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Geochronology of selected andesitic lavas from the King George Bay area (SE King George Island)

Magdalena PAŃCZYK and Jerzy NAWROCKI

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Volcanic rocks from the Lions Rump area, which are the basement for a sequence of glaciomarine sediments of the Polonez Cove Formation, and lava flows from the Turret Point–Three Sisters Point area were sampled for thermogeochronological and palaeomagnetic investigations. Generally, andesitic lavas from King George Bay area consist mainly of clinopyroxene (Ti-augite) orthopyroxene (hyperstene) and plagioclase phenocrysts. The groundmass comprises mostly plagioclase laths, clinopyroxene, titanomagnetite and rare orthopyroxene crystals. However, the modal content, size, shape and distribution of phenocrysts are variable and specific for each sample. The Ar-Ar plateaus ages calculated for lavas from the Lions Rump area are very homogenous and point to middle Eocene age (Lutetian, ~44.5 Ma). The similar and consistent ages for volcanic basement for that area excluded the thesis about separate tectonic evolution of the Warszawa and Kraków blocks at least since the middle Eocene. The lavas from Turret Point and Three Sister Point are younger and were emplaced during the late Eocene (Bartonian/Priabonian: 37.3 ±0.4 Ma and Priabonian: 35.35 ±0.15 Ma, respectively). The results of isotopic investigations are consistent with magnetic polarities of the rocks indicating that the samples from the Lions Rump area are coeval with the lower part of the C20 polarity chron whereas the sample from Turret Point can be correlated with the upper part of the C17 polarity chron.

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INTRODUCTION

King George Island is the largest island within the South Shetland magmatic arc (Fig. 1A) that was formed after the Gondwana break-up, during the subduction of the Phoenix Plate beneath the Antarctic Plate between the latest Jurassic or earliest Cretaceous and the middle Miocene (Pankhurst and Smellie, 1983; Willan and Kelley, 1999). The opening of Drake Passage between South America and the Antarctic Peninsula started in the Eocene and continued through the Oligocene (Barker and Burrell, 1977; Lawver *et al*., 1992; Livermore *et al*., 2005). The archipelago was separated from the Antarctic Peninsula during the formation of the Bransfield Strait and the developing of a marginal basin presumably in Pliocene time (Barker, 1982; Barker and Dalziel, 1983).

The volcanic processes on King George Island are associated with Phenix Plate subduction, and are coeval with a tectonic rearrangement that accompanied the opening of Drake Passage that took place between 50 and 20 Ma (Barker and Burrell, 1977; Lawver *et al*., 1992; Livermore *et al*., 2005). The oldest known lava flows from King George Island (Paradise Cove) are Upper Cretaceous in age (Birkenmajer *et al*., 1983; Nawrocki *et al*., 2010).

The main aim of this study is to determine the age of the volcanic rocks from the King George Bay area, which occur as the basement for middle to late Oligocene glaciomarine sediments of the Polonez Cove Formation (Birkenmajer, 1982; Troedson and Smellie, 2002). The age of lava flows from that area is poorly constrained. Thus, the combination of thermochronology (whole-rock ^{40}Ar-^{39}Ar dating) and magnetostratigraphy methods was applied.

GEOLOGY OF KING GEORGE BAY AND SAMPLING SITE

King George Island is subdivided into four major tectonostratigraphic units: the axial Barton Horst, the northern

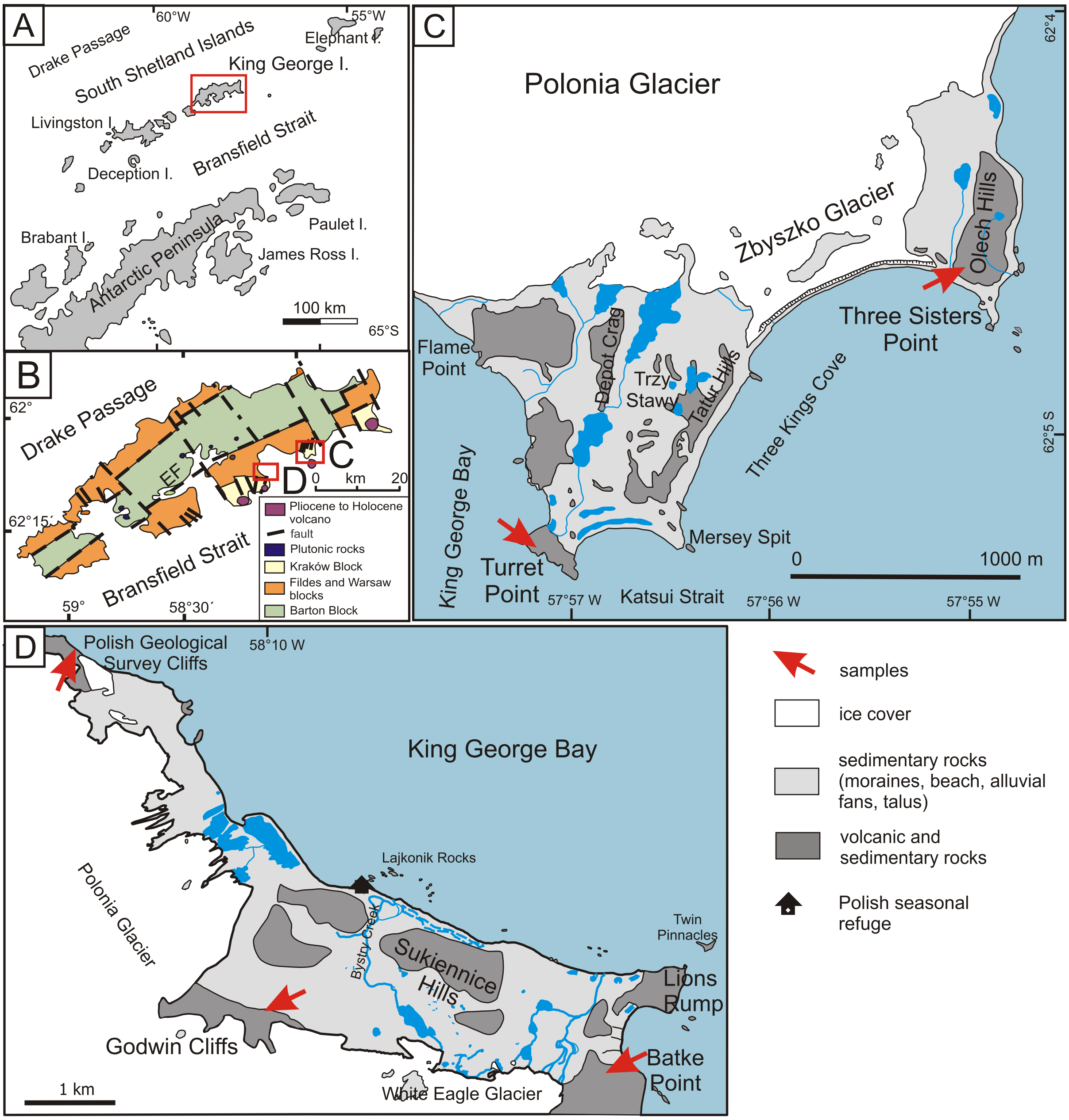

Fig. 1. Location of the study area on King George Island (South Shetland Islands, northern Antarctic Peninsula)

A – location of the King George Island in the South Shetland Islands; **B** – structural units of King George Island (after Birkenmajer, 1983): EF – Ezcurra Fault; **C** – sites of isotopic and palaeomagnetic studies on the background of a geological map of the Turret Point–Three Sisters Point area, King George Island – compilation of a topographic map of Pudełko (2008) and a geological map of Paulo and Tokarski (1982); **D** – sites of isotopic and palaeomagnetic studies on the background of a geological map of the Lions Rump area – compilation of an unpublished topographic map – extent of ice cover (2009) of Angiel (pers. comm.) and a schematic geological map showing approximate extent of exposures of the Polonez Cove Formation by Troedson and Smellie (2002)

Fildes Block. the southern Warszawa Block and the southernmost Kraków Block (Birkenmajer, 1983; Fig. 1B). The studied volcanic rocks are exposed in the southeastern part of the island within the Warszawa and Kraków blocks (Fig. 1 B).

The stratigraphy and field relation of lava flows from the King George Bay area are unclear and very complicated (Fig. 2). The Mazurek Point Formation (lowest part of the Chopin Ridge Group, *sensu* Birkenmajer, 1981) is attributed to the Kraków Block and occurs in the southern part of the Kraków Peninsula and between King George Bay and Sherrat Bay (Turret Point–Three Sister Point). The basaltic and andesitic lavas are the basement for glaciomarine sediments of the Polonez Cove Formation. Additionally, Birkenmajer (1981) introduced a separate unit – the Polonia Glacier Group, for a sequence of volcanic rocks exposed between the Lions Rump and Polonia Glacier (Warszawa Block; Fig. 2A), which is subdivided into the Lions Cove Formation (lower part) and Sukiennice Hills Formation (upper part). However, Troedson

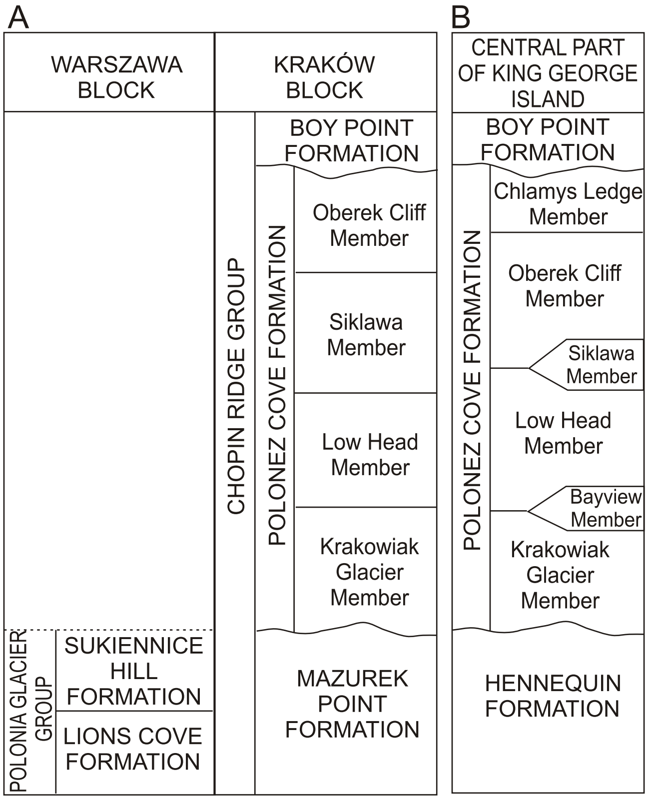

Fig. 2. Generalized lithostratigraphy of volcanic and glaciomarine sedimentary rocks from King George Bay area (A) after Birkenmajer (1982) and (B) after Troedson and Smellie (2002)

and Smellie (2002), as well as previously Smellie *et al.* (1984), do not divide the volcanic sequence into two tectonic blocks (Kraków and Warszawa; Fig. 2B) and described the volcanic basement of the Lions Rump area as the Hennequin Formation which corresponds also to volcanic rocks occurring in the Mount Wawel area (Admiralty Bay). Troedson and Smellie (2002) identified the Polonez Cove Formation within the new outcrop – Godwin Cliff section, which is located to the north-west of glaciomarine sediments described by Birkenmajer (1980, 1982) and by Porębski and Gradziński (1987) and exposed on the coast, south of the Lions Rump and at Mazurek Point.

The age of the volcanic formations is still controversial. Birkenmajer and Gaździcki (1986) suggested a Late Cretaceous age (K-Ar method, ~74 Ma) for andesites of the Mazurek Point Formation, whereas Troedson and Smellie (2002), basing on whole-rock K-Ar age (42 ±0.5 Ma; Smellie *et al*., 1984) and new unpublished Ar-Ar ages, point out that the Mazurek Point Formation is equivalent to the Eocene Hennequin Formation *sensu* Smellie *et al.* (1984). There are only whole-rock K-Ar ages of 34.4 ±0.5 Ma for andesitic lavas from Turret Point (Birkenmajer *et al*., 1989) suggesting a late Eocene age of the extrusions.

The samples were collected for investigations from two areas located on both shores of King George Bay. The following three exposures of lava flows were sampled near the Lions Rump:

- Polish Geological Survey Cliffs (PGS Cliffs)* (Fig. 3A and B; sample PR-3): the new exposure (noted during 2008/2009 summer season) is situated to the north-west of the Polish seasonal refuge. The best outcrops, less altered, are located along the coast, where the massive, steep cliffs (columnar jointed), over 30 m high and about 200 m long, appear. The upper and northern part of the exposure is capped by an ice cover of the Polonia Glacier. The southwestern flank of the new outcrop, situated close to the Polonia Glacier, is strongly altered. The rock is cut by veins and micro-veins infilled by hydrothermal minerals. Thus, the sample for isotopic analysis, as well as for palaeomagnetic investigations was chosen from the northeastern part of the PGS Cliff (S 62°07.059, W 58°10.959; Figs. 1D and 3B);
- Godwin Cliffs (Fig. 3C; sample SK-1): The cliffs are located inland – about three kilometres to the west of the Lions Rump (Fig. 1D). The section was detailed described by Troedson and Smellie (2002), who divided the basal lava flows (Hennequin Fm.), the sequence of glaciomarine sediments interbedded with lava flows (Polonez Cove Fm.), and the lava flows of the Boy Point Fm. within the upper part of the section. The sample taken exclusively for isotopic dating originated from the first lava flow within the western part of the exposure;
- Batke Point (Fig. 3D; sample LR-3): the exposure is located to the south of the Lions Rump (Fig. 1D). The sample was taken from the first lava flow within the Batke Point section. The dark grey, fresh, columnar andesitic lavas are covered by a sequence of tillite, basaltic conglomerate and sandstones of the Polonez Cove Formation (Birkenmajer, 1982). At the top of the exposure are porphyritic lavas of the Boy Point Formation.

The exposures situated on the opposite coast of King George Bay (Turret Point–Three Sisters Point) were thoroughly sampled. The sequence of volcanic rocks from the Turret Point area comprises five andesitic-basaltic lava flows which are cut by volcanic breccias, dykes and a plug, whereas the sequence from the Three Sisters Point area contains andesitic lava flows interbedded with volcaniclastic rocks (agglomerate, tuff and tuffite), regolith and, within the uppermost part, with tillite (Paulo and Tokarski, 1982). We choose least altered, massive andesitic lava flows for isotopic and palaeomagnetic investigation from the following localities:

- Turret Point area: one sample (TR-8) was collected for analyses from the second andesitic lava flows exposed near the cliffs at a small cove of Turret Point (Figs. 1C and 3F).

* we are introducing a new name for the outcrop which has never been described before

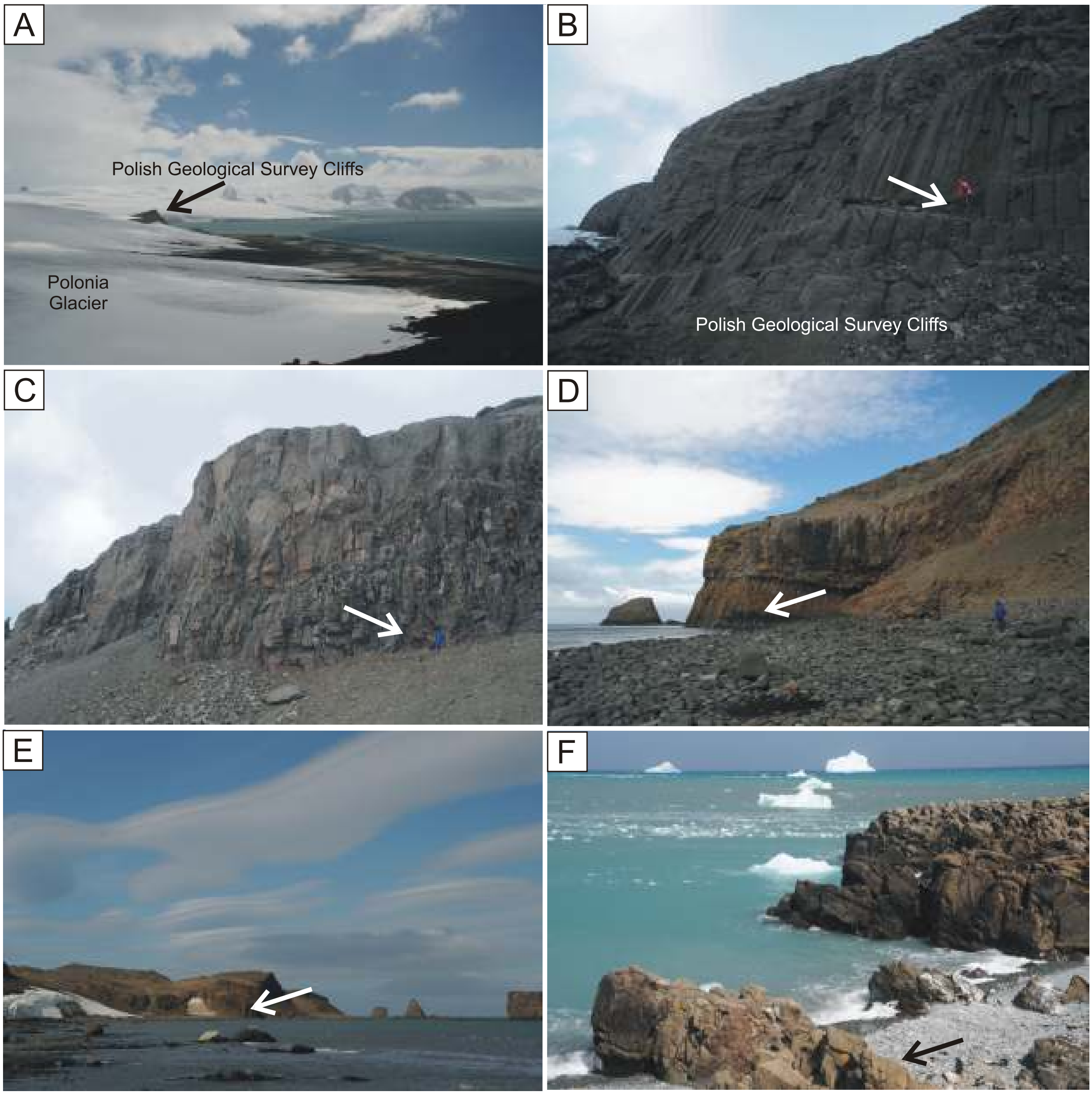

Fig. 3. Photo images of sampling sites

A – Polish Geological Survey Cliff, view towards the Polonia Glacier; **B** – view showing columnar jointed basalts of Polish Geological Survey Cliffs; **C** – bottom part of the Godwin Cliffs section; **D** – panoramic view showing the Batke Point section; **E** – Three Sister Point and Four Brother Rocks, view from the Olech Hills; **F** – cliffs of Turret Point

– Three Sisters Point area (3S5): the andesitic lava flow from the upper part of volcanic rocks (*sensu* Paulo and Tokarski, 1982) was chosen for analyses. The sampled exposure is located at Three Kings Cove close to the Zbyszko Glacier (Figs. 1C and 3E).

PETROGRAPHY

Generally, the dark grey andesitic lavas from the Lions Rump area are massive and crystal-rich rocks and display porphyritic, rarely glomeroporphyric, intersertal (Godwin Cliff and Batke Point) or intergranular (PGS Cliffs) texture. The rocks are characterized by a very similar mineral paragenesis in a different proportion. The modal content, size, shape and distribution of phenocrysts are variable and specific for each sample. The lava flows from the Lions Rump area contain plagioclase, clinopyroxene (Ti-augite) and orthopyroxene (hyperstene) phenocrysts (Fig. 4A and B) that may even exceed 6–7 mm length. The groundmass contains plagioclase and sporadically clinopyroxene, orthopyroxene, titanomagnetite, apatite crystals and, rarely, glass. Plagioclase crystals occur as euhedral and subhedral phenocrysts, which sporadically form glomerocrysts (Fig. 4F), and as small (less than 0.3 mm in length), decussate

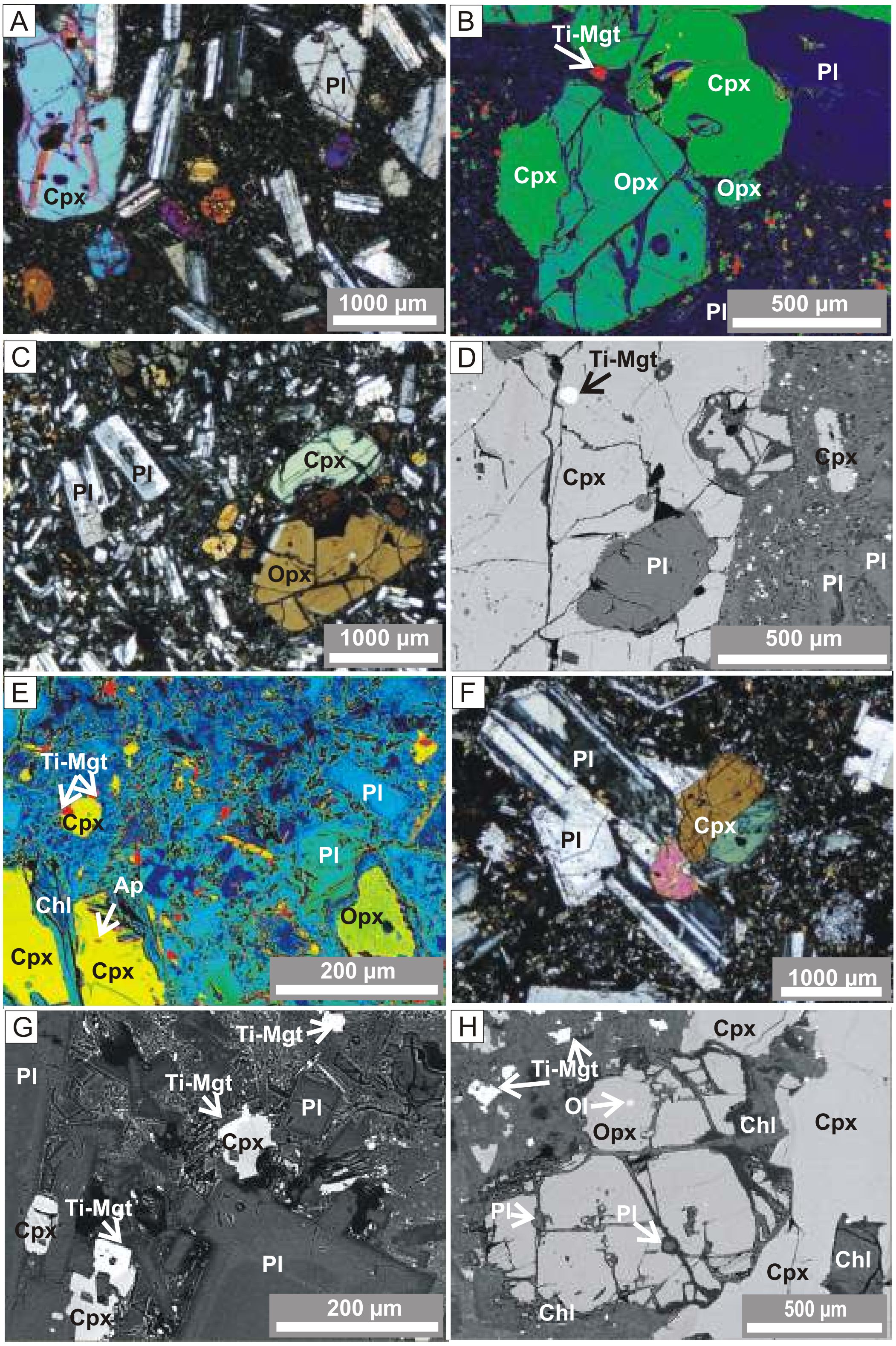

Fig. 4. Photomicrographs of andesitic rocks from the Lions Rump area

A – clinopyroxene and plagioclase phenocrysts surrounded by a groundmass of glass, plagioclase and clinopyroxene crystals, Batke Point (crossed polars); **B** – orthopyroxene (hyperstene) and clinopyroxene (Ti-augite) phenocrysts, Batke Point (BSE – back-scatter electron image in a Quanti color scale); **C** – andesitic lava flow from Godwin Cliffs (crossed polars); **D** – clinopyroxene phenocryst with inclusions of plagioclase and titanomagnetite, Godwin Cliffs (BSE image); **E** – clinopyroxene phenocryst (Ti-augite, slightly chloritised) with inclusions of apatite and titanomagnetite, orthopyroxene (hyperstene) and plagioclase, Godwin Cliffs (BSE image in a Quanti color scale); **F** – glomerocryst of plagioclase and clinopyroxene, Polish Geological Survey Cliffs (crossed polars); **G** – plagioclase phenocryst showing chemical zoning within the groundmass comprising plagioclase, clinopyroxene and titanomagnetite crystals, Polish Geological Survey Cliffs (BSE image); **H** – clinopyroxene (Ti-augite) and orthopyroxene (hyperstene) phenocrysts slightly altered (chloritisation), clinopyroxene phenocryst contains an inclusion of tiny olivine, Polish Geological Survey Cliffs (BSE image); mineral symbols after Kretz (1983): Ap – apatite, Chl – chlorite, Cpx – clinopyroxene, Pl – plagioclase, Ol – olivine, Opx – orthopyroxene, Ti-Mgt – titanomagnetite; all BSE images were performed at the Polish Geological Institute – National Research Institute in Warsaw using a *Cameca SX 100* instrument laths in the groundmass (Fig. 4A and C). Almost all of the plagioclase crystals show chemical zoning (Fig. 4C and G). The core and the rims of plagioclase phenocrysts have a labradorite and andesine composition, respectively. The lavas contain two generations of clinopyroxene (Ti-augite), which occur as euhedral, rarely twinned phenocrysts and as subhedral crystals of the groundmass. Clinopyroxene phenocrysts contain inclusions of plagioclase, titanomagnetite (Fig. 4D) and rare apatite (Fig. 4E). Orthopyroxene phenocrysts contain olivine inclusions (Fig. 4H), whereas plagioclase phenocrysts – clinopyroxene, olivine, orthopyroxene and titanomagnetite inclusions. Locally, clinopyroxene crystals are slightly chloritised.

The andesitic lavas from Turret Point are characterized by porphyritic, crystal-rich, fluidal texture which is strongly emphasized by the orientation of plagioclase laths (Fig. 5A). The rock contains single phenocrysts of clinopyroxene (Ti-augite; Fig. 5B) and plagioclase of labradorite and andesine composition. The groundmass comprises mostly plagioclase laths and rare orthopyroxene, clinopyroxene, titanomagnetite and ilmenite crystals. Clinopyroxene crystals are slightly altered (chloritisation).

The andesitic lavas from Three Sisters Point are characterized by crystal-rich, porphyritic locally glomeroporphyritic texture. The rock contains plagioclase clinopyroxene and pseudomorphs after mafic minerals. Almost all of the phenocrysts are plagioclases, which occur as euhedral and subhedral crystals and show chemical zoning. The core and the rims of the plagioclase crystals yielded the labradorite and andesine compositions, respectively. The groundmass (Fig. 5C) consists of plagioclase, clinopyroxene (Ti-augite), ilmenite and titanomagnetite, which sporadically occur even as 1 cm diameter crystals (Fig. 5D). The lava is much more altered than that from the volcanic rocks of Turret Point and the Lions Rump area.

The lava flows from King George Bay area contain between 56.45–59.11 wt.% of SiO_2. On the TAS classification diagram (Fig. 6; Le Maitre *et al*., 1989), the rocks are mainly andesites. The volcanic rocks from Turret Point and Lions Rump area fall within the andesite field, only the sample from Polish Geological Survey Cliffs plot within the basaltic andesite field. The studied lava flow from Three Sister Point fall within the trachyandesite field, close to the border with andesite field.

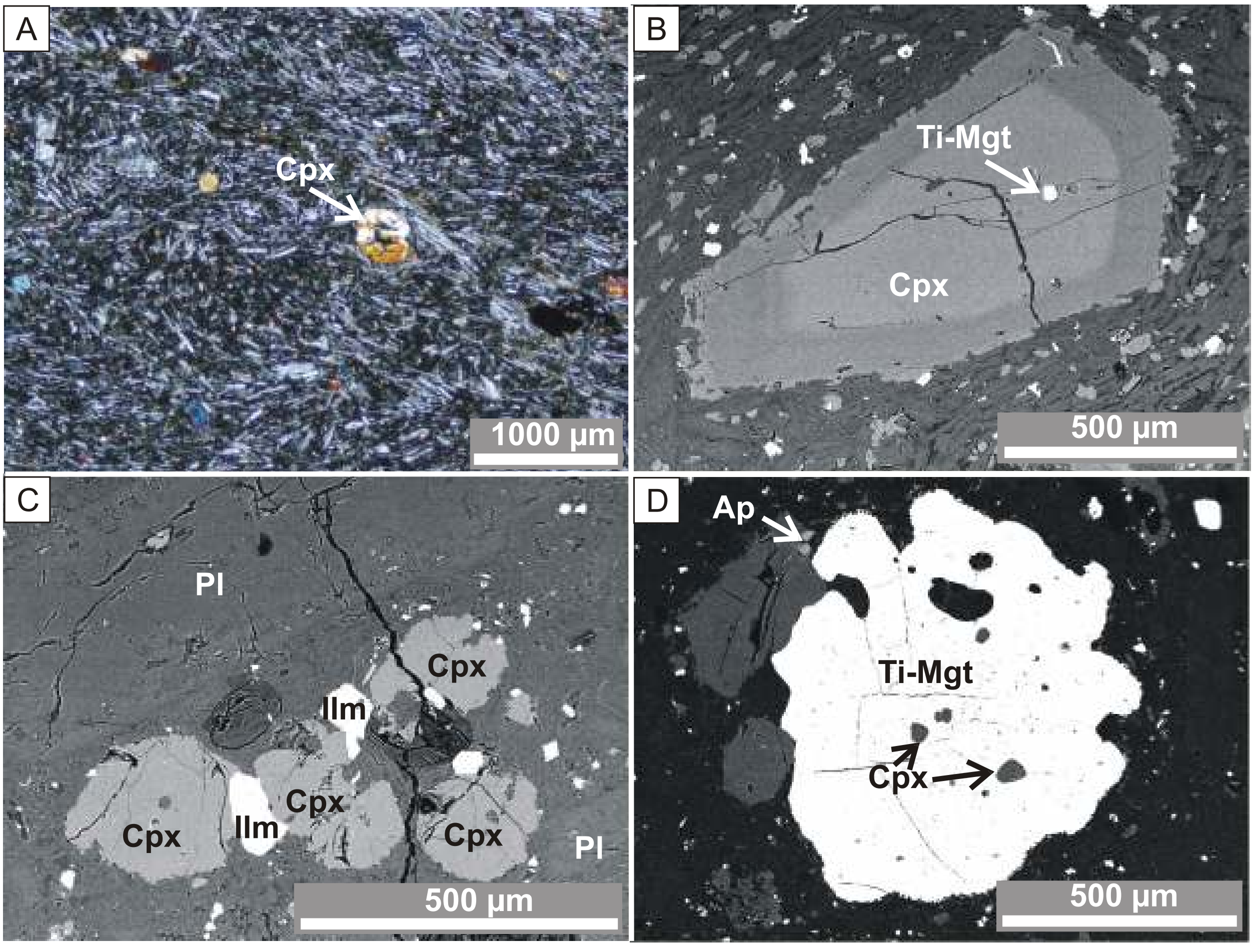

Fig. 5. Photomicrographs of andesitic rocks from the Turret Point–Three Sisters Point area

A – fluidal texture of andesitic lava flow emphasized by the orientation of plagioclase laths, Turret Point (crossed polars); **B** – clinopyroxene phenocryst with chemical zoning and titanomagnetite inclusion, Turret Point (BSE image); **C** – plagioclase phenocryst and the groundmass containing clinopyroxene and ilmenite crystals, Three Sisters Point (BSE image); **D** – titanomagnetite crystal, Three Sisters Point (BSE image); mineral symbols after Kretz (1983): Ap – apatite, Cpx – clinopyroxene, Ilm – ilmenite, Pl – plagioclase, Ti-Mgt – titanomagnetite; all BSE images were performed at the Polish Geological Institute – National Research Institute in Warsaw using a *Cameca SX 100* instrument

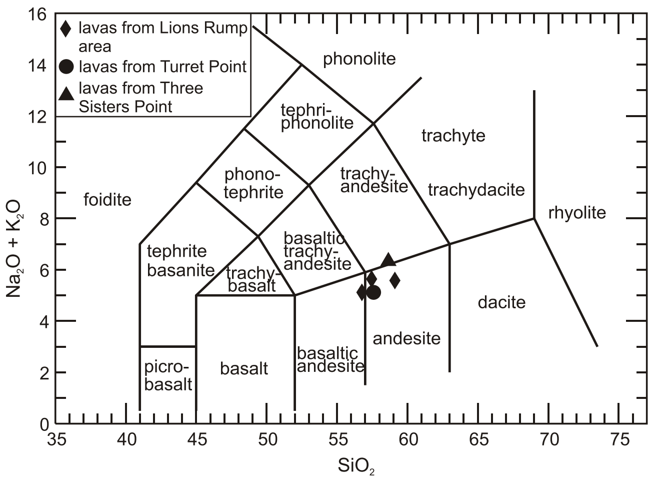

Fig. 6. Chemical classification of the volcanic rocks on total alkalis *versus* silica (TAS) diagram of Le Maitre *et al*. (1989)

RESULTS OF WHOLE ROCK ^{40}Ar-^{39}Ar DATING

Samples for whole rock ^{40}Ar-^{39}Ar isotope dating were selected from fresh, massive parts of lava flows, as far as possible from dykes or hydrothermal veins. Geochronological investigations were performed at the ^{40}Ar/^{39}Ar Geochronology Laboratory of the University of Lund, Sweden. The rocks were prepared according to standard procedures excluding any contamination. The powdered samples were cleaned and processed into a range of grain-sizes and the 0.25–0.5 mm fraction was selected. Phenocrysts were removed from the sample. Additionally, plagioclase crystals were separated for isotopic analyses from the Three Sisters Point sample. The details of the method and analytical process are in Nawrocki *et al*. (2011).

Age plateaus were determined using the criteria of Dalrymple and Lamphere (1971), which specify the presence of at least three contiguous incremental heating steps with statistically indistinguishable ages and constituting greater than 50% of the total ^{39}Ar released during the experiment. ^{40}Ar/^{39}Ar geochronology data were produced, plotted and fitted using the argon programme provided by Al Deino from the Berkeley Geochronology Centre, USA.

The results of the ^{40}Ar-^{39}Ar whole rock age estimation are presented in Figure 7. The measurement data of mass spectrometry analysis are listed in Table 1. The obtained results from the Lions Rump area are very homogenous. The andesitic whole-rock samples LR-3, SK-1 and PR-3 gave well-defined Ar-Ar plateau ages of 44.8 ±0.2 Ma, 44.7 ±0.3 Ma and 44.5 ±0.3 Ma, respectively (Table 1, Fig. 7A–C), with low and medium MSWDs (0.28 and 2.5) and medium probabilities of χ^2 distribution.

The five steps defining the plateaus for volcanic rock from Turret Point correspond to about 56.9% of the ^{39}Ar released (Fig. 7D). The andesitic lava flow gave well-defined Ar-Ar plateau ages of 37.3 ±0.4 Ma with medium MSWDs (2.33; calculated for n-1 degrees of freedom) and low probability (ρ – probability of occurrence based on Chi Square Tables).

It is clearly visible that the andesitic lava flow from Three Sisters Point yielded a statistically significant plateau age of 35.35 ±0.15 Ma (Fig. 7E). The eight steps defining the plateaus for whole-rock sample correspond to about 66.8% of the ^{39}Ar released. The mean square weighted deviation (MSWD) for the plateau age is 1.15 and the corresponding ρ value is 0.33. Additionally, the analyses of separated plagioclase crystals from Three Sister Point were provided for comparison. The obtained results differ from the whole-rock data. The set of plagioclase crystals gave well-defined Ar-Ar plateau ages of 29.1 ±0.2 Ma (Fig. 7F) with low MSWDs (0.85) and medium probability (0.52). The six steps defining the plateaus for separated plagioclase crystals correspond to about 51.2% of the ^{39}Ar released.

MAGNETOSTRATIGRAPHY OF THE DATED SAMPLES

Geographically oriented hand samples for isotopic studies were also served as objects of palaeomagnetic studies. Four core specimens, 2.5 cm diameter and 2.2 cm length, were drilled from each hand sample (LR-3, PR-3, TR-8, 3S5). They were subjected to alternating field (AF) demagnetisation experiment. Natural remanent magnetisations (NRM) were measured with a *Geofyzika JR6A* spinner magnetometer. Demagnetisation results were analysed using orthogonal vector plots (Zijderveld, 1967), and the directions of linear segments were calculated using principal component analysis (Kirschvink, 1980).

The intensity of NRM ranged from 0.24 to 0.87 A/m, evidently being the highest in sample 3S5 (andesitic lava flow from Three Sisters Point). The NRM was demagnetised in an alternating field of amplitude up to 100 mT and more than 90% of the initial intensity of NRM was removed in the fields 30–60 mT (Fig. 8A). Samples LR-3 and PR-3 from the Lions Rump area revealed the presence of well-defined characteristic directions with steep positive inclinations grouping in the second and third quarters of the hemisphere (Fig. 8B). The reverse magnetic polarity of these samples is therefore evident. This polarity corresponds well to the global polarity-time scale GPTS (Gradstein *et al*., 2004) indicating that the rock studied is coeval with the lower reverse part of the C20 polarity chron.

Normal polarity directions are common for samples 3S5 and TR8. Characteristic directions with steep negative inclinations isolated from these samples are grouping in the fourth quarter of the hemisphere (Fig. 8B). The magnetic polarity of sample TR8 corresponds in the limit of errors to the global polarity-time scale GPTS (Gradstein *et al*., 2004) indicating that these rocks can be correlated with the upper normal polarity part of the C17 polarity chron (early Priabonian). Sample 3S5 can not be correlated with any particular magnetozone because several normal magnetozones of the C15 and C16 polarity chrons occur within errors of age estimations.

T a b l e 1

$^{40}Ar/^{39}Ar$ analytical data for lava flows from the Lions Rump area, Turret Point and Three Sisters Point (King George Island)

Step	Pwr/T°C	Ca/K	$^{36}Ar/^{39}Ar$	$\%^{36}Ar(Ca)$	$^{40*}Ar/^{39}Ar$	Mol ^{39}Ar x10^{-14}	% Step	Cum. %	$\%^{40}Ar^*$	Age [Ma]	± Age
LR-3 (J = 0.005959 ±5.700000e-6)											
1.	· 2	1.99399	0.236084	0.1	4.4718	0.3342	2.7	2.7	6	47.44474	2.93283
2.	· 2.1	2.0459	0.030514	0.8	4.25864	1.2007	9.7	12.4	32.2	45.21124	0.56366
3.	· 2.3	2.1009	0.009526	2.6	4.27278	1.7733	14.4	26.8	60.9	45.35951	0.23787
4.	· 2.5	2.04879	0.005323	4.5	4.20358	1.604	13	39.8	73.7	44.63388	0.18688
5.	· 2.7	2.3364	0.006043	4.5	4.20458	1.5778	12.8	52.6	71.1	44.64431	0.20277
6.	· 2.9	2.7996	0.006752	4.8	4.17661	1.0021	8.1	60.7	68.7	44.35093	0.34295
7.	3.1	2.92587	0.007033	4.8	4.10187	1.2435	10.1	70.8	67.4	43.56683	0.28122
8.	3.3	3.10215	0.007332	4.9	4.0985	2.0184	16.4	87.2	66.5	43.53147	0.19687
9.	3.5	2.81494	0.008352	3.9	4.00329	1.579	12.8	100	62.8	42.53201	0.21972
Integ. age =										44.3	0.4
(·) Plateau age =			MSWD = 1.99 ρ = 0.08 steps 1–6				60.7			44.8	0.2
SK-1 (J = 0.005959 ± 5.700000e-6)											
1.	· 2	1.84255	0.155054	0.1	4.62214	0.3158	3.6	3.6	9.2	49.0183	2.14071
2.	· 2.1	1.658	0.01657	1.2	4.2919	1.2133	14	17.6	47	45.55994	0.40819
3.	· 2.3	1.70364	0.008274	2.4	4.22579	1.143	13.2	30.8	63.9	44.86674	0.32454
4.	· 2.5	1.85102	0.005548	3.9	4.19173	1.0969	12.7	43.5	72.7	44.50959	0.22633
5.	· 2.7	2.53609	0.007026	4.2	4.18758	0.9665	11.1	54.6	67.8	44.46605	0.27988
6.	2.9	2.83163	0.007422	4.4	4.07427	0.8977	10.4	65	66	43.27717	0.316
7.	3.1	2.95818	0.006261	5.5	4.06889	0.8227	9.5	74.5	69.9	43.22074	0.26774
8.	3.3	3.13755	0.006867	5.3	3.93416	1.4421	16.6	91.1	67.2	41.80601	0.24533
9.	3.5	2.59118	0.006849	4.4	3.90608	0.7714	8.9	100	66.9	41.51099	0.30991
Integ. age =										43.9	0.4
(·) Plateau age =			MSWD = 2.5 ρ = 0.04 steps 1–5				54.6			44.7	0.3
PR-3 (J = 0.006007 ±8.200000e-6)											
1.	· 2	1.24358	0.049439	0	4.05624	1.3514	12.1	12.1	21.7	43.43081	0.73878
2.	· 2.1	1.59798	0.014087	0	4.18993	2.0608	18.4	30.5	50.2	44.84466	0.29811
3.	· 2.3	1.61994	0.007913	0	4.16117	1.8846	16.8	47.4	64	44.54064	0.24214
4.	· 2.5	1.88612	0.005847	0	4.14043	1.6629	14.9	62.2	70.6	44.32126	0.21802
5.	2.7	2.58587	0.005881	0	4.04778	1.092	9.8	72	70	43.3413	0.20829
6.	2.9	3.87311	0.006671	0	3.96269	0.6051	5.4	77.4	66.8	42.44087	0.34806
7.	3.1	4.27301	0.006926	0	3.94746	0.6596	5.9	83.3	65.9	42.27971	0.36435
8.	3.3	4.45889	0.006606	0	3.85278	1.2597	11.3	94.5	66.4	41.27713	0.27934
9.	3.5	5.78157	0.008501	0	3.79329	0.6099	5.5	100	60.2	40.64689	0.42533
Integ. age =										43.5	0.4
(·) Plateau age =			MSWD = 1.37 ρ = 0.25 steps 1–4				62.2			44.5	0.3
TR-8 (J = 0.006007 ±8.200000e-6)											
1.	2	2.27937	0.337394	0	2.67266	0.2776	4.9	4.9	2.6	28.73381	4.20615
2.	2.1	3.16148	0.063799	0	3.1873	0.6336	11.1	16	14.5	34.21458	1.00375
3.	· 2.3	3.70771	0.020336	0	3.573	0.7418	13	29	37.3	38.31129	0.51362
4.	· 2.5	4.05164	0.012914	0	3.44273	0.7913	13.9	42.9	47.4	36.92866	0.41659
5.	· 2.7	4.48906	0.010809	0	3.3993	0.6433	11.3	54.2	51.6	36.46746	0.43891
6.	· 2.9	4.8766	0.010063	0	3.47566	0.4884	8.6	62.8	53.9	37.27823	0.48628
7.	· 3.1	5.24732	0.00996	0	3.51461	0.5776	10.1	72.9	54.4	37.69168	0.38004
8.	3.3	6.17748	0.012163	0	3.32849	0.7904	13.9	86.8	48.1	35.71529	0.41366
9.	3.5	6.72955	0.013107	0	3.36868	0.7521	13.2	100	46.5	36.14219	0.3588
Integ. age =										36.2	0.8
(·) Plateau age =			MSWD = 2.33 ρ = 0.05 steps 3–7				56.9			37.3	0.4

Tab. 1 cont.

3S3 (J = 0.0061013 ±5.400000e-6)											
Step	Pwr/T°C	Ca/K	$^{36}Ar/^{39}Ar$	$\%^{36}Ar(Ca)$	$^{40*}Ar/^{39}Ar$	Mol ^{39}Ar $x10^{-14}$	% Step	Cum. %	$\%^{40}Ar^*$	Age (Ma)	± Age
1.	2	0.04215	0.072047	0	1.87012	0.2379	6.1	6.1	8.1	20.46831	0.8229
2.	2.1	0.03897	0.025833	0	2.79163	0.2718	6.9	13	26.8	30.46933	0.41112
3.	2.3	0.04974	0.013685	0	3.15061	0.4366	11.1	24.1	43.8	34.35037	0.25018
4.	· 2.5	0.03947	0.008191	0.1	3.25081	0.4548	11.6	35.7	57.3	35.43217	0.19108
5.	· 2.7	0.04164	0.005958	0.1	3.24129	0.4655	11.9	47.6	64.8	35.32935	0.18951
6.	· 2.9	0.05416	0.0057	0.1	3.25371	0.3861	9.9	57.5	65.9	35.4634	0.19186
7.	· 3.1	0.0407	0.004559	0.1	3.22976	0.4305	11	68.4	70.6	35.20489	0.15358
8.	· 3.3	0.05018	0.00313	0.2	3.23597	0.3233	8.2	76.7	77.8	35.27194	0.17199
9.	· 3.5	0.05124	0.002527	0.3	3.27396	0.2401	6.1	82.8	81.5	35.68202	0.1957
10.	· 3.7	0.0495	0.003276	0.2	3.20739	0.1808	4.6	87.4	76.8	34.96347	0.23071
11.	· 4.0	0.08826	0.00316	0.4	3.26599	0.1391	3.5	91	77.8	35.59602	0.29203
12.	4.5	0.0903	0.005299	0.2	3.07913	0.1399	3.6	94.5	66.3	33.57817	0.32033
13.	5.2	0.30085	0.005665	0.7	2.7711	0.1156	2.9	97.5	62.5	30.24709	0.4007
14.	6	0.73061	0.009709	1	2.20116	0.0984	2.5	100	43.7	24.06743	0.52614
Integ. age =										33.5	0.3
(·) Plateau age =			MSWD = 1.15 ρ = 0.33 steps 4–11				66.8			35.35	0.15
3S3 Plagioclase (J = 0.0061013 ±5.400000e-6)											
1.	2	0.0266	0.020541	0	0.31982	0.2346	13	13	5	3.51694	1.67937
2.	2.1	0.14126	0.030966	0.1	2.85121	0.0343	1.9	14.9	23.8	31.11402	1.52973
3.	2.3	0.12352	0.02086	0.1	3.14528	0.0957	5.3	20.2	33.8	34.29282	0.6884
4.	2.5	0.08224	0.009689	0.1	2.9597	0.1303	7.2	27.4	50.9	32.28737	0.39785
5.	2.7	0.09333	0.005816	0.2	2.89554	0.132	7.3	34.6	62.8	31.59359	0.3744
6.	2.9	0.0963	0.004496	0.3	2.82409	0.1061	5.9	40.5	68.1	30.82064	0.41144
7.	3.1	0.11842	0.004047	0.4	2.78419	0.1502	8.3	48.8	70	30.38882	0.2822
8.	· 3.3	0.1133	0.003235	0.5	2.74433	0.095	5.2	54.1	74.2	29.95731	0.48302
9.	· 3.5	0.11092	0.004334	0.3	2.63505	0.0782	4.3	58.4	67.4	28.77393	0.56699
10.	· 3.7	0.09996	0.00379	0.4	2.6698	0.1512	8.4	66.7	70.5	29.15026	0.30252
11.	· 4.0	0.08502	0.003246	0.4	2.65531	0.1474	8.1	74.9	73.5	28.99332	0.28118
12.	· 5.0	0.05183	0.003273	0.2	2.66108	0.3687	20.4	95.3	73.4	29.05581	0.16362
13.	· 6.0	0.07167	0.003048	0.3	2.69774	0.0858	4.7	100	75	29.45289	0.47632
Integ. age =										27	3
(·) Plateau age =			MSWD = 0.85 ρ = 0.52 steps 8-13				51.2			29.1	0.2

Step – number of heating steps; Pwr/T°C – degassing power (dot indicates plateau); Ca/K are element ratios; Mol ^{39}Ar – mol ^{39}Ar released at each step; % Step – % of total ^{39}Ar released at each step; Cum. % – cumulative ^{39}Ar release; $\%^{40}Ar^*$ – % of ^{40}Ar released; errors are 2-sigma

DISCUSSION

The new ^{40}Ar-^{39}Ar ages for lava flows from the Lions Rump area are very consistent and suggest middle Eocene (Lutetian) age of eruption. Samples for isotopic analyses were collected from both tectonic blocks *sensu* Birkenmajer (1983; Warszawa and Kraków blocks). The results of palaeomagnetic studies confirm the isotopic results. The reverse magnetic polarity of these samples and the results of ^{40}Ar-^{39}Ar dating correspond well to the global polarity-time scale GPTS (Gradstein *et al*., 2004), indicating that the rocks are coeval with the lower reverse part of the C20 polarity chron. Thus, combined ^{40}Ar-^{39}Ar and palaeomagnetic data imply a middle Lutetian age of andesitic lava flows that are the basement for glaciomarine sediments of the Polonez Cove Formation. It should be stressed that neither isotopic ages nor palaeomagnetic properties indicate that these rocks were formed in the area of two separate tectonic domains i.e. the Kraków and Warszawa blocks.

Volcanic rocks from the Turret Point–Three Sisters Point area are younger and were crystallised and extruded during the late Eocen (Bartonian/Priabonian 37.3 ±0.4 Ma and 35.35 ±0.15 Ma, respectively). Palaeomagnetic data might support the isotopic age only for a volcanic rock from the cliffs of Turret Point. In this case, the normal polarity magnetisation could be correlated with the upper normal polarity part of the C17 polarity chron (Bartonian/Priabonian).

Generally, the calculated whole-rocks ^{40}Ar-^{39}Ar plateau ages are 2–3 Ma older than the formerly obtained whole-rocks K-Ar ages (Smellie *et al.*, 1984; Birkenmajer *et al*., 1989). Most probably, previous results for andesitic lavas from the King George Bay area, suggesting younger age of crystallisation and emplacement, are the effect of Ar loss. On the other hand, analyses of plagioclase crystals separated from

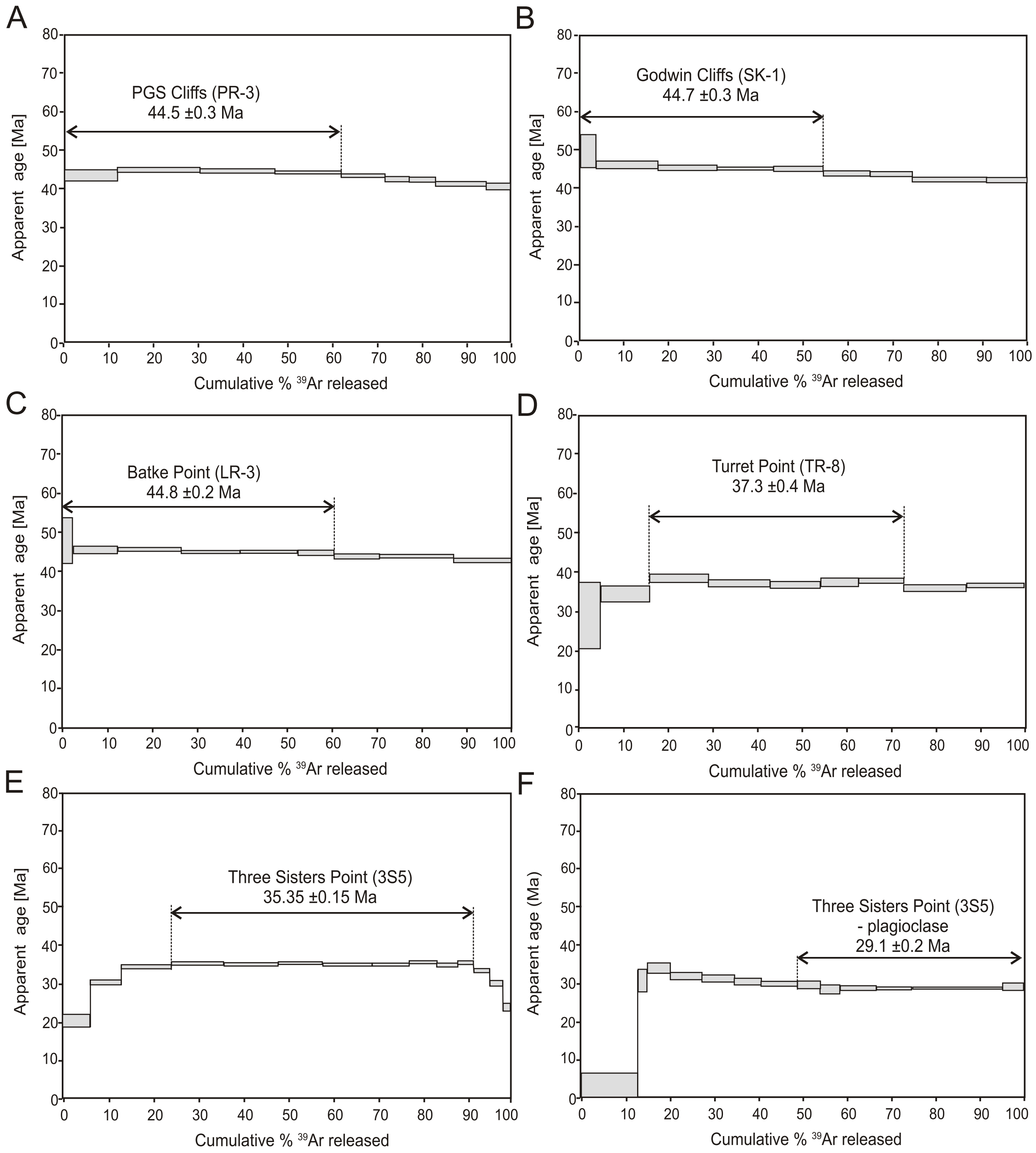

Fig. 7. Stepwise argon release spectrum for whole-rock lava samples from the Lions Rump area (A–C), Turret Point (D) and Three Sisters Point (E–F)

Vertical and horizontal axes define age (Ma) and percentage of ^{39}Ar released; errors are 2-sigma

the andesitic lava flow from Three Sisters Point gave a younger age (29 Ma). A comparable situation was observed for an andesitic lava sample from the Hervé Cove section, overlying the diamictite. The plagioclases gave a plateau age of 41.5 ± 0.8 Ma (Nawrocki *et al.*, 2011, this issue). However, the obtained whole-rock ^{40}Ar-^{39}Ar age (well-defined plateau age of 48.1 ±0.2 Ma. Nawrocki *et al.*, 2011, this issue) was equal within uncertainty to the mean SHRIMP zircon age (48.9 ±0.7 Ma) measured on the same piece of lava flow and consistent with the palaeomagnetic results (Nawrocki *et al.*, 2010).

CONCLUSIONS

1. The new isotopic ages for andesitic rocks from the Lions Rump area, which are the basement for glaciomarine sediments of the Polonez Cove Formation, constrain the age of magma extrusion to the middle Eocene (Lutetian, ~44 Ma). The andesitic lava flows from Turret Point and Three Sisters Point are younger, displaying the plateau age of 37.3 ±0.4 Ma and 35.35 ±0.15 Ma, respectively.

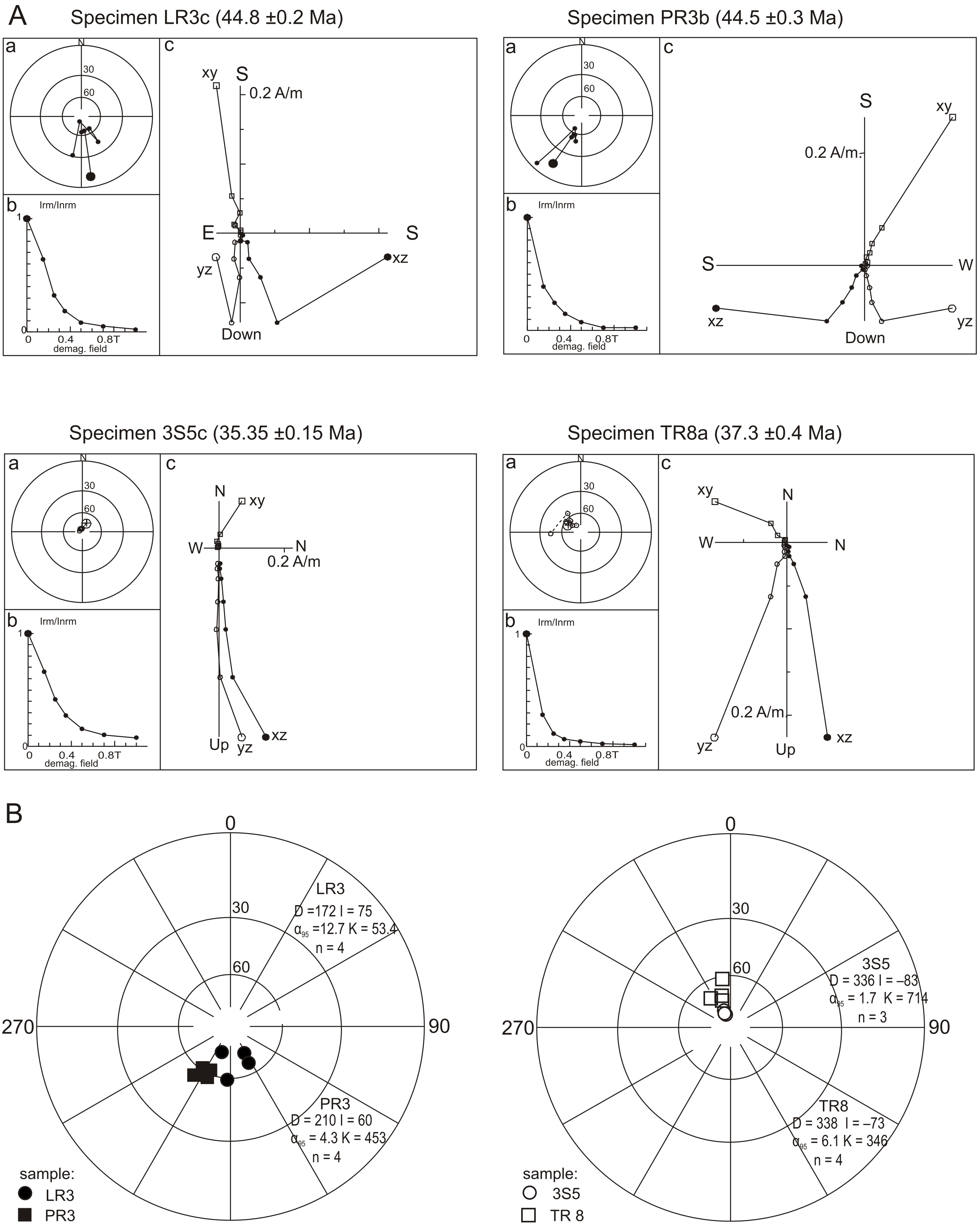

Fig. 8A – typical demagnetisation characteristics (a – demagnetisation paths, b – intensity decay curves, c – orthogonal plots) of the volcanic rocks from the Lions Rump area (Batke Point – LR3c; Polish Geological Survey Cliff – PR3b), Turret Point (TR8a) and Three Sisters Point (3S5c) section; B – stereographic projections of line-fit mean (on the specimen level) palaeomagnetic directions isolated from the Lions Rump area (Batke Point – LR3c; Polish Geological Survey Cliff – PR3b), Turret Point (TR8a) and Three Sisters Point (3S5c); the diagrams were prepared by means of a computer package developed by Lewandowski *et al.* (1997)

A: Irm – intensity of remnant magnetisation, Inrm – initial intensity of natural remnant magnetisation; ; Ar-Ar ages defined for particular sample are shown in brackets; **B**: open (closed) symbols denote upward (downward) pointing inclinations; D, I – mean declination and inclination on the sample level, α_{95}, K – Fisher's statistics parameters, n – number of specimens

2. Isotope ages are consistent with magnetic polarities of the studied rocks indicating that the samples from the Lions Rump area (LR-3 and PR-3) are coeval with the lower part of the C20 polarity chron (middle Lutetian). On the other hand, the sample from Turret Point (TR-8) can be correlated with the upper part of the C17 polarity chron (Bartonian/Priabonian).

3. Common isotopic ages and palaeomagnetic properties of basal volcanic rocks (samples LR-3 and PR-3) in the Lions Rump area (King George Bay) do not support the thesis about separate tectonic evolution of the Warszawa and Kraków blocks at least since the middle Eocene.

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REFERENCES

BARKER P. F. (1982) – The Cenozoic subduction history of the Pacific margin of the Antarctic Peninsula: ridge crest-trench interactions. J. Geol. Soc. London, **139**: 787–801.

BARKER P. F. and BURRELL J. (1977) – The opening of Drake Passage. Marine Geol., **25**: 15–34.

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

BIRKENMAJER K. (1980) – Discovery of Pliocene glaciation on King George Island, South Shetland Islands (West Antarctica). Bull. Pol. Acad. Sc. Ser. Sc. Terre., **27**: 59–67.

BIRKENMAJER K. (1981) – Geological relations at Lions Rump. King George Island (South Shetland Island, Antarctica). Stud. Geol. Pol., **72**: 75–87.

BIRKENMAJER K. (1982) – Pliocene tyllite-bearing succession of King George Island (South Shetland Islands, Antarctica). Stud. Geol. Pol., **74**: 7–72.

BIRKENMAJER K. (1983) – Late Cenozoic phases of block-faulting on King George Island (South Shetland Island, West Antarctica). Bull. Acad. Pol. Sc. Ser. Sc. Terre., **30**: 21–32.

BIRKENMAJER K. and GAŹDZICKI A. (1986) – Age of the Pecten conglomerate on King George Island, West Antarctica. Bull. Pol. Acad. Sc. Earth Sc., **34**: 219–226.

BIRKENMAJER K., NARĘBSKI W., NICOLETTI M. and PETRUCCIANI C. (1983) – K-Ar ages of "Jurassic volcanics" and "Andean" intrusions of King George Island South Shetland Islands (West Antarctica). Bull. Acad. Pol. Sc., Sér. Sc. Terre, Sc., **30** (3–4): 121–131.

BIRKENMAJER K., SOLIANI E. jr. and KAWASHITA K. (1989) – Geochronology of Tertiary glaciations on King George Island, West Antarctica. Bull. Pol. Acad. Sc. Earth Sc., **37**: 27–48.

DALRYMPLE G. B. and LAMPHERE M. A. (1971) – $^{40}Ar/^{39}Ar$ technique of K/Ar dating: a comparison with the conventional technique. Earth Planet. Sc. Lett., **12**: 300–308.

GRADSTEIN F. M., OGG J. G. and SMITH A. (2004) – Geological Time Scale 2004. Cambridge University Press, Cambridge.

KIRSCHVINK J. L. (1980) – The least square line and plane and the analysis of paleomagnetic data. Geoph. J. Royal Astronomical Soc., **62**: 699–718.

KRETZ R. (1983) – Symbols for rock-forming minerals. Am. Miner., **68**: 277–279.

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 Subcomission on the Systematics of Igneous Rocks. Blackwell, Oxford.

LAWVER L. A., GAHAGAN L. M. and COFFIN M. F. (1992) – The development of paleoseaways around Antarctica. Am. Geoph. Union Publ. Antarctic Res. Ser., **56**: 7–30.

LEWANDOWSKI M., WERNER T. and NOWOŻYŃSKI K. (1997) – PCA – a package of Fortran programs for paleomagnetic data analysis. Instit. Geoph., Pol. Acad. Sc., Manuscript.

LIVERMORE R., NANKIVELL A., EAGLES G. and MORRIS P. (2005) – Paleogene opening of Drake Passage. Earth Planet. Sc. Lett., **236**: 459–470.

NAWROCKI J., PAŃCZYK M. and WILLIAMS I. S. (2010) – Isotopic ages and palaeomagnetism of selected magmatic rocks from King George Island (Antarctic Peninsula). J. Geol. Soc. London., **167**: 1063–1079.

NAWROCKI J., PAŃCZYK M. and WILLIAMS I. S. (2011) – Isotopic ages of selected magmatic rocks from King George Island (West Antarctica) controlled by magnetostratigraphy. Geol. Quart., **55** (4) 301–322.

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 Planet. Sc. Lett., **66**: 214–222.

PAULO A. and TOKARSKI A. K. (1982) – Geology of the Turret Point – Three Sisters Point area, King George Island (South Shetland Islands, Antarctica). Stud. Geol. Pol., **74**: 39–79.

PORĘBSKI S. J. and GRADZIŃSKI R. (1987) – Depositional history of the Polonez Cove Formation (Oligocene), King George Island. West Antarctica: a record of continental glaciation shallow-marine sedimentation and contemporaneous volcanism. Stud. Geol. Pol., **97**: 7–62.

PUDEŁKO R. (2008) – Two new topographic maps for sites of scientific interest on King George Island, West Antarctica. Pol. Polar Res., **29**: 291–297.

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. Br. Antarct. Surv. Sc. Rep., **87**.

TROEDSON A. L. and SMELLIE J. L. (2002) – The Polonez Cove Formation of King George Island, Antarctica: stratigraphy, facies and implications for mid-Cenozoic cryosphere development. Sedimentology, **49**: 277–301.

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. J. Geoph. Res., **104**: 23051–23068.

ZIJDERVELD J. D. A. (1967) – AC demagnetization of rocks: analysis of results. In: Methods in paleomagnetism (eds. D. W. Collinson *et al*.): 254–287. Elsevier, New York.