Isotope age constraint for the Blue Dyke and Jardine Peak subvertical intrusions of King George Island, West Antarctica

Magdalena PAŃCZYK[1,2], Jerzy NAWROCKI[1,2] and Ian S. WILLIAMS[3]

[1]*Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy, Rakowiecka 4, 00-975 Warszawa, Poland <magdalena.panczyk@pgi.gov.pl> <jerzy.nawrocki@pgi.gov.pl>*

[2]*Zakład Biologii Antarktyki, Polska Akademia Nauk, Ustrzycka 10/12, 02-141 Warszawa, Poland*

[3]*Research School of Earth Sciences, Building 61, ANU College of Physical Sciences, The Australian National University, Canberra ACT 0200, Australia*

Abstract: The Blue Dyke and Jardine Peak are subvertical hypabyssal intrusions cutting a stratiform volcanic sequence in the Admiralty Bay area on King George Island (South Shetlands, Antarctica). The rocks are porphyritic, crystal-rich basaltic andesites. Tiny zircon crystals were used for single grain SHRIMP U-Pb dating. The mean ages calculated for the zircon populations from both intrusions indicates Late Oligocene (Chattian) formations. Zircon grains from the Blue Dyke gave the mean age of 27.9±0.3 Ma, whereas those from the Jardine Peak are slightly younger displaying the mean age of 25.4 ± 0.4 Ma: a Late Oligocene (Chattian) crystallization age the inferred of both these intrusions. These are much younger than previous Eocene K-Ar and Ar-Ar ages for such rocks and suggest that formation of the King George Island intrusions can be related to tectonic processes that accompanied the opening of the Drake Passage.

Key words: Antarctica, King George Island, Late Oligocene, U-Pb SHRIMP dating.

Introduction

The South Shetland Islands magmatic arc was formed after Gondwana break-up, during the subduction of the Phoenix Plate beneath the Antarctic Plate. This process commenced during the latest Jurassic in the northeastern part of the archipelago and during the earliest Cretaceous in the southwestern part and lasted until middle Miocene times (Pankhurst and Smellie 1983; Willan and Kelley 1999). The opening of the Drake Passage between South America and the Antarctic Peninsula took place during the Oligocene (Barker and Burrell 1977; Lawver *et al.* 1992). The archipelago was separated from the Antarctic Peninsula during the formation of the Bransfield Strait and the development of a back-arc basin presumably in the Plio-
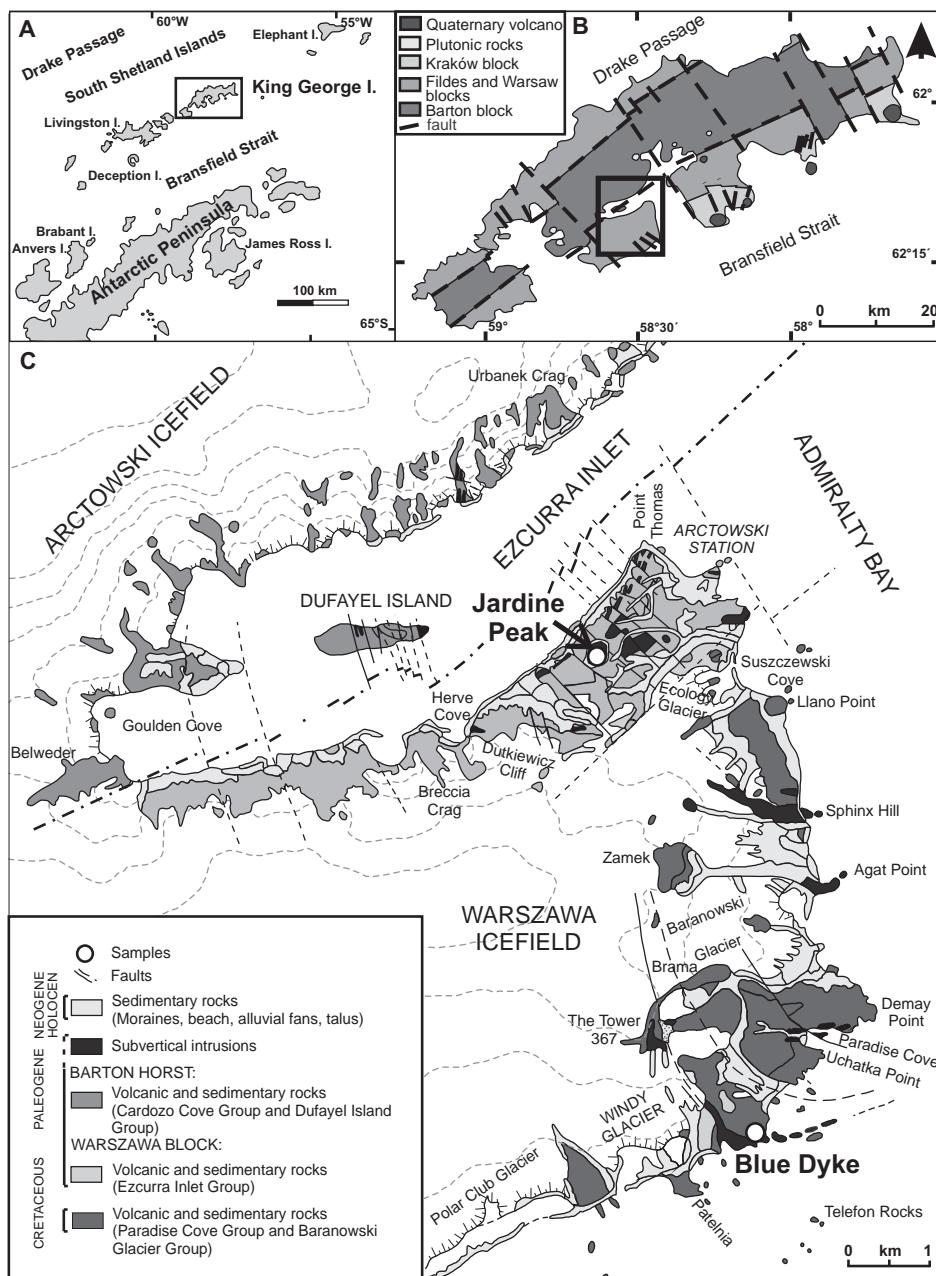
Fig. 1. **A**. Location of King George Island in the South Shetland Islands Archipelago. **B**. The study area shown on a tectonic map with structural units after Birkenmajer (1983). **C**. Location of the Blue Dyke and Jardine Peak on a geological map of the Warszawa Block *sensu* Birkenmajer (1983, 2002).

cene (Barker 1982; Barker and Dalziel 1983). King George Island located in the middle of the volcanic arc, is the largest of the South Shetland Islands. The

Fig. 2. Photographs of the subvertical intrusions. **A**. Blue Dyke **B**. Jardine Peak.

volcanogenic sequence (mostly basaltic and andesitic rocks with terrestrial sedimentary intercalations) is cut by numerous hypabyssal dykes and plugs (Birkenmajer 2001, 2003). The age of magmatic rocks from King George Island is still poorly constrained. Many of volcanic rocks, as well as the hypabyssal intrusions from King George Island have been dated using whole-rock K-Ar and Ar-Ar methods (*e.g.* Watts 1982; Birkenmajer *et al.* 1983, 1986, 2005; Smellie *et al.* 1984, 1998; Willan and Armstrong 2002; Kraus 2005; Kraus *et al.* 2007; Kraus and del Valle 2008).

The whole-rock K-Ar age of the Jardine Peak (54.2±1.1 Ma; Birkenmajer *et al.* 1986) pointed to a Paleocene/Eocene time of formation of intrusion. More recently, detailed investigations of magmatic dykes from the Livingston, Nelson, King George and Penguin Islands were conducted by Kraus (2005), Kraus and del Valle (2008) and Kraus *et al.* (2007, 2008). Following petrographic and (isotope-) geochemical analyses, these authors determined Ar-Ar ages on plagioclase mineral separates of eighteen dykes in the South Shetland Islands, among them three dykes from the Admiralty Bay area: Agat Point, Sphinx Hill and Komandor Peak. The results suggest a Lutetian age for the Sphinx Hill- and Komandor Peak dykes (47.09 ± 0.56 Ma and 45.41 ± 0.61 Ma, respectively). The Agat Point dyke is the oldest investigated intrusion and yielded a Ypressian age (54.00 ± 1.5 Ma). Based on these and other Ar-Ar ages obtained from dykes elsewhere in the island, the au-

thors (Kraus 2005; Kraus *et al.* 2007) concluded that the majority of dykes on King George Island intruded during the Eocene, and emphasized that there are no dyke intrusions younger than 45 Ma in this area.

The Blue Dyke forms one of the most impressive subvertical intrusion exposures on the south-eastern coast of King George Island (Figs 1, 2a), and continues as a set of small islands inside Bransfield Strait, whereas the Jardine Peak intrusion is exposed on the south coast of Ezcurra Inlet as a steeply dipping, columnar-jointed intrusive rock. Both of these hypabyssal intrusions are attributed to the Admiralty Bay Group *sensu* Birkenmajer (1980, 2003), which is subdivided into five informal units of formation rank. The Blue Dyke belongs to the "Sphinx Hill Dykes" unit cutting the Late Cretaceous stratiform volcano-sedimentary complex (Paradise Cove Group; Birkenmajer 1980; Birkenmajer *et al.* 1981), whereas the second intrusion is included in the "Jardine Peak Plugs" unit intruded into a volcanic rocks of the Arctowski Cove Formation. There are only whole-rock K-Ar ages of 54.2 ± 1.1 Ma for the Jardine Peak rocks (Birkenmajer *et al.* 1986), suggesting a Paleocene/Eocene boundary age of the intrusion.

Knowledge of the age of magmatic events is crucially important for reconstruction of tectonic evolution and understanding of the magmatic processes. Thus, the main aim of this study is to precisely define the ages of the spectacular Blue Dyke and the Jardine Peak intrusions which cut the volcanogenic sequence within the Warszawa Block *sensu* Birkenmajer (1980). For this purpose U-Pb dating of single zircon grains was performed on a SHRIMP ion microprobe. This is the first application of the SHRIMP technology to the age determination of magmatic rocks on the King George Island.

Petrography

The Blue Dyke and Jardine Peak basaltic rocks are crystal-rich, porphyritic, dark grey rocks, containing *ca* 56% of SiO_2. In the total alkalis versus silica (TAS) classification diagram (Le Maitre *et al.* 1989), both fall within the basaltic andesite field (Fig. 3). They are characterized by porphyritic, rarely glomeroporphyritic, intersertal or intergranular texture.

The basaltic andesite from Jardine Peak (Fig. 4a–d) comprises plagioclase, clinopyroxene and quartz megacrysts that may exceed 12–15 mm in length. The groundmass contains plagioclase, clinopyroxene, titanomagnetite, apatite and zircon crystals and rare anhedral quartz and chlorite crystals (presumably previously glass; Fig. 4d). The plagioclase crystals occur as euhedral and subhedral phenocrysts showing zoning and resorption (Fig. 4a–b) which sporadically form glomerocrysts, and as small (less than 0.5 mm in length), irregularly- and randomly-orientated laths in the groundmass. These all show chemical zoning. The core and the rims of plagioclase crystals are of bytownite and labradorite composition, respectively. The quartz
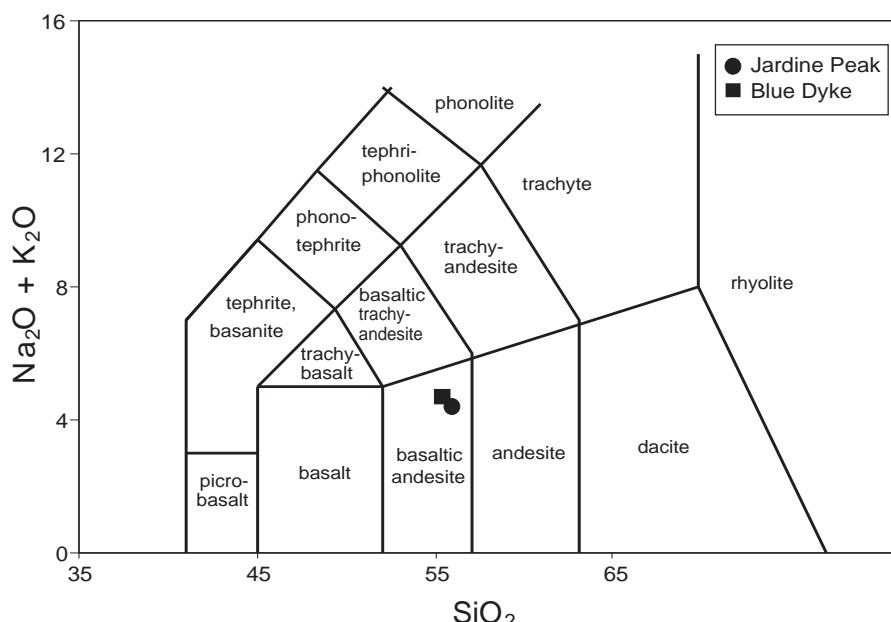
Fig. 3. Chemical classification of the hypabyssal rocks on the total alkalis versus silica (TAS) diagram of Le Maitre *et al.* (1989).

megacrysts commonly show the effects of resorption (Fig. 4c). Unbroken crystals are embayed, partly rounded and surrounded by a reaction rim of minute rod-shaped clinopyroxenes. The presence of partially resorbed quartz xenocrysts in a basaltic andesite groundmass most probably indicates contamination by crustal materials.

In contrast, the Blue Dyke basaltic andesite (Fig. 4e–h) is much more altered, which could be explained by hydrothermal activity related to the intrusion. The Blue Dyke rocks comprise a slightly different paragenesis of minerals. The phenocrysts are mostly plagioclase (Fig. 4e) and rarely clinopyroxene (Fig. 4f). The altered groundmass contains plagioclase laths, very small crystals of apatite, zircon, magnetite, ilmenite, titanomagnetite and anhedral quartz (Fig. 4h). Neither quartz xenocrysts nor small clinopyroxene crystals are observed within the groundmass. Both plagioclase generations (phenocrysts and groundmass laths) are altered (albite, calcite, chlorite), with relicts of primary chemical composition which were identified as bytownite (core) and labradorite (rims). Zircons and apatite occur as tiny crystals within the groundmass and also as inclusions within magnetite grains (Fig. 4g).

Methods and samples

The samples of the Blue Dyke and Jardine Peak rocks taken for single-grain U-Pb dating were collected from massive and less altered parts of the intrusions.
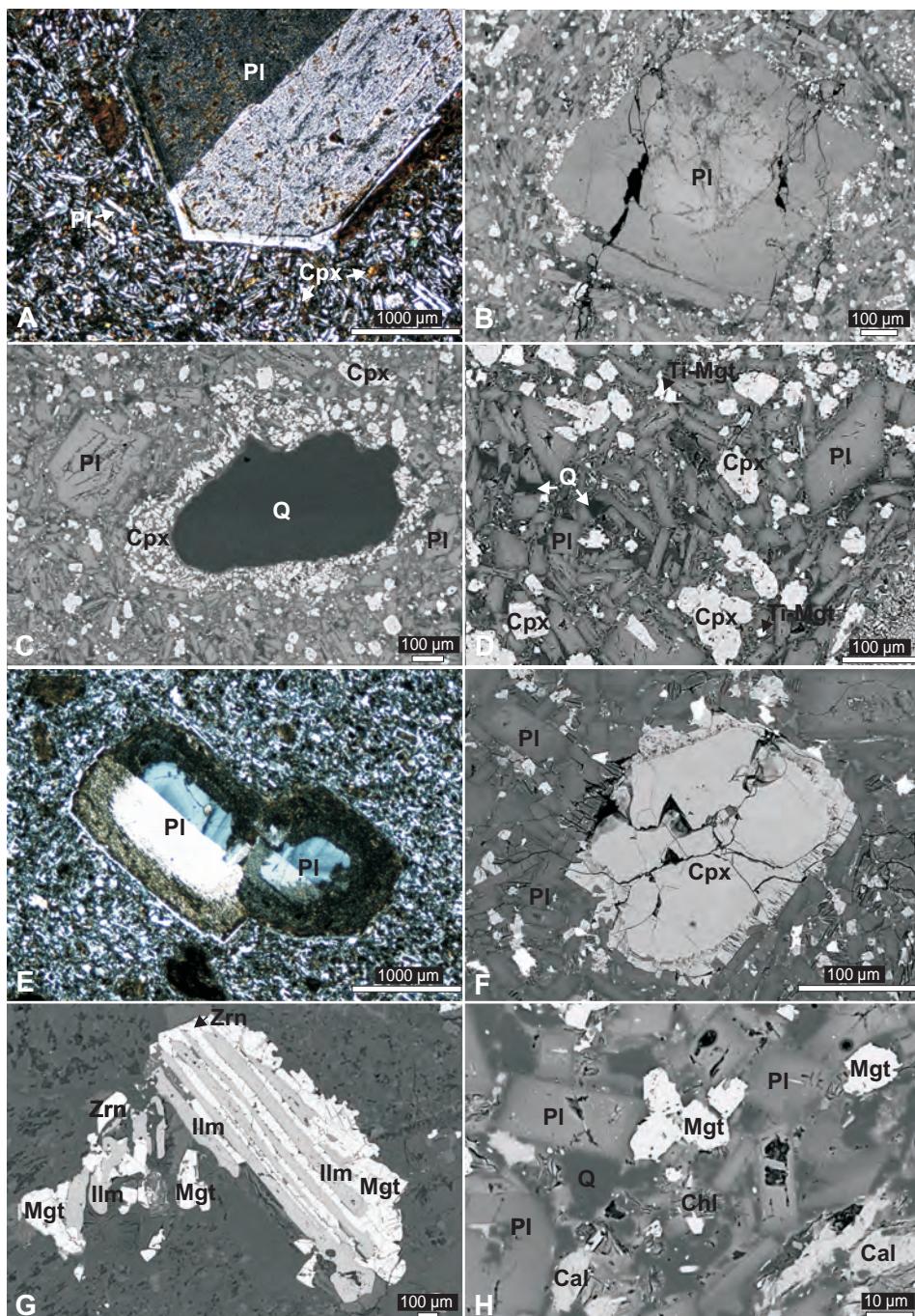
Fig. 4. Microphotographs of Jardine Peak (A–D) and Blue Dyke (E–H) basaltic andesite: **A**. Plagio-clase phenocryst with reaction rim surrounded by the groundmass comprising plagioclase laths, clinopyroxene and titanomagnetite crystals (XN). **B**. BSE image of plagioclase phenocryst with core →
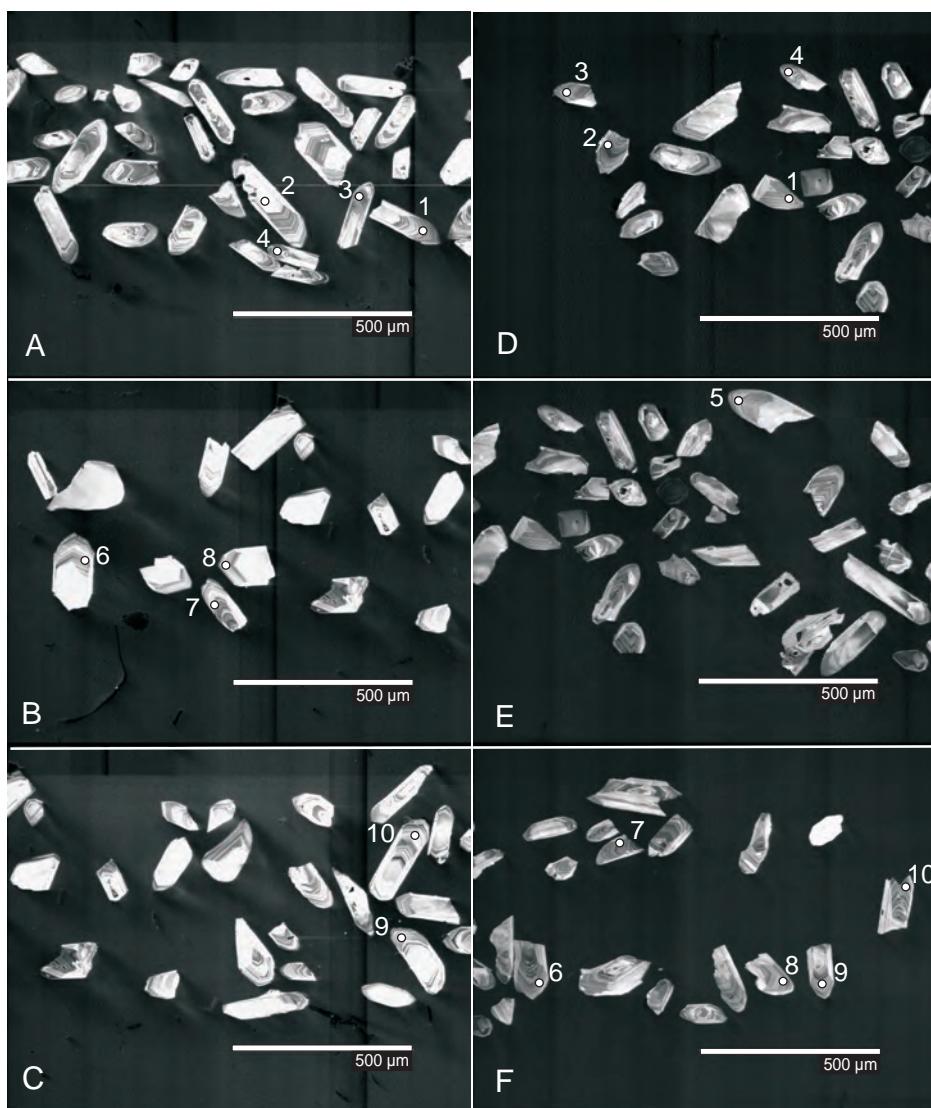
Fig. 5. CL images of zircon crystals with locations of the analyzed spots. a–c zircons from Jardine Peak basaltic andesite; d–f zircons from Blue Dyke basaltic andesite.

of bytownite and rim of labradorite. **C**. BSE image of rounded quartz xenocrysts surrounded by clinopyroxenes. **D**. BSE image of the groundmass. **E**. Plagioclase phenocryst with reaction rim surrounded by altered groundmass comprising plagioclase laths and tiny magnetite crystals (XN). **F**. BSE image of clinopyroxene phenocryst. **G**. paragenesis of accessory minerals occurring within the groundmass (magnetite, ilmenite and zircons). **H**. BSE image of altered groundmass containing plagioclase and magnetite crystals with quartz, chlorite and calcite occurring between the crystals. Mineral symbols after Kretz (1983): Cal – calcite; Chl – chlorite; Cpx – clinopyroxene; Ilm – ilmenite; Mgt – magnetite; Pl – plagioclase; Q – quartz; Ti-Mgt – titanomagnetite; Zrn – zircon.
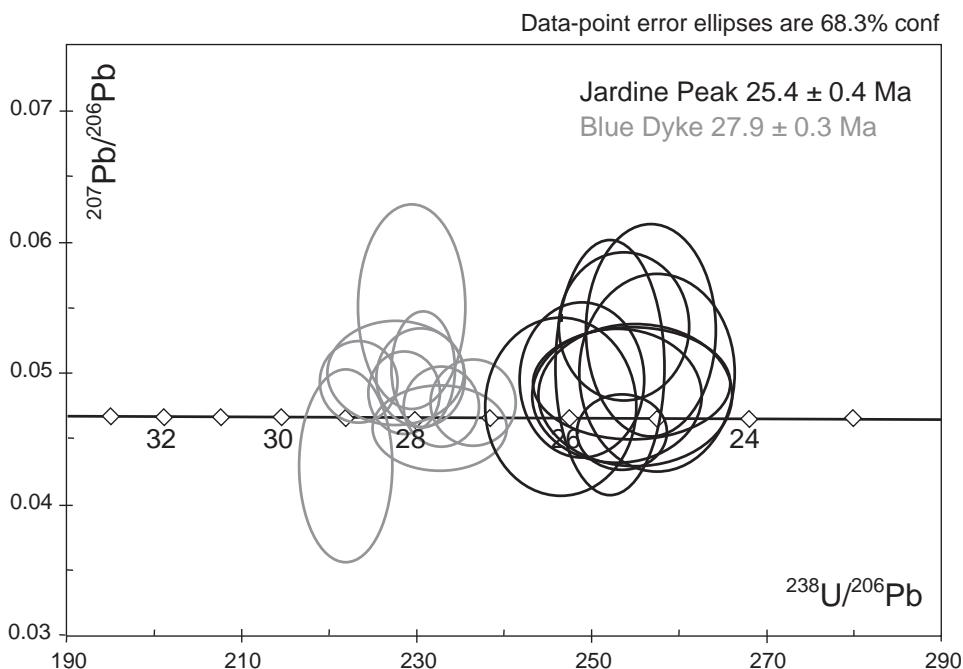
Fig. 6. Tera-Wasserburg concordia diagram for zircon grains from Blue Dyke and Jardine Peak rocks.

The eight-kilogram samples were crushed and sieved after thorough examination of thin sections on a LEO electron microprobe in the Polish Geological Institute (Warsaw). The heavy mineral fractions were separated using conventional heavy liquid and magnetic separation techniques. Zircon grains were hand picked from the concentrates using a petrographic microscope. All selected crystals were mounted in epoxy with zircon standards, polished and documented by transmitted- and reflected light microscopy as well as imaged in cathodoluminescence (CL) using the *Hitachi* S-2250N SEM. Cathodoluminescence images were used to characterize each grain in terms of size, morphology and internal structure. Following CL examination, ten zircon grains from each population were chosen for single-grain U-Pb dating. Isotope analyses were performed using the SHRIMP II ion microprobe at the Research School of Earth Sciences, Australian National University, Canberra. Sri Lankan zircon standard SL13, and procedures based on those described by Williams and Cleasson (1987), were used. The samples were analyzed under the following conditions: the primary ion beam ($10 \, kV \, O_2^-$) was focused to a *ca* 25 μm diameter spot; the mass resolution was *ca* 5000 R; the isotopic species were determined by ion counting using single electron multiplier and cyclic peak stepping. The obtained date were recalculated using the *SQUID Excel Macro* of Ludwig (2000), whereas a Tera-Wasserburg concordia diagram was ploted using the *ISOPLOT/EX* program (Ludwig 2003). Ages were calculated using the con-

stants recommended by the IUGS Subcommission on Geochronology (Steiger and Jäger 1977).

The zircon population from Jardine Peak rocks is very homogenous (Fig. 5a–c). Almost all zircons are generally transparent, pale-coloured and sharply--euhedral prismatic crystals. They range from 80 to 300 μm in length and 40 to 100 μm in width with an average aspect ratio of about 3. Evidences of minor dissolution of the zircon crystals is rare. The zircons recovered from the Blue Dyke rocks (Fig. 5d–f) are a relatively uniform population containing fragments of pale-coloured, prismatic crystals. Only a few zircons have sharp euhedral terminations. Almost all crystals have rounded terminations and/or scalloped faces indicating partial dissolution. They range from 60 to 250 in length and 40 to 80 μm in width with an average aspect ratio of about 3.

Results

The results of our studies are listed in Table 1. The cathodoluminescence images of zircon grains with all spot-analysis locations are shown in Fig. 5. The zircon grains from the Blue Dyke basaltic andesite have moderate U and Th contents (562–1333 ppm and 148–612 ppm, respectively) similar to those of the Jardine Peak rocks (U: 547–1277 ppm; Th: 190–600 ppm). The Th/U ratio is typical of igneous zircons and is slightly lower in zircon grains from the Blue Dyke rocks than from the Jardine Peak, ranging from 0.22 up to 0.46 and from 0.31 to 0.68, respectively. The SHRIMP results are concordant for each population and form two clusters (Fig. 6). The mean age calculated for the zircon grains from the Blue Dyke is 27.9 ± 0.3 Ma, whereas that for the Jardine Peak rocks is slightly younger at 25.4 ± 0.4 Ma. These results are taken to date both magma intrusions as Late Oligocene in age (Gradstein *et al.* 2004).

Discussion

The new zircon isotopic ages presented here constrain the age of crystallization and emplacement of magma to the Late Oligocene (Chattian) in the Admiralty Bay area. Quartz xenocrysts in the Jardine Peak basaltic andesite suggests that the parental melt was contaminated by crustal rocks. However, there is no evidence for inherited zircons. All zircons are euhedral, prismatic crystals without strong evidence of dissolution. On the other hand, zircons separated from Blue Dyke rocks have rounded terminations indicating partial dissolution. Nevertheless, the common occurrence of plagioclase phenocrysts with reaction rims against melt might indicate magma mixing processes. Reaction rims between the dissolving plagioclase crystals and enclosing melt might also reflect their disequilibrium during

Table 1

Results of SHRIMP U-Pb analyses of zircons from Blue Dyke and Jardine Peak rocks

No	Pb ppm	U ppm	Th ppm	Th/U	$^{204}Pb/^{206}Pb$	±	$^{207}Pb/^{206}Pb$	±	$^{208}Pb/^{206}Pb$	±	$^{208}Pb/^{232}Th$	±	$^{206}Pb/^{238}U$	±	$^{207}Pb/^{235}U$	±	f6(7) %	$^{208}Pb/^{232}Th$ (Ma)	±	$^{206}Pb/^{238}U$ (Ma)	±
Jardine Peak																					
1	3	710	457	0.64	4.11E-04	3.45E-04	0.0492	0.0027	0.2108	0.0112	0.00128	0.00008	0.00393	0.00011	0.0267	0.0018	0.30	25.1	1.8	25.2	0.7
2	3	763	264	0.35	9.46E-04	4.94E-04	0.0496	0.0039	0.1271	0.0112	0.00148	0.00013	0.00402	0.00008	0.0275	0.0023	0.33	28.1	3.5	25.8	0.5
3	5	1277	566	0.44	7.22E-04	4.77E-04	0.0455	0.0018	0.1416	0.0064	0.00126	0.00006	0.00395	0.00005	0.0248	0.0011	-0.11	25.9	1.5	25.4	0.3
4	4	889	600	0.67	1.71E-04	1.96E-04	0.0483	0.0034	0.2225	0.0112	0.00130	0.00007	0.00395	0.00010	0.0263	0.0020	0.19	25.8	1.8	25.4	0.7
5	2	547	238	0.43	1.26E-03	8.12E-04	0.0484	0.0036	0.1425	0.0164	0.00129	0.00015	0.00392	0.00011	0.0262	0.0022	0.21	25.2	3.5	25.2	0.7
6	2	600	242	0.40	7.17E-04	7.44E-04	0.0501	0.0050	0.1571	0.0106	0.00151	0.00011	0.00388	0.00009	0.0268	0.0028	0.39	28.8	3.2	24.9	0.6
7	4	830	566	0.68	1.21E-03	7.86E-04	0.0505	0.0064	0.2196	0.0160	0.00128	0.00010	0.00397	0.00006	0.0276	0.0036	0.44	24.6	2.7	25.4	0.5
8	2	604	190	0.31	2.82E-03	1.01E-03	0.0533	0.0053	0.1252	0.0093	0.00155	0.00012	0.00389	0.00007	0.0286	0.0030	0.74	27.2	4.0	24.9	0.5
9	3	650	287	0.44	7.19E-04	5.02E-04	0.0536	0.0037	0.1392	0.0112	0.00124	0.00010	0.00394	0.00008	0.0291	0.0022	0.77	22.0	2.6	25.2	0.5
10	3	708	266	0.38	2.27E-03	1.10E-03	0.0475	0.0045	0.1355	0.0102	0.00146	0.00011	0.00405	0.00009	0.0266	0.0027	0.11	29.0	3.3	26.1	0.6
Blue Dyke																					
1	2	562	148	0.26	1.36E-03	8.13E-04	0.0551	0.0052	0.1103	0.0085	0.00183	0.00015	0.00436	0.00008	0.0331	0.0033	0.94	30.0	5.1	27.8	0.5
2	5	1006	453	0.45	7.38E-04	7.12E-04	0.0485	0.0021	0.1462	0.0064	0.00142	0.00006	0.00438	0.00005	0.0293	0.0013	0.22	27.7	1.6	28.1	0.3
3	4	914	230	0.25	1.12E-03	5.46E-04	0.0494	0.0021	0.0819	0.0074	0.00146	0.00013	0.00448	0.00006	0.0305	0.0014	0.31	27.0	3.3	28.7	0.4
4	4	867	285	0.33	1.99E-04	1.67E-04	0.0458	0.0022	0.1045	0.0091	0.00137	0.00012	0.00430	0.00009	0.0272	0.0015	-0.08	28.1	2.9	27.7	0.6
5	3	727	180	0.25	2.00E-05	2.00E-05	0.0430	0.0049	0.0819	0.0124	0.00149	0.00023	0.00451	0.00007	0.0267	0.0031	-0.39	33.3	6.4	29.1	0.5
6	6	1333	612	0.46	9.52E-04	5.06E-04	0.0504	0.0029	0.1466	0.0064	0.00138	0.00006	0.00434	0.00005	0.0301	0.0018	0.42	26.2	1.8	27.8	0.3
7	4	999	432	0.43	2.01E-03	8.54E-04	0.0478	0.0022	0.1427	0.0087	0.00140	0.00009	0.00423	0.00006	0.0279	0.0014	0.14	27.6	2.1	27.2	0.4
8	3	773	171	0.22	1.66E-03	7.17E-04	0.0497	0.0025	0.0767	0.0061	0.00151	0.00012	0.00434	0.00006	0.0297	0.0016	0.35	27.4	3.4	27.8	0.4
9	5	1220	364	0.30	3.29E-04	2.33E-04	0.0474	0.0020	0.1020	0.0057	0.00147	0.00008	0.00430	0.00005	0.0281	0.0013	0.10	29.1	2.2	27.6	0.3
10	4	857	294	0.34	3.16E-05	6.59E-05	0.0500	0.0026	0.1135	0.0131	0.00145	0.00017	0.00440	0.00010	0.0303	0.0018	0.38	27.2	3.8	28.2	0.7

* Corrected for common Pb using $^{207}Pb/^{206}Pb$, assuming the common Pb to be laboratory-derived surface contaminants $^{204}/^{206} = 0.0625$, $^{207}/^{206} = 0.9618$. $^{208}/^{206} = 2.229$; f6(7)% – percentage of total ^{206}Pb that is common ^{206}Pb, estimated from the measured $^{207}Pb/^{206}Pb$ by assuming concordance. Analytical uncertainties 1σ precision estimates.

magma ascent. It should be stressed that the isotope ages determined for the rims and cores of the zircon grains are similar. Previous K-Ar ages for Jardine Peak suggested older age of emplacement (54.2 ± 1.1 Ma; Birkenmajer *et al.* 1986). Such substantial discrepancy between U-Pb single zircon grain and whole-rocks K-Ar ages might be the effect of inherited Ar.

The tectonic rearrangement that accompanied the opening of Drake Passage took place between 50 and 20 Ma (Barker and Burrell 1977; Lawver *et al.* 1992; Livermore *et al.* 2005). The first, Eocene stage of this process was constrained to the opening of small oceanic basins, with the probable formation of a shallow gateway only, because the oldest sea floor within Drake Passage is evidently younger than 34–30 Ma (Livermore *et al.* 2005). The sea floor formation due to spreading at the West Scotia Ridge led to further opening of the Drake Passage and formation of a deep gateway by the Middle Oligocene. By the Late Oligocene the tectonic regime was changed and W-E spreading on South American – Antarctic Ridge started to be prevailing (Livermore *et al.* 2005). It is possible that the generation of the basaltic magmas that were emplace as the hypabyssal intrusions on King George Island were related just to this phase of tectonic processes forming the Drake Passage.

Conclusions

- The Blue Dyke and Jardine Peak subvertical intrusions on King George Island contain zircon crystals that are precisely dated using single-grain U-Pb SHRIMP dating.
- This first reconnaissance to apply the SHRIMP dating method to the magmatic rocks on the King George Island appears to have been successful. The Blue Dyke and Jardine Peak intrusions were emplaced during the Late Oligocene (Chattian).
- The intrusions on King George Island are coeval with the tectonic processes that occurred during the younger stages of opening of the Drake Passage between South America (Tierra del Fuego) and the Antarctic Peninsula when W-E spreading on South American – Antarctic Ridge began to dominate.
- Our new results indicate that precise dating of volcanic and hypabyssal rocks from the still tectonically active area of the South Shetland Islands is possible.

References

BARKER P.F. 1982. The Cenozoic subduction history of the Pacific margin of the Antarctic Peninsula: ridge crest-trench interactions. *Journal of Geological Society of London* 139: 787–801. doi:10.1144/gsjgs.139.6.0787

BARKER P.F. and BURRELL J. 1977. The opening of Drake Passage. *Marine Geology* 25: 15–34. doi:10.1016/0025-3227(77)90045-7

BARKER P.F. and DALZIEL I.W.D. 1983. Progress in geodynamics in the Scotia Arc region. *In*: R. Cabre (ed.) Geodynamics of the Eastern Pacific Region, Caribbaen and Scotia Arcs. *Geodynamics Series* 9: 137–170.

BIRKENMAJER K. 1980. A revised lithostratigraphic standard for the Tertiary of King George Island, South Shetland Islands (West Antarctica). *In*: K. Birkenmajer (ed.) Geological results of the Polish Antarctic expeditions. Part I. *Studia Geologica Polonica* 64: 7–65.

BIRKENMAJER K. 1983. Late Cenozoic phases of block-faulting on King George Island (South Shetland Islands, West Antarctica). *Bulletin of the Polish Academy of Sciences: Earth Sciences* 30: 21–32.

BIRKENMAJER K. 2001. Mesozoic and Cenozoic stratigraphic units in parts of the South Shetland Island and northern Antarctic Peninsula (as used by the Polish Antarctic Programmes). *In*: K. Birkenmajer (ed.) Geological results of the Polish Antarctic expeditions. Part XIII. *Studia Geologica Polonica* 118: 1–188.

BIRKENMAJER K. 2002. Admiralty Bay, King George Island, South Shetland Islands, West Antarctica. Geological map and Cross-sections 1 : 50,000. Department of Antarctic Biology PAS, Warszawa.

BIRKENMAJER K. 2003. Admiralty Bay, King George Island (South Shetland Islands, West Antarctica): A geological monograph. *In*: K. Birkenmajer (ed.) Geological results of the Polish Antarctic expeditions. Part XIV. *Studia Geologica Polonica* 120: 1–75.

BIRKENMAJER K., NARĘBSKI W., SKUPIŃSKI A. and BAKUN-CZUBAROW N. 1981. Geochemistry and origin of the Tertiary Island-arc volcanics suite at Admiralty Bay, King George Island (South Shetland Islands, West Antarctica). *In*: K. Birkenmajer (ed.) Geological results of the Polish Antarctic expeditions. Part II. *Studia Geologica Polonica* 72: 7–57.

BIRKENMAJER K., NARĘBSKI W., NICOLETTI M. and PETRUCCIANI C. 1983. Late Cretaceous through Late Oligocene K-Ar ages of the King George Island Supergroup volcanic, South Shetland Islands (West Antarctica). *Bulletin of the Polish Academy of Sciences: Earth Sciences* 30: 133–143.

BIRKENMAJER K., DELITALA M.C., NARĘBSKI W., NICOLETTI M. and PETRUCCIANI C. 1986. Geochronology of Tertiary island arc volcanic and glacigenic deposits, King George Island, South Shetland Islands (West Antarctica). *Bulletin of the Polish Academy of Sciences: Earth Sciences* 34: 257–273.

BIRKENMAJER K., GAŹDZICKI A., KRAJEWSKI K.P., PRZYBYCIN A., SOLECKI A., TATUR A. and YOON H.I. 2005. First Cenozoic glaciers in West Antarctica. *Polish Polar Research* 26: 3–12.

GRADSTEIN F.M., OGG J.G. and SMITH A. 2004. *Geological Time Scale 2004*. Cambridge University Press, Cambridge: 1–589.

KRAUS S. 2005. Magmatic dyke systems of the South Shetland Islands volcanic arc (West Antarctica): reflections of the geodynamic history. Dissertation, LMU Munich: Faculty of Geosciences: 160 pp. http://nbn-resolving.de/urn:nbn:de:bvb:19-38277.

KRAUS S. and DEL VALLE R.A. 2008. Geology, tectonics and Ar-Ar ages of the magmatic dykes from Potter Peninsula (King George Island, South Shetland Islands). *In*: C. Wiencke, G.A. Ferreyra, D. Abele and S. Marenssi (eds) The Antarctic Ecosystem of Potter Cove, King-George Island (Isla 25 de Mayo): Synopsis of Research performed 1999–2006 at the Dallmann Laboratory and Jubany Station. *Reports on Polar and Marine Research, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven* 571: 20–30.

KRAUS S., McWILLIAMS M. and PECSKAY Z. 2007. New 40Ar/39Ar and K/Ar ages of dikes in the South Shetland Islands (Antarctic Peninsula). *In:* A.K. Cooper and C.R. Raymond (eds) *Antarctica: A Keystone in a Changing World* – Online Proceedings of the 10th ISAES, USGS Open-File Report 2007-1047, Short Research Paper 035, p. 3.

KRAUS S., MILLER H., DIMOV D., HEGNER E., McWILLIAMS M. and PECSKAY Z. 2008. Structural geology of the Mesozoic Miers Bluff Formation and crosscutting Paleogene dikes (Livingston Island, South Shetland Islands, Antarctica) – Insights into geodynamic history of the northern Antarctic Peninsula. *Journal of South American Earth Sciences* 26: 498–512. doi:10.1016/j.jsames.2008.08.009

KRETZ R. 1983. Symbols for rock-forming minerals. *American Mineralogist* 68: 277–279.

LAWVER L.A., GAHAGAN L.M. and COFFIN M.F. 1992. The development of paleoseaways around Antarctica. *American Geophysical Union Publication. Antarctic Research Series* 56: 7–30.

Le MAITRE R.W., BATEMAN P., DUDEK A., KELLER J., LAMEYRE J., LE BAS M., SABINE P.A., SCHMID R., SORENSEN H., STRECKEISEN A., WOOLEY A.R. and ZANETTIN B. 1989. *A classification of igneous rocks and glossary of terms. Recomendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks.* Blackwell, Oxford, 1–193.

LIVERMORE R., NANKIVELL A., EAGLES G. and MORRIS P. 2005. Paleogene opening of Drake Passage. *Earth and Planetary Science Letters* 236: 459–470. doi:10.1016/j.epsl.2005.03.027

LUDWIG K.R. 2000. SQUID 1.00. A User's Manual. *Berkeley Geochronology Center Special Publications* 2.

LUDWIG K.R. 2003. ISOPLOT/EX ver. 3.0. A geochronological toolkit for Microsoft Excel. *Berkeley Geochronology Center Special Publications.* 1a.

PANKHURST R.J. and SMELLIE J.L. 1983. K-Ar geochronology of the South Shetland Islands, Lesser Antarctica: apparent lateral migration of Jurassic to Quaternary island arc volcanism. *Earth Planetary Sciences Letters* 66: 214–222. doi:10.1016/0012-821X(83)90137-1

SMELLIE J.L., PANKHURST R.J., THOMSON M.R.A. and DAVIES R.E.S. 1984. The Geology of the South Shetland Islands: VI. Stratigraphy, Geochemistry and Evolution. *British Antarctic Survey Scientific Reports* 87: 1–85.

SMELLIE J.L., MILLAR I.L., REX D.C. and BUTTERWORTH P.J. 1998. Subaqueous, basaltic lava dome and carapace breccias on King George Island, South Shetland Islands, Antarctica. *Bulletin of Volcanology* 59: 245–261. doi:10.1007/s004450050189

STEIGER R.H. and JÄGER E. 1977. Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology. *Earth Planetary Sciences Letters* 36: 359–362. doi:10.1016/0012-821X(77)90060-7

WATTS D.R. 1982. Potassium-argon ages and palaeomagnetic results from King George Island, South Shetland Islands. *In:* C. Craddock (ed.) *Antarctic Geoscience.* The University of Wisconsin Press, Madison: 255–261.

WILLAN R.C.R. and KELLEY S.P. 1999. Mafic dyke swarms in the South Shetland Islands volcanic arc: unraveling multi-episodic magmatism related to subduction and continental rifting. *Journal of Geophysical Research* 104: 23051–23068. doi:10.1029/1999JB900180

WILLAN R.C.R. and ARMSTRONG D.C. 2002. Successive geothermal, volcanic-hydrothermal and contact-metasomatic events in Cenozoic volcanic-arc basalts, South Shetland Islands, Antarctica. *Geological Magazine* 139: 209–231. doi:10.1017/S0016756802006301

WILLIAMS I.S. and CLEASSON S. 1987. Isotopic evidence for Precambrian provenance and Caledonian metamorphism of high grade paragneisses from the Seve Nappes, Scandinavian Caledonides: II. Ion microprobe zircon U-Th-Pb. *Contribution to Mineralogy and Petrology* 97: 205–217. doi:10.1007/BF00371240