thermobarometry to be performed
49
50 318 due to the high variance of the interpreted peak mineral assemblage. Phase diagrams showing
51
52 319 the P – T conditions over which equilibrium mineral assemblages are calculated to occur in a
53
54 320 specific bulk-rock composition (pseudosections) were constructed using THERMOCALC
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56 321 v3.40i and the internally consistent thermodynamic data set ds55 (Powell and Holland 1988;
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3 322 Holland and Powell 1998; updated to August 2004) in the $\text{Na}_2\text{O}-\text{CaO}-\text{K}_2\text{O}-\text{FeO}-\text{MgO}-$
4
5 323 $\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}-\text{TiO}_2-\text{O}$ (NCKFMASHTO) compositional system. The following activity-
6
7 324 composition relations for solid-solution phases were used: clinoamphibole (calcic, sodic-
8
9 325 calcic, and sodic amphibole; Diener and Powell 2012), clinopyroxene (diopside and
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11 326 omphacite, Diener and Powell 2012), muscovite and paragonite (Coggon and Holland 2002),
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13 327 talc and epidote (Holland and Powell 1998), chlorite (Holland *et al.* 1998), biotite and garnet
14
15 328 (White *et al.* 2007), plagioclase and K-feldspar (Holland and Powell 2003), ilmenite and
16
17 329 hematite (White *et al.* 2000). Albite, lawsonite, rutile, titanite, quartz, kyanite, and H_2O were
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19 330 treated as pure phases.
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25 331 *5.1. Metamorphic mineral equilibria modelling parameters*

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27 332 Bulk-rock compositions used for modelling were obtained via XRF analysis, as discussed
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29 333 previously (Supplementary Table 2). Point counting was applied to the entire thin section
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31 334 image, aside from areas that do not actually contain pieces of the rock (e.g. as it is not a
32
33 335 perfect rectangle). 500 points were sufficient in this case, as we kept track of the evolving
34
35 336 proportions during analyses and the values converged on final results after ~300 points or so.
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37 337 For sample 7c, areas adjacent to shear bands were excluded from consideration during point
38
39 338 counting such that the proportions obtained represent unsheared portions of the sample that
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41 339 equilibrated prior to deformation.
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45 340 The fluid contents for each bulk rock composition during metamorphism were
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47 341 calculated using the proportions of hydrous phases present in each equilibrium mineral
48
49 342 assemblage, assuming H_2O was present in stoichiometric amounts. Mixed-component fluids
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51 343 were not considered due to the lack of reliable a-x relations for C-O-H fluids at elevated
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53 344 pressures; nonetheless, however, this should not have any significant effects on our calculated
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55 345 diagrams, as unsheared sample N5 does not contain carbonate, unsheared sample 14 contains
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57 346 only a minor proportion (2.2 vol. %), and carbonate veins in sheared sample 7c are
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3 347 interpreted from microstructural constraints to post-date final metamorphism and textural
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5 348 equilibration. Pressure uncertainties for assemblage field boundaries are approximately ± 0.1
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7 349 GPa (Powell and Holland 2008; Palin *et al.* 2016).
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11 351 *5.1.1. Unsheared samples*

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14 352 Calculated mineral assemblages matching those observed in unsheared samples N5 and 14
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16 353 constrain peak P – T conditions of subduction-zone metamorphism to ~ 1.8 – 2.0 GPa and ~ 420 –
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18 354 560 °C, with the calculated proportions and compositions of major minerals best matching
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20 355 observed values at ~ 1.9 GPa and ~ 480 – 520 °C. These conditions lie along the global range of
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22 356 P – T conditions predicted to occur at the surface of subducted oceanic crust in modern-day
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24 357 subduction zones (Syracuse *et al.* 2010; Penniston-Dorland *et al.* 2015).
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27 359 *5.1.2. Sheared sample*

28
29 360 In contrast with the undeformed samples, the observed mineral assemblage in sample 7c was
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31 361 calculated to be stable at the notably lower pressure and slightly lower temperature conditions
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33 362 of ~ 0.2 – 0.6 GPa and ~ 420 – 490 °C, with observed and calculated mineral proportions and
34
35 363 compositions matching best at ~ 0.6 GPa and ~ 470 °C. Semi-independent constraints on P – T
36
37 364 conditions using the avPT function of THERMOCALC for each sample produced similar and
38
39 365 statistically robust results of 2.05 ± 0.22 GPa and 489 ± 39 °C for N5, 1.95 ± 0.18 GPa and
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41 366 541 ± 34 °C for 14, and 0.60 ± 0.23 GPa and 464 ± 76 °C for 7c (Supplementary Table 4)
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43 367 corroborating the results obtained by phase diagram modelling.
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51 368 **6. U–Pb geochronology**

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53 369 U–Pb isotopic analysis of carbonate grains was carried out on metabasite samples 14
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55 370 (unsheared), 11 (sheared), 3b and 13, which equilibrated at different stages of the
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57 371 subduction–exhumation cycle. Carbonate crystals within dynamically recrystallised veins
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3 372 were preferentially selected for analyses; however, suitable matrix minerals were also
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5 373 investigated in order to perform a check on the analysed carbonates, which generally have a
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7 374 low U content. Results of the isotopic composition of the Nagaland blueschists are presented
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10 375 in Supplementary Table 5 and isochrons are shown in Figure 9. Measured $^{207}\text{Pb}/^{206}\text{Pb}$ ratios
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12 376 range from 0.205 to 0.836 (sample 3b), 0.735 to 0.848 (sample 13), 0.776 to 0.845 (sample
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14 377 11) and 0.809 to 0.846 (sample 14), and measured $^{238}\text{U}/^{206}\text{Pb}$ ratios range from 0.361 to 9.752
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16 378 (sample 3b), 0.043 to 10.53 (sample 13), 0.118 to 5.474 (sample 11) and 0.809 to 0.846
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18 379 (sample 14). All data for each sample lie on a single array on an isochron diagram, indicating
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20 380 that each attained isotopic equilibrium, and give well-defined least squares fit indices with
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22 381 MSWD values of 0.35–1.17 (Figure 9). The U concentrations in the minerals range between
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24 382 0 and 3 ppb and model Th/U ratios show a wide variation, with most lying between 0.015 and
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26 383 5, but some reaching up to ~46. These analyses show that unsheared samples 14 and 11
27
28 384 equilibrated at 95.3 ± 5.9 Ma and 93.7 ± 4.0 Ma, respectively, and sheared samples 3b and 13
29
30 385 experienced exhumation-related shear deformation at 90.6 ± 3.4 Ma and 88.8 ± 2.7 Ma,
31
32 386 respectively. Although the unsheared sample dataset is within uncertainty of all the sheared
33
34 387 sample dates, an overall age progression may be reconstructed from the sheared and
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36 388 unsheared samples. Considering the well-behaved dataset in the studied samples with a low
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38 389 MSWD, it can be broadly inferred that the analysed phases had the same initial isotopic ratio
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40 390 and that the system was at equilibrium during closure of the isotopic system.

41 391 **7. Discussion and implications**

42 392 Most natural carbonate occurs in the form of calcite and can be transported to the Earth's
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44 393 interior via subduction of carbonate-rich sediments or metasomatized oceanic crust (Zhang *et*
45
46 394 *al.* 2018). Calcite transforms to aragonite at high pressure. Although may revert back to calcite
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48 395 during exhumation if there are no kinetic limitations. At the P – T conditions of peak
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50 396 metamorphism for samples N5 and 14, the carbonate likely stabilised in the form of aragonite,
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3 397 whereas carbonate in sheared samples 11 and 7c is calcite, which indicates polymorphic
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5 398 transformation following exhumation from peak depths. Representative BSE images showing
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8 399 the analysed spots are presented in Figure 10.
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10
11 401 The tectonothermal evolution of the Indo-Myanmar Tethyan ophiolite belt is poorly
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14 402 understood owing to a lack of integrated thermobarometry and geochronology. Here, we have
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16 403 combined microstructurally constrained U–Pb data with P – T conditions calculated for peak
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18 404 and retrograde metamorphism in order to constrain the exhumation history of the Nagaland
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20 405 region of this ophiolite complex (Figure 11). The investigated samples show considerable
21
22 406 microstructural variation, ranging from largely undeformed (N5 and 14) to sheared (11, 3b,
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24 407 7c, and 13). The contrasting textures and ages of the studied rocks, together with reported
25
26 408 metamorphic recrystallizations ages in the adjoining ophiolite belts in Myanmar (Shi *et al.*
27
28 409 2008; Yui *et al.* 2013; Liu *et al.* 2016) suggest that the terrain has undergone several
29
30 410 metamorphic events. In terms of texture, the blueschist facies rocks (N5 and 14) do not show
31
32 411 any obvious preferred orientation that they were formed predominantly under near-
33
34 412 hydrostatic conditions, without apparent shear deformation. By contrast, the sheared samples
35
36 413 record deformation and post-tectonic (annealing) recrystallization, as the constituent minerals
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38 414 display preferred orientation, bending, and curving.
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44 415 Mineral assemblages in the unsheared samples N5 and 14 constrain peak P – T
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46 416 conditions of subduction-zone metamorphism to ~ 1.8 – 2.0 GPa and ~ 420 – 560 °C, with the
47
48 417 calculated proportions and compositions of major minerals matching observed values at ~ 1.9
49
50 418 GPa and ~ 480 – 520 °C (Figure 6).
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53 419 By contrast, the observed mineral assemblage in sheared (sample 7c) was calculated to
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55 420 be stable at notably lower P – T conditions of ~ 0.2 – 0.6 GPa and ~ 420 – 490 °C, with observed
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57 421 and calculated mineral proportions and compositions matching best at ~ 0.6 GPa and ~ 470 °C.
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59 422 The calculated peak metamorphic conditions for the unsheared samples agree with P – T
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3 423 conditions previously reported for the area (Chatterjee and Ghose 2010). The P – T conditions
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5 424 are far-removed from the slab-top range for modern-day subduction reported by Syracuse *et*
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7 425 *al.* (2010). The calculated pressures of ~ 1.9 GPa for peak metamorphism and ~ 0.6 GPa for
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9 426 retrograde equilibration are approximately equivalent to depths of 60 km and 15 km,
10
11 427 respectively, assuming no significant tectonic overpressure. In Figure 10, the P – T path
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13 428 calculated here is compared with published examples for other blueschist samples from the
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15 429 Naga ophiolites and other studies with thermal models of the global active subduction zones
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17 430 (Syracuse *et al.* 2010).
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22 431 The age of the high- P metamorphic event is crucial to the reconstruction of the geological
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24 432 history of this little-known terrain; however, reliable metamorphic age data has been lacking,
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26 433 and ages for the Nagaland ophiolite are poorly resolved whereas it is not so in the Eastern Belt.
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28 434 We have integrated our new age and P – T data into a revised tectonic model for the evolution
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30 435 of the Naga ophiolite belt, as shown in Figure 12. Only one whole-rock K–Ar isotopic age of
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32 436 148 ± 4 Ma (Upper Jurassic) has been reported from a volcanic rock in this area (Sarkar *et al.*
33
34 437 1996), which is supported by a radiolarian age (Baxter *et al.* 2011), whereas recently, a younger
35
36 438 U–Pb zircon age of 115 Ma (Lower Cretaceous) has been reported from a plagiogranite (Singh
37
38 439 *et al.* 2017). Based on the available geochronological and radiolarian ages, the formation age
39
40 440 of the Nagaland ophiolite crust thus likely ranges between Early Cretaceous (Liu *et al.* 2016;
41
42 441 our unpublished data) and Late Jurassic (Figure 12a). Past plate reconstructions during this
43
44 442 period suggest that early subduction off the coast of Myanmar dipped to the west during the
45
46 443 Jurassic, but there was a reversal in polarity immediately prior to the Early Cretaceous (Figure
47
48 444 12b; Bhowmik and Ao, 2015). This reversal caused the proto-Nagaland ophiolite complex
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50 445 oceanic crust to experience subduction along an eastern-dipping convergent margin during the
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52 446 Early Cretaceous, with U–Pb ages of the blueschist associated with the Nagaland ophiolite
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3 447 suggesting that peak high-pressure metamorphism was reached at around this time (Figure
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5 448 12c).

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7 449 Utilizing the integrated petrologically constrained *in situ* ages and thermobarometry
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9
10 450 shows that the unsheared sample 14 yielded a U–Pb age of 95.3 Ma while sheared samples
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12 451 yielded ages ranging between 93.7 Ma (sample 11) and 88.8 Ma (sample 13) Ma, illustrating
13
14 452 an age difference between the sheared and unsheared samples. This suggests that the
15
16 453 Mesozoic ophiolite underwent *HP–LT* subduction-related metamorphism c. 95 Ma and that
17
18 454 exhumation was a continuous process that lasted until c. 89 Ma (Figure 12d). This age range
19
20 455 is in agreement with the Guillot *et al.* (2008)’s *HP* metamorphic age inferred from K–Ar
21
22 456 whole rock and mineral (phengite, glaucophane) ages of 100 to 80 Ma for the western
23
24 457 Himalayan Tethyan ophiolites. Based on a zircon isotopic study, an older age of 115 Ma has
25
26 458 been reported from the garnetiferous amphibolite of the adjoining Myanmar ophiolite (Liu *et*
27
28 459 *al.* 2016). However, no petrological information was presented, making it hard to evaluate the
29
30 460 significance of this age. As a consequence, it is unclear whether the available ages record a
31
32 461 prolonged emplacement event, discrete metamorphic events or if the older amphibolite
33
34 462 represents remnants of metamorphic sole of the ophiolite belt. Although the unsheared
35
36 463 sample dataset is within uncertainty of the sheared sample dates, an overall age progression is
37
38 464 evident from the studied sheared and unsheared samples. Based on the combined U–Pb age
39
40 465 dataset and the calculated *P–T* regime, it can be inferred that the Nagaland blueschist rocks
41
42 466 were exhumed at a rate of ~1 cm/year (~45 km in 5 Ma), which is in the order of rates of
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44 467 plate tectonic processes on the Phanerozoic Earth. However, exhumation along the slab
45
46 468 interface would imply overall faster transport rates to achieve this vertical rate.

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49 469 U–Pb dating of low-uranium minerals such as calcite, prehnite, epidote, amphibole at
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51 470 small scale is a new and promising geochronological method. In the present study, we
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53 471 focussed on both carbonate and other cogenetic silicate phases such as prehnite, epidote,
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3 472 amphibole etc. formed at the same time and the isotopic systems seem to be closed since the
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5 473 metamorphic event. The reported age uncertainty could be improved by using well
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7 474 characterised specific with less scatter age and matrix matched standards (e.g., carbonate
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9 475 minerals normalisation of Pb–Pb isotope is currently achieved using a synthetic glass other
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11 476 than a carbonate, Roberts et al. 2020) reference materials (both carbonate and silicate phases)
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13
14 477 Although the behaviour of uranium in carbonates that have undergone high *P*/low *T* is not
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16 478 clear because of the lack of studies in natural and synthetic systems, our study suggest that
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18 479 the U–Pb systematics of carbonate can withstand temperatures up to 500 °C without
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20 480 resetting. These data thus encourage the ongoing development of in-situ dating of carbonates
21
22 481 and low uranium silicate minerals as a tool to understand the rates and ages of tectonic
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24 482 processes.
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30 484 **Acknowledgements**

31
32
33 485 BM began this work during his visits to JGU Mainz on a BOYSCAST Fellowship and
34
35 486 continued during the INSA-DFG Exchange programme visit to Bonn. BM thanks the Council
36
37 487 of Scientific and Industrial Research, Government of India for financial support in the form
38
39 488 of a project. Sample processing equipment were procured under a Department of Science and
40
41 489 Technology, Government of India FIST program. This is FIERCE contribution XX. BM
42
43 490 acknowledges Yhunyulo Tep for the help during the field work. Lorenzo Fedele (Napoli) and
44
45 491 four anonymous journal reviewers are appreciated for their insightful comments.
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49 492

50 51 493 **References**

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12 693 **Figure captions**

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14 694 Figure 1. (A) Regional geological map of Indo-Myanmar Range and part of Myanmar (after
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16 695 Acharyya 2015). (B) Geological map of the Indo-Myanmar ophiolite belt (after Geological
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18 696 Survey of India M.N.C. DRG No. 42/87) (C) Geological map of the Nagaland ophiolite belt
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20 697 showing sample locations (after Anon. 1986, Ao and Bhowmick, 2016). (D) Field
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22 698 photographs (1) Unfoliated/Unsheared sample occur as boulders. Person for reference. (2)
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24 699 Unsheared sample showing the slicken sided face, chisel is for reference. (3) Blueschist
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26 700 samples present as blocky boulders. (4) Sheared sample showing foliation on a freshly broken
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28 701 face. Pen shows the foliation trend.
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33 703 Figure 2. Thin-section photomicrographs showing representative mineral assemblages and
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35 704 microstructures for undeformed samples N5 (a–b) and 14 (c–d). All thin section images are
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37 705 shown under plane-polarized light. Scale bar is 1 mm. (a–b) Glaucophane- and epidote-rich
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39 706 matrix in sample N5, with minor garnet porphyroblasts associated with quartz and muscovite.
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41 707 (c) Small millimetre-scale garnet in sample 14 mostly occurs in quartz-rich domains that are
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43 708 relatively epidote- and barroisite-poor. (d) Barroisite grains enclose epidote crystals. Mineral
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45 709 use in 2(a) Gln – Glaucophane, Grt – Garnet, Ep – Epidote, Ms – Muscovite. 2(b) Gln –
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47 710 Glaucophane, Grt – Garnet, Ep – Epidote, Ms – Muscovite, Qtz – quartz, 2(c) Brs –
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49 711 Barroisite, Carb – Carbonate, Grt – Garnet, Ep – Epidote. 2(d) Brs – Barroisite, Ep – Epidote,
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51 712 Ms – Muscovite, Qtz – quartz, Ttn – Titanite.
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3 714 Figure 3. Thin-section photomicrographs showing representative mineral assemblages and
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5 715 microstructures in sheared samples 7c (a–b) and 11 (c–f). All thin section images are shown
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7 716 under plane-polarized light (unless stated otherwise) and oriented perpendicular to the
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9 717 dominant metamorphic foliation. Scale bar is 1 mm. (a) The metamorphic foliation in sample
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11 718 7c is defined by aligned crystals of epidote, sodic-calcic amphibole, and calcic amphibole, (b)
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13 719 and is crosscut by quartz- and carbonate-filled veins that also cause localized deflections at
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15 720 their intersections. Sample 11 contains olive-green aegirine–augite (c) and garnet (d)
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17 721 porphyroblasts that are wrapped by a glaucophane–magnesioriebeckite foliation defined by
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19 722 alternating glaucophane- and quartz-rich bands. Sheared veins filled with carbonate (e) and
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21 723 quartz (f) exhibit ductile deformation microstructures and dynamic recrystallization. Mineral
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23 724 abbreviation use in Figure 3(a) Brs – Wnc: Barroisite – Winchite, Ep – Epidote, Prg – Ed:
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25 725 Pargsite – Edinite, Ttn: Titanite, Figure 3(b) Qtz – Quartz, Carb – Carbonate, Brs –
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27 726 Barroisite, Wnc – Winchite, Ep – Epidote, Ms – Muscovite, Kfs – K-feldspar, Ab – Albite,
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29 727 3(c) Agt – Aegirine augite, Gln: Glaucophane, Fgl – Ferroglacuphane, Grt – Garnet, Qtz –
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31 728 Quartz, Ms – Muscovite, Figure 3(d) Alb – Albite, Carb – Carbonate, Gln – Glaucophane,
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33 729 Fgl – Ferroglaucophane, Quartz – Quartz, Figure 3(e) Carb – Carbonate, Ms – Muscovite,
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35 730 Qtz – Quartz, Figure 3(f) Carb – Carbonate, Qtz – Quartz.
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45 732 Figure 4. Compositional line profile for a garnet porphyroblast of from the unshered sample
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47 733 N5, running from rim to rim (~0.75 mm diameter). (a) Cation mole fractions of divalent
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49 734 cations. (b) X-ray compositional map of divalent cations showing relative concentrations
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51 735 from core to rim. Colours do not represent equivalent cation concentrations between images.
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56 737 Figure 5. Compositions of amphiboles from all studied samples, classified according to the
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58 738 classification scheme of Hawthorne *et al.* (2012). Discrimination between calcic (group 2),
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3 739 calcic-sodic (group 3), and sodic (group 4) amphiboles is based upon the Na content of the
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5 740 M4 crystallographic site, with the ranges <0.5, 0.5–1.5, and >1.5, respectively for a 23-
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7 741 oxygen recalculation. Representative compositions are given in Supplementary Table 2.
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12 743 Figure 6. Results of mineral equilibria modelling for unshheard sample N5. (a) Pressure–
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14 744 temperature (P – T) pseudosection constructed for the bulk composition given in
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16 745 Supplementary Table 3. Dotted overlay represents the global range of P – T conditions
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18 746 modelled to occur at the surface of subducting ocean crust in present-day subduction zones
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20 747 (Syracuse *et al.* 2010). Gray star and associated dashed ellipses represent the results of avPT
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22 748 calculations (Supplementary Table 4) and are shown at 1 and 2 S.D. Bold line marks the
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24 749 extent of H₂O-bearing assemblage fields. Numbered fields are as follows: 1 – Grt Ms Cld Tlc
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26 750 Omp, 2 – Grt Ms Cld Tlc Omp Gln, 3 – Grt Ms Cld Tlc Omp Gln Lws, 4 – Grt Ms Cld Tlc
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28 751 Omp Ky Lws, 5 – Grt Ms Act Cld Tlc Ky Lws, 6 – Grt Ms Bt Cld Act Gln, 7 – Grt Chl Bt
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30 752 Cld Act Gln, 8 – Grt Bt Act Gln Mag, 9 – Grt Bt Chl Hbl Gln, 10 – Bt Omp Hbl Pl H₂O, 11 –
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32 753 Bt Omp Hbl Pl Ab H₂O, 12 – Grt Ms Omp Hbl H₂O, 13 – Grt Ms Gln H₂O, 14 – Grt Chl Ms
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34 754 Omp Gln, 15 – Grt Chl Ms Brs Gln, 16 – Grt Chl Ms Omp Gln Lws, 17 – Grt Ms Cld Omp
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36 755 Gln Lws. Some small, minor fields are unlabelled for clarity. (b) Interpreted peak assemblage
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38 756 field showing isolines of modal proportions of selected phases. Red star indicates the best
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40 757 match between observed and calculated mineral abundances. Dashed line labelled XNaM₄Act
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42 758 = 0.25 marks the division between actinolite (<0.25) at low- T and barroisite (>0.25) at high-
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44 759 T . (c) Bar chart showing degree of correlation between observed volume proportions (%) of
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46 760 minerals and calculated proportions at 1.9 GPa and 485 °C (red star in b).
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56 762 Figure 7. Results of mineral equilibria modelling for unshheard sample 14. (a) Pressure–
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58 763 temperature (P – T) pseudosection constructed for the bulk composition given in
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3 764 Supplementary Table 3. Dotted overlay represents the global range of P – T conditions
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5 765 modelled to occur at the surface of subducting ocean crust in present-day subduction zones
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7 766 (Syracuse *et al.* 2010). Gray star and associated dashed ellipses represent the results of avPT
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9 767 calculations (Supplementary Table 4) and are shown at 1 and 2 S.D. Bold line marks the
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11 768 extent of H₂O-bearing assemblage fields. Numbered fields are as follows: 1 – Grt Ms Pg
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13 769 Omp Act Gln, 2 – Grt Ms Bt Omp Act Gln, 3 – Grt Bt Omp Act Gln Ab, 4 – Grt Bt Omp Act
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15 770 Gln Ilm Mag Ab (–Rt), 5 – Grt Bt Omp Act Gln Mag Ab (–Rt), 6 – Grt Bt Omp Brs Gln
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17 771 Mag, 7 – Bt Omp Brs Gln Hbl Mag, 8 – Grt Bt Omp Brs Hbl, 9 – Bt Di Brs Hbl H₂O, 10 – Bt
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19 772 Di Hbl Ttn H₂O (–Rt), 11 – Bt Di Hbl, 12 – Grt Ms Bt Omp Act H₂O, 13 – Grt Ms Tlc Omp
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21 773 Act H₂O, 14 – Grt Ms Tlc Omp H₂O, 15 – Grt Ms Tlc Omp Brs Lws, 16 – Grt Chl Ms Omp
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23 774 Brs, 17 – GrtChl Ms Omp Brs H₂O. Some small, minor fields are unlabelled for clarity. (b)
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25 775 Red star indicates the best match between observed and calculated mineral abundances.
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27 776 Interpreted peak assemblage field showing isolines of modal proportions of selected phases.
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29 777 Dashed line labelled XNaM₄Act = 0.25 marks the division between actinolite (<0.25) at low-
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31 778 T and barroisite (>0.25) at high-T. (c) Bar chart showing degree of correlation between
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33 779 observed volume proportions (%) of minerals and calculated proportions at 2.0 GPa and 525
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35 780 °C (red star in part b).
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45 782 Figure 8. Results of phase equilibria modelling for sheared sample 7c. (a) Pressure–
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47 783 temperature (P – T) pseudosection constructed for the bulk composition given in
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49 784 Supplementary Table 3. Dotted overlay represents the global range of P – T conditions
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51 785 modelled to occur at the surface of subducting ocean crust in present-day subduction zones
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53 786 (Syracuse *et al.* 2010). Gray star and associated dashed ellipses represent the results of avPT
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55 787 calculations (Table 4) and are shown at 1 and 2 S.D. Bold line marks the extent of H₂O-
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57 788 bearing assemblage fields. Numbered fields are as follows: 1 – Omp Act Gln Mag Rt Hem (–
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3 789 Ttn), 2 – Omp Act Gln Mag Rt, 3 – Omp Act Gln Mag, 4 – Omp Act Gln Mag Ab, 5 – Act
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5 790 Gln Mag Ab, 6 – Omp Act Hbl Gln Mag Rt (–Ttn), 7 – Omp Act Hbl Gln Ab, 8 – Act Hbl
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7 791 Gln Mag Ab, 9 – Chl Act Hbl Mag Ab, 10 – Chl Act Hbl Ab H₂O, 11 – BrsHbl Ab, 12 –
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10 792 Omp Act Hbl Ab, 13 – Di Act Hbl Ab H₂O, 14 – Di Hbl Ab H₂O, 15 – Di Act Hbl Pl, 16 –
11
12 793 Di Hbl Pl Mag Hem (–Ttn, Ep), 17 – Omp Act Hbl Gln Rt Hem (–Ttn), 18 – Omp Brs Hbl
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14 794 Gln Rt Hem (–Ttn), 19 – Omp Brs Hbl Gln Rt (–Ttn), 20 – Omp Act Hbl Gln Rt (–Ttn), 21 –
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16 795 Omp Brs Hbl Gln, 22 – Omp Act Hbl Gln, 23 – Omp Brs Gln Rt Hem (–Ttn), 24 – Omp Act
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18 796 Hem (–Ttn), 25 – Omp Act (–Ttn). Some small, minor fields are unlabelled for clarity. (b)
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20 797 Red star indicates the best match between observed and calculated mineral abundances.
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22 798 Interpreted peak assemblage field showing isolines of modal proportions of selected phases.
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24 799 Dashed line labelled $X_{\text{NaM}_4\text{Act}} = 0.25$ marks the division between actinolite (<0.25) at low-
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26 800 T and barrosite (>0.25) at high-T. (c) Bar chart showing degree of correlation between
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28 801 observed volume proportions (%) of minerals and calculated proportions at 0.6 GPa and 465
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30 802 °C (red star in b).
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804 Figure 9. Isochrons for all dated samples. A: Unsheared sample 14. B: Sheared sample 11. C:
805 Sheared sample 3b. D: Sheared sample 13. All ellipses are shown at the 2σ confidence
806 interval and n = number of analyses.
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808 Figure 10. Representative back scattered electron images of analysed samples 14 (a), 11 (b),
809 3b (c) and 13 (d). U–Pb analysed spots are showing in ellipse (white: silicate phases and
810 yellow: carbonates).
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812 Figure 11. Pressure–temperature diagram summarizing the proposed model for the
813 tectonometamorphic evolution of blueschist-facies rocks from the Nagaland ophiolite
814 complex. Red boxes represent calculated conditions of metamorphism and thick grey arrow

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3 815 represents the interpreted P – T – t evolution. Paths for Nagaland blueschists reported by
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5 816 Chatterjee and Ghose (2010) and Ao and Bhowmik (2014) are shown (CG10 and AB14,
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7 817 respectively) for comparison. Aragonite-calcite stability curve is from Johannes and Puhan
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9 818 (1971).
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15 820 Figure 12. Schematic tectonic model for formation and exhumation of the Nagaland ophiolite
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17 821 belt and its metamorphic suite. (a) Westward-dipping subduction away from Myanmar during
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19 822 the Jurassic, with future Nagaland ophiolite belt oceanic crust on the overlying plate. (b)
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21 823 Reversal in the subduction dip direction prior to the Early Cretaceous, leading to burial of
22
23 824 future Nagaland ophiolitic crust and mantle. (c) Peak metamorphism of the studied samples
24
25 825 was achieved during the Middle Cretaceous, with (d) slab break-off and buoyancy-driven
26
27 826 exhumation and associated shearing of these units during the Middle to Late Cretaceous. (e)
28
29 827 the final configuration of the Indo-Myanmar plates and suture zone between following
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31 828 collisional orogenesis (modified after Khogenkumar *et al.* 2021). Yellow star indicates
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33 829 locations of the studied samples during metamorphism and deformation.
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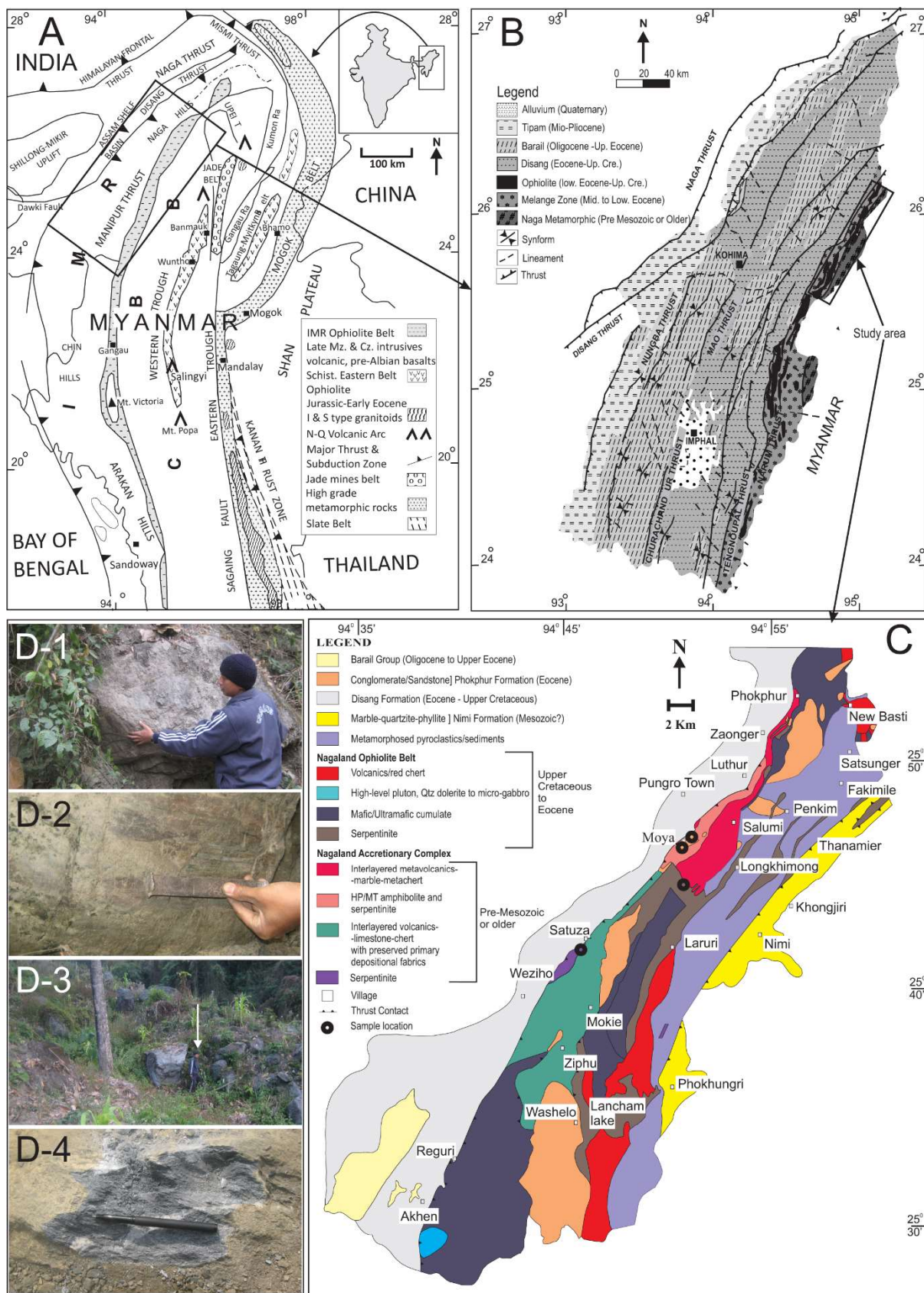


Fig. 1

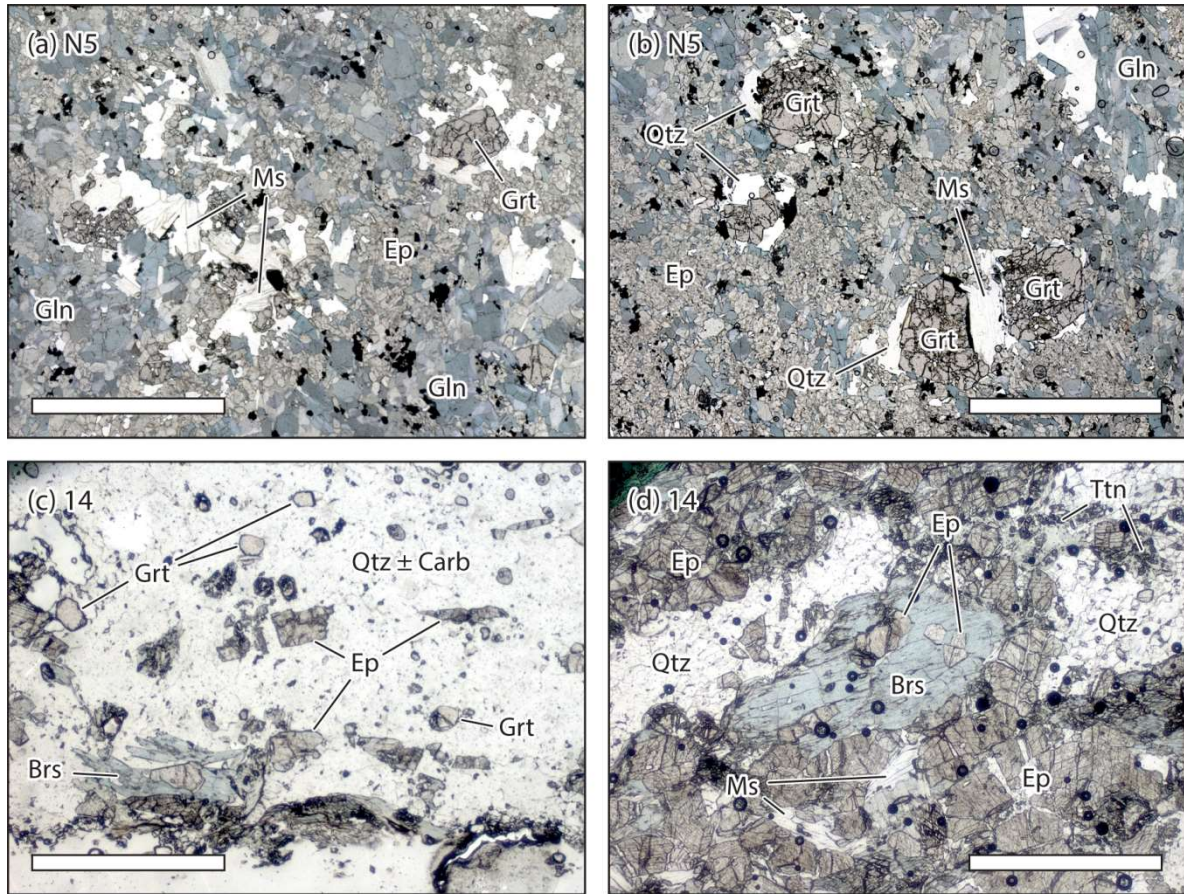


Fig. 2

Review Only

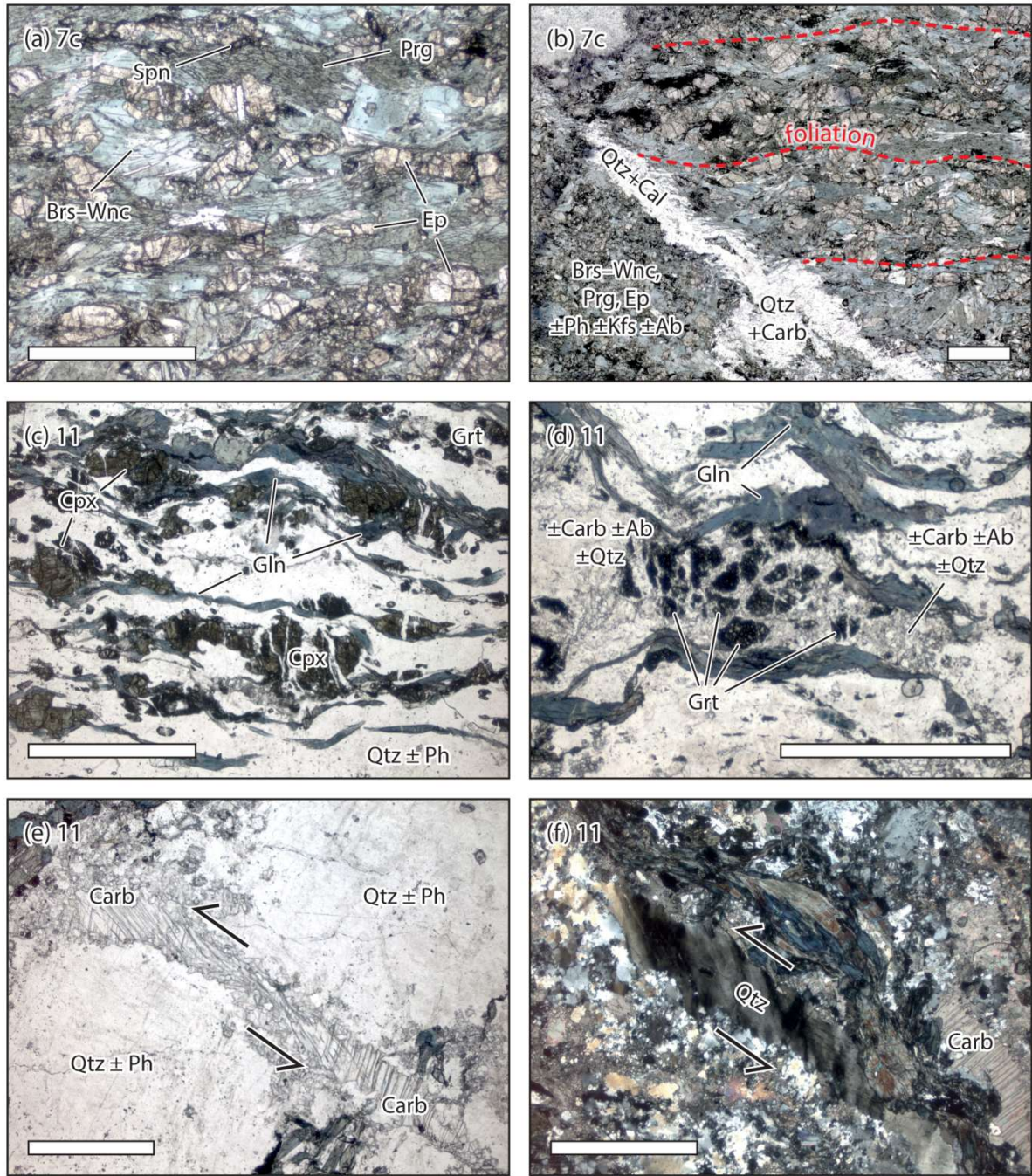
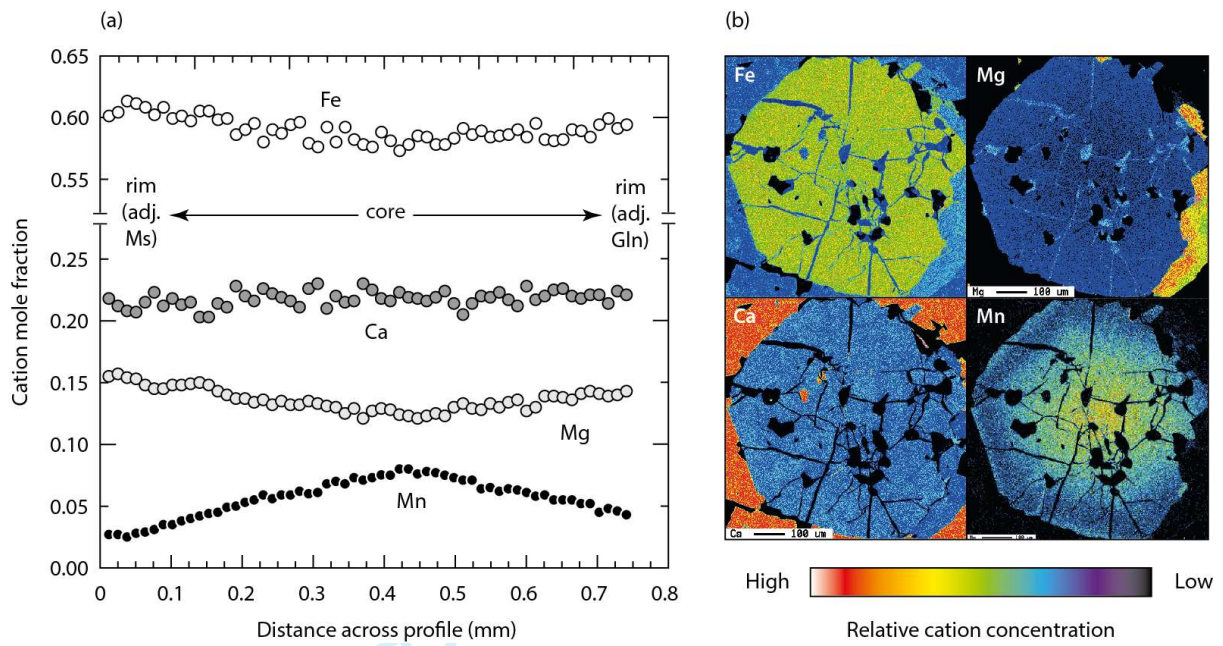


Fig. 3

**Fig. 4**

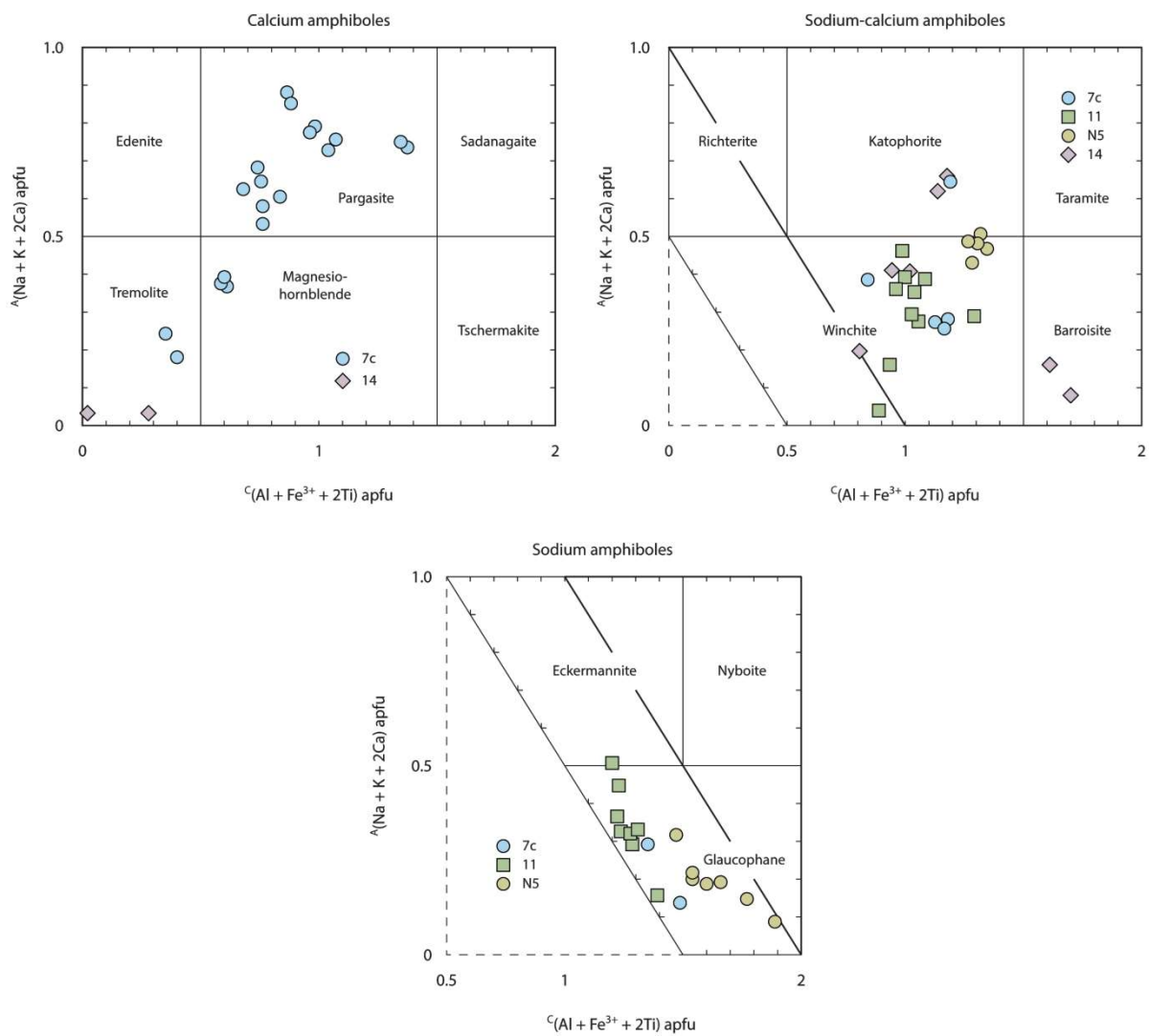


Fig. 5

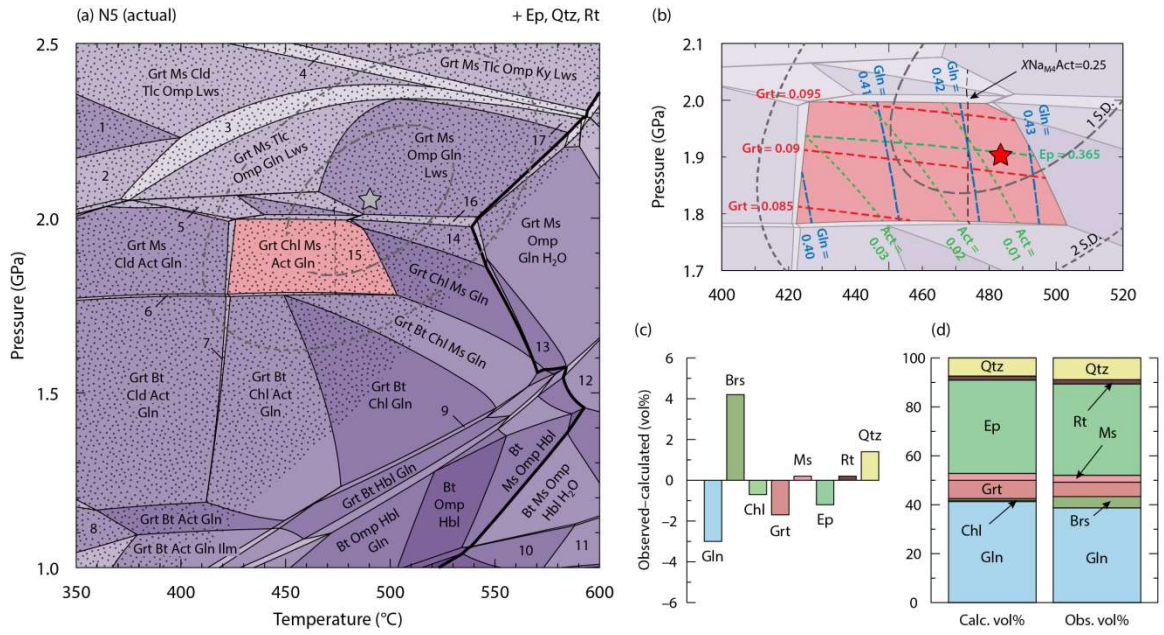


Fig. 6

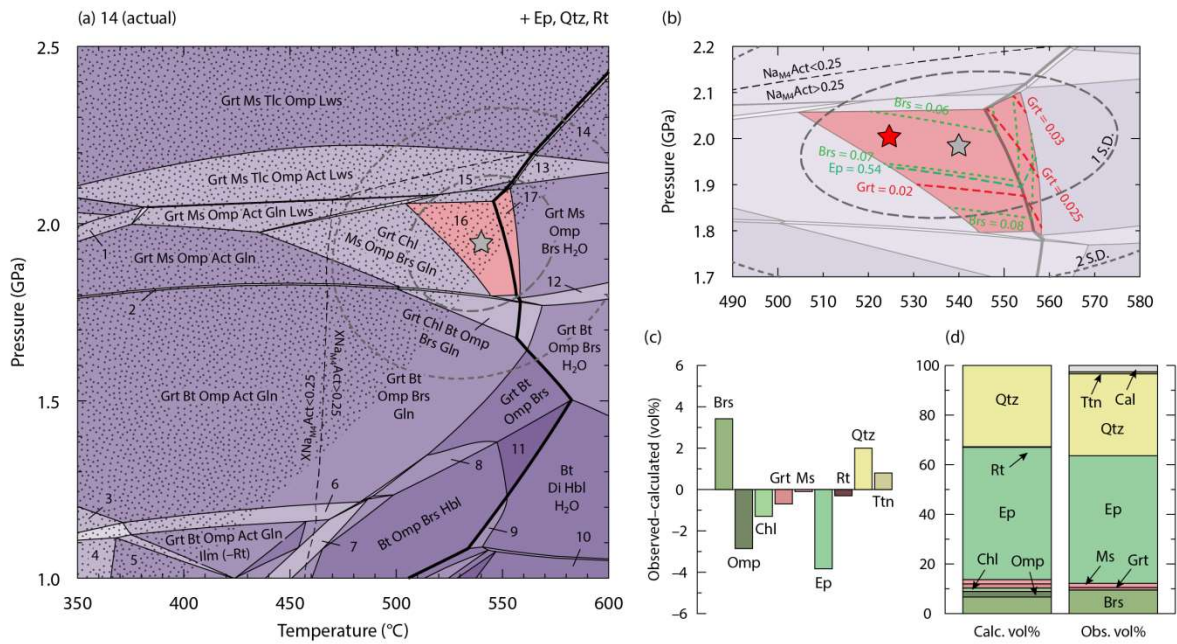


Fig. 7

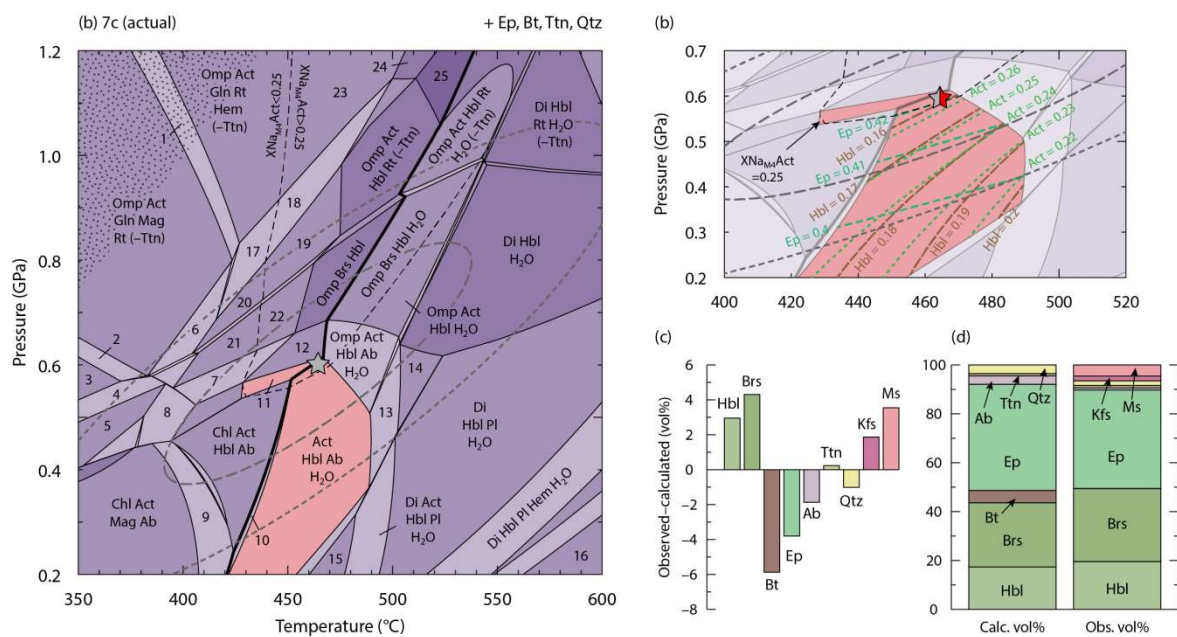


Fig. 8

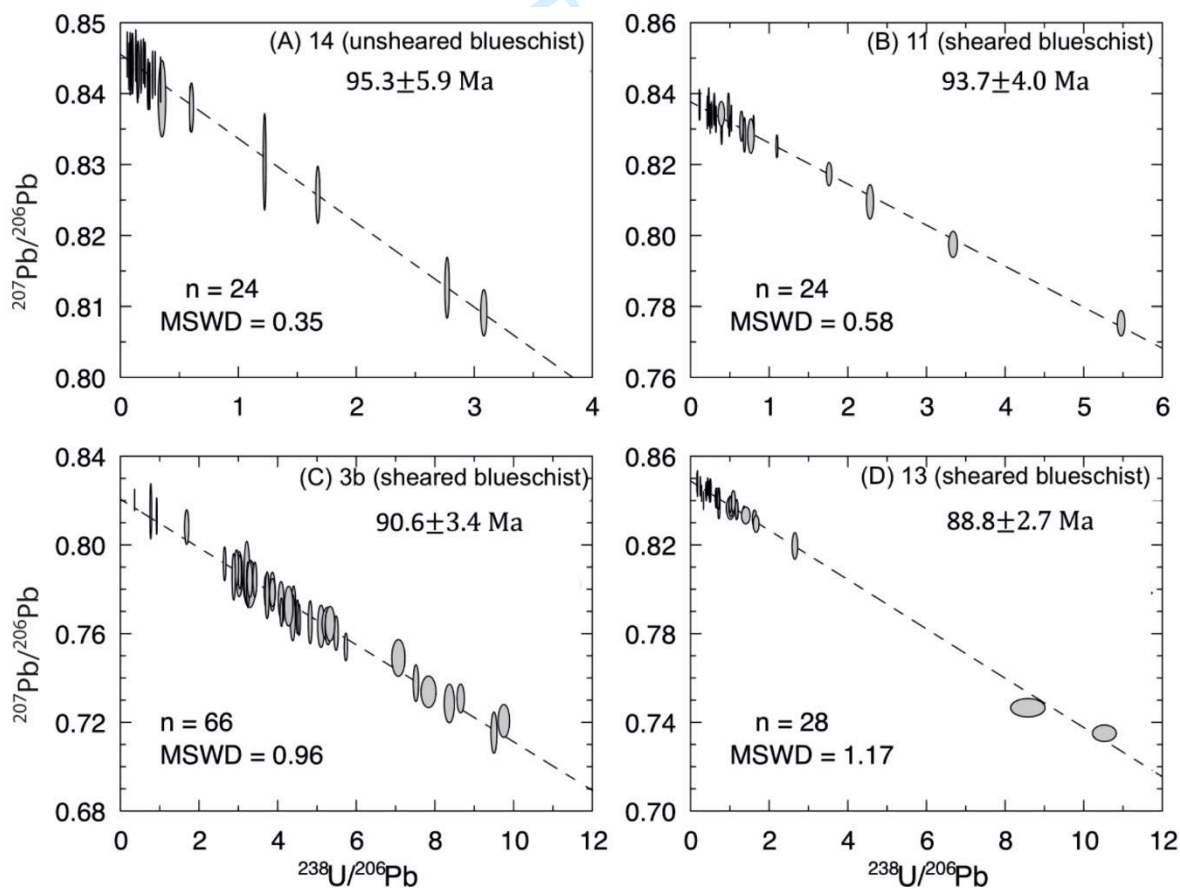


Fig. 9

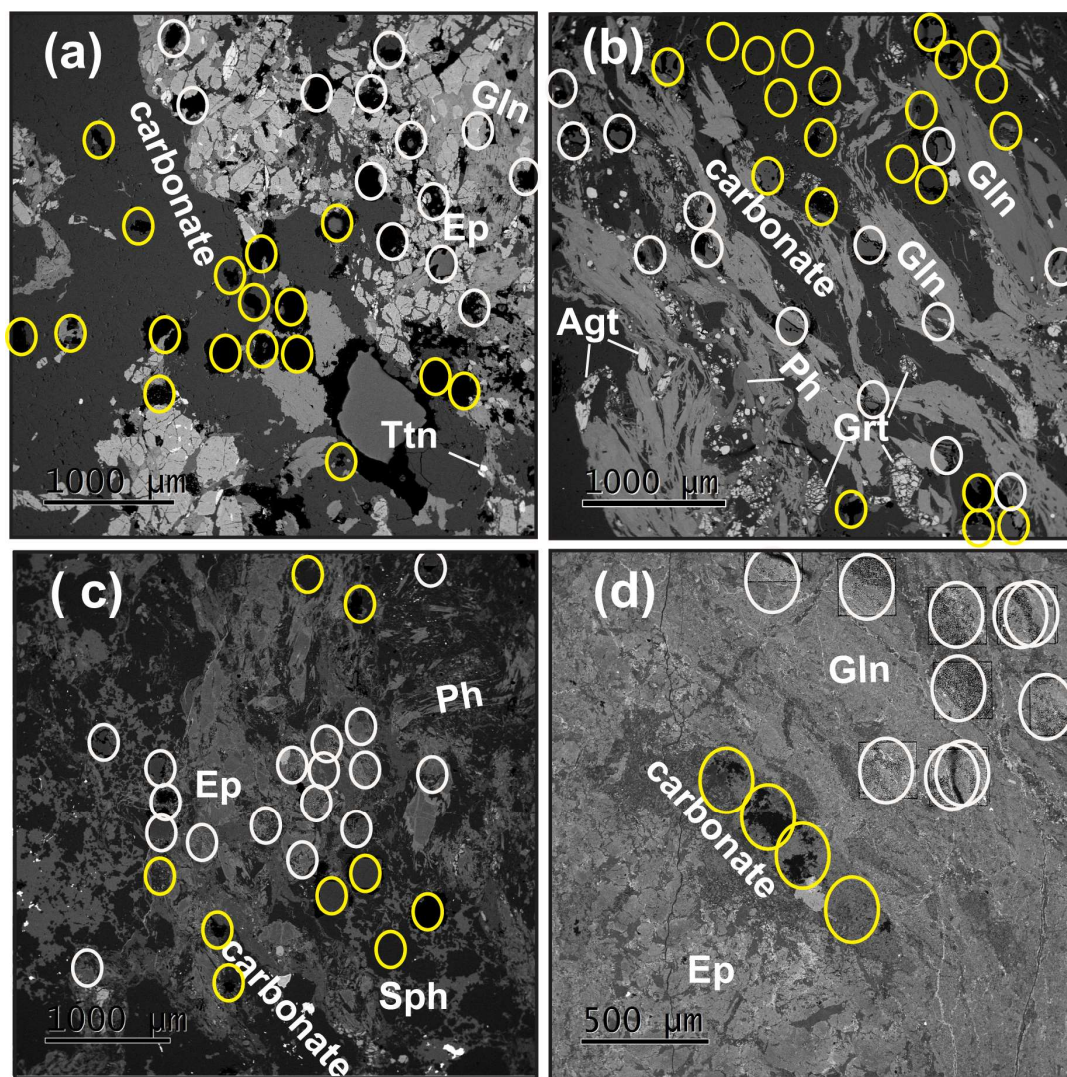


Fig. 10

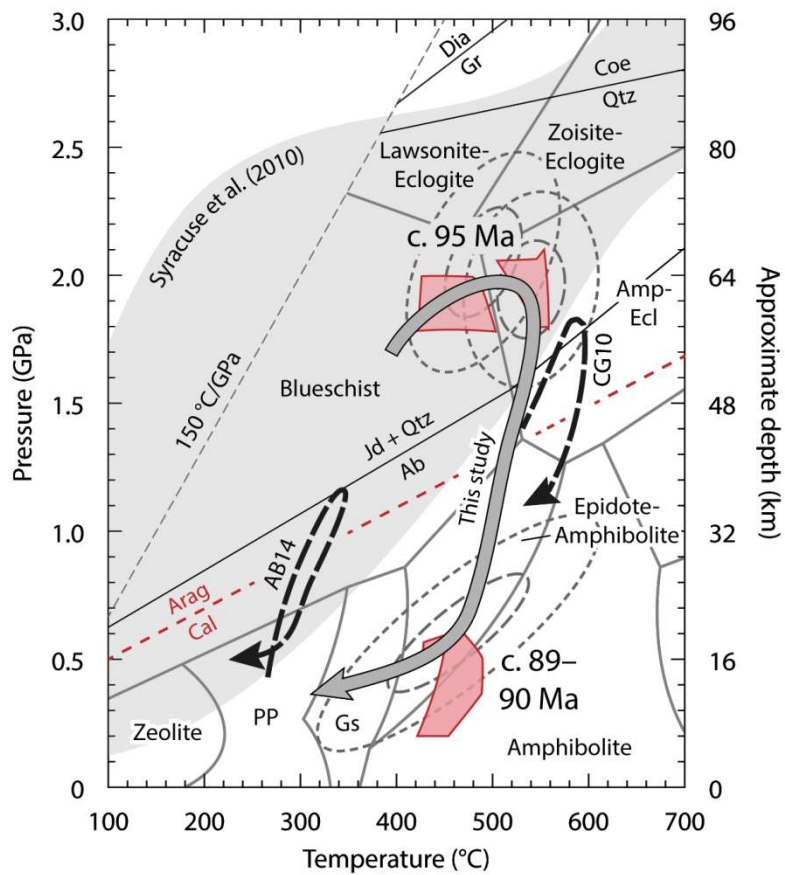


Fig. 11

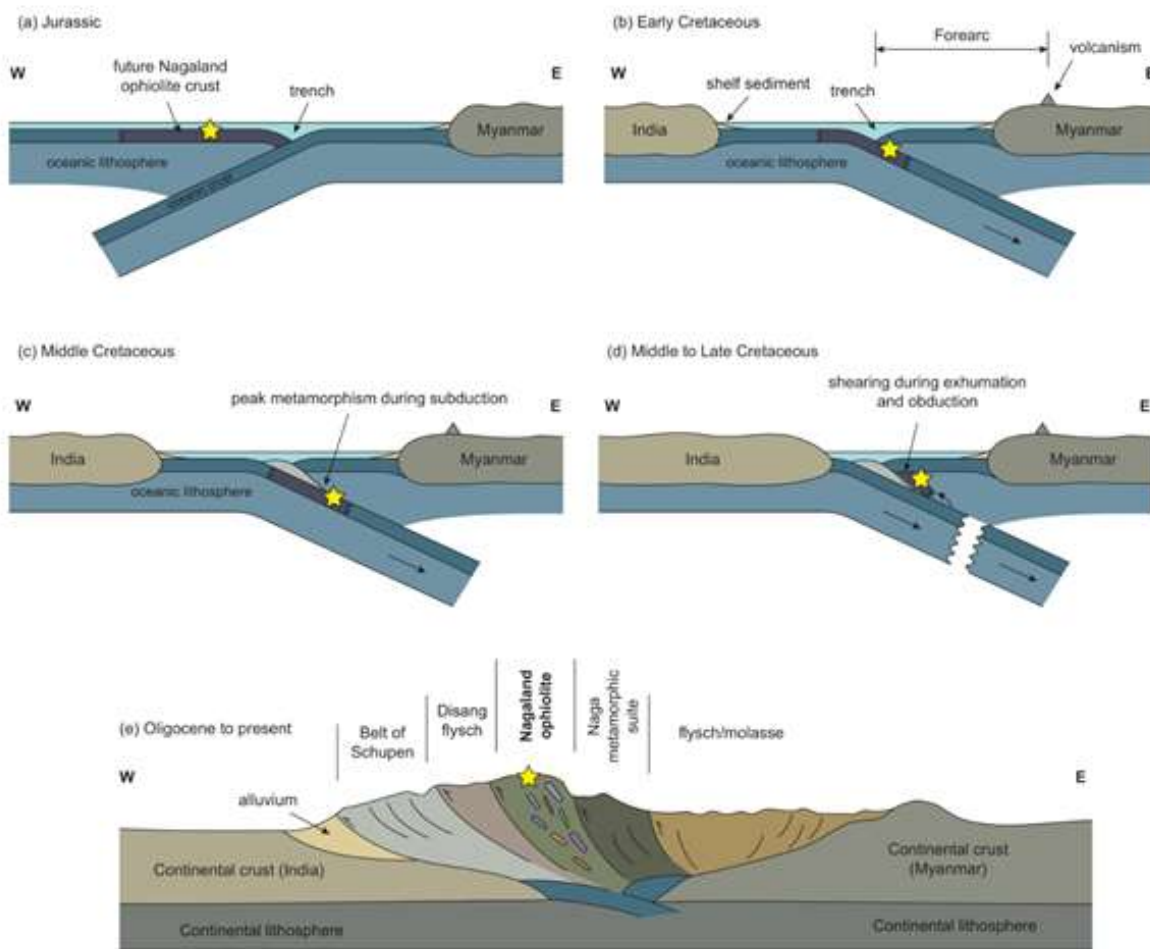


Fig. 12

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3 1 **SUPPLEMENTARY INFORMATION for:**
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5 2 **Dating blueschist-facies metamorphism within the Naga ophiolite,**
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7 3 **Northeast India, using sheared carbonate veins**

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9 4
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34 17
35 18 **Contents:**

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37 19 Supplementary Tables 1-5

38
39 20
40 21 **Extended sample description**

41
42 22 GPS coordinates for each sample are given in Supplementary Table 1. These samples can be
43
44 23 divided into sheared and unsheared units. Major-element mineral compositional data were
45
46 24 obtained on a JEOL JXA-8200 electron microprobe at the Institute of Geosciences, Johannes
47
48 25 Gutenberg University of Mainz, Germany. Operating conditions included an acceleration
49
50 26 voltage of 15 kV, a beam current of 12 nA, and a 2- μ m spot size. A matrix correction for atomic
51
52 27 number, absorption, and fluorescence was automatically applied to all analyses. For the data
53
54 28 presented below, mineral compositions were recalculated to a standard number of oxygens per
55
56 29 formula unit (pfu), with H₂O assumed to be present in stoichiometric amounts. Where
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58 30 stoichiometric criteria could be applied, the proportion of ferric iron was calculated using the
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60 31 software AX (Holland, 2009). Representative compositions of major minerals for all samples
32 are given in Supplementary Table 2. Mineral abbreviations are after Kretz (1983).

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Supplementary Table 1. Lithological descriptions and GPS co-ordinates for all studied samples.

Superscript numbers denote whether samples were used for thermobarometry (1) or geochronology (2).

Sample	Lithology	Northing	Easting	Locality
N5 ¹	Unsheared blueschist			Near Satuza
14 ^{1,2}	Unsheared blueschist	25°46'02.8"	94°51'03.6"	Moya
7c ¹	Sheared blueschist with cross-cutting carbonate veins	25°36'56.3"	94°51'39.8"	Moya
13 ²	Sheared blueschist	25°46'06.6"	94°51'26.4"	Moya
3b ²	Sheared blueschist	25°49'19.0"	94°54'58.9"	Luthur-Salomi
11 ^{1,2}	Sheared blueschist with cross-cutting carbonate veins	25°45'25.4"	94°52'16.7"	Salomi-Longkhimong

Supplementary Table 2. Representative mineral compositions.

Sample	N5 (Unsheared)							14 (Unsheared)						
Mineral	Gln	Ep	Brs	Ms	Rt	Grt	Grt	Brs	Cal	Ep	Grt	Ms	Chl	Ttn
Location	Matrix	Matrix	Matrix	Matrix	Matrix	Core	Rim	Matrix	Vein	Matrix	Pblast	Matrix	Matrix	Matrix
<u>Weight %</u>														
SiO ₂	56.99	38.32	48.82	50.30	0.03	38.65	38.03	50.55	0.04	38.31	38.44	49.16	28.76	30.67
TiO ₂	0.03	0.06	0.31	0.31	99.21	0.10	0.10	0.37	0.00	0.21	0.07	0.48	0.01	37.92
Al ₂ O ₃	7.74	25.28	10.87	27.78	0.03	21.55	21.90	7.58	0.04	25.01	20.89	26.30	17.26	1.16
Fe ₂ O ₃	3.84	9.68	2.30	0.54	0.00	0.03	0.08	2.94	0.00	10.65	1.66	1.51	0.00	0.00
FeO	10.06	0.61	11.27	2.60	0.87	26.63	27.83	11.11	0.09	0.00	17.44	2.11	20.86	0.49
MnO	0.18	0.03	0.15	0.03	0.01	3.62	1.25	0.55	0.67	0.19	7.25	0.02	0.45	0.13
MgO	10.80	0.08	11.76	3.32	0.03	3.17	3.92	12.92	0.03	0.02	3.44	3.56	19.57	0.00
CaO	1.29	23.40	7.72	0.00	0.02	7.88	7.37	8.17	62.13	23.30	11.79	0.00	0.03	28.37
Na ₂ O	6.89	0.02	4.17	0.68	0.00	0.06	0.00	3.42	0.07	0.03	0.00	0.44	0.00	0.06
K ₂ O	0.01	0.00	0.37	10.32	0.00	0.00	0.02	0.66	0.00	0.00	0.00	10.38	0.04	0.00
Total	97.85	97.53	97.74	96.05	100.27	101.73	100.52	98.38	63.12	97.79	101.04	94.10	87.07	98.85
<u>Cations per formula unit</u>														
Si	7.95	3.03	7.04	3.35	0.00	3.01	2.98	7.27	0.00	3.03	2.99	3.35	2.98	1.00
Ti	0.00	0.00	0.03	0.02	0.99	0.01	0.01	0.04	0.00	0.01	0.00	0.02	0.00	0.93
Al	1.27	2.36	1.85	2.18	0.00	1.98	2.02	1.29	0.00	2.33	1.92	2.11	2.11	0.04
Fe ³⁺	0.41	0.58	0.25	0.03	0.00	0.00	0.01	0.32	0.00	0.64	0.10	0.08	0.00	0.00
Fe ²⁺	1.17	0.04	1.36	0.14	0.01	1.73	1.82	1.34	0.00	0.00	1.14	0.12	1.81	0.01
Mn	0.02	0.00	0.02	0.00	0.00	0.24	0.08	0.07	0.02	0.01	0.48	0.00	0.04	0.00
Mg	2.25	0.01	2.53	0.33	0.00	0.37	0.46	2.77	0.00	0.00	0.40	0.36	3.02	0.00
Ca	0.19	1.98	1.19	0.00	0.00	0.66	0.62	1.26	1.97	1.97	0.98	0.00	0.00	1.00
Na	1.86	0.00	1.17	0.09	0.00	0.01	0.00	0.95	0.00	0.00	0.00	0.06	0.00	0.00
K	0.00	0.00	0.07	0.88	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.90	0.01	0.00
Sum	15.14	8.00	15.50	7.01	1.00	8.00	8.00	15.44	2.00	8.00	8.00	7.01	9.97	3.00
Oxygens	23	12.5	23	11	2	12	12	23	3	12.5	12	11	14	5
X _{Mg}	0.66	0.18	0.65	0.70	0.00	0.18	0.20	0.67	0.00	1.00	0.26	0.75	0.63	0.00

Supplementary Table 2 (Continued). Representative mineral compositions.

Sample	7c (sheared)									11						
	Ab	Mhb	Wnc	Cal	Ep	Ep	Kfs	Ms	Ttn	Agt	Ab	Mrbk	Wnc	Cal	Grt	Ms
Mineral	Vein	Matrix	Matrix	Vein	Core	Rim	Matrix	Matrix	Matrix	Pblast	Matrix	Core	Rim	Vein	Pblast	Matrix
Location	Vein	Matrix	Matrix	Vein	Core	Rim	Matrix	Matrix	Matrix	Pblast	Matrix	Core	Rim	Vein	Pblast	Matrix
<u>Weight %</u>																
SiO ₂	68.39	51.36	56.25	0.07	37.97	37.28	63.73	51.57	30.24	51.81	67.73	54.78	54.62	0.03	37.75	46.31
TiO ₂	0.00	0.07	0.01	0.00	0.26	0.06	0.00	0.27	38.14	0.13	0.00	0.02	0.08	0.00	0.07	0.39
Al ₂ O ₃	19.22	5.07	2.81	0.03	25.84	22.27	18.04	25.08	1.21	4.91	19.61	3.72	5.09	0.01	19.47	25.57
Fe ₂ O ₃	0.00	2.44	8.97	0.00	9.29	14.65	0.31	3.95	0.00	9.64	0.10	10.32	4.41	0.00	2.31	5.66
FeO	0.00	10.50	8.10	0.17	0.00	0.00	0.00	1.52	0.47	3.70	0.00	10.02	13.02	0.04	8.15	2.18
MnO	0.00	0.27	0.19	0.06	0.11	0.29	0.00	0.05	0.09	0.86	0.04	0.42	0.53	0.69	22.88	0.07
MgO	0.00	14.48	12.45	0.01	0.15	0.02	0.02	4.04	0.00	8.49	0.02	9.37	10.42	0.00	2.57	3.13
CaO	0.00	9.48	3.17	63.12	23.38	23.01	0.00	0.03	28.52	15.78	0.02	0.83	2.68	60.75	7.15	0.00
Na ₂ O	11.71	2.51	5.72	0.01	0.00	0.01	0.20	0.12	0.01	4.76	11.53	6.82	6.15	0.11	0.03	0.49
K ₂ O	0.02	0.43	0.03	0.02	0.00	0.02	16.02	8.53	0.00	0.03	0.04	0.04	0.05	0.00	0.00	10.36
Total	99.41	96.72	97.73	63.50	97.12	97.68	98.36	95.26	98.68	100.16	99.14	96.37	97.09	61.63	100.48	94.17
<u>Cations per formula unit</u>																
Si	3.00	7.47	7.98	0.00	3.00	2.99	3.00	3.43	0.99	1.93	2.98	7.98	7.90	0.00	3.01	3.22
Ti	0.00	0.01	0.00	0.00	0.02	0.00	0.00	0.01	0.94	0.00	0.00	0.00	0.01	0.00	0.00	0.02
Al	1.00	0.87	0.47	0.00	2.41	2.11	1.00	1.97	0.05	0.22	1.02	0.64	0.87	0.00	1.83	2.09
Fe ³⁺	0.00	0.27	0.96	0.00	0.57	0.89	0.01	0.20	0.00	0.27	0.00	1.07	0.48	0.00	0.14	0.30
Fe ²⁺	0.00	1.28	0.96	0.01	0.00	0.00	0.00	0.09	0.01	0.12	0.00	1.28	1.58	0.00	0.54	0.13
Mn	0.00	0.03	0.02	0.00	0.01	0.02	0.00	0.00	0.00	0.03	0.00	0.05	0.06	0.02	1.55	0.00
Mg	0.00	3.14	2.63	0.00	0.02	0.00	0.00	0.40	0.00	0.47	0.00	2.03	2.25	0.00	0.31	0.32
Ca	0.00	1.48	0.48	1.99	1.98	1.98	0.00	0.00	1.00	0.63	0.00	0.13	0.42	1.97	0.61	0.00
Na	1.00	0.71	1.57	0.00	0.00	0.00	0.02	0.02	0.00	0.34	0.99	1.93	1.72	0.01	0.00	0.07
K	0.00	0.08	0.01	0.00	0.00	0.00	0.97	0.72	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.92
Sum	5.00	15.34	15.09	2.00	8.00	8.00	5.00	6.84	3.00	4.00	5.00	15.13	15.29	2.00	8.00	7.06
Oxygens	8	23	23	3	12.5	12.5	8	11	5	6	8	23	23	3	12	11
X _{Mg}	0.00	0.71	0.73	0.00	1.00	1.00	1.00	0.82	0.00	0.80	1.00	0.61	0.59	0.00	0.36	0.72

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Supplementary Table 3. Results of AVPT calculations

Sample	Temperature (°C)*	Pressure (kbar)*	Cor [†]	Fit [§]	N [#]	Excluded end members
N5	489 ± 39	20.5 ± 2.2	0.22	1.53 (1.63)	8	spss, ru, fgl
14	541 ± 34	19.5 ± 1.8	0.15	1.20 (1.49)	7	spss, sph, fgl
7c	464 ± 76	6.0 ± 2.3	0.93	1.18 (1.61)	5	ep, sph, ab,
7c*	476 ± 65	6.2 ± 2.0	0.93	0.90 (1.54)	6	sph, ab, fgl

*Calculated value with associated uncertainty (± 1 S.D.).

[†]Calculated correlation coefficient for pressure and temperature results, ranging between 0 (wholly uncorrelated) and 1 (perfectly correlated).

[§]Calculated fit statistic, with sample-specific maximum legal value for 95% confidence given in parentheses.

[#]Number of independent reactions calculated between end members.

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Supplementary Table 4. Bulk-rock compositions used for mineral equilibria modelling

Sample	Figures	H ₂ O	SiO ₂	Al ₂ O ₃	CaO	MgO	FeO	K ₂ O	Na ₂ O	TiO ₂	O
N5	6	5.88	49.66	9.44	11.70	7.41	9.31	0.17	2.64	1.78	2.01
14	7	4.57	59.38	9.56	15.67	2.34	5.56	0.11	0.38	0.29	2.14
7c	8	6.49	45.35	8.11	15.09	10.00	9.93	0.55	1.37	0.39	2.72

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Supplementary Table 5. U–Pb isotopic data of the studied blueschist samples

Sample No.	grain	$^{206}\text{Pb}^a$ (cps)	U ^b (ppb)	Pb ^b (ppb)	Th ^b U	$^{238}\text{U}^d$ ^{206}Pb	$\pm 2\sigma$ (%)	$^{207}\text{Pb}^d$ ^{206}Pb	$\pm 2\sigma$ (%)	Phase
3b	A06	46683	0.57	0.35	2.574	5.486	0.8	0.7604	0.84	C
3b	A07	45228	0.42	0.34	1.726	4.13	0.6	0.7724	0.74	S
3b	A08	40049	0.41	0.30	1.362	4.504	0.6	0.7678	0.82	S
3b	A09	313580	0.26	2.48	3.194	0.3611	0.5	0.8205	0.5	S
3b	A10	29838	0.21	0.22	1.590	3.238	0.9	0.7891	0.81	C
3b	A11	29405	0.26	0.16	1.744	8.365	1.3	0.7287	0.98	C
3b	A12	30144	0.30	0.23	2.554	4.406	1.0	0.7726	0.97	S
3b	A13	26045	0.56	0.19	2.917	9.752	1.2	0.7208	0.84	S
3b	A14	37615	0.26	0.29	2.114	3.05	1.0	0.7856	0.82	S
3b	A15	30660	0.53	0.21	2.603	9.501	0.7	0.7155	1.1	S
3b	A16	32154	0.12	0.26	2.137	1.686	2.6	0.8082	0.8	S
3b	A17	21010	0.23	0.16	3.933	4.827	0.8	0.7653	1.0	S
3b	A18	24380	0.24	0.19	2.908	4.383	1.2	0.7674	1.1	S
3b	A19	13694	0.11	0.11	2.518	3.288	4.0	0.7827	1.1	C
3b	A20	43860	0.36	0.34	1.454	3.703	1.0	0.7796	0.74	S
3b	A21	41984	0.73	0.32	2.377	7.516	0.7	0.7379	0.92	S
3b	A22	51471	0.54	0.41	2.461	4.544	0.6	0.7664	0.76	S
3b	A23	36041	0.22	0.29	2.390	2.652	1.0	0.7917	0.79	S
3b	A24	27563	0.25	0.22	2.167	3.866	1.5	0.7792	0.92	S
3b	A25	22581	0.16	0.18	1.152	3.022	2.2	0.787	1.1	C
3b	A26	26644	0.27	0.21	2.932	4.28	2.1	0.7726	0.95	S
3b	A27	17740	0.13	0.14	2.387	3.215	1.8	0.7881	1.4	S
3b	A28	44024	0.57	0.34	2.988	5.735	0.6	0.7542	0.68	S
3b	A29	40662	0.27	0.31	3.544	3.036	1.2	0.788	0.8	S
3b	A30	21547	0.19	0.17	1.798	3.733	1.1	0.7775	1.1	S
3b	A31	31724	0.27	0.26	0.712	3.246	0.9	0.7822	1.1	C
3b	A32	65329	0.14	0.54	10.798	0.9236	1.0	0.8133	0.84	C
3b	A38	19073	0.15	0.15	2.008	3.293	1.7	0.7846	0.84	C
3b	A39	48827	0.83	0.36	2.106	8.653	0.9	0.7309	0.73	S
3b	A40	33413	0.41	0.27	2.700	5.103	1.4	0.7635	1.0	S
3b	A41	28942	0.40	0.21	2.739	7.071	1.9	0.7492	0.9	S
3b	A42	34281	0.38	0.26	3.654	5.264	2.1	0.7645	0.8	S
3b	A43	9252	0.02	0.08	5.821	0.7733	2.2	0.8154	1.3	C
3b	A44	42860	0.53	0.34	1.464	5.28	1.2	0.763	0.85	S
3b	A45	39968	0.50	0.32	2.191	5.332	1.8	0.7646	0.84	S
3b	A46	30215	0.25	0.25	1.716	3.421	1.2	0.7846	0.82	S
3b	A165	28595	0.29	0.30	1.800	2.955	1.4	0.79	0.83	S
3b	A166	36178	0.39	0.34	1.537	3.866	1.5	0.7787	0.67	S
3b	A167	6215	0.03	0.06	2.502	1.62	2.3	0.7771	0.84	S
3b	A168	24685	0.25	0.22	1.660	4.086	1.4	0.7754	0.87	S
3b	A169	38043	0.44	0.36	1.698	4.098	0.7	0.7698	0.68	S
3b	A170	18218	0.15	0.17	1.663	2.882	1.2	0.7858	0.76	S

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3	3b	A171	67145	0.82	0.50	2.548	7.836	2.0	0.7339	0.79	S
4											
5	13	A60	159418	0.42	1.42	8.280	1.016	8.4	0.8368	0.5	C
6	13	A61	313237	0.05	2.66	5.537	0.06115	2.0	0.8398	0.38	C
7	13	A62	261899	0.65	2.19	2.420	1.028	4.1	0.8373	0.42	C
8	13	A63	55562	0.10	0.47	3.605	0.7208	3.4	0.839	0.69	S
9	13	A64	158085	0.42	1.38	4.167	1.087	4.1	0.8399	0.47	S
10	13	A65	526092	0.36	4.39	2.059	0.2806	0.4	0.8435	0.37	C
11	13	A66	191738	1.16	34.10	10.125	2.654	2.2	0.8198	0.6	S
12	13	A72	388843	1.01	3.06	12.566	1.359	2.1	0.834	0.37	C
13	13	A73	193233	5.51	1.70	0.169	10.53	2.4	0.7353	0.41	S
14	13	A74	988575	0.20	8.57	1.319	0.08119	0.7	0.8332	0.32	S
15	13	A75	527603	1.88	4.67	3.614	1.406	6.4	0.8336	0.37	S
16	13	A76	283119	0.81	2.45	2.090	1.181	2.3	0.8356	0.35	S
17	13	A77	427752	0.31	3.41	2.592	0.3309	0.9	0.8403	0.41	S
18	13	A78	237016	0.15	2.10	5.531	0.2493	2.2	0.8467	0.43	S
19	13	A79	161435	0.07	1.41	3.403	0.1762	3.5	0.8479	0.57	S
20	13	A80	240641	0.99	2.16	6.213	1.627	2.6	0.8322	0.38	C
21	13	A81	213705	0.41	1.99	3.326	0.6789	6.6	0.8414	0.42	S
22	13	A82	190452	0.21	1.68	9.824	0.4379	1.5	0.8464	0.39	S
23	13	A83	295855	0.29	2.56	10.553	0.3994	2.8	0.8444	0.42	S
24	13	A84	211768	0.35	2.12	3.368	0.5029	3.6	0.8455	0.45	S
25	13	A85	309000	0.37	2.64	7.666	0.4901	2.1	0.844	0.44	S
26	13	A86	1006451	0.12	9.69	2.300	0.04261	1.6	0.8355	0.38	C
27	13	A87	472813	0.96	3.48	1.363	1.012	2.6	0.8385	0.37	S
28	13	A88	294608	0.75	3.29	5.596	0.7062	3.2	0.8405	0.43	C
29	13	A89	1980020	0.29	17.72	12.090	0.05791	2.9	0.8394	0.33	S
30	13	A90	214418	0.09	1.86	0.926	0.1674	2.5	0.8485	0.45	C
31	13	A091	2134501	0.32	18.16	0.600	0.0622	4.4	0.8377	0.32	C
32	13	A92	314456	1.31	2.71	0.458	1.669	3.7	0.8297	0.37	C
33	13	A93	580143	0.41	3.95	2.470	0.4795	0.5	0.8455	0.35	C
34	13	A94	276122	0.42	2.32	18.890	0.6495	1.9	0.8414	0.44	S
35	13	A95	247814	0.68	2.05	2.381	1.171	2.4	0.8362	0.45	S
36	13	A96	1268062	0.98	6.95	12.461	0.5039	1.7	0.8431	0.35	S
37	13	A97	330147	3.14	1.69	1.738	8.582	4.2	0.7468	0.45	S
38	13	A98	1511920	1.04	13.25	4.565	0.2732	5.1	0.8384	0.31	S
39	13	A99	585406	0.50	4.90	0.633	0.3547	6.5	0.8384	0.35	S
40											
41	11	A100	550329	1.62	3.33	0.995	3.338	1.4	0.7978	0.38	C
42	11	A101	643865	0.43	5.47	2.447	0.2659	0.3	0.8348	0.33	C
43	11	A107	726889	1.91	6.13	8.982	1.099	1.0	0.8255	0.32	C
44	11	A108	321175	0.26	2.79	0.137	0.3235	1.1	0.8332	0.38	C
45	11	A109	895619	6.69	7.54	4.678	3.002	1.3	0.7838	0.34	S
46	11	A110	427471	0.23	3.70	2.364	0.2135	0.4	0.8343	0.39	C
47	11	A111	260406	0.53	2.48	45.947	0.8021	0.7	0.8304	0.37	C
48	11	A112	167449	0.81	1.57	0.194	1.732	1.9	0.7945	0.54	S
49	11	A113	162814	0.05	1.56	0.227	0.1177	0.9	0.8448	0.49	S

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3	11	A114	129813	0.06	1.28	0.183	0.1681	0.8	0.8405	0.54	S
4	11	A115	74811	0.08	0.73	0.152	0.3965	1.7	0.8316	0.56	C
5	11	A116	88180	0.57	0.85	0.271	2.282	1.6	0.8098	0.49	S
6	11	A117	122657	0.21	1.02	0.226	0.7684	4.2	0.8284	0.48	S
7	11	A118	365557	0.11	3.10	0.339	0.1198	2.3	0.8369	0.37	C
8	11	A119	85225	0.15	0.76	7.786	0.6861	1.7	0.8287	0.49	C
9	11	A120	284139	0.47	2.55	12.306	0.6485	2.7	0.8311	0.42	S
10	11	A121	432625	0.67	4.94	17.064	0.3922	8.5	0.8346	0.34	S
11	11	A122	1885183	2.38	17.00	6.513	0.494	0.9	0.8313	0.3	S
12	11	A123	1437266	3.18	9.84	8.088	1.762	1.6	0.8176	0.33	S
13	11	A124	481565	0.33	4.17	2.304	0.2727	0.9	0.834	0.34	S
14	11	A125	185421	0.18	1.68	4.353	0.3782	3.3	0.8421	0.42	S
15	11	A126	217816	0.06	1.95	0.861	0.1141	3.4	0.8372	0.43	C
16	11	A127	316865	0.37	2.87	8.533	0.4547	2.6	0.842	0.37	S
17	11	A128	123976	0.07	1.05	0.224	0.2328	2.0	0.8365	0.54	S
18	11	A129	224359	0.10	1.98	2.837	0.1777	1.5	0.8427	0.41	C
19	11	A130	439692	1.44	2.62	10.548	5.474	0.7	0.7756	0.38	C
20	11	A131	147942	0.16	1.16	2.536	0.4829	2.2	0.8356	0.49	S
21	11	A132	237211	0.13	2.07	2.142	0.215	0.7	0.8355	0.41	C
22	11	A133	591044	0.38	5.20	1.967	0.2514	0.3	0.8332	0.42	C
23	11	A134	192938	0.14	1.62	0.405	0.3029	1.9	0.8359	0.45	C
24	11	A135	458317	0.61	3.03	2.160	1.097	0.6	0.8233	0.37	C
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31	14	A136	390768	0.65	2.62	0.545	1.672	0.9	0.826	0.4	S
32	14	A137	688012	0.35	6.94	1.298	0.1749	1.6	0.8443	0.35	S
33	14	A138	1170631	0.83	11.88	2.712	0.2475	1.2	0.8413	0.33	C
34	14	A139	1931275	0.99	16.01	0.699	0.2946	0.5	0.8431	0.3	S
35	14	A140	817585	1.01	4.77	4.519	3.079	0.7	0.8094	0.33	C
36	14	A141	1377486	0.67	11.55	0.789	0.2726	0.9	0.8429	0.33	S
37	14	A142	102777	0.65	1.51	1.546	1.222	0.8	0.8306	0.68	S
38	14	A143	1889857	2.33	16.77	5.000	0.5913	0.2	0.8381	0.32	C
39	14	A144	181455	0.08	1.33	2.755	0.3524	7.3	0.8395	0.53	S
40	14	A145	2133448	0.73	17.86	0.535	0.1957	0.6	0.8448	0.31	S
41	14	A151	1728879	0.79	13.25	1.646	0.3401	0.3	0.8422	0.31	S
42	14	A152	732208	0.40	5.15	7.157	0.6019	2.3	0.8383	0.34	S
43	14	A153	1122112	0.20	7.77	0.182	0.208	1.4	0.8443	0.32	S
44	14	A154	634125	0.25	6.79	0.425	0.1307	1.8	0.8456	0.35	S
45	14	A155	247895	0.06	2.65	1.102	0.08261	4.5	0.8444	0.43	S
46	14	A156	508240	0.23	5.36	1.686	0.1454	3.5	0.8431	0.41	S
47	14	A157	1049201	0.18	11.18	0.479	0.05772	1.5	0.8457	0.31	S
48	14	A158	369712	0.13	4.23	1.415	0.1012	7.2	0.8445	0.42	S
49	14	A159	1040233	0.22	11.17	0.464	0.07095	0.9	0.8441	0.32	C
50	14	A160	498591	0.30	2.82	2.304	2.768	0.6	0.8129	0.43	C
51	14	A161	1012897	0.47	13.87	0.378	0.09687	3.6	0.8444	0.32	S
52	14	A162	460864	0.21	4.94	1.221	0.1502	4.3	0.8436	0.4	S
53	14	A163	1508708	0.80	16.24	0.341	0.1755	0.2	0.8435	0.32	S
54	14	A164	606128	0.43	6.57	5.745	0.2345	1.9	0.8416	0.35	S

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4 Spot size = 235 μm ; depth of crater $\sim 20\mu\text{m}$. $^{238}\text{U}/^{206}\text{Pb}$ error is the quadratic additions of the within
5 run precision (2 SE) and the external reproducibility (2 SD) of the NIST 614. $^{207}\text{Pb}/^{206}\text{Pb}$ error
6 propagation (^{207}Pb signal dependent) following Gerdes and Zeh (2009).
7

8
9 ^aWithin run background-corrected mean ^{207}Pb signal in cps (counts per second).
10

11 ^bU and Pb content and Th/U ratio were calculated relative to NIST SRM-614.
12

13 ^c percentage of the common Pb on the ^{206}Pb . b.d. = below detection limit.
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15 ^d Corrected for background, within-run Pb/U fractionation (in case of $^{206}\text{Pb}/^{238}\text{U}$) and subsequently
16 normalized to NIST 614 (ID-ICPMS value/measured value).
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20 S – Amphibole/Epidote

21 C – Calcite
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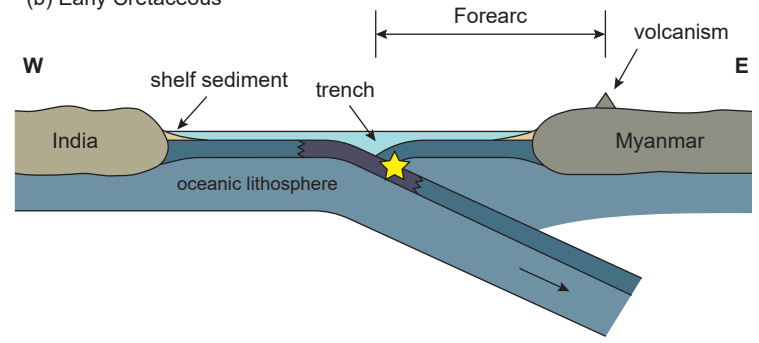
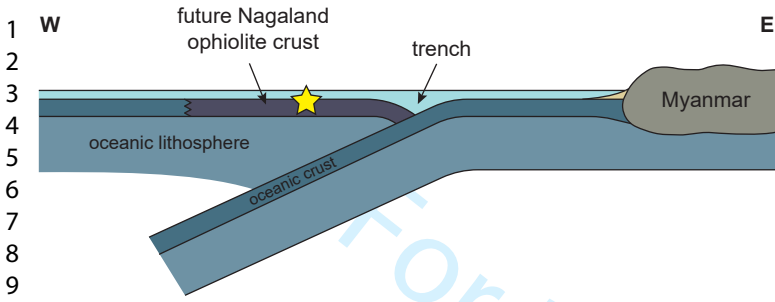
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Highlights

- (a) Naga ophiolite has undergone polymetamorphic events.
- (b) Unsheared samples peak P – T conditions of ~ 1.9 GPa and ~ 480 – 520 °C.
- (c) Sheared sample stable at lower P – T conditions of ~ 0.6 GPa and ~ 470 °C
- (d) U–Pb ages of the Nagaland blueschist underwent peak and retrograde metamorphism
c. 95 Ma and c. 90 Ma.
- (e) Combined U–Pb age and calculated P – T that Nagaland blueschist rocks exhumed at a
rate of ~ 1 cm/year

(a) Jurassic

(b) Early Cretaceous



(c) Middle Cretaceous

(d) Middle to Late Cretaceous

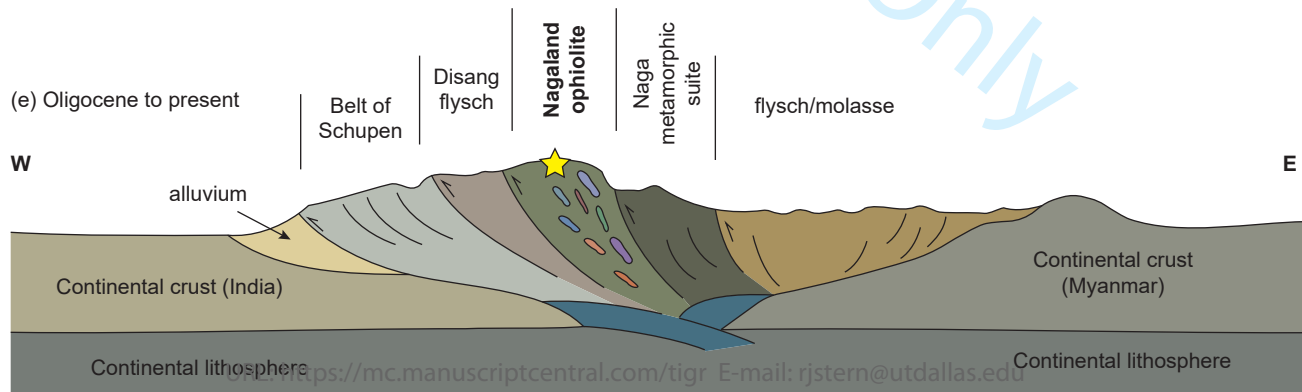
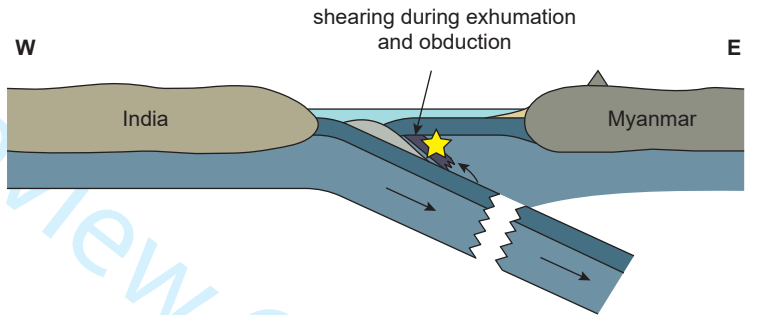
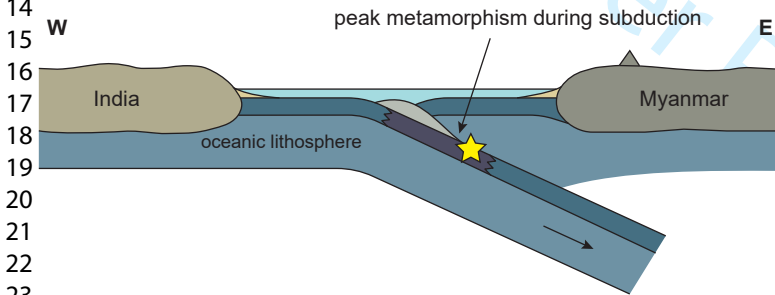


Fig. 11

Reviewer: 1

Comments to the Author

Review of "Dating blueschist-facies metamorphism within the Naga ophiolite, Northeast India, using sheared carbonate veins" by Maibam et al., submitted to International Geology Review.

This is a quite interesting and concisely written paper that presents the results of a classical tectonometamorphic study combined with a novel approach to absolute dating. Overall, the conclusions drawn sound convincing and well supported by the provided data, which are undoubtedly of high quality. However, I have made some remarks about some aspects that in my opinion need to be carefully elucidated and/or better presented before the article can be considered ready for publication. In the following lines I am summarising the main points of my criticism, but the authors are referred to the attached pdf file for more detailed comments and specific suggestions.

My first concern regards the "Geological background" section, which is too brief and general in my opinion (please refer to the attached comments). I think the authors should spend some additional effort into providing more detailed information about the geology of the investigated area, so that a reader that is not familiar with such topics (like I am) can easily understand what is the general context and what are the main points of debate in the scientific literature. In this way, the authors will not only help the reader to get into the presented topics, but also, and most importantly, to get convinced about the significance of their study, explaining what is the great contribution they are giving in order to resolve those issues that are still a matter of debate. In the present version of the manuscript I am not sure this is completely clear, especially as regards the geochronological issues. The authors mention numerous age data from the existing literature and then conclude that there is "a paucity of reliable geochronological age data" (lines 151-152), although they actually do not explain on what basis they can say this. I think they should definitely add some more specific information and comments about this, in order to sound completely convincing and to give further strength to their novel approach.

As regards the "Analytical methods" and "Sample petrology" sections, I have found a number of controversial points that need to be elucidated.

- first of all, I think that the section on the analytical techniques should include also some information about the investigated samples, before describing what was done. Few notes on sampling activities, including locations, stratigraphic positions, lithotypes, number of collected samples etc., would be sufficient (and absolutely necessary, in my opinion).

- mineral abundances are said to have been calculated ("Calculated volume proportions of minerals in each sample are given below", lines 164-165), but in the following sections of the manuscript these are said to have been determined via point counting ("Mineral proportions for each sample were

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3 determined using the software JMicroVision”, lines 308-309). This needs to be clarified. I do not think
4 that these were calculated, but if so, the authors should explain how this was made. In addition,
5 where they mention that mineral abundances were obtained by point counting, the authors say that
6 this was made on a total of 500 points for each of the analysed samples in thin section. I am not sure
7 this can be considered sufficient to yield statistically reliable modal proportions. To my knowledge,
8 point counting is generally made on at least 3000-4000 points per sample. Please also consider that
9 the investigated samples include a relatively large number of different mineral phases (7 major
10 phases plus 3 accessory phases for sample N5; 8 plus 3 for sample 14; 8 plus 2 for sample 7c; 8 plus
11 4 for sample 11), so counting only 500 randomly chosen points throughout the entire thin section can
12 very likely bias the final results.

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15 - bulk rock samples are said to have been analysed by XRF (lines 168-177), but the results are not
16 reported neither in the main manuscript, nor in the Supplementary Files. But what is more important,
17 later in the text, in the “Thermobarometry” section, rock compositions are said to have been
18 calculated using mineral modes and compositions (lines 306-307). I warmly invite the authors to
19 clarify this.

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22 - the analysed samples are said to be six, but those that are described are just 4: the sheared N5 and
23 14 and the unshaped 7c and 11. Two additional sheared samples, 3b and 13, are in some instances
24 mentioned, but nothing is reported about their petrography, mineral chemistry or bulk rock
25 composition. I think this should be amended, providing a description of the general petrographic and
26 mineral chemistry features of these samples, exactly the same way this is done for the other 4
27 samples. If for some reason, this is not possible, I think the authors should explicitly mention it and
28 provide full explanations.

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31 - the unshaped sample 14 is said to be a blueschist (or a metabasite) sample like all the other
32 investigated samples, but I have to say that I find it hard to agree with that. Its mineral composition is
33 dominated by epidote (50%) and quartz (35%), with only 10% Na-Ca amphibole (i.e., the “blue” or
34 “glaucofanite” amphibole; see lines 236-238). In addition, the bulk composition reported in the
35 Supplementary Table 3 is much richer in SiO₂ and poorer in MgO and FeO with respect to the other
36 samples. I think this requires to be taken into account by the authors.

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39 - since bulk rock compositions have been obtained for the investigated samples (whether directly,
40 through XRF analyses, or indirectly, calculated using mineral modes and compositions – see previous
41 point), I expect that a paragraph of the “Sample petrology” section is devoted to a brief description of
42 these. I think this would be absolutely necessary, also considering that these compositions are then
43 used for phase equilibria modeling, so that the reader can understand why the authors chose the
44 specific model system they employed for such calculations.

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47 As regards the “Thermobarometry” (which I think should be renamed more properly as, e.g., “Phase
48 equilibria modeling”) and the “Discussion and implications” sections I have a few smaller remarks:

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51 - only one of the 4 unshaped samples was used for calculating bulk rock pseudosections (i.e.,
52 sample 7c), but the authors do not provide any explanation about their choice to focus on this sample
53 only. I think at least a few notes on this should be added.
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4 - the authors did not explain why they assumed that some phases are in excess, which I think needs
5 to be adequately elucidated.
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7 - in constraining peak P-T conditions for unsheared samples, the authors use together the results for
8 the two investigated samples N5 and 14. I think it would be much better if they present the results for
9 these two samples separately, and then they propose a single P-T range by comparing them and see
10 where the best matches for both samples overlap.
- 11
12 - the authors usually refer to the “best matching assemblages” but to me this sounds like a very vague
13 concept, if they do not explain what was the strategy they employed in order to identify such best
14 matches. I guess these are defined as those minimizing the differences between observed and
15 calculated mineral abundances, but maybe this can be done in more than just one single way, e.g.,
16 not only by minimizing the differences of mineral abundances, but maybe also by minimizing the
17 squared residuals of the differences, or maybe even in some other way.
- 18
19 - in the conclusive section, when presenting the results of their estimates for P-T conditions, I think
20 the authors can simply refer to the conditions obtained for the best matching assemblages, rather
21 than repeating again what is the total range for the peak and retrograde assemblages (which were
22 already discussed in the “Thermobarometry” section). I think they should report such tighter ranges
23 also in the other sections of the paper (e.g., abstract, conclusions) where they mention the results of
24 their models.
- 25
26 - since the proposed P-T-t path (Fig. 10) is quite different from those from the available literature
27 reported for comparison, I would expect that this was discussed a little bit, trying to provide some
28 explanations for such mismatches [which are particularly evident for the path from Ao and Bhowmik
29 (2014)]. On the other hand, the authors simply present the proposed P-T-t path in just three lines
30 (400-402), completely avoiding any comment on the compared models. I think this issue needs to be
31 addressed.

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40 Finally, as regards the Supplementary Files (i.e., Electronic Appendix), I have to say that most of the
41 contents that are presented are actually just a repetition of what was already reported in the main text.
42 The authors should report in this section only additional material that was not previously included in
43 any parts of the manuscript, like their Supplementary Tables and Supplementary Figure 5 (which thus
44 should be renamed to “Supplementary Figure 1”). In addition, as regards mineral analyses reported in
45 Supplementary Table 2, I think these should include not only a selection of some representative ones,
46 but the entire dataset available to the authors, not only because there are no space limitations for
47 electronic supplementary materials, but also because providing a large dataset surely adds
48 robustness and value to their work.

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56 Lorenzo Fedele

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58 Dipartimento di Scienze della Terra,
59 dell'Ambiente e delle Risorse (DiSTAR)
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15 **Reviewer: 2**

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18 Comments to the Author

19 This manuscript presents petrological and geochronological data for blueschist facies rocks from the
20 Nagaland ophiolite. The paper connects pressure-temperature conditions for two distinctly different
21 types of samples – one unsheared and one sheared - with geochronology to interpret the timing of
22 metamorphism and rate of exhumation for these samples. The paper will be of interest primarily to
23 structural and metamorphic geologists, and those interested in the tectonics of exhumation.
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28 I found the paper to be well-written and the concepts were clearly and concisely described. The P-T
29 conditions are clearly quite different for the two suites of mineral assemblages and the textural
30 differences are clearly shown in the figures. The interpretation, if is supported fully, could be an
31 interesting and exciting contribution. However, I think that more attention needs to be paid to
32 providing the context for the analytical spots and a fuller discussion of recrystallization in the context
33 of the spots analyzed could be provided.
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38 Analytical spot context: The context for the spots analyzed needs to be better documented. The text
39 in the abstract for the manuscript states that the geochronology is “U-Pb in situ analysis of carbonate
40 grains (aragonite-calcite)”. However in line 90-91 this is now described as “millimetre-sized minerals
41 and mineral assemblages (e.g., carbonate, epidote, amphibole, etc.)”. A look through the data table
42 indicates that <25% of the analyses for sample 3b are carbonate. The other samples also have fewer
43 than 50% carbonate analyses. This raises a number of questions. A look at supplemental Figure 5
44 shows back-scattered electron imaging of the samples with white circles on the analytical spots. This
45 figure is incredibly important as it provides context for the analyses. It might be worth incorporating
46 this as a regular figure of the paper. However, looking at this figure it is still not clear from the figure
47 which spots are on which mineral(s), and whether the placement of the spots on carbonate are indeed
48 in recrystallized veins as is described in the text. The vein-like regions labeled “carbonate” are
49 remarkably devoid of analytical spots. This may be a simple issue solved by better labeling. One way
50 to improve this would include to color code the spots on the diagram to highlight the carbonate
51 analyses, in particular those that are recrystallized carbonate. As it looks right now, many of the spots
52 fall on black parts of the image (are those minerals or holes in the section?), and it looks like the
53 minority are on carbonate. The inset figures do not provide much useful information because their
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3 position on the larger scale image is not marked and there are no analytical spots located on those
4 images. The text of the abstract should be changed to reflect that these analyses are of both silicate
5 minerals and carbonates. Would the data interpretation change if only carbonate data were
6 evaluated? If so, it would strengthen the interpretation to demonstrate that.
7
8
9

10 Thanks for the comment on the documentation of the analysed spots. We would like to share the
11 presented BSE images and the analysed spots are representative. We do not present the full thin
12 sections. As suggested, we have increased the labelling of the spots. Reviewer has rightly pointed out
13 the black parts in the images are laser holes, where the laser spot has penetrated the phases.
14
15
16

17 The inset images have deleted. The abstract has been modified with the insertion of silicate phase
18 analysis. Geochronology data is improved when we consider the carbonate and cogenetic silicate
19 phases, compared to the carbonate data only.
20
21
22

23 Additionally, a more in-depth discussion of the likely recrystallization of the various minerals analyzed
24 would be helpful in supporting the conclusions of the study. It is stated that the carbonate is selected
25 from recrystallized veins. Is the carbonate in the unsheared sample still aragonite or might it be
26 calcite? If it has reverted, did it recrystallize upon reversion and thus is the age for the unsheared
27 sample possibly not a peak age? Are the other minerals dated in the sheared samples (epidote,
28 amphibole) likely to recrystallize during exhumation or might they simply be reoriented and not
29 recrystallized?
30
31
32
33

34 Thanks for the comment but we cannot comment much on the likely crystallisation of the
35 various minerals. We have inferred the carbonates in the sheared and unsheared samples as
36 calcite and aragonite on the basis of the estimated P-T range and well-established aragonite-
37 calcite stability curve.
38

39 We cannot comment on the recrystallisation affecting the isotopic values. As presented in the
40 text, in the present study instead of dating single accessory mineral domains, millimetre -
41 sized minerals and mineral assemblages (e.g., carbonate, epidote, amphibole etc.) that
42 recrystallised and equilibrated during a single tectonic event and which contain measurable
43 amounts of U and Pb can be used to determine crystallization ages. Here we apply this
44 method to dynamically recrystallised carbonate veins and selected mineral assemblages
45 (amphibole, epidote) in blueschists within the Kiphire District of the Nagaland ophiolite belt
46 and integrate these ages with thermobarometric data to produce new constraints on the timing
47 and rates of subduction and exhumation cycle of Neo -Tethyan crust in the Indo - Myanmar
48 region.
49
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51

52 Below I discuss specific comments keyed to section and line numbers in the manuscript draft.
53
54

55 Specific comments

56 Abstract, line 39 – This should be reworded to indicate that other minerals were included in the
57 analytical data set.
58
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5 Done
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9 Line 50 – “HT-LP” here should be “HP-LT”
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11 Done
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15 Lines 94-101 – This section seems like it would be more appropriate in the Methods section.
16
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18 Done
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21

22 Geological Background – There are a lot of names here, some of which need to be more clearly
23 defined/stated near the beginning of the section. In particular the Manipur ophiolitic nappe isn't
24 defined, it is just part of a description in line 136, so it needs to be clearly stated what/where it is
25 before that. Also it should be made clear in the first paragraph of this section which ophiolite is the
26 Naga ophiolite. It appears first on line 130 as “Nagaland ophiolite belt” without a clear introduction. As
27 it is the focus of the paper, it would be helpful to more clearly define it early on.
28
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30
31

32 The geological has improved with additional information taking account of the suggestions.
33
34

35 Lines 164-165 – How are the volume proportions described here calculated? This needs to be
36 explained.
37
38

39 It has been explained.
40
41

42 Line 210 – “sheared OR unsheared” rather than “and”
43
44

45 Done
46
47

48 Line 308-311 – This information seems more appropriate for the Methods section. Perhaps this
49 addresses the question I had in lines 164-165? Also it is worth considering putting the information
50 about how phase diagrams were calculated in the Methods section (lines 293-304).
51
52
53

54 Have transferred to the Method section.
55
56

57 Lines 353+ U-Pb geochronology - It is difficult to see clearly that recrystallized calcite was chosen for
58 analysis, based on the images in the supplementary file. This raises the question of whether minerals
59 recrystallized during deformation or not. Discussion of whether older ages could be preserved during
60

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3 shearing would be important. Would resetting be expected during shearing of these minerals?
4 Preferred orientation, bending and curving (lines 390-391) do not require recrystallization.
5
6

7
8 **Thanks for the comment but the represented figures are for representative purpose only and**
9 **do not reflect the overall feature.**

10
11 **As given above we cannot comment on the recrystallisation affecting the isotopic values. In**
12 **the present study instead of dating single accessory mineral domains, millimetre -sized**
13 **minerals and mineral assemblages (e.g., carbonate, epidote, amphibole etc.) that recrystallised**
14 **and equilibrated during a single tectonic event and which contain measurable amounts of U**
15 **and Pb can be used to determine crystallization ages.**
16
17

18
19 Line 401 – If these are slab-top temperatures from Syracuse et al., 2010 that should be indicated
20 here.
21

22
23 **Indicated**

24
25
26 Line 405 – Change “out” to “our”
27

28
29 **Done**

30
31
32 Lines 435-437 – The uplift rate calculated here would be vertical uplift since the distance is based on
33 changes in pressure. However, as indicated in Figure 11, some or all of the exhumation may not be
34 100% vertical, and there may be some component along the subduction plate interface. This
35 possibility should be discussed and included in estimates.
36
37

38
39 **Possibility is discussed with additional info.**
40

41
42 **Reviewer: 3**

43
44 Comments to the Author

45
46 Comments:
47

48
49 1. Pseudosections/Phase equilibria modeling. MnO is critical to control the garnet stability. It is OK to
50 omit the modeling, but reasonable explanations are necessary. Naturally, pseudosections in the Mn-
51 free system have a risk of explaining observed mineral assemblages.
52
53

54
55 **There are no manganese bearing activity composition models available for either the**
56 **amphiboles or clinopyroxene, it is not currently possible to consider manganese in any**
57 **confident way in meta basic systems.**
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3 In Supplementary Figures 6 and 7, please illustrate isopleths of garnet end-member compositions and
4 phengite Si apfu.
5
6

7 We have not contoured these isopleths as we don't believe this is necessary for the overall
8 interpretation of the rocks in question. it is unclear from the comment why the reviewer wants
9 these isopleths calculated and for what purpose.
10
11

12 In the Supplementary Figures, I'm curious about the assumption (?) of excess Ep (and also Rt) in the
13 whole P-T range (1.0–2.5 GPa and 350–600°C). The stability of biotite also looks strange to me.
14
15

16 In these calculations epidote and rutile are found to be in excess (stable in all fields) rather
17 than assumed to be in excess. Therefore, the in excess notation is simply to simplify the
18 labelling of diagrams. In addition, without clarification of what is considered to be odd will
19 strange in the stability biotite it's difficult to comment on this. the stability biotype in the
20 diagram is what is predicted by the thermodynamic modelling.
21
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24

25 2. Sodic amphibole compositions. In Figure 5, please add $Fe^{3+}/(Fe^{3+}/Al)$ versus Mg# diagram for
26 analyzed sodic amphibole. Also, please discuss the consistency of the composition of sodic
27 amphibole and the modeled amphibole composition, especially Fe^{3+} .
28
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30
31

32 We don't feel the suggested plot would be particularly informative. Furthermore, given that
33 the Mg# is somewhat dependent on the estimation of ferrous vs ferric iron from the probe
34 analyses there is a danger of there being a correlation of errors or co-dependent variables in
35 such a plot. Further, a direct comparison between the model compositions and the probe
36 analyses would involve considerable new calculation to extract this information from the
37 model results.
38
39
40

41 3. Sodic pyroxene (aegirine-augite). Sample 11 contains aegirine-augite + quartz + albite. This
42 mineral association is helpful to constrain P-T.
43
44

45 Thanks for the comment. Preliminary investigation of phase equilibria stability in sample 11
46 did not allow for reliable thermobarometry to be performed due to the high variance of the
47 interpreted peak mineral assemblage
48
49

50 4. In general, vein formation requires brittle deformation.
51
52

53 While classic straight sharp-edged veins require brittle deformation many other vein-like
54 structures do not (for example in migmatites where a ductile parting process may operate, see
55 papers by Brown, Sawyer etc.)
56
57

58 5. Rutile. Why don't you try rutile U-Pb dating to compare the results? I think dating is more
59 straightforward than carbonate dating.
60

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5 We have tried to analyse rutile but because of low U concentration, could not yield a producible age.
6
7

8 6. Occurrence of carbonate in unreformed samples. Petrographic information on sample 14 is weak.
9 Please describe more about the dated carbonate mineral. The authors considered the calcite in
10 unreformed samples was aragonite. Do you see any topotactic pseudomorphs after aragonite? For
11 example, see Bradt et al. (2004)

12 [https://doi.org/10.1016/S0191-8141\(03\)00099-3](https://doi.org/10.1016/S0191-8141(03)00099-3)
13
14

15
16 We have inferred the carbonates in the sheared and unsheared samples as calcite and
17 aragonite on the basis of the estimated P-T range and well-established aragonite-calcite
18 stability curve.
19
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21
22
23 7. Others

24
25
26 Line 144. 1 kbar ==> 0.1 GPa

27
28 Done
29

30
31 Line 150-151. ~11.5 kbar ==> 1.15 GPa; 6 kbar ==> 0.6 GPa

32
33 Done
34

35
36
37 Line 230. Si = 3.34–3.38 pfu ==> Si = 3.34–3.38 pfu for O = 11

38
39 Done
40

41
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43 Line 237. sphene ==> titanite

44
45 Done
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47
48
49 Lines 269, 273, 278. muscovite ==> phengite

50
51 Done
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53
54
55 Line 287. Please add the jadeitite component of the aegirine-augite.

56
57 Done
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3 Line 326. 1 kbar ==> 0.1 GPa
4
5

6 Done
7
8

9 Line 384. I think better to say "metamorphic recrystallizations"
10
11

12 Done
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14

15 Supplementary Table 4.

16 - Please use "GPa" instead of "kbar"
17
18

19 Done
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22 Supplementary Figure 5.

23 Ms ==> Ph

24 Sph ==> Ttn
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28 Done
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review Only

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4 1 **Dating blueschist-facies metamorphism within the Naga ophiolite,**
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7 2 **Northeast India, using sheared carbonate veins**
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10 3

11
12 4 **Bidyananda Maibam^{a*}, Richard M. Palin^b, Axel Gerdes^{c,d}, Richard W. White^e, Stephen**
13
14 5 **Foley^f**
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19 7 *^aDepartment of Earth Sciences, Manipur University, Canchipur, Imphal-795003, India*

20
21 8 *^bDepartment of Earth Sciences, University of Oxford, Oxford, OX1 3AN, United Kingdom*

22
23 9 *^cDepartment of Geosciences, Goethe-University Frankfurt, 60438 Frankfurt, Germany*

24
25 10 *^dFrankfurt Isotope and Element Research Center (FIERCE), Goethe-University Frankfurt,*
26
27 11 *60438 Frankfurt, Germany*

28
29 12 *^eSchool of Earth and Environmental Sciences, University of St. Andrews, KY16 9AL, United*
30
31 13 *Kingdom*

32
33 14 *^fARC Centre of Excellence for Core to Crust Fluid Systems, Department of Earth &*
34
35 15 *Environmental Sciences, Macquarie University NSW 2109, Australia*

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37 16
38 17 **corresponding author: bmaibam@yahoo.com*
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54 19 **Keywords:** blueschist; dynamic recrystallisation; exhumation; petrological modelling; U–Pb
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56 20 carbonate geochronology
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60

54 22 **ABSTRACT**

55
56 23 The tectonic significance of blueschist-facies rocks associated with the Indo-Myanmar
57
58 24 ophiolite belt is uncertain, given their lack of detailed petrological study and the paucity of
59
60

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3 25 reliable age data for different stages in their geological evolution. Here, we present new
4
5 26 integrated petrological and geochronological data for samples from the Nagaland complex of
6
7 27 the Indo-Myanmar ophiolite belt, northeastern India, which constrains the pressure–
8
9 28 temperature conditions and absolute ages of peak and retrograde metamorphism. Several
10
11 29 samples of blueschist were collected from the region, which have been variably deformed and
12
13 30 subjected to shear recrystallization. Based on microstructural constraints and mineral
14
15 31 geochemistry, garnet, omphacite, barroisite, chlorite and muscovite are interpreted to
16
17 32 represent a high-pressure prograde-to-peak metamorphic assemblage, and omphacite,
18
19 33 actinolite, hornblende and albite represent a lower-pressure retrograde metamorphic
20
21 34 assemblage that formed during shear-related exhumation. Petrological modelling and
22
23 35 thermobarometry indicates that unsheared samples equilibrated at ~1.9 GPa and ~~~420–560~~
24
25 36 ~~°C~~ **~480–520 °C (LARGE T RANGE AT FIXED P EXPLAINED IN THE TEXT)** at
26
27 37 peak metamorphism, indicating subduction to ~60 km depth, whereas sheared and
28
29 38 recrystallised samples re-equilibrated at ~0.6 GPa and ~470 °C **(EXTREMELY PRECISE**
30
31 39 **P-T RANGE INSTEAD)** during retrograde metamorphism associated with obduction of the
32
33 40 Naga ophiolite onto the Indian foreland. U–Pb *in-situ* analysis of carbonate grains (aragonite–
34
35 41 calcite) **and associated silicate phases (epidote, prehnite, amphibole etc.)** in different
36
37 42 microstructural positions, including within dynamically recrystallised shear bands that cross-
38
39 43 cut older metamorphic fabrics and cogenetic silicate phases, constrains the age of peak
40
41 44 metamorphism to be c. 95 Ma and retrograde metamorphism to be c. 90 Ma. Based on the
42
43 45 overall progression of ages in the sheared and unsheared samples, we interpret that the area
44
45 46 experienced ~~atypically slow~~ exhumation at a time-averaged rate of ~1 cm/year **in the order of**
46
47 47 **Phanerozoic period plate tectonic rate (ARE YOU SURE THIS CAN BE CONSIDERED**
48
49 48 **A SLOW EXHUMATION RATE? TO MY KNOWLEDGE, RATES IN THE ORDER**
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51 49 **OF MM/YR ARE ALSO COMMON, SEE E.G., MANZOTTI ET AL., 2008,**
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3 50 **CORRECTED**), which is in the order of rates of plate tectonic processes on the Phanerozoic
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5 51 Earth

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9
10 53 **1. Introduction**

11
12 54 High-pressure metamorphic belts provide a critical record of the geological evolution of
13
14 55 paleo-plate boundaries, and provide valuable constraints on tectonothermal models of both
15
16 56 modern and ancient orogenesis **orogeneses** (e.g. Ernst 1973; Carswell 1990). Blueschist-
17
18 57 facies rocks form at high-pressure–low-temperature (**HFP–LPT**) metamorphic conditions
19
20 58 characteristic of subduction zones (Miyashiro 1961; Cloos 1985; Palin and White 2016) or
21
22 59 ephemerally in the embryonic stages of collisional orogeny (Wang and Foley, 2020), where
23
24 60 they may subsequently recrystallize to greenschists or amphibolites under higher
25
26 61 temperatures and/or lower pressures (Ernst 1973). Combining mineral equilibria constraints
27
28 62 on the thermobarometric conditions under which sequential assemblages formed with
29
30 63 absolute ages obtained via *in-situ* geochronology, can elucidate the timing and timescales of
31
32 64 geodynamic processes that control the subduction–exhumation cycle (e.g. Terry *et al.* 2000;
33
34 65 Rubatto and Hermann 2001; St-Onge *et al.* 2013).

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40 66 The power of this integrated technique is demonstrated here using the example of **in the**
41
42 67 **case of** the Indo-Myanmar ophiolite belt, a part of the Indo-Myanmar Range that extends to
43
44 68 the east and southeast of the Himalayan orogen. The geological history and tectonic evolution
45
46 69 of this belt is currently poorly understood, such that more precise constraints on the pressure–
47
48 70 temperature–time (P – T – t) path of key lithologies ~~from the complex~~ are necessary to
49
50 71 improving our geological understanding of this part of southeast Asia. Much of the current
51
52 72 uncertainty concerning the tectonic evolution and significance of these Indian-plate ophiolitic
53
54 73 rocks stems from a lack of reliable petrochronological data. In particular, the timing and P – T
55
56 74 conditions of high-pressure metamorphism in the Indo-Myanmar belt is poorly constrained
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3 75 due to the general absence of datable mineral phases in mafic igneous rocks that are reactive
4
5 76 at subsolidus subduction-zone *HP–LT* metamorphic conditions. Zircon from jadeitites in this
6
7 77 region have previously produced yielded U–Pb ages ranging from Late Jurassic (c. 147 Ma:
8
9 78 Shi *et al.* 2008) to Late Cretaceous (c. 77 Ma: Yui *et al.* 2013), although all of these data
10
11 79 show significant scatter due to incomplete recrystallization of magmatic grains and
12
13 80 metasomatic/hydrothermal activity during subduction and exhumation, which can partially
14
15 81 reset isotope systems (Wang and Griffin 2004). Furthermore, these former studies performed
16
17 82 geochronology on zircon grains separated from the host rocks, which prohibits inhibits direct
18
19 83 correlation of age data with *P–T* conditions derived from metamorphic assemblages and
20
21 84 microstructures, leading to potentially unreliable geological interpretations.
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25

26 85 The zircon U–Pb isotope system is widely applied for dating the crystallization and re-
27
28 86 crystallization of mineral assemblages during high-temperature metamorphic events (e.g.
29
30 87 Williams and Claesson, 1987; Parrish, 1990; Robb *et al.* 1999, Rubatto *et al.*, 2001). However,
31
32 88 some lithologies and/or geological processes often cannot be dated directly by this technique
33
34 89 due to the absence of appropriate minerals that incorporate measurable amounts of radiogenic
35
36 90 nuclides. Examples of such rocks can be found in shear zones, such as mylonites and tectonic
37
38 91 carbonates, but this issue also extends to *HP–LT* metamorphic rocks, ore mineralisations,
39
40 92 diagenetic minerals and cements, some sedimentary rocks, and some alteration assemblages
41
42 93 (e.g. Gilley *et al.* 2003). Recent studies have focused on the application of *in-situ* U–Pb isotope
43
44 94 analyses of low-U minerals (e.g., carbonates, epidotes, amphiboles etc.) in thin section by laser
45
46 95 ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) for geochronological
47
48 96 study (Millonig *et al.* 2012; Coogan *et al.* 2016; Ring and Gerdes 2016; Roberts and Walker
49
50 97 2016; Li *et al.* 2014). Thus, instead of dating single accessory mineral domains, millimetre-
51
52 98 sized minerals and mineral assemblages (e.g., carbonate, epidote, amphibole etc.) that
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54 99 recrystallised and equilibrated during a single tectonic event and which contain measurable
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3 100 amounts of U and Pb can be used to determine crystallization ages (e.g. Burisch *et al.* 2017;
4
5 101 Ring and Gerdes 2016).

6
7
8 102 ~~According to Rasbury and Cole (2009), a linear regression taken through a group of~~
9
10 103 ~~samples from the same system produces a slope from which an age can be calculated using the~~
11
12 104 ~~accepted decay rate for the parent isotope. If the system being analysed has no initial~~
13
14 105 ~~heterogeneity, and it remained closed throughout the duration of the decay process, all scatter~~
15
16 106 ~~of data points about the isochron can be explained by analytical uncertainties. A statistical test~~
17
18 107 ~~of this is the mean squared weighted deviate (MSWD). Closed isotopic systems will plot as a~~
19
20 108 ~~line, giving a precise age and low mean squared weighted deviate (MSWD) of ~1, while~~
21
22 109 ~~systems that have not remained closed will show scatter and have a high MSWD (>>1). Here~~
23
24 110 we apply ~~this~~ the isochron method to dynamically recrystallised carbonate veins and selected
25
26 111 mineral assemblages (~~amphibole, epidote~~) in blueschists within the Kiphire District of the
27
28 112 Nagaland ophiolite belt and integrate these ages with thermobarometric data to produce new
29
30 113 constraints on the timing and rates of subduction and exhumation of Neo-Tethyan crust in the
31
32 114 Indo-Myanmar region.

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116 2. Geological background

117 The Indo-Myanmar Range is thought to represent a relict eastward-dipping subduction zone
118 that runs from the eastern edge of the Himalayan Range in southeast Tibet to the island of
119 Sumatra in the south (Allen *et al.* 2008; **Fig. 1**). **The Eastern Himalayas, about 700 km long,**
120 **trends ENE-WSW. Broadly N-S trending to sigmoid IMR has subdivided into three sectors**
121 **from north to south of about 400 km length each e.g., Naga Hills, Chin Hills and Arakan**
122 **Yoma (Acharyya 2015). The belt continues as the Anadaman Nicobar island arc in the south.**
123 **Belts of narrow tectonised but nearly continues, late Mesozoic-Eocene ophiolite and**
124 **associated sediments skirt along the northern margin of the Himalayas (Indus-Tsangpo**

1
2
3 125 **Ophiolite-ITO) and the eastern margin of the Himalayas IMR.** Structural relationships show
4
5 126 that Indian-plate oceanic crust was overridden by units of the **West Burma Block (ANY**
6
7 127 **INFORMATION ABOUT THESE? JUST A FEW NOTES ABOUT E.G.,**
8
9 128 **LITHOLOGY, TECTONIC SIGNIFICANCE ETC. WOULD BE USEFUL)** (e.g. Holt *et*
10
11 129 *al.* 1991; Mitchell *et al.* 2007; Searle *et al.* 2007), although its age of formation and the
12
13 130 timing of its obduction are poorly known. The Indo-Myanmar ophiolite belt separates
14
15 131 subducted Indian-plate oceanic lithosphere to the west from a closely associated high-
16
17 132 pressure metamorphic belt and Jurassic to Cretaceous magmatic arc–forearc complex of the
18
19 133 Burmese plate to the east (Mitchell *et al.* 2012). The Naga Hills ophiolite **is represented by**
20
21 134 **peridotite, cumulate mafic-ultramafic, mafic volcanics, eclogite, glaucophane schist,**
22
23 135 **amphibolite and late felsic intrusives. The ophiolite sequence has an east-dipping thrust**
24
25 136 **contact with the underlying flysch-like sediments of the Disang and Barail Formations**
26
27 137 **exposed to the west, and are overthrust from the east by continental metamorphic rocks of the**
28
29 138 **Naga Metamorphics consisting of quartz mica-schist, garnet mica-schist, quartzite, and**
30
31 139 **granitic gneiss (Brunnschweiler, 1966). The mid-Cretaceous, fossil-bearing Nimi Formation**
32
33 140 **occurs at the contact between the ophiolite and the Naga Metamorphics (Chatterjee and**
34
35 141 **Ghose, 2010).** Within this belt, blueschist- and eclogite-facies **mafic** rocks (SOME
36
37 142 **INFORMATION ABOUT THESE ROCKS, ARE THESE MAFIC? CARBONATIC?) occur**
38
39 143 **as tectonic slices (or detached layers and lenses) intercalated with unmetamorphosed**
40
41 144 **(MAYBE YOU SHOULD explicitly mention THIS, OTHERWISE IT MIGHT SOUND**
42
43 145 **A LITTLE BIT ODD, SINCE ALSO BLUESCHISTS AND ECLOGITES ARE MAFIC**
44
45 146 **ROCKS, DONE)** mafic and ultramafic units. Basement lithologies underlie Palaeogene
46
47 147 sediments in the ophiolite belt, although their geological history and lithological constitution
48
49 148 are uncertain (Acharyya 2015). Ophiolitic rocks within the Indo-Myanmar belt have been
50
51 149 subdivided into two parallel groups: the **(I AM NOT SURE THEY DISPLAYED IN FIG.**
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3 150 **1, AS I THINK THEY SHOULD)** ‘Eastern’ and ‘Western’ belts (Mitchell 1993), although
4
5 151 both show similar structural and petrological characteristics. Accretion of the Eastern Belt,
6
7 152 which contains metamorphosed ultramafic rocks in northern Myanmar that host world-
8
9 153 famous jadeitites, is thought to have occurred sometime after the Mesozoic (Gansser 1980;
10
11 154 Mitchell 1993; Shi *et al.* 2008). The Western Belt along the Naga and Manipur hills, which
12
13 155 forms part of the Indo-Myanmar Range, formed due to collision between India and the
14
15 156 Burmese microplate during the late Oligocene (Sengupta *et al.* 1990).

16
17 157 **There is still controversy about emplacement ages of ophiolites in these two belts: the**
18
19 158 **‘Eastern Belt’ is inferred to mark the locus of the subduction zone into which the ophiolites**
20
21 159 **were accreted since Mesozoic, whilst the ‘Western Belt’ was inferred to have been caused by**
22
23 160 **a late Oligocene terminal collision between the Indian and the Burmese continental blocks**
24
25 161 **(Shit *et al.*, 2014 and references therein).** In the ‘Western Belt’ a combination of radiolarian
26
27 162 biostratigraphy and whole-rock K–Ar geochronology suggests an Upper Jurassic age
28
29 163 (Kimmeridgian–Lower Tithonian) for marine sedimentation and volcanism in the **(YOU DID**
30
31 164 **NOT MENTION WHETHER THIS BELONGS TO WESTERN OR EASTERN BELT**
32
33 165 **DONE – NOW MENTIONED AT THE START OF THE SENTENCE)** Nagaland ophiolite
34
35 166 belt (Sarkar *et al.* 1996; Baxter *et al.* 2011). The mid-Cretaceous, fossiliferous Nimi
36
37 167 Formation occurs at the contact between the ophiolite and the Naga metamorphic units, and
38
39 168 so gives a maximum age constraint on the initiation of obduction. Recently, Singh *et al.*
40
41 169 (2017) reported U–Pb zircon ages ranging between 116 and 119 Ma from the plagiogranite
42
43 170 **(YOU DID NOT MENTION THE OPHIOLITE SEQUENCE EARLIER, THIS IS THE**
44
45 171 **FIRST TIME ONE READ ABOUT THIS PLAGIOGRANITE UNITS? WHICH I**
46
47 172 **THINK IT IS NOT A GOOD IDEA. MAYBE YOU MIGHT WANT TO INCLUDE**
48
49 173 **FEW NOTES ABOUT THE STRUCTURE OF THE NAGALAND OPHIOLITE**
50
51 174 **BEFORE THIS DESCRIPTION OF THE AVAILABLE GEOCHRONOLOGICAL**
52
53
54
55
56
57
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1
2
3 175 **DATA? DONE**) of the studied ophiolite. In the 'Eastern Belt' falling in the Myanmar Shi *et*
4
5 176 *al.* (2008) reported a sensitive high-resolution ion microprobe (SHRIMP) U–Pb zircon age of
6
7 177 146.5 ± 3.4 Ma ~~from~~ **for** jadeitites of the Jade Mines area, Myanmar, and ~~suggested~~ **proposed**
8
9 178 that subduction may have begun during the Late Jurassic. Mitchell (1993) suggested that the
10
11 179 Manipur ophiolitic nappe was emplaced along the Indo-Myanmar ranges during the Mid-
12
13 180 Eocene and was followed by a switch to east-dipping subduction from the mid-Miocene
14
15 181 onwards. Recently, Liu *et al.* (2016) reported a c. 125 Ma U–Pb zircon crystallisation age for
16
17 182 rodingite associated with formation of the ophiolite, and a c. 115 Ma age ~~from~~ **for** garnet
18
19 183 amphibolites ~~that may date metamorphism~~ within the Kalaymo ophiolite belt, which lies
20
21 184 adjacent to the Indo-Myanmar ophiolite belt. Shi *et al.* (2014) reported superimposed tectono-
22
23 185 metamorphic ages (**NOT SURE ABOUT BY THESE SUPERIMPOSED**
24
25 186 **TECTONOMETAMORPHIC AGES, MAYBE YOU SHOULD ELUCIDATE A**
26
27 187 **LITTLE**, we are reporting the ages as interpreted by Shi *et al.*, 2014 and cannot elucidate
28
29 188 **any further than the conclusions provided in that work**) of phengitic mica Ar–Ar ages from
30
31 189 blueschist-facies rocks in the Tagaung-Myitkyina Belt. They interpreted a Jurassic age (152.4
32
33 190 ± 1.5 Ma) obtained from glaucophane (**DID YOU MENTION THAT THEY DATED**
34
35 191 **PHENGITIC MICA**, they have analysed both the phengite and glaucophane) as the lower
36
37 192 limit of the subduction age and suggested that Eocene (45.0 ± 1.3 Ma) (**OBTAINED IN**
38
39 193 **WHAT KIND OR MINERAL PHASE, DONE**) ages recorded an intra-continental shearing
40
41 194 deformation event.

42
43 195 Chatterjee and Ghose (2010) documented eclogite- and blueschist-facies (**AGAIN**
44
45 196 **ANY INFORMATION ABOUT THE LITHO-TYPE, DONE**) rocks present as thrust
46
47 197 slices and lenses within the volcanic and ultramafic rocks of the **Naga ophiolite belt**
48
49 198 **complexes (IS THIS THE SAME AS NAGALAND OPHIOLITE BELT? PLEASE**
50
51 199 **NOTE THAT EVEN THOUGH THIS MIGHT SOUND ABSOLUTELY OBVIOUS TO**

1
2
3 200 **YOU, THIS IS NOT THE CASE FOR A READER WHO IS NOT FAMILIAR WITH**
4
5 201 **THE LOCAL GEOLOGY (AS I AM), TO WHICH ALL THESE FOREIGN NAMES**
6
7 202 **SOUND NEW AND POSSIBLY CONFUSING, DONE).** Ao and Bhowmik (2014)
8
9 203 deduced the thermal history of the eclogite and blueschist rocks ranging from ~~~11.5 kbar~~ **1.15**
10
11 **GPa** and ~340 °C to ~~6 kbar~~ **0.6 GPa** and 335 °C. Despite an improved understanding of the
12
13 204 tectonic evolution of the Indian ophiolite belt, a paucity of reliable geochronological age data
14
15 205 **(I AM NOT SURE ABOUT THIS IS EVIDENT FROM WHAT YOU REPORTED**
16
17 206 **ABOVE, YOU MENTION NUMEROUS AGE DATA, WHICH MIGHT SOUND**
18
19 207 **PERFECTLY RELIABLE IF YOU DO NOT EXPLAIN WHY DO NOT CONSIDER**
20
21 208 **THEM SO. MAY BE YOU MIGHT ADD SOME MORE SPECIFIC COMMENTS**
22
23 209 **ABOUT THIS, EXPLAINING WHY THE DATA IS AT LEAST QUESTIONABLE. I**
24
25 210 **AM SURE THIS WILL HELP THE READER (ESPECIALLY THE non-expert ONE)**
26
27 211 **TO UNDERSTAND WHAT IS THE POINT OF STRENGTH OF YOUR NOVEL**
28
29 212 **APPROACH TO SUCH TOPICS, DONE)** has hindered the correlation of sutures and
30
31 213 collisional deformation episodes within the region **(AGAIN I AM AFRAID THAT IF YOU**
32
33 214 **DO NOT PROVIDE SOME ADDITIONAL DETAILS (POSSIBLE WITH SOME**
34
35 215 **EXAMPLES), IT IS NOT COMPLETELY CLEAR WHAT ARE THE PROBLEMS**
36
37 216 **HERE. PLEASE NOTE THAT IS A RATHER GENERAL STATEMENT THAT**
38
39 217 **MIGHT APPLY VIRTUALLY TO ANY CASE STUDY. SO I WARMLY INVITE**
40
41 218 **YOU TO INCLUDE SOME ADDITIONAL DETAIL. I AM NOT SAYING YOU**
42
43 219 **SHOULD MAKE A THOROUGH REVIEW ABOUT THESE ISSUES BUT SIMPLY**
44
45 220 **ADD SOME INFORMATION ABOUT E.G., THE MOST PROBLEMATIC POINTS**
46
47 221 **OF DEBATE THAT MIGHT BENEFIT FROM THE RESULTS OF YOUR WORK)**
48
49
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224 3. Analytical methods

1
2
3 225 The eclogites and blueschists rocks of Naga Hills occur as NE–SW to N–S oriented, steeply
4
5 226 east-dipping shear fault-bound tectonic slices or detached layers and lenses intercalated with
6
7 227 basaltic and ultramafic units parallel to the shear faults in the Naga Hills ophiolite of Phek
8
9 228 district, Nagaland (Chatterjee and Ghose, 2010). In the area eclogite constitutes the core of
10
11 229 some lenses, which are surrounded by successive layers of garnet-blueschist, glaucophanite
12
13 230 and greenschist. Twenty metamorphosed samples were collected between Longkhimong and
14
15 231 Moya villages, after systematic petrographic study six samples were selected for detailed
16
17 232 study. Mineral compositional data for all samples (**YOU NEVER DESCRIBED THESE**
18
19 233 **EARLIER IN THE TEXT. I THINK IT WOULD BE BETTER TO FIRST EXPLAIN**
20
21 234 **WHAT KIND OF SAMPLES WERE INVESTIGATED, AND THEN HOW. MAYBE**
22
23 235 **YOU CAN ADD SOME NOTES ABOUT THE SAMPLING ACTIVITIES,**
24
25 236 **INCLUDING LOCATIONS, STRATIGRAPHIC POSITIONS, LITHOTYPES,**
26
27 237 **NUMBER OF COLLECTED SAMPLES ETC. DONE**) were obtained on a JEOL JXA-
28
29 238 8200 electron microprobe housed at the Institute of Geosciences, Johannes-Gutenberg
30
31 239 University of Mainz, Germany. Operating conditions included an acceleration voltage of 15
32
33 240 kV, a beam current of 12 nA, and a 2 μm spot size. A matrix correction for atomic number
34
35 241 (Z), absorption (A), and fluorescence (F) was automatically applied to all analyses. For the
36
37 242 data presented below, mineral compositions were recalculated to standard numbers of
38
39 243 oxygens per formula unit (pfu) using the software AX (Holland 2009), with OH assumed to
40
41 244 be present in stoichiometric amounts. The proportion of ferric iron in different mineral
42
43 245 species was also calculated using the software AX (Holland 2009). Mineral proportions for
44
45 246 each sample were determined using the software JmicroVision (Roduit 2010), with each
46
47 247 individual count consisting of five hundred points randomly distributed over a digitally
48
49 248 scanned thin-section image. Calculated volume proportions (**HOW HAVE THIS BEEN**
50
51 249 **CALCULATED? I THINK YOU SHOULD SPECIFY THIS, ALSO CONSIDERING**
52
53
54
55
56
57
58
59
60

1
2
3 250 **THAT YOU DID NOT JUST MAKE A MODAL BY SIMPLE POINT COUNTING.**
4
5 251 **THEREFORE, I THINK IT IS ABLUTELY NEVESSARY TO EXPLAIN HOW DID**
6
7 252 **YOU MAKE THIS KIND OF CALCULATION)** of minerals in each sample are given
8
9
10 253 below. These bulk compositions are given in Supplementary Table 3. ~~Mineral proportions for~~
11
12 254 ~~each sample were determined using the software JmicroVision (Roduit 2010), with each~~
13
14 255 ~~individual count consisting of five hundred points randomly distributed over a digitally~~
15
16 256 ~~scanned thin-section image.~~ Mineral abbreviations are after Kretz (1983). Representative
17
18 257 **(WHY ONLY SOME REPRESENTATIVES? YOU CAN INCLUDE ALL YOUR**
19
20 258 **DATASET IN THE ESM – we believe that providing all data in electronic appendices**
21
22 259 **offers no significant benefit from providing representative examples. This is our preferred**
23
24 260 **style for data presentation and indeed it is commonplace in petrological studies to only show**
25
26 261 **representative examples.)** compositions of major minerals for all samples are given in
27
28
29 262 Supplementary Table 2 and photomicrographs of microstructural features and assemblages
30
31
32 263 are shown in [Figures 2 and 3](#).

33
34
35 264 Bulk-rock compositions for use in petrological modelling were obtained from X-ray
36
37 265 fluorescence (XRF) via the production of glass ~~pellets beads~~ **(IS THIS CORRECT? TO**
38
39 266 **MY KNOWLEDGE, YOU CAN HAVE “PRESSED POWDER PELLETS”, BUT**
40
41 267 **FUSED SAMPLES ARE REFERRED TO AS ‘GLASS BEADS’ PLEASE CHECK**
42
43 268 **DONE)** in order to guarantee standardised and reproducible analyses. Powdered rock samples
44
45 269 were initially dried overnight at 105 °C. Approximately 5.2 g of lithium tetraborate ($\text{Li}_2\text{B}_4\text{O}_7$)
46
47 270 flux and 0.4 g of powdered rock sample were then weighed, homogenized, and melted in a
48
49 271 Vulcan AMA melting device to produce each glass ~~pellet beads~~ **(HERE AND IN THE**
50
51 272 **FOLLOWING: AS IN THE PREVIOUS COMMENT, PLEASE CHECK IF ‘PELLET’**
52
53 273 **IS APPROPRIATE).** These ~~pellets beads~~ were then analyzed in a Philips MagXPRO
54
55 274 spectrometer with a rhenium X-ray tube housed in the Institute of Geoscience, Johannes
56
57
58
59
60

1
2
3 275 Gutenberg University of Mainz, Germany. Detection limits are estimated to be $100 \mu\text{g g}^{-1}$ for
4
5 276 light elements (Na, Mg, Al) and $10 \mu\text{g g}^{-1}$ for heavy elements (K to U). Analysed major
6
7 277 oxides comprised SiO_2 , Al_2O_3 , total Fe_2O_3 , MnO, MgO, CaO, Na_2O , K_2O , TiO_2 , P_2O_5 , SO_3 ,
8
9 278 Cr_2O_3 , and NiO.

12 279 All U–Pb ages **for the analysed carbonate grains and silicate phases** were acquired *in*
13
14 280 *situ* from polished thin sections by laser ablation-inductively coupled plasma-mass
15
16 281 spectrometry (LA-ICP-MS) at the Goethe University Frankfurt (GUF), using a Element2
17
18 282 (Thermo-Scientific) sector field ICP-MS coupled to a RESOLUTION ArF Excimer laser
19
20 283 (Compex Pro 102). The applied method was similar as described in Ring and Gerdes (2016),
21
22 284 Burisch *et al.* (2017), Hansman *et al.* (2018) and Salih *et al.* (2019). Ablation spot size was
23
24 285 $213 \mu\text{m}$ and crater depth was $\sim 20 \mu\text{m}$. Samples were screened by LA-ICP-MS for suitable Pb
25
26 286 and U concentration and variability, and selected spots were subsequently analysed in fully
27
28 287 automated mode. Spot analyses consisted of 20 s background acquisition followed by 20 s
29
30 288 sample ablation. Surface contamination was removed prior to each spot analysis via a 3-s pre-
31
32 289 ablation. Soda-lime glass SRM-NIST 614 was used as a reference material together with two
33
34 290 carbonate reference materials – WC-1 and a Zechstein dolomite – to bracket sample analysis.
35
36 291 SRM-NIST 614 yielded a depth penetration of about $0.5 \mu\text{m s}^{-1}$ and an average sensitivity of
37
38 292 $280,000 \text{ cps}/\mu\text{g g}^{-1}$ for ^{238}U . The detection limits for ^{206}Pb and ^{238}U were ~ 0.1 and 0.05 ng
39
40 293 g^{-1} , respectively. All data were corrected using an MS Excel spreadsheet program (Gerdes
41
42 294 and Zeh, 2006, 2009). NIST 614 was used as a standard for the analysis of silicate phases
43
44 295 **(SO YOU ANALYSED SILICATE PHASES ALSO? THIS IS NOT WHAT IS**
45
46 296 **REPORTED IN THE ABSTRACT. PLEASE ELUCIDATE, DONE)**. The possible offset
47
48 297 related to sample matrix is within the analytical uncertainty of the quoted ages.

51
52 298 The $^{207}\text{Pb}/^{206}\text{Pb}$ ratio was corrected for mass bias (0.3%) and the $^{206}\text{Pb}/^{238}\text{U}$ ratio for
53
54 299 inter-element fraction (ca. 5%) using SRM-NIST 614. An additional correction of 4% was
55
56
57
58
59
60

1
2
3 300 applied on the $^{206}\text{Pb}/^{238}\text{U}$ to correct for difference in the fractionation due to the carbonate
4
5 301 matrix. This resulted in a lower intercept age of 23 WC-1 spot analyses of 254.1 ± 1.5
6
7 302 (MSWD = 1.5; anchored at $^{207}\text{Pb}/^{206}\text{Pb}$ of 0.851) and 253.9 ± 3.4 (MSWD = 1.5; n = 17) for
8
9 303 the Zechstein dolomite used as an in-house reference material in Frankfurt. Data were plotted
10
11 304 on a Tera-Wasserburg diagram and ages calculated as lower intercepts using Isoplot 3.71
12
13
14 305 (Ludwig 2007). All uncertainties are reported at the 2 sigma level.

15
16
17 306 According to Rasbury and Cole (2009), a linear regression taken through a group of
18
19 307 samples from the same system produces a slope from which an age can be calculated using
20
21 308 the accepted decay rate for the parent isotope. If the system being analysed has no initial
22
23 309 heterogeneity, and it remained closed throughout the duration of the decay process, all scatter
24
25 310 of data points about the isochron can be explained by analytical uncertainties. ~~A statistical~~
26
27 311 ~~test of this is the mean squared weighted deviate (MSWD).~~ Closed isotopic systems will plot
28
29 312 as a line, giving a precise age and low **mean squared weighted deviate (MSWD) of ~1,**
30
31 313 while systems that have not remained closed will show scatter and have a high MSWD ($\gg 1$).
32
33
34
35
36

37 314

38 315 **4. Sample petrology**

39
40 316 ~~Out of the twenty collected samples we have selected four metabasite samples for systematic~~
41
42 317 ~~study and well-constrained P-T conditions could derived from four samples~~
43
44 318 ~~only thermobarometry~~ Six metabasite samples were collected from (AS SAID IN A
45
46
47 319 **PREVIOUS COMMENT, I THINK THAT GENERAL INFORMATION ABOUT THE**
48
49 320 **INVESTIGATE SAMPLES SHOULD BE REPORTED IN THE TEXT. ALSO YOU**
50
51 321 **SAY THAT YOU COLLECTED 6 SAMPLES, BUT IN THE FOLLOWING SECTION**
52
53 322 **IT SEEMS TO ME THAT YOU ARE DESCRIBING ONLY 4 OF THEM: THE**
54
55 323 **UNSHEARED N5 AND 14 AND THE SHEARED 7C AND 11. PLEASE ELUCIDATE)**
56
57 324 ~~around Moya and Longkhimong (Fig. 1C) to place constraints on the metamorphic and~~
58
59
60

1
2
3 325 ~~deformational history of the Nagaland ophiolite belt.~~ Locality information and GPS co-
4
5 326 ordinates for each outcrop are given in Supplementary Table 1 **and location map is presented**
6
7 **in Figure 1C.** Field photographs of the studied samples are presented in Figure 1D. The
8 327
9
10 328 samples occur as meter-sized boulder blocks, which occur individually and in clusters (Fig. 1
11
12 329 D1, D3) within serpentinites. Samples are thus classified as either sheared ~~and-or~~ unsheared
13
14 330 based on the occurrence of key deformational features present at the field, hand sample, and
15
16 331 microscopic scale. Samples N5 and 14 lack evidence of post-peak shear-driven
17
18 332 recrystallization and likely represent relics of undeformed, peak metamorphic blueschists. By
19
20 333 contrast, samples 7c, 13, 3b, and 11 are strongly sheared and represent subsequently
21
22 334 deformed equivalents of these older units.
23
24
25
26 335

28 336 *4.1. Sample description*

30 337 *4.1.1. Unsheared samples N5 and 14*

32 338 Unsheared samples N5 and 14 exhibit a largely unfoliated microstructure and show no
33
34 339 evidence of pervasive retrogression following peak blueschist-facies metamorphism during
35
36 340 subduction, though localised retrogression does occur. Sample N5 is a blueschist that
37
38 341 contains abundant sodic amphibole (38%) and epidote (37%), with minor quartz (9%), garnet
39
40 342 (6%), sodic-calcic amphibole (4%), phengite (3%), and rutile (2%). Accessory pyrite, zircon,
41
42 343 and apatite (~~all <<1%~~) also occur. Garnet porphyroblasts are between 0.5 and 2 mm in
43
44 344 diameter (Figures 2a–b) and exhibit no substantial major element compositional zoning, with
45
46 345 core compositions of $\text{Alm}_{56-58}\text{Prp}_{12-14}\text{Grs}_{21-22}\text{Sps}_{7-8}$ and rim compositions of $\text{Alm}_{60-61}\text{Prp}_{15-}$
47
48 346 $_{16}\text{Grs}_{22-23}\text{Sps}_{3-4}$ (Supplementary Table 2 and Fig. 4). Core regions contain inclusions of
49
50 347 pumpellyite, phengite, epidote, barroisite, actinolite, and quartz, and rims contain inclusions
51
52 348 of phengite, epidote, actinolite, rutile, and quartz. Some grains show replacement by chlorite
53
54 349 at their outermost rims. Matrix phengite ~~contains~~ **has** Si = 3.34–3.38 pfu (**on a 11 O basis;**
55
56
57
58
59
60

Supplementary Table 2) and grains included in the outer rims of garnet ~~contain~~ **has** Si = 3.32–3.35 pfu. Epidote shows no significant compositional zoning from core to rim, with a minor range in pistacite content ($\{XPs = Fe^{3+}/(Al^{3+}+Fe^{3+})\}$) of 0.18–0.21 (Supplementary Table 2). According to the classification scheme of Hawthorne *et al.* (2012), sodic and sodic-calcic amphiboles in the matrix are glaucophane and winchite–katophorite, respectively (Figure 5).

Sample 14 is modally dominated by epidote (50%) and quartz (35%), with lesser garnet (1%), sodic-calcic amphibole (10%), phengite (2%), rutile (0.5%), ~~sphene–titanite~~ (0.5%), and carbonate (21%) **(BASED ON SUCH MINERALOGY, HOW CAN YOU CONSIDER THIS TO BE A BLUESCHIST (METABASIC) ROCK? ALSO PLEASE NOTE THAT SUM OF THE LISTED MINERALS IS 101% We follow the definition of Ernst (1963) in that a blueschist defined by the presence of the minerals glaucophane + (lawsonite or epidote) +/- jadeite +/- albite or chlorite +/- garnet +/- muscovite in a rock of roughly basaltic composition)**. Accessory minerals include chlorite, apatite, and zircon (all <<1%). Although sample 14 ~~contains~~ **displays** no foliation, it is mildly anisotropic, with alternating centimetre-scale quartz- and epidote-rich domains. In contrast to the large porphyroblasts present in sample N5, garnet forms <0.1 mm diameter grains that are restricted to quartz-rich regions (Figure 2). These garnet grains have no inclusions and are compositionally homogeneous ($Alm_{36-39}Prp_{10-13}Grs_{31-36}Sps_{36-39}$) **(VERY DIFFERENT FROM SAMPLE N5, FURTHER HIGHLIGHTING THAT THIS CANNOT BE CONSIDERED SAME ROCK TYPE AS THE REPIUOS, IN MY OPINION we do not consider this the same rock type. it is simply grouped here with 14 due to it being unsheared. the degree of deformation is the primary discriminator in this work.)**. Epidote shows no significant zoning, with core and rim compositions both having similar pistacite contents of 0.20–0.24 (Supplementary Table 2). Matrix rutile is partially or fully replaced by titanite (Figure 2), though rare inclusions in sodic-calcic amphibole lack such pseudomorph textures.

1
2
3 375 Phengite contains Si = 3.34–3.35 pfu (for 11 oxygens; Supplementary Table 2) and in places
4
5 376 is intimately intergrown with chlorite, though the extremely fine-grained nature of these
6
7 377 intergrowths prohibited reliable compositional analysis of either phase. Sodic-calcic
8
9
10 378 amphibole in the matrix is barroisite–winchite–katophorite (Hawthorne *et al.* 2012; Figure 5),
11
12 379 with rare tremolite, likely representing minor post-peak retrograde mineralogical
13
14
15 380 transformation.

16
17 381 Most natural carbonate occurs in the form of calcite and can be transported to the
18
19 382 Earth's interior via subduction of carbonate-rich sediments or metasomatized oceanic crust
20
21 383 (*Zhang et al.* 2018). Calcite transforms to aragonite at high pressure. Although may revert
22
23 384 back to calcite during exhumation if there are no kinetic limitations. At the *P–T* conditions of
24
25 385 peak metamorphism for samples N5 and 14 (see below), the carbonate likely stabilised in the
26
27 386 form of aragonite, whereas carbonate in sheared samples 11 and 7c is calcite, which indicates
28
29 387 polymorphic transformation following exhumation from peak depths (**IN MY OPINION,**
30
31 388 **THIS IS NOT APPROPRIATE FOR A SAMPLE DESCRIPTION SECTION LIKE**
32
33 389 **THIS IS. I THINK IT SHOULD BE MOVED TO THE DISCUSSION SECTION.**
34
35 390 **ALSO, I WOULD SUGGEST ADDING A FEW REFERENCES FOR THE GENERAL**
36
37 391 **STATEMENT ABOUT CARBONATE MINERALS AND ON**
38
39 392 **CALCITE/ARAGONITE TRANSITIONS AT THE BEIGINNING OF THIS PIECE**
40
41 393 **OF TEXT.**) Analysed spots are presented in Supplementary Figure 5.
42
43
44
45
46
47
48

49 395 4.1.2. Sheared samples 11 and 7c

50
51 396 In contrast to N5 and 14, (**SO YOU THINK THAT SAMPLES N5 AND 14 ARE**
52
53 397 **MINERALOGICALLY HOMOGENEOUS? I FRANKLY CANNOT AGREE WITH**
54
55 398 **IT, SINCE ONE IS BASICALLY GLN+EP, THE OTHER IS EP+Wtz. I THINK**
56
57 399 **YOU SHOULD CAREFULLY RE-CONSIDER THIS** The confusion here emanates from
58
59
60

1
2
3
4 400 poor wording, which we have corrected. We do not think that both samples are similar
5
6 401 (mineralogically) or homogenous – just that they are unsheared. The text has been modified
7
8 402 accordingly.) sheared samples 11 and 7c ~~are mineralogically heterogeneous,~~ containing
9
10 403 distinct spaced foliations that are truncated by carbonate- and quartz-filled veins. These
11
12 404 crosscutting veins commonly form shear bands (Figures 3e–f) and locally deflect the main
13
14 405 metamorphic foliations at their boundaries (Figure 3b), indicating that shearing and vein
15
16 406 formation post-dated subduction metamorphism. The host rock domains in sample 7c are
17
18 407 dominated by epidote (39%), calcic amphibole (32%), and sodic–calcic amphibole (18%),
19
20 408 with minor ~~phengite~~ ~~muscovite~~ (4%), albite (2%), K-feldspar (2%), titanite (1%), and quartz
21
22 409 (2%). Apatite and zircon occur as accessory phases (**PLEASE NOTE THAT SUM OF THE**
23
24 410 **PHASES LISTED ABOVE IS ALREADY 100%** these are simply rounding issues and
25
26 411 accessory phases, by definition, have very minor volumetric proportions. if we are to round
27
28 412 the volume of the accessories to the nearest integer, they would have 0% volume anyway,
29
30 413 leaving a total of 100%). The main metamorphic foliation is defined by elongate and aligned
31
32 414 crystals of epidote and amphibole (Figure 3a). Large green calcic amphibole is mostly
33
34 415 pargasite with thin magnesiohornblende outer rims, and sodic-calcic amphibole is winchite
35
36 416 (Figure 5). Matrix ~~muscovite~~ ~~phengite~~ has Si = 3.39–3.43 pfu and epidote cores have XPs =
37
38 417 0.19–0.25 and rims have XPs = 0.26–0.33 (Supplementary Table 2). Quartz- and carbonate -
39
40 418 filled veins crosscut and offset this epidote- and amphibole-defined metamorphic foliation
41
42 419 (Fig. 3b).

49 420 Sample 11 contains abundant sodic amphibole (33%), quartz (34%), carbonate (14%),
50
51 421 and sodic pyroxene (11%), with subsidiary sodic–calcic amphibole (2%), ~~muscovite~~ ~~phengite~~
52
53 422 (1%), garnet (2%), and albite (1%). Accessory pyrite, titanite, apatite, and zircon (all <<1%)
54
55 423 also occur. Alternating sodic amphibole (glaucophane) and quartz-rich bands define a spaced
56
57 424 foliation that wraps around porphyroblasts of pyroxene and garnet (Figure 3c). Grains of the
58
59
60

1
2
3 425 latter are commonly less than 1 mm in diameter and are variably replaced by aggregates of
4
5 426 carbonate, albite and/or quartz (Figure 3d). Though individual grains lack any significant
6
7
8 427 major-element compositional zoning from core to rim, compositions vary significantly
9
10 428 between grains; the majority are spessartine-rich ($\text{Alm}_{19-24}\text{Prp}_{10-14}\text{Grs}_{17-20}\text{Sps}_{45-51}$), while
11
12 429 others are richer in almandine and grossular ($\text{Alm}_{26-29}\text{Prp}_{12}\text{Grs}_{23-32}\text{Sps}_{28-37}$). Minor sodic-
13
14 430 calcic amphibole in the matrix is winchite, and sodic pyroxene porphyroblasts are
15
16 431 compositionally classified as aegirine–augite ($X_{\text{Jd}} = 0.04-0.23$) (**GIVE JADEITITE**
17
18 432 **COMPONENT**) (Morimoto *et al.* 1988).
19
20
21 433

22
23
24 434 **5. Thermobarometry/Phase equilibria modelling (MAY BE A DIFFERENT NAME**
25
26 435 **LIKE E.G., “PHASE EQUILIBRIA MODELLING” WOULD BE MORE**
27
28 436 **APPROPRIATE, DONE)**

29
30 437 Constraints on the P – T conditions of peak subduction-zone metamorphism were obtained
31
32 438 from unsheared samples N5 and 14, whereas constraints on the P – T conditions of subsequent
33
34 439 ductile shearing were obtained from sheared sample 7c (**WHAT ABOUT THE OTHER**
35
36 440 **SHEARED SAMPLE 11? WHY YOU DID NOT USE THIS HERE? I THINK YOU**
37
38 441 **SHOULD ADD SOME EXPLANATION**). Preliminary investigation of phase equilibria
39
40 442 stability in sample 11 did not allow for reliable thermobarometry to be performed due to the
41
42 443 high variance of the interpreted peak mineral assemblage. Phase diagrams showing the P – T
43
44 444 conditions over which equilibrium mineral assemblages are calculated to occur in a specific
45
46 445 bulk-rock composition (pseudosections) (**SINCE YOU ARE USING BULK ROCK**
47
48 446 **COMPOSITIONS HERE I THINK YOU SHOULD ADD A SECTION ABOVE IN**
49
50 447 **WHICH ROCK COMPOSITIONS ARE PRESENTED AND DESCRIBED, AT LEAST**
51
52 448 **A LITTLE BIT. THIS IS NECESSARY ALSO TO UNDERSTAND WHY DID YOU**
53
54 449 **CHOOSE THAT SPECIFIC MODEL SYSTEM. This is unnecessary – the petrological**
55
56
57
58
59
60

1
2
3 450 modelling community has well-defined compositional systems for use in modelling particular
4
5 451 protoliths (e.g. metabasalts). These are constrained by the available a-x relations rather than
6
7 452 the mineralogy of the rocks themselves.) were constructed using THERMOCALC v3.40i and
8
9 453 the internally consistent thermodynamic data set ds55 (Powell and Holland 1988; Holland
10
11 454 and Powell 1998; updated to August 2004) in the Na₂O–CaO–K₂O–FeO–MgO–Al₂O₃–SiO₂–
12
13 455 H₂O–TiO₂–O (NCKFMASHTO) compositional system. The following activity–composition
14
15 456 relations for solid-solution phases were used: clinoamphibole (**WHAT IS THE SOURCE**
16
17 457 **FOR THIS**) (calcic, sodic-calcic, and sodic amphibole; Diener and Powell 2012),
18
19 458 clinopyroxene (diopside and omphacite, Diener and Powell 2012), muscovite and paragonite
20
21 459 (Coggon and Holland 2002), talc and epidote (Holland and Powell 1998), chlorite (Holland *et*
22
23 460 *al.* 1998), biotite and garnet (White *et al.* 2007), plagioclase and K-feldspar (Holland and
24
25 461 Powell 2003), ilmenite and hematite (White *et al.* 2000). Albite, lawsonite, rutile, titanite,
26
27 462 quartz, kyanite, and H₂O were treated as pure phases.
28
29
30
31
32
33

34 463 *5.1. Metamorphic mineral equilibria modelling parameters*

35
36 464 Bulk-rock compositions used for modelling were obtained via XRF analysis, as discussed
37
38 465 previously (Supplementary Table 2) (**THIS IS GETTING TORTOUS. IN THE**
39
40 466 **ANALYTICAL TECHNIQUES SECTIONS YOU SAID YOU ACTUALLY**
41
42 467 **DETERMINED BULK ROCK COMPOSITIONS VIS XRF ANALYSES. SO WHY**
43
44 468 **YOU DID NOT USE THEM? NOT EVEN MENTIONING THAT IN THE**
45
46 469 **‘ANALYTICAL METHOD’ SECTION YOU EXPLICITLY REPORTED THAT**
47
48 470 **‘BULK-ROCK’ COMPOSITION FOR USE IN PETROLOGICAL MODELLING**
49
50 471 **WERE OBTAINED FROM X-RAY FLOURESCENCE (XRF)’ (LINES 168-169). IN**
51
52 472 **ADDITION, YOU REFER TO SOME SORT OF CALCULATION FOR OBTAINING**
53
54 473 **MINERAL ABUNDANCES, SO I AM WONDERING IF THE ‘MINERAL**
55
56 474 **PROPORTIONS’ INDICATED HERE ARE ACTUALLY MODAL PROPORTIONS**
57
58
59
60

1
2
3 475 **(I.E., DETERMINED DIRECTLY, VIA POINT COUNTING) OR RATHER WERE**
4
5 476 **CALCULATED IN SOME SORT OF WAY (WHICH NEEDS TO BE SPECIFIED).**
6
7 477 **PLEASE CAREFULLY ELUCIDATE ALL THIS. AFTER GOING THROUGH THE**
8
9 478 **MANUSCRIPT, I'VE NOTICED THAT THE RESULTS OF XRF ANALYSES ARE**
10
11 479 **NEVER EVEN REPORTED IN THE ELECTRONIC APPENDIX. ALL THIS IS**
12
13 480 **DEFINITELY NEEDS TO BE CLARIFIED – this was an unfortunate typo; we apologize**
14
15 481 **for the confusion. XRF data were used.**) These bulk compositions are given in
16
17 482 Supplementary Table 3. Mineral proportions for each sample were determined using the
18
19 483 software JMicroVision (~~SO FINALLY, THE MODAL PROPORTIONS TURN OUT TO~~
20
21 484 ~~BE DETERMINED (NOT CALCULATED) VIA POINT COUNTING. I THINK THIS~~
22
23 485 ~~SHOULD BE SAID MUCH EARLIER, IN THE ANALYTICAL TECHNIQUES~~
24
25 486 ~~SECTION.)~~ (Roduit 2010), with each individual count consisting of five hundred points
26
27 487 (~~ARE YOU SURE THESE ARE SUFFICIENT? TO MY KNOWLEDGE, YOU NEED~~
28
29 488 ~~TO HAVE MUCH MORE POINTS (3-4 THOUSANDS) IN ORDER TO CONSIDER~~
30
31 489 ~~YOUR MODAL ANALYSIS STATISTICALLY RELIABLE.)~~ randomly distributed
32
33 490 over a digitally scanned thin section image (~~NOT CLEAR TO ME: IS THIS IMAGE~~
34
35 491 ~~COVERING THE ENTIRE THIN SECTION AREA, OR JUST A PART OF IT? I~~
36
37 492 ~~GUESS (AND HOPE) THE SECOND, BUT MAY BE IT WOULD BE USEFUL TO~~
38
39 493 **EXPLICITLY MENTION THIS – point counting was applied to the entire thin section**
40
41 494 **image, aside from areas that do not actually contain pieces of the rock (e.g. as it is not a**
42
43 495 **perfect rectangle). 500 points were sufficient in this case, as we kept track of the evolving**
44
45 496 **proportions during analyses and the values converged on final results after ~300 points or so;**
46
47 497 **thus, adding an extra 500 or 1000 points onto this initial 500 will produce no better**
48
49 498 **precision.**) For sample 7c, areas adjacent to shear bands were excluded from consideration
50
51
52
53
54
55
56
57
58
59
60

1
2
3 499 during point counting such that the proportions obtained represent unsheared portions of the
4
5 500 sample that equilibrated prior to deformation.
6

7
8 501 ~~Although Schmidt and Poli (1998) suggest that seafloor hydrated metabasites can~~
9
10 502 ~~contain up to 5–6 wt.% H₂O, prograde metamorphism during subduction results in the~~
11
12 503 ~~breakdown of hydrous phases such as chlorite, epidote, and amphibole, leading to progressive~~
13
14 504 ~~dehydration and fluid loss from the local environment (e.g. Guiraud *et al.*, 2007, Hernandez-~~
15
16 505 ~~Uribe *et al.*, 2020) (THIS IS COMMON KNOWLEDGE. I DO NOT THINK IT IS~~
17
18 506 **NECESSARY TO REPORT IT. MOREOVER, I DO NOT THINK IT APPROPRIATE**
19
20 507 **IN THIS SECTION, WHERE I EXPECT TO SEE ONLY INFORMATION ABOUT**
21
22 508 **HOW YOU PERFORMED YOUR MODELS - deleted).** The effective fluid contents of
23
24 509 ~~for~~ each bulk rock composition during metamorphism were calculated using the proportions
25
26 510 of hydrous phases present in each equilibrium mineral assemblage, assuming H₂O was
27
28 511 present in stoichiometric amounts. Mixed-component fluids were not considered due to the
29
30 512 lack of reliable ~~a-x relations~~ for C–O–H fluids at elevated pressures (**NOT SURE ABOUT**
31
32 513 **WHAT YOU MEAN WITH THIS. WHAT ARE THESE ‘RELIABLE C-O-H FLUIDS’**
33
34 514 **THAT LACK AT ELEVATED PRESSURES? DO YOU MEAN MODELS FOR**
35
36 515 **SUCH KIND OF FLUIDS” PLEASE ELUCIDATE.** ~~done~~); ~~nonetheless~~, however, this
37
38 516 should not have any significant effects on our calculated diagrams, as ~~unsheared~~ sample N5
39
40 517 does not contain carbonate, ~~unsheared~~ sample 14 contains only a minor proportion (2.2 vol.
41
42 518 %), and carbonate veins in sheared sample 7c are interpreted from microstructural constraints
43
44 519 to post-date final metamorphism and textural equilibration. Pressure uncertainties for
45
46 520 assemblage field boundaries are approximately ~~±1 kbar~~ **0.1 GPa** (Powell and Holland 2008;
47
48 521 ~~Palin *et al.* 2016). Calculated *P–T* pseudosections for each sample are given below.~~
49
50
51
52
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54
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522
523 *5.1.1. Unsheared samples*

1
2
3 524 ~~The range of mineral parageneses and microstructural features in each sample allows $P-T$~~
4
5 525 ~~constraints to be placed on peak metamorphism and exhumation-related ductile shearing.~~
6
7 526 Calculated mineral assemblages matching those observed in unsheared samples N5 and 14 (I
8
9
10 527 **THINK IT WOULD BE MUCH BETTER IF YOU PRESENT THE RESULTS FOR**
11
12 528 **THESE TWO SAMPLES SEPARATELY. THEN YOU SHOULD PROPOSE A**
13
14 529 **SINGLE P-T RANGE BY COMPRAING THEM AND SEE WHERE THE BEST**
15
16 530 **MATCHES FOR BOTH SAMPLES OVERLAP. We disagree – we are grouping samples**
17
18 531 **together according to whether they are sheared or unsheared.)** constrain peak $P-T$ conditions
19
20 532 of subduction-zone metamorphism to $\sim 1.8\text{--}2.0$ GPa and $\sim 420\text{--}560$ °C, with the calculated
21
22 533 proportions and compositions of major minerals best matching (**THIS IS A VERY VAGUE**
23
24 534 **CONCEPT. I MEAN, HOW DO YOU EVALUATE WHICH ONE IS THE BEST**
25
26 535 **MATCH? GENERALLY SPEAKING, I GUESS YOU CAN SAY THIS IS THE ONE**
27
28 536 **MINIMIZING THE DIFFERENCES BETWEEN THE OBSERVED AND**
29
30 537 **CALCULATED MINERAL ABUNDANCES, BUT MAY BE THIS CAN DONE IN**
31
32 538 **SOME OTHER WAY LIKE, E.G., MINIMIZING THE SQUARED RESIDUALS OF**
33
34 539 **THE DIFFERENCES, OR MAY BE EVEN IN SOME OTHER WAYS. IN ANY CASE**
35
36 540 **I THINK YOU SHOULD EXPLICITLY REPORT WHAT WAS YOUR STRATEGY,**
37
38 541 **ALONG WITH ALL THE OTHER INFORMATION WHICH CAN HELP THE**
39
40 542 **READER FIGURING OUT WHAT WAS DONE.)** observed values at ~ 1.9 GPa and
41
42 543 $\sim 480\text{--}520$ °C. These conditions lie along the global range of $P-T$ conditions predicted to
43
44 544 occur at the surface of subducted oceanic crust in modern-day subduction zones (Syracuse *et*
45
46 545 *al.* 2010; Penniston-Dorland *et al.* 2015).

546

547 *5.1.2. Sheared sample* (**STILL WONDERING WHY SAMPLE 11 WAS NOT USED**548 **FOR SUCH MODELS) Preliminary inspection did not reveal it to be useful or**

1
2
3 549 thermobarometry – not all rocks are useful, and this is a trial and error procedure that cannot
4
5 550 be easily predicted ahead of time.
6

7
8 551 In contrast with the undeformed samples, the observed mineral assemblage in sample 7c was
9
10 552 calculated to be stable at the notably lower pressure and slightly lower temperature conditions
11
12 553 of ~0.2–0.6 GPa and ~420–490 °C, with observed and calculated mineral proportions and
13
14 554 compositions matching best at ~0.6 GPa and ~470 °C. These P – T conditions are far removed
15
16 555 from the slab-top range for modern-day subduction reported by Syracuse *et al.* (2010). The
17
18 556 calculated pressures of ~1.9 GPa for peak metamorphism and ~0.6 GPa for retrograde
19
20 557 equilibration are approximately equivalent to depths of 60 km and 15 km, respectively,
21
22 558 assuming no significant tectonic overpressure (MAY BE THIS IS MORE APPROPRIATE
23
24 559 IN THE DISCUSSION SECTION. HERE YOU SHOULD SIMPLY PRESENT THE
25
26 560 RESULTS OF YOUR MODEL. ALSO NOTE THAT THES DEPTH ESTIMATES
27
28 561 REFER NOT ONLY TO THE SHEARED SAMPLES, THE SUBJECT OF THIS
29
30 562 PARAGRAPH BUT ALSO TO THE UNSHEARED ONES, THE SUBJECT OF THE
31
32 563 PREVIOUS PARAGRAPH (I.E., SO WHY NOT REPORTING DEPTH ESTIMATES
33
34 564 IN THE FORMER PARAGRAPH FOR THESE LATTER ONES?). Semi-independent
35
36 565 constraints on P – T conditions using the avPT function of THERMOCALC (MAYBE YOU
37
38 566 SHOULD EXPLAIN A LITTLE BIT WHAT IS THIS, SO THAT READERS THAT
39
40 567 ARE NOT FAMILIAR WITH ALL THE OPTIONS OF THE THERMOCALC
41
42 568 SOFTWARE CAN UNDERSTAND WHAT IS THIS FUNCTION AND WHY IT
43
44 569 COULD BE USED TO TEST THE RESULTS FROM PSEUDOSECTION. JUST A
45
46 570 FEW BRIEF NOTES COULD BE SIFFICIENT. AS FAR AS I KNOW, THIS
47
48 571 SHOULD BE FOR MULTIPLE-REACTION THERMOBAROMTRY, BUT I HAVE
49
50 572 TO SAY THAT I AM NOT SURE YOU CAN CONSTRAIN BOTH P AND T WITH
51
52 573 THE SAME MODEL. HOW ABOUT CONSTRAINING P AND T
53
54
55
56
57
58
59
60

1
2
3 574 **INDEPENDENTLY, USING TWO DIFFERENT MODELS BASED ON MULTIPLE**
4
5 575 **REACTION EQUILIBRIA? TO MY KNOWLEDGE, THERMOCALC SHOULD**
6
7 576 **HAVE ALSO AVP AND AVT FUNCTIONS, EXACTLY FOR SUCH PURPOSES. The**
8
9 577 **avPT function is well known in metamorphic petrology community and is well documented**
10
11 578 **in the source papers. We find the reviewer's comments inconsistent, whereby they ask us to**
12
13 579 **remove some descriptions for being too obvious, but ask other descriptions to be added for**
14
15 580 **things that we also perceive as being 'obvious'.)** for each sample produced similar and
16
17 581 statistically robust results of 2.05 ± 0.22 GPa and 489 ± 39 °C for N5, 1.95 ± 0.18 GPa and
18
19 582 541 ± 34 °C for 14, and 0.60 ± 0.23 GPa and 464 ± 76 °C for 7c (Supplementary Table 4)
20
21 583 **(SEE/ HERE YOU REPORT VALUES FOR SAMPLE N5 AND VALUES FOR**
22
23 584 **SAMPLE 14 SEPERATELY. SO WHY NOT PRESENTING PSEUDOSECTION**
24
25 585 **RESULTS FOR THE TWO SAMPLES SEPERATELY ALSO (AS ASKED IN A**
26
27 586 **PREVIOUS COMMENT)?) See previous note of grouping samples according to their**
28
29 587 **deformation history.**, corroborating the results obtained by phase diagram modelling.
30
31
32
33
34
35

36 588 **6. U–Pb geochronology**

37
38 589 U–Pb isotopic analysis of **carbonate grains** was carried out on metabasite samples 14
39
40 590 **(unsheared), 11 (sheared), 3b and 13 (SO ARE THESE THE MISSING TWO SHEARED**
41
42 591 **SAMPLES? I THINK THESE SHOULD BE TREATED EXACTLY AS THE OTHER**
43
44 592 **SAMPLES (I.E., REPORT PETROGRAPHY, MINERAL CHEMISTRY, WHOLE**
45
46 593 **ROCK COMPOSITION AND PERFORM THERMOBAROMETRIC MODELS),**
47
48 594 **UNLESS, FOR SOME REASON THIS CANNOT BE DONE. BUT IN THIS LATTER**
49
50 595 **INSTANCE, YOU SHOULD GIVE FULL EXPLAINATION ABOUT THIS),** which
51
52 596 equilibrated at different stages of the subduction–exhumation cycle. Carbonate crystals
53
54 597 within dynamically recrystallised veins were preferentially selected for analyses; however,
55
56 598 suitable matrix minerals were also investigated in order to perform a check on the analysed
57
58
59
60

1
2
3 599 carbonates, which generally have a low U content. Results of the isotopic composition of the
4
5 600 Nagaland blueschists are presented in Supplementary Table 5 and isochrons are shown in
6
7
8 601 Figure 9. Measured $^{207}\text{Pb}/^{206}\text{Pb}$ ratios range from 0.205 to 0.836 (sample 3b), 0.735 to 0.848
9
10 602 (sample 13), 0.776 to 0.845 (sample 11) and 0.809 to 0.846 (sample 14), and measured
11
12 603 $^{238}\text{U}/^{206}\text{Pb}$ ratios range from 0.361 to 9.752 (sample 3b), 0.043 to 10.53 (sample 13), 0.118 to
13
14 604 5.474 (sample 11) and 0.809 to 0.846 (sample 14), as shown in Figs. 9a, b, c and d. All data
15
16 605 for each sample lie on a single array on an isochron diagram, indicating that each attained
17
18 606 isotopic equilibrium, and give well-defined least squares fit indices with MSWD values of
19
20 607 0.35–1.17 (Figure 9). The U concentrations in the minerals range between 0 and 3 ppb and
21
22 608 model Th/U ratios show a wide variation, with most lying between 0.015 and 5, but some
23
24 609 reaching up to ~46. Results of the isotopic composition of the Nagaland blueschists are
25
26 610 presented in Supplementary Table 5 and isochrons are shown in Fig. 9. These analyses show
27
28 611 that unshered samples 14 and 11 equilibrated at 95.3 ± 5.9 Ma and 93.7 ± 4.0 Ma,
29
30 612 respectively, and shered samples 3b and 13 experienced exhumation-related shear
31
32 613 deformation at 90.6 ± 3.4 Ma and 88.8 ± 2.7 Ma, respectively. Although the unshered
33
34 614 sample dataset is within uncertainty of all the shered sample dates, an overall age
35
36 615 progression may be reconstructed from the shered and unshered samples. Considering the
37
38 616 well-behaved dataset in the studied samples with a low MSWD, it can be broadly inferred
39
40 617 that the analysed phases had the same initial isotopic ratio and that the system was at
41
42 618 equilibrium during closure of the isotopic system.

50 619 7. Discussion and implications

51
52 620 Most natural carbonate occurs in the form of calcite and can be transported to the Earth's
53
54 621 interior via subduction of carbonate-rich sediments or metasomatized oceanic crust (Zhang *et*
55
56 622 *al.* 2018). Calcite transforms to aragonite at high pressure. Although may revert back to calcite
57
58 623 during exhumation if there are no kinetic limitations. At the P – T conditions of peak
59
60

624 metamorphism for samples N5 and 14, the carbonate likely stabilised in the form of aragonite,
625 whereas carbonate in sheared samples 11 and 7c is calcite, which indicates polymorphic
626 transformation following exhumation from peak depths. Representative BSE images showing
627 the analysed spots are presented in Figure 10.

628
629 The tectonothermal evolution of the Indo-Myanmar Tethyan ophiolite belt is poorly
630 understood owing to a lack of integrated thermobarometry and geochronology. Here, we have
631 combined microstructurally constrained U–Pb data with P – T conditions calculated for peak
632 and retrograde metamorphism in order to constrain the exhumation history of the Nagaland
633 region of this ophiolite complex (Figure 4011). The ~~samples documented~~ **investigated**
634 **samples** show considerable microstructural variation, ranging from largely undeformed (N5
635 and 14) to sheared (11, 3b, 7c, and 13). The contrasting textures and ages of the studied
636 rocks, together with reported metamorphic **recrystallizations** ages in the adjoining ophiolite
637 belts in Myanmar (Shi *et al.* 2008; Yui *et al.* 2013; Liu *et al.* 2016) suggest that the terrain
638 has undergone several metamorphic events. In terms of texture, the blueschist facies rocks
639 (N5 and 14) do not show any obvious preferred orientation ~~The almost intact crystal shapes~~
640 ~~of the constituent minerals (Fig. 2a) allow us to suggest~~ that they were formed
641 predominantly under near-hydrostatic conditions, without apparent shear deformation. By
642 contrast, the sheared samples record deformation and post-tectonic (annealing)
643 recrystallization, **as**; the constituent minerals display preferred orientation, bending, and
644 curving.

645 Mineral assemblages in the unsheared samples N5 and 14 constrain peak P – T
646 conditions of subduction-zone metamorphism to ~ 1.8 – 2.0 GPa and ~ 420 – 560 °C, with the
647 calculated proportions and compositions of major minerals matching observed values at ~ 1.9
648 GPa and ~ 480 – 520 °C (Figure 6) **(I THINK YOU CAN SIMPLY CONCLUDE THAT**
649 **THE ESTIMATED P-T CONDITIONS ARE THOSE OF THE BEST-MATCH**

1
2
3 650 ASSEMBLAGES, THERE IS NEED TO REPEAT AGAIN WHAT IS THE TOTAL
4
5 651 RANGE FOR THE PEAK ASSEMBLAGE, YOU ALREADY DISCUSSED THIS IN
6
7 652 THE PREVIOUS SECTION. I THINK YOU SHOULD REPORT THIS TIGHTER
8
9 653 RANGE ALSO IN THE OTHER SECTION OF THE PAPER (E.G., ABSTRACT,
10
11 654 CONCLUSIONS) WHERE YOU MENTION THE RESULTS OF YOUR MODELS
12
13
14
15 655 Done).

16
17 656 By contrast, the observed mineral assemblage in sheared (sample 7c) was calculated to
18
19 657 be stable at notably lower P - T conditions of ~0.2–0.6 GPa and ~420–490 °C, with observed
20
21 658 and calculated mineral proportions and compositions matching best at ~0.6 GPa and ~470 °C
22
23
24 659 (AS FOR THE PREVIOUS: YOU CAN SIMPLY REPORT 0.6 GPa AND 470°C
25
26 660 Done). The calculated peak metamorphic conditions for the unsheared samples agree with P -
27
28 661 T conditions previously reported for the area (Chatterjee and Ghose 2010). The P - T
29
30 662 conditions are far-removed from the slab-top range for modern-day subduction reported by
31
32 663 Syracuse *et al.* (2010). The calculated pressures of ~1.9 GPa for peak metamorphism and
33
34 664 ~0.6 GPa for retrograde equilibration are approximately equivalent to depths of 60 km and 15
35
36 665 km, respectively, assuming no significant tectonic overpressure. In Figure 10, the P - T path
37
38 666 calculated here is compared with published examples for other blueschist samples from the
39
40 667 Naga ophiolites (NO COMMENT ON THESE? THEY TOOK PRETTY DIFFERENT
41
42 668 FROM YOURS (ESPECIALLY THE ONE LABELLED AB14), MAYBE YOU CAN
43
44 669 TRY TO PROPOSE SOME EXPLANATION ABOUT THIS MISMATCH) and other
45
46 670 studies with thermal models of the global active subduction zones (Syracuse *et al.* 2010).

47
48
49 671 The age of the high- P metamorphic event is crucial to the reconstruction of the geological
50
51 672 history of this little-known terrain; however, reliable metamorphic age data has been lacking,
52
53 673 and ages for the Nagaland ophiolite are poorly resolved whereas it is not so in the Eastern Belt
54
55 674 (AS SAID IN A PREVIOUS COMMENT, I THINK YOU SHOULD SPEND SOME
56
57
58
59
60

1
2
3 675 **ADDITIONAL WORD ON THIS, OTHERWISE IT IS NOT COMPLETELY CLEAR**
4
5 676 **WHY YOU THINK THAT THERE IS SUCH LACK OF RELIABLE AGE DATA**
6
7
8 677 **ADDED**). We have integrated **our** new age and P – T data into a revised tectonic model for the
9
10 678 evolution of the Naga ophiolite belt, as shown in Figure 1+2. Only one whole-rock K–Ar
11
12 679 isotopic age of 148 ± 4 Ma (Upper Jurassic) has been reported from a volcanic rock in this area
13
14 680 (Sarkar *et al.* 1996), which is supported by a radiolarian age (Baxter *et al.* 2011), whereas
15
16 681 recently, a younger U–Pb zircon age of 115 Ma (Lower Cretaceous) has been reported from a
17
18 682 plagiogranite (Singh *et al.* 2017). Based on the available geochronological and radiolarian ages,
19
20 683 the formation age of the Nagaland ophiolite crust thus likely ranges between Early Cretaceous
21
22 684 (Liu *et al.* 2016; **our** unpublished data) and Late Jurassic (Figure 1+2a). Past plate
23
24 685 reconstructions during this period suggest that early subduction off the coast of Myanmar
25
26 686 dipped to the west during the Jurassic, but there was a reversal in polarity immediately prior to
27
28 687 the Early Cretaceous (Figure 11b; Bhowmik and Ao, 2015). This reversal caused the proto-
29
30 688 Nagaland ophiolite complex oceanic crust to experience subduction along an eastern-dipping
31
32 689 convergent margin during the Early Cretaceous, with U–Pb ages of the blueschist associated
33
34 690 with the Nagaland ophiolite suggesting that peak high-pressure metamorphism was reached at
35
36 691 around this time (Figure 1+2c).

37
38
39
40
41
42 692 Utilizing the integrated petrologically constrained *in situ* ages and thermobarometry
43
44 693 shows that the unsheared sample 14 yielded a U–Pb age of 95.3 Ma while sheared samples
45
46 694 yielded ages ranging between 93.7 Ma (sample 11) and 88.8 Ma (sample 13) Ma, illustrating
47
48 695 an age difference between the sheared and unsheared samples. ~~The present study shows~~ **This**
49
50 696 **suggests** that the Mesozoic ophiolite underwent HP – LT subduction-related metamorphism c.
51
52 697 95 Ma and that exhumation was a continuous process that lasted until c. 89 Ma (Figure 1+2d).
53
54 698 This age range is in agreement with the Guillot *et al.* (2008)'s reported HP metamorphic age
55
56 699 **inferred from K–Ar whole rock and mineral (phengite, glaucophane) ages of 100 to 80 Ma**
57
58
59
60

1
2
3 700 (MAYBE YOU SHOULD ADD SOME DETAIL HOW THIS TIME HAS BEEN
4
5 701 ESTIMATED (I.E., IS THIS COMING FROM GEOCHRONOLOGICAL
6
7 702 ANALYSES? IF SO, WHAT IS THE METHOD THAT WAS APPLIED? **DONE**) for
8
9 703 the western Himalayan Tethyan ophiolites. Based on a zircon isotopic study, an older age of
10
11 704 115 Ma has been reported from the garnetiferous amphibolite of the adjoining Myanmar
12
13 705 ophiolite (Liu *et al.* 2016). However, no petrological information was presented, making it
14
15 706 hard to evaluate the significance of this age. ~~It~~ **As a consequence**, it is unclear whether the
16
17 707 available ages (~~Liu *et al.* 2016 and our data~~) record a prolonged emplacement event, discrete
18
19 708 metamorphic events or if the older amphibolite represents remnants of metamorphic sole of
20
21 709 the ophiolite belt. Although the unsheared sample dataset is within uncertainty of the sheared
22
23 710 sample dates, an overall age progression is evident from the studied sheared and unsheared
24
25 711 samples. Based on the combined U–Pb age dataset and the calculated P – T regime, it can be
26
27 712 inferred that the Nagaland blueschist rocks were exhumed at a rate of ~ 1 cm/year (~ 45 km in
28
29 713 5 Ma), which is in the order of rates of plate tectonic processes on the Phanerozoic Earth.
30
31 714 **However, exhumation along the slab interface would imply overall faster transport rates to**
32
33 715 **achieve this vertical rate. (I THINK THIS STATEMENT NEEDS SOME**
34
35 716 **APPROPRIATE SUPPORTING REFERENCE. IN ANY CASE, PLEASE NOTE**
36
37 717 **THAT THIS IS CONTRAST WITH WHAT YOU REPORTED IN THE ABSTRACT,**
38
39 718 **WHERE YOU SAID THAT THIS EXHUMATION IS ‘A TYPICAL SLOW’ (LINE**
40
41 719 **44). PLEASE CORRECT IN ORDER TO AVOID INCONSISTENCIES**
42
43 720 **CORRECTED).**
44
45
46
47
48
49
50

51 721 U–Pb dating of low-uranium minerals such as calcite, prehnite, epidote, amphibole
52
53 722 (YOU DID NOT SAY YOU MADE U-PB ANALYSES OF SUCH KIND OF
54
55 723 MINERALS. SO I AM NOT SURE IT IS APPROPRIATE TO MENTION THESE
56
57 724 **TOO, IT HAS BEEN MENTIONED**) at small scale is a new and promising
58
59
60

1
2
3 725 geochronological method. In the present study, we focussed on both carbonate and other
4
5 726 cogenetic silicate phases **such as prehnite, epidote, amphibole etc. (SO YOU ACTUALLY**
6
7 727 **PERFORMED U-PB DATINGS ALSO ON OTHER PHASES? IF SO, WHY YOU**
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9 728 **DIDN'T REPORT THIS IN THE U-PB GEOCHRONOLOGY SECTION? THIS IS**
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11 729 **GETTING REALLY CONFUSING, I WARMLY INVITE YOU TO ELUCIDATE**
12
13 730 **AND MAKE IT EXTEMEY CLEAR THROUGHOUT THE MANUSCRIPT. DONE)**
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15 731 formed at the same time and the isotopic systems seem to be closed since the metamorphic
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17 732 event. The reported age uncertainty could be improved by using **well characterised specific**
18
19 733 **with less scatter age and matrix matched standards (e.g., carbonate minerals normalisation of**
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21 734 **Pb–Pb isotope is currently achieved using a synthetic glass other than a carbonate, Roberts et**
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23 735 **al. 2020) standards improved** reference materials (both carbonate and silicate phases)
24
25 736 **(WHAT DO MEAN BY THIS? IN WHAT SENSE THESE REFERENCE**
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27 737 **MATERIALS SHOULD BE IMPROVED? I THINK SOME ELUCIDATION MIGHT**
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29 738 **BE USEFUL, DONE)** Although the behaviour of uranium in carbonates that have undergone
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31 739 high *P*/low *T* is not clear because of the lack of studies in natural and synthetic systems, our
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33 740 study ~~shows~~ **suggest** that the U–Pb systematics of carbonate can withstand temperatures up to
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35 741 500 °C without resetting. These data thus encourage the ongoing development of in-situ
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37 742 dating of carbonates and low uranium silicate minerals as a tool to understand the rates and
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39 743 ages of tectonic processes.
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745 **Acknowledgements**

746 BM began this work during his visits to JGU Mainz on a BOYSCAST Fellowship and
747 continued during the INSA-DFG Exchange programme visit to Bonn. BM thanks the Council
748 of Scientific and Industrial Research, Government of India for financial support in the form
749 of a project. Sample processing equipment were procured under a Department of Science and
60

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3 750 Technology, Government of India FIST program. This is FIERCE contribution XX. BM
4
5 751 acknowledges Yhunyulo Tep for the help during the field work. **Lorenzo Fedele (Napoli) and**
6
7
8 752 **four anonymous** journal reviewers are appreciated for their insightful comments.
9

10 753

11 12 754 **References**

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29 954 **Figure captions**

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31 955 Figure 1. (A) Regional geological map of Indo-Myanmar Range and part of Myanmar (after
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33 956 Acharyya 2015). (B) Geological map of the Indo-Myanmar ophiolite belt (after Geological
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35 957 Survey of India M.N.C. DRG No. 42/87) (C) Geological map of the Nagaland ophiolite belt
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37 958 showing sample locations (after Anon. 1986, Ao and Bhowmick, 2016). (D) Field
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39 959 photographs (1) Unfoliated/Unsheared sample occur as boulders. Person for reference. (2)
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41 960 Unsheared sample showing the slicken sided face, chisel is for reference. (3) Blueschist
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43 961 samples present as blocky boulders. (4) Sheared sample showing foliation on a freshly broken
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45 962 face. Pen shows the foliation trend.
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51 964 Figure 2. Thin-section photomicrographs showing representative mineral assemblages and
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53 965 microstructures for undeformed samples N5 (a–b) and 14 (c–d). All thin section images are
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55 966 shown under plane-polarized light. Scale bar is 1 mm. (a–b) Glaucophane- and epidote-rich
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57 967 matrix in sample N5, with minor garnet porphyroblasts associated with quartz and muscovite.
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3 968 (c) Small millimetre-scale garnet in sample 14 mostly occurs in quartz-rich domains that are
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5 969 relatively epidote- and barroisite-poor. (d) Barroisite grains enclose epidote crystals. Mineral
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7 970 use in 2(a) Gln – Glaucophane, Grt – Garnet, Ep – Epidote, Ms – Muscovite. 2(b) Gln –
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9 971 Glaucophane, Grt – Garnet, Ep – Epidote, Ms – Muscovite, Qtz – quartz, 2(c) Brs –
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11 972 Barroisite, Carb – Carbonate, Grt – Garnet, Ep – Epidote. 2(d) Brs – Barroisite, Ep – Epidote,
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13 973 Ms – Muscovite, Qtz – quartz, Ttn – Titanite.
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19 975 Figure 3. Thin-section photomicrographs showing representative mineral assemblages and
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21 976 microstructures in sheared samples 7c (a–b) and 11 (c–f). All thin section images are shown
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23 977 under plane-polarized light (unless stated otherwise) and oriented perpendicular to the
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25 978 dominant metamorphic foliation. Scale bar is 1 mm. (a) The metamorphic foliation in sample
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27 979 7c is defined by aligned crystals of epidote, sodic-calcic amphibole, and calcic amphibole, (b)
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29 980 and is crosscut by quartz- and carbonate-filled veins that also cause localized deflections at
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31 981 their intersections. Sample 11 contains olive-green aegirine–augite (c) and garnet (d)
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33 982 porphyroblasts that are wrapped by a glaucophane–magnesioriebeckite foliation defined by
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35 983 alternating glaucophane- and quartz-rich bands. Sheared veins filled with carbonate (e) and
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37 984 quartz (f) exhibit ductile deformation microstructures and dynamic recrystallization. Mineral
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39 985 abbreviation use in Figure 3(a) Brs – Wnc: Barroisite – Winchite, Ep – Epidote, Prg – Ed:
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41 986 Pargsite – Edinite, Ttn: Titanite, Figure 3(b) Qtz – Quartz, Carb – Carbonate, Brs –
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43 987 Barroisite, Wnc – Winchite, Ep – Epidote, Ms – Muscovite, Kfs – K-feldspar, Ab – Albite,
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45 988 3(c) Agt – Aegirine augite, Gln: Glaucophane, Fgl – Ferroglacuphane, Grt – Garnet, Qtz –
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47 989 Quartz, Ms – Muscovite, Figure 3(d) Alb – Albite, Carb – Carbonate, Gln – Glaucophane,
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49 990 Fgl – Ferroglaucophane, Quartz – Quartz, Figure 3(e) Carb – Carbonate, Ms – Muscovite,
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51 991 Qtz – Quartz, Figure 3(f) Carb – Carbonate, Qtz – Quartz.
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3 993 Figure 4. Garnet e-Compositional line profile for [a garnet porphyroblast of from the unshheard](#)
4
5 994 sample N5, running from rim to rim across a representative sized euhedral grain (~0.75 mm
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7 995 diameter). (a) Cation mole fractions of divalent cations. (b) X-ray compositional map of
8
9 996 divalent cations showing relative concentrations from core to rim. Colours do not represent
10
11 997 equivalent cation concentrations between images.
12
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15 998

16
17 999 Figure 5. Compositions of amphiboles from all studied samples, ~~eategorized~~ [classified](#)
18
19 1000 according to the classification scheme of Hawthorne *et al.* (2012). Discrimination between
20
21 1001 calcic (group 2), calcic-sodic (group 3), and sodic (group 4) amphiboles is based upon the Na
22
23 1002 content of the M4 crystallographic site, with the ranges <0.5, 0.5–1.5, and >1.5, respectively
24
25 1003 for a 23-oxygen recalculation. Representative compositions are given in [Supplementary](#)
26
27 1004 Table 2.
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31 1005

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33 1006 Figure 6. Results of mineral equilibria modelling for [unshheard](#) sample N5. (a) Pressure–
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35 1007 temperature (P – T) pseudosection constructed for the bulk composition given in
36
37 1008 [Supplementary](#) Table 3. Dotted overlay represents the global range of P – T conditions
38
39 1009 modelled to occur at the surface of subducting ocean crust in present-day subduction zones
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41 1010 (Syracuse *et al.* 2010). Gray star and associated dashed ellipses represent the results of avPT
42
43 1011 calculations ([Supplementary](#) Table 4) and are shown at 1 and 2 S.D. Bold line marks the
44
45 1012 extent of H₂O-bearing assemblage fields. Numbered fields are as follows: 1 – Grt Ms Cld Tlc
46
47 1013 Omp, 2 – Grt Ms Cld Tlc Omp Gln, 3 – Grt Ms Cld Tlc Omp Gln Lws, 4 – Grt Ms Cld Tlc
48
49 1014 Omp Ky Lws, 5 – Grt Ms Act Cld Tlc Ky Lws, 6 – Grt Ms Bt Cld Act Gln, 7 – Grt Chl Bt
50
51 1015 Cld Act Gln, 8 – Grt Bt Act Gln Mag, 9 – Grt Bt Chl Hbl Gln, 10 – Bt Omp Hbl Pl H₂O, 11 –
52
53 1016 Bt Omp Hbl Pl Ab H₂O, 12 – Grt Ms Omp Hbl H₂O, 13 – Grt Ms Gln H₂O, 14 – Grt Chl Ms
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55 1017 Omp Gln, 15 – Grt Chl Ms Brs Gln, 16 – Grt Chl Ms Omp Gln Lws, 17 – Grt Ms Cld Omp
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3 1018 Gln Lws. Some small, minor fields are unlabelled for clarity. (b) Interpreted peak assemblage
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5 1019 field showing isolines of molar modal proportions of selected phases. Red star indicates the
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7 1020 best match between observed and calculated mineral abundances. Dashed line labelled
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9 1021 $XNaM_4Act = 0.25$ marks the division between actinolite (<0.25) at low- T and barroisite
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11 1022 (>0.25) at high- T . (c) Bar chart showing degree of correlation between observed volume
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13 1023 proportions (%) of minerals and calculated proportions at 1.9 GPa and 485 °C (red star in part
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15 1024 b). (d) Graphical representation of the calculated (Calc. vol.%) and observed (Obs. Vol%)
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17 1025 volume proportions for sample N5 at 1.9 GPa and 485 °C.
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24 1027 Figure 7. Results of mineral equilibria modelling for unsheared sample 14. (a) Pressure–
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26 1028 temperature (P – T) pseudosection constructed for the bulk composition given in
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28 1029 Supplementary Table 3. Dotted overlay represents the global range of P – T conditions
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30 1030 modelled to occur at the surface of subducting ocean crust in present-day subduction zones
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32 1031 (Syracuse *et al.* 2010). Gray star and associated dashed ellipses represent the results of avPT
33
34 1032 calculations (Table 4) and are shown at 1 and 2 S.D. Bold line marks the extent of H_2O -
35
36 1033 bearing assemblage fields. Numbered fields are as follows: 1 – Grt Ms Pg Omp Act Gln, 2 –
37
38 1034 Grt Ms Bt Omp Act Gln, 3 – Grt Bt Omp Act Gln Ab, 4 – Grt Bt Omp Act Gln Ilm Mag Ab
39
40 1035 (–Rt), 5 – Grt Bt Omp Act Gln Mag Ab (–Rt), 6 – Grt Bt Omp Brs Gln Mag, 7 – Bt Omp Brs
41
42 1036 Gln Hbl Mag, 8 – Grt Bt Omp Brs Hbl, 9 – Bt Di Brs Hbl H_2O , 10 – Bt Di Hbl Ttn H_2O (–
43
44 1037 Rt), 11 – Bt Di Hbl, 12 – Grt Ms Bt Omp Act H_2O , 13 – Grt Ms Tlc Omp Act H_2O , 14 – Grt
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46 1038 Ms Tlc Omp H_2O , 15 – Grt Ms Tlc Omp Brs Lws, 16 – Grt Chl Ms Omp Brs, 17 – GrtChl
47
48 1039 Ms Omp Brs H_2O . Some small, minor fields are unlabelled for clarity. (b) Red star indicates
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50 1040 the best match between observed and calculated mineral abundances. Interpreted peak
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52 1041 assemblage field showing isolines of molar modal proportions of selected phases. Dashed
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54 1042 line labelled $XNaM_4Act = 0.25$ marks the division between actinolite (<0.25) at low- T and
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3 1043 barroisite (>0.25) at high-T. (c) Bar chart showing degree of correlation between observed
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5 1044 volume proportions (%) of minerals and calculated proportions at 2.0 GPa and 525 °C (red
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7
8 1045 star in part b). (d) Graphical representation of the calculated (Calc. vol.%) and observed (Obs.
9
10 1046 Vol%) volume proportions for sample 14 at 2.0 GPa and 525 °C.

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12 1047

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15 1048 Figure 8. Results of phase equilibria modelling for [sheared](#) sample 7c. (a) Pressure–
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17 1049 temperature (P – T) pseudosection constructed for the bulk composition given in
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19 1050 [Supplementary](#) Table 3. Dotted overlay represents the global range of P – T conditions
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21 1051 modelled to occur at the surface of subducting ocean crust in present-day subduction zones
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23 1052 (Syracuse *et al.* 2010). Gray star and associated dashed ellipses represent the results of avPT
24
25 1053 calculations (Table 4) and are shown at 1 and 2 S.D. Bold line marks the extent of H_2O -
26
27 1054 bearing assemblage fields. Numbered fields are as follows: 1 – Omp Act Gln Mag Rt Hem (–
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29 1055 Ttn), 2 – Omp Act Gln Mag Rt, 3 – Omp Act Gln Mag, 4 – Omp Act Gln Mag Ab, 5 – Act
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31 1056 Gln Mag Ab, 6 – Omp Act Hbl Gln Mag Rt (–Ttn), 7 – Omp Act Hbl Gln Ab, 8 – Act Hbl
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33 1057 Gln Mag Ab, 9 – Chl Act Hbl Mag Ab, 10 – Chl Act Hbl Ab H_2O , 11 – BrsHbl Ab, 12 –
34
35 1058 Omp Act Hbl Ab, 13 – Di Act Hbl Ab H_2O , 14 – Di Hbl Ab H_2O , 15 – Di Act Hbl Pl, 16 –
36
37 1059 Di Hbl Pl Mag Hem (–Ttn, Ep), 17 – Omp Act Hbl Gln Rt Hem (–Ttn), 18 – Omp Brs Hbl
38
39 1060 Gln Rt Hem (–Ttn), 19 – Omp Brs Hbl Gln Rt (–Ttn), 20 – Omp Act Hbl Gln Rt (–Ttn), 21 –
40
41 1061 Omp Brs Hbl Gln, 22 – Omp Act Hbl Gln, 23 – Omp Brs Gln Rt Hem (–Ttn), 24 – Omp Act
42
43 1062 Hem (–Ttn), 25 – Omp Act (–Ttn). Some small, minor fields are unlabelled for clarity. (b)

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45 1063 [Red star indicates the best match between observed and calculated mineral abundances.](#)

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47 1064 Interpreted peak assemblage field showing isolines of molar [modal](#) proportions of selected
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49 1065 phases. Dashed line labelled $X_{NaM_4Act} = 0.25$ marks the division between actinolite (<0.25)
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51 1066 at low-T and barroisite (>0.25) at high-T. (c) Bar chart showing degree of correlation
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53 1067 between observed volume proportions (%) of minerals and calculated proportions at 0.6 GPa
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1068 and 465 °C (red star in part b). (d) Graphical representation of the calculated (Calc. vol.%)
 1069 and observed (Obs. Vol%) volume proportions at 0.6 GPa and 465 °C.

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1071 Figure 9. Isochrons for all dated samples. A: Unsheared sample 14. B: Sheared sample 11. C:
 1072 Sheared sample 3b. D: Sheared sample 13. All ellipses are shown at the 2σ confidence
 1073 interval and n = number of analyses.

1074

1075 [Figure 10. Representative back scattered electron images of analysed samples 14 \(a\), 11 \(b\),](#)
 1076 [3b \(c\) and 13 \(d\). U–Pb analysed spots are showing in ellipse \(white: silicate phases and](#)
 1077 [yellow: carbonates\).](#)

1078

1079 Figure 10. Pressure–temperature–time ($P-T-t$) diagram summarizing the history [proposed](#)
 1080 [model for the tectonometamorphic evolution](#) of blueschist-facies rocks from the Nagaland
 1081 ophiolite complex. Red boxes represent calculated conditions of metamorphism and thick
 1082 grey arrow represents the interpreted $P-T-t$ evolution. Paths for Nagaland blueschists
 1083 reported by Chatterjee and Ghose (2010) and Ao and Bhowmik (2014) are shown (CG10 and
 1084 AB14, respectively) for comparison. Aragonite-calcite stability curve is from Johannes and
 1085 Puhan (1971).

1086

1087 Figure 11. Schematic tectonic model for formation and exhumation of the Nagaland
 1088 ophiolite belt and its metamorphic suite. ~~Final tectonic configuration of tectonostratigraphic~~
 1089 ~~slices is modified after Khogenkumar et al. (2020).~~ (a) Westward-dipping subduction away
 1090 from Myanmar during the Jurassic, with future Nagaland ophiolite belt oceanic crust on the
 1091 overlying plate. (b) Reversal in the subduction dip direction prior to the Early Cretaceous,
 1092 leading to burial of future Nagaland ophiolitic crust and mantle. (c) Peak metamorphism of
 1093 the studied samples was achieved during the Middle Cretaceous, with (d) slab breakaway

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3 1094 [break-off](#) and buoyancy-driven exhumation and associated shearing of these units during the
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5 1095 Middle to Late Cretaceous. (e) the final configuration of the Indo-Myanmar plates and suture
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8 1096 zone between following collisional orogenesis ([modified after Khogenkumar *et al.* 2021](#)).
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10 1097 Yellow star indicates locations of the studied samples during metamorphism and
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12 1098 deformation.
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