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The Pele Offset Dykes, Sudbury impact structure, Canada

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Draft

Abstract

The Offset Dykes are impact-melt bearing dykes related to the 1.85 Ga Sudbury impact structure. Currently, the dykes extend radially outward from – or occur concentrically around – the Sudbury Igneous Complex, which is the remnant of a differentiated impact melt sheet and the source of the dykes. The recently identified three Pele Offset Dykes intrude into the Archean rocks north of the Sudbury Igneous Complex. In this study, the Pele dykes are characterized for the first time by a combination of fieldwork, optical microscopy, electron microprobe analyses, and bulk geochemical analyses. The Pele Offset Dykes stand out from the other Offset Dykes at Sudbury in two significant ways: (1) All other known Offset Dykes consist of an inclusion-rich lithology in the centre of the dyke and an inclusion-poor lithology along the margins. The Pele dykes, however, are only composed of the inclusion-poor phase. (2) The Pele dykes – particularly the Central and Eastern dykes – have a more evolved chemical composition relative to the other Offset Dykes. These observations suggest that the Pele dykes were emplaced after the other known Offset Dykes during two injection events: the Western followed by the Central and Eastern Pele dykes.

Keywords: Sudbury, Offset Dyke, impact crater, geochemistry, petrography

33 Introduction

34 The so-called Offset Dykes formed at ~ 1.85 Ga, when impact melt material from the
35 Sudbury impact event was injected into the fractured footwall rocks of the crater floor. The
36 Offset Dykes have an average chemical composition of granodiorite, but their lithology is
37 traditionally referred to as inclusion-poor quartz diorite (QD) and inclusion-rich quartz diorite
38 (IQD). These traditional terms, although geochemical misnomers, are unfortunately entrenched
39 in the literature and are, therefore, used herein. The Offset Dykes are an important host of Ni-Cu
40 sulfide and PGE metal ores at Sudbury (e.g., Ames et al. 2008), but despite a long history of
41 exploration there is still considerable controversy regarding their formation, particularly
42 regarding the timing of their emplacement relative to the impact cratering process. For example,
43 Murphy and Spray (2002) suggested that the Whistle and Parkin Offset Dykes were emplaced
44 during two stages, one forceful outward injection of inclusion-rich quartz diorite (IQD), during
45 the early excavation stage, and a second, inclusion-poor quartz diorite (QD), during the
46 modification stage, of crater formation. By comparison, Lightfoot and Farrow (2002) proposed
47 that the Worthington Offset Dyke formed from an early QD injection followed by a later
48 injection of IQD. The recently discovered Pele Offset Dykes (Smith et al. 2013) are a small
49 cluster of dykes located in the footwall rocks of the North Range of the Sudbury impact
50 structure. In this study, the Pele Offset Dykes are characterized, for the first time, using a
51 combination of field observations, optical microscopy, electron microprobe and whole rock
52 geochemical analyses.

53 Background Geology

The Sudbury impact structure is the remnant of a 1.85 Ga old, ~150–200 km diameter impact crater in central Ontario, Canada (Grieve et al. 2008). It is located at the present-day contact between the Archean granite, greenstone, and gneiss terrain of the Superior Province to the northwest, and the Paleoproterozoic metavolcanics and metasediments of the Southern Province to the southeast (Fig. 1). The Sudbury impact structure consists of three major components: 1) the Whitewater Group, post-impact sediments that now fill the Sudbury Basin; 2) the Sudbury Igneous Complex (SIC), a ~ 2.5–3 km thick differentiated impact melt sheet; and 3) the fractured and brecciated footwall rocks surrounding the SIC (Dressler 1982; Grieve et al. 1991; Therriault et al. 2002; Rousell et al. 2003; Ames et al. 2008). The so-called Sublayer lies below the Main Mass of the SIC, which is subdivided into five units. From the bottom of the melt sheet to the top, the Main Mass of the SIC consists of: so-called Norite, Quartz Gabbro, Transition Zone, Granophyre (Naldrett et al. 1970; Therriault et al. 2002), and Upper Contact Unit (Anders et al. 2015).

The Offset Dykes are derived from the SIC and are composed generally of IQD in the centre of the dyke and QD along the margins of the dyke (Lightfoot et al., 1997). The dykes are subdivided into three groups based on their current orientation relative to the SIC (Grant and Bite 1984): (1) Concentric Offset Dykes oriented sub-parallel to the base of the current outcrop of the SIC (Fig. 1; e.g., Hess and Manchester), (2) Discontinuous or breccia-hosted Offset Dykes characterized by isolated pods of quartz diorite within Sudbury Breccia (e.g., Frood Stobie and MacLennan), and (3) Radial Offset Dykes radial to the current outcrop of the SIC (e.g., Pele, Copper Cliff, Worthington, Ministic, Foy, Whistle-Parkin, and Trill Offset Dykes).

The Pele Offset Dykes are located ~500 m west of the well-known Foy Offset Dyke and consist of three separate radial dykes, which are referred to, herein, as the Western, Central, and

Eastern Pele dykes (Fig. 2). They are primarily hosted in the Archean-aged Cartier Batholith of the Superior Province. The Pele dykes also cut across several Nipissing diabase bodies, which are found throughout the Sudbury region and are dated at $2219.4 \pm 3.6/-3.5 -3.5/+3.6$ Ma (Corfu and Andrews 1986). The Eastern Pele dyke was first studied by Tuchscherer (1998), who referred to it as the “Parallel Foy”. The Central and Western Pele dykes were recently discovered by Wallbridge Mining Company Limited (Smith et al. 2013), who have trenched several new outcrops at all three Pele dykes.

Previous research on the Pele Offset Dykes has been limited. Tuchscherer (1998) observed an outcrop of the Eastern Pele dyke located north of the Hess (Fig. 1) and described the lithology of the dyke as a dark grey rock “devoid of inclusions” and composed of biotite and amphibole set in a groundmass of granophyric intergrowths of quartz and orthoclase. One sample from this region was analysed by Tuchscherer (1998), using X-Ray Fluorescence. Relative to the rest of the Foy dyke, Tuchscherer (1998) observed that the sample had elevated SiO_2 content (60.7 wt. %), a low Mg # (0.16), and an enrichment in REE, and concluded that the Eastern Pele dyke likely originated from a more evolved source than the Foy dyke. A sample of the southern portion of the Eastern Pele dyke (Fig. 2) has been dated at 1848.5 ± 0.8 Ma, using U-Pb isotopic dating of baddeleyite (Bleeker et al. 2015) and is similar to the age of the SIC determined by Davis (2008), using $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic dating of zircons (1849.53 ± 0.21 Ma for the North Range Felsic Norite, and 1849.11 ± 0.19 Ma for the South Range Norite). This study examines data from new trenches of the Pele dykes and uses petrographic and geochemical analysis to demonstrate that the dykes have some variation in terms of composition and differ from the nearby Foy Offset Dyke (Fig. 2).

Methods

Fieldwork was completed in the summers of 2013 and 2015 (Fig. 2). Thirty-two samples were collected: nineteen from the Central Pele dyke, and twelve samples from the Western Pele dyke. Due to lack of exposure, only one outcrop is known and, thus, one sample was collected from the Eastern Pele dyke. Eight samples of Nipissing Diabase in the proximity of Pele dykes were also collected. Thin sections were examined using optical microscopy. A JEOL JXA-8530F field-emission electron microprobe at Western University was used to analyse plagioclase from six samples (averages reported in Table 1). A counting time of 10 seconds was used, with an accelerating voltage of 20 kV, a beam current of 20 nA, and a beam size of 5 μm . Three types of corrections were applied to the data: atomic number correction, absorption correction, and fluorescence correction.

Samples were prepared for whole rock geochemical analysis at Western University. Samples were first crushed in a Chipmunk Jaw Crusher and clasts > 1 mm in size of local host rocks were removed manually using visual inspection. The remaining rock was powdered using a Micro Powder Grinding Mill for 60 seconds. Care was taken during this procedure to avoid cross-contamination of samples. The crusher was cleaned between each sample. After a sample was powdered, quartz sand was run through the mill before cleaning the mill.

The powder was sent to ALS Minerals in Vancouver, BC, for acid digestion and chemical analyses (Table 2). Two hundred milligrams of the sample were then mixed with 0.90 g of lithium metaborate and fused at 1000 °C. This mixture was dissolved in a 100-mL solution of 4 % HNO_3 and 2 % HCl . Major element oxides were analysed using inductively coupled plasma-atomic emission spectroscopy (ICP-AES) and the results were corrected for spectral inter-element interferences. Oxide concentration is calculated from the determined elemental concentration and the result is reported in that format as weight percent oxide (wt. %). Trace

elements were analysed using inductively coupled plasma-mass spectrometry (ICP-MS) and the results are reported as parts per million (ppm).

Geochemical data from Wallbridge Mining Company Limited was also included as a part of this study (Table 2; Fig. 2). Clasts larger than ~1 cm were removed from these samples, using visual inspection. Samples were sent to ALS Minerals and were ground to a fine powder. Two hundred fifty milligrams of the sample were then digested with four acid digestion (perchloric, nitric, hydrofluoric and hydrochloric acids). The residue was topped up with dilute hydrochloric acid and analysed by ICP-AES. Results are corrected for spectral inter-element interferences. Representative analyses are available in Table 2, and the complete dataset is available as supplementary information. The precision and accuracy of these measurements are $\pm 10\%$ (of the concentration) ± 1 limit of detection for duplicate analyses and in-house standards. These limits apply at, or greater than, fifty times the limit of detection.

Results

Field Observations and Petrography

The Pele dykes range from 5 m to 20 m wide (Fig. 2) and are composed of a medium grained grey to light green rock that is almost, but not entirely free of inclusions (Figs. 3A and 3B). It is notable that no inclusion-rich quartz diorite was found in the centre of any of the Pele dykes. Clasts of the coarse-grained Cartier granite host rock can, however, be found close to the dyke margins (Fig. 3B). These clasts are up to ~10 cm long, oriented parallel to the dyke margins, and occur along with smaller sub-rounded mineral clasts of plagioclase and quartz (Fig. 3B).

The samples of the Central and Eastern dykes are composed of, in volume percent, coarse grained pale to deep green amphiboles (30–40 %), platy biotite (~25%), coarse grained euhedral plagioclase laths (~10%) and fine- to medium-grained quartz (~5%), set in a groundmass of granophyric intergrowths of quartz (15–25%) and K-feldspar (~5%) (Figs. 3C and 3D). Many of the samples display varying degrees of alteration, including pervasive epidote alteration in places (Fig. 3C), the occasional carbonate- and sericite-bearing veinlet (Fig. 3E), and chloritization of amphiboles (Figs. 3D and 3F). Samples contain trace amounts of anhedral pyrite and chalcopyrite, typically < 20 µm in size. Samples of the Western dyke contain higher proportions of amphibole (40–50 %), along with plagioclase (~20 %), quartz (10–15 %), biotite (10–15 %), and magnetite with exsolution of ilmenite (~5 %) (Fig. 3F). Plagioclase within the Pele dykes is commonly intergrown with quartz or occurs as tabular euhedral crystals, and is very sodic in composition, varying from albite to oligoclase (Table 1). Samples of the Western dyke contain higher proportions of subhedral pyrite and chalcopyrite, up to ~2 %. Accessory minerals in all three Pele dykes include magnetite with lamellar exsolutions of ilmenite, apatite, chlorite, and zircon.

Geochemistry

Representative geochemical analyses from the Pele dykes are reported in Table 2. When the Pele dyke samples' CIPW normative mineralogies are plotted on a QAP diagram (Fig. 4), the Central and Eastern dykes would be classified as a granodiorite and the Western dyke would be classified as a quartz monzodiorite. For the Central and Eastern dykes, the average contents of SiO₂, Fe₂O₃, and CaO are 60.6 wt. %, 10.1 wt. %, and 5.3 wt. %, respectively (Table 2). By comparison, the Western dyke is more mafic, with average contents of SiO₂, Fe₂O₃, and CaO of 54.9 wt. %, 13.9 wt. %, and 5.2 wt. %, respectively (Table 2). The Central and Eastern dykes

167 have a very low average Mg # of 15 and the Western dyke has an average Mg # of 23. By
168 comparison, the Foy dyke has an average Mg # of 32 (Tuchscherer 1998), while the Granophyre
169 unit of the SIC has an average Mg # of 13 (Therriault et al. 2002). This difference in magnesium
170 content is highlighted in Figures 5A and 5B, which shows how the Pele quartz diorite dykes are
171 enriched in SiO₂ and TiO₂ and depleted in MgO relative to the SIC or the Foy dyke. The Central
172 and Eastern dykes also have very low sulfur contents, below 0.05 wt. %; whereas, the Western
173 dyke contains up to 0.25 wt. % sulfur (Table 2) and the Foy dyke has an average sulfur content
174 of 0.13 wt. % (n = 13, Lightfoot et al., 1997).

175 There are several differences in trace element ratios and abundances between the Pele
176 dykes. The Central and Eastern dykes typically have higher La/Nb, La/Sm, Th/Zr, and Sr/Y
177 ratios compared to the Western dyke (Figs. 5C and 5D). The Central and Eastern dykes are
178 particularly enriched in incompatible trace elements compared to the Western dyke (Table 2).
179 This can be seen in Figure 6, which plots average incompatible trace element compositions from
180 the Pele dykes and the Granophyre and Norite units of the SIC as spider diagrams normalized to
181 the average Foy dyke (Tuchscherer 1998). The Central and Eastern dykes (Figs. 7A and 7B) are
182 also enriched in both light and heavy rare earth elements (REE), relative to the Western dyke
183 (Fig. 7C).

184 The Pele Offset Dykes have a very similar appearance in the field to some of the
185 Nipissing Diabase dykes in the region. The Nipissing Diabase samples, however, are easily
186 distinguished by their chemistry and the plagioclase within the Nipissing diabase samples is
187 typically very blocky in shape and is very calcium rich, varying from labradorite to bytownite
188 (Table 1). For example, the Nipissing Diabase samples are more mafic than the Pele Offset
189 Dykes, and have average contents of SiO₂, Fe₂O₃, and CaO of 49.9 wt. %, 12.4 wt. %, and 9.7

wt. %, respectively (Table 2), and have an average Mg # of 38. When compared to the Pele Offset Dykes, the Nipissing Diabase samples also have much lower La/Nb and Th/Zr ratios (Fig. 5C) and are very depleted in light rare earth elements (LREE) (Figs. 7A and 7B).

Discussion

Field Relationships and Mineralogy

The Pele Offset Dykes are much narrower (5–20 m) than most other radial Offset Dykes, which commonly reach thicknesses of up to 100 m (e.g., Murphy and Spray 2002; Tuchscherer 1998). The Pele dykes, however, are comparable in width to the Trill Offset Dyke, which is, in places, only 3–20 m wide (Coulter 2015). Additionally, the Pele Offset Dykes do not contain an “exotic” inclusion-rich phase (Fig. 3). The only clasts visible in the Pele Offset Dykes are the occasional rip-up clasts from the host rock along the margins of the dyke (e.g., Fig. 3B). This is significant, as all other known Offset Dykes consist of both an inclusion-poor and an inclusion-rich phase (Grant and Bite 1984; Lightfoot et al. 1997). The distal portions of some Offset Dykes, such as the Foy and Trill, have been known to consist only of the inclusion-poor phase, and are also very thin, only ~10–20 m (Murphy and Spray 2002; Tuchscherer 1998; Coulter 2015), however, inclusions are common at other sections of these dykes. Considering that the Pele dykes contain no inclusion-rich phase, the dykes were likely intruded from a portion of the SIC that was barren in clasts at the time.

The CIPW normative mineralogy of the samples from the Central and Eastern dykes is granodiorite; whereas, the Western dyke would be considered a quartz monzodiorite (Fig. 4). The samples are composed predominantly of amphibole, biotite, plagioclase, and granophyric intergrowths of quartz and K-feldspar (Fig. 3). This mineralogy is quite typical among the other

Offset Dykes, such as the Foy, Parkin, Hess and Trill dykes (e.g., Tuchscherer 1998; Wood 1998; Murphy and Spray 2002; Coulter 2015). The Pele Offset Dykes, however, do contain a higher proportion of granophyric intergrowths than the other Offset Dykes and, in addition, the Western dyke contains a higher proportion of amphibole, pyrite, magnetite, and ilmenite. Samples from the Western dyke typically display higher degrees of hydrothermal alteration, compared to Pele East. This is reflected in thin section by a higher abundance of epidotization and chloritization (Figs. 3C and 3D).

Chemical Variation

Cross-cutting relationships between the Western, Central, and Eastern Pele dykes are not observable in the field. As a result, an attempt is made to interpret their temporal relationship by comparing the chemical compositions of the Pele dykes to their source, the SIC. It is generally believed that the SIC formed from crystal differentiation of a largely homogenous impact melt by orthopyroxene and plagioclase crystallization, and the crystallization of the residual melt from the base-up and the top-down (e.g., Naldrett and Hewins 1984; Grieve et al. 1991; Warner et al. 1998; Lightfoot et al. 1997; Lightfoot et al. 2001; Therriault et al. 2002, etc.). If this working hypothesis is correct, Offset Dykes emplaced later (relative to the differentiation of the SIC) would have a more evolved chemical composition. As there are known chemical and mineralogical differences between the North and South Ranges of the SIC (see Lightfoot 2016 and references therein), data from the SIC for this comparison is taken from Therriault et al. (2002), whose data for the composition of the SIC are from three drill cores in the North Range.

First, we must consider the chemical evidence in support of the hypothesis that the Pele dykes are a part of the Offset Dyke system. The Central and Eastern Pele dykes have trace element ratios that are nearly identical to that of the Granophyre and Norite units of the SIC. This

is particularly evident in Figures 5C and 5D, which plot data from the Pele dykes in comparison to the Norite and Granophyre units of the SIC and the Foy Offset Dyke. The Pele dykes have La/Nb, Th/Zr, and La/Sm ratios nearly identical to those from the SIC (Figs. 5C and 5D) and a Sr/Y ratio that falls roughly between that of the Granophyre and Norite units of the SIC (Fig. 5D). Additionally, Dy/Dy* ratios (the measured value of Dy compared with the value interpolated between La and Yb) were calculated using (see Davidson et al. 2013; Fig. 5E). The Dy/Dy* value measures the concavity of a REE. Davidson et al. (2013) found that in suites of samples from a single volcano Dy/Dy* and Dy/Yb decrease with differentiation. The Pele dykes fall along the trendline defined by the samples from the SIC in figure 5E. The Western Pele dyke has slightly higher Dy/Dy* and Dy/Yb values than the Central or Eastern Pele dykes. This indicates that if the three Pele dykes originated from the same source, the Central and Eastern dykes represent the more chemically evolved end of the spectrum. These observations suggest that, while the Pele dykes may have a unique chemistry in terms of major element oxides compared to other Offset Dykes, they are related to the SIC and are a part of the Offset Dyke system. This is consistent with their age of 1848.5 ± 0.8 (Bleeker et al. 2015), which is indistinguishable from the age of the SIC (Davis 2008).

The Central and Eastern Pele dykes have a more evolved chemical composition than the other Offset Dykes. They are enriched in SiO₂ (Fig. 4), and have a lower Mg # (average of 15) compared to the other Offset Dykes, such as the Foy dyke, which has an average Mg # of 32 (Tuchscherer 1998). The Central and Eastern Pele dykes are enriched in incompatible elements relative to the Norite, with abundances similar to that of the Granophyre unit of the SIC (Fig. 6). Similarly, Tuchscherer (1998) observed that the Pele dyke was enriched in REE relative to the Foy dyke, and Smith et al. (2013) observed that the Pele dykes have similar textures and

compositions to the upper Granophyre of the SIC. While our results are consistent with these previous observations, it is important to note that the Granophyre has undergone pervasive metasomatism (Stewart 2017), which has altered its primary chemistry. Therefore, while our results show that the Central and Eastern Pele dykes have a more evolved chemistry when compared to the other Offset Dykes, their relationship with the Granophyre unit of the SIC remains uncertain.

If the SIC differentiated via fractional crystallization, then the more-evolved chemistry of the Central and Eastern Pele dykes suggest that the Pele dykes were intruded later than the other North Range Offset Dykes, relative to the differentiation of the SIC. This would suggest that the Central and Eastern Pele dykes may be examples of the last known Offset Dykes to be emplaced, relative to the fractional crystallization of the SIC. This is consistent with the lack of the IQD phase as discussed above. In other words, any clasts had either sunk or been assimilated in their source region of the SIC by the time the Pele dykes were intruded.

By comparison, the Western Pele dyke has a more mafic chemical composition (Figs. 4, 5A, and 5B) and a higher average Mg # of 23 due to its higher amphibole content. While it is possible that the Western Pele dyke could have been emplaced from a more mafic portion of the SIC melt, it is unlikely that the dykes tapped from different sources of the SIC given their proximity. What is more likely is that the Pele dykes were emplaced at different times throughout the differentiation history of the SIC. This is supported by the elevated Dy/Dy* ratios in the Western dyke relative to the Central and Eastern dykes (Fig. 5E). The Western dyke also have higher sulfur and nickel contents due to the dyke's higher sulfide content. The Western dyke is also depleted in REE relative to the Central and Eastern dykes (Figs. 6 and 7). These observations suggest that the Western dyke has a less evolved chemical composition than the

Central or Eastern dykes. These observations suggest that the Pele Offset Dyke system was emplaced during two separate injection events: an early emplacement of a relatively more sulfide-rich quartz monzodiorite melt that formed the Western dyke, and a later emplacement of sulfide-poor granodiorite melt that formed the Central and Eastern dykes.

Results herein suggest that the three Pele dykes are a part of the Offset Dyke system, and likely originated from the SIC. Given the chemically evolved nature of the Central and Eastern dykes (i.e., granodiorite melt, Fig. 4), we believe that these two Pele dykes may have been emplaced at some point during the differentiation of the SIC, and tapped from a more chemically-evolved SIC melt. To test the hypothesis that the Pele dykes were emplaced during two separate intrusive events, principal component analysis was used to compare groups of correlated variables between the three dykes.

Principal Component Analysis

The chemical variations between the Pele dykes and the SIC are clearest displayed when examining multiple geochemical variables. To compare multiple variables at once, principal components analysis can be used to transform a group of correlated variables (e.g., the major element oxides), such that the first few components account for a large proportion of the variance of the original data set (Jolliffe 2014). For this study, robust principal component analysis (RPC) was used to correct for the effect of outliers (Campbell 1980), and the covariance (i.e., the variance between the variables) was calculated by weighting each of the samples by their robustly estimated Mahalanobis distance (Maronna 1976; De Maesschalck et al. 2000). The first principal component (RPC1) defines the maximum variation through the cluster, and the second principal component (RPC2) defines the maximum spread at right angles to RPC1, and so on when many variables are considered. Thus, the majority of variability in the original dataset can

be plotted by examining RPC1 versus RPC2. Robust principal component analysis was calculated using the program ioGAS version 6.1 for the Pele dykes, the different units of the SIC (data from Therriault et al. 2002) and the Foy Offset Dyke (data from Wallbridge Mining Company Limited).

The chemical variations between the Pele dykes and the units of the SIC are highlighted in Figure 8, which uses robust principal component analysis (RPC) to calculate the variation between the major oxides (Fig. 8A) and immobile elements (Fig. 8B). Data is depicted as Mahalanobis ellipses for the Granophyre and Norite units of the SIC, and the Foy Offset Dyke. The Central and Eastern Pele dykes have CaO, MgO, SiO₂, K₂O, and Na₂O values that fall between that of the Norite and Granophyre units of the SIC, but are enriched in Fe₂O₃, P₂O₅, and TiO₂ (Fig. 8A). The Central and Eastern dykes also have immobile element compositions similar to the Granophyre unit of the SIC, but with elevated TiO₂ and Y (Fig. 8B). By comparison, the Western dyke is more mafic in composition, comparable to the Norite unit of the SIC (Fig. 8A), but again with elevated Fe₂O₃, P₂O₅, and TiO₂ values (Fig. 8A). The Western dyke is also depleted in immobile elements relative to the Central and Eastern dykes (Fig. 8B). This demonstrates that the three Pele dykes have a more evolved chemical composition than the other Offset Dykes such as the Foy. Furthermore, the Central and Eastern dykes are more evolved than the Western dyke, which suggests the Pele dyke system was emplaced during two intrusive events: a more primitive (i.e., quartz monzodiorite melt, Fig. 4) sulfide-bearing melt that formed the Western dyke, followed by intrusion of a more chemically evolved (i.e., granodiorite melt, Fig. 4) that formed the Central and Eastern dykes.

The exact timing of formation of the Pele dykes – in the context of the other Offset Dykes and the SIC – remain uncertain. It is generally believed that the inclusion- and sulfide-

poor QD was emplaced shortly after the formation of the superheated impact melt sheet (see Lightfoot 2016 and references therein). This was followed by sulfide saturation of the impact melt sheet and emplacement of the sulfide-rich IQD. After formation of the Offset Dykes, differentiation and crystallization of the SIC occurred. Results herein suggest that the Central and Eastern Pele dykes were emplaced from a more chemically evolved SIC melt, however, at this time, no Offset Dykes have been observed to cross-cut the SIC itself. Furthermore, if the Western dyke was emplaced earlier than the Central and Eastern dykes, why does it also lack an inclusion-bearing quartz diorite phase – as is observed at every other Offset Dyke? Although these questions remain uncertain, several conclusions can be drawn regarding the composition of these unique Offset Dykes.

Concluding Remarks

1. Field observations and petrography of the Pele Offset Dykes are generally consistent with previous findings by Tuchscherer (1998) and Bleeker et al. (2015), which were based on one sample each. The mineralogy of the Pele dykes consists of amphiboles, biotite, granophyric intergrowths of quartz and K-feldspar, plagioclase, and quartz. The Pele Offset Dykes typically have much higher proportions of granophyric intergrowths and are enriched in magnetite and ilmenite compared to other Offset Dykes.
2. When compared to the Foy Offset Dyke, the Pele dykes have a more evolved chemical composition, being considerably more felsic and enriched in incompatible elements. If one considers a simple uniform fractionating melt sheet, these observations, along with age dating by Bleeker et al. (2015), suggest that, although the Pele Offset Dykes are a

part of the Offset Dyke system, they may have been one of the last known Offset Dykes to have been emplaced, relative to the differentiation of the SIC.

3. The Western dyke – when compared to the Central or Eastern dykes – is more mafic, has higher rare earth and immobile element compositions, has higher Dy/Dy^* and Dy/Yb ratios, and is sulfide-bearing. This suggests that the Western dyke is less evolved than the Central and Eastern dykes, and was likely emplaced earlier, relative to the differentiation of the SIC (again, given a simple uniform fractionating melt sheet).
4. The Pele Offset Dykes do not have an inclusion-rich phase, which suggests that the Pele dykes were emplaced from a portion of the SIC that was barren in clasts at the time of intrusion.

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Draft

Tables

Table 1. Representative electron microprobe analyses of plagioclase from the matrix of the Pele dykes reported as means with standard deviation given in parenthesis.

Sample	Dyke	An (Mole %)	SiO ₂ (Wt. %)	Al ₂ O ₃ (Wt. %)	Na ₂ O (Wt. %)	MgO (Wt. %)	TiO ₂ (Wt. %)	CaO (Wt. %)	K ₂ O (Wt. %)
809930 (n=16)	West Pele Dyke	10.71 (± 8.15)	67.2 (± 1.38)	21.21 (± 0.79)	11.11 (± 0.65)	0.01 (± 0.01)	0.02 (± 0.02)	1.25 (± 1.06)	0.05 (± 0.01)
809963 (n=16)	West Pele Dyke	5.69 (± 6.45)	67.79 (± 1.03)	20.83 (± 0.75)	11.37 (± 0.43)	0.01 (± 0.01)	0.02 (± 0.01)	0.65 (± 0.76)	0.06 (± 0.01)
703829 (n=16)	Centre Pele Dyke	8.07 (± 6.26)	67.63 (± 0.94)	20.71 (± 0.69)	11.28 (± 0.47)	0.03 (± 0.06)	0.01 (± 0.01)	0.92 (± 0.75)	0.05 (± 0.01)
SI-013 (n=14)	Centre Pele Dyke	2.76 (± 0.95)	68.28 (± 0.57)	19.97 (± 0.27)	11.6 (± 0.26)	0.01 (± 0.01)	0.04 (± 0.03)	0.3 (± 0.1)	0.06 (± 0.01)
SI-005 (n=16)	Diabase	71.75 (± 5.12)	53.8 (± 1.46)	29.08 (± 0.96)	4.95 (± 0.69)	0.07 (± 0.03)	0.03 (± 0.02)	11.49 (± 1.22)	0.11 (± 0.05)
SI-010 (n=12)	Diabase	69.34 (± 6.58)	54.23 (± 1.98)	28.9 (± 1.22)	5.21 (± 0.88)	0.08 (± 0.04)	0.03 (± 0.01)	10.8 (± 1.44)	0.13 (± 0.05)

Sample	Dyke	FeO (Wt. %)	MnO (Wt. %)	Cr ₂ O ₃ (Wt. %)	BaO (Wt. %)	SrO (Wt. %)	Eu ₂ O ₃ (Wt. %)	Total (Wt. %)
809930 (n=16)	West Pele Dyke	0.31 (± 0.07)	0.01 (± 0.01)	0.007 (± 0.006)	0.016 (± 0.009)	0.109 (± 0.056)	0.02 (± 0.01)	101.29 (± 0.27)
809963 (n=16)	West Pele Dyke	0.16 (± 0.08)	0.01 (± 0.01)	0.01 (± 0.006)	0.038 (± 0.043)	0.056 (± 0.036)	0.03 (± 0.023)	100.97 (± 0.32)
703829 (n=16)	Centre Pele Dyke	0.15 (± 0.06)	0.01 (± 0.01)	0.01 (± 0.007)	0.011 (± 0.007)	0.034 (± 0.019)	0.03 (± 0.021)	100.84 (± 0.4)
SI-013 (n=14)	Centre Pele Dyke	0.28 (± 0.11)	0.01 (± 0.01)	0.013 (± 0.009)	0.021 (± 0.014)	0.039 (± 0.019)	0.019 (± 0.01)	100.57 (± 1.02)
SI-005 (n=16)	Diabase	0.69 (± 0.19)	0.01 (± 0.01)	0.011 (± 0.005)	0.025 (± 0.019)	0.044 (± 0.025)	0.016 (± 0.01)	100.28 (± 0.23)
SI-010 (n=12)	Diabase	0.72 (± 0.29)	0.01 (± 0.01)	0.006 (± 0.004)	0.019 (± 0.014)	0.055 (± 0.027)	0.013 (± 0.008)	100.17 (± 0.23)

Table 2. Representative geochemistry of the Pele Offset Dykes. Coordinates reported in NAD83.
b.d.l. = below detection limit; n.d. = no data. Lower limits of detection are reported in parentheses.

	Nipissing Diabase			Western Pele Dyke			Central Pele Dyke			Eastern Pele Dyke
	120501	SI-005	SI-011	809926	809954	809957	604356	703828	703847	604275
	476752	476734	476162	474894	474590	474497	476154	476053	475825	476489
	5179554	5179594	5178231	5180877	5181408	5181745	5178071	5179287	5181144	5180762
Major Oxide (weight %)										
SiO ₂ (0.01)	50.20	50.00	52.60	56.50	56.40	55.30	62.10	63.20	64.60	62.90
Al ₂ O ₃ (0.01)	13.40	15.50	13.20	12.60	12.80	12.40	13.20	13.20	12.20	12.60
Fe ₂ O ₃ (0.01)	14.15	12.50	15.00	13.60	13.95	14.50	9.40	9.10	9.30	8.70
CaO (0.01)	9.83	10.80	8.73	6.19	5.74	4.59	4.40	3.90	4.10	4.90
MgO (0.01)	6.18	5.68	5.24	2.82	2.87	4.39	1.50	1.50	1.30	1.40
Na ₂ O (0.01)	2.13	2.16	2.54	3.32	3.78	3.95	3.40	3.20	3.00	3.20
K ₂ O (0.01)	0.85	0.62	0.86	1.61	1.63	1.27	2.70	2.70	2.50	2.70
TiO ₂ (0.01)	0.97	1.00	1.25	1.70	1.72	1.68	1.60	1.50	1.60	1.50
MnO (0.01)	0.21	0.20	0.26	0.19	0.19	0.23	0.20	0.20	0.10	0.10
P ₂ O ₅ (0.01)	0.09	0.08	0.15	0.40	0.40	0.39	0.50	0.50	0.40	0.50
BaO (0.01)	0.02	0.02	0.03	0.05	0.07	0.06	0.10	0.10	0.10	0.10
S (0.01)	0.04	0.06	0.05	0.09	0.10	0.25	0.10	0.10	b.d.l.	b.d.l.
Total	98.11	98.66	99.93	99.13	99.70	99.03	99.20	99.30	99.40	98.70
Mg number	46.39	47.37	40.90	29.12	28.96	37.49	24.02	24.62	21.69	24.17
Trace element (ppm)										
Li (10)	10.0	b.d.l.	10.0	17.9	16.7	19.8	16.9	16.1	17.5	11.4
Sc (1)	42.0	37.0	36.0	26.2	26.9	26.2	n.d.	24.5	26.5	n.d.
V (5)	323.0	326.0	361.0	207.0	212.0	213.0	68.0	62.0	63.0	75.0
Cr (10)	120.0	140.0	30.0	4.0	5.0	2.0	8.0	3.0	b.d.l.	9.0
Ni (1)	76.0	50.0	59.0	13.1	14.9	14.4	4.0	1.0	1.5	3.0
Zn (2)	126.0	95.0	206.0	115.0	135.0	190.0	105.0	111.0	100.0	960.0
As (0.1)	1.0	0.2	0.2	0.6	0.3	0.4	2.7	1.5	1.9	1.0
Se (0.2)	0.4	0.6	0.5	2.0	2.0	3.0	1.0	3.0	2.0	2.0
Rb (0.2)	47.3	22.0	36.4	119.0	78.6	74.5	102.0	112.0	153.0	139.0
Sr (0.1)	166.5	141.5	179.5	413.0	428.0	200.0	335.0	320.0	337.0	377.0
Y (0.5)	23.0	23.1	30.9	29.7	31.1	30.0	33.4	33.6	29.9	36.4
Zr (2)	80.0	85.0	138.0	156.0	154.5	161.5	224.0	233.0	247.0	229.0
Nb (0.2)	3.8	4.3	6.7	10.3	10.4	9.9	14.7	15.3	15.6	14.2
Mo (1)	b.d.l.	b.d.l.	b.d.l.	4.0	1.5	12.6	1.6	1.8	1.8	2.0
Cd (0.5)	b.d.l.	b.d.l.	0.5	0.1	0.1	0.2	0.1	0.1	0.1	1.3
Sn (1)	1.0	1.0	1.0	1.4	1.4	1.4	1.8	1.7	2.6	2.0
Sb (0.05)	0.3	b.d.l.	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.1
Cs (0.01)	0.6	0.5	0.2	1.6	1.2	1.3	2.5	0.7	3.1	0.8
Ba (0.5)	200.0	155.0	251.0	440.0	580.0	470.0	810.0	860.0	830.0	650.0
La (0.5)	9.7	9.1	16.5	33.9	34.9	35.6	56.6	54.2	47.0	52.9
Ce (0.5)	20.3	20.2	35.0	78.3	82.2	81.3	104.0	110.0	91.0	114.5
Pr (0.03)	2.6	2.6	4.3	8.6	8.9	8.8	13.6	13.3	11.1	12.9
Nd (0.1)	11.8	10.9	17.9	35.2	36.5	35.6	52.0	50.1	44.6	49.8
Sm (0.03)	3.1	2.8	4.2	7.1	7.2	7.0	9.4	9.1	8.1	8.8
Eu (0.03)	1.0	1.0	1.2	2.0	2.1	1.9	2.3	2.2	2.1	2.9
Gd (0.05)	3.8	3.4	4.7	6.1	6.3	6.2	8.5	8.3	7.9	8.8
Tb (0.01)	0.7	0.6	0.9	0.9	1.0	1.0	1.3	1.2	1.1	1.1
Dy (0.05)	4.2	3.9	5.5	5.0	5.1	5.0	6.0	6.2	5.7	6.2
Ho (0.01)	0.9	0.9	1.2	1.0	1.0	1.0	1.3	1.2	1.2	1.1
Er (0.03)	2.6	2.6	3.2	2.6	2.6	2.6	3.5	3.5	3.3	3.4
Tm (0.01)	0.4	0.4	0.5	0.4	0.3	0.4	0.5	0.5	0.5	0.5
Yb (0.03)	2.7	2.5	3.4	2.2	2.2	2.2	3.2	3.2	3.1	2.9
Lu (0.01)	0.4	0.4	0.5	0.3	0.3	0.3	0.5	0.5	0.5	0.4
Ta (0.1)	0.3	0.3	0.5	0.6	0.6	0.6	0.9	0.9	1.0	1.0
Pb (2)	9.0	2.0	11.0	11.5	12.3	18.7	36.8	9.1	13.3	7.0
Bi (0.01)	0.0	0.0	0.0	0.1	0.1	0.1	b.d.l.	b.d.l.	0.1	0.1
Th (0.05)	1.8	2.0	4.1	6.8	6.7	6.4	11.5	11.6	12.0	11.4
U (0.05)	0.6	0.4	0.9	1.5	1.4	1.3	2.5	2.5	2.4	2.9

Figure Captions

Figure 1. A simplified map of the Sudbury impact structure, showing the Whitewater Group, the primary components of the Sudbury Igneous Complex, the Offset Dykes (named on map), and the fractured footwall target rocks of the Southern Province and Superior Province. Modified from OGS bedrock 1:250,000 (2003) and Wallbridge Mining Company Limited mapping.

Figure 2. Geologic map of the Pele Offset Dykes, their surrounding host rocks, and sample locations.

Figure 3. Field photographs and photomicrographs from the Pele QD dykes. A. Coarse grained QD from the Central dyke. B. Fine grained QD from the Eastern dyke with small granite clasts. C. Photomicrograph from the Central Pele dyke with granophyric intergrowths of quartz and feldspar. Plagioclase is overprinted by epidote and sericite alteration. D. Photomicrograph from the Eastern Pele dyke with coarse grained euhedral amphiboles partially altered to chlorite. E. Photomicrograph from the Central Pele dyke with a thin vein of fine grained carbonate and mica. F. Photomicrograph from the Western Pele dyke showing chlorite and a small euhedral amphibole set in a quartz-rich matrix.

Figure 4. QAP normative diagram showing the lithological compositions of the Pele Offset Dykes and nearby Nipissing Diabase dykes (after Streckeisen, 1976).

Figure 5. Comparison of the geochemical variations between the Pele Offset Dykes, the Foy Offset Dyke, and the Granophyre and Norite units of the SIC. The data from the Foy (Pilles et al. 2017) and the SIC (Therriault et al., 2002) are depicted as ellipses, which represents the $p = 0.95$ Mahalanobis Contour Ellipses (De Maesschalck et al. 2000). A. SiO_2 vs MgO . B. MgO vs. TiO_2 .

484 C. La/Nb vs Th/Zr. D. Sr/Y vs La/Sm. E. Dy/Yb vs Dy/Dy*. Dy/Dy* was calculated using
485 modified chondritic normalizing values of Nakamura (1974) as reported by Kelley et al. (2003).

486 **Figure 6.** Spider diagram of average incompatible elements from the Pele dykes normalized to
487 the average Foy Offset Dyke (Tuchscherer and Spray 2002). The data from the Granophyre and
488 Norite units of the SIC are from Therriault et al. (2002).

489 **Figure 7.** Spider diagrams of REE normalized to the average quartz diorite (QD) from the Foy
490 dyke (Tuchscherer and Spray 2002). A. Samples from the Eastern Pele dyke. B. Samples from
491 the Central Pele dyke. C. Samples from the Western Pele dyke.

492 **Figure 8.** Robust principal component robust (RPC) analysis using major element oxides (A,
493 82.8% of the total variation) and immobile elements (B, 89.7% of the total variation) as
494 variables. Comparison of the geochemical variations between the Pele dykes, the Foy Offset
495 Dyke, and the Granophyre and Norite units of the SIC. The data from the Foy (Pilles et al. 2017)
496 and the SIC (Therriault et al., 2002) are depicted as ellipses, which represents the $p = 0.95$
497 Mahalanobis Contour Ellipses (De Maesschalck et al. 2000).

Legend

Whitewater Group	Superior Province
Onaping Formation	Southern Province
Granophyre	Grenville Province
Norite, Sublayer, and Offset Dikes	Faults

Sample / Average Foy QD

<https://mc.manuscriptcentral.com/cjes-pubs>

Central & Eastern Pele Dykes (n=20)
Western Pele Dykes (n=12)
Granophyre (n=24)
Norite (n=22)

A

Quartz Diorite

Nipissing
Diabase

B

Quartz Diorite

Nipissing Diabase

C

Quartz Diorite

Supplementary table: Geochemistry of the Pele Offset Dykes. Coordinates reported in NAD83. b.d.l. = below detection limit; n.d. = no data. Lower limits of detection are reported in parentheses.

Central Pele Dyke										
Sample ID	SI-013	602863	604356	605021	703815	703827	703828	703829	703849	703835
Easting	476160	476157	476154	476151	476144	476011	476053	476022	475846	475916
Northing	5178115	5178118	5178071	5178093	5178725	5179513	5179287	5179497	5181313	5179858
Major Oxide (weight %)										
SiO ₂ (0.01)	61.80	63.50	62.10	60.80	63.70	61.80	63.20	62.60	62.90	61.80
Al ₂ O ₃ (0.01)	12.30	12.80	13.20	12.70	12.90	13.60	13.20	12.40	12.30	12.30
Fe ₂ O ₃ (0.01)	8.90	8.90	9.40	9.20	8.50	9.40	9.10	9.40	9.40	9.40
CaO (0.01)	4.20	3.90	4.40	4.30	3.30	4.30	3.90	3.90	4.00	4.10
MgO (0.01)	1.50	1.30	1.50	1.50	1.60	1.50	1.50	1.50	1.30	1.40
Na ₂ O (0.01)	3.40	3.30	3.40	3.20	3.40	3.30	3.20	3.20	3.10	3.20
K ₂ O (0.01)	2.50	2.70	2.70	2.50	2.80	2.70	2.70	2.60	2.80	2.50
TiO ₂ (0.01)	1.50	1.40	1.60	1.60	1.50	1.60	1.50	1.60	1.50	1.60
MnO (0.01)	0.10	0.20	0.20	0.10	0.10	0.10	0.20	0.20	0.10	0.10
P ₂ O ₅ (0.01)	0.50	0.50	0.50	0.50	0.50	0.60	0.50	0.50	0.50	0.50
BaO (0.01)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
S (0.01)	b.d.l.	0.10	0.10	0.10	b.d.l.	b.d.l.	0.10	b.d.l.	b.d.l.	b.d.l.
Total	97.60	98.60	99.20	96.80	98.40	99.00	99.30	98.10	98.10	97.10
Mg number	25.03	22.44	24.02	24.41	27.16	24.02	24.62	24.02	21.51	22.78
Trace Elements (ppm)										
Li (10)	10.0	12.6	16.9	23.1	12.1	20.4	16.1	23.3	27.7	17.1
Sc (1)	23.0	n.d.	n.d.	n.d.	24.6	25.5	24.5	23.8	19.5	26.1
V (5)	86.0	49.0	68.0	82.0	66.0	79.0	62.0	71.0	57.0	70.0
Cr (10)	10.0	1.0	8.0	3.0	2.0	7.0	3.0	3.0	b.d.l.	1.0
Ni (1)	b.d.l.	b.d.l.	4.0	2.0	2.0	4.0	1.0	3.0	1.0	2.3
Zn (2)	142.0	195.0	105.0	92.0	52.0	106.0	111.0	150.0	145.0	141.0
As (0.1)	2.1	1.9	2.7	2.1	0.7	1.8	1.5	1.4	1.0	1.4
Se (0.2)	0.6	0.5	1.0	1.0	3.0	3.0	3.0	1.0	1.0	1.0
Rb (0.2)	111.0	79.0	102.0	107.0	230.0	220.0	112.0	101.0	206.0	120.0
Sr (0.1)	325.0	297.0	335.0	340.0	301.0	325.0	320.0	309.0	316.0	317.0
Y (0.5)	31.2	28.9	33.4	33.4	33.3	33.8	33.6	29.8	23.3	30.4
Zr (2)	232.0	192.0	224.0	198.0	236.0	207.0	233.0	227.0	198.0	228.0
Nb (0.2)	13.5	13.2	14.7	14.7	15.4	15.3	15.3	13.9	11.3	14.8
Mo (1)	b.d.l.	1.7	1.6	1.5	1.3	1.6	1.8	1.6	1.3	1.7
Cd (0.5)	b.d.l.	0.2	0.1	0.1	0.1	b.d.l.	0.1	0.1	b.d.l.	0.1
Sn (1)	2.0	2.3	1.8	1.9	1.5	2.2	1.7	1.9	1.5	2.0
Sb (0.05)	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.2
Cs (0.01)	2.0	0.7	2.5	2.4	1.5	2.8	0.7	1.2	2.3	2.2
Ba (0.5)	935.0	870.0	810.0	820.0	600.0	720.0	860.0	870.0	820.0	840.0
La (0.5)	51.8	59.5	56.6	54.1	48.5	52.7	54.2	53.5	52.6	50.0
Ce (0.5)	109.0	108.0	104.0	102.5	105.5	107.0	110.0	99.7	77.9	97.4
Pr (0.03)	12.8	13.7	13.6	13.1	12.0	13.0	13.3	13.0	12.5	12.3
Nd (0.1)	49.5	53.4	52.0	51.2	44.9	49.4	50.1	49.9	49.9	47.6
Sm (0.03)	9.6	9.6	9.4	9.2	8.2	9.3	9.1	9.1	8.8	8.5
Eu (0.03)	2.2	2.2	2.3	2.3	2.3	2.3	2.2	2.1	2.2	2.1
Gd (0.05)	7.9	8.6	8.5	8.3	7.8	8.4	8.3	8.0	8.5	7.8
Tb (0.01)	1.1	1.2	1.3	1.2	1.1	1.2	1.2	1.1	1.2	1.1
Dy (0.05)	5.8	6.0	6.0	6.1	6.0	6.4	6.2	5.9	6.1	5.9
Ho (0.01)	1.2	1.2	1.3	1.2	1.2	1.3	1.2	1.2	1.2	1.2
Er (0.03)	3.3	3.5	3.5	3.5	3.5	3.6	3.5	3.4	3.5	3.4
Tm (0.01)	0.5	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Yb (0.03)	2.8	3.1	3.2	3.1	3.1	3.2	3.2	3.0	3.1	3.0
Lu (0.01)	0.5	0.4	0.5	0.5	0.5	0.5	0.5	0.4	0.5	0.4
Ta (0.1)	0.8	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.9
Pb (2)	24.0	26.6	36.8	18.0	41.1	12.2	9.1	12.3	8.6	12.4
Bi (0.01)	0.1	0.1	b.d.l.	b.d.l.	b.d.l.	0.8	b.d.l.	0.1	0.1	0.1
Th (0.05)	11.1	11.6	11.5	11.0	10.8	11.1	11.6	12.4	10.0	12.8
U (0.05)	2.5	2.5	2.5	2.3	2.5	2.5	2.5	2.2	1.9	2.3

	Central Pele Dyke								Eastern Pele Dyke	
	703837	703838	703840	703841	703842	703843	703846	703847	703848	604275
	475858	475866	476202	475844	475847	475846	475834	475825	475829	476489
	5180477	5180593	5178221	5181276	5181230	5181235	5181407	5181144	5181034	5180762
Major Oxide (weight %)										
SiO ₂ (0.01)	63.00	63.40	63.20	62.10	65.90	62.70	63.50	64.60	63.70	62.90
Al ₂ O ₃ (0.01)	12.60	12.60	12.70	12.20	12.00	12.80	12.50	12.20	12.40	12.60
Fe ₂ O ₃ (0.01)	9.30	9.30	9.30	9.10	6.70	9.70	9.60	9.30	9.40	8.70
CaO (0.01)	4.00	3.50	4.00	4.00	6.90	4.00	4.20	4.10	3.90	4.90
MgO (0.01)	1.30	1.70	1.70	1.30	1.30	1.40	1.50	1.30	1.50	1.40
Na ₂ O (0.01)	3.40	3.60	3.60	3.00	1.10	3.20	2.20	3.00	3.10	3.20
K ₂ O (0.01)	2.90	2.40	2.10	2.70	2.80	2.70	2.70	2.50	2.70	2.70
TiO ₂ (0.01)	1.50	1.60	1.70	1.40	1.40	1.50	1.50	1.60	1.50	1.50
MnO (0.01)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
P ₂ O ₅ (0.01)	0.50	0.50	0.50	0.50	0.30	0.50	0.50	0.40	0.50	0.50
BaO (0.01)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
S (0.01)	b.d.l.	b.d.l.	b.d.l.	0.10	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Total	99.00	98.80	99.20	96.70	98.80	99.00	98.50	99.40	98.90	98.70
Mg number	21.69	26.59	26.59	22.06	27.77	22.24	23.64	21.69	24.02	24.17
Trace Elements (ppm)										
Li (10)	22.2	22.4	20.1	34.6	14.0	22.8	43.1	17.5	17.1	11.4
Sc (1)	25.0	23.0	26.8	26.5	22.8	25.5	25.9	26.5	25.4	n.d.
V (5)	59.0	62.0	87.0	60.0	88.0	61.0	61.0	63.0	63.0	75.0
Cr (10)	1.0	b.d.l.	b.d.l.	2.0	1.0	1.0	b.d.l.	b.d.l.	b.d.l.	9.0
Ni (1)	1.6	1.9	2.8	1.3	5.1	1.5	1.5	1.5	1.5	3.0
Zn (2)	111.0	63.0	110.0	121.0	40.0	143.0	111.0	100.0	93.0	960.0
As (0.1)	1.8	1.0	0.8	1.1	1.5	1.6	0.9	1.9	1.5	1.0
Se (0.2)	1.0	1.0	2.0	2.0	1.0	2.0	1.0	2.0	1.0	2.0
Rb (0.2)	101.0	108.0	144.0	109.0	117.0	125.0	365.0	153.0	120.0	139.0
Sr (0.1)	319.0	245.0	316.0	339.0	682.0	327.0	374.0	337.0	288.0	377.0
Y (0.5)	30.0	27.9	31.7	31.8	28.5	30.3	30.2	29.9	30.2	36.4
Zr (2)	242.0	219.0	240.0	234.0	230.0	243.0	208.0	247.0	236.0	229.0
Nb (0.2)	15.0	13.2	14.6	15.5	13.5	15.1	14.9	15.6	14.9	14.2
Mo (1)	1.7	1.5	1.0	1.9	1.5	1.9	1.1	1.8	1.7	2.0
Cd (0.5)	0.1	b.d.l.	b.d.l.	b.d.l.	0.1	0.1	b.d.l.	0.1	b.d.l.	1.3
Sn (1)	2.6	2.4	1.0	1.9	2.3	1.9	2.1	2.6	2.4	2.0
Sb (0.05)	0.2	0.1	0.1	0.2	0.4	0.2	0.1	0.3	0.2	0.1
Cs (0.01)	2.6	0.9	3.6	2.8	1.8	2.6	3.4	3.1	2.4	0.8
Ba (0.5)	930.0	610.0	510.0	940.0	670.0	850.0	810.0	830.0	860.0	650.0
La (0.5)	52.0	55.1	58.0	54.2	37.2	52.5	53.4	47.0	51.6	52.9
Ce (0.5)	97.1	85.1	95.9	104.0	69.4	99.0	99.8	91.0	96.2	114.5
Pr (0.03)	12.8	13.4	13.5	13.2	8.5	12.6	12.6	11.1	12.3	12.9
Nd (0.1)	49.1	51.0	51.6	50.7	33.4	49.0	48.7	44.6	47.9	49.8
Sm (0.03)	9.0	9.5	9.4	9.2	6.3	8.6	8.7	8.1	8.6	8.8
Eu (0.03)	2.2	2.4	2.2	2.3	2.6	2.2	2.2	2.1	2.3	2.9
Gd (0.05)	8.1	8.5	8.7	8.4	6.6	8.4	8.5	7.9	8.3	8.8
Tb (0.01)	1.1	1.2	1.2	1.2	0.9	1.1	1.1	1.1	1.1	1.1
Dy (0.05)	6.2	6.3	6.5	6.2	5.3	6.0	6.1	5.7	6.0	6.2
Ho (0.01)	1.2	1.3	1.9	1.2	1.1	1.2	1.2	1.2	1.2	1.1
Er (0.03)	3.5	3.6	3.7	3.6	3.1	3.6	3.4	3.3	3.5	3.4
Tm (0.01)	0.5	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.5	0.5
Yb (0.03)	3.2	3.2	3.2	3.2	2.8	3.4	3.1	3.1	3.1	2.9
Lu (0.01)	0.5	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.5	0.4
Ta (0.1)	1.0	0.9	1.0	1.0	0.9	1.0	1.0	1.0	1.0	1.0
Pb (2)	10.3	6.1	8.1	12.4	15.0	12.1	11.1	13.3	10.0	7.0
Bi (0.01)	0.1	0.1	b.d.l.	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Th (0.05)	13.3	11.6	13.5	13.7	8.3	13.0	13.7	12.0	12.8	11.4
U (0.05)	3.0	2.3	2.8	2.5	3.8	2.4	4.2	2.4	2.4	2.9

Western Pele Dyke										
	809926	809928	809929	809930	809954	809955	809956	809957	809958	809959
	474894	475228	475150	475300	474590	474650	474563	474497	474506	474492
	5180877	5180466	5180499	5180424	5181408	5181260	5181515	5181745	5181834	5181574
Major Oxide (weight %)										
SiO ₂ (0.01)	56.50	55.90	54.80	55.80	56.40	56.60	56.10	55.30	50.80	53.80
Al ₂ O ₃ (0.01)	12.60	13.00	13.60	12.90	12.80	12.80	12.50	12.40	12.35	12.50
Fe ₂ O ₃ (0.01)	13.60	13.55	11.75	13.90	13.95	13.55	14.25	14.50	17.15	13.55
CaO (0.01)	6.19	2.07	1.86	5.86	5.74	5.52	5.11	4.59	7.86	6.03
MgO (0.01)	2.82	5.75	6.34	3.05	2.87	3.02	3.44	4.39	5.46	3.01
Na ₂ O (0.01)	3.32	2.79	2.90	3.43	3.78	3.71	3.69	3.95	2.04	3.04
K ₂ O (0.01)	1.61	1.10	1.18	1.30	1.63	1.71	1.65	1.27	1.32	1.76
TiO ₂ (0.01)	1.70	1.76	1.85	1.72	1.72	1.70	1.71	1.68	1.44	1.61
MnO (0.01)	0.19	0.09	0.09	0.19	0.19	0.20	0.20	0.23	0.27	0.17
P ₂ O ₅ (0.01)	0.40	0.41	0.42	0.39	0.40	0.40	0.39	0.39	0.15	0.39
BaO (0.01)	0.05	0.02	0.03	0.06	0.07	0.08	0.08	0.06	0.04	0.07
S (0.01)	0.09	0.10	0.06	0.09	0.10	0.09	0.10	0.25	0.05	0.15
Total	99.13	96.56	94.89	98.74	99.70	99.43	99.26	99.03	99.00	96.13
Mg number	29.12	45.67	51.67	30.30	28.96	30.63	32.35	37.49	38.68	30.56
Trace element (ppm)										
Li (10)	17.9	29.4	40.5	20.1	16.7	21.1	25.9	19.8	17.8	25.0
Sc (1)	26.2	27.4	28.3	27.9	26.9	26.6	27.0	26.2	53.4	26.9
V (5)	207.0	212.0	235.0	232.0	212.0	216.0	226.0	213.0	359.0	214.0
Cr (10)	4.0	4.0	2.0	4.0	5.0	3.0	4.0	2.0	49.0	2.0
Ni (1)	13.1	17.1	17.2	15.2	14.9	15.3	14.7	14.4	62.0	14.4
Zn (2)	115.0	107.0	102.0	187.0	135.0	175.0	174.0	190.0	165.0	112.0
As (0.1)	0.6	1.1	0.3	3.0	0.3	1.3	3.0	0.4	0.3	0.5
Se (0.2)	2.0	2.0	2.0	3.0	2.0	2.0	2.0	3.0	2.0	2.0
Rb (0.2)	119.0	106.5	96.9	66.1	78.6	79.9	75.9	74.5	113.5	131.5
Sr (0.1)	413.0	118.5	56.6	458.0	428.0	425.0	372.0	200.0	213.0	438.0
Y (0.5)	29.7	32.3	25.8	29.6	31.1	30.2	29.7	30.0	40.9	31.3
Zr (2)	156.0	174.0	187.0	144.5	154.5	158.5	154.0	161.5	94.1	152.0
Nb (0.2)	10.3	10.4	11.1	9.9	10.4	10.1	10.1	9.9	7.9	10.3
Mo (1)	4.0	1.4	1.6	1.6	1.5	1.2	1.5	12.6	0.8	1.3
Cd (0.5)	0.1	0.0	0.0	0.4	0.1	0.3	0.3	0.2	0.2	0.1
Sn (1)	1.4	1.5	1.6	1.5	1.4	1.4	1.4	1.4	1.2	1.5
Sb (0.05)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Cs (0.01)	1.6	1.4	1.1	1.5	1.2	1.6	1.7	1.3	1.4	1.8
Ba (0.5)	440.0	180.0	230.0	530.0	580.0	680.0	700.0	470.0	330.0	630.0
La (0.5)	33.9	29.3	28.2	34.1	34.9	36.1	34.4	35.6	13.3	33.8
Ce (0.5)	78.3	69.4	63.1	78.0	82.2	81.1	79.6	81.3	32.8	86.2
Pr (0.03)	8.6	7.5	6.4	8.5	8.9	9.1	8.7	8.8	3.7	9.7
Nd (0.1)	35.2	30.7	25.4	35.4	36.5	37.5	35.7	35.6	16.8	36.4
Sm (0.03)	7.1	6.4	5.0	7.0	7.2	7.5	7.1	7.0	4.3	7.5
Eu (0.03)	2.0	1.7	1.6	2.2	2.1	2.2	2.0	1.9	1.3	2.1
Gd (0.05)	6.1	5.7	4.7	6.0	6.3	6.3	5.9	6.2	4.5	6.6
Tb (0.01)	0.9	0.9	0.8	0.9	1.0	1.0	0.9	1.0	0.9	1.0
Dy (0.05)	5.0	5.4	4.5	5.0	5.1	5.0	4.8	5.0	5.8	5.0
Ho (0.01)	1.0	1.1	0.9	0.9	1.0	0.9	0.9	1.0	1.2	1.0
Er (0.03)	2.6	2.9	2.5	2.5	2.6	2.6	2.5	2.6	3.5	2.6
Tm (0.01)	0.4	0.4	0.4	0.3	0.3	0.4	0.4	0.4	0.6	0.4
Yb (0.03)	2.2	2.5	2.3	2.2	2.2	2.2	2.1	2.2	3.6	2.1
Lu (0.01)	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.6	0.3
Ta (0.1)	0.6	0.6	0.6	0.5	0.6	0.6	0.6	0.6	0.4	0.6
Pb (2)	11.5	4.3	2.5	45.6	12.3	36.5	18.9	18.7	23.8	11.3
Bi (0.01)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.1
Th (0.05)	6.8	6.9	7.1	6.1	6.7	6.6	6.4	6.4	2.2	7.1
U (0.05)	1.5	1.6	1.6	1.3	1.4	1.3	1.3	1.3	0.6	1.5

	Western Pele Dyke				Nipissing Diabase					
	809960	809963	120202	120501	SI-004	SI-005	603522	604270	SI-010	SI-011
	475433	475580	476752	476752	476738	476734	476167	476499	476157	476162
	5180271	5180050	5179554	5179554	5179600	5179594	5178860	5180865	5178242	5178231
Major Oxide (weight %)										
SiO ₂ (0.01)	53.50	53.70	48.70	50.20	50.20	50.00	50.50	47.80	51.40	52.60
Al ₂ O ₃ (0.01)	12.60	12.65	14.25	13.40	13.05	15.50	15.65	13.35	12.65	13.20
Fe ₂ O ₃ (0.01)	13.40	13.40	13.35	14.15	13.70	12.50	8.32	15.05	14.45	15.00
CaO (0.01)	5.51	6.17	9.68	9.83	7.49	10.80	10.70	6.38	8.66	8.73
MgO (0.01)	2.60	2.96	5.88	6.18	7.33	5.68	8.84	6.92	5.52	5.24
Na ₂ O (0.01)	3.61	3.33	2.55	2.13	3.35	2.16	2.72	3.46	2.15	2.54
K ₂ O (0.01)	1.74	1.55	0.83	0.85	0.41	0.62	0.42	0.46	1.27	0.86
TiO ₂ (0.01)	1.65	1.69	0.92	0.97	1.10	1.00	0.50	1.13	1.13	1.25
MnO (0.01)	0.17	0.17	0.21	0.21	0.25	0.20	0.13	0.35	0.24	0.26
P ₂ O ₅ (0.01)	0.34	0.33	0.08	0.09	0.09	0.08	0.04	0.14	0.11	0.15
BaO (0.01)	0.08	0.07	0.02	0.02	0.01	0.02	0.01	0.01	0.04	0.03
S (0.01)	0.06	0.16	0.05	0.04	0.02	0.06	0.04	0.05	0.04	0.05
Total	95.30	96.21	96.55	98.11	97.02	98.66	97.95	95.15	97.70	99.93
Mg number	27.77	30.44	46.60	46.39	51.46	47.37	67.79	47.67	43.08	40.90
Trace element (ppm)										
Li (10)	14.8	9.4	20.0	10.0	10.0	b.d.l.	10.1	11.4	10.0	10.0
Sc (1)	28.4	27.3	38.0	42.0	43.0	37.0	n.d.	n.d.	40.0	36.0
V (5)	225.0	234.0	296.0	323.0	330.0	326.0	177.0	292.0	364.0	361.0
Cr (10)	2.0	5.0	100.0	120.0	80.0	140.0	227.0	173.0	50.0	30.0
Ni (1)	13.8	15.2	62.0	76.0	63.0	50.0	145.0	69.7	68.0	59.0
Zn (2)	134.0	124.0	113.0	126.0	147.0	95.0	84.0	208.0	149.0	206.0
As (0.1)	0.2	0.2	0.7	1.0	0.6	0.2	0.4	1.2	1.1	0.2
Se (0.2)	2.0	2.0	0.4	0.4	0.4	0.6	1.0	2.0	0.6	0.5
Rb (0.2)	80.3	97.5	50.5	47.3	19.9	22.0	17.0	23.0	77.4	36.4
Sr (0.1)	374.0	324.0	169.5	166.5	87.5	141.5	311.0	247.0	194.0	179.5
Y (0.5)	31.7	29.3	21.7	23.0	23.9	23.1	10.9	28.1	30.2	30.9
Zr (2)	161.5	147.5	78.0	80.0	94.0	85.0	27.4	83.9	118.0	138.0
Nb (0.2)	10.8	9.7	3.6	3.8	4.1	4.3	1.7	5.7	6.4	6.7
Mo (1)	1.2	1.3	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.2	0.4	b.d.l.	b.d.l.
Cd (0.5)	0.1	0.1	b.d.l.	b.d.l.	0.5	b.d.l.	0.2	0.0	0.5	0.5
Sn (1)	1.5	1.4	1.0	1.0	1.0	1.0	0.5	1.0	1.0	1.0
Sb (0.05)	0.1	0.1	0.2	0.3	b.d.l.	b.d.l.	0.1	0.1	0.1	0.1
Cs (0.01)	1.4	1.2	0.5	0.6	0.2	0.5	0.4	0.5	0.5	0.2
Ba (0.5)	770.0	590.0	213.0	200.0	126.5	155.0	110.0	100.0	352.0	251.0
La (0.5)	32.3	32.4	10.4	9.7	9.6	9.1	5.1	8.8	12.1	16.5
Ce (0.5)	83.2	81.4	20.1	20.3	20.1	20.2	13.3	23.5	25.6	35.0
Pr (0.03)	9.3	9.3	2.7	2.6	2.6	2.6	1.4	2.7	3.2	4.3
Nd (0.1)	35.7	35.3	11.4	11.8	11.0	10.9	6.5	12.4	14.2	17.9
Sm (0.03)	7.5	7.5	3.2	3.1	2.9	2.8	1.4	2.9	3.7	4.2
Eu (0.03)	2.0	2.1	1.0	1.0	0.8	1.0	0.5	0.8	1.2	1.2
Gd (0.05)	6.6	6.5	3.3	3.8	3.4	3.4	1.6	3.8	4.5	4.7
Tb (0.01)	1.0	1.0	0.6	0.7	0.6	0.6	0.2	0.6	0.8	0.9
Dy (0.05)	5.0	4.9	3.9	4.2	4.1	3.9	1.8	4.5	5.2	5.5
Ho (0.01)	1.0	0.9	0.9	0.9	0.9	0.9	0.3	0.9	1.2	1.2
Er (0.03)	2.8	2.6	2.6	2.6	2.3	2.6	1.1	2.8	3.1	3.2
Tm (0.01)	0.4	0.4	0.4	0.4	0.4	0.4	0.2	0.4	0.5	0.5
Yb (0.03)	2.2	2.1	2.5	2.7	2.6	2.5	1.0	2.9	3.2	3.4
Lu (0.01)	0.3	0.3	0.4	0.4	0.4	0.4	0.1	0.3	0.5	0.5
Ta (0.1)	0.6	0.6	0.3	0.3	0.3	0.3	0.1	0.4	0.5	0.5
Pb (2)	18.6	11.6	14.0	9.0	7.0	2.0	20.2	3.6	15.0	11.0
Bi (0.01)	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Th (0.05)	6.7	6.1	1.8	1.8	2.2	2.0	2.6	1.9	3.0	4.1
U (0.05)	1.4	1.3	0.5	0.6	0.5	0.4	0.3	0.5	0.8	0.9