Introduction

In June 2019, the population of Bougainville, a southwest Pacific island of 9,380 km², will vote on whether to remain an autonomous region of Papua New Guinea or become the world’s newest nation. Proponents of an independent Bougainville are looking for sources of revenue to kick-start the island’s economic development, including reopening the mothballed Panguna copper-gold mine (Barrett, 2017). However, significant local opposition to such a step remains (e.g., Davidson, 2018), so the future exploration prospects for the island are uncertain.

Panguna commenced production in 1972, as the world’s largest copper mine, with total metal endowment of 18 billion pounds of copper and 30 million ounces of gold (historic production and remaining JORC-compliant resource; Collier et al., 2011; Bougainville Copper Limited, 2016). The operation closed 17 years later amid a prolonged campaign of sabotage by the Bougainville Revolutionary Army, stemming from social, environmental, and economic issues catalyzed by the mine (Denoon, 2000; Barrett, 2017). The Autonomous Bougainville Government and Papua New Guinea Government currently each own 36.4% of Bougainville Copper Limited, the publicly listed administrator of the mine after Rio Tinto divested their stake in the company during 2016.

Bougainville has 17 post-Miocene volcanoes, including the active or dormant Bagana, Balbi, and Loloru volcanoes (Blake, 1967). There are more than 60

FIGURE 1. Tectonic setting of Bougainville and neighboring islands of Papua New Guinea and the Solomon Islands. Metal endowment of major deposits was calculated from resource and/or production data. Modified from figure 2 of Holm et al. (2016). Shaded areas occur above the 2,000-m bathymetric contour and show major oceanic crustal features.
volcanic vents and intrusive centers and numerous active or extinct fumarolic, acid sulfate-altered areas (Blake and Miezitis, 1967; Rogerson et al., 1989). Small-scale gold mines operated intermittently in the Kupei and Panguna areas from 1930 to 1960 (Blake and Miezitis, 1967). Apart from a geologic survey mapping and sampling program during the 1980s, little or no mineral exploration has occurred outside the Panguna mine lease since 1971. A decades-long moratorium on exploration and mining was lifted in October 2015. The Autonomous Bougainville Government’s Mining Act 2015 paves the way for a new generation of mineral exploration on the island, which remains highly prospective for porphyry, epithermal, and skarn deposits.

This article provides an overview of the tectonic and structural setting, stratigraphy, magmatic history, and geochemistry of Bougainville. Magmatic fertility indicators and whole-rock and stream sediment geochemical data were combined with the interpreted geology to delineate areas that are prospective for magmatic-related copper and gold deposits. A database of 269 X-ray fluorescence and instrumental neutron activation analyses was compiled from published papers and unpublished Ph.D. theses. Sample coordinates from the Panguna mine grid were transformed into latitude/longitude using a registered Google Earth image, color plate 2 from Clark (1990), and the original grid orientation (J. Lew, pers. commun., 2017). Linear topographic features, extracted from an ASTER digital elevation model, were combined with published interpreted structures over the island.

Stratigraphy

The stratigraphic nomenclature of Bougainville, outlined in Blake and Miezitis (1967), was updated by Rogerson et al. (1989) following additional mapping, the incorporation of offshore seismic data, and a review of available fossil, C, and K-Ar dates. The Kieتا Volcanics were divided into the Atamo Volcanics, Toniva Formation, and Arawa Conglomerate. The oldest unit, the Atamo Volcanics (Fig. 2), is a package of pillowed and nonpillowed basalt-andesite lavas and minor volcanioclastic sandstone, conglomerate, and dolerite to diorite intrusions, exposed in the Crown Prince Range (Rogerson et al., 1989). The younger Keriaka Limestone platform is a shallowly WSW dipping massive to diffusely bedded organic limestone, originally deposited 20 to 30 m deep, and is 1,300 m thick (Blake and Miezitis, 1967). The Keriaka Limestone is unconformably overlain and onlapped by the Toniva Formation (Fig. 2), a middle to late Miocene unit of interbedded volcanioclastic sandstone, mudstone, and basalt-andesite lavas. Surrounding the Crown Prince Range is the Bougainville Group of Quaternary andesitic volcanic centers, including the oldest Emperor Range, Numa Numa, Tore, Billy Mitchell, Taroka, and Takuan volcanics, and the younger Bagana, Balbi, and Loloru volcanics. These units, comprising andesitic lavas, agarlomerate, and diorite stocks and dikes, are exposed as variably dissected stratovolcanoes with lava flows, resurgent domes, and crater lakes.

There are four major Miocene to Quaternary intrusive complexes on Bougainville and numerous smaller stocks and dikes as feeders to the overlying volcanic sequence (Fig. 2; Table 1). The Isinai Monzonite (7.43–4.82 Ma) consists of quartz monzonite, monzonite, and microsyenite (Rogerson et al., 1989). The Kupei Intrusive Complex (4.9–1.3 Ma), hosting the Panguna copper-gold porphyry deposit, comprises diorite, quartz diorite, granodiorite, and quartz-feldspar porphyry (Ford, 1976; Clark, 1990). Within the Emperor Range Volcanics are the Puspa (2.11 Ma) and Melilup (1.72–0.676 Ma) intrusions. Both comprise biotite + hornblende or biotite + pyroxene leucmonzonite. Elsewhere in the Crown Prince and Duero ranges are numerous small, Pliocene to Quaternary diorite to microdiorite stocks within the Toniva Formation and Atamo Volcanics, including at Jaba River, Malabita Hill, Ummum River, Kangu Hill, and Karatu (Ford, 1976; Rogerson et al., 1989). The Isinai and Kupei complexes have intruded middle to late Miocene andesitic volcanic rocks of the Toniva Formation and a sequence of coarse-grained fragmental rocks of Pliocene age, referred to as the “Arawa Conglomerate” (Fig. 2).

The multiphase Kupei intrusion includes, from oldest to youngest, the Panguna Andesite intrusive phases, Kaverong Quartz Diorite, Biuro Granodiorite, and Nautango Andesite (Ford, 1976; Clark, 1990). Leucocratic feldspar porphyry bodies intruded the first three units. Rogerson et al. (1989) argued that the informal names used at the mine, “Biotite Diorite” and “Biotite Granodiorite” (e.g., Collier et al., 2011), were potassic-altered phases of the Kaverong Quartz Diorite. The lowest copper and gold grades are in the Biotite Granodiorite and late-mineral Biuro Granodiorite. Hydrothermal biotite from the Panguna deposit yielded a K-Ar age of 3.42 ± 0.25 Ma (Page and McDougall, 1972).
Structures

Although previous workers found little field evidence for major faulting, three dominant structural orientations have been recognized (Figs. 2, 3; Blake and Miezitis, 1967; Rogerson et al., 1989; this study):

1. West-northwest (270°–300°), defined by the long axis of Eocene to Miocene units exposed in the Crown Prince and Deuro ranges,
2. North-northwest (335°–340°), defined by the long axis of Buka Island, and
3. Northwest (~320°), represented by the axis of Pleistocene to Holocene volcanic vents, including Taroka, Takuan, and Balbi volcanoes.

In addition, ENE-, NE-, and NNE-trending faults occur offshore and throughout the island, within Eocene to Miocene units. Intersections of these structures have produced rhombic and triangular fault blocks, onshore and offshore of Bougainville (Fig. 3). The Crown Prince and Deuro ranges are characterized by numerous WNW-trending arc-parallel faults with apparent sinistral offsets. The Miocene intrusive complexes appear compartmentalized between WNW- and NNE-trending structures (Figs. 2, 3). The Panguna porphyry copper-gold deposit occurs at the intersection between one of these WNW-trending arc-parallel faults and potentially an NNE-trending arc-transverse fault. In the northern part of Bougainville, the Melilup and Puspa intrusive complexes lie along NE- to NNE-trending arc-transverse structures. The volcanosedimentary rocks on Bougainville have undergone minor folding and tilting. Oligocene to Miocene and Pleistocene platform carbonates units dip less than 5° (Blake and Miezitis,
Return to Bougainville—Reassessing the Mineral Potential of a Long-Forgotten Island (continued)

### TABLE 1. Features of Major Intrusions and Selected Volcanic Units in Bougainville

<table>
<thead>
<tr>
<th>Unit/location</th>
<th>K/Ar age</th>
<th>Lithology</th>
<th>Composition</th>
<th>Sr/Y</th>
<th>(Eu/Eu*)/Yb</th>
<th>Cu max ppm</th>
<th>Zn max ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isinai</td>
<td>7.43 ± 0.17–4.83 ± 0.05 Ma</td>
<td>Quartz monzonite, syenite</td>
<td>High-K calc-alkaline to alkaline</td>
<td>5–40 (5)</td>
<td>0.65–0.88 (4)</td>
<td>234 (5)</td>
<td>103 (5)</td>
</tr>
<tr>
<td>Kupei</td>
<td>4.9–1.3 Ma</td>
<td>Quartz diorite, granodiorite, andesite</td>
<td>Medium-K calc-alkaline</td>
<td>28–70 (35)</td>
<td>1.17–3.12 (4)</td>
<td>701 (35)</td>
<td>329 (35)</td>
</tr>
<tr>
<td>Puspa</td>
<td>2.11 ± 0.03 Ma</td>
<td>Monzonite, syenite</td>
<td>Alkaline</td>
<td>24–43 (3)</td>
<td>0.75–1.16 (2)</td>
<td>64 (3)</td>
<td>137 (3)</td>
</tr>
<tr>
<td>Mellup</td>
<td>1.72 ± 0.03–1.11 ± 0.03 Ma</td>
<td>Monzonite</td>
<td>Alkaline</td>
<td>31–40 (2)</td>
<td>0.60–1.16 (2)</td>
<td>0 (2)</td>
<td>133 (2)</td>
</tr>
<tr>
<td>Jaba River</td>
<td></td>
<td>Bt + cpx + opx phryic diorite</td>
<td>Alkaline</td>
<td>34–52 (4)</td>
<td>1.69 (1)</td>
<td>18 (4)</td>
<td>93 (4)</td>
</tr>
<tr>
<td>Malabita Hill</td>
<td>4.63 ± 0.85 Ma</td>
<td>Diorite and andesite</td>
<td>High-K calc-alkaline</td>
<td>22 (1)</td>
<td>1.23 (1)</td>
<td>150 (1)</td>
<td>BDL (1)</td>
</tr>
<tr>
<td>Pinei River</td>
<td>4.63 ± 0.85 Ma</td>
<td>Qtz + hbl phryic microdiorite</td>
<td>Medium-K calc-alkaline</td>
<td>22 (1)</td>
<td>-</td>
<td>31 (1)</td>
<td>57</td>
</tr>
<tr>
<td>Arawa</td>
<td></td>
<td>Andesite/diorite</td>
<td>Medium-K calc-alkaline</td>
<td>67 (1)</td>
<td>-</td>
<td>BDL (1)</td>
<td>65 (1)</td>
</tr>
<tr>
<td>Kangu Hill</td>
<td></td>
<td>Cpx phryic microdiorite</td>
<td>High-K calc-alkaline</td>
<td>22 (1)</td>
<td>-</td>
<td>168 (1)</td>
<td>63 (1)</td>
</tr>
<tr>
<td>Balbi Volcanics</td>
<td></td>
<td>Basaltic andesite, andesite</td>
<td>High-K calc-alkaline</td>
<td>22–38 (28)</td>
<td>0.89–1.23 (6)</td>
<td>147 (28)</td>
<td>91 (28)</td>
</tr>
<tr>
<td>Bagana Volcanics</td>
<td></td>
<td>Basaltic andesite, andesite</td>
<td>Medium-K calc-alkaline</td>
<td>33–54 (44)</td>
<td>1.47–2.81 (11)</td>
<td>81 (44)</td>
<td>327 (44)</td>
</tr>
<tr>
<td>Billy Mitchell Volcanics</td>
<td></td>
<td>Andesite</td>
<td>Medium-K calc-alkaline</td>
<td>35–61 (9)</td>
<td>1.86–1.95 (3)</td>
<td>39 (9)</td>
<td>65 (9)</td>
</tr>
<tr>
<td>Tarkoa Volcanics</td>
<td></td>
<td>Andesite</td>
<td>Medium-K calc-alkaline</td>
<td>35–49 (7)</td>
<td>1.48–2.21 (3)</td>
<td>63 (7)</td>
<td>61 (7)</td>
</tr>
</tbody>
</table>

**Notes:** Radiometric ages were from Rogerson et al. (1989) and Page and McDougall (1972); ranges and/or maximum Sr/Y, (Eu/Eu*)/Yb, copper, and zinc values are shown; number of analyses are in parentheses; whole-rock geochemical data were sourced from the references listed in Figure 4

**Abbreviations:** bt = biotite, cpx = clinopyroxene, hbl = hornblende, opx = orthopyroxene, qtz = quartz

Whole-rock analyses from least-altered volcanic and intrusive rocks were chosen using the selection criteria of Loucks (2014): volatile-free major element oxides sum to 97.5 to 101.5 wt %, and loss on ignition or H2O + CO2 + S content oxides sum to 97.5 to 101.5 wt %, whereas those from central and southern parts of the island are mostly high-K andesite, whereas those from central and southern parts of the island are mostly high-K andesite, and basaltic andesite—spatial trend previously recognized by Rogerson et al. (1989). Six samples from Eocene to Miocene units, including the Toniva Formation and Arawa Conglomerate, are basalt. One sample each from the Toniva Formation, Numa Numa Volcanics, and Emperor Range Volcanics plots as absarokite or shoshonite. Both alkaline and calc-alkaline series intrusive rocks occur on Bougainville. Samples from the Kupei Intrusive Complex, adjacent Jaba River Diorite, and Isinai Monzonite plot mostly as medium- to high-K diorite, quartz diorite, and granite on total alkali versus SiO2 and K2O versus SiO2 diagrams (Fig. 4B, C). The Puspa and Mellup intrusive complexes, hosted in the Emperor Range Volcanics of northern Bougainville, comprise syenite, syenodiorite, and alkali granite, plotting in the shoshonite field of a K2O versus SiO2 diagram. Samples from the Pinei River, Malabita Hill, Arawa, and Kangu Hill areas were classified as diorite and quartz diorite.

The samples have trace elements typical of an island-arc setting. Volcanic and intrusive rocks are enriched in K, Rb, Pb, and Sr and depleted in Nd and Ti compared to normal mid-ocean ridge basalt (N-MORB) compositions (Fig. 4D), indicating they were derived from enclaved mantle in a subduction zone (e.g., Wilson, 1989; Richards, 2003). Within and between individual units, the more evolved samples are enriched in light rare earth elements compared to N-MORB in the order dacite > andesite > basaltic andesite, consistent with normal fractionation trends.

### Copper and Gold Fertility Indicators

Whole-rock fertility indicators such as Sr/Y ratios and normalized Yb concentrations have been applied to intrusions (e.g., Baldwin and Pearce, 1982; Loucks, 2014) and cogenetic volcanic rocks (e.g., Behnsen et al., 2017) to predict if the causative magmas were hydrous and therefore prospective for copper-gold mineralization (Richards, 2003; Muller and Groves, 2016). Volatile-rich and oxidized magmas are known to produce copper and gold deposits. High Sr/Y ratios, >35 (Loucks, 2014), and depleted Yb and Y concentrations (Richards, 2011) indicate fractional crystallization of hornblende from a hydrous magma at the expense of plagioclase. Strong positive Eu anomalies may also result from crystallization and accumulation of plagioclase (Bea, 2015). Although the presence of hornblende could not be confirmed in original samples, Sr/Y and
(Eu/Eu*)/Yb ratios were calculated using whole-rock geochemical data from Bougainville and correlated with the reference samples of Loucks (2014). The europium anomaly (Eu/Eu*) was determined by comparing the N-MORB-normalized Eu, Sm, and Tb values, using 

\[ \text{Eu}^* = \left( \frac{\text{Sm}}{\text{N}} \right)^{2/3} \left( \frac{\text{Tb}}{\text{N}} \right)^{1/3} \]

(eq. 3a of Lawrence and Kamber, 2006) rather than the conventional equation, as Gd was rarely included in the historical analyses.

A large proportion of intrusive rocks and some of the volcanic rocks from the Bougainville database had high Sr/Y ratios and plotted in the field for copper-gold–productive intrusions (Figs. 5, 6; Table 1). Samples with the highest Sr/Y were from the Bagana Volcanics, Kaverong Quartz Diorite, Biuro Granodiorite, Toniva Formation dacite dome, and Billy Mitchell Volcanics. Samples from the Jaba River Diorite and the Isinai, Puspa, and Melilup intrusive complexes returned maximum Sr/Y values of 40 to 52. The highest (Eu/Eu*)/Yb ratios were from the Kaverong Quartz Diorite and Biuro Granodiorite phases of the Kupei Intrusive Complex, Bagana Volcanics, Taroka Volcanics andesite dome, and Toniva Formation dacite dome. Samples from the Jaba River Diorite and Puspa, Isinai, and Melilup intrusive complexes had maximum (Eu/Eu*)/Yb values of 0.88 to 1.69.

**Exploration Geochemistry**

During the 1980s, two field seasons undertaken by the Geological Survey of Papua New Guinea yielded rock chip samples and 860 stream sediment samples, mostly from second- and third-order creeks. Surface geochemical anomalies were identified using cutoff values of 0.6 ppm Au, 1.3 ppm Ag, 0.8 ppm Te, 44 ppm Cu, and 84.4 ppm Zn (Rogerson et al., 1989). These anomalies (Fig. 6) indicate areas that are prospective for porphyry, skarn, volcanogenic massive sulfide, and epithermal deposits. The geochemical anomalies encompass the Melilup and Puspa intrusive complexes and large areas of the Emperor Range and Balbi volcanics in northern Bougainville (Fig. 6). There are also anomalies within the Isinai Monzonite and throughout the Atamo Volcanics and Toniva Formation in central Bougainville.

**Copper**

High stream sediment copper values occurred in the pre-Pleistocene rocks of central Bougainville, including the Karatu, Kopani, and Kupei areas surrounding the Panguna mine (Figs. 2, 6). Whole-rock geochemical analyses of samples from the Emperor Range Volcanics and Isinai Monzonite yielded up to 241 and 234 ppm Cu, respectively (Fig. 6). In the geologic survey study, a quartz vein sample from the Kupei adit returned 7.25% Cu (Rogerson et al., 1989).

**Gold**

Two point three percent of stream sediment samples returned >0.6 ppm Au. High stream sediment gold values were correlated to areas containing the Arawa Conglomerate and late Miocene to Pliocene intrusions (Figs. 2, 6; Rogerson et al., 1989). These samples delineated areas previously known for copper and gold anomalism. Free gold was associated with magnetite-pyrite skarn, where a diorite had intruded the Keria Lime in the Atamo area. Rogerson et al. (1989) reported two samples containing 10 g/t Au from the Puspa Intrusive Complex in northern Bougainville and a creek surrounding the Panguna mine.

**Zinc**

Most of the stream sediment samples had high, >300-ppm background zinc concentrations (Rogerson et al., 1989). In this study, volcanic rocks of Bougainville were found to have 60 to 70 ppm Zn (Fig. 6). Samples from the Kupei Intrusive Complex yielded up to 329 ppm Zn, whereas those from the surrounding Arawa Conglomerate and Toniva Formation contained up to 112 ppm Zn. The Melilup and Puspa intrusive complexes and Isinai Monzonite returned up to 133, 137, and 103 ppm Zn, respectively.

**Total alkalis**

Samples from the Melilup and Puspa intrusive complexes and Emperor Range...
Volcanics had >7.5 wt % total alkalis, as did three samples from the Isinai Monzonite (Fig. 6). The more primitive volcanic samples, with <5 wt % total alkalis, were from the Atamo Volcanics, Toniva Formation, and Arawa Conglomerate, immediately surrounding the Panguna mine.

**Discussion and Conclusions**

The oldest rocks on Bougainville record the transition from mafic to intermediate-composition magmas and from submarine to subaerial volcanism during the early Miocene. The Atamo Volcanics, Toniva Formation, and Arawa Conglomerate contain pillow basalt with <5 wt % total alkalis, whereas the younger Bougainville Group comprises basaltic andesite and andesite. In contrast, the Pliocene to Holocene New Georgia Group in the Solomon Islands includes large volumes of picrite lavas and gabbric intrusions, reflecting mantle mixing and a greater proportion of primitive mantle in the arc magmas, due to subduction of the adjacent Woodlark oceanic crust (e.g., Schuth et al., 2004; Chadwick et al., 2009).

Intrusions on Bougainville Island are controlled by multiple structural orientations. Oblique convergence between the Australian and Pacific plates, ongoing collision of the Ontong Java plateau with the Melanesian trench, and the involvement of microplates has led to a major arc flexure, whereby the older Miocene to Pliocene intrusions occur along WNW-trending arc-parallel faults and the younger Pleistocene intrusions and recent volcanic centers appear to be controlled by NNW-, NNE-, and ENE-trending structures. The intersection of these arc-parallel and oblique structures has provided a conduit for the rapid ascent of mantle-derived material to the upper crust, required for mineralization (e.g., Muller and Groves, 2016). Slab tears, crustal thickening, and potential detachment of the Pacific plate at the Melanesian arc resulting from the collision of the Ontong Java plateau have played a role in the generation of long-lived, mantle-derived magma chambers beneath Bougainville and their consequent uplift and erosion.

Bougainville has both medium-K and high-K, calc-alkaline to alkaline
intrusions capable of hosting porphyry, skarn, and telescoped epithermal deposits. The Isinai, Puspa, and Melilup intrusive complexes and the Jaba River Diorite had high K concentrations and total alkalis, Sr/Y ratios >35, and variable but generally high (Eu/Eu*)/Yb ratios, indicating that they resulted from hydrous arc magmas rich in potassium. The Isinai, Puspa, and Melilup intrusive complexes yielded rock and stream sediment samples anomalous in Cu, Zn, Au, Ag, and Te. Samples from the Kupei Intrusive Complex hosting the Panguna porphyry copper-gold deposit had the highest Sr/Y and (Eu/Eu*)/Yb ratios and the highest copper and zinc concentrations. In the Atamo, Karatu, and Pinei River areas of central Bougainville, diorite bodies have intruded the Oligocene to Miocene Keriaka Limestone and are prospective for copper-gold skarn mineralization. One of these intrusions has been partly altered to magnetite and sheds free gold into adjacent streams (Rogerson et al., 1989).

Rogerson et al. (1989) found, based upon conventional K-Ar dates, that Bougainville intrusions ranged in age from 8.19 to 0.7 Ma and concluded that there was little evidence for discrete magma pulses or temporal and spatial relationships between the medium- and high-K suites. However, in view of modern high-precision radiometric dating techniques and additional samples, the ages of individual intrusive phases could be resolved more accurately.

This study has highlighted the potential for the younger volcanic stratigraphy to host porphyry and epithermal deposits. Except for the Emperor Range Volcanics, stream sediment anomalies are not observed within volcanic facies of the Bougainville Group. However, the Balbi, Billy Mitchell, Taroka, and Bagana volcanics had Sr/Y >35, moderate to high (Eu/Eu*)/Yb ratios of up 2.81, and anomalous Cu and Zn concentrations. Ford (1976) concluded that a modern porphyry deposit may be forming beneath the Balbi volcano, citing the following evidence: (1) explosive volcanism and active fumaroles, (2) structural control due the intersection of NE-, N-, and
E-trending faults, (3) numerous vents of differing age, indicating multiple conduits linked to a large, multiphase intrusion at depth, and (4) evolved high-K andesite lavas that are enriched in Pb, Zr, Th, U, Nb, Mo, and heavy rare earth elements compared to medium-k volcanic rocks.

Geothermal activity and argillic alteration have been observed on the summit and flanks of the active to recently dormant Bagana, Balbi, and Loloru volcanoes. This includes water vapor and sulfur dioxide emissions, deposition of native sulfur, and accumulation of acidic hot springs (Blake and Mieizitis, 1967; Rogerson et al., 1989). These areas are undergoing acid sulfate alteration and may be associated with precious and base metal epithermal veins at depth.

Bougainville Island has had a complex tectonic and magmatic history dominated by two phases of magmatism, separated by a hiatus caused by the collision of the Ontong Java oceanic plateau with the Melanesian arc and consequent reversal in subduction polarity. The world-class Panguna porphyry copper-gold deposit formed during the second phase of magmatism. With the application of modern exploration techniques, there is significant potential for the discovery of porphyry, epithermal, and skarn deposits on an island that has received very little exploration expenditure during the last 47 years.

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