AN IGNEOUS EVENT AT THE FILDES PENINSULA (KING GEORGE ISLAND) AND AROUND FORT POINT (GREENWICH ISLAND), SOUTH SHETLAND ISLANDS, ANTARCTICA

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Resumo *EVENTOS IGNEOS NA PENINSULA FILDES (ILHA REI GEORGE) E NO PONTAL FORT (ILHA GREENWICH), ISLAS SHETLAND DO SUL – ANTARTICA* As ilhas estudadas fazem parte do arquipélago Shetland do Sul, com a ilha Rei George a nordeste e a ilha Greenwich na parte central do arquipélago. As suítes vulcânicas estudadas se manifestam como derrames e de maneira sub vulcânica, de composições basáltico-andesítica e andesítica. As rochas intrusivas variam de composição diorítica a granítica. Os padrões geoquímicos indicam a similaridade geoquímica de todas as rochas e que o vulcanismo precedeu o plutonismo. O comportamento dos elementos traço incompatíveis mostra a afinidade cálcio-alcálica de todas as rochas e sua geração em zonas de subdução. Anomalias negativas de Ta, Ti, P e Nb, típicas de arcos de ilhas, também são observadas. As razões iniciais Sr87/Sr86 e os valores positivos de eNd sugerem origem mantélica do(s) magma(s), com pouca ou nenhuma assimilação de crosta continental. As razões isotópicas de Pb atestam a similaridade isotópica entre todas as rochas. Com base nos resultados petrográficos, geoquímicos e isotópicos, conclui-se que: (a) as rochas vulcânicas do Pontal Fort e Península Fildes são contemporâneas; (b) as rochas intrusivas representam termos mais evoluídos; (c) estas rochas se originaram a partir de uma única fonte magmática e sofreram processos de evolução similares e; (d) considerando as idades existentes, estas rochas posicionaram-se durante o Eoceno inferior.

Palavras-chave: Antártica, magmatismo, geoquímica, ambiente tectônico.

Abstract King George Island is located at the northeastern and Greenwich Island at the southwestern portions of the South Shetland Islands. The studied volcanic suits were emplaced as flows and subvolcanics of basaltic-andesitic and andesitic compositions. The intrusive rocks display dioritic to granitic compositions. Geochemical patterns indicate the geochemical similarity of the rocks and that the volcanism preceded the plutonism. Incompatible trace element behavior shows a calc-alkaline affinity and that these rocks were generated in a subduction zone. Large negative Ta, Ti, P and Nb anomalies, typical of an island-arc environment, are also observed. The initial Sr87/Sr86 ratios and the positive eNd suggest derivation from a mantle source with little or no assimilation of continental crust. Pb isotopic ratios attest to the isotopic similarity of all the rocks. Based on petrographic, geochemical and isotopic data, it is concluded that: (a) the volcanic rocks from Fort Point and the Fildes Peninsula are contemporaneous; (b) the intrusive rocks represent more evolved terms; (c) these rocks were originated from one single magmatic source and have undergone similar evolution processes and; (d) considering the available ages, these rocks were emplaced during Early Eocene.

Keywords: Antarctica, magmatism, geochemistry, tectonic environment.

INTRODUCTION The studied areas are located in Greenwich Island (Fig. 1) and King George Island (Fig. 2), which are part of the South Shetland Islands. This islands is about 550 km long, along a NE-SW trend parallel to the Antarctic Peninsula. It is located 950 km southwest of Cape Horn, the southern extremity of South America, and 150 km northwest of the Antarctic Peninsula. The South Shetland Islands are separated from South America by the Drake Sea, and from the Antarctic Peninsula by the Bransfield Strait. Although the two studied islands are not adjacent, they belong to a group of islands that supposedly share the same geological and tectonic history. The South Shetland Islands contain volcanic and plutonic rocks of Early Cretaceous to Early Miocene age, related to the subduction of the SE Pacific oceanic crust beneath the Antarctic continent (Smellie 1983, Birkenmajer et al. 1988). Subsequent volcanism from Early Miocene (Birkenmajer

et al. 1990) to recent times (e.g. Fisk 1990) is associated with rifting in the Bransfield Strait.

The aim of this paper is to petrographically and geochemically characterize the plutonic and volcanic rocks of the Fildes Peninsula (FP) and Fort Point (FPt), in order to determine the temporal relations between the magmatism in the two regions.

The research comprised a petrographic study complemented by electron microprobe (EMP) analyses of selected minerals to determine the petrographic similarities and differences between intrusive and volcanic rocks from the two islands. The EMP analyses were carried out at Federal University of Rio Grande do Sul (UFRGS). Additionally, nine samples from the Fildes Peninsula were geochemically analyzed in the X-ray Fluorescence Laboratory at UFRGS and at the Energy, Nuclear and Neutron Activation Research at Universidade de São Paulo (USP). From Fort Point, 14

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samples were analyzed for major, trace and rare-earth elements at the Activation Laboratories Ltd (ACTILAB), Canada. Isotopic analyses ($\text{Sr}^{87}/\text{Sr}^{86}$, $\text{Nd}^{143}/\text{Nd}^{144}$ and Pb) were carried out in the Isotopic Geochemistry Laboratory at the University of Kansas (UK), U.S.A., in the Department of Geology and Geophysics at the University of Adelaide (UA), Australia, and in the Institute of Geosciences at the Federal University of Rio Grande do Sul.

The Fort Point (FPt) area is located at the southeastern extreme of Greenwich Island (Fig. 1), in an area that lies between the parallels $62^{\circ}32'30''$ and $62^{\circ}34'00''$ south, and the meridians $59^{\circ}32'30''$ and $59^{\circ}37'30''$ west. The studied area (FPt) covers approximately 15 km^2 . The Fildes Peninsula (FP) is located at the southwestern extreme of King George Island (Fig. 2), between $62^{\circ}08'30''$ and $62^{\circ}13'45''$ south, and $58^{\circ}51'00''$ and $59^{\circ}00'30''$ west.

GEOLOGICAL SETTING The region of Fort Point shows in an area of about 25 km^2 a thick succession of volcanic rocks (olivine basalts and andesitic basalts) covered by volcanoclastic and sedimentary rocks (breccia, lapillite, conglomerates and psamites) that make up the Coppermine Formation (late Cretaceous) and intrusions of microgranites and granodiorite from the Greenwich Intrusive Suite (early Paleocene) (Fig. 1).

Fensterseifer *et al.* (1991) identified a stock of granitic-granodioritic composition, located at southeastern Greenwich Island, as the Greenwich Intrusive Suite. A gabbroic body associated with the multiple intrusions at Atrio Point, at the northwestern extreme of the island, has been identified as well. Hansen *et al.* (1994), working on geochemical and petrographic data from Fort William Point (Greenwich Island), have found little compositional variation in the intrusive and volcanic rocks (basaltic to basaltic andesites). Almeida *et al.* (2000) reported that, in the FPt region, the intrusive rocks of dioritic to granitic composition

occur as an epizonal body co-genetic with the volcanic rocks, and that volcanism preceded plutonism, all rocks showing a calc-alkaline affinity.

The radiometric data listed in Table 1 and shown in figure 1, correspond to the ages of volcanic and intrusive rocks found in the Greenwich Island published by Fensterseifer *et al.* (1991). The samples were collected during the IX and X Antarctic Operations of the Brazilian Antarctic Program (PROANTAR) and processed at the Geochronological Research Centre of the Universidade de São Paulo (USP).

The Fildes Peninsula, with about 25,8 km^2 , consists of a thick succession of basaltic and andesitic (may even be dacitic) volcanic rocks with intercalations of volcanoclastic rocks, which altogether represent the Fildes Peninsula Group (Hawkes 1961). Fensterseifer *et al.* (1998) proposed the following formations for this group: Clement Hill (late Cretaceous), Fildes Strait, Schneider Bay and Winkel Point (early Eocene) (Fig. 2). The intrusions, represented by dikes, sills and plugs were included in the Admiralty Bay Group (Birkenmajer 1980).

Using the K-Ar method, Grikurov *et al.* (1970), Valêncio *et al.* (1979) and Watts (1982) dated some rocks magmatic from the FP, the Barton Peninsula and the Admiralty Bay, as being of Mesozoic age, but the intense alteration of the rocks has cast doubt on these results. According to Smellie *et al.* (1984), in the southeastern region of King George Island and the northern region of Greenwich and Livingston islands, the volcanic rocks are of Tertiary to Quaternary age. Later work (Pankhurst and Smellie 1983, Birkenmajer *et al.* 1983, Soliani *et al.* 1988) has not confirmed the Mesozoic ages. Radiometric ages of the volcanic rocks found on King George Island are listed below Table 2 and plotted in Fig. 2.

PETROGRAPHY AND MINERAL CHEMISTRY Volcanic

Figure 1 – Location map of the studied area, showing the Greenwich Island in detail and the available geochronological data and the geological map.

Table 1 – Ages of volcanic and intrusive rocks from Greenwich Island.

Place	Age (K/Ar) (Ma)	Rock	Lithostratigraphic unit
Triângulo Point	54,5 ± 1.1	Basalt lava flow	Península Fildes Group (Paleocene-Eocene)
Spark Point	70.3 ± 1.9	Basalt/andesite lava flow	Coppermine Formation (Late Cretaceous – Early Paleocene)
Spark Point	77.6 ± 2.3	Basalt/andesite lava flow	Coppermine Formation (Late Cretaceous – Early Paleocene)
Esporão Point	55.3 ± 5.0	Dolerite intrusion	Península Fildes Group (Paleocene-Eocene)
Spit Point	51.6 ± 1.4	Basal/andesite dike	Península Fildes Group (Paleocene-Eocene)
Atrio Point	71.0 ± 3.8	Gabbro intrusion	Atrio Point Gabbro * (Late Cretaceous)

* Informal stratigraphic unit.

Figure 2 – Location map of the studied area, showing the King George Island in detail and the available geochronological data and the geological map.

rocks The volcanic activity was marked by the eruption of andesites and andesitic basalts. They display glomeroporphyritic textures, and a pilotaxitic, subophitic and intergranular groundmass. The mineral assemblage of these rocks is characterized by phenocrysts of zoned plagioclases, uraltized clinopyroxenes that are sometimes diffuse and altered (to epidote, carbonate), microphenocrysts of plagioclases, clinopyroxenes and opaque minerals, as well as interstitial glass. At the FP, partially- or completely-altered olivine is also present in the andesitic basalts. The subvolcanic facies has a very similar composition, although it presents amphibole formed from pyroxene (by uraltization), and biotite in the groundmass. In addition, the accessory phases are magnetite and titanomagnetite. Orthopyroxene is a rare phase, present only in the andesitic basalts.

The mineral chemistry shows that in the lava-flow rocks plagioclase phenocrysts are normally-zoned, with more calcic nuclei (An_{61-93}) and more sodic borders (An_{58-79}) (Almeida et al. 2000). Where un-zoned, they are usually of the bytownite type

(An_{72-89}), and may reach the anorthite end-member (An_{90-95}). The subvolcanic facies presents zoned plagioclases with bytownite (An_{74-83}) composition in the center, and andesine (An_{49}) along the borders. The composition of un-zoned plagioclases corresponds to labradorite An_{59} (at FPT) and An_{50-69} (at FP), and subordinate andesine An_{40-49} (only at FPT). Biotites from the subvolcanic facies are aluminum-poor.

Chemical analyses on pyroxenes and olivines have only been performed in samples from the FP by previous workers. Machado et al. (1998) have shown that clinopyroxene phenocrysts are augite (En_{37-52} ; Fs_{13-26} ; Wo_{21-42}), or more rarely pigeonite (En_{52-67} ; Fs_{22-33} ; Wo_{8-15}) and the orthopyroxene bronzite (En_{69-71} ; Fs_{25-27} ; Wo_{3-4}). The latter two have only been identified in basaltic andesites. Olivine composition is chrysolite (Fo_{79-81}).

Intrusive rocks The intrusive rocks, studied only at Fort Point form an epizonal body of dioritic, tonalitic, and granitic compositions. These rocks display inequigranular texture with

Table 2 – Ages of volcanic and intrusive rocks from King George Island

Place	Age (K/Ar) (Ma)	Lithology	Authors
Fossil Hill	58 - 59	Basaltic andesite	Pankhurst & Smellie (1983)
Center north Fildes Peninsula	46.6 - 42.9	Basalt/andesite lava flow	Fensterseifer <i>et al</i> (1988)
NE Fildes Peninsula	47.5 - 58.5	Intrusions and lava flow	Soliani <i>et al</i> (1988)
Fildes Peninsula	52	Volcanic rock	Li and Liu (1991), Li (1994)
Mount Zamek	77 - 66	Basal-andesite	Birkenmajer <i>et al</i> (1983)
Point Thomas (Admiralty Bay)	51 - 49 and 47	Intrusive andesite	Pankhurst & Smellie (1983)
Point Thomas	37.4±1.1	Basaltic andesite	Birkenmajer <i>et al</i> (1983)
Rakusa Point	21.0±0.8 / 66.7±1.5	Dacite / Andesite	Birkenmajer <i>et al</i> (1983)
Point Hennequin	43.9 - 44 - 45	Basaltic andesite	Birkenmajer <i>et al</i> (1983)
Point Hennequin	46 - 47	Basaltic andesite	Pankhurst & Smellie (1983)
South Smock	28.3 - 24.5	Base plug and flow	Birkenmajer <i>et al</i> (1983)

altered plagioclases, uraltized clinopyroxenes (although the latter is not present in the granites) and biotite, which sometimes is chloritized. Apatite, zircon and titanite are uncommon accessories.

Almeida *et al.* (2000) report that the composition of zoned plagioclase of intrusive rocks usually ranges from oligoclase (An₁₇) to andesine (An₄₅₋₄₉) at the borders, and from labradorite (An₅₁₋₅₉) to anorthite (An₉₃₋₉₄) in the core. Clinopyroxene ranges from augite (En₃₈₋₄₀; Fs₁₄₋₁₈; Wo₄₂₋₄₄) to diopside (En₃₇₋₃₈; Fs₁₅₋₁₇; Wo₄₃₋₄₅). The only mica is biotite.

GEOTECTONIC SETTING The Antarctic Peninsula and the South Shetland Islands were formed as the result of subduction of the Pacific Ocean crust beneath the Antarctic Continental crust during the Mesozoic and Cenozoic. Hence the Antarctic Peninsula is interpreted as a continental magmatic arc, and the larger South Shetland Islands from an island arc of Cretaceous-Early Tertiary age (Smellie 1983, Smellie *et al.* 1986).

The magmatic record of the post-Paleozoic subduction (Birkenmajer 1981) along the west coast of the Antarctic Peninsula indicates two main stages of subduction during the Jurassic-Cretaceous and Tertiary. Subduction was probably more intense around the Cretaceous-Tertiary boundary as a result of the Andean Orogeny.

Subduction has created a tectonic trench of fore-arc type and generated three volcanic, island-arc type cycles on the west coast of the Antarctic Peninsula. This has formed a Tertiary calc-alkaline suite with tholeiitic affinity (Barker 1972, Smellie *et al.* 1984) on a continental platform 15 to 20 km thick (Ashcroft 1972), which became the South Shetland Islands. Cenozoic subduction ceased along most of the west margin of the Antarctic Peninsula during the Middle Tertiary. Plate consumption continued to the northeast at the Aluk Plate (Fig. 3), and in only one section of oceanic crust near the South Shetland Islands. Subduction continued through the Late Tertiary (Barker 1970, Barker and Griffiths 1972). The arc volcanism associated with rifting in three of the South Shetland Islands (Livingston, Greenwich and King George) is thought to have ceased around 15 and 25 Ma (Keller *et al.* 1991). Crustal extension has occurred in the region between the Antarctic Peninsula and the South Shetland Islands since the Late Oligocene. These movements have separated the South Shetland Islands from the Antarctic Peninsula by creating a young, narrow marginal basin, the Bransfield Strait, in the beginning of the Pliocene.

Contrary to other authors, Trouw and Gambôa (1992) have suggested that the South Shetland Islands is part of a remnant magmatic arc (the Antarctic Peninsula) that was separated from

the South Shetland Islands by the Bransfield Rift during the Neogene-Quaternary.

King George Island, which is part of the South Shetland Islands, is formed by a large number of tectonic blocks delimited by longitudinal faults. Birkenmajer *et al.* (1986) obtained a Tertiary age for the strike-slip faults on King George Island, based on K-Ar dating of a system of plugs and dykes. These strike-slip movements are thought to have begun around 54 Ma (Paleocene-Eocene) and to have lasted at least 33 Ma until the Early Miocene, when a new system of transverse faults formed, followed by intrusions and dykes parallel to the faults (Birkenmajer *et al.* 1986).

According Tokarski (1987), the three stages in the structural development of the volcanic rocks from King George Island correspond to three successive plate tectonic events to the north of the Antarctic Peninsula. The first stage is related to the eastward subduction of the Aluk Plate (Fig. 3), the second one apparently reflects main reorganization of the plates, which resulted in the opening of the Scotia Sea and the cessation of Aluk Plate subduction, and the third stage is characterized by a period of stabilization.

WHOLE-ROCK GEOCHEMISTRY AND ISOTOPIC ANALYSES The results shown in Table 3a correspond to volcanic rocks from the Fildes Peninsula and in Table 3b, to volcanic and intrusives rocks from the Fort Point.

From a chemical standpoint, the volcanic and subvolcanic rocks studied, represented in a Nb/Y versus Zr/TiO₂ diagram (Winchester and Floyd 1977, Fig. 4a), plot in the andesite field (five samples) and andesite/basalt field (seven samples). The intrusive rocks, represented in a R1-R2 diagram (De la Roche, 1976, Fig. 4b), plot in the dioritic field (five samples), tonalitic field (two samples) and the sample that represents the border facies of the intrusive rocks plots in the gabbro-diorite field.

All samples show low TiO₂ content (below 1%) and relatively high Al₂O₃ content, especially those from the FP. The latter displays an average of 19.2% Al₂O₃ in the volcanic and subvolcanic rocks and 22% in the dykes. Al₂O₃ content is "normal" in samples from FPt. Zr presents a positive correlation with Nb and REE (Figs. 5a, 5b and 5c). The same behavior can be observed in Rb versus K₂O, and Ce versus La diagrams (Figs. 6a and 6b), as well as in Zr versus Y. This shows that, in all the diagrams, the intrusive rocks correspond to the more evolved members. The high concentration of Nb in sample HA-18.1 (Fig. 5a) may be explained through the presence of titanite, observed in thin section. The higher K₂O and Rb content in sample HA-16.2A is due to the high acidity (76.26%)

Figure 3 – Plate limit at the Scotia Sea region (modified after Tokarski 1987) showing the position of the Aluk plate.

Figure 4 - Chemical rock classification (a) the volcanic rocks in the bivariate Nb/Y versus Zr/TiO₂ diagram according to Winchester & Floyd 1977; (b) the intrusive rocks represented in a R1 – R2 diagram according to De la Roche 1976.

and alkalinity of this sample (8.37%), which suggests that it corresponds to a late dyke. In the $Al_2O_3 + Na_2O + K_2O$ versus $Al_2O_3 + CaO + Na_2O + K_2O$ diagram (Maniar and Piccolli 1980), the rocks are metaluminous, except the dyke from FPt.

All the rocks show low MgO, Co, Ni and Cr contents. This indicates their evolved character, and also confirms that the intrusive rocks (FPt) are more evolved than the volcanic and subvolcanic rocks from the FP and FPt.

In the REE distribution diagram, normalized to chondrite after Nakamura (1977, Figs. 7a and 7b), all the rocks display calc-alkaline affinity and LREE enrichment in relation to HREE. The intrusive rocks show the most evolved pattern, and a slightly negative Eu (Fig. 7a) anomaly due to plagioclase fractioning. The dykes from the FP are an exception to this. They present a slightly positive Eu anomaly that may be indicative of plagioclase cumulates. The Eu/Sm ratio is over 0.244.

If normalized to a standard N-MORB pattern in a multi-element diagram (LILEs, HFSEs) after Sun and McDonough (1989, Figs. 8a and 8b), a similar pattern is observed for all groups, confirming the co-genetic relation between these rocks. The pattern is characterized by strong negative Ta, Nb, P, and Ti anomalies, typical of island-arc environments, and higher LILE element content in relation to HFSE, typical of orogenic rocks.

In the FeO versus $K_2O + Na_2O$ versus MgO diagram (Irvine and Baragar 1971, Fig. 9a), most of the rocks analyzed show a typical

calc-alkaline pattern, except for the four samples from the FP which show a tholeiitic pattern. The calc-alkaline character is confirmed in the Zr versus Y diagram (McLean and Barret 1993, Fig. 9b). Zr content is 38 to 97 ppm for samples from the FP, and 37 to 234 ppm for those from FPt.

The classic Hf/3 versus Th versus Nb/16 diagrams of Wood (1980, Fig. 9c), and FeO versus MgO versus Al_2O_3 of Pearce *et al.* (1977), suggest that these rocks were generated in orogenic zones where subduction was taking place. The Zr versus Ti diagram of Pearce (1982) confirms the volcanic arc environment of these rocks. In magmatic arcs, a typical HFSE depletion is found due to the fractionation of HFSE-rich phases (*e.g.* zircon, apatite, titanite) in the parental magma (Figs. 8a and 8b).

Initial $^{87}Sr/^{86}Sr$ ratios decrease from 0.703836 in Greenwich Island (FPt) to between 0.703719 and 0.703373 in King George Island (FP). ϵNd varies from +4.61 to +6.12 in Fort Point, and +6.51 to +7.3 in the FP (Table 4).

$^{143}Nd/^{144}Nd$ ratios are similar in the two regions, with values between 0.5129 and 0.5128 in FPt, and 0.5129 in the FP. Although no radiometric ages are available for rocks from FPt, a K-Ar age of 51.6 ± 1.4 Ma was obtained in a volcanic rock from Spit Point (Fensterseifer *et al.* 1991 – Fig. 1, Table 1). This agrees with other ages obtained in different regions of Greenwich Island (Table 1), similar to the 52 Ma age from a volcanic rock sample from the FP (Li & Liu 1991, Li 1994), as well as other ages obtained in rocks from

Table 3a - Chemical data for samples from the Fildes Peninsula (according to Machado et al. 1998). Major elements in %; trace elements and REE elements in ppm; n.a. = not analyzed. The analyses were carried out at the Laboratório de Fluorescência de Raios-X from Universidade Federal do Rio Grande do Sul-UFRGS, for major and trace elements (V, Rb, Sr, Zr, Nb e Ba) of the samples AF-16A and AF-16B, while the Instituto de Pesquisas Energéticas e Nucleares from Universidade de São Paulo (USP) was responsible for the analyses of Sc, Co, Rb, Cs, Ba, La, Ce, Nd, Sm, Eu, Tb, Yb, Lu, Hf, Ta, Th and U, through Neutronic Activation, for the samples AF-16A and AF-16B (following the method of Figueiredo & Marque, 1989). The samples AF-2A, AF-2B, AF-5, AF-12A, AF-14, AF-20 and AF-21 were analyzed for major elements, trace elements (Sc, V, Cr, Co, Ni, Cu, Zn, Ga, Ge, As, Rb, Sr, Y, Zr, Nb, Mo, Sn, Sb, Cs, Ba, Hf, Ta, W, Ti, Pb, Th e U) and REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) at the Activation Laboratories LTD (ACTLABS), Canada, with the Argonium Plasma Spectrometry (ICP) technique

	Dikes		Subvolcanic Rocks			Volcanic Rocks (lava flows)				
Sample	AF-12A	AF-16B	AF-16A	AF-2A	AF-2B	AF-5	AF-14	AF-20	AF-21	
SiO ₂	50.34	48.41	52.64	51.44	53.22	50.34	50.14	49.15	52.14	
TiO ₂	0.74	0.85	0.71	0.93	0.88	0.45	0.84	0.83	0.85	
Al ₂ O ₃	21.98	21.43	20.64	16.75	17.18	20.56	19.89	21.13	17.96	
Fe ₂ O ₃	8.29	6.33	7.96	8.79	8.22	7.59	9.64	9.35	10.05	
MnO	0.14	0.11	0.14	0.14	0.14	0.12	0.18	0.12	0.18	
MgO	3.34	2.65	4.25	4.98	4.68	6.15	4.31	3.04	3.73	
CaO	10.06	13.83	10.39	8.41	8.35	10.9	9.97	10.07	7.79	
Na ₂ O	2.93	1.75	1.84	2.95	3.18	2.16	3.31	3.12	3.58	
K ₂ O	0.27	0.07	0.4	0.94	1.03	0.79	0.57	0.35	0.67	
P ₂ O ₅	0.11	0.15	0.12	0.14	0.14	0.09	0.13	0.13	0.15	
P.F.	4.51	4.66	0.11	4.08	2.62	1.78	1.01	3.46	2.03	
Total	100.99	100.7	99.53	99.55	99.64	100.93	100.04	100.75	99.13	
Ba	109	188	151	201	204	155	149	139	174	
Rb	5	2	6	18	18	11	5	3	11	
Sr	528	593	535	483	467	608	575	539	514	
Ta	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
Nb	1	2	2	4	4	1	1	1	2	
Hf	1	2	2	2	3	1	1	1	2	
Zr	38	94	87	84	97	54	44	50	64	
Y	11	0	0	14	15	10	12	14	16	
Th	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
La	4.63	10.5	7.2	9.66	10.24	6.24	6.45	6.005	7.69	
Ce	10.27	16.38	16.6	21.08	21.98	13.88	14	13.11	16.38	
Pr	1.345	0	0	2.473	2.627	1.698	1.82	1.789	2.318	
Nd	7.4	16	13	12.07	13.98	8.76	9.68	8.87	11.67	
Sm	1.81	3.1	2.6	2.98	3.42	2.15	2.76	2.5	2.96	
Eu	0.738	1.18	1.02	0.883	0.883	0.632	0.921	0.9	1.096	
Gd	1.82	n.a.	n.a.	2.57	2.94	1.57	2.36	2.17	2.64	
Th	0.35	n.a.	n.a.	0.45	0.5	0.27	0.39	0.38	0.46	
Dy	2.06	n.a.	n.a.	2.91	2.8	1.86	2.34	2.56	3.09	
Ho	0.42	n.a.	n.a.	0.48	0.55	0.3	0.45	0.48	0.59	
Er	1	n.a.	n.a.	1.34	1.5	0.93	1.27	1.36	1.64	
Tm	0.15	n.a.	n.a.	0.19	0.211	0.142	0.158	0.177	0.233	
Yb	1.05	1.3	1.2	1.55	1.41	1.06	1.08	1.45	1.59	
Lu	0.244	0.24	0.19	0.251	0.272	0.155	0.2	0.233	0.268	

Table 4 - Sr, Sm-Nd and Pb from Fort Point and Fildes Peninsula. Were carried out in the Isotopic Geochemistry Laboratory at the University of Kansas (UK), U.S.A., at the Department of Geology and Geophysics at the University of Adelaide (UA), Australia, and in the Institute of Geosciences at the Federal University of Rio Grande do Sul - UFRGS. n.d = not detected.

Amostra	⁸⁷ Sr/ ⁸⁶ Sr m	⁸⁷ Sr/ ⁸⁶ Sr i	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd	εNd	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb
Fort Point, Greenwich Island								
HA-1.1	0.703836	0.703797	0.15881	0.512919	5.87	18.576	15.551	38.204
HA-8.2A	n.d.	n.d.	0.14610	0.512898	5.59	---	---	---
HA-19.1	n.d.	n.d.	0.14342	0.512924	6.12	---	---	---
HA-20	n.d.	n.d.	0.13519	0.512842	4.61	---	---	---
HA-26.3	n.d.	n.d.	0.16439	0.512888	5.21	---	---	---
HA-28.3	n.d.	n.d.	0.17391	0.512912	5.58	---	---	---
Fildes Peninsula, King George Island								
AF-2B	0.703416	0.703345	n.d.	n.d.	n.d.	---	---	---
AF-5	0.703373	0.703337	0.14839	0.512995	7.30	18.555	15.568	38.254
AF-14	0.703472	0.703456	0.15333	0.512967	6.72	18.455	15.490	38.123
AF-20	0.703719	0.703709	0.16179	0.512959	6.51	18.564	15.571	38.257

King George Island (Table 2). Pb isotopic ratios demonstrate the isotopic similarity between rocks from FPT and the FP (Table 4), with a positive correlation between Pb²⁰⁶/Pb²⁰⁴ versus Pb²⁰⁸/Pb²⁰⁴ showing a behavior equivalent to the Pacific MORB rocks (Fig. 10). The Pb-Sr isotopic system displays enrichment of Pb over Sr. The sediments are relatively enriched in Pb, what would confirm the great mobility of Pb in comparison with Sr in aqueous systems (Brenan et al. 1995).

DISCUSSION AND CONCLUSIONS The fact that intrusive

rocks are only found on Greenwich Island (as they are probably absent on the FP) may be explained by uplifting or by regional dipping towards northeast, with more severe erosion occurring on the islands located to the southwest.

Some minerals, such as olivine and orthopyroxene, were only found in basalts and basaltic andesites, respectively, from the FP. This may indicate that the initial magmatic crystallization phases were present in this region, where the Mg content in the primary magma was high enough to form minerals such as bronzite and chrysolite. This did not take place in the FPT region.

Table 3b - Chemical analyses for the Fort Point samples, according to Almeida et al. 2000. Major elements in %; trace elements and REE in ppm. The geochemical analyses were performed at the Activation Laboratories (ACTLAB), Canada, with the Argonium Plasma Spectrometry (ICP) technique.

	Dike	Border	Intrusives rocks							Subvolcanic rocks		Vulcanic rocks (lava flows)			
Sample	HA1 6.2A	HA26.3	HA7.3	HA8.1.1	HA8.2a	HA9.1	HA18.1	HA20	HA23.2	HA16 .2b	HA19. I	HA17. 2a	HA28.1	HA28.3	HA1.1
SiO ₂	76.26	53.33	57.93	57.99	57.26	57.46	63.4	63.72	56.7	54.36	56.22	55.99	68.6	53.95	47.47
TiO ₂	0.2	0.59	0.69	0.75	0.78	0.87	0.5	0.48	0.61	0.83	0.45	0.61	0.28	0.78	0.83
Al ₂ O ₃	11.33	19.29	15.95	16.36	16.42	16.1	16.31	15.77	17.47	17.98	17.1	17.4	15.78	18.87	25.74
Fe ₂ O ₃	1.31	7.8	8.09	7.26	7.59	7.66	5.25	5.16	8.45	8.08	6.7	7.46	3.41	8.49	8.67
MnO	0.02	0.19	0.15	0.13	0.13	0.15	0.13	0.12	0.13	0.11	0.12	0.14	0.08	0.16	0.12
MgO	0.17	4.74	3.3	3.07	3.21	3.28	2.05	2.04	3.62	3.24	4.78	3.89	1.61	4.57	3.06
CuO	0.34	9.16	6.25	6.61	7.05	6.44	4.75	4.39	7.44	7.64	8.54	7.26	4.95	9.2	9.33
Na ₂ O	2.46	3.06	4.31	3.66	3.47	3.49	4.19	4.02	3.63	3.76	2.95	3.67	4.06	2.95	3.23
K ₂ O	5.91	0.36	1.21	1.79	1.59	1.83	1.75	2.06	0.68	0.6	1.05	1.05	0.6	0.2	0.45
P ₂ O ₅	0.02	0.09	0.18	0.15	0.18	0.18	0.15	0.13	0.03	0.21	0.2	0.13	0.08	0.11	0.04
LOI	0.39	1.44	0.49	0.79	0.74	1.15	1.53	1.17	0.98	1.44	1.96	1.49	1.02	0.59	2.01
Total	98.21	100.05	98.53	98.55	98.41	98.61	100.0	99.67	99.73	98.24	100.2	98.57	100.5	99.87	100.9
Ba	936.9	100	385	349	345	381	443	405	275	235	263	263	351	112	184
Rb	108.9	7.46	28.34	51.68	46.58	54.32	44.91	53.79	53.79	13.87	25.28	27.44	14.4	3.36	10
Sr	90.34	501	413	454	476	425	466	428	428	482	491	470	554	477	686
Ta	0.462	0.98	0.28	0.40	0.38	0.43	0.34	0.36	0.18	0.24	0.20	0.23	0.20	0.10	0.1
Nb	3.34	0.94	4.06	5.48	5.28	6.41	14.24	4.32	2.67	3.42	2.6	2.97	2	1.43	1.24
Hf	3.78	1.09	2.9	6.36	6.4	5.13	3.74	4.14	3.15	3.02	2.91	2.68	2.11	1.61	1
Zr	113.7	37.31	97.18	231.3	234.5	172.3	133.4	142.1	102.1	106.7	97.4	95.13	74.69	55.45	44
Y	11.5	11.9	23.6	21.8	26.1	25.5	17.6	18.1	27	26.4	12.4	14.4	7.3	17.4	13
Th	7.18	0.38	4.05	6.09	5.34	7.54	5.53	7.03	9.72	2.93	5.31	4.58	3.02	0.63	1
La	10.79	5.63	16.07	16.58	18.81	21.02	17.11	17.39	11.25	15.58	12.11	12.25	13.42	5	5.22
Ce	20.57	12.14	32.8	34.24	40.42	42.77	33.5	34.86	24.65	33.26	24.15	24.71	22.85	11.65	12.17
Pr	2.018	1.47	3.63	3.73	4.44	4.70	3.42	3.60	3.05	3.76	2.52	2.63	2.08	1.42	2
Nd	8.56	7.65	17.8	16.9	20.9	21.2	16.2	16.2	15.9	18.4	11.3	12.6	8.8	8.17	8.72
Sm	1.98	2.08	4.52	4.13	5.06	5.04	3.54	3.62	4.64	4.79	2.69	2.84	1.78	2.35	2.19
Eu	0.875	0.77	1.19	1.08	1.14	1.20	1.01	0.98	1.21	1.35	0.71	0.88	0.64	0.88	0.94
Gd	1.94	2.11	4.58	4.34	4.97	5.25	3.68	3.66	4.39	4.86	2.65	2.86	1.81	2.73	2.05
Tb	0.29	0.37	0.77	0.69	0.81	0.81	0.54	0.61	0.65	0.82	0.41	0.46	0.23	0.5	0.39
Dy	1.84	2.08	4.28	3.94	4.51	4.52	3.09	3.13	4.96	4.62	2.15	2.71	1.34	3.13	2.46
Ho	0.4	0.45	0.89	0.79	0.9	0.88	0.61	0.64	1.02	0.88	0.44	0.52	0.26	0.61	0.44
Er	1.35	1.32	2.62	2.38	2.83	2.72	1.87	1.95	2.86	2.66	1.39	1.61	0.8	1.93	1.26
Tm	0.224	0.17	0.36	0.35	0.40	0.37	0.27	0.28	0.41	0.39	0.21	0.22	0.13	0.27	0.16
Yb	1.73	1.32	2.84	2.58	2.84	2.71	1.96	2.03	2.97	2.56	1.47	1.61	0.87	1.89	1.47
Lu	0.298	0.23	0.42	0.41	0.44	0.42	0.33	0.34	0.47	0.42	0.22	0.28	0.16	0.31	0.2

The un-zoned plagioclases are more calcic in the lava flows (bytownite-anorthite) than in other subvolcanic rocks (labradorite-andesine). The latter, however, is a more differentiated member. These results are similar to those of Ewart (1982), which demonstrate the predominance of bytownite in low-K and calc-alkaline basalts, and the high An content in basalt plagioclases characteristic of island-arc basalts (IAB). According to Ewart (1982), chrysotile is common in low-K and calc-alkaline basalts.

Plagioclases in the intrusive rocks are more sodic than those in the volcanic rocks, which is normal in more evolved rocks.

In the volcanic rocks, the behavior of immobile trace elements such as Zr, Ce, REE and Y is similar for the samples from the two islands. In the intrusive rocks, these elements are more evolved. Considering that the LILEs in the volcanic rocks at FPt are higher than those in the FP (while HFSE show a similar behavior), it can be said that the volcanic rocks in the FP are less evolved.

The enrichment of LREE in relation to HREE is probably due to partial melting in the mantle, with a La/Yb_N ratio showing values suggestive of a slight migration from NE (the FP) to SW (FP) during the evolution of the magmatic event. This may be due to differences in the depth of the subducting plate, and/or to different degrees of crustal contamination. The Eu/Sm ratios above 0.244 suggest differentiation at shallower depths. The negative La/Cr ratio suggests that the rare earth element content was controlled by clinopyroxene fractionation (Almeida et al. 2000).

The higher LILE content in relation to HFSE suggests either metasomatism of the mantle source, with transfer of LILE from the

lithospheric plate and/or sediments to the ocean floor (Machado et al. 1998), or a significant fractionation of HFSE elements, abundant during the initial phase of the magma. The negative Nb, Ti and P anomalies may be attributed to the presence of a residual phase with rutile, titanite, apatite, ilmenite or perovskite during partial melting (McCulloch and Gamble 1991).

The initial Sr ratios (0.703373-0.703836) suggest a mantle source for the magma, with no crustal contamination and the similar and positive values for eNd confirms the juvenile origin of the magma. The relative increase in eNd from FPt to the FP may reflect heterogeneity of the mantle wedge, or alternatively it may be the result of differences in the melting rate. The similarity between the rocks from FPt and from FP can be also demonstrated through the Pb isotopic ratios. All the rocks are classified as Pacific MORB, according to the Pb²⁰⁸/Pb²⁰⁴ versus Pb²⁰⁶/Pb²⁰⁴ behavior.

Reported ages for the volcanic rocks in the FP (52 Ma Li and Liu 1991, Li 1994) and Greenwich Island, (51.6 ± 1.4 Ma Fenterseifer et al 1991) suggest that this volcanic event has taken place in the Early Eocene. Along with the stratigraphic, geochemical and isotopic data, they suggest that the studied rocks formed from a similar magma source and have undergone similar processes in both islands, which could also suggest that these rocks are co-genetic.

In conclusion, the geochemical and isotopic signature indicates that volcanism at Greenwich Island preceded the plutonism, therefore confirming the field observations, and the probable co-genetic origin. The magma was initially expressed extrusively (from

northeast to southwest), and later, intrusively. It represents a calc-alkaline manifestation generated through the melting of metasomatized mantle material, with no crustal contamination, rich in LREE and LILE, in an island arc environment.

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Figure 5 - Bivariate diagrams of Zr versus Nb, La and Lu, showing the positive correlation between these parameters, which confirms the most evolved character of the intrusives rocks. Symbols as in figure 4.

Figure 6 - Bivariate diagrams of Rb versus K₂O (a) and Ce versus La (b), showing the positive correlation between these elements, which also shows the most evolved character of the intrusives rocks. Symbols as in figure 4.

Figure 7 - Chondrite-normalized REE diagram (Nakamura 1977) that shows the calc-alkaline pattern of the rocks, as well as an enrichment in LREE related to HREE. (a): Fort Point, according to Almeida et al. 2000 and (b): Fildes Peninsula. Symbols as in figure 4.

Figure 8 - Multi-element spider diagrams. Normalized values from Sun & McDonough (1989), showing a similar pattern for all the rocks. (a): Fort Point according to Almeida et al. 2000 and (b): Fildes Peninsula. Symbols as in figure 4.

Figure 9 - a) AFM diagram, according to Irvine & Baragar (1971). The rocks of Fort Point and Fildes Peninsula have a typically calc-alkaline pattern and some samples from Fildes Peninsula show a tholeiitic pattern; b) Zr x Y diagram of McLean & Barret (1993), showing the calc-alkaline character of the rocks from Fort Point and Fildes Peninsula; c) Wood's (1983) diagram of tectonic discrimination showing that these rocks were generated in a destructive plate margin zone. A: N-MORB; B: E-MORB and tholeiitic WPB and differentiates; C: Alkaline WPB and differentiates; D: destructive plate-margin basalts and differentiates. Symbols as in figure 4.

Figure 10 - Pb^{206}/Pb^{204} versus Pb^{208}/Pb^{204} diagram. Fields for other arcs in the area are shown for comparison. The studied rocks belong to the Pacific MORB field.

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