Deep crustal crystallization of tholeiitic melt:
Insights from Manguao Basalt, Palawan, Philippines

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Manguao Basalt is a Plio-Pleistocene basaltic lava flow located on the northeastern edge of Palawan Island, Philippines. The absence of active trenches surrounding the Palawan Continental Block (PCB) poses a challenge regarding the nature and origin of magmatism in the region. This study presents the petrographic and geochemical character of Manguao Basalt, as well as provides insights to the melt formation beneath the PCB.

Manguao Basalt samples are olivine-phyric with minor pyroxenes, set in a plagioclase-dominated microcrystalline groundmass. Average bulk-rock major element composition of Manguao Basalt shows similarities to common olivine basalt tholeiite. Petrographic observations of the phenocrysts, however, show the unusual precedence of pyroxenes in the crystallization sequence. Calculated formation temperatures and pressures of the modal assemblage are consistent with this idea of early pyroxene formation. Simulations of mantle melting using the MELTS program show the formation of pyroxene-saturated primitive liquids. The evolution of these primitive liquids reaches similarities with Manguao Basalt composition at 1230–1260 °C. Simulations of equilibrium and fractional crystallization demonstrate the formation of olivine or orthopyroxene as the first crystals. However, the simulations done at equilibrium conditions are more consistent with the observed mineral chemistry of pyroxene phenocrysts in Manguao Basalt. Hence, maintaining the equilibrium between the source and melt is crucial for replicating the observed pyroxene chemistry. Magmatic underplating provides an excellent model for visualizing the melting and crystallization processes beneath the PCB. The model is also consistent with the narrative of other magmatic units in northern Palawan (e.g., Capoas Granite). The significant findings of this study contribute to the understanding of the tectonic evolution of the PCB.

Keywords: Tholeite melts, MELTS program, Manguao Basalt

INTRODUCTION

Magmatic arcs are important contributors to the growth and evolution of the crust. In active arc systems, the prevalent tectonic influence plays a dominant role in melt generation and volcanism of a region. Active magmatic arcs in the Philippines are mostly related to subduction zones that bound the archipelago (Aurelio, 2000). Although majority of young (Plio-Quaternary) Philippine volcanic events are related to these active trenches (i.e., the Luzon volcanic arc is related to the subduction along the Manila Trench), there are few reported magmatic occurrences that are unrelated to any identified subduction zone (e.g., Central Mindanao lavas of Sajona et al., 2000).

A Plio–Pleistocene basaltic lava flow field (Manguao Basalt) is found located on the northeast tip of Palawan Island, Philippines. The present tectonic setting of Palawan does not show any nearby active trench, indicating melt generation that is unrelated to a subduction zone. Hence, the existence of the lava flow is proof that not all young Philippine volcanic events are subduction-related. This study focuses on providing detailed petrographic and geochemical information about the Manguao Basalt lava flow, as well as giving insights to the melt generation and evolution of the Palawan region.
GEOLOGICAL BACKGROUND

The Philippines is an archipelagic country located on the western side of the Pacific. The formation of the Philippine islands is interpreted as the amalgamation of arc-derived units, ophiolitic suites, and transported continental blocks (e.g., Mindoro and Palawan islands). Tectonic activity in the country is the result of the interaction between three major plates: Eurasian, Pacific, and Indo-Australian (Karig, 1983; Aurelio, 2000). Geologically, the Philippines is divided into two distinct units (Fig. 1): (1) the Philippine Mobile Belt (PMB) and (2) the Palawan Continental Block (PCB)/North Palawan Block (NPB). Active volcanism and major strike-slip faulting occur more frequently in PMB, which contrasts to the relatively more stable PCB (Taylor and Hayes, 1980; Holloway, 1982; Aurelio, 2000; Aurelio et al., 2013).

The active nature of the PMB is attributed to the surrounding subduction zones (East Luzon Trough and Philippine Trench in the east; Manila Trench, Negros-Sulu Trench, and Cotabato Trench in the west). Young (Plio-Quaternary) magmatic arcs reflect the activity in these nearby subduction zones and define the different volcanic belts that are found in the country (Luzon Central-Cordillera Arc, Northern Sierra Madre-Catanduanes Arc, Negros Arc, East Philippine Arc, Cotabato Arc, and Sulu-Zamboanga Arc; Aurelio, 2000).

The Palawan region (Fig. 2), on the other hand, is a contrast to the character of the PMB (i.e., active volcanism is absent in the entire island). No active subduction zone surrounds the Palawan Island, and igneous units in the region are very few (i.e., Palawan Ophiolite and Kapoas Granite). The Manguao Basalt lava flow represents the youngest unit in the Northern Palawan stratigraphic group. Formerly known as Manguao Volcanics, the Manguao Basalt is a Plio-Pleistocene formation consisting of por-

Figure 1. Simplified tectonic map of the Philippines showing the distribution of volcanic arcs (red shaded regions in dashed outline) and adjacent active trenches. Tectonic features modified from Magro et al. (2013) and Aurelio (2000). ① Luzon Central Cordillera Arc is controlled by the activity of the Manila Trench in the west. ② Northern and Southern Sierra Madre-Catanduanes Arcs are related to the Philippine Trench in the east and former activity of the East Luzon Trough. ③ Negros Arc is related to the Negros-Sulu Trench. ④ East Philippine Arc is related to the Philippine Trench. ⑤ Magmatic activity in the Central Mindanao Arc (shaded blue) is related to a completely subducted oceanic slab with partial influence from activity of the Philippine Trench. ⑥ Cotabato Arc is related to the Cotabato Trench. ⑦ Sulu-Zamboanga Arc is related to the Negros-Sulu Trench. The boundaries of the Palawan Continental Block are derived from Liu et al. (2014). Base Philippine image generated from Shuttle Radar Topography Mission (SRTM; 90-m resolution) data from philgis.org. Color version is available online from https://doi.org/10.2465/jmps.191211.

Figure 2. Simplified geologic map of North Palawan Island showing the distribution of lithologic units with continental affinity. Red, light red, and pink indicate igneous units. Manguao Basalt is assigned with a Plio-Pleistocene age. Other magmatic units include the Middle Miocene Cepoas and Bay Peak Granite, and the Middle Eocene Central Palawan Granite. Cretaceous-Eocene units included in the map are members of the Palawan Ophiolite. The Ulugan Fault is a structural boundary separating the Palawan Continental Block from the Palawan Ophiolite. Map reconstructed from Suggate et al. (2014) and Almasco et al. (2000). Base image generated from SRTM DEM (90-m resolution; from philgis.org). Color version is available online from https://doi.org/10.2465/jmps.191211.
Phyritic vesicular basalts, shales, siltstones, conglomerates and associated pyroclastic rocks (Peña, 2008). Exposures of the lava and associated pyroclastic rocks (Peña, 2008). Exposures of the lava and associated pyroclastic rocks (Peña, 2008). Exposures of the lava and associated pyroclastic rocks (Peña, 2008). Exposures of the lava and associated pyroclastic rocks (Peña, 2008).

**Figure 3.** Palawan Island (inset) and Manguao Basalt lava field (dashed region). Yellow circles denote sampling locations (WP 1–16; Point 14 are two samples taken at proximity, WP 14–15). Tadpole-shaped feature in the middle of the lava field is a scoria cone. Manguao Lake is found northwest of the lava field exposure. Map generated using Landsat 7 ETM+ (15-m spatial resolution; 3-spectral bands) and SRTM DEM (90-m resolution) from philgis.org. Color version is available online from https://doi.org/10.2465/jmps.191211.

**Brief geologic history of Palawan Island and associated magmatism**

The northern half of the Palawan Island is an extended oceanic portion of the Eurasian plate, which separated from the mainland during the opening of the South China Sea (Taylor and Hayes, 1980; Hall, 2002; Yumul et al., 2009; Aurelio et al., 2013; Guan et al., 2016). The transport of this block resulted to regional metamorphism of the northern end (Williams, 1997; Almasco et al., 2000; Aurelio, 2000; Militante-Matias et al., 2000; Yumul et al., 2009; Aurelio et al., 2013; Guan et al., 2016). Continent-derived sedimentary and metamorphic rocks are the oldest (Permian) and the dominant lithologic units in the northern Palawan region (Holloway, 1982; Hall, 1997). Magmatic intrusions, like the Capoas Granite (Middle Miocene), represent the post-rifting melt formation during the Cenozoic (Encarnación and Mukasa, 1997; Williams, 1997; Almasco et al., 2000; Aurelio, 2000; Yumul et al., 2009). Manguao Basalt, on the other hand, is the youngest volcanic activity in the Palawan region.

At present, no active trench surrounds Palawan Island. The absence of a subducting slab beneath the island is attested by the P-wave tomography study of Fan et al. (2017). Instead, a low-velocity region appears to underlie the continental crust. Geophysical investigation of Liu et al. (2014) described PCB as a ‘hyper-extended continental crust intruded with magmatic bodies’. The structural map of Pubellier et al. (2018) seems to agree with this idea; showing numerous NW-trending extensional faults that coincide with the locations of the different magmatic units found in the north Palawan region. The origin of other igneous units in the area (e.g., Capoas Granite) attests to the presence of magmatism in a ‘post-rifting, non-collisional tectonic setting’ (Encarnación and Mukasa, 1997).

**METHODS**

Manguao Basalt lava flow samples were obtained from nearshore and inland surface exposures in Taytay, North Palawan, Philippines. Thin sections of the basaltic rocks were prepared at the National Institute of Geological Sciences-University of the Philippines Diliman (NIGS-UPD), Philippine Department of Energy (DOE), and Akita University, Japan. Whole-rock geochemical analyses were done using X-ray fluorescence spectroscopy (XRF), Inductively-coupled plasma mass spectrometer (ICP-MS), and Inductively-coupled plasma optical emission spectrometer (ICP-OES) from Intertek Testing Services Philippines. Wavelength-dispersive instrument, Panalytical AxiosMax PW: 4400/40 was used for XRF, while Agilent Technologies 7700x and Agilent Technologies 5100 Radial were used for ICP-MS and ICP-OES, respectively. The resulting major and trace element compositions are provided in Table 1.
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Mineral chemistry analyses were done using a scanning electron microscope with energy dispersive spectroscopy (SEM–EDS) and electron probe microanalysis (EPMA) from Akita University. We used a JEOL JSM–IT300 with Oxford EDS detector X-MaxN for SEM–EDS and JEOL JXA–8230 for EPMA. Operating conditions of SEM–EDS for all semi–quantitative point analyses were done at high vacuum conditions, 10 mm working distance, 15 kV accelerating voltage, and probe current of 2.20 nA. A 50–s acquisition time for point analyses was done on carbon coated samples (~ 30 nm thickness at 2.25 g/cm³ carbon coat density). EPMA operating conditions for all point analyses were done at 15 kV accelerating voltage, 5 µm probe diameter, and at 20 nA probe current. Quantitative mineral analyses of samples were obtained from EPMA using the JEOL silicate standards set (for SiO₂, CaO, FeO, Al₂O₃, MgO, TiO₂, MnO, Na₂O, K₂O, Cr₂O₃, and NiO). EPMA results with weight percent oxide (wt%) totals within 99–101 wt% were included for stoichiometric, geothermometry, and geobarometry calculations. A list of all pertinent equations used is available online as Supplementary Table S1 (https://doi.org/10.2465/jmps.191211).

MELTS Parameters

Simulations of melting and crystallization processes were done using the MELTS program of Gualda et al. (2012) and Ghiorso and Gualda (2015). Melting was primarily induced by depressurization of the upper mantle. This is following the idea of a thinned continental lithosphere (Liu et al., 2014), the presence of melting within the upper mantle (low–velocity region; Fan et al., 2017), and the extensional features observed in the region (Pubellier et al., 2018). Fertile (KLB–1 Peridotite of Davis et al., 2009) and depleted (Depleted Mantle of Workman and Hart, 2005) mantle sources were used as starting compositions for the upper mantle. Melting experiments of dry peridotites by Hirose and Kushiro (1993) provided the initial pressure and temperature conditions of a fertile upper mantle source (KLB–1) at equilibrium; 15 kbar and 1350 °C, respectively. Initial input of the mantle compositions and parameters in the MELTS program produced an essentially solid mantle, which ensured that the simulations reflect the early phase of upper mantle melting. In addition, the modal compositions of mantle produced in the simulations resembled the respective calculated modes of KLB–1 and depleted mantle (Table 2).

From the initially solid upper mantle, simulations of depressurization melting were done at isothermal conditions (1350 °C) and QFM buffer. The pressure was lowered every 0.1 kbar until the system reached the highest obtained pressures from geobarometry (pressure conditions during the crystallization of the first crystals, orthopyroxenes; ~ 5 kbar). Two melting scenarios were done on both fertile and depleted mantle sources: (1) retaining equilibrium between source and melt, and (2) liquid fractionation. The resulting primitive melt compositions were

| Equipment/Procedure | XRF | ICP |
|---------------------|-----|-----|
| Element             | SiO₂| TiO₂| Al₂O₃| FeO⁺| MnO| MgO| CaO| Na₂O| K₂O| P₂O₅| Total| Ni| Co| Zn| Cr |
| Units               | wt% |     |     |     |     |     |     |     |     |     |     |     | ppm |
| Detection Limit     | 0.01| 0.01| 0.01| 0.01| 0.01| 0.01| 0.01| 0.01| 0.01| 0.01| 0.01| 0.01|     |
| WP 1                | 51.11| 2.16| 14.97| 10.05| 0.15| 8.49| 8.35| 2.54| 0.62| 0.31| 98.75| 147| 42| 123| 335 |
| WP 2                | 48.37| 2.17| 15.27| 10.85| 0.17| 9.41| 8.34| 2.58| 0.56| 0.38| 98.09| 222| 48| 117| 333 |
| WP 3                | 52.90| 2.04| 14.05| 9.53| 0.15| 8.04| 7.94| 2.65| 1.07| 0.36| 98.73| 178| 43| 115| 340 |
| WP 4                | 51.45| 2.10| 14.47| 9.88| 0.15| 8.36| 8.19| 2.65| 0.86| 0.46| 98.58| 170| 46| 124| 327 |
| WP 5                | 52.19| 2.02| 13.94| 9.50| 0.15| 8.72| 8.06| 2.83| 0.97| 0.36| 98.74| 178| 41| 110| 336 |
| WP 6                | 52.37| 1.99| 13.99| 9.47| 0.15| 8.49| 7.86| 2.71| 1.03| 0.35| 98.40| 177| 42| 110| 306 |
| WP 7                | 52.58| 1.99| 14.03| 9.29| 0.14| 8.94| 7.90| 2.75| 0.89| 0.34| 98.85| 164| 74| 110| 309 |
| WP 8                | 52.73| 1.96| 13.85| 9.25| 0.14| 8.12| 7.81| 2.58| 0.97| 0.31| 97.72| 148| 42| 112| 282 |
| WP 9                | 52.45| 1.94| 13.69| 9.05| 0.14| 9.03| 7.72| 2.61| 0.86| 0.31| 97.8| 171| 78| 114| 279 |
| WP 10               | 52.31| 1.95| 13.72| 9.27| 0.15| 8.58| 7.73| 2.60| 0.99| 0.31| 97.61| 188| 45| 113| 276 |
| WP 11               | 52.23| 1.99| 13.69| 9.21| 0.15| 8.88| 7.91| 2.70| 0.94| 0.33| 98.03| 176| 44| 115| 275 |
| WP 12               | 51.45| 2.05| 14.15| 9.62| 0.15| 8.44| 8.04| 2.56| 0.84| 0.41| 97.71| 182| 49| 129| 300 |
| WP 13               | 52.84| 1.98| 13.71| 9.32| 0.15| 8.30| 7.79| 2.52| 1.03| 0.31| 97.95| 172| 45| 119| 275 |
| WP 14               | 48.59| 2.13| 15.00| 10.62| 0.17| 9.52| 8.27| 2.48| 0.55| 0.34| 97.67| 238| 50| 121| 296 |
| WP 15               | 50.79| 2.10| 14.70| 9.78| 0.15| 8.63| 8.18| 2.46| 0.60| 0.28| 97.67| 160| 45| 125| 305 |
| WP 16               | 52.95| 2.02| 14.23| 9.50| 0.15| 8.35| 8.00| 2.74| 1.01| 0.34| 98.97| 146| 40| 111| 312 |

XRF, X–ray Fluorescence Spectrometer; ICP, Inductively-coupled Plasma Mass Spectrometer and Inductively-coupled Plasma Optical Emission Spectrometer.
All samples were analyzed by Intertek Testing Services Philippines Laboratory (PNS ISO/IEC 17025:2005 LA–2010–167B).
On the other hand, all crystallization simulations were done at isobaric conditions (~5 kbar) and QFM buffer. Pressure was kept constant to simplify the conditions during the formation of the first crystals. The temperature was lowered every 10 °C until the liquid completely solidified. Two crystallization scenarios were done: (1) retaining the equilibrium between melt and crystals, and (2) crystal fractionation. The resulting simulated pyroxene compositions (orthopyroxenes and clinopyroxenes) were compared with the compositions of pyroxenes in Manguao Basalt. The evolving melt compositions were also summarized in Table 3. Data for melt evolution and compositions of other mineral components (olivine and plagioclase) are available online as Supplementary Tables S2–S6 from https://doi.org/10.2465/jmps.191211.

### RESULTS

Exposures of the lava flow field are preserved in several areas near the coast (Fig. 4). The lava flow generally appears blocky and constrained within channels. Lava flow features and structures, such as levees and tumuli, are still intact and identifiable. Sixteen (16) samples were obtained from different sites in the lava flow field (WP 1–16). All basalt samples are porphyritic, vesicular, and contain numerous chert xenoliths.

### Petrography and Mineral Chemistry

Manguao Basalt samples are porphyritic and vesicular. Phenocryst size ranges from 0.5 to 2 mm. The phenocryst...
assemblage is composed mostly of olivine (> 90%; Fig. 5a) and minor pyroxenes (Figs. 5b and 5c). Chert xenoliths and mineral clusters (Fig. 5d) are also present in most samples. The fine–grained fraction, on the other hand, comprises the microcrystalline groundmass (Fig. 5d) and volcanic glass. The groundmass assemblage consists mainly of plagioclase, pyroxenes, and opaque minerals (e.g., Ilmenite). Plagioclase laths are the largest units in the groundmass (0.3–0.5 mm). Smaller (0.1–0.3 mm) anhedral pyroxenes are found between the plagioclase laths. Blebby volcanic glass fills the interstitial spaces between the plagioclase laths and groundmass pyroxenes. Classification of the identified mineral components (olivine, pyroxenes, and plagioclase) are summarized in Figure 6.

Olivine. Olivine (Ol) occurrence is generally restricted to the phenocrysts (0.5–1.0 mm). The observed crystals are euhedral to subhedral (Fig. 5a) and mostly show skeletal textures and resorbed edges. Few Ol phenocrysts were observed attached to the edge of a larger pyroxene phenocryst. This is a petrographic evidence of a pyroxene forming much earlier than Ol in the crystallization sequence (Figs. 7a–7c).

Core Ol magnesium number \( \{ \text{Mg}\#_{\text{Ol}} = 100[X_{\text{Mg}}/(X_{\text{Mg}} + X_{\text{Fe}} + X_{\text{Mn}})] \} \) ranges from 71 to 83. Chemical zoning in Ol is only observable...
from backscattered electron images (Figs. 8a–8b). Majority of the Ol crystal interiors have uniform Mg# (core to mantle) and only the outermost edges (rim) show distinctly lower Mg# (66–76; Fig. 8a). Ol with lower core Mg# (<80) also show more pronounced pyroxene reaction rims (Fig. 8b).

**Pyroxenes.** Pyroxenes exist as coarse- and fine-grained units in Manguao Basalt. Orthopyroxenes are generally found as phenocrysts, while clinopyroxenes are present in both phenocryst and groundmass assemblages.

Orthopyroxene (Opx) phenocrystals (Fig. 8c) represent the largest (i.e., with some crystals exceeding 2 mm) and highest Mg# (76–86) of any major silicate phase present. Zoning patterns observed in large Opx crystals show a 'rounded' magnesian core (Mg# = 82–86) surrounded by less magnesian mantle (Mg# = 80–82) and least magnesian rim (Mg# = 76–80). The presence of this rounded zoning pattern possibly reflects the melt evolution and Opx resorption during crystal growth.

Clinopyroxene (Cpx) phenocrystals are smaller (100–300 µm; Fig. 8d) and less abundant than Opx. Cpx Mg# shows the widest range from 65 to 83, as it is present in both phenocryst (>80) and groundmass assemblages (<80). Like Opx, a few observed Cpx phenocrystals also shows evidence of earlier formation than Ol (Fig. 9a). While Opx and Ol phenocrystals occur as individual crystals, Cpx phenocrystals occur in aggregates. The ‘rounded’ zones are also found in Cpx phenocrysts but are not as distinct as those found in Opx.

![Figure 7](https://doi.org/10.2465/jmps.191211)

**Figure 7.** (a) Illustrations of Opx and Ol growth as seen in petrography: ① growth of large euhedral Opx, ② the start of Ol formation, using Opx as a nucleation site, and ③ interruption during Ol growth creates skeletal texture. Bottom images (b) and (c) are the actual Opx and Ol phenocrysts observed in Manguao Basalt. Color version is available online from https://doi.org/10.2465/jmps.191211.

![Figure 8](https://doi.org/10.2465/jmps.191211)

**Figure 8.** Backscattered electron images (BSE) of representative phenocrysts in Manguao Basalt. (a) Ol phenocryst with resorbed edges. Brighter rim attributed to a lower Mg#. (b) Two kinds of Ol present in Manguao Basalt: darker with higher Mg# (>80) and lighter with less Mg# (<80). Higher-Mg# olivines are more polygonal and rarely show pyroxene reaction rims. (c) Zones in Opx phenocrysts. Unlike regular polygonal zones, opx zoning shows smooth boundaries, indicating resorption during growth of the crystal. (d) Cpx phenocrysts with “wispy” zones. Unlike Opx phenocrysts, Cpx commonly form clusters and rarely occur as large single crystals. Color version is available online from https://doi.org/10.2465/jmps.191211.

![Figure 9](https://doi.org/10.2465/jmps.191211)

**Figure 9.** Backscattered electron images (BSE) of phenocrysts and groundmass components in Manguao Basalt. (a) Cpx with an ‘attached’ Ol. Similar with Opx phenocrysts, high-Mg# Cpx (>80) can also be observed with Ol grains partially ‘engulfing’ or ‘attached’ to it. Wispy zoning can also be observed in the interior of Cpx. (b) Groundmass components in Manguao Basalt. Pl laths dominate the groundmass. Anhedral Cpx is found between spaces of Pl laths. Blbleby volcanic glass fills the interstitial spaces. (c) Illustration showing the formation of the groundmass: ① formation of the Pl laths, ② melted trapped between laths form anhedral Cpx, and ③ remaining melt forms the interstitial glass. Color version is available online from https://doi.org/10.2465/jmps.191211.
Mineral clusters observed from petrography were identified as Cpx clusters (Fig. 5d). These clusters occur as large (>4 mm) distinct bulbous aggregates, possibly cumulus in origin. The Mg# of Cpx in the cluster varies from 65 to 83, similar to the Mg# range of phenocryst and groundmass Cpx.

Plagioclase. Plagioclase (Pl) occurs as euhedral to subhedral laths that dominate the microcrystalline groundmass (Fig. 9b). Pl crystals are unzoned and anorthite content ranges from 50 to 60. The occurrence of Pl laths, on the other hand, appears to be generally restricted in the groundmass. Mineral textures observed from the groundmass components (Pl and Cpx) indicate the earlier formation of the larger and euhedral Pl laths (Fig. 9c).

Crystallization Sequence. The pyroxene phenocrysts show earlier formation than Ol, based on the observed mineral relationship from petrography. The span of Ol crystallization marks the transition between phenocryst and groundmass formation. The skeletal textures observed in the Ol phenocrysts possibly recorded the change in cooling rate from melt removal. Meanwhile, the crystallization of Pl spans most of the groundmass formation. Melt trapped in between the crystal mush formed the anhedral Cpx and blebby volcanic glass. The melt parameters and conditions producing this unusual crystallization sequence (Pyroxene phenocrysts → Ol → Pl → Groundmass Cpx) were investigated further using geochemistry and MELTS simulations.

Major and Trace Element Chemistry

The average bulk-rock major element compositions (TiO₂, Al₂O₃, FeO⁴, MnO, and MgO) of Manguao Basalt samples (Table 4) show similarities with common olivine tholeiites of Wilkinson (1986). Silica (SiO₂) and alkalies (e.g., Na₂O and K₂O) are slightly higher for Manguao Basalt, while the calcium (CaO) content is distinctly lower. Using the total-alkali-silica (TAS) diagram of Pecceiillo and Taylor (1976), Manguao Basalt samples plot within the basalt to basaltic andesite field of the subalkaline series (Fig. 10a). Miyashiro (1974) plots, on the other hand, show the straddling of points within the boundary of tholeiitic and calc-alkaline rocks (Fig. 10b). The presence of the chert xenoliths, however, may have affected the bulk silica concentrations and shifted the plots towards the calc-alkaline field. AFM ternary diagram plots show the affinity for early Fe-enrichment, characteristic of tholeiite melts (Fig. 10c).

Table 4. Major element composition of Manguao Basalt in comparison with other common basalts of Wilkinson (1986)

|                  | Manguao Basalt | Wilkinson (1986) |
|------------------|---------------|-------------------|
|                  | No. of Analyses |                  |
|                  | SiO₂ | TiO₂ | Al₂O₃ | FeO⁴ | MnO | MgO | CaO | Na₂O | K₂O | P₂O₅ | Total |
| Highest Value    | 16   | 52.95 | 2.13 | 15.00 | 10.62 | 0.17 | 9.52 | 8.27 | 2.74 | 1.03 | 0.41 | 98.97 |
| Lowest Value     | 16   | 48.37 | 1.94 | 13.69 | 9.05  | 0.14 | 8.03 | 7.72 | 2.46 | 0.55 | 0.28 | 97.61 |
| Average          | 51.71| 2.04  | 14.22 | 9.64  | 0.15  | 8.62 | 8.01 | 2.62 | 0.86 | 0.34 | 98.21 |
| MORB-type, low K, low-Al Olivine-Tholeiite | 530 | 50.08 | 1.55 | 15.07 | 9.89  | 0.10 | 8.12 | 11.51 | 2.53 | 0.14 | 0.13 | 98.21 |
| MORB-type, low K, high-Al Olivine-Tholeiite | 309 | 49.88 | 1.17 | 16.95 | 8.65  | 0.07 | 7.95 | 11.89 | 2.42 | 0.13 | 0.10 | 98.43 |
| Olivine Tholeiite | 458 | 49.22 | 2.16 | 14.10 | 11.05 | 0.17 | 8.75 | 10.34 | 2.39 | 0.56 | 0.25 | 97.97 |
| Calc-Alkaline, Low-K/Na, Olivine-Basalt | 395 | 50.15 | 1.35 | 17.89 | 9.23  | 0.14 | 6.57 | 10.05 | 2.82 | 0.76 | 0.21 | 98.32 |
| Calc-Alkaline, Medium-K/Na, Olivine-Basalt | 53  | 50.58 | 1.27 | 18.57 | 8.81  | 0.34 | 5.73 | 9.07 | 2.73 | 1.78 | 0.35 | 98.42 |

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Major and Trace Element Chemistry

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sequence were investigated further using geothermobarometers and MELTS simulations.

**Pressure and Temperature Calculations**

Formation temperatures obtained from mineral–based thermometers are consistent with the idea of early pyroxene crystallization (Fig. 12 and Table 5). Pressure-independent Ol-based and liquid–pyroxene thermometers (Arndt, 1977; Helz and Thornber, 1987; Putirka, 2008) show a wide range of formation temperatures (1185–1235 °C). A pressure dependent Ol thermometer from Putirka (2008) requires pressures of 1.1 to 4.6 kbar to reach this range of formation temperatures. A similar pressure-dependent Ol-based thermometer of Beattie (1993) gives a narrower temperature range (1203–1222 °C) compared to the pressure-independent thermometers. The thermometer of Beattie (1993) and aluminum-based barometers of Putirka (2008) yielded the highest obtained average Opx formation temperatures (1234–1252 °C) and pressures (3.0–5.7 kbar). P-independent Cpx thermometer of Putirka et al. (1996) shows higher average Cpx formation temperatures (1233 °C) compared with P-dependent Cpx thermometers of Nimis and Taylor (2000) and Putirka et al. (1996; 2003; 1137–1186 °C). Cpx has the widest range of formation temperatures (1103–1254 °C) as it is both present in the phenocryst and groundmass assemblages. The formation temperatures from Pl–based thermometer of Putirka (2005) show the lowest average values (1136–1154 °C).

Formation temperatures obtained from liquid–based thermometers, on the other hand, show a different crystallization sequence (Ol → Opx → Cpx → Pl). Ol saturation temperatures from Beattie (1993) and Yang et al. (1996) give the highest values (1200–1256 °C), while Opx saturation temperatures (Putirka, 2008) are slightly lower (1216–1243 °C). On the other hand, Cpx saturation temperatures (Putirka, 2008; 1169–1202 °C) are higher than Pl (Putirka, 2008; 1145–1167 °C), indicating an earlier formation. The discrepancies we observed in the formation temperatures are possibly related to the variables used in the respective calculations. Thermometers based on liquid-only components are more susceptible to offsets caused by small changes in bulk chemistry. Nevertheless, the formation temperatures obtained from mineral–based thermometers are consistent with the narrative of unusual crystallization sequence for Manguao Basalt. Hence, the succeeding discussion will rely only on the data provided by mineral–based thermometers.

**DISCUSSION**

Manguao Basalt samples are characterized by an Ol-dominated phenocryst assemblage, with minor pyroxenes. The groundmass is composed of Pl and pyroxenes, set in an intersertal texture. Although this modal assemblage is common for basalts, petrographic evidence from observed Opx–Ol and Cpx–Ol relationships show the earlier
formation of the pyroxenes. In addition, the calculated formation temperatures of pyroxene phenocrysts are also higher compared to Ol. This unusual crystallization sequence observed in Manguao Basalt implies possible partial melting and fractionation at high pressures. Experimental data from Green and Ringwood (1964) demonstrate the emergence of primary Opx in the liquidus phase at pressures of partial melting reaching 15 kbar. The crystallization of this high-pressure partial melt produces ‘aluminous orthopyroxene and not olivine as the first crystals’ (Green and Ringwood, 1964). The succeeding discussion focuses on the potential of these high-pressure partial melts in producing the unusual crystallization sequence observed in Manguao Basalt.

Simulations of Mantle Melting

Experimental investigation on natural basalts of Green and Ringwood (1967) showed that magma compositions are not determined by the depth of partial melting, but by the depth of magma segregation. In this study, we simulated two different scenarios of fertile and depleted mantle melting: (1) keeping the liquid in equilibrium with source, and (2) immediate removal of the forming melt. The partial melting of both fertile and depleted mantle sources produced significant melt fractions as soon as the pressures dropped below 11 kbar (Fig. 13). Pyroxenes were the dominant contributors to the melting fraction. The resulting primitive melt compositions were all similar (Table 3), consistent with the study of Green and Ringwood (1967). Comparing the primitive melts to the average whole-rock composition of Manguao Basalt, the primitive liquids have noticeably higher CaO and MgO, but lower in titanium (TiO2) and total iron (FeOt).

Simulations of Melt Crystallization

The generated primitive mantle melts were too enriched in pyroxene components (i.e., higher CaO and MgO contents) to resemble the composition of Manguao Basalt. Following the idea of Green and Ringwood (1964), Opx will form earlier than Ol when the liquid crystallizes at depth. Therefore, the formation and removal of these early pyroxenes should generate an evolved melt with composition like Manguao Basalt. In this study, we simulated equilibrium and fractional crystallization of all four primitive melts: (1) equilibrium melt from fertile source, (2) fractionated melt from fertile source, (3) equilibrium melt from depleted source, and (4) fractionated melt from de-
Completed source.

All simulations of crystallization produced evolved liquids with compositions like Manguao Basalt (Fig. 14). The crystallization of the pyroxenes and Ol induced melt evolution to reach similarities with Manguao Basalt composition around 1230–1260 °C. However, even though all crystallization simulations were able to replicate average Manguao Basalt composition, the mineral chemistry of the early crystals showed some remarkable differences.

Mineral Chemistry from Fractional Crystallization. All simulations of fractional crystallization were able to produce Opx as the first crystals (Fig. 15). Opx formation was immediately followed by Ol in most sequences (from 1330 °C), then by Cpx (1310 °C), and finally by feldspars (1260–1280 °C). Although these simulated crystallization sequences were able to show the early Opx formation, the simulated Opx mineral compositions did not appear to show similarities to observed Manguao Basalt Opx (Table 6). Manguao Basalt Opx have lower MgO and higher total iron (FeOt) than the simulated Opx. Furthermore, the temperature window of Opx formation under fractional crystallization was narrow (1310–1340 °C) and higher than the calculated formation temperatures of Manguao Basalt Opx (1230–1260 °C). Hence, the immediate removal of the early-formed crystals might not be a likely scenario for Manguao Basalt.

Mineral Chemistry from Equilibrium Crystallization. Simulations of equilibrium crystallization produced Opx or Ol as the first crystals (Fig. 16). Melts that were kept at equilibrium with the source during mantle melting formed Opx earlier than Ol. Melts that were fractionated from source, on the other hand, crystallized Ol first. The crystallization of Opx or Ol continued until 1300–1310 °C, where Cpx started to form. Feldspars appeared last in the sequence (1260–1280 °C).

| Reference | \( T \) (°C) | \( P \) (kbar) |
|-----------|-------------|---------------|
| Ol        | 1200        | 1228          |
| Beattie (1993)* | 1237        | 1256          |
| Opx       | 1216        | 1243          |
| Cpx       | 1169        | 1202          |
| Pl        | 1145        | 1167          |

* Expressions are available and calibrated in Putirka (2008).

Figure 13. Evolution of fertile and depleted mantle source rocks during polybaric melting (15–5 kbar, 1350 °C, and QFM buffer). Melting is controlled primarily by Cpx. Complete melting of Cpx happens between 6 to 8 kbar. Opx melting commences right after (until pressure reaches 5 kbar).
The early formation of the pyroxenes in the crystallization simulations is consistent with the presented evidences of pyroxene precedence over OI. The simulated Opx and Cpx from equilibrium crystallization showed compositional similarities with the observed pyroxene phenocrysts in Manguao Basalt (Tables 7 and 8). The major oxide compositions (SiO$_2$, FeO, MgO, and CaO) of simulated Opx become similar to observed Manguao Basalt Opx at crystallization temperatures reaching 1270–1290 °C, close to the highest temperature obtained from Manguao Basalt Opx (~ 1260 °C; P-dependent thermometer of Beattie, 1993 at 4.6 kbar). The simulated Cpx (for high-Mg#; >80) also become compositionally similar with Manguao Basalt Cpx (phenocrysts) at crystallization temperatures of 1230–1260 °C. The Cpx formation temperatures calculated using the P-independent thermometer of Putirka et al. (1996) showed the closest average value (1233 °C).

Despite the success of producing compositionally similar pyroxene phenocrysts in Manguao Basalt, the formation of the groundmass components could not be reconciled with any of the simulations. This is because our initial assumptions were based on the complete crystallization of the melt at isobaric conditions (5 kbar). Such an assumption was made in order to simplify the conditions during the formation of the first crystals. Nevertheless, our simulations of crystallization showed that keeping the equilibrium between the melt and the forming crystals is critical in producing the early Opx and Cpx in Manguao Basalt.
Summary of results and simulations

The unusual precedence of pyroxenes from Ol were observed in petrography. The average whole-rock major element composition of Manguao Basalt showed similarities to common olivine basalt tholeiites of Wilkinson (1986). Our initial assumptions on the MELTS parameters and conditions were based on the geologic history of the PCB (i.e., limited magmatism in the region), the present tectonic setup of Palawan (i.e., absence of subduction and presence of melting at upper mantle depths), and the magmatic history of the region (i.e., deep-seated melts generating the heat for Kapoas Granite formation; Encarnación and Mukasa, 1997).

The simulations done in this study provided some insights on the melt formation and magmatic evolution processes responsible for the formation of Manguao Basalt as follows:

1. The depressurization melting of fertile (KLB–1; Davis et al., 2009) or depleted mantle source (Workman and Hart, 2005) at similar conditions (\( T_i = 1350 \) °C, starting pressure of 15 kbar and QFM buffer)

| Table 6. Evolution of Opx composition during fractional crystallization |
|---|
| \( T (^{\circ} C) \) | wt% SiO\(_2\) | wt% FeO\(^{t}\) | wt% MgO | wt% CaO | Mg# |
|---|
| --- | --- | --- | --- | --- | --- |
| 1340 | 56.09 | 6.55 | 32.91 | 1.80 | 89.95 |
| 1330 | 55.98 | 6.74 | 32.62 | 1.95 | 89.61 |
| 1320 | 55.87 | 6.93 | 32.32 | 2.12 | 89.26 |
| 1310 | 55.75 | 7.13 | 31.99 | 2.32 | 88.89 |

| Equilibrium melt from fertile Source | Equilibrium melt from depleted source |
|---|---|
| Equilibrium melt from fertile Source | Equilibrium melt from depleted source |
| 1340 | 56.09 | 6.55 | 32.91 | 1.80 | 89.95 | 55.89 | 6.58 | 32.84 | 1.75 | 89.90 |
| 1330 | 55.98 | 6.74 | 32.62 | 1.95 | 89.61 | 55.77 | 6.76 | 32.56 | 1.89 | 89.57 |
| 1320 | 55.87 | 6.93 | 32.32 | 2.12 | 89.26 | 55.65 | 6.95 | 32.26 | 2.05 | 89.21 |
| 1310 | 55.75 | 7.13 | 31.99 | 2.32 | 88.89 | 55.53 | 7.15 | 31.95 | 2.23 | 88.85 |

| Equilibrium melt fractionated from fertile source | Equilibrium melt fractionated from depleted source |
|---|---|
| --- | --- |
| --- | --- |

| Table 7. Evolution of Opx composition during equilibrium crystallization |
|---|
| \( T (^{\circ} C) \) | wt% SiO\(_2\) | wt% FeO\(^{t}\) | wt% MgO | wt% CaO | Mg# |
|---|
| --- | --- | --- | --- | --- | --- |
| 1340 | 56.19 | 6.23 | 33.13 | 1.82 | 90.46 |
| 1330 | 56.09 | 6.39 | 32.86 | 1.97 | 90.15 |
| 1320 | 55.98 | 6.57 | 32.57 | 2.14 | 89.83 |
| 1310 | 55.87 | 6.75 | 32.25 | 2.34 | 89.49 |
| 1300 | 55.58 | 7.07 | 31.97 | 2.24 | 88.97 |
| 1290 | 55.24 | 7.40 | 31.69 | 2.11 | 88.41 |
| 1280 | 54.90 | 7.74 | 31.39 | 1.99 | 87.84 |
| 1270 | 54.57 | 8.10 | 31.09 | 1.88 | 87.26 |
| 1180* | 53.27 | 11.67 | 28.62 | 1.60 | 81.39 |
| 1170 | 53.21 | 12.09 | 28.31 | 1.61 | 80.67 |
| 1160 | 53.20 | 12.23 | 28.24 | 1.59 | 80.47 |

| Equilibrium Melt from Depleted Source |
|---|
|---|
| Equilibrium Melt from Depleted Source |
| 1340 | 55.99 | 6.25 | 33.06 | 1.77 | 90.40 |
| 1330 | 55.88 | 6.43 | 32.79 | 1.91 | 90.09 |
| 1320 | 55.77 | 6.60 | 32.50 | 2.06 | 89.77 |
| 1310 | 55.65 | 6.79 | 32.20 | 2.25 | 89.43 |
| 1300 | 55.33 | 7.10 | 31.90 | 2.15 | 88.90 |
| 1290 | 54.95 | 7.45 | 31.59 | 2.01 | 88.32 |
| 1280 | 54.58 | 7.79 | 31.28 | 1.89 | 87.74 |
| 1270* | 53.07 | 11.25 | 28.83 | 1.57 | 82.04 |
| 1180* | 53.01 | 11.67 | 28.53 | 1.58 | 81.34 |
| 1170 | 52.95 | 12.10 | 28.22 | 1.58 | 80.61 |
| 1160 | 52.92 | 12.33 | 28.07 | 1.57 | 80.24 |

\( ^{*} \)Opx formation below 1270 °C is replaced by low-Ca Cpx in simulations.

Opx reemerges in the crystallizing phase from 1180 °C.

Figure 16. Equilibrium Crystallization of different primitive melts derived from fertile and depleted mantle sources. Crystallization commences at 1350 °C and maintains isobaric (5 kbar) condition and QFM buffer. Primitive melts that remained in equilibrium with the source produce Opx as the first crystals. On the other hand, primitive melts fractionated from the source produce Ol as the first crystals. ‘Clinopyroxene1’ refers to high-Ca clinopyroxenes forming at higher temperatures. ‘Clinopyroxene2’ refers to low-Ca clinopyroxenes. Color version is available online from https://doi.org/10.2465/jmps.191211.
produced melts with similar compositions. The resulting bulk compositions of these primitive melts had higher concentrations in pyroxene components (e.g., Ca and Mg) when compared to Manguao Basalt. Thus, fractionation was necessary (i.e., crystallization and removal of the early pyroxenes) to produce an evolved liquid like Manguao Basalt.

(2) The resulting melt evolution from isobaric crystallization (5 kbar) produced liquids like Manguao Basalt, regardless of whether the formed crystals remained at equilibrium with the liquid. Although the simulations showed the possibilities of replicating Manguao Basalt composition, the corresponding mineral chemistry showed some notable differences. Both equilibrium and fractional crystallization were able to produce Opx as the first crystals. However, only the equilibrated melts were able to produce Opx and Cpx with compositions like those observed in Manguao Basalt. This implied the importance of maintaining the source–melt equilibrium at some point during the formation of the first crystals.

**A model for the origin of Manguao Basalt**

In this study, we propose the concept of magmatic underplating as the model for visualizing the conditions and processes in the formation of Manguao Basalt (Fig. 17). This model effectively encompasses the key features we presented as follows:

1. The partial melting of upper mantle peridotite at high pressures (15–5 kbar) produces primitive melts of basaltic composition. The crystallization of these basaltic liquids at depth would produce Opx as the first crystals.

2. The ponding of basaltic magma at Moho depths is critical for maintaining the equilibrium between the source and melt. The identified low velocity (P-wave) region beneath the PCB (Fan et al., 2017) is an important detail for inferring potential melt presence and production at greater depths (approximately 50 km). The presence of melt at deeper levels makes it possible to have the initial crystallization already occurring at high pressures. Melt residency is also reflected in the barometric calculations done on Opx chemistry (~ 5 kbar). Assuming a normal continental lithostatic pressure gradient (24.5 MPa/km; Cas and Simmons, 2018), this translates to approximate depths of 20 km. Geophysical investigation of the Moho region by Liu et al. (2014) shows a 20 to 25 km Moho depth beneath the PCB.
The isobaric crystallization of primitive melts produces evolved liquids which are compositionally like Manguao Basalt. The subsequent removal of the early solids depletes the liquid of pyroxene components. The corresponding magmatic evolution is recorded by the rounded zoning found in Opx and Cpx phenocrysts.

Ol formation represents the subsequent crystallization from the evolved melt. Our initial assumptions on crystallization (i.e., isobaric) were made to simplify the conditions during formation of the first crystals. Hence, the melt composition and prevalent conditions from Ol crystallization are no longer represented by the simulations. The prevalent skeletal features observed in Ol phenocrysts, in addition, possibly reflect such melt removal.

CONCLUSIONS

Manguao Basalt is a basalt–basaltic andesite lava flow field located on the northeast tip of Palawan, Philippines. Manguao Basalt samples are Ol–phyric with minor pyroxenes, set in a Pl-dominated groundmass. The petrogenesis of Manguao Basalt, in this study, is constrained by the following conditions:

1. Manguao Basalt major element compositions show trend and affinity typical of tholeiitic melts. Major element bivariate diagrams reflect the early fractionation of Ol and limited fractionation of later–formed phases (e.g., Pl).

2. Pyroxenes precede Ol in the crystallization sequence, based on evidences from petrography, mineral chemistry, and thermometry.

3. Decompression melting of fertile or depleted mantle source produces melts that are saturated in pyroxene components. Major element compositions of simulated melts are very similar regardless of whether the liquid remained in equilibrium with the source. Maintaining equilibrium between melt and the forming crystals, however, is essential for producing Opx and Cpx like those observed in Manguao Basalt.

4. Equilibrium or fractional crystallization of simulated primitive melts produce evolved liquids that reach similarities with Manguao Basalt bulk composition at 1230–1260 °C.

5. Melt evolution from fractionation (i.e., Ca depletion from Cpx removal) is essential prior to the later crystallization of Ol and groundmass phases.

6. Magmatic underplating provides an excellent model for visualizing melt residency, crystallization, and fractionation beneath the Palawan microcontinent.

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Supplementary Materials

Color version of Figures 1–12, 14–16, and Supplementary Tables S1–S6 are available online from https://doi.org/10.2465/jmps.191211.

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