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Eocene age of the Baranowski Glacier Group at Red Hill, King George Island, West Antarctica

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Abstract: Radiometric and geochemical studies were carried out at Red Hill in the southern part of King George Island (South Shetland Islands, northern Antarctic Peninsula) on the Bransfield Strait coast. The rock succession at Red Hill has been determined to represent the Baranowski Glacier Group that was previously assigned a Late Cretaceous age. Two formations were distinguished within this succession: the lower Llano Point Formation and the upper Zamek Formation. These formations have stratotypes defined further to the north on the western coast of Admiralty Bay. On Red Hill the Llano Point Formation consists of terrestrial lavas and pyroclastic breccia; the Zamek Formation consist predominantly of fine to coarse tuff, pyroclastic breccia, lavas, tuffaceous mud-, silt-, and sandstone, locally conglomeratic. The lower part of the Zamek Formation contains plant detritus (*Nothofagus*, dicotyledonous, thermophilous ferns) and numerous coal seams (vitrinitic composition) that confirm the abundance of vegetation on stratovolcanic slopes and surrounding lowlands at that time. Selected basic to intermediate igneous rocks from the succession have been analysed for the whole-rock K-Ar age determination. The obtained results indicate that the Red Hill succession was formed in two stages: (1) from about 51–50 Ma; and (2) 46–42 Ma, *i.e.* during the Early to Middle Eocene. This, in combination with other data obtained from other Baranowski Glacier Group exposures on western coast of Admiralty Bay, confirms the recently defined position of the volcano-clastic succession in the stratigraphic scheme of King George Island. The new stratigraphic position and lithofacies development of the Red Hill succession strongly suggest its correlation with other Eocene formations containing fossil plants and coal seams that commonly occur on King George Island.

Key words: Antarctica, King George Island, Red Hill, Eocene, volcanogenic succession, K-Ar dating, flora.

Introduction

The northern Antarctic Peninsula region contains a geological record of the evolution of West Antarctica, reflecting a series of paleoclimatic and paleoenvironmental changes that led to the emergence and development of the Antarctic ice sheet

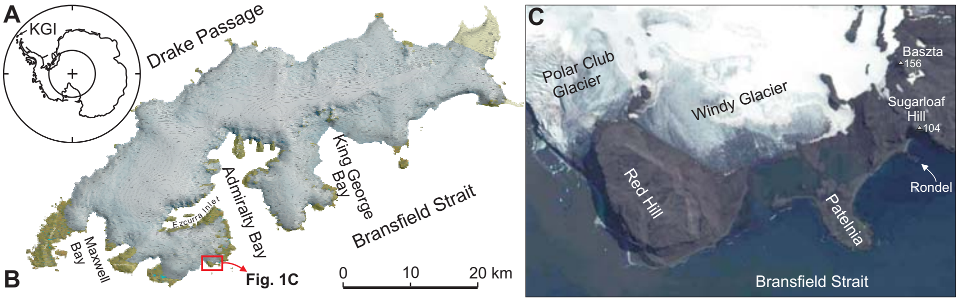

Fig. 1. **A**. Location of King George Island (KGI) in Antarctica. **B**. Topographic map of King George Island, with location of study area (based on Topographic Map 2001). **C**. Satellite image of Red Hill area.

close to the Eocene/Oligocene boundary (Dingle and Lavelle 2000; Birkenmajer *et al.* 2005; Ivany *et al*. 2006; Francis *et al*. 2009). The Cenozoic strata on King George Island (KGI) comprise mostly basaltic and andesitic rocks intruded by dykes and plugs (*e.g.* Smellie *et al*. 1984; Birkenmajer 2003) and contain at places terrestrial and marine sedimentary intercalations, which are of crucial importance in reconstructing this geological history (Birkenmajer 2001; Davies *et al*. 2012).

In this paper we present results of integrated research of the Red Hill succession in the southern part of King George Island that provides new evidence of the Eocene preglacial conditions in the northern Antarctic Peninsula region (Fig. 1). This succession has been classified as the Baranowski Glacier Group on the basis of geological correlation with rock outcrops located further north on the western coast of Admiralty Bay (Birkenmajer 2003). The group consists of two formations (in ascending order): (1) the Llano Point Formation (predominantly basaltic lavas), and (2) the Zamek Formation (basaltic and andesitic lavas, agglomerates, and plant-bearing tuffs), see Birkenmajer (1979, 1980a, b). The group (up to 1140 m thick) overlies the ?Late Cretaceous–Paleocene Paradise Cove Group, extending from Ecology Glacier in the southwestern part of Admiralty Bay to Patelnia and Red Hill at Bransfield Strait (Fig. 2).

Existing age estimates of the Baranowski Glacier Group. — Since the first study of the Baranowski Glacier Group (Birkenmajer 1979), it was assigned different geological ages and geographical extent on King George Island. A review of the research history is outlined below. Surprisingly, it seems that the Red Hill area, which provides one of the best outcrops of the group, has never been investigated in detail. The Baranowski Glacier Group has been tentatively dated as Oligocene (Birkenmajer 1979, 1980a) on the basis of its lithostratigraphic position in the King George Island succession. Another attempt to assign geological age to the group was by Birkenmajer (1980b), who suggested Early–Middle Oligocene, on the basis of plant remains collected in the moraine below Zamek hill between the Baranowski and Ecology glaciers. One more suggestion was a Middle Oligocene age of the group (Birkenmajer 1980c). In these publications, the Red Hill area was

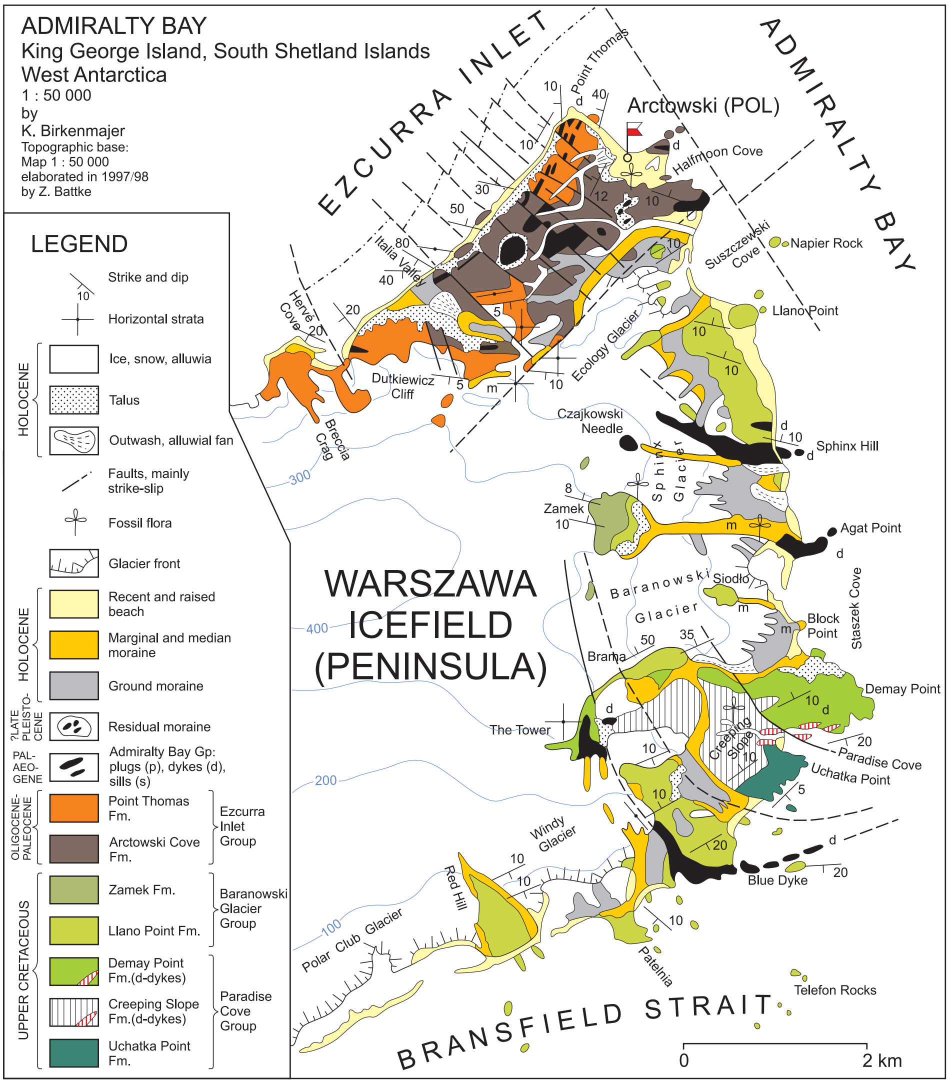

Fig. 2. Geological map of the western side of Admiralty Bay, King George Island (after Birkenmajer 2003).

considered to represent either the whole Baranowski Glacier Group (Birkenmajer 1979, 1980b) or only its lower part, *i.e.* Llano Point Formation (Birkenmajer 1980c). The occurrence of the Zamek Formation was originally confined to only Zamek hill, with the same Middle Oligocene age suggested for the Baranowski Glacier Group (Birkenmajer *et al.* 1981).

The first results of radiometric dating of the volcanic rocks from the Baranowski Glacier Group published by Birkenmajer *et al.* (1983) shifted the age of the unit down to the Late Cretaceous. They were obtained from lavas at two locations: (1) the bottom of the Llano Point Formation (77±4 Ma) at Zamek hill, and (2) the bottom of the overlying Ezcurra Inlet Group (66.7±1.5 Ma). These Late Cretaceous (Maastrichtian) dates were commonly referred to in the literature (Birkenmajer and Zastawniak 1989; Zastawniak 1990, 1994; Birkenmajer *et al*. 1991; Askin 1992; Lindner-Dutra and Batten 2000; Mohr 2001; Poole and Cantrill 2006) with further detailed description as Late Cretaceous (Maastrichtian). In recent geological compilations Birkenmajer (2001, 2003) ascribes the Santonian to Middle Campanian, and the Middle Campanian to Middle Maastrichtian age ranges to the Llano Point and Zamek formations, respectively. Although Dutra (1989) described taphoflora from a moraine at "Block Point" in front of Baranowski Glacier as "Tertiary", Birkenmajer (2001) sustained the Cretaceous age of the Zamek Formation. In his sketches and geological maps, the Red Hill area is depicted as the Baranowski Glacier Group (Birkenmajer 1979, 1980b; Birkenmajer *et al*. 1986) or only as the Llano Point Formation (Birkenmajer 1980c, 2001, 2003; see Fig. 2).

New age estimates of the Baranowski Glacier Group. — The Late Cretaceous age of the Baranowski Glacier Group (Birkenmajer *et al.* 1983) could be considered unreliable. In their comprehensive summary of current knowledge on the vegetation in Antarctica, Cantrill and Poole (2012) refers to the Late Cretaceous age of the Zamek Formation, but state that the age is disputable and may in fact be early Cenozoic (T. Dutra, *personal comm*. 2010). Volcanic-sedimentary sequence on the south coast of King George Island was recently studied by Nawrocki *et al*. (2010). They used a combination of U-Pb SHRIMP and Ar-Ar methods supported by magnetostratigraphy. A Cretaceous age was obtained for the Uchatka Point Formation only (75.4±0.9 Ma). The youngest formation of the Paradise Cove Group, the Demay Point Formation (that is overlain by basaltic lavas of the Baranowski Glacier Group), traditionally been assigned to the Cretaceous. However, the U-Pb ages, supported by ^{40}Ar-^{39}Ar data, obtained by Nawrocki *et al*. (2010), indicate its Early Eocene age (50.8–53.7 Ma), which in combination with palaeomagnetic data, allow to date the rocks even more precisely to a narrow range of 51–52 Ma. The U-Pb dating of lava flow from the top of the Point Thomas Formation (48.9±0.7 Ma) and the Demay Point Formation dating mentioned above allow to suppose that the Baranowski Glacier and the Ezcurra Inlet Groups are likely to be of Early Eocene (Ypresian) age (Nawrocki *et al.* 2010). Next paper by Nawrocki *et al*. (2011) refines age of the Llano Point Formation by the Ar-Ar method to be between ~51–49.5 Ma. The recent work of Warny *et al.* (2015) refers to these investigations and also suggest Eocene age for the Zamek Formation at Zamek locality.

The outcrop of the Baranowski Glacier Group on the western rocky face of Red Hill was discovered and preliminarily described during exploration trip in austral summer 2006/2007. The general facies development of the succession and first findings of flora seemed to question the Cretaceous age of the group, and constituted the foundation for this work. Main field work at Red Hill area was conducted during the 35th Polish Antarctic Expedition in 2010/11 on KGI and led to the discovery of new plant fossil sites and redefinition of the age of the rock succession.

The new radiometric ages presented in this study locate the Baranowski Glacier Group in the Early to Middle Eocene, and ascribe the age of the contained flora to the same stratigraphic period. This position and the lithofacies development show similarities to other Eocene plant- and coal-bearing formations on KGI. The K-Ar analyses were done at the Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI) in Debrecen, Hungary.

Geological setting

The study area is located in the southern part of King George Island (South Shetland Islands, northern Antarctic Peninsula region) on the Bransfield Strait coast (Fig. 2A–C). The South Shetland Islands (SSI) magmatism resulted from the slow subduction of the former Phoenix (Aluk) plate beneath the Antarctic Peninsula (Smellie *et al*. 1984; Grad *et al.* 1993; Janik *et al.* 2014). Geophysical surveys suggest that SSI constitute a small, separate microplate (Ashcroft 1972), limited by a young rift structure of Bransfield Strait on the south-east and by subductive oceanic trench on the north-west. The Red Hill section of the Baranowski Glacier Group shows approximately 180 m high rocky cliff, where the lower boundary of the group is under the sea level, and the upper boundary is erosional and partly covered by moraine sediments. Horizontally bedded layers are gently inclined (about 10°) southward. The succession is separated into blocks by several normal faults and cut by basaltic dykes.

The succession at Red Hill comprises volcanoclastic rocks composed of alternating terrestrial lava flows of basaltic to basaltic andesite composition and fine to coarse tuffs, lapilli tuffs and breccias (Fig. 3). This succession overlies a massive volcanic substratum of considerable thickness, for which only the uppermost part is exposed. These two parts of the Baranowski Glacier Group can be tentatively attributed to the Llano Point Formation (the bottom part) and the Zamek Formation (the main part of the section), which were distinguished within the group further north along the western coast of Admiralty Bay (Birkenmajer 2001). The boundary between the formations is erosional and uneven, though neither weathering profile nor regolith pavement were observed over the exposed a few tens of meters of the contact. In the lower part of the section (lower part of the Zamek Formation), there occur tuffaceous sandstones and siltstones containing coal seams (up to 5 cm thick) and coaly layers with plant detritus (Fig. 4). The coal shows dominant vitrinitic composition. The plant fossils are poorly preserved due to mechanical degradation in flowing water. Among the dominating undeterminable plant fragments the remains of ferns, angiosperms and *Nothofaus* leaves were identified (Fig. 5). The Red Hill show facies and floral composition similar to the Zamek Formation at Zamek hill, the latter has been considered so far to represent the only unquestionable Late Cretaceous flora on KGI. Our new geochronology data indi-

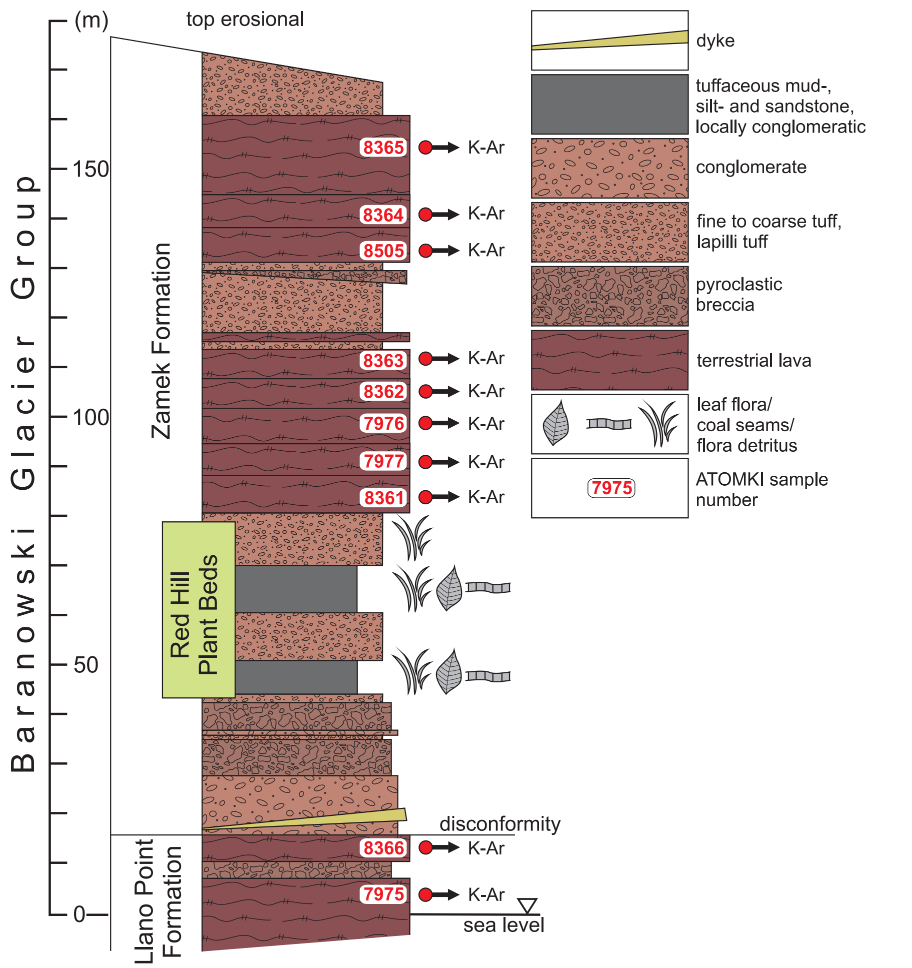

Fig. 3. Schematic lithologic profile of Red Hill outcrop.

cate that this flora is of Eocene age, and similar to Eocene floras described from other parts of KGI, *e.g.* from the Ezcurra Inlet Group in Ezcurra Inlet, the Point Hennequin Group at Wawel in Admiralty Bay, and the Lions Cove Formation in King George Bay (Mozer 2012, 2013).

Analytical techniques

Geochemistry. — The geochemical analysis of the major, minor, and trace elements was done at ACME Labs in Vanouver, Canada. Preparation of samples embraced crushing, averaging and thumbing of approx. 10 g of rock material. The content of major oxides (SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, MnO, TiO_2, P_2O_5, Cr_2O_3) and Sc was determined using ICP-ES (*Inductively Coupled*

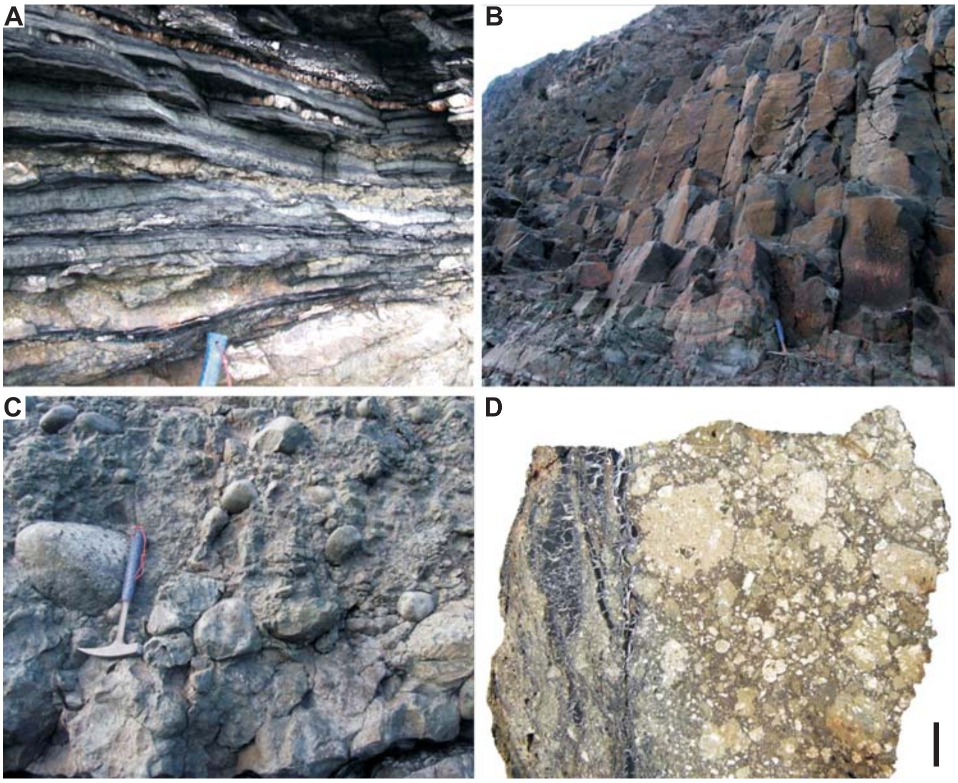

Fig. 4. Some details of Red Hill section. **A**. Intercalations of volcanic ash and beds containing organic matter (black seams with coal). **B**. Contact of basaltic lava flow with underlying mudstone/siltstone. Note columnar joint within basalt. **C**. Conglomerate from the upper part of Zamek Formation. **D**. Fragment of pyroclastic breccia with incorporated wood. Hammer as a scale 33 cm, scale bar 1 cm.

Plasma Emission Spectrometry) on 0.2 g sample melted with a mixture of $LiBO_2/Li_2B_4O_7$. The total content of carbon and sulfur (TOT/C, TOT/S) was determined by LECO combustion technique. Trace and rare earth elements were determined using ICP-MS (*Inductively Coupled Plasma Mass Spectrometry*). For these analysis 0.5 g sample was dissolved in 3 ml of a solution of concentrated acids ($HCl + HNO_3$) at 95°C for 1 hour and then the obtained solution was diluted to 10 ml. Details of the analytical procedure and measurement precision can be found at http://acmelab.com/. For the total alkali silica (TAS) diagram, the results were recalculated to 100% main oxides.

K-Ar procedure. — The K-Ar analyses of whole-rock samples were done at the K-Ar Laboratory of the Institute of Nuclear Research, Hungarian Academy of Sciences (ATOMKI). Approximately 0.05g of finely ground sample was digested in acids and finally dissolved in 0.2M HCl. Potassium was determined by flame photometry with a Na buffer and Li internal standard. The inter-laboratory standards Asia 1/65, LP-6, HD-B1 and GL-O were used for checking the measure-

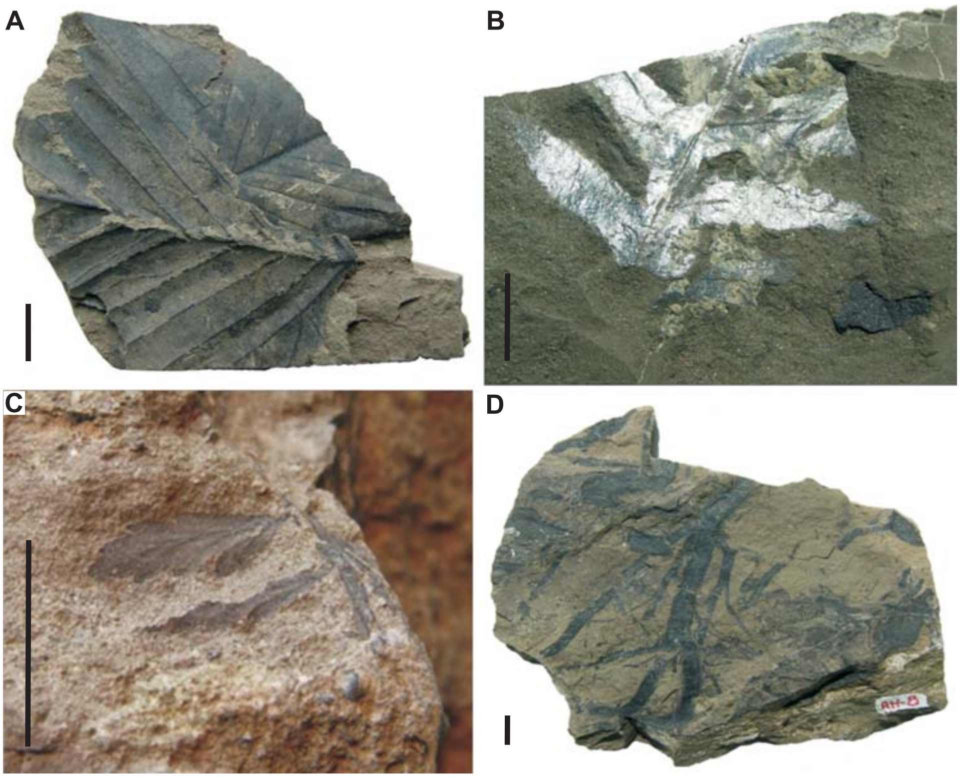

Fig. 5. Fossil flora found at Red Hill section. **A**. Fragment of the *Nothofagus* leaf imprint. **B**, **C**. Impressions of fragmented fern frond. **D**. Accumulation of various plant remains. Scale bars 1 cm.

ments. Argon was extracted from the samples by RF fusion in Mo crucibles in previously backed stainless steel vacuum system. ^{38}Ar spike was added from gas pipette system and the evolved gases were cleaned using Ti and SAES getters and liquid nitrogen traps, respectively. The purified Ar was transported directly into the mass spectrometer and Ar isotope ratio was measured in the static mode using a 15 cm radius magnetic sector type mass spectrometer build in Debrecen. Details of the instruments, the applied methods and results of calibration have been described by Balogh (1985) and Odin *et al*. (1982). Ages were calculated according to decay constants of Steiger and Jäger (1977). All analytical errors represent one standard deviation (*i.e.* 68% analytical confidence level). Since we base our analitycal errors on the long time stability of instruments and on the deviation of our results obtained on standard samples from the interlaboratory mean the analytical errors are likely to be overestimated. For stratigraphic allocation of the numerical results the International Chronostratigraphic Chart v 2015/01 (Cohen *et al.* 2013, updated) was used. All the radiometric ages were evaluated using detailed investigation of thin sections in order to reveal possible features of rock alteration that might have affected the K-Ar isotopic system.

Results

Petrographic observations. — The samples of basaltic andesites that represent the Llano Point formation no. 7975 (Red Hill-3) and 8366 (RHAM-02) are medium altered with porphyritic texture. Palagonite-smectite alteration of volcanic glass that occupies the residual space between plagioclase laths in the groundmass is noted. The observed phenocrysts are plagioclase and clinopyroxene. The minerals in groundmass are plagioclase, clinopyroxene, olivine, magnetite and volcanic glass. The medium content of $^{40}Ar_{rad}$ and the low content of K suggest an opening of the system, but the presence of fresh plagioclase crystals argues for reliable numerical ages.

The samples no. 7977, 7976 and 8505 (Red Hill-1, Red Hill-2 and RHAM-16) that belong to the Zamek Formation represent clinopiroxene-, olivine-phyric basalt with porphyritic and intersertal texture. Phenocrysts are dominated by plagioclase, clinopyroxene and olivine, while minerals in groundmass were plagioclase, clinopyroxene, magnetite and altered volcanic glass. The samples show strong alteration manifested by common clay minerals and relatively low $^{40}Ar_{rad}$ contents (20.4, 17.8 and 13.5%, respectively). This suggests that the isotope system was disturbed. Consequently some Ar loss from the rock is highly probable, thus the reported K/Ar ages (44–46 Ma) should be considered minimum ages.

In the sample no. 8361 (RHAM-21), no alteration of feldspars was detected, while iddingsite alteration of olivine and palagonite-smectite alteration of volcanic glass was observed. The sample represent clinopiroxene-, olivine-phyric basalt with porphyritic and intersertal texture. Phenocrysts are represented by plagioclase, clinopyroxene, olivine, while minerals in groundmass are plagioclase, clinopyroxene, magnetite and altered volcanic glass. The rock is relatively fresh and the concentration of $^{40}Ar_{rad}$ is the highest among the investigated samples (*i.e.* 66%), thus the obtained age of 48 Ma can be accepted as reliable.

The sample no. 8362 (RHAM-10) represents olivine-phyric basalt with porphyritic and intersertal texture. Phenocrysts are represented by plagioclase and olivine, while minerals in groundmass are plagioclase, clinopyroxene, magnetite and altered volcanic glass. Similarly to the sample 8361 (RHAM-21), only iddingsite alteration of olivine and palagonite-smectite alteration of volcanic glass was observed. This, in combination with rather high content of $^{40}Ar_{rad}$ (49.7%), allow to consider the obtained age of 41 Ma as reliable.

The sample no. 8363 (RHAM-12) represents olivine-, clinopyroxene-phyric basalt with seriate intersertal texture. Phenocrysts are represented by plagioclase, clinopyroxene and olivine, while minerals in groundmass are plagioclase, clinopyroxene, magnetite and volcanic glass (altered to brownish translucent palagonite and locally smectite). The individual plagioclase crystals are fresh and only locally the glass inclusions show weak palagonite-smectite alteration. Thus, the obtained radiometric age (~43 Ma) seems to be reliable.

The sample no. 8364 (RHAM-17) represent the same type of rock, olivine-, clinopyroxene-phyric basalt with seriate intersertal texture. Phenocrysts are dominated by plagioclase, clinopyroxene and olivine, while minerals in groundmass are plagioclase, clinopyroxene, magnetite and altered volcanic glass. The sample is characterised by a variety of alterations: iddingsite alteration of olivine, palagonite-smectite alteration of volcanic glass and argillic alteration of plagioclase crystals. However, it shows a high content of $^{40}Ar_{rad}$, far above the threshold of 10% below which errors rise exponentially (54.9%). Due to the various and intense alterations, the obtained radiometric age (42 Ma) should be considered minimum age.

The sample no. 8365 (RHAM-17A) represent clinopyroxene-phyric basalt with porphyritic texture. Phenocrysts are represented by plagioclase and clinopyroxene, while minerals in groundmass are plagioclase, clinopyroxene, magnetite and altered volcanic glass. The sample shows palagonite-smectite alteration of volcanic glass, that occupies the residual space between plagioclase laths in the groundmass. The presence of plagioclase crystals without any signs of alteration, and the contents of $^{40}Ar_{rad}$ (%) = 34.0 and K mean (%) = 0.57 suggest that the obtained age of 46 Ma is reliable.

Geochemical classification of igneous rocks. — The results of chemical analysis of volcanic rocks from the Red Hill section are presented in Table 1. Based on similarity of geochemical composition between volcanic rocks analyzed here and in other papers from KGI as well as the results from Red Hill that have not been included in this presentation, it is certain that the volcanic rocks of the study area were derived from an magmatic arc environment (Smellie *et al.* 1984; Yeo *et al.* 2004; Machado *et al*. 2005). Detailed geochemical study conducted by Yeo *et al.* (2004) suggests that Paleocene–Eocene volcanism in King George Island (Barton and Weave peninsulas) occurred in an immature island arc without thickened continental-type crust.

The Red Hill volcanic succession is a complex of intermediate to basic rocks (48.4–52.5 SiO_2 %wt). The total alkali silica (TAS) diagram (LeMaitre *et al*. 2002) shows that all samples from the Zamek Formation are basalts (Fig. 6A). Their alkali content ranges from 2.9% to 4.4%, and their silica content is between 48.7% and 50.5%. Two samples that represent the Llano Point Formation plot in the basaltic andesite field (alkali and silica contents range between 3.5% and 4.7% and 51.9% and 52.5%, respectively). Plotted on the chemical classification diagram of Zr/TiO_2 *vs*. Nb/Y (Winchester and Floyd 1977), the composition of the lavas from the Zamek Formation fall in the subalkaline basalt field, and the lavas from Llano Point Formation fall in the andesite/basalt field (Fig. 6B). The data plotted on the two diagrams gather into two groups with slightly different chemical composition, which are representative for volcanic island arc tectonic environment.

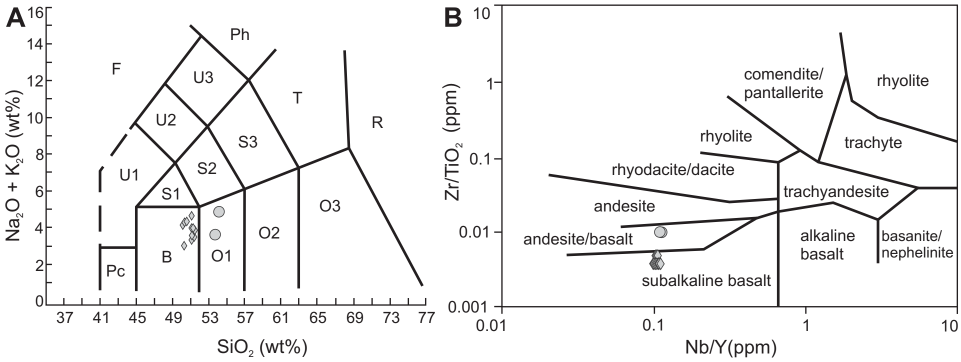

Fig. 6. **A**. Chemical classification of the volcanic rocks on total alkali silica (TAS) diagram of Le Maitre *et al*. (2002). **B**. Chemical classification of volcanic suite using Zr/TiO_2 *vs*. Nb/Y diagram (Winchester and Floyd 1977). Circles – Llano Point Formation, diamonds – Zamek Formation.

K-Ar dating. — The new K-Ar ages obtained from the Red Hill section are shown in Table 2. Microscopic observations confirm that all selected rock samples for K-Ar analysis are slightly or no alternated, and have the anatically required content of K and $^{40}Ar_{rad}$. The obtained results are shown in the diagram of potassium content *vs*. K-Ar age (Fig. 7).

Ten whole-rock K-Ar analysis of volcanic (basalt-basaltic andesite) rocks gave us consistent ages between 51 Ma and 42 Ma. No ages older than Ypresian have been obtained. The K-Ar ages for the Llano Point Formation and for the Zamek Formation range from 51.18±2.15 Ma to 50.49±2.57 Ma, and from 46.14±3.19 Ma to

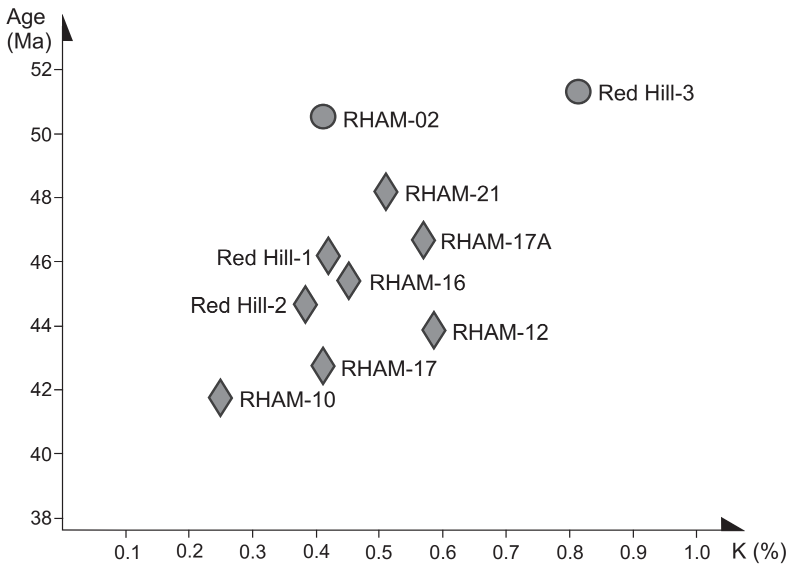

Fig. 7. A diagram of potassium content *vs*. the K-Ar age of the igneous rocks of the Baranowski Glacier Group at Red Hill. Circles – Llano Point Formation, diamonds – Zamek Formation.

Table 1

Major, trace and rare earth element concentrations of selected magmatic rock samples.

		RHAM-17A	RHAM-17	RHAM-16	RHAM-12	RHAM-10	RHAM-21	Red Hill-2	Red Hill-1	RHAM-02	Red Hill-3
		8365	8364	8505	8363	8362	8361	7976	7977	8366	7975
		basalt	basalt	basalt	basalt	basalt	basalt	basalt	basalt	basaltic andesite	basaltic andesite
SiO_2	%	50.53	49.07	49.24	49.28	49.83	48.74	50.17	50.31	51.93	52.52
Al_2O_3	%	21.50	21.72	21.56	19.52	19.90	19.80	19.39	19.49	17.91	18.41
Fe_2O_3	%	8.41	8.22	8.16	9.48	9.12	9.25	9.41	9.11	8.92	8.28
MgO	%	3.15	3.80	3.58	3.82	3.77	4.37	3.93	4.08	3.91	3.22
CaO	%	10.19	9.74	9.27	8.55	10.40	10.46	9.45	10.21	9.08	8.35
Na_2O	%	3.31	3.44	3.68	3.88	2.95	2.67	3.29	2.97	3.11	3.70
K_2O	%	0.60	0.62	0.51	0.58	0.29	0.28	0.42	0.45	0.40	1.02
TiO_2	%	0.87	0.85	0.84	1.01	0.94	0.97	1.00	0.92	0.99	1.01
P_2O_5	%	0.19	0.21	0.18	0.26	0.20	0.21	0.24	0.21	0.28	0.30
MnO	%	0.16	0.18	0.14	0.14	0.15	0.17	0.16	0.15	0.18	0.17
Cr_2O_3	%	<0.002	<0.002	<0.002	<0.002	0.004	0.002	0.003	0.003	0.003	0.004
Ni	ppm	<20	<20	<20	<20	<20	22	<20	<20	<20	<20
Sc	ppm	24	23	22	25	24	24	26	24	25	27
LOI	%	0.9	1.9	2.6	3.2	2.2	2.9	2.3	1.9	3.0	2.8
Sum	%	99.79	99.78	99.77	99.78	99.77	99.76	99.78	99.77	99.76	99.78
Ba	ppm	195	210	292	271	177	181	224	194	286	311
Be	ppm	1	2	1	<1	<1	2	<1	2	2	1
Co	ppm	18.9	18.9	18.8	21.8	26.1	24.7	22.8	23.9	22.7	19.9
Cs	ppm	0.1	0.1	0.4	0.2	2.0	0.1	0.3	1.7	0.2	0.1
Ga	ppm	18.7	21.4	20.4	20.2	20.0	18.8	18.6	19.2	18.9	20.2
Hf	ppm	1.5	1.8	1.7	2.2	1.5	1.8	2.0	2.1	2.9	2.8
Nb	ppm	1.4	1.9	1.8	2.1	1.5	1.8	2.0	1.7	3.5	3.2
Rb	ppm	6.2	6.7	6.8	4.1	4.2	1.3	1.9	3.4	2.2	15.1
Sn	ppm	<1	<1	<1	<1	<1	1	<1	<1	2	<1
Sr	ppm	655.5	654.7	636.2	571.4	722.6	707.8	671.4	707.6	728.2	528.1
Ta	ppm	<0.1	0.1	<0.1	<0.1	0.1	0.1	<0.1	<0.1	0.2	0.2
Th	ppm	0.8	1.0	0.9	1.6	2.0	1.7	1.6	1.8	1.7	1.9
U	ppm	<0.1	0.3	0.3	0.6	0.3	0.6	0.5	0.4	0.5	0.6
V	ppm	254	252	236	274	303	286	292	292	227	234
W	ppm	<0.5	3.9	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Zr	ppm	49.3	49.5	48.9	65.4	60.6	62.9	66.6	58.4	94.3	96.0
Y	ppm	12.9	14.2	13.4	16.6	13.7	16.0	16.2	14.2	23.5	20.7
La	ppm	8.2	8.2	7.5	9.9	9.5	10.2	11.1	9.7	12.2	13.3
Ce	ppm	17.8	18.1	16.3	22.5	22.3	23.8	25.0	21.1	27.8	30.5
Pr	ppm	2.69	2.73	2.56	3.68	3.25	3.53	3.66	3.18	4.15	4.24
Nd	ppm	12.0	12.4	11.4	17.3	15.2	18.1	15.9	15.3	19.7	19.1
Sm	ppm	2.88	2.92	2.91	3.97	3.67	3.95	3.99	3.32	4.63	4.43
Eu	ppm	1.02	1.11	1.05	1.40	1.33	1.33	1.37	1.22	1.43	1.41
Gd	ppm	2.99	3.23	2.89	3.81	3.61	3.67	4.18	3.41	4.52	4.87
Tb	ppm	0.46	0.45	0.44	0.56	0.56	0.53	0.57	0.52	0.69	0.72

Table 1 – *continued.*

		RHAM-17A	RHAM-17	RHAM-16	RHAM-12	RHAM-10	RHAM-21	Red Hill-2	Red Hill-1	RHAM-02	Red Hill-3
		8365	8364	8505	8363	8362	8361	7976	7977	8366	7975
		basalt	basalt	basalt	basalt	basalt	basalt	basalt	basalt	basaltic andesite	basaltic andesite
Dy	ppm	2.68	2.64	2.57	3.01	2.84	3.09	3.20	2.85	3.85	3.85
Ho	ppm	0.50	0.49	0.50	0.63	0.57	0.56	0.55	0.53	0.77	0.74
Er	ppm	1.39	1.41	1.33	1.65	1.68	1.55	1.77	1.61	2.35	2.40
Tm	ppm	0.20	0.23	0.21	0.24	0.24	0.25	0.25	0.20	0.36	0.32
Yb	ppm	1.44	1.37	1.30	1.54	1.52	1.57	1.73	1.59	2.19	2.23
Lu	ppm	0.19	0.21	0.18	0.24	0.22	0.22	0.24	0.20	0.33	0.33
TOT/C	%	0.05	0.02	0.02	0.05	0.05	0.18	0.05	0.05	0.18	0.17
TOT/S	%	<0.02	<0.02	<0.02	0.03	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Mo	ppm	0.5	0.5	0.3	0.7	0.6	0.5	0.6	0.7	0.5	0.8
Cu	ppm	131.2	100.9	112.2	167.9	124.2	164.8	143.0	134.5	127.5	108.1
Pb	ppm	1.1	1.6	2.1	3.6	2.6	4.6	2.8	2.0	3.8	3.1
Zn	ppm	39	49	50	68	46	52	53	44	50	69
Ni	ppm	3.4	3.2	3.5	7.5	11.5	11.7	7.6	11.5	10.6	12.6
As	ppm	<0.5	<0.5	1.6	1.0	6.2	1.1	3.7	3.1	8.8	1.0
Cd	ppm	0.3	<0.1	<0.1	<0.1	0.3	<0.1	0.4	0.3	<0.1	0.3
Sb	ppm	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Bi	ppm	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1
Ag	ppm	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Au	ppm	1.5	1.4	<0.5	<0.5	2.0	<0.5	<0.5	<0.5	<0.5	<0.5
Hg	ppm	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Tl	ppm	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Se	ppm	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5

41.88±1.51Ma, respectively. Therefore, these results indicate an Early to Middle Eocene age of the succession, embracing a time span from 51 to 47 Ma for fossil flora from the lower part of Zamek Formation.

Discussion

The Eocene magmatic activity was the most extensive in the north-eastern part of the South Shetland Islands, leading to the formation of the largest volume of magma in that part of the magmatic arc (Nawrocki *et al.* 2011). Isotopic dates suggesting the Paleocene and Oligocene volcanism are sparse, reported from the Fildes Peninsula and the King George Bay areas, respectively. However, there are also reports of older (Late Cretaceous) volcanic rocks from the western coast of Admiralty Bay in the so-called Warszawa tectonic block (Cao 1994). On the geological map of Admiralty Bay (Geological Map 2003), the volcanogenic successions with the supposed Late Cretaceous ages have been classified into the

Table 2

K-Ar ages obtained in this study.

Formation	No. of sample	ATOMKI Lab No. of sample	Rock type	Dated fraction	K (%)	K mean (%)	$^{40}Ar_{rad}$ (ccSTP/g)	$^{40}Ar_{rad}$ (%)	K/Ar age (Ma)
Zamek Formation	RHAM-17A	8365	basalt	whole rock	0.577 0.573	0.575	1.0564×10^{-6}	34.0	46.65±2.10
	RHAM-17	8364	basalt	whole rock	0.406 0.421	0.414	6.9595×10^{-7}	54.9	42.73±1.47
	RHAM-16	8505	basalt	–	0.458	–	8.1946×10^{-7}	13.5	45.45±4.56
	RHAM-12	8363	basalt	whole rock	0.582 0.586	0.584	1.0103×10^{-6}	31.2	43.96±2.11
	RHAM-10	8362	basalt	whole rock	0.256 0.253	0.254	4.1841×10^{-7}	49.7	41.88±1.51
	RHAM-21	8361	basalt	whole rock	0.517 0.520	0.518	9.8233×10^{-7}	66.0	48.13±1.56
	Red Hill-2	7976	basalt	whole rock	0.379 0.400	0.389	6.8288×10^{-7}	17.8	44.60±3.46
	Red Hill-1	7977	basalt	whole rock	0.421 0.423	0.422	7.6672×10^{-7}	20.4	46.14±3.19
Llano Point Formation	RHAM-02	8366	basaltic andesite	whole rock	0.417 0.421	0.419	8.3412×10^{-6}	28.8	50.49±2.57
	Red Hill-3	7975	basaltic andesite	whole rock	0.814 0.823	0.818	1.6509×10^{-6}	37.5	51.18±2.15

Paradise Cove Group and the Baranowski Glacier Group. The Cretaceous part of this stratigraphic scheme has been contested in more recent publications, which is strongly supported by the data presented here.

The taphoflora from a moraine at "Block Point" in front of the Baranowski Glacier, commonly though to belong to the Zamek Formation was described by Dutra (1989) to be typical of Tertiary floras. This flora is believed to represent the Zamek Formation. However, in the subsequent study on the Zamek Formation (Lindner-Dutra and Batten 2000) the autors refer to the K-Ar ages published by Birkenmajer *et al*. (1983) and repeated by Zastawniak (1994). These papers were commonly cited in the geological literature, highlighting a Late Cretaceous age of the Zamek Formation (Birkenmajer 2001, 2003; Birkenmajer and Zastawniak 1989; Askin 1992; Zastawniak 1994; Mohr 2001; Poole and Cantrill 2006). However, along with the progress of research in Admiralty Bay area, there have appeared doubts concerning the age of this formation.

Nawrocki *et al*. (2010, 2011) subdivided volcanic activity on KGI into five magmatic phases. The oldest, Late Cretaceous is represented by basalts of the Uchatka Point Formation. It was followed by next phase, considered as the most extensive, dated as Early–Middle Eocene (from ~53 to ~43 Ma), responsible for producing the largest volume of magma in this part of the island. According to new isotopic ages controlled by magnetostratigraphy received for Llano Point Formation was dated as Eocene age (Ypresian; ~51–49.5 Ma). Particular dates obtained for the Llano Point Formation at Patelnia Peninsula were 50.8±1.2 Ma (^{40}Ar-^{39}Ar), and 52.3±0.5 Ma (^{40}Ar-^{39}Ar) near Blue Dyke. Next magmatic activity are represented by lava flows or vertical intrusions dated as late Eocene (~37–35 Ma), late Oligocene dykes linked with opening of the Bransfield Strait (~28–25 Ma; *i.a.* Blue Dyke) and late Pliocene to Holocene activity (Penguin Island volcano). Cantrill and Poole (2012) go back to a Late Cretaceous age for the Zamek Formation, though consider this age as disputable. Relying on Dutra personal communication (2010) they presume Early Cenozoic age for this unit. Doubts about the age of formation were also expressed by Warny *et al*. (2015) who, based on Nawrocki *et al.* (2010, 2011), suggested Eocene age for Zamek Formation.

In this paper we document that the Baranowski Glacier Group exposed in slopes and rocky walls of Red Hill facing the Bransfield Strait is of the late Early to Middle Eocene age. The new whole-rock K-Ar analyses of volcanic (basalt-basaltic andesite) rocks from the Red Hill section gave us ages between 51 Ma and 42 Ma and no ages older than Ypresian have been obtained.

Furthermore, although it is notoriously difficult to make reliable correlations based on plant fossils, fossil plant assemblages that crop out at Red Hill seems to reveal affinity to other preglacial plant-bearing successions on King George Island. Similar fossil plant assemblages have been found in the Ezcurra Inlet Group (Arctowski Cove and Point Thomas formations) in Ezcurra Inlet, in the Mount Wawel Formation at Wawel and in the Lions Cove Formation in King George Bay (Mozer 2012, 2013). The K-Ar ages of volcanic intercalations in these preglacial successions fall in the range between 47–40 Ma (Lutetian and early Bartonian), which confirm an Middle Eocene age of the fossil flora.

Conclusions

Ten new K-Ar ages from volcanic rocks of the Baranowski Glacier Group (Llano Point and Zamek formations) at Red Hill in the southern part of King George Island indicate a late Early to Middle Eocene age of the succession (51–42 Ma). This corresponds to the major and most extensive phase of volcanic activity on the island (Nawrocki *et al*. 2010, 2011). Our results support the hypothesis that the peak of subduction-related volcanism in the north-eastern part of the South Shetland Islands was confined to the Eocene Epoch (Smellie *et al*. 1984). Chronostratigraphy of Birkenmajer's subdivisions improved by Nawrocki *et al.* (2010, 2011) seems to be valid also for the Red Hill exposure.

Our results also demonstrate that the flora in the Zamek Formation found at Red Hill is not of the Late Cretaceous age, which was repeatedly mentioned in the literature. The age of plant-bearing beds fall in range between *ca.* 51 and 47 Ma. The fossil plant assemblage from Red Hill shows similarity to other early Paleogene plant occurrences on King George Island.

The analysis of the Red Hill section calls for a revision of the position of the Baranowski Glacier Group in the stratigraphic scheme of King George Island.

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