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Cumulate gabbros in the South Andaman Island Ophiolite Suite (India): their bearing on the tectonic setting.

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Running title: Gabbros of the South Andaman Ophiolite Suite (India).

Abstract

The Andaman Ophiolite of south-eastern India is located on the outer arc of the Andaman-Java subduction zone. It is represented by thrust slices formed in the Mesozoic Neo-Tethyan Ocean. Lithologically, it consists of dismembered mafic and ultramafic rocks and associated oceanic pelagic sediments. The present study focuses on the mafic cumulate rocks of the Andaman Ophiolite preserved in the Kodiaghat and the Mundapahar area of the South Andaman Island. The mafic cumulates are represented by olivine-bearing and olivine-free gabbros. The sequence of crystallisation in the gabbros is olivines (Fo_{~80}) ± chromian spinels (Cr# 59 - 57), plagioclases (An₉₅₋₆₁), clinopyroxenes (Mg# = 89 - 82) and amphiboles (Mg-hornblende, edenite and pargasite). Major oxide and trace element whole rock geochemistry and mineral compositions are consistent with a hybrid signature of Island Arc Tholeiite (IAT) - Mid Oceanic Ridge Basalt (MORB). Geochemical modelling shows that trapped melt fractions of 0 – 20 % can produce the observed trace element signatures of these gabbros. Our findings suggest that the gabbroic cumulates of the Andaman ophiolite were formed in an oceanic back-arc and oceanic arc setting developed in the Neo-Tethyan oceanic domain between the Indian and the Burmese plates during Late Cretaceous age.

Keywords: South Andaman ophiolite; cumulate gabbro; intra-oceanic subduction; parental melt; suprasubduction zone; equilibrium distribution method.

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29 **Competing interests**

30 The authors declare that they have no competing interests.

31 **Availability of data and materials**

32 All data presented in the text of the article are fully available without restriction from authors

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34 **Author's contributions**

35 AS: Field – data generation – writing (lead); SA: Field - writing (supporting); PN: writing

36 (supporting)

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38 1. Introduction

39 The oceanic crust comprises thick sections of cumulus peridotites and gabbros. These
40 lithologies are not usually recovered during dredging and drilling of the ocean floor. Much of
41 our current knowledge of the lower oceanic crust is based on studies of comparable rocks
42 present in Ophiolite suite. Petrologic and geochemical studies of the ophiolitic assemblages
43 provide information on the nature of the lower oceanic crust and the magma chamber processes
44 operating beneath spreading centres and suprasubduction zones. Although cumulate rocks do
45 not represent the liquid line of descent, they can provide geochemical constraints on the nature
46 of the parent magma. These constraints are particularly relevant when the extrusive and high-
47 level intrusive rocks in the Ophiolite suite are extensively altered.

48 The South Andaman Island is a part of the Andaman Islands located in the south-eastern fringe
49 of the Indian plate margin. Tectonically the Islands are associated with the Burma-Andaman-
50 Java subduction zone of the Indonesian arc system. The Burma-Andaman-Java subduction
51 zone preserves several Mesozoic ophiolitic exposures (Hamilton 1978). The position of these
52 Ophiolites between the Himalayan collision zone and the Indonesian arc system makes them
53 suitable candidates for understanding the Tethyan tectonics vis-a-vis subduction initiation in
54 the eastern Neotethyan realm (Zahirovic et al. 2013; Bandyopadhyay et al. 2020; Pal 2020).
55 The South Andaman Island Ophiolite comprises basal serpentized and tectonized mantle
56 peridotite overlain by ultramafic and mafic cumulate units, followed by massive and pillow
57 basalts (Halder 1985; Ray et al. 1988; Roy 1992; Saha et al. 2010).

58 Here, we describe the petrography, mineral chemistry, major oxide and trace element
59 compositions for gabbros from the cumulate section of the South Andaman Island Ophiolite
60 suite. We use this data to constrain the origin of the gabbroic cumulates and present a plausible
61 tectonic setting for their generation. Secondly, this study constrains the nature of the parental

magma of the cumulates and establishes the source of the melt for the cumulate gabbros of the South Andaman Ophiolite. This study will also allow us to understand the area's geodynamic evolution through time up to the present-day Burma-Andaman-Java subduction zone.

2. Geological background

The Indus Yarlung Tsangpo Suture Zone (IYTSZ) is a well-studied zone of continent-continent collision representing India's collision with Eurasia. This zone preserves the remnants of the once extensive Mesozoic Tethyan ocean, which separated the India and the Asia. Ophiolitic and associated rocks of IYTSZ are distributed along the north-eastern margin of the Indian plate and sweep in a clockwise direction around the eastern Himalayan syntaxis of Namcha Barwa and then southward along the Indo Burma ranges to the Andaman Sea. (Acharyya 2010, 2015; Baxter et al. 2011; Sloan et al. 2017; Aitchinson et al. 2019; Pal 2020). In the Indo Burma region and the Myanmar area, two ophiolite belts are present: (1) Western Ophiolite belt, (2) Eastern Ophiolite belt. The western belt comprises the Naga Hills Ophiolite (Brunnschweiler 1966; Acharyya 2007, 2010) and the Chin Hills Ophiolite (Socquet et al. 2002; Morley and Searle 2017). The eastern belt comprises the Jade Mines Ophiolite and the Tagaung-Myktyina Ophiolite (Hutchison 1975; Searle et al. 2017). The Andaman Ophiolite is positioned in the southeast end of the Tethyan Ophiolite belt. It is an extension of the western Ophiolite belt of the Indo Burma region. The Andaman Ophiolite consists of several dismembered ophiolitic slices trending N-S all along the Andaman Islands (Allen et al. 2008; Ghosh et al. 2009; Saha et al. 2010; Bandyopadhyay et al. 2020; Pal 2020).

The Andaman Islands represent the central part of the Burma-Sunda-Java subduction complex and the eastern suture of the Indian plate (Sengupta et al. 1990; Acharyya 2007; Acharya 2015). Lithostratigraphically, the Andaman Islands have been divided into four units: the Ophiolite Group of Cretaceous to Paleocene age, the Mithakhari Group of Middle to late Eocene age, the

Andaman Flysch Group of Upper Eocene to Oligocene age and the Archipelago Group of Pliocene age (Oldham 1885; Guha and Mohan 1965; Karunakaran et al. 1968; Ray 1982; Pal et al. 2003; Pal 2011; Ghosh et al. 2013, 2017; Bhattacharya et al. 2013) (Fig. 1).

The Ophiolite Group consists of metamorphic rocks, *mélange* and ophiolitic rocks with pelagic cover sediments occurring as dismembered bodies (Halder 1985; Ray et al. 1988; Roy 1992).

A tectonic stack of ophiolitic rocks is interleaved with ophiolite derived clastic sediments. The ophiolitic rocks invariably show thrust contacts with underlying sediments (Pal et al. 2003).

The thrust slices of Ophiolite occur as coherent bodies and run several kilometres in the eastern part and occur as small, isolated klippen in the Island chain's western part (Pal 2020). In the

Andaman Island Ophiolite suite, all the litho members of a classic ophiolite sequence namely the plutonic complex, the intrusive and extrusive lava series and the pelagic sediments are well preserved except the sheeted dykes. Previous works follow a two-fold subdivision of the Ophiolite suite. The subdivision consists firstly of a mantle sequence represented by serpentinitized harzburgite and pods of altered dunite and secondly of a crustal sequence marked

by an assemblage of plutonic and extrusive rocks. The plutonics of the crustal section consist mainly of layered cumulates of peridotites-gabbros, overlain by non-cumulate gabbros and a high level intrusive suite of plagiogranites-diorites-andesites cross-cut by thin dykes of basalt and diabase. The pillowed and non-pillowed lavas overlying this dyke complex represents the uppermost part of the Ophiolite suite. This sequence is overlain by the Upper Cretaceous radiolarian cherts (Ling et al. 1996). The mantle section representing mainly peridotites, a few dunite pods and rarely some chromitite pods, occurs in large volumes in the Middle-and North-Andaman and Rutland Islands. In contrast, cumulate, intrusive and extrusive rocks are predominant in the South Andaman Islands (Pal 2020).

Many studies have attempted to understand the origin and emplacement of the Andaman Ophiolite based on paleontological, petrological and geochemical approaches (Jaffri et al. 1993; Shastri et al. 2001; Pal et al. 2003; Srivastava et al. 2004; Bandhopadhyay 2005; Ghosh et al. 2009; Pederson et al. 2010; Ghosh et al. 2017; Bandyopadhyay 2020; Bhattacharyya et al. 2020). Previous work on gabbros of the Andaman Ophiolite include studies by Saha et al. (2010), Ghosh et al. (2014) and Rasool et al. (2015). Saha et al. 2010 discussed a preserved complete Ophiolite suite from the South Andaman. This study discussed the mineral chemistry of the gabbros. Ghosh et al. (2014) discussed the mineral and trace element chemistry of the gabbros and other ultramafic cumulates of the South Andaman Ophiolite suite in light of the Moho transition zone. Their study suggests melt-mantle interactions for the observed trace element signatures in clinopyroxenes of the mafic and ultramafic cumulates. In support of their findings, a switch over from MORB- to Arc-type geodynamic settings was suggested. Based on whole rock geochemical data, Rasool et al. (2015) have ascertained a cumulate origin for the gabbros of the South Andaman Island Ophiolite suite. The findings of the study suggest that these rocks originated in a suprasubduction zone. Contradictory propositions based on a specific type of data set in limited studies that have been carried out so far on the South Andaman Island Ophiolite suite's gabbros provide scope for a detailed investigation of the South Andaman Island's cumulate gabbros.

Studies reveal that the volcanic rocks of the Andaman Ophiolite are geochemically diverse and have been divided into pillow basalts and east coast volcanics/massive basalts. These volcanic groups are interpreted to have signatures of basalts generated in mid-oceanic ridge (MOR), island-arc and back-arc settings (e.g. Srivastava et al. 2004; Jafri et al. 2010; Pal 2011; Jafri and Sheikh 2013; Ghosh et al. 2017). A recent work by Akhtar et al. (2021) on the pillow and the massive basalts of the South Andaman Island Ophiolite suggests a back-arc basin origin for these basalts.

The mantle sections of the South Andaman Ophiolite show variation across the different islands of the Andaman region. Ghosh et al. (2009, 2013) studied the mantle peridotites of Rutland Island and reported them to be of arc origin. On the contrary, Middle and North Andaman's peridotites are similar to those generated in the back-arc basin setting (Ghosh et al. 2018). The observed variations in the peridotites have been credited to variable degrees of partial melting and melting modes. The spatial distribution of these different varieties of mantle rocks and their association with the other rock types of the Ophiolite suite suggest a complex evolution of the Andaman Ophiolite.

An exhaustive study encompassing petrographical, mineral chemical and geochemical characterisation of the South Andaman Ophiolite suite is needed to resolve its development history. Robust geochronological data of all rocks present in the suite will further constrain the timeline for their generation and emplacement.

3. Sampling and analytical methods

3.1 Sample materials and thin section preparation

Representative samples were collected from outcrops of mafic cumulates around the Kodiaghat and the Munda Pahar area of the South Andaman Ophiolite (Fig. 2) during February 2012. These outcrops occur in association with ultramafic cumulates as massive, coarse-grained dark bodies. No visible banding was observed in the gabbros (Fig. 3). Each sample weighed at least ~5 kg to ensure representativity for the whole-rock analysis.

For the preparation of thin sections, visually discoloured or otherwise altered material was removed with a water-cooled diamond blade. Billets of ~25×45×25 mm were cut and then planarised on 400 mesh silicon carbide paper, epoxy-mounted on a standard-sized petrographic carrier glass 27 × 47 mm. The billets were then made into 30 µm thin sections, following

routine procedures discussed in Humphries (1992). The thin section surfaces were polished with diamond pastes 6-3-1 μm on a cloth to achieve a mirror finish. Finalised sections were studied in a Nikon E-200 POL petrographic microscope using a plane and cross-polarized transmitted light to identify locations suitable for in-situ assessment of mineral chemistry by Electron-Probe Micro-Analyser (EPMA) instrument, i.e. without surface scratches and mineral/fluid inclusions. Mineral names are abbreviated where appropriate, after Whitney and Evans (2010). Modal contents were visually estimated in volume per cent (vol.%) by point counting under a microscope.

3.2 Mineral chemistry by Electron-Probe Micro-Analysis (EPMA)

Microprobe analyses were performed on six representative polished thin sections of mafic cumulates of the South Andaman Ophiolite. Before analysis, polished sections were covered with ~ 20 nm carbon in a Polaron CC7650 coater to minimise charging effects. Major element mineral composition was determined in a Cameca SX5 instrument equipped with five wavelength-dispersive spectrometers (WDS) with a range of LTAP, LPET, LiF, LPET, PET, and TAP crystals, located at the Department of Earth Sciences, IIT Mumbai (India). The instrument was operated under a high vacuum with acceleration voltage set to 15 kV and a probe current of 10 nA (on Faraday cup). The counting time was 100 s on the peak with a nominal beam diameter of 1 μm and 10 s each on the upper and lower background. The standards used for internal instrument calibration were Th glass for Si, diopside for Ca and Mg, rhodonite for Mn, albite for Na, Al_2O_3 for Al, hematite for Fe, orthoclase for K, apatite for P, Cr_2O_3 for Cr and TiO_2 for Ti, halite for Cl, ZrSiO_4 for Zn, apatite for F and BaSO_4 for Ba. All elements were measured on their respective $K\alpha$ lines. Sodium was assigned to two opposite WDS detectors at the beginning of each analytical run to minimise migration effects. Raw data for every major element was ZAF-corrected using the PAP-algorithm of Pouchou and Pichoir

(1985). Corrected element contents were converted to major element oxides in weight per cent (wt.%), assuming stoichiometry. Total iron (oxide) content has been reported as FeO_T . Major oxide contents were recast into the number of cations in atoms per formula unit (apfu) as per Deer et al. (2013). Ferric iron content in nominally anhydrous minerals was calculated using Droop (1987). IMA-approved nomenclature was applied to mineral compositions, Morimoto et al. (1988) for clinopyroxenes, Hawthorne et al. (2012) for amphiboles.

3.3 Whole-rock geochemistry by X-ray fluorescence (XRF)

A total of ten samples of gabbros were analysed for major oxide and trace element contents. About 5 kgs of the material were comminuted in two steps. Firstly in a jaw crusher with tungsten-carbide lined jaws to pass a 40 mesh (0.42 mm) sieve. Then secondly crushed material was split using the cone-and-quartering method in multiple iterations to obtain ~50 g sub-samples for pulverisation in an agate-lined ring-and-puck mill into a powder < 50 μm . For every sample, all comminution equipment was recleaned with pure quartzite and acetone.

A precisely weighed 8.0 ± 0.001 g amount of dry sample powder was mixed with 2.0 ± 0.001 g (= 25 wt.%) acrylic wax and pressed under 25 tons for 120 s into a pellet for analysis. Blind duplicates and in-house standards UBN and AMH were added to the sample series for calibration and quality control. The relative standard deviation (RSD) was < 5 % for the major and minor oxides and < 12 % for the trace elements. The average precision is better than 2 % (Purohit et al. 2006; Saini et al. 2007).

The pressed pellet were analysed in a Bruker S8 Tiger Sequential X-ray spectrometer, located at the Wadia Institute of Himalayan Geology, Dehradun, India. The Rh-target tube was operated without filter and in vacuum at 40 kV for major elements and at 60 kV for trace elements. Ignition loss (LOI) was determined gravimetrically in a graphite crucible on a

separate 2.0 ± 0.001 g aliquot by ignition at 1000 °C. Selected data is provided in Table 1.

Major oxide contents (exclusive LOI) were modelled using a modified CIPW-norm calculation using Kurt Hollocher excel sheet (<http://minerva.union.edu/hollochk/c-petrology/norms>), to determine normative mineral modal contents of plagioclase, olivine, and clinopyroxene.

3.4 Whole-rock rare-earth element (REE) geochemistry

Rare-earth element (REE) contents were determined by inductively coupled plasma-mass spectrometry (ICP-MS) using a Perkin Elmer SCIEX ELAN DRC-e quadrupole instrument, also located at the Wadia Institute of Himalayan Geology, Dehradun, India. The procedures adopted for sample digestion and preparation of solutions were by Balaram et al. (1990).

About 0.5 ± 0.0001 g of sample powder was digested in 10 mL of mixed concentrated strong acids $5\text{HClO}_4:3\text{HNO}_3:2\text{HF}$ in a PTFE-lined autoclave at 150 °C for 48 h. After this, the autoclave was opened and evaporated until incipient dryness at 80 °C. The above procedure was reiterated with the same acid mixture under the same conditions and for the same duration. Next, 10 mL of 1N HNO_3 was added to the residue and the volume made up with double-distilled water to 50 mL at $\sim\text{pH}_2$ for analysis. Blind duplicate samples, the USGS standard BHVO 1 and the JGS standard JBI 1a were added to the sample series for calibration and quality control. The RSD for most of the samples was $< 10\%$. Values of standards used for XRF and ICP-MS are provided in Supplementary Table S1.

4. Results

4.1 Petrography

Mafic cumulates of the South Andaman Ophiolite are composed of coarse-grained olivine-bearing gabbros and olivine-free gabbros (hereafter referred to as gabbros). The olivine-bearing gabbros consist mainly of plagioclases (~ 60 vol.%, 100 - 150 mm grain size), clinopyroxenes

(40 vol.% and 50 - 100 mm grain size), olivines (~2 - 5 vol.%, 50 - 100 mm grain size), intercumulus amphiboles (~1 vol.%) and a minor amount of Fe-Ti oxide (Fig. 4 a & b). The gabbros are composed of plagioclases (30 - 50 vol.%, 100 - 200 mm grain size), clinopyroxenes (30 - 40 vol.%, 100 - 150 mm grain size), amphiboles (1 - 2 vol.%) and a minor amount of Fe - Ti oxide (Fig. 4 c-f). (Fig. S1, Table S1).

Both varieties of gabbros exhibit orthocumulate and mesocumulate textures. Olivines, clinopyroxenes, plagioclases and amphiboles occur as cumulus and intercumulus phases in variable proportions with a minor amount of disseminated Fe - Ti oxide. Plagioclases comprise the most common mineral phase with well-developed twin lamellae (Fig. 4c). The plagioclase crystals also show triple junctions among three grain boundaries. The clinopyroxenes are the next most dominant phase and are in contact with plagioclases and amphiboles. At places, the clinopyroxene grain rims show minor deuteric alteration into amphiboles (Fig. 4f). Amphiboles and olivines both occur in volumetrically low proportions. The primary amphiboles occur in association with plagioclases. The olivines occupy interstitial spaces and are anhedral grains with curved cracks.

4.2 Mineral chemistry

4.2.1 Olivines

Olivines constitute ~2-5% of the olivine-bearing gabbros. Representative olivine analyses are listed in Table S2. The olivines are homogenous from the core to the rim, with no zoning and have Mg # ranging from 81 to 82 (Fo_{~80}). As the olivines do not exhibit a variable Fo content, the span of olivine crystallisation seems restricted. The NiO content is very low (0.08 - 0.1 wt.%). Thus, the parental magma for these gabbros may have undergone an early removal of olivines with high Fo values before their emplacement.

4.2.2 Plagioclases

Plagioclases occur in both the olivine-bearing gabbros and gabbros. Representative plagioclase analyses are given in Table S3. The plagioclase grains are generally homogenous from the core to the rim with no evidence of zoning. Representative analyses for the plagioclases indicate anorthite (An) contents between 92 - 95 mol.% in olivine-bearing gabbros and 61 - 95 mol.% in gabbros (Fig. 5a).

4.2.3 Clinopyroxenes

Clinopyroxenes are present in both the olivine-bearing gabbros and the gabbros. Representative clinopyroxene analyses are listed in Table S4. The clinopyroxenes show no zonation and constitute 30 - 35 % of the modal composition. In terms of quadrilateral components, clinopyroxenes of olivine-bearing gabbros have a composition of $\text{En}_{41-45}\text{Fs}_{8-9}\text{Wo}_{45-50}$ and clinopyroxenes of the gabbros have a composition of $\text{En}_{42-50}\text{Fs}_{8-12}\text{Wo}_{41-49}$ (Fig. 5b). The Cr_2O_3 content of clinopyroxenes varies between 0 - 0.2 wt.% in olivine-bearing gabbros and 0 - 0.8 wt.% in gabbros. The unzoned nature and uniform composition of clinopyroxenes may indicate either subsolidus re-equilibration or slow cooling, or both (Flower et al. 1977). In our analysed clinopyroxenes, the presence of large amounts of Si relative to tetrahedral Al indicates derivation from a tholeiitic melt, based on the divisions by Kushiro (1960).

4.2.4 Amphiboles

Mg-hornblendes, edenites and pargasites are the primary amphiboles present in the olivine-bearing gabbros and the gabbros (Fig. 6a (1) & b). Representative results are listed in Table S4. They contain 7 - 11 wt.% of Al_2O_3 , 0 - 1.4 wt.% of TiO_2 , 0.8 - 2 wt.% of Na_2O and 0 - 0.07 wt.% of K_2O in olivine-bearing gabbros whereas the gabbros have Al_2O_3 content of 0.23 - 12.43 wt.%, TiO_2 content of 0.3 - 3.93 wt.%, Na_2O content of 0.3 - 2 wt.% and K_2O content of 0 - 0.18 wt.%. The X_{Mg} [$X_{\text{Mg}} = \text{Mg} / (\text{Mg} + \text{Fe}^{2+})$] values range from 0.81 - 0.94 in olivine-bearing gabbros and 0.80 - 0.99 in the gabbros.

The secondary amphiboles are the product of alteration of pyroxenes. Compositionally, the amphiboles can be classified as tremolites, actinolites and tschermakites (Fig. 6a (2), Table S5). They may have formed by late-stage recrystallisation due to interaction of gabbroic rocks with hydrothermal fluids.

4.2.5 *Spinels*

Cr-Spinels are observed only (Table S6) in the gabbros. They have a high Cr# = 57 - 59, low Mg# of 0.1 and high TiO₂ contents of 3.59 - 7.08 wt.%.

4.3 Whole rock chemistry

The whole rock major and trace element data of olivine-bearing gabbros and the gabbros are listed in Table 1. They contain 44.91 - 49.83 wt.% of SiO₂, 14.95 - 22.61 wt.% of Al₂O₃ and 7.63 - 18.46 wt.% of CaO. They also contain 6.17 - 16.68 wt.% of MgO and 2.31 - 8.39 wt.% of Fe₂O₃, yielding Mg# [=Mg/(Mg+Fe²⁺)] values of 0.76 - 0.88. Their Na₂O contents are about 0.65 wt.% - 1.68 wt.% and the TiO₂ contents are > 0.21 wt.%. Loss on Ignition (LOI) values for the gabbroic rocks vary from 1.6 - 6.6 wt.%. The Sr content varies from 99 - 386 ppm, the Ni content from 28 - 561 ppm, the Co content from 9 - 72 ppm, and the Cr content from 223 - 1247 ppm in the studied samples.

The variations and correlations of a few selected major and trace elements for the studied gabbros are presented in Fig. 7 along with the previous data on gabbros (Pal 2011; Rasool et al. 2015) and ultramafics (Pal 2011; Bhattacharya et al. 2013; Saha et al. 2018) from the Andaman Ophiolite. The Al₂O₃ and CaO values display negative correlation with MgO content. This correlation suggests Ca-pyroxene and anorthite crystallisation in the studied gabbros. The trends demonstrated by our data are similar to those of Pal (2011), but the data of Rasool et al. (2015) demonstrate clustering but with no specific trends. The ultramafics show

raised CaO , Al_2O_3 and MgO content, which suggests the cumulate nature of these rocks. The observed general trend from Mg-rich to Ca- and Al-rich cumulates is a consequence of magmatic accumulation of olivines, clinopyroxenes and plagioclases marking progressive differentiation in the South Andaman Ophiolite magma chamber. Gabbro data from this study and data from earlier work show that Ni and Co correlate positively with MgO, whereas Ga, V, Sc and Sr contents show a negative correlation with MgO. Progressive differentiation in the South Andaman magma chamber from ultramafic to mafic cumulates is discernible. Ultramafic cumulates exhibit higher Co and Ni concentrations but lower Sc, Ga, V and Sr concentrations than our studied mafic cumulate samples.

The chondrite normalised REE data and the Normal Mid-Oceanic Ridge Basalt (N-MORB) normalised trace element data of the studied gabbros are presented in Fig. 8 a & b. The REE trends are controlled by plagioclases, clinopyroxenes and to some extent by olivines. The plagioclases prefer LREE over HREE, whereas the reverse holds for clinopyroxenes. Clinopyroxenes preferentially concentrate Eu^{2+} relative to the other trivalent REE contents. Four distinct trends can be distinguished for the gabbroic rocks in terms of their REE patterns. Samples AN 10/21, AN 10/16 and AN 10/1 show variations in $(\text{La/Yb})_N$ from 0.69 to 1.60, indicating moderate fractionation of LREE relative to HREE. Still, the ratio of MREE to HREE $[(\text{Sm/Yb})_N = 0.67 - 1.19]$ shows no such significant variations. It shows an almost flat trend with a prominent positive Eu ($\text{Eu}/\text{Eu}^* = 1.23 - 1.49$) anomaly. Sample AN 27/40 has a high $(\text{La/Yb})_N$ value of 8.2, indicating significant fractionation of LREE relative to HREE. Also, MREE to HREE ratio $[(\text{Sm/Yb})_N = 2.6]$ suggests a moderately fractionated trend with no positive Eu anomaly $[(\text{Eu}/\text{Eu}^* = 0.93)]$. Sample AN 27/42 (olivine-bearing gabbro) and AN 27/45 show depleted LREE in comparison to HREE $[(\text{La/Yb})_N = 0.59 - 2.08]$ with a prominent Ce and Eu anomaly $[(\text{Ce}/\text{Ce}^*) = 0.60 - 0.65, (\text{Eu}/\text{Eu}^*) = 1.46 - 1.53]$. The MREE and HREE also show moderate fractionation $[(\text{Sm/Yb})_N = 0.69 - 2.07]$. Samples AN 10/5, AN 10/8, AN

7/17 and AN 10/14 show $(\text{La/Yb})_N$ ratio of 1.45 - 2.12, indicating a considerable amount of fractionation with a pronounced positive Eu anomaly ($\text{Eu/Eu}^* = 1.51 - 2.49$). These samples also exhibit a considerable Ce anomaly ($\text{Ce/Ce}^* = 0.68 - 0.88$). The positive Eu anomaly in these rocks is due to the accumulation of calcic plagioclases and reflects their cumulate nature (e.g., Berger et al. 2001; Greene et al. 2006). Moreover, the flat HREE patterns shown by the samples are in accordance with the existence of considerable amounts of clinopyroxenes (e.g., Berger et al. 2001).

We compared our normalised REE data with the REE trends of prior published data on the gabbros (Pal 2011; Rasool et al. 2015) and ultramafic rocks (Saha et al. 2018). No conclusive similarity could be established between the gabbros data of previous work and the current study. Nevertheless, the chondrite-normalised REE patterns for the ultramafic and the mafic cumulate samples are parallel and systematically increase in abundance from peridotite to the gabbros. This suggests that the diverse rock types are related to each other by differentiation from the same primary magma (e.g., Kelemen et al. 1997; Marchesi et al. 2006). The N-MORB normalised multi-element diagram (Fig. 8b) of the studied gabbroic rocks indicates that they are depleted in HFSE elements (P, Ti etc.) and are enriched in LILE (K, Rb, Sr Ba, etc.).

In comparison, the peridotites (Saha et al. 2018) are mostly depleted in LILEs such as K, Rb, Sr and Ba and a few HFSEs including Zr, Nb and Ti, relative to N-MORB. Relatively low concentrations of the incompatible trace elements are due to the high proportions of cumulus minerals and the low amounts of intercumulus liquids in the magma chamber (e.g., Parlak et al. 1996, 2000, 2002; Berger et al. 2001). The incompatible trace element values gradually increase from the peridotites to the gabbros (Fig. 8b). This could represent the intercumulus liquids becoming more evolved as other phases (olivines, clinopyroxenes and plagioclases) are progressively fractionated, resulting in an enrichment of trace element concentrations in the

residual liquids.

5. Discussion

5.1 Petrogenesis

5.1.1 Mid-Oceanic Ridge (MOR) vs. Suprasubduction Zone (SSZ) origin

Numerous studies have addressed whether Ophiolites have formed in the Mid-Oceanic Ridge (MOR) environment as showcased by their structures or in the marginal basin (SSZ) as revealed by their geochemistry (Moores et al. 2000; Hawkins 2003; Pearce 2003). Apart from geological evidence, various approaches based on petrological studies, isotopic ratios, whole-rock geochemistry (particularly immobile trace elements) and mineral chemistry have been adopted to categorise ophiolites formed within MOR and SSZ environments (Pearce 2003).

Textures like plagioclases being interstitial to pyroxenes, pyroxene inclusions within plagioclases or embayment of plagioclases within clinopyroxenes (See Fig. S2) suggests late crystallisation of plagioclases relative to pyroxenes. These textures support differentiation in hydrous basalt, where clinopyroxenes crystallise before plagioclases. In contrast, low pressure fractionation of dry MORB melt would crystallize plagioclases before clinopyroxenes (e.g. Grove and Baker 1984; Dick et al. 1992; Ross and Elthon 1993). Water activities within magmas from subduction zones are usually high, which results in early crystallisation of clinopyroxenes relative to plagioclases (Gaetani et al. 1993). Therefore, it is likely that the gabbros of this study have crystallised from hydrous melts.

Mineral compositions of pyroxenes, plagioclases and amphiboles also support derivation of the studied gabbros from hydrous melts instead of dry MORB melts. The Mg# values between 82 – 89 of the clinopyroxenes and Ca-rich plagioclases (An 92 - 95 mol.%) of the studied gabbros are a product of fractional crystallisation in hydrous magma with high Ca/Na ratios and high P_{H_2O} (Grove and Baker 1984; Sisson and Grove 1993; Panjasawatwong et al. 1995; Kohut and Nielsen 2003; Claeson and Meurer 2004; Takagi et al. 2005; Feig et al. 2006). Experiments

373 have shown that anorthite (An) content of liquidus plagioclases and the exchange coefficient
374 of Ca and Na between plagioclases and the melt increases with increasing H₂O concentrations.
375 Moreover, nearly H₂O saturated conditions are considered optimal for the crystallisation of
376 plagioclases with An > 88 from a hydrous arc magma (e.g., Sisson and Grove 1993; Takagi et
377 al. 2005; Feig et al. 2006). It has been proposed that crystallisation of anorthitic plagioclases
378 occurs when parental melts contain either CaO/Na₂O ratio > 8 or water content > 6 wt.%
379 (Panjasawatwong et al. 1995). There are also reports of low volume ultra-depleted refractory
380 melts with high CaO/Na₂O within the oceanic lithosphere, produced at the end of fractional
381 melting (Ross and Elthon 1993; Sobolev and Shimizu 1993). Melts can have a raised Ca/Na
382 ratio through the dissolution of pyroxenes in fertile lherzolites (Dick and Natland 1996). In the
383 case of our samples, clinopyroxenes have crystallized earlier than plagioclase, which would
384 decrease the CaO/Na₂O ratio in the residual magma. In such a scenario, calcic-rich plagioclases
385 would not crystallize from Ca-rich melt. Instead, the Ca-rich plagioclases observed in our
386 samples have resulted due to wet fractionation of the parental melt. Ca-rich plagioclases have
387 generally been found in the cumulate sequence of many Ophiolites of island arc origin
388 (Ballantyne 1992).

389 Aluminium (Al) and Titanium (Ti) contents of clinopyroxenes also help to discriminate
390 between MOR and island arc settings (Beccaluva et al. 1989). Clinopyroxene compositions of
391 the gabbros display low Al and Ti contents showing affinity with island arc tholeiites Fig. 9a.
392 The clinopyroxene compositions also suggest a sub-alkaline source origin for the studied
393 gabbros (Fig. 9b).

394 Amphiboles in the studied gabbros occur either as isolated grains interstitial between other
395 minerals or replace clinopyroxenes and plagioclases at their grain boundaries. Minor amounts
396 of primary magmatic amphibole pargasite, edenite and Mg - hornblende have been documented
397 for the gabbros with Al₂O₃ > 10 wt.% and SiO₂ of ~46 wt.%. These amphiboles are undoubtedly

derived from a hydrous parental melt. Studies have shown that magmatic amphibole crystallisation requires higher Na_2O content in the parental melt. With insufficient Na_2O content, the melt is unlikely to crystallise hornblende irrespective of its water content (Sisson and Grove 1993). However, tremolite and actinolite amphiboles overgrow and sometimes replace Ca-rich clinopyroxenes and plagioclases in the studied gabbros. These amphiboles of hydrothermal origin have high SiO_2 , low Al_2O_3 and low TiO_2 contents. These secondary amphiboles were probably formed during seawater alteration at low temperatures.

The environment in which gabbros form can also be inferred from the Cr-number of spinels present in gabbros. In general, spinels in the MOR-type gabbros have Cr# below 50, whereas spinels in subduction-related gabbros and cumulates have Cr# around 60 or higher (Dick and Bullen 1984; Allan et al. 1988; Hébert et al. 1989). The spinels of the studied gabbros have Cr# between 57 - 59 suggesting subduction related arc origin for these gabbros (Fig. 9c). Moreover, the studied gabbros have major oxide compositions similar to arc-related ultramafic and mafic cumulates reported in study by Beard (1986) (Fig. S3).

5.1.2 Parental melt calculations using the Equilibrium Distribution Method (EDM).

An estimate of the amount of trapped melt (trapped melt fraction or TMF) crystallised within a mineral matrix can be obtained using the Equilibrium Distribution Method (EDM) proposed by Bédard (1994). This mass balance model is based on the bulk rock trace element and modal compositions and assumes that the trapped melt fraction is a phase crystallising with solid/liquid $D = 1$. Hence it allows to calculate the changes in trace element composition of minerals assuming different TMF.

Parental liquids for the South Andaman Island Ophiolite gabbros were calculated using the EDM after Bédard (1994). The inputs for our calculations were whole rock REE compositions, mineral proportions, mineral/melt partition coefficients and melt fractions. Mineral modes (Table S7) were calculated from volatile-free adjusted CIPW norm, assuming $\text{Fe}^{3+}/\text{Fe}_{\text{total}} = 0.1$.

Small proportions of normative orthoclase were added to plagioclases. Very small amounts of normative apatite, ilmenite, magnetite and chromite were added to the dominant ferromagnesian silicates (e.g. Bédard et al. 2009). The small amounts of normative nepheline present in some samples were excluded from the EDM calculations. The REE composition of samples AN 27/45 and AN 7/17 having plagioclases and clinopyroxenes as the dominant minerals were selected for the EDM calculations.

The partition coefficients (D) for plagioclase-melt and clinopyroxene-melt were calculated using the parameterisation of Bédard (2006) and Bédard (2014), respectively. This required the estimation of melt MgO and SiO₂ values in samples, which were calculated using the linear regression $\text{MgO} = 11.69\text{Mg\#} - 0.2388$ and $\text{SiO}_2 = -0.51\text{MgO} + 54.67$ of Bédard (2001). The SiO₂ (wt.%) content in whole rock, Ca content in plagioclases and Al^{IV} values in clinopyroxenes were also used to calculate D values. For Ho in plagioclase, D values were taken from Bédard (2001). The D values for olivine-melt and orthopyroxene-melt were taken from Kelemen et al. (2003).

Variations in the calculated clinopyroxene REE compositions at trapped melt fraction (TMF) 0, 5, 10, 15 and 20 % for samples AN 27/45 and AN 7/17 are shown in Fig. 10a and 10b, respectively. The DMM composition (Workman and Hart 2005), N-MORB (Gale et al. 2013) and average clinopyroxene compositions of abyssal peridotites (Warren 2016) are also plotted for comparison.

Sample AN 27/45 shows that the calculated clinopyroxene composition ranges from 0 – 20 %. TMF falls within the measured clinopyroxene composition from the Andaman gabbros (Ghosh et al. 2018). However, the calculated La and Ce abundances show a slight enrichment for the measured compositions. Moreover, the calculated REE compositions are roughly parallel to the average abyssal peridotite trend of Warren (2016). The overall calculated compositions lie below the DMM curve.

Compared to sample AN 27/45, the calculated clinopyroxene REE composition for sample AN 7/17 shows relatively more depleted and slightly negative trends from HREE to MREE, but the LREE displays similar enrichment. The HREE of DMM (Workman and Hart 2005) also shows a slightly negative trend. The calculated Yb and Lu at TMF 10 – 20 % display similar enrichment as clinopyroxenes from the Rutland Island of Andaman (Ghosh et al. 2018). The variations in melt fraction compositions at TMF 5, 10, 15 and 20 % in samples AN 27/45 and AN 7/17 are shown in Fig. 10c and 10d, respectively. The DMM (Workman and Hart 2005), N-MORB (Gale et al. 2013) and average abyssal peridotite (Niu 2004) REE compositions are also shown for comparison. The melt fraction composition calculated using the EDM model is comparable to those calculated using Shaw (1970) non-modal batch melting model.

5.2 Inferred Tectonic environment and geodynamic implications

The geochemical compositions of the gabbros are consistent with IAT formation in an arc-related tectonic environment. The analysed plagioclase and olivine compositional pairs from gabbros of the South Andaman Island Ophiolite plot in the field of island arcs of type III after Beard 1986 (Fig. 11a). However, the studied gabbros display characteristics of both arc-related gabbros and MORB-related gabbros in the covariation diagram of Mg # in clinopyroxenes vs. An content of the plagioclases (Fig. 11b). All the studied gabbros show compositional similarities to IAT and MORB in the Ti vs. V diagram (Fig. 12a). Moreover, the studied gabbros display compositional similarity to N-MORB on the $\text{SiO}_2/100\text{-TiO}_2\text{-Na}_2\text{O}$ ternary diagram (Fig. 12b). The analysed clinopyroxenes of the studied gabbros show compositional overlap between N-MORB, back-arc basin basalt and arc tholeiites in the Al_2O_3 vs. $(\text{TiO}_2 + \text{Cr}_2\text{O}_3)$ diagram (Fig. 12c). The observed hybrid MORB-like and arc-like elemental signature observed in the studied gabbros is usually associated with BAB basalts (Volpe et al. 1987;

Pearce and Peate 1995; Pearce and Stern 2006). Earlier studies have shown that BAB basalts can form in an intra-ocean arc lithosphere and on a continental basement (Gribble et al. 1996; Shinjo et al. 1999). Generally, intra-oceanic back-arc basin basalts have a composition similar to N-MORB and intra-ocean arc magmas. On the other hand, continental back-arc basin basalt compositions are similar to E-MORBs and continental arc magmas (Ghazi et al. 2012). The chondrite normalised REE patterns of the studied Andaman Ophiolite gabbros are comparable to N-MORB. Moreover, the studied gabbros have $(La / Yb)_N = 0.78 - 2.11$ (except for sample AN 27/40 with a value of 4.26), $Ba/La = 10 - 33$ and $(Sm / Nd)_N = 0.72 - 1.39$, which are comparable to values suggested for intra - oceanic BAB basalts (Hawkins 1995; Hickey Vargas et al.1995). Therefore, it is most likely that the South Andaman Ophiolite gabbros are related to an oceanic back-arc and oceanic arc settings. Our findings conform to the idea that the subduction in the Andaman Islands is of an intra-oceanic setting. Previous observation on disposition of the Andamn Ophiolite slices and the overlying Eocene sediments in an accretionary complex and the field relationship amongst the Ophiolite slices and the forearc sediments implies an autochthonous nature for the South Andaman Ophiolite and the associated Eocene sediments (Ghosh et al. 2009, 2013; Pal 2011, Pal 2020). These observations also support an intra-oceanic setting

Recent geochronological studies on the Andaman Ophiolites include a U-Pb zircon SHRIMP crystallisation age of 93.6 ± 1.3 Ma for plagiogranite (Sarma et al. 2010). Since the Andaman ophiolitic rocks predate the plagiogranite, the former were probably not generated in the currently active Late-Miocene Andaman-Java subduction zone. The Ophiolite suite got obducted onto the leading edge of the Eurasian continent during the early Cretaceous time. U-Pb zircon dating of a trondhjemitic rock using LA-ICPMS from Chriyatapu in the South Andaman Island gives an age of 95 ± 2 Ma for crust formation (Pedersen et al. 2010). This data shows that the Andaman volcanic arc was built on Cenomanian ophiolite-oceanic crust and the

subduction was initiated at this time along with the Tethys. Paleontological data from oceanic sediments closely associated with ophiolites have shown that the sediments have ages of Upper Cretaceous to Early Eocene (Bandopadhyay and Ghosh 1998; Bandopadhyay 2005). Allen et al. (2008) suggested that the Mithakhari Group was deposited in the late Paleocene - Eocene, with a maximum age of ca. 60 Ma and the Oligocene Andaman Flysch was deposited between 30-20 Ma and was uplifted by 20 Ma. Both units are known to overlie the Andaman Ophiolites. An arc-continent collision during the Cretaceous has also been suggested for the Andaman Ophiolite origin (Plunder et al. 2020). Plunder et al. 2020 also reports an age of 106.4 ± 2.1 Ma and 105.3 ± 1.6 Ma using the Ar/Ar method for the metamorphic sole rock of the Andaman Ophiolite. The same study has arrived at a mixed age between 105 to 98 Ma for the gabbros. Their findings infer at least 5 My of magmatism, with a diverse geochemical signature suggesting an arc setting for parts of the Andaman Ophiolites. Bandyopadhyay et al. (2020) have also reported zircon U/Pb age of 99–93 Ma for magmatic arc rocks (gabbro and plagiogranite) of the Andaman Islands. This study also identifies an inherited ~105 Ma age for the gabbros. Moreover, Jafri et al. (2006) also had reported thin ash layers within Upper Cretaceous radiolarian cherts that intercalate with pillow lavas of South Andaman, suggesting explosive volcanism during or not long after the magmatic sequence of the Ophiolite suite was formed.

Two geodynamic models have been proposed for the Ophiolite suite exposed in the Andaman Islands. One school suggests that the Andaman Ophiolite suite is the upthrust oceanic crust accreted during a prolonged period of subduction (Pal et al. 2003; Curray 2005) along the western margin of the island arc since the Late Mesozoic. The alternative idea suggests that the Ophiolite suite ranges in age between Late Mesozoic and Early Eocene. It was tectonically emplaced at the leading edge of the Eurasian continent during Middle Eocene to the Late Oligocene event. This was before the Andaman-Java subduction which was initiated during

the Late Miocene (Sengupta et al. 1990; Acharyya 2007). Studies by Ghosh et al. (2009, 2013) and Pal (2011) discuss Andaman Ophiolite's origin in a SSZ setting. Advokaat et al. (2018) proposed that when corrected for post-Cretaceous tectonic motion along the Sunda forearc, the Andaman Ophiolites were restored adjacent to and west of the now extinct intra-oceanic Woyla arc, which at present is located on Sumatra and West-Java. Their findings suggest that this arc collided with the Sundaland margin in the Late Cretaceous. Advokaat et al. (2018) postulated that the Andaman SSZ Ophiolites might have formed during a subduction polarity reversal within or adjacent to the Woyla arc upon its collision with Sundaland. Bandyopadhyay et al. (2020) has also provided a three-stage regional kinematic history based on the available geochemical and new geochronological constraints and have argued for an SSZ origin for the Andaman Ophiolite. Based on petrological attributes, the associated Naga Hills Ophiolite of the Indo Burma Region has also been attributed to the SSZ environment (Ghosh et al. 2009; Saha et al. 2018; Pal 2020; Verencar et al. 2021). The veracity of various theories on development of the Andaman Ophiolite is debatable due to the lack of all-inclusive work (especially the major and trace chemistry of minerals) spanning the various rock types exposed on the Andaman Islands. These rocks and the Ophiolite exposures need to be investigated in the context of their relevant tectonic positions within the suprasubduction zone.

Based on our findings and the available regional data, we propose the following stages (Fig. 13) for the geotectonic evolution of the studied gabbros in a suprasubduction zone. (a) The first stage involved the initiation of BAB spreading and basaltic magmatism, which formed the BAB crust with N-MORB signature. (b) The BAB crust gradually moved closer to the magmatic arc axis due to spreading at BAB and the tectonic erosion of the forearc basin. Subsequently, the BAB crust was overlapped by the magmatic arc axis and formed the Oceanic Island Arc basement. In this process, due to fluid-induced melting of the overlying slab, cumulate keels were formed at the asthenospheric mantle, which is known to generate both

mafic and ultra-mafic rocks. (c) In due course, the Island Arc basaltic magmatism led to crustal anatexis of the Oceanic Island Arc basement, thereby generating granitoids of arc affinities. Contemporaneously, BAB basaltic magmatism under the spreading centre developed the BAB crust with IAB to MORB signatures, on which pelagic sediments were deposited. (d) These components collided and then accreted to the eastern margin of the Indian continent during the Late Cretaceous, forming the South Andaman Ophiolite suite.

Our model reconciles the observed mixed signatures of MORB and IAT found in the gabbroic cumulate rocks of the South Andaman Island Ophiolite and establishes a complex interplay of converging plates, mantle upwelling, generation of new oceanic crust and a sialic proto-continental crust in an SSZ environment in the Neo-Tethyan Oceanic domain. This will further our understanding of the subduction initiation in the eastern Neotethyan oceanic domain and the associated Ophiolites of the Indo-Burma range that is believed to mark the suturing of the India and the Eurasia.

7. Conclusions

The main conclusions from this study are summarised below:

1. The mafic cumulates of the South Andaman Ophiolite are mostly olivine-bearing gabbro and olivine-free gabbros. The crystallisation order for the gabbroic cumulate rocks is olivines $\pm$ Cr-spinels $\rightarrow$ clinopyroxenes $\rightarrow$ plagioclases $\rightarrow$ amphiboles.

2. Whole-rock trace element geochemistry shows that South Andaman gabbros are variably enriched in LREE with respect to the N-MORB composition and can be broadly correlated with either E-MORB or P-MORB. However, many geochemical indicators show compositional continuity from moderately enriched to highly enriched rocks.

3. The presence of highly magnesian olivines ($\text{Fo}_{\sim 80}$), Ca-rich plagioclases (An_{92-95}) and

clinopyroxenes with Mg# 82-90 along with magmatic amphiboles indicate the crystallisation of gabbros from a hydrous parental melt in a subduction-related setting. The textural relationships between the constituent mineral phases in gabbros also support the same. Trapped melt fraction calculations suggest that the gabbroic rocks were derived from a source more depleted than the DMM.

4. A possible tectono-magmatic model can explain the generation of different rock-types in the Southern Neo-Tethys Ocean. This model implies that spreading resulted in the formation of intra-oceanic back-arc basin in the Neo-Tethyan oceanic domain connecting the Indian plate and the Burmese plate. This was followed by the initiation of early-stage subduction in the Neo-Tethyan oceanic environment with proto-arc formation. In this stage, due to the fluid-induced melting of the mantle wedge, a cumulate keel was formed at the root of the intra-oceanic island arc, where fractionation and accumulation of the gabbros of Andaman Ophiolite occurred. With the erosion of the fore-arc area, the back-arc crust then migrated towards the magmatic arc axis. Hence, hybrid signatures are observed in the gabbroic cumulates of island arc origin.

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References

- 594 Acharyya, S.K. 2007. Collisional emplacement history of the Naga-Andaman ophiolites and
595 the position of the eastern Indian suture. *Journal of Asian Earth Sciences*, 29: 229-
596 242. doi:10.1016/j.jseaes.2006.03.003.
- 597 Acharyya, S.K. 2010. Tectonic evolution of Indo Burma range with special reference to Naga
598 Manipur Hills. *Memoir Geological Society India*, 75: 25– 43.
- 599 Acharyya, S.K. 2015. Indo-Burma Range: a belt of accreted microcontinents, ophiolites and
600 Mesozoic–Paleogene flyschoid sediments. *International Journal of Earth Sciences*,
601 104:1235-1251. doi:10.1007/s00531-015-1154-6.
- 602 Advokaat, E.L., Bongers, M.L.M. Rudyawan, A., BouDagher-Fadel, M.K., Langereis, C.G.,
603 and van Hinsbergen, D.J.J. 2018. Early Cretaceous origin of the Woyla Arc
604 (Sumatra, Indonesia) on the Australian plate. *Earth Planetary Science Letters*, 498:
605 348–361. doi:10.1016/j.epsl.2018.07.001.
- 606 Akhtar, S., Saikia, A., Negi, P., Kalita, B.J. 2021. Back-arc basin origin for the basalts of the
607 South Andaman Island Ophiolite (India), Episodes.
608 doi.org/10.18814/epiiugs/2021/021001.
- 609 Allan, J.F., Sack, R.O., and Batiza, R. 1988. Cr-rich spinels as petrogenetic indicators; MORB-
610 type lavas from the Lamont seamount chain, eastern Pacific. *American*
611 *Mineralogist*, 73: 741-753.
- 612 Allen, R., Carter, A., Najman, Y., Bandopadhyay, P.C., Chapman, H.J., Bickle, M.J., Garzanti,
613 E., Vezzoli, G., Andò, S., Foster, G.L., Gerring, C., Draut, A.E., Clift, P.D., and
614 Scholl, D.W. 2008. New constraints on the sedimentation and uplift history of the
615 Andaman-Nicobar accretionary prism, South Andaman Island. *In* Formation and
616 Applications of the Sedimentary Record in Arc Collision Zones. *Edited by* A.
617 Draut, P.D. Clift, and D.W. Scholl. Geological Society of America, Boulder,
618 Special Paper 436: 223-255. doi:10.1130/2007.2436(11).
- 619 Aitchinson, J.C., Ao, A., Bhowmik, S.K., Clarke, G.L., Ireland, T.R., Kachovich, S., Lokho,
620 K., Stojanovic, D., Roeder, T., Truscott, N., Zhen, Y., and Zhou, R. 2019. Tectonic
621 evolution of the western margin of the Burma microplate based on new fossil and
622 radiometric age constraints. *Tectonics*, 38 (5): 1718-1741.
623 doi:10.1029/2018TC005049.
- 624

- 625 Balaram, V., Saxena, V.K, Manikyamba, C., and Ramesh, S.L. 1990. Determination of rare
626 earth elements in Japanese rock standards by inductively coupled plasma mass
627 spectrometry. *Atomic Spectroscopy*, 11(1): 19-23.
- 628 Ballantyne, P. 1992. Petrology and geochemistry of the plutonic rocks of the Halmahera
629 ophiolite, eastern Indonesia, an analogue of modern oceanic forearcs. *Geological*
630 *Society, London, Special Publications*, 60: 179-202.
631 doi:10.1144/GSL.SP.1992.060.01.11.
- 632 Bandopadhyay, P.C. 2005. Discovery of abundant pyroclasts in the Namunagarh Grit, South
633 Andaman: evidence for arc volcanism and active subduction during the Palaeogene
634 in the Andaman area. *Journal of Asian Earth Sciences*, 25: 95-107.
635 doi:10.1016/j.jseaes.2004.01.007.
- 636 Bandopadhyay, P.C., and Ghosh, M. 1998. Facies, Petrology and Depositional Environment
637 of the Tertiary Sedimentary Rocks, Around Port Blair, South Andaman. *Journal of*
638 *the Geological Society of India*, 52: 53–66.
- 639 Bandyopadhyay, D., Ghosh, B., Guilmette, C., Plunder, A., Corfu, F., Advokaat, E.L.,
640 Bandopadhyay, P.C., and van Hinsbergen, D.J.J. 2020. Geochemical and
641 geochronological record of the Andaman Ophiolite, SE Asia: From back-arc to
642 forearc during subduction polarity reversal ? *Lithos*: 380-381: 105853.
643 doi:10.1016/j.lithos.2020.105853.
- 644 Baxter, A.T., Aitchison, J.C., Zyabrev, S. V., and Ali, J.R. 2011. Upper Jurassic radiolarians
645 from the Naga Ophiolite, Nagaland, northeast India. *Gondwana Research*, 20: 638–
646 644. doi:10.1016/j.gr.2011.02.001.
- 647 Beard, J.S. 1986. Characteristic mineralogy of arc-related cumulate gabbros: Implications for
648 the tectonic setting of gabbroic plutons and for andesite genesis. *Geology*, 14: 848-
649 851. doi: 10.1130/0091-7613(1986)14<848:CMOACG>2.0.CO;2.
- 650 Beccaluva, L., Macciotta, G., Piccardo, G.B., and Zeda, O. 1989. Clinopyroxene composition
651 of ophiolite basalts as petrogenetic indicator. *Chemical Geology*, 77: 165-182. doi:
652 10.1016/0009-2541(89)90073-9.
- 653 Bédard, É., Hébert, R., Guilmette, C., Lesage, G., Wang, C.S., and Dostal, J. 2009a. Petrology
654 and geochemistry of the Saga and Sangsang ophiolitic massifs, Yarlung Zangbo

- 655 Suture Zone, Southern Tibet: Evidence for an arc–back-arc origin. *Lithos*, 113: 48-
656 67. doi: 10.1016/j.lithos.2009.01.011.
- 657 Bédard, J.H., Leclerc, F., Harris, L.B., and Goulet, N. 2009*b*. Intra-sill magmatic evolution in
658 the Cummings Complex, Abitibi greenstone belt: Tholeiitic to calc-alkaline
659 magmatism recorded in an Archaean subvolcanic conduit system. *Lithos*, 111: 47-
660 71. doi:10.1016/j.lithos.2009.03.013.
- 661 Bédard, J.H. 1994. A procedure for calculating the equilibrium distribution of trace elements
662 among the minerals of cumulate rocks, and the concentration of trace elements in
663 the coexisting liquids. *Chemical Geology*, 118: 143-153. doi:10.1016/0009-
664 2541(94)90173-2.
- 665 Bédard, J.H. 2001. Parental magmas of the Nain Plutonic Suite anorthosites and mafic
666 cumulates: a trace element modelling approach. *Contributions to Mineralogy and
667 Petrology*, 141: 747-771. doi:10.1007/s004100100268.
- 668 Bédard, J.H. 2006. Trace element partitioning in plagioclase feldspar. *Geochimica et
669 Cosmochimica Acta*, 70: 3717-3742. doi:10.1016/j.gca.2006.05.003.
- 670 Bédard, J.H., 2014. Parameterisations of calcic clinopyroxene—Melt trace element partition
671 coefficients. *Geochemistry, Geophysics, Geosystems*, 15: 303-336. doi:
672 10.1002/2013GC005112.
- 673 Berger, S., Cochrane, D., Simons, K., Savov, I., Ryan, J.G., and Peterson, V.L. 2001. Insights
674 from rare earth elements into the genesis of the Buck Creek complex, Clay County,
675 North Carolina. *South Eastern Geology*, 40 (3): 201–212.
- 676 Bhattacharya, A., Pal, T., and Ghosh, B. 2013. Characterisation of the accreted ophiolite slices
677 of Rutland Island, Andaman Sea: evolution in a suprasubduction zone setting.
678 *Ophiolite*, 38:121–142.
- 679 Bhattacharya, S., Pande, K., Kumar, A., Kingson, O., and Ray, J.S. 2020. Timing of Formation
680 and Obduction of the Andaman Ophiolite. *In The Andaman Islands and Adjoining
681 Offshore: Geology, Tectonics and Palaeoclimate. Edited by Ray J and
682 Radhakrishna M. Society of Earth Scientists Series. Springer, Cham. doi
683 :10.1007/978-3-030-39843-9_2*
- 684 Bhat, G.R., Balaji, S., Iqbal, V., Balakrishna, B., and Yousuf, M. 2019. Neotectonics and
685 related crustal deformation along Carbyn thrust fault, South Andaman, India:

- 686 implications of the frontal surface faulting and propagation of tectonic activity
 687 towards Andaman trench. *Arabian Journal of Geosciences*, 12: 149.
 688 doi:10.1007/s12517-019-4282-7.
- 689 Brown, G.C. 1982. Calc – alkaline intrusive rocks: their diversity, evolution and relation to
 690 volcanic rocks. *In Andesites orogenic, Andesites and Related Rocks. Edited by R.S*
 691 *Thorpe. Wiley, New York. pp. 437-46.*
- 692 Brunnschweiler, R.O .1966. On the geology of the Indoburman ranges. *Australian Journal of*
 693 *Earth Science* 13: 137-194. doi:10.1080/00167616608728608.
- 694 Burns, L.E.1985. The Border Ranges ultramafic and mafic complex, south-central Alaska:
 695 cumulate fractionates of island-arc volcanics. *Canadian Journal of Earth Sciences*
 696 , 22:1020-1038. doi:10.1139/e85-106.
- 697 Claeson, D.T., and Meurer, W.P. 2004. Fractional crystallisation of hydrous basaltic “arc-type”
 698 magmas and the formation of amphibole-bearing gabbroic cumulates.
 699 *Contributions to Mineralogy and Petrology*, 147(3): 288-304. doi:10.1007/s00410-
 700 003-0536-0.
- 701 Curray, J.R. 2005. Tectonics and history of the Andaman Sea region. *Journal of Asian Earth*
 702 *Sciences*, 25: 187-232. doi:10.1016/j.jseaes.2004.09.001.
- 703 Deer, W.A., Howie, R.A., and Zussman, J. 2013. An introduction to the rock forming minerals.
 704 3rd excerpted student edition. Mineralogical Society London, United Kingdom,
 705 485-489. doi:10.1080/00357529.2014.926186.
- 706 Dick, H.J.B., and Bullen, T. 1984. Chromian spinel as a petrogenetic indicator in abyssal and
 707 alpine-type peridotites and spatially associated lavas. *Contributions to Mineralogy*
 708 *and Petrology*, 86: 54-76. doi:10.1007/BF00373711.
- 709 Dick, H.J.B., Robinson, P.T., and Meyer, P.S. 1992. The plutonic foundation of a slow-
 710 spreading ridge. *In Synthesis of Results from Scientific Drilling in the Indian*
 711 *Ocean: Geophysical Monograph 70. Edited by R.A. Duncan, D.K. Rea, R.B. Kidd,*
 712 *U. von Rad and J.K. Weissel. American Geophysical Union, pp. 1–39.*
 713 doi:10.1029/GM070p0001.
- 714 Dick, H.J.B., and Natland, J.H. 1996. Late-stage melt evolution and transport in the shallow
 715 mantle beneath the East Pacific Rise. *Proceeding of the Ocean Drilling Program,*
 716 *Scientific Results*, 147: 103–134.

- 717 Droop, G.T.R. 1987. A general equation for estimating Fe^{3+} concentrations in ferromagnesian
718 silicates and oxides from microprobe analyses, using stoichiometric criteria.
719 Mineralogical Magazine, 51: 431-435. doi:10.1180/minmag.1987.051.361.10.
- 720 Feig, S.T., Koepke, J., and Snow, J.E. 2006. Effect of water on tholeiitic basalt phase equilibria:
721 an experimental study under oxidising conditions. Contributions to Mineralogy and
722 Petrology, 152: 611-638. doi:10.1007/s00410-006-0123-2.
- 723 Flower, M.F.J., Robinson, P.T., Schmincke, H.U., and Ohnmacht, W. 1977. Magma
724 fractionation systems beneath the mid-Atlantic ridge at 36–37°N. Contributions to
725 Mineralogy and Petrology, 64: 167-195.
- 726 Gaetani, G.A., Grove, T.L., and Bryan, W.B. 1993. The influence of water on the petrogenesis
727 of subduction-related igneous rocks. Nature, 365: 332-334. doi:10.1038/365332a0.
- 728 Gale, A., Dalton, C., Langmuir, C., Su, Y., and Schilling, J.G. 2013. The mean composition of
729 ocean ridge basalts. Geochemistry Geophysics Geosystems, 14: 489-518.
730 doi:10.1029/2012GC004334.
- 731 Ghazi, J.M., Moazzen, M., Rahgoshay, M., and Shafaii Moghadam, H. 2012. Geochemical
732 characteristics of basaltic rocks from the Nain ophiolite (Central Iran); constraints
733 on mantle wedge source evolution in an oceanic back arc basin and a geodynamical
734 model. Tectonophysics, 574-575: 92-104. doi:10.1016/j.tecto.2011.10.001.
- 735 Ghosh, B., Pal, T., Bhattacharya, A., and Das, D. 2009. Petrogenetic implications of ophiolitic
736 chromite from Rutland Island, Andaman—a boninitic parentage in supra-
737 subduction setting. Mineralogy and Petrology, 96: 59. doi:10.1007/s00710-008-
738 0039-9.
- 739 Ghosh, B., Morishita, T., and Bhatta, K. 2013. Significance of chromian spinels from the
740 mantle sequence of the Andaman ophiolite, India: paleogeodynamic implications.
741 Lithos, 164–167: 86–96. doi:10.1016/j.lithos.2012.08.004.
- 742 Ghosh, B., Morishita, T., Gupta, B.S., Tamura, A., Arai, S., and Bandyopadhyay, D. 2014.
743 Moho transition zone in the Cretaceous Andaman ophiolite, India: A passage from
744 the mantle to the crust. Lithos, 198-199: 117-128. doi:
745 10.1016/j.lithos.2014.03.027
- 746 Ghosh, B., Bandyopadhyay, D., Morishita, T., Bandyopadhyay, P.C., and Carter, A. 2017.
747 Andaman–Nicobar Ophiolites, India: origin, evolution and emplacement, The

- 748 Andaman–Nicobar Accretionary Ridge: Geology, Tectonics and Hazards.
749 Geological Society of London, Memoirs, 47: 95–110. doi: 10.1144/M47.7.
- 750 Ghosh, B., Mukhopadhyay, S., Morishita, T., Tamura, A., Arai, S., Bandyopadhyay, D.,
751 Chattopadhyaya, S., and Oving, T.N. 2018. Diversity and evolution of suboceanic
752 mantle: Constraints from Neotethyan ophiolites at the eastern margin of the Indian
753 plate. *Journal of Asian Earth Sciences*, 160: 67-77. doi:
754 10.1016/j.jseas.2018.04.010.
- 755 Greene, A.R., DeBari, S.M., Kelemen, P.B., Blusztajn, J., and Clift, P.D. 2006. A detailed
756 geochemical study of island arc crust: the Talkeetna Arc section, south-central
757 Alaska. *Journal of Petrology*, 47(6): 1051–1093. doi:10.1093/petrology/egl002.
- 758 Gribble, R.F., Stern, R.J., Bloomer, S.H., Stüben, D., O’Hearn, T., and Newman, S. 1996.
759 MORB mantle and subduction components interact to generate basalts in the
760 southern Mariana Trough back-arc basin. *Geochimica et Cosmochimica Acta*,
761 60(12): 2153-2166.doi:10.1016/0016-7037(96)00078-6.
- 762 Grove, T.L., and Baker, M.B. 1984. Phase equilibrium controls on the tholeiitic versus calc-
763 alkaline differentiation trends. *Journal of Geophysical Research: Solid Earth*, 89:
764 3253-3274. doi:10.1029/JB089iB05p03253.
- 765 Guha, D.K., and Mohan, M. 1965. On the ostracod from the Neogene of Andaman Island.
766 *Journal of the Geological Survey of India*, 9: 58–66.
- 767 Halder, D. 1985. Some aspects of the Andaman Ophiolite Complex: Geological Survey of
768 India, 115: 1–11.
- 769 Hamilton, W.B. 1978. Mesozoic tectonics of the western United States. *Pacific Section Society*
770 *of Economic Paleontologists and Mineralogists, Paleogeography Symposium 2*,
771 pp. 33–70.
- 772 Hawkins, J.W. 1995. The Geology of the Lau Basin. *In Backarc Basins: Tectonics and*
773 *Magmatism. Edited by B.Taylor. Springer US, Boston, MA, pp. 63-138.*
- 774 Hawkins, J.W. and Allan, J.F. 1994. Petrologic evolution of Lau Basin Sites 834 through 839.
775 *In Proceedings of the Ocean Drilling Program, Scientific Results, College Station,*
776 *TX (Ocean Drilling Program). Edited by J. Hawkins, L. Parson, J. Allan et al.*
777 *Pangea*, 135, pp. 427-470. doi.org/10.2973/odp.proc.sr.135.136.1994.

- 778 Hawkins, J.W. 2003. Geology of supra-subduction zones—Implications for the origin of
779 ophiolites. *In* Ophiolite concept and the evolution of geological thought. *Edited by*
780 Y. Dilek, and S. Newcomb, Geological Society of America Special Paper 373, pp.
781 227–268. doi:10.1130/0-8137-2373-6.227.
- 782 Hawthorne, F.C., Oberti, R., Harlow, G.E., Maresch, W.V., Martin, R.F., Schumacher, J.C.,
783 and Welch, M. 2012. IMA Report – Nomenclature of the amphibole supergroup.
784 *American Mineralogist* 97, (11-12): pp. 2031-2048.
- 785 Hébert, R., Serri, G., and Hékinian, R. 1989. Mineral chemistry of ultramafic tectonites and
786 ultramafic to gabbroic cumulates from the major oceanic basins and Northern
787 Apennine ophiolites (Italy) - A comparison. *Chemical Geology*, 77: 183-207.
788 doi:10.1016/0009-2541(89)90074-0.
- 789 Hickey-Vargas, R., Hergt, J., and Spadea, P. 1995. The Indian Ocean Type Isotopic Signature
790 in Western Pacific Marginal Basins: Origin and Significance. Washington DC
791 American Geophysical Union Geophysical Monograph Series, 88: 175-197.
792 doi:10.1029/GM088p0175.
- 793 Humphries, D.W. 1992. The preparation of thin sections of rocks, minerals and ceramics. Roy
794 Microsc Soc, Oxford Sci Pubs, Microscopy Handbooks (24): pp.83
- 795 Huot, F., Hébert, R., Varfalvy, V., Beaudoin, G., Wang, C., Liu, Z., Cotten, J., and Dostal, J.
796 2002. The Beimarang mélange (southern Tibet) brings additional constraints in
797 assessing the origin, metamorphic evolution and obduction processes of the
798 Yarlung Zangbo ophiolite. *Journal of Asian Earth Sciences*, 21: 307-322.
799 doi:10.1016/S1367-9120(02)00053-6.
- 800 Hutchison, C.S. 1975. Ophiolite in southeast Asia. *Geological Society of America Bulletin*, 86:
801 797–806.
- 802 Irvine, T.N., and Baragar, W.R.A. 1971. A Guide to the Chemical Classification of the
803 Common Volcanic Rocks. *Canadian Journal of Earth Sciences*, 8: 523-548.
804 doi:10.1139/e71-055.
- 805 Jafri, S.H., Balaram, V., and Govil, P.K. 1993. Depositional environments of Cretaceous
806 radiolarian cherts from Andaman-Nicobar Islands, northeastern Indian Ocean.
807 *Marine Geology*, 112: 291-301. doi:10.1016/0025-3227(93)90174-T.

- 808 Jafri, S.H., Subba Rao, M.V., and Ramesh, S.L. 2006. Occurrence of ash beds in radiolarian
809 cherts from the South Andaman Island, Bay of Bengal, India: evidence for Late
810 Cretaceous explosive volcanism. *Current Science*, 91: 1614–1615.
- 811 Jafri, S.H., Sarma, D. and Sheikh, J. 2010. Hyaloclastites in pillow basalts, South Andaman
812 Island, Bay of Bengal, India. *Current science*. 99. 1824-1828.
- 813 Jafri, S.H., and Sheikh, J. 2013. Geochemistry of pillow basalts from Bompoka, Andaman–
814 Nicobar islands, Bay of Bengal, India. *Journal of Asian Earth Sciences*. 64. 27-37.
815 doi: 10.1016/j.jseaes.2012.11.035.
- 816 Karunakaran, C., Roy, K.K., and Saha, S.S. 1968. Tertiary Sedimentation in the Andaman-
817 Nicobar Geosyncline. *Journal of the Geological Society of India*, 9: 32–39.
- 818 Kelemen, P.B., Koga, K., and Shimizu, N. 1997. Geochemistry of gabbro sills in the
819 crustmantle transition zone of the Oman ophiolite: implications for the origin of
820 the oceanic lower crust. *Earth and Planet Science Letters*, 146 (3–4): 475–488.
821 doi:10.1016/S0012-821X(96)00235-X.
- 822 Kelemen, P.B., Yogodzinski, G.M., and Scholl, D.W. 2003. Along strike variation in the
823 Aleutian island arc: genesis of high-Mg# andesite and implications for continental
824 crust. *In* *Inside the Subduction Factory*. Geophysical Monograph, vol. 138. *Edited*
825 *by* J. Eiler. American Geophysical Union, Washington, pp. 223–276.
826 doi:10.1029/138GM11.
- 827 Kohut, E., and Nielsen, R. 2003. Low-pressure phase equilibria of anhydrous anorthite-bearing
828 mafic magmas. *Geochemistry Geophysics Geosystems*, 4(7): 1057.
829 doi:10.1029/2002GC000451.
- 830 Kushiro, I. 1960. Si-Al relation in clinopyroxenes from igneous rocks. *American Journal of*
831 *Science*, 258: 548- 554. doi:10.2475/ajs.258.8.548.
- 832 Leterrier, J., Maury, R.C., Thonon, P., Girard, D., and Marchal, M. 1982. Clinopyroxene
833 composition as a method of identification of the magmatic affinities of paleo-
834 volcanic series. *Earth and Planetary Science Letters*, 59: 139-154.
835 doi:10.1016/0012-821X(82)90122-4.
- 836 Ling, H. Y., Chandra, R., and Karkare, S. G. 1996. Tectonic significance of Eocene and
837 Cretaceous radiolaria from South Andaman Island, northeast Indian Ocean. *Island*
838 *Arc*, 5:166–179. doi:10.1111/j.1440-1738.1996.tb00023.x.

- Marchesi, C., Garrido, C.J., Godard, M., Proenza, J.A., Gervilla, F., and Blanco-Moreno, J. 2006. Petrogenesis of highly depleted peridotites and gabbroic rocks from Mayarí-Baracoa ophiolite belt (Eastern Cuba). *Contribution to Mineralogy and Petrology*, 151: 717–736. doi:10.1007/s00410-006-0089-0
- Moore, E.M., Kellogg, L.H., Dilek, Y., Dilek, Y., Moore, E.M., Elthon, D., and Nicolas, A. 2000. Tethyan ophiolites, mantle convection, and tectonic “historical contingency”: A resolution of the “ophiolite conundrum”, *Ophiolites and oceanic crust: new insights from field studies and the Ocean Drilling Program*. Geological Society of America Special Papers, 349: 3–12. doi:10.1130/0-8137-2349-3.3.
- Morimoto, N., Fabries, J., Ferguson, A.K., Ginzburg, I.V., Ross, M., Seifert, F.A., Zussman, J., Aoki, K., and Gottardi, G. 1988. Nomenclature of pyroxenes. *American Mineralogist*, 73: 1123–1133.
- Morley, C.K., and Searle, M. 2017. Regional tectonics, structure and evolution of the Andaman-Nicobar Islands from ophiolite formation and obduction to collision and back-arc spreading. *In The Andaman-Nicobar accretionary ridge: geology, tectonics and hazards. Edited by P.C Bandopadhyay and A Carter*. Geological Society London Memoir, 47:51–74. pp. 235.
- Niu, Y. 2004. Bulk-rock Major and Trace Element Compositions of Abyssal Peridotites: Implications for Mantle Melting, Melt Extraction and Post-melting Processes Beneath Mid-Ocean Ridges. *Journal of Petrology*, 45: 2423–2458. doi: 10.1093/petrology/egh068.
- Oldham, R.D. 1885. Notes on the geology of Andaman Islands. *Record of the Geological Survey of India*, 18: 135–145.
- Pal, T., Chakraborty, P.P., Gupta, T.D., and Singh, C.D. 2003. Geodynamic evolution of the outer-arc–forearc belt in the Andaman Islands, the central part of the Burma–Java subduction complex. *Geological Magazine*, 140 (3): 289–307. doi: 10.1017/S0016756803007805.
- Pal, T. 2011. Petrology and geochemistry of the Andaman ophiolite: melt–rock interaction in a suprasubduction-zone setting. *Journal of the Geological Society*, 168: 1031–1045. doi:10.1144/0016-76492009-152.

- 869 Pal, T. 2020. Structural Imprints of Andaman Accretionary Prism and Its Tectonic Relation
870 with Ophiolite Belt of Indo-Burma Ranges. *In* Structural Geometry of Mobile Belts
871 of the Indian Subcontinent. *Edited by* T.K. Biswal et al. Society of Earth Scientists
872 Series, pp. 111-130.
- 873 Panjasawatwong, Y., Danyushevsky, L.V., Crawford, A.J., and Harris, K.L. 1995. An
874 experimental study of the effects of melt composition on plagioclase-melt
875 equilibria at 5 and 10 kbar: implications for the origin of magmatic high-An
876 plagioclase. *Contributions to Mineralogy and Petrology*, 118: 420-432.
877 doi:10.1007/s004100050024.
- 878 Parlak, O., Delaloye, M., and Bingol, E. 1996. Mineral chemistry of ultramafic and mafic
879 cumulates as an indicator of the arc-related origin of the Mersin ophiolite (southern
880 Turkey). *Geologische Rundschau*, 85: 647–661. doi: 10.1007/BF02440102.
- 881 Parlak, O., Hock, V., and Delaloye, M. 2000. Supra-subduction zone origin of the Pozanti-
882 Karsanti ophiolite (southern Turkey) deduced from whole-rock and mineral
883 chemistry of the gabbroic cumulates. *In* Tectonics and Magmatism in Turkey and
884 the Surrounding Area, vol. 173. *Edited by* E. Bozkurt, J.A. Winchester and J.D.A.
885 Piper. Geological Society of London Special Publication, pp. 219–234.
- 886 Parlak, O., Hock, V., and Delaloye, M. 2002. The supra-subduction zone Pozanti-Karsanti
887 ophiolite, southern Turkey: evidence for high-pressure crystal fractionation of
888 ultramafic cumulates. *Lithos*, 65(1): 205–224. doi:10.1016/S0024-4937(02)00166-
889 4.
- 890 Pearce, J. 2003. Supra-subduction zone ophiolites: The search for modern analogues. *Special*
891 *Paper of the Geological Society of America*, 373: 269-293. doi:10.1130/0-8137-
892 2373-6.269.
- 893 Pearce, J. , and Peate, D. 1995. Tectonic Implications of the Composition of Volcanic ARC
894 Magmas. *Annual Review of Earth and Planetary Sciences*, 23: 251-285.
895 doi:10.1146/annurev.earth.23.050195.001343.
- 896 Pearce, J., and Stern, B. 2006. Origin of Back-Arc Basin Magmas: Trace Element and Isotope
897 Perspectives. *Monograph Series American Geophysical Union*, 166: 63-86.
898 doi:10.1029/166GM06.

- 899 Pedersen, R.B., Searle, M.P., and Carter, A., Bandopadhyay, P.C. 2010. U–Pb zircon age of
900 the Andaman ophiolite: implications for the beginning of subduction beneath the
901 Andaman–Sumatra arc. *Journal of the Geological Society*, 167: 1105–1112.
902 doi:10.1144/0016-76492009-151.
- 903 Plunder, A., Bandyopadhyay, D., Ganerød, M., Advokaat, E.L., Ghosh, B., Bandopadhyay, P.,
904 and van Hinsbergen, D.J.J. 2020. History of Subduction Polarity Reversal During
905 Arc-Continent Collision: Constraints From the Andaman Ophiolite and its
906 Metamorphic Sole, *Tectonics*. 39: e2019TC005762. doi:10.1029/2019TC005762.
- 907 Pouchou, J.L., and Pichoir, F., 1985. ‘PAP’(ψ–ρ–Z) procedure for improved quantitative
908 microanalysis. *In Microbeam Analysis. Edited by J.T Armstrong*. San Francisco,
909 CA: San Francisco Press, pp. 104–106.
- 910 Purohit, K.K., Mukherjee, P.K., Saini N K., Khanna, P.P. and Rathi, M.S., 2006, Geochemical
911 survey of stream sediments from upper parts of Alaknanda, Mandakini, Bhilangana
912 and Bhagirathi catchments, Garhwal Himalaya. *Himalayan Geology*, 27(1): 31–39.
- 913 Rasool, QA, Ramanujam, N., and Biswas, S.K. 2015. Petrology and Geochemistry of Gabbros
914 from the Andaman Ophiolite: Implications for their Petrogenesis and Tectonic
915 Setting. *Journal of Geology and Geophysics*, 4: 226. doi:10.4172/2381-
916 8719.1000226
- 917 Ray, K.K., 1982. A review of the geology of Andaman and Nicobar Islands, vol 42. Geological
918 Survey of India Miscellaneous Publications, pp 110–125.
- 919 Ray, K.K., Sengupta, S., and Van den hul, H.J.1988. Chemical characters of volcanic rocks
920 from Andaman ophiolite, India. *Journal of the Geological Society*, 145(3): 393-
921 400. doi:10.1144/gsjgs.145.3.0393.
- 922 Ross, K., and Elthon, D. 1993. Cumulates from strongly depleted mid-ocean-ridge basalt.
923 *Nature*, 365: 826–829. doi:10.1038/365826a0.
- 924 Roy, S. 1992. Accretionary prism in Andaman Forearc. Geological Survey of India Special
925 Publication, 29: 273–278.
- 926 Saha, A., Dhang, A., Ray, J., Chakraborty, S., and Moecher, D. 2010. Complete preservation
927 of ophiolite suite from south Andaman, India: A mineral-chemical perspective.
928 *Journal of Earth System Science*, 119: 365–381. doi:10.1007/s12040-010-0017-6.

- 929 Saha, A., Santosh, M., Ganguly, S., Manikyamba, C., Ray, J., and Jagadish Dutta, J. 2018.
 930 Geochemical cycling during subduction initiation: Evidence from serpentinitised
 931 mantle wedge peridotite in the south Andaman ophiolite suite. *Geoscience*
 932 *Frontiers*, 9(6): 1755-1775. doi:10.1016/j.gsf.2017.12.017.
- 933 Saini, N.K., Mukherjee, P.K., Khanna, P.P., and Purohit, K.K. 2007. A proposed amphibolite
 934 reference rock sample (AM-H) from Himachal Pradesh. *Journal of the Geological*
 935 *Society of India*, 69: 799–802.
- 936 Sarma, D.S., Jafri, S.H., Fletcher, I.R., and McNaughton, N.J. 2010. Constraints on the
 937 Tectonic Setting of the Andaman Ophiolites, Bay of Bengal, India, from SHRIMP
 938 U-Pb Zircon Geochronology of Plagiogranite. *The Journal of Geology*, 118(6):
 939 691-697. doi:10.1086/656354.
- 940 Sengupta, S., Ray, K.K., Acharyya, S.K., and de Smeth, J.B. 1990. Nature of ophiolite
 941 occurrences along the eastern margin of the Indian plate and their tectonic
 942 significance. *Geology*, 18(5): 439-442. doi:10.1130/0091-
 943 7613(1990)018<0439:NOOOAT>2.3.CO;2.
- 944 Searle, M.P., Morley, C.K., Waters, D.J., Gardiner, N.J., Htun, U.K., Nu, T.T and Robb L.J.,
 945 2017. Tectonic and metamorphic evolution of the Mogok Metamorphic and Jade
 946 Mines belts and ophiolitic terranes of Burma (Myanmar). *In Myanmar: Geology,*
 947 *Resources and Tectonics. Edited by A.J. Barber, K. Zaw and M.J.Crow. Geological*
 948 *Society London Memoirs*, 48, pp. 261–293. doi:10.1144/M48.12.
- 949 Shastry, A., Srivastava, R., Chandra, R., and Jenner, G. 2001. Fe–Ti-enriched mafic rocks from
 950 south Andaman ophiolite suite: Implication of late stage liquid immiscibility.
 951 *Current Science*, 80 (3): 453-454.
- 952 Shaw, D.M. 1970. Trace element fractionation during anatexis. *Geochimica et Cosmochimica*
 953 *Acta*, 34 (2): 237-243. doi: 10.1016/0016-7037(70)90009-8.
- 954 Shervais, J.W. 1982. Ti-V plots and the petrogenesis of modern and ophiolitic lavas. *Earth and*
 955 *Planetary Science Letters*, 59: 101-118. doi:10.1016/0012-821X(82)90120-0.
- 956 Shinjo, R., Chung, S.-L., Kato, Y., and Kimura, M. 1999. Geochemical and Sr-Nd isotopic
 957 characteristics of volcanic rocks from the Okinawa Trough and Ryukyu Arc:
 958 Implications for the evolution of a young, intracontinental back arc basin. *Journal*

- 959 of Geophysical Research: Solid Earth, 104: 10591-10608.
960 doi:10.1029/1999JB900040.
- 961 Sisson, T.W., and Grove, T.L. 1993. Experimental investigations of the role of H₂O in calc-
962 alkaline differentiation and subduction zone magmatism. *Contributions to*
963 *Mineralogy and Petrology*, 113(2): 143-166. doi:10.1007/BF00283225.
- 964 Sloan, R.A., Elliott, J.R., Searle, M.P. and Morley, C.K. 2017. Active tectonics of Myanmar
965 and the Andaman Sea. *In Myanmar: Geology, Resources and Tectonics. Edited by*
966 *A.J. Barber, K. Zaw and M.J. Crow. Geological Society London Memoirs*, 48, pp.
967 19–52. doi:10.1144/M48.2.
- 968 Sobolev, A.V., and Shimizu, N. 1993. Ultra-depleted primary melt included in an olivine from
969 the Mid-Atlantic Ridge. *Nature*, 363(6425): 151-154. doi:10.1038/363151a0.
- 970 Socquet, A., Goffé, B., Pubellier, M., and Rangin, C. 2002. Le métamorphisme Tardi-Crétacé
971 à Éocène des zones internes de la chaîne Indo-Birmane (Myanmar occidental):
972 implications géodynamiques. *Comptes Rendus Geosciences* 334:573–580.
- 973 Srivastava, R.K., Chandra, R., and Shastri, A. 2004. High-Ti type N-MORB parentage of
974 basalts from the south Andaman ophiolite suite, India. *Journal of Earth System*
975 *Science*, 113: 605-618. doi:10.1007/BF02704025.
- 976 Stakes, D., and Franklin, J.M. 1994. Petrology of Igneous Rocks at Middle Valley, Juan de
977 Fuca Ridge. *Proceedings of the Ocean Drilling Program, Scientific Results*, 139:
978 79-102. doi:10.2973/odp.proc.sr.139.212.1994.
- 979 Sun, W., and McDonough, W. 1989. Chemical and isotopic systematics of oceanic basalts:
980 Implications for mantle composition and processes. *Geological Society of London,*
981 *Special Publications*, 42: 313–345. doi:10.1144/GSL.SP.1989.042.01.19.
- 982 Takagi, D., Sato, H., and Nakagawa, M. 2005. Experimental study of a low-alkali tholeiite at
983 1–5 kbar: optimal condition for the crystallisation of high-An plagioclase in
984 hydrous arc tholeiite. *Contributions to Mineralogy and Petrology*, 149(5):527-540.
985 doi:10.1007/s00410-005-0666-7.
- 986 VanderLaan, S., Arculus, R., Pearce, J., Jorge, J., and Murton, B. 1992. Petrography, Mineral
987 Chemistry, and Phase Relations of the Basement Boninite Series of Site 786, Izu-
988 Bonin Forearc. *Proceedings of the Ocean Drilling Program, Scientific Results*,
989 125:171-201. doi:10.2973/odp.proc.sr.125.139.1992.

- 990 Verencar, A., Saha, A., Ganguly, S., and Manikyamba, C. 2021. Tectono-magmatic evolution
991 of Tethyan oceanic lithosphere in supra subduction zone forearc regime:
992 Geochemical fingerprints from crust-mantle sections of Naga Hills Ophiolite.
993 *Geoscience Frontiers*, 12(3) 101096. doi:10.1016/j.gsf.2020.10.003.
- 994 Volpe, A.M., Douglas Macdougall, J., and Hawkins, J.W. 1987. Mariana Trough basalts
995 (MTB): trace element and SrNd isotopic evidence for mixing between MORB-like
996 and Arc-like melts. *Earth and Planetary Science Letters*, 82(3-4): 241-254.
997 doi:10.1016/0012-821X(87)90199-3.
- 998 Warren, J.M. 2016. Global variations in abyssal peridotite compositions. *Lithos*, 248-251: 193-
999 219. doi:10.1016/j.lithos.2015.12.023.
- 1000 Whitney, D.L., and Evans, B.W. 2010. Abbreviations for names of rock-forming minerals.
1001 *American Mineralogist*, 95(1): 185-187. doi:10.2138/am.2010.3371.
- 1002 Workman, R.K., and Hart, S.R. 2005. Major and trace element composition of the depleted
1003 MORB mantle (DMM). *Earth and Planetary Science Letters*, 231: 53-72. doi:
1004 10.1016/j.epsl.2004.12.005.
- 1005 Zahirovic, S., Seton, M., and Müller, R. 2013. The Cretaceous and Cenozoic tectonic evolution
1006 of Southeast Asia. *Solid Earth Discussions*. 5. 1335-1422. doi: 10.5194/sed-5-
1007 1335-2013
- 1008

1009 **Table captions**

1010 Table 1. XRF and ICP-MS analysis data of gabbros of South Andaman Ophiolite. Oxides are
 1011 given in wt.% and trace elements in ppm, LOI = Loss On Ignition, BDL = Below Detection
 1012 Limit.

1013

1014 **Figure captions**

1015 Figure 1. Generalized geological map of the Andaman Islands showing the distribution of the
 1016 Ophiolite suite and the Tertiary sedimentary units (modified after Pal 2020). Shown in inset is
 1017 a map of India indicating the Andaman Islands location in the Bay of Bengal. (Map was created
 1018 using Grapher Software, Version 13)

1019 Figure 2. Map of the South Andaman Island modified after Bhat et al. (2019), with
 1020 georeferenced (using Surfer 11) sample locations of gabbros marked in red stars in the South
 1021 Andaman Ophiolite, India. (Map was created using Grapher Software, Version 13)

1022 Figure 3. Photographs of gabbro outcrops at Kodiaghat location of South Andaman Island
 1023 Ophiolite (a: N11°31'21.2", E92°43'9.2"; b: N11°31'21.2", E92°43'9.3").

1024 Figure 4. Photomicrographs of the gabbros of the South Andaman Ophiolite, India: (a) & (b)
 1025 Olivine-bearing gabbros under cross polarised light show plagioclases and clinopyroxene
 1026 occurring as cumulus phases along with olivines. The presence of cracks marks the olivine
 1027 grains. (c) Plagioclase grains in gabbros showing triple junction. (d) & (e) Gabbros under cross
 1028 polarised light showing the occurrence of clinopyroxenes and plagioclases. (f) Gabbros under
 1029 cross-polarised light showing secondary amphiboles occurring at the rim of clinopyroxenes
 1030 along with plagioclases. (Abbreviations: Cpx = clinopyroxene, Pl = plagioclase, Ol = olivine,
 1031 Amp = amphibole).

1032 Figure 5. (a) Nomenclature of plagioclases occurring in the cumulate gabbros of the South
 1033 Andaman Ophiolite. (Abbreviations: An = anorthite, Ab = albite, Or = orthoclase). (b)

Pyroxene quadrilateral after Morimoto et al. (1988), showing the compositions of clinopyroxenes of the cumulate gabbros from the South Andaman Ophiolite. Fields of island arc gabbroic rocks and Skaergaard trends are from Burns (1985). (Abbreviations: En = enstatite, Fs = ferrosilite, Wo = wollastonite).

Figure 6 (a1 & a2) Backscattered images depicting the primary and secondary amphiboles observed in the gabbros of the South Andaman Ophiolite. (Abbreviations: Cpx = clinopyroxene, Pl = plagioclase, Amp = amphibole) (b) Nomenclature of amphiboles from the South Andaman Ophiolite's cumulate gabbros (after Hawthorne et al. 2012).

Figure 7. Harker variation diagrams for the cumulate gabbros of the South Andaman Ophiolite for selected major oxides and trace elements. Available data of previous works on gabbro's and ultramafic cumulates (harzburgite and lherzolite) and mantle peridotite of South Andaman Ophiolite are plotted for comparison. A clear differentiation trend can be discerned from Mg rich ultramafics to Ca rich mafic cumulates.

Figure 8. (a) Chondrite normalised rare earth element trends of the South Andaman Ophiolite's cumulate gabbros. Normalising values of chondrite are after Sun and McDonough (1989). (b) Spidergram of N-MORB-normalised trace element abundances in the studied gabbros of South Andaman Ophiolite. Normalising values of N-MORB are after Sun and McDonough (1989). Prior published data of gabbro (Pal 2011; Rasool et al. 2015) and ultramafics (Saha et al. 2018) are also shown for comparison.

Figure 9 (a) Ti vs. Al^{iv} tectonic classification diagram based on clinopyroxene compositions of the South Andaman Ophiolite's cumulate gabbros after Beccaluva et al. (1989). (b) Discrimination diagrams based on clinopyroxene compositions of the cumulate gabbros of the South Andaman Ophiolite Ti vs. Ca + Na diagram after Leterrier et al. (1982). (c) Al_2O_3 vs. Cr_2O_3 chromian spinel discrimination diagram suggests arc signature for the studied gabbros of the South Andaman Ophiolite.

Figure 10 Chondrite-normalised diagram showing trapped melt and clinopyroxene REE compositions for samples **(a)** AN 27/45 and **(b)** and AN 7/17. REE compositions of the clinopyroxenes have been calculated using the EDM model of Bédard (1994), assuming TMF of 0, 5, 10, 15 and 20%. Measured clinopyroxene data of Andaman gabbros (Ghosh et al. 2018) are also shown. The clinopyroxene-melt partition coefficient is calculated from the parameterisation of Bédard (2014). Clinopyroxene composition of DMM (Workman and Hart, 2005), N-MORB (Gale et al. 2013) and average abyssal peridotite (Warren 2016) are also shown for comparison. Normalisation values are from Sun and McDonough (1989). Whole rock chondrite-normalised diagram showing trapped melt and REE compositions for samples **(c)** AN 27/45 and **(d)** AN 7/17. Melt compositions have been calculated using the EDM model of Bédard (1994, 2001), assuming TMF of 0, 5, 10, 15 and 20%. The whole rock composition of DMM (Workman and Hart 2005), N-MORB (Gale et al. 2013) and average abyssal peridotite (Niu 2004) are also shown for comparison.

Figure 11 (a) Anorthite (An) content of plagioclases plotted against forsterite (Fo) content of coexisting olivines in cumulate gabbros of the South Andaman Ophiolite. Fields of island arcs, oceanic islands and mid-ocean ridges (modified after Beard 1986) are shown comparison. The island arcs are classified into three types (Beard 1986): Type I comprises cumulates consisting primarily of olivine-bearing gabbros and subordinate olivine-free gabbro norites. Type II cumulates are dominated by olivine bearing ultramafic rocks and olivine-free gabbro norites. Type III cumulates contain amphibole as a cumulus phase and characteristically comprise hornblende-olivine gabbro, hornblende gabbro and amphibole rich ultramafic rocks. The South Andaman Ophiolite gabbros are petrographically similar to Type III gabbros. (b) Composition of coexisting plagioclases (An mol.%) and clinopyroxenes (Mg#) in the South Andaman Ophiolite's cumulate gabbros compared to the MORB and arc gabbros. Fields of MORB and arc gabbros after Burns (1985).

1084 Figure 12. (a) On the plot of Ti (ppm) vs. V (ppm) after Shervais 1982, the South Andaman
1085 Ophiolite gabbros display both IAT and MORB characteristics (b) The analysed gabbro data
1086 of the South Andaman ophiolites plot in the N-MORB field in the TiO_2 - SiO_2 / 100 - Na_2O
1087 ternary diagram of clinopyroxene composition after Beccaluva et al. 1989. (c) Al_2O_3 vs. (TiO_2
1088 + Cr_2O_3) diagram (adapted after Hout et al. 2002) wherein the clinopyroxene compositions of
1089 the South Andaman Ophiolite gabbros plot in the overlapping area between N-MORB and back-
1090 arc basin basalt. Fields outline clinopyroxene compositions in boninites (VanderLaan et al.
1091 1992), island-arc tholeiites and back-arc basin basalts (Hawkins and Allan 1994), and N-
1092 MORB (Stakes and Franklin 1994).

1093 Figure 13. Proposed geotectonic model for the Cretaceous Intra-Oceanic Island Arc-Back Arc
1094 Basin system of the South Andaman Ophiolite, India. See text for details.

Figure 1

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Figure 2

Figure 3

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Figure 4

92x45mm (300 x 300 DPI)

Figure 5

386x140mm (300 x 300 DPI)

Figure 6

Figure 7

185x268mm (300 x 300 DPI)

Figure 8

388x162mm (300 x 300 DPI)

Figure 9

601x160mm (300 x 300 DPI)

Figure 10

321x195mm (150 x 150 DPI)

Figure 11

314x132mm (300 x 300 DPI)

Figure 12

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Figure 13

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Table 1 Major element oxides, trace elements, and rare-earth elements contents in cumulate gabbros from the South Andaman Island ophiolite, by XRF and ICP-MS. LOI = Loss On Ignition, BDL = Below Detection Limit.

Sample no.	AN 10/21	AN 10/16	AN 10/1	AN 27/40	AN 27/45	AN 10/5	AN 10/8	AN 7/17	AN 10/14	AN 27/42
Lithology	Gabbro	Gabbro	Gabbro	Gabbro	Gabbro	Gabbro	Gabbro	Gabbro	Gabbro	Olivine gabbro
Major oxide (XRF results, wt %)										
SiO ₂	45.65	46.87	46.76	46.88	49.83	45.79	46.5	44.91	46.23	45.92
TiO ₂	0.21	0.2	0.31	0.16	0.17	0.11	0.1	0.07	0.09	0.12
Al ₂ O ₃	15.66	14.95	16.25	18.09	17.36	15.66	18.45	22.61	18.18	20.58
Fe ₂ O ₃	8.39	7.27	5.85	4.06	2.31	6.08	3.62	2.92	2.69	3.04
MnO	0.13	0.15	0.11	0.08	0.06	0.1	0.07	0.03	0.04	0.06
MgO	13.89	13.72	15.17	10.48	8.79	16.68	13.28	6.17	10.13	8.7
CaO	9.38	10.3	7.63	17.65	17.95	8.53	9.08	18.46	13.57	17.8
Na ₂ O	1.27	1.25	1.41	0.65	1.41	1.28	1.68	1.45	1.58	0.85
K ₂ O	0.04	0.07	0.95	0.01	0.13	0.58	0.58	0.08	1.54	0.02
P ₂ O ₅	0.03	0.02	0.01	<0.01	0.01	<0.01	0.01	0.01	0.04	<0.01
LOI	5.7	5.16	5.62	1.61	2.72	5.41	6.61	2.37	5.59	2.16
Total	100.35	99.96	100.07	99.67	100.74	100.22	99.98	99.08	99.68	99.25
Trace elements (XRF results, ppm)										

Ba	14	5	<5	<5	<5	8	9	15	18	<5
Cr	1058	811	407	507	603	264	223	228	1247	361
V	62	78	65	74	103	36	10	12	3	58
Co	72	53	48	29	17	49	40	9.1	12.4	22
Ni	561	340	402	182	65	416	427	28	131	97
Cu	76	88	7	BDL	1	14	78	13	2	2
Zn	56	61	30	21	40	25	33	11	13	18
Ga	11.73	11.09	10.82	8.35	8.36	8.8	8.81	13	9	10.01
Pb	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Th	1.41	BDL	BDL	BDL	0.75	0.88	0.68	BDL	BDL	BDL
Rb	BDL	1	6	BDL	1	5	4	1	8	BDL
Sr	111	99	113	180	216	161	182	386	300	240
Y	10	10	10	3	2	2	2	1	2	2
Zr	229	175	50	BDL	BDL	BDL	BDL	44	38	BDL
Nb	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Sc	29	31	18	50	46	14	12	16.4	15.1	39
Rare earth elements (ICP-MS results, ppm)										
La	1.33	1.39	2.03	15.15	0.64	0.53	0.53	0.44	0.55	0.50
Ce	3.53	3.52	5.31	31.85	1.07	0.97	0.975	0.86	1.28	0.99
Pr	0.71	0.66	0.81	4.56	0.3	0.20	0.22	0.17	0.23	0.27
Nd	3.65	3.21	3.61	19.28	1.35	0.76	0.74	0.79	1	1.30
Sm	1.31	1.14	1.13	4.55	0.61	0.25	0.22	0.27	0.31	0.59

Eu	0.74	0.63	0.61	1.43	0.34	0.24	0.20	0.21	0.17	0.32
Gd	1.76	1.50	1.46	4.90	0.77	0.34	0.28	0.32	0.38	0.75
Tb	0.32	0.27	0.27	0.74	0.15	0.06	0.04	0.05	0.07	0.14
Dy	2.22	1.88	1.82	4.42	0.95	0.42	0.30	0.34	0.43	0.93
Ho	0.50	0.42	0.41	0.94	0.20	0.09	0.06	0.07	0.09	0.20
Er	1.29	1.13	1.11	2.56	0.50	0.25	0.17	0.18	0.26	0.49
Tm	0.19	0.17	0.17	0.39	0.07	0.04	0.028	0.02	0.04	0.07
Yb	1.22	1.11	1.16	2.55	0.44	0.26	0.18	0.16	0.24	0.41
Lu	0.19	0.16	0.17	0.40	0.06	0.04	0.02	0.02	0.03	0.06