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Pliocene age of the oldest basaltic rocks of Penguin Island (South Shetland Islands, northern Antarctic Peninsula)

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The Penguin Island volcano is located on the southern shelf of King George Island (South Shetland Islands, West Antarctica). Its activity is regarded as connected with the opening of the Bransfield Strait. Penguin Island is dominated by a 180 m high basaltic stratocone (Deacon Peak) with a 350 m wide crater containing a small basaltic plug inside and radial dykes, and it has a second principal vent – the Petrel Crater maar – that was formed during a phreatomagmatic eruption about 100 years ago. A low-potassium, calc-alkaline sequence of basaltic lava flows with intercalations of beach deposits (Marr Point Formation) forms the basement of the stratocone. The Marr Point Formation lava flows have never been dated before. Combined whole rock ^{40}Ar-^{39}Ar isotopic dating and magnetostratigraphy were applied for this purpose. We obtained an isotopic ^{40}Ar-^{39}Ar plateau age of 2.7 ±0.2 Ma, and together with the palaeomagnetic data, middle Pliocene age (Piacenzian) is implied for the basaltic plateau of Penguin Island.

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INTRODUCTION

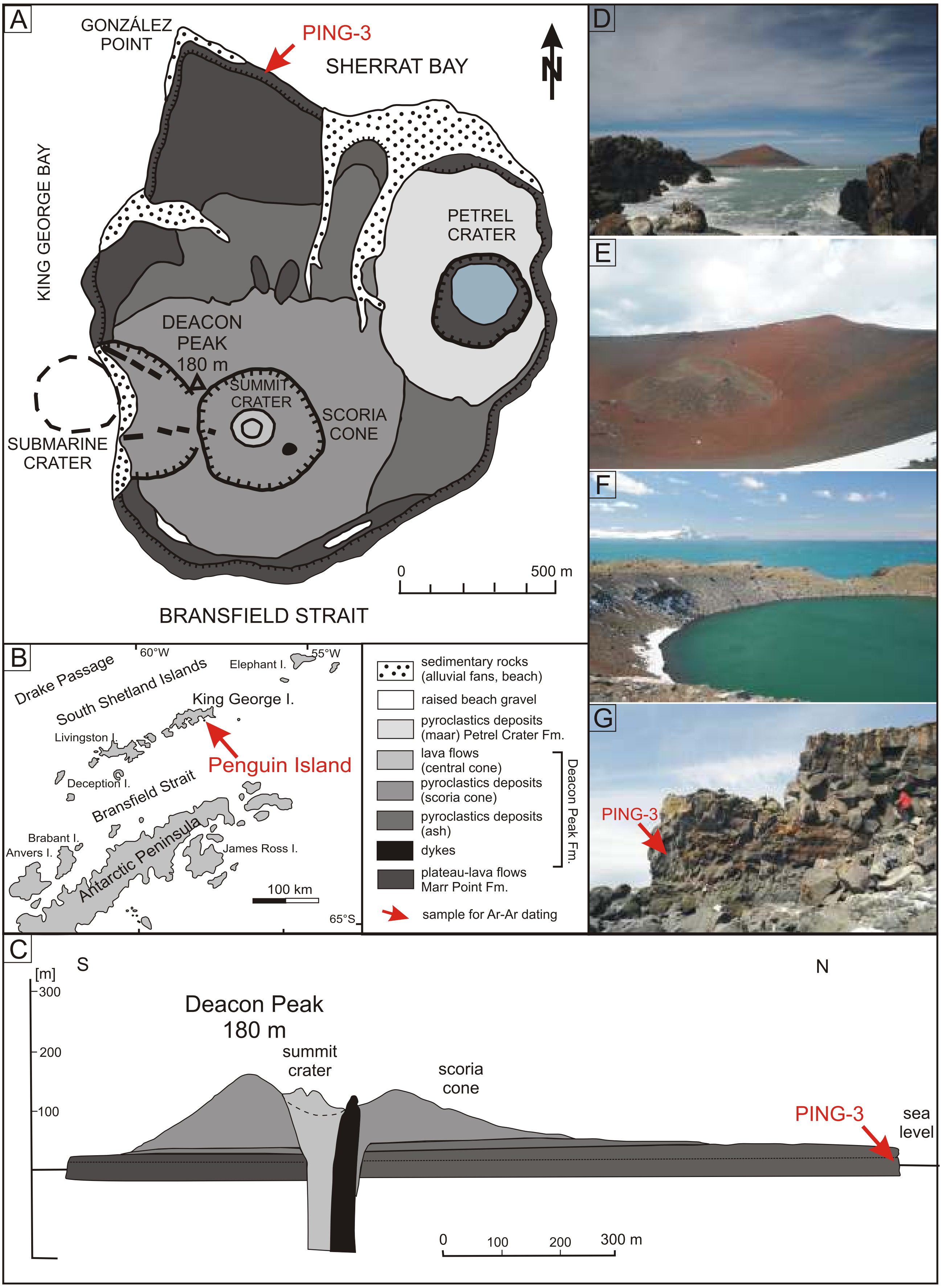
The South Shetland Archipelago was separated from the Antarctic Peninsula during the formation of the Bransfield Strait and development of the Bransfield Rift presumably in the Pliocene (about 4 Ma; Barker, 1982; Barker and Dalziel, 1983). Bransfield Strait was formed by rifting processes within a continental magmatic arc (Lawver *et al*., 1995, 1996; Galindo-Zaldivar *et al*., 2006). This extension is accompanied most probably by trench roll-back at the South Shetland Trench (Barker, 1982; Maldonado *et al*., 1994; Barker and Austin, 1998). Fretzdorff *et al.* (2004) classified the Bransfield Strait as an actively extending marginal basin.

Quaternary submarine and subaerial volcanism occurs along the axis of the Bransfield Strait (Bridgeman Island, Deception Island, seamounts) and also lies off the rift axis on the South Shetland Islands shelf (Weaver *et al*., 1979; Smellie, 1990; Keller *et al*., 1991; Smellie *et al*., 2002). Generally, the volcanic rocks are compositionally transitional between island arc basalts and mid-ocean ridge basalts (MORB; Fisk, 1990; Keller and Fisk, 1992). The volcanic and geochemical variations are not systematic along the axis and do not reflect the unidirectional propagation of rifting suggested by geophysical data (Keller *et al*., 2002).

Penguin Island is situated north of the present axis of rifting, close to King George Island being located between King George Bay and Sherrat Bay (Fig. 1B). The small volcanic island (1.84 km^2; Fig. 1C, D) with about 180 m high basaltic scoria cone (Deacon Peak) and a 350 m wide crater with a small basaltic plug inside and radial dykes, measures between 1.4 and 1.8 km in diameter (Fig. 1A, E). The second principal vent on Penguin Island is Petrel Crater maar (Fig. 1A, F) that was formed during a phreatomagmatic eruption about 100 years ago. Birkenmajer (1980) distinguished three lithostratigraphic units within the Penguin Island Group:

- the oldest basaltic lavas with intercalation of raised beach deposits – the Marr Point Formation;
- the sequence of lava flows and pyroclastic rocks of central scoria cone (stratocone) – the Deacon Peak Formation;
- the youngest pyroclastic rocks – the Petrel Crater Formation.

The age of volcanic rocks from Penguin Island is still poorly constrained. In the early 1960ies, Barton (1961, 1965) and Hawkes (1961) concluded that the basaltic platform of


A
GONZÁLEZ POINT
PING-3
SHERRAT BAY
N
KING GEORGE BAY
PETREL CRATER
DEACON PEAK 180 m
SUMMIT CRATER
SCORIA CONE
SUBMARINE CRATER
0 500 m
BRANSFIELD STRAIT
B
60°W
55°W
Drake Passage
South Shetland Islands
Elephant I.
King George I.
Livingston I.
Penguin Island
Deception I.
Bransfield Strait
Brabant I.
Anvers I.
Antarctic Peninsula
James Ross I.
100 km
65°S
sedimentary rocks (alluvial fans, beach)
raised beach gravel
pyroclastics deposits (maar) Petrel Crater Fm.
lava flows (central cone)
pyroclastics deposits (scoria cone)
pyroclastics deposits (ash)
dykes
Deacon Peak Fm.
plateau-lava flows Marr Point Fm.
sample for Ar-Ar dating
D
E
F
G
PING-3
C
S
N
[m]
300
200
100
Deacon Peak 180 m
summit crater
scoria cone
PING-3
sea level
0 100 200 300 m

Penguin Island and lava flows from Lions Rump, Turret Point, Three Sisters Point, Melville Peak and Cape Melville (all on King George Island) are Pliocene to Recent in age. These ideas were subsequently reinterpreted and most of these outcrops are substantially older than, and unrelated to, Penguin Island (Birkenmajer, 1979, 1982; Smellie *et al*., 1984; Troedson and Riding, 2002; Troedson and Smellie, 2002). Birkenmajer (1982, 2001) suggested a late Pleistocene age for the basaltic platform (Marr Point Formation) on the Penguin Island. The Deacon Peak scoria cone and Petrel Crater maar have been dated using the lichenometry method (Birkenmajer, 1979). The formation of Deacon Peak was dated at about 300 years ago, whereas the eruption forming Petrel Crater maar was dated at about 1905 AD. These results were supported by anecdotal historical observations of whalers and seal hunters. More recently, investigations of radial dykes which cut the principal cone of the Penguin volcano were conducted by Kraus (2005), who determined Ar-Ar ages on plagioclase mineral separates. The obtained results suggest an improbable Tortonian age (8.8 ±2.4 Ma) for the dykes cutting the western slope of the scoria cone.

STUDY AREA AND RESEARCH MATERIAL

The basaltic lavas alternating with beach deposits form the lowest unit of the Penguin Island Group and underlie the Deacon Peak scoria cone. They are covered by pyroclastic rocks (ashes, lapilli and bombs) deposited during the last eruptions. Birkenmajer (1979, 1982) suggested that the volcanic centre for the basal lavas lies to the north-east of the island. The sequence of lavas is up to 50 m thick and is mostly exposed as steep cliffs around the islands and in the inner slopes of Petrel Crater. The best and most easily accessible exposures of the basaltic platform are located along the northern margin of the island, especially close to the Gonzales Point where there are steep cliffs over 20 m high and about 300 m long (Fig. 1G). Locally, there is a noticeable contact between two lava flows emphasized by the presence of autobreccia between the two flows. Macroscopically, two main lithological and textural varieties of porphyritic basalts are visible: vesicular outer parts of the lava flow (carapace facies) and a massive core. The vesicles are commonly elongated in shape, rarely irregular, and exceed 1 cm in length. Their shape, if elongated, usually corresponds with a flow-banded texture. Locally, there is a noticeable flow folding. Moreover, due to shearing (Dadd, 1992), stretching and brecciation of flow-banded volcanic rocks are sporadically observed. The volcanic rocks are not altered. Veins and vesicles filled by hydrothermal minerals were not observed.

The dark grey basaltic lavas of the plateau display porphyritic, rarely glomeroporphyric, intersertal or intergranular texture. Locally, they are scoriaceous. The studied rocks comprise olivine, plagioclase and clinopyroxene phenocrysts that may exceed up to 1.2 mm in length (Fig. 2). The groundmass contains plagioclase, olivine, clinopyroxene and chromite crystals and also glass. Plagioclase crystals occur as euhedral and subhedral phenocrysts sporadically showing zoning (Fig. 2) and as small (less than 0.3 mm in length), decussate laths in the groundmass. The core and the rims of plagioclase phenocrysts have a bytownite and labradorite compositions, respectively. Clinopyroxenes (Ti-augite; Fig. 2A) occur as euhedral, rarely twinned phenocrysts (~300 μm in length) and as groundmass, subhedral crystals (70 μm). The lavas contain two generation of olivine, which is the main mafic mineral. The phenocrysts (Fig. 2B–D), typically 600 μm in length, occur sporadically as glomerocrysts. Chromite occurs as a groundmass crystals (up to 200 μm in diameter; Fig. 2D) and as inclusions within olivine phenocrysts (50–100 μm in diameter; Fig. 2B).

All the analysed samples are low-potassium, calc-alkaline basalts containing *ca*. 50% of SiO_2 (Table 1). Weaver *et al*. (1979) suggested that the Penguin Island lavas are magnesian, mildly alkaline olivine basalts with up to 4% normative nepheline. In the total alkalis *versus* silica (TAS) classification diagram (Le Maitre *et al*., 1989), all the samples fall within the basaltic field. The rocks are enriched in large-ion lithophile elements and depleted in high field strength elements relative to N-MORB (Normal Mid-Ocean Ridge Basalt; Fig. 3A). The basalts are characterized by a relatively high concentration of elements such as Co, Cr and Ni. The absolute content of rare earth elements vary from 49.47 to 59.73 ppm for all the samples. Chondrite-normalized REE diagrams (Sun and McDonough, 1989) are relatively smooth and show steep patterns for LREE and MREE (Fig. 3B). The enrichment in LREE is clearly decipherable as the $(La/Lu)_{CN}$ ratio ranges from 4.7 to 6.3. These rocks are also characterized by the lack of any Eu anomalies or, in some samples slight positive anomaly.

MATERIAL AND METHODS

The sample for whole-rock ^{40}Ar-^{39}Ar isotope dating and for palaeomagnetic study was selected from fresh, massive parts of the older lava after thorough examination of thin sections. The studied lava flow is exposed in cliffs, about 200 m

Fig. 1 A – location of the analysed sample (PING-3) on a geological map of the Penguin Island volcano (slightly modified after Birkenmajer, 1979, 1982); B – location of the Penguin Island volcano in the South Shetland Islands; C – geological cross-section of the Penguin Island volcano (based on Birkenmajer, 1979, 1982; modified); D–G – photographs of the Penguin Island volcano: D – Penguin Island (Deacon Peak), view from Turret Point; E – crater of principal cone with a small basaltic plug; F – Petrel maar, view towards Melville Peak; G – two lava flows of the basaltic plateau of the Penguin Island volcano with detailed location of the analysed sample

Table 1

Whole-rock major and trace element data for basaltic lavas of the Penguin Island plateau

Sample	Maar-2	PING-1a	PING-3a	PING-3c	PING-3
SiO_2	49.8	50	50	49.3	48.8
TiO_2	1.12	1.29	1.13	1.12	1.08
Al_2O_3	15.6	16.45	15.85	15.45	15.6
Fe_2O_3	9.39	9.34	9.33	9.47	9.67
MnO	0.15	0.14	0.15	0.15	0.16
MgO	9.84	8.15	9.55	9.83	10.65
CaO	9.69	9.75	9.74	9.82	9.73
Na_2O	3.16	3.55	3.3	3.13	3.29
K_2O	0.48	0.62	0.49	0.47	0.48
P_2O_5	0.23	0.44	0.23	0.26	0.24
LOI	0.1	0	–0.29	–0.39	0.8
Total	99.56	99.73	99.48	98.61	100.5
Ba	125.5	153	135	136	149
Co	40.7	37.8	42.4	43.4	47.4
Cr	490	350	510	520	580
Cs	0.1	0.14	0.05	0.08	0.08
Cu	107	80	119	113	127
Ga	17.7	20.4	19.5	18.7	20.1
Hf	1.6	2	1.8	1.8	1.9
Nb	2.7	3.5	2.9	2.8	3
Ni	173	122	169	186	223
Pb	5	5	5	5	6
Rb	4.9	6.2	4.4	4.3	5.1
Sr	463	568	498	493	536
Ta	0.2	0.2	0.2	0.2	0.2
Th	0.93	1.14	0.98	1	1.04
U	0.21	0.25	0.15	0.15	0.17
V	229	272	257	257	273
W	4	3	5	6	8
Y	12.1	12.6	13.1	13	13.9
Zn	70	78	76	75	79
Zr	56	68	63	61	60
La	7.5	9.5	8.2	8.1	8.8
Ce	17.6	22.1	19.3	19	20.3
Pr	2.41	3.03	2.68	2.57	2.91
Nd	10.3	12.5	11.4	11.1	12.2
Sm	2.37	2.84	2.57	2.55	2.88
Eu	0.83	0.99	0.89	0.93	0.96
Gd	2.57	2.81	2.77	2.64	3.14
Tb	0.4	0.43	0.43	0.43	0.49
Dy	2.31	2.38	2.29	2.42	2.74
Ho	0.47	0.46	0.51	0.49	0.55
Er	1.26	1.26	1.34	1.39	1.56
Tm	0.17	0.17	0.19	0.19	0.2
Yb	1.11	1.1	1.2	1.19	1.29
Lu	0.17	0.16	0.19	0.18	0.2

The major oxides were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES) at ALS Laboratory in Canada and reported in wt.% with total Fe as Fe_2O_3, whereas the trace elements, including REE, were measured by inductively coupled plasma mass spectrometry (ICP-MS) and reported in ppm

south-east of González Point (PING-3, S 62°05.730', W 57°55.820').

The sample was prepared according to the standard procedures: cut with a diamond saw, washed, hand-crushed and then pulverised in a tungsten carbide mill. Samples were cleaned and processed into a range of grain-sizes and the 0.25–0.5 mm fraction was selected. Additionally, phenocrysts were removed from the samples. Geochronological investigation was performed at the ^{40}Ar-^{39}Ar Geochronology Laboratory of the University of Lund, Sweden. The samples selected for ^{40}Ar-^{39}Ar geochronology were irradiated together with the TCR sanidine standard (28.34 Ma following Renne *et al.*, 1998), for 24 hours in the Oregon State research reactor. J-values were calculated with a precision of <0.25% and are reported for each sample in the data tables. Decay constants utilized were those given in Steiger and Jäger (1977). The ^{40}Ar-^{39}Ar geochronology laboratory at the University of Lund contains a *Micromass 5400* mass spectrometer with a Faraday and an electron multiplier. 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.

Five core specimens, 2.5 cm diameter and 2.2 cm length, were drilled from the studied hand sample for palaeomagnetic investigations. They were subjected to an alternating-field (AF) demagnetisation experiment. The 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 the linear segments were calculated using principal component analysis (Kirschvink, 1980).

RESULTS

WHOLE-ROCK ^{40}Ar-^{39}Ar ISOTOPE DATING

The results of the ^{40}Ar-^{39}Ar whole rock age estimation are presented in Figure 4. The measurement data of mass spectrometry analysis are listed in Table 2. It is clearly visible that the Marr Point Formation lava yielded a statistically significant plateau age of 2.7 ±0.2 Ma. The five steps defining the plateaus correspond to about 50.5% of the ^{39}Ar released. The mean square weighted deviation (MSWD; calculated for n-1 degrees of freedom) for the plateau age is 1.66 and the corresponding ρ values is 0.16 (ρ – probability of occurrence based on Chi Square Tables).

MAGNETOSTRATIGRAPHY

All the specimens were strongly magnetised. The intensity of NRM ranged from 7.2 to 8.8 A/m. The NRM was demagnetised

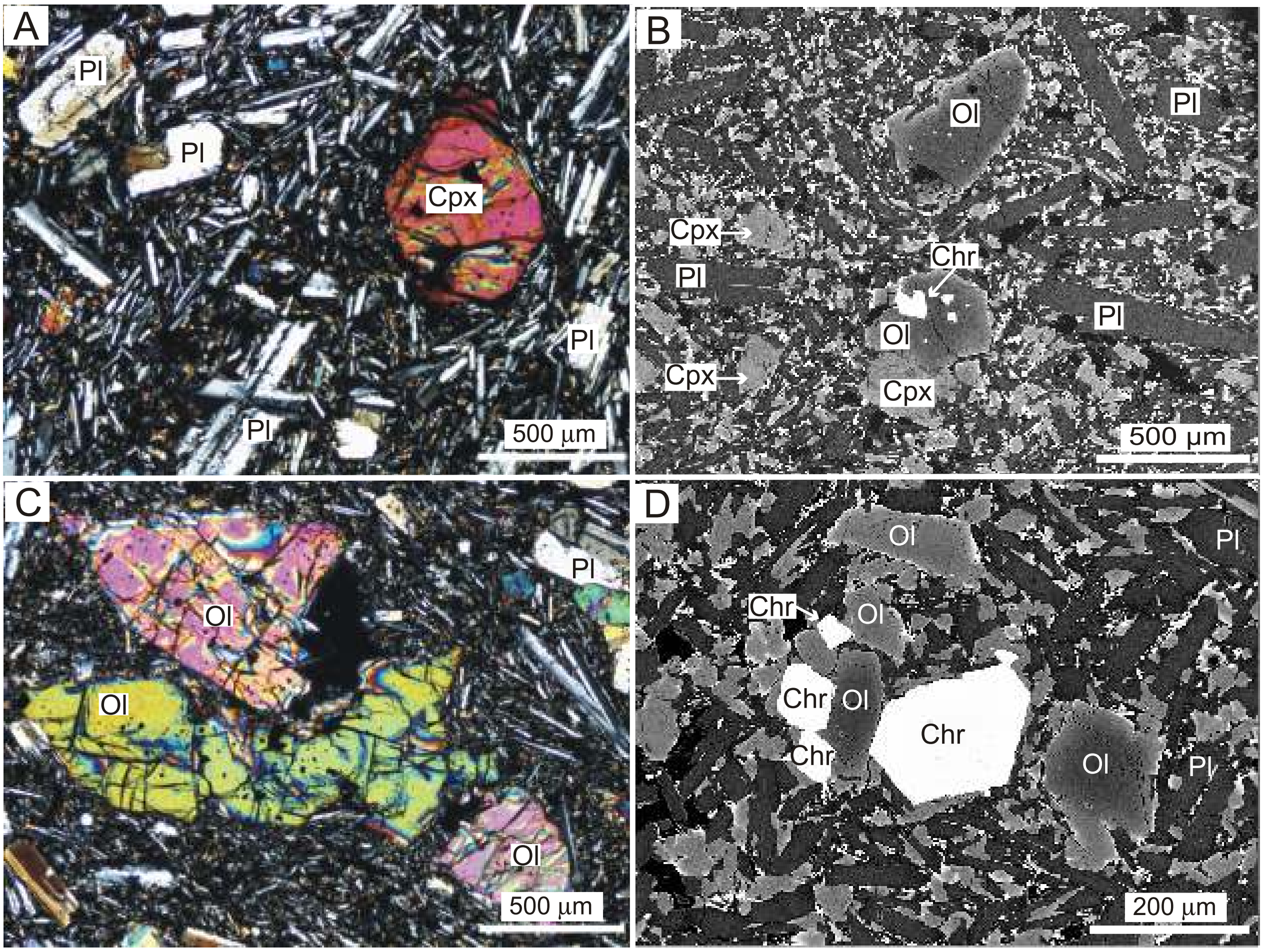


Fig. 2. Photomicrographs of basaltic rocks from Penguin Island (Marr Point Formation)

A – clinopyroxene phenocryst surrounded by groundmass of plagioclase laths, clinopyroxene olivine crystals and glass, crossed polars; **B** – BSE (back-scattered electrons) image of clinopyroxene, plagioclase and olivine phenocrysts with chromite inclusions; the groundmass containing plagioclase laths, clinopyroxene, olivine and also chromite crystals; **C** – olivine phenocrysts crossed polars; **D** – BSE image of olivine and chromite crystals; mineral symbols after Kretz (1983): Chr – chromite, Cpx – clinopyroxene, Pl – plagioclase, Ol – olivine; BSE images performed using *Cameca SX 100* instrument in Polish Geological Institute – National Research Institute in Warsaw

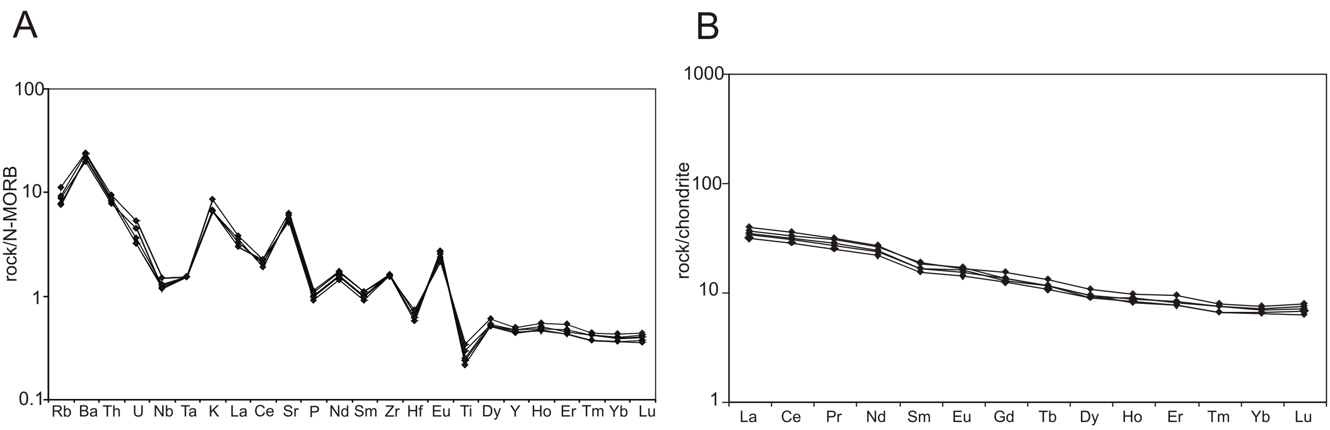


Fig. 3. N-MORB-normalised multi-element patterns (A) and chondrite-normalised REE patterns (B) for basaltic lavas from Penguin Island

The normalisation values for N-MORB and chondrite are from Sun and McDonough (1989)

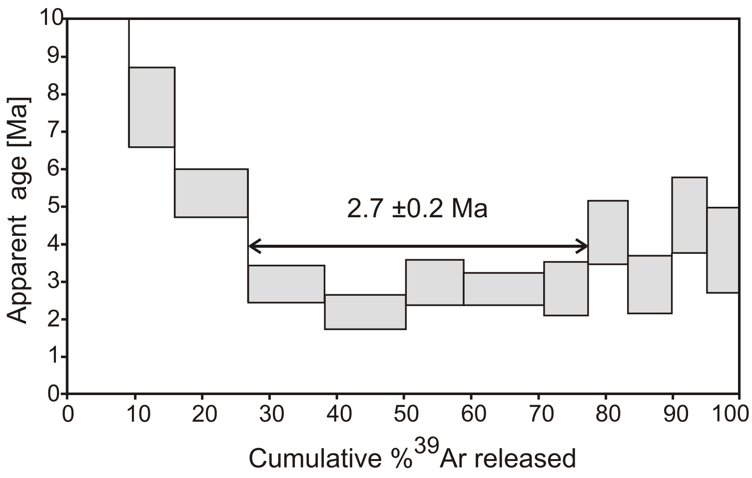


Fig. 4. Stepwise argon release spectrum for a whole-rock lava sample from the Marr Point Formation of Penguin Island volcano

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

in an alternating field of amplitude up to 100 mT and more than 90% of the initial intensity of NRM was removed in a field not higher than 35 mT (Fig. 5A). Well-defined characteristic directions with steep negative inclinations group in the second quarter of the hemisphere. A normal magnetic polarity for the studied sample is therefore evident. The normal polarity of sample 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 rock studied is coeval with the upper part of the Magnetozone Gauss (Fig. 5B).

CONCLUSIONS

1. The new isotopic age presented here constrains the age of crystallisation and emplacement of basaltic magma forming the basal part of Penguin Island (Marr Point Formation) to the middle Pliocene (2.7 ±0.2 Ma). Combined ^{40}Ar-^{39}Ar and palaeomagnetic data imply a Piacenzian age for the basaltic plateau of Penguin Island.

2. The lava flows that built up the Penguin Island platform are more "primitive" than typical volcanic rocks from King George Island except for the Low Head lava dome (Smellie *et al*., 1998). The lavas are characterized by higher MgO, Cr, Ni and Co contents, than subduction-related lavas and they show some compositional characteristics of alkaline magmas.

3. Volcanism within Bransfield Strait is believed to have started in the Pleistocene at about 0.3 Ma (e.g., Birkenmajer and Keller, 1990; Keller *et al.*, 1992). On the other hand, subduction-related magmatism is unknown after 9.8 Ma in the South Shetland Islands area (Smellie *et al*., 1984; Birkenmajer *et al*., 1986). Our new data indicate that the first signs of volca-

Table 2

^{40}Ar-^{39}Ar analytical data for a basalt lava from the Marr Point Formation (Penguin Island)

PING-3 (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 ×10^{-14}	% Step	Cum [%]	^{40}Ar* [%]	Age [Ma]	±Age
1	2	0.38475	0.034703	0.1	2.03833	0.1587	9.1	9.1	16.6	22.29797	0.59428
2	2.1	0.33555	0.014211	0.3	0.69465	0.1144	6.6	15.7	14.2	7.63005	0.5218
3	2.3	0.65711	0.008705	1	0.48556	0.1955	11.2	26.9	16	5.33672	0.31572
4	•2.5	0.56536	0.005601	1.4	0.26801	0.1985	11.4	38.3	14.1	2.9381	0.25411
5	•2.7	0.58218	0.004424	1.8	0.2005	0.2046	11.8	50.1	13.5	2.19846	0.23023
6	•2.9	1.03788	0.003624	3.9	0.27046	0.1527	8.8	58.9	20.8	2.96486	0.29909
7	•3.1	0.57898	0.003581	2.2	0.2536	0.2093	12	70.9	19.7	2.78018	0.21588
8	•3.3	0.63335	0.00362	2.4	0.25573	0.1142	6.6	77.5	19.7	2.80351	0.35681
9	3.5	1.30355	0.003906	4.5	0.39325	0.1037	6	83.4	26.3	4.30944	0.40547
10	3.7	1.00503	0.005323	2.5	0.2664	0.1115	6.4	89.8	14.8	2.92047	0.38718
11	4	1.43212	0.0069	2.8	0.43476	0.0931	5.3	95.2	18	4.76366	0.4918
12	4.5	1.48271	0.009903	2	0.34925	0.0837	4.8	100	10.9	3.82772	0.56215
Integ. age =										5.4	0.3
(•) Plateau age =			MSWD = 1.66 ρ = 0.16 steps 4–8				50.5			2.7	0.2

Codes for the column titles are as follows: step – number of heating steps; Pwr/T°C – degassing power (dot indicate plateau); Ca/K – 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

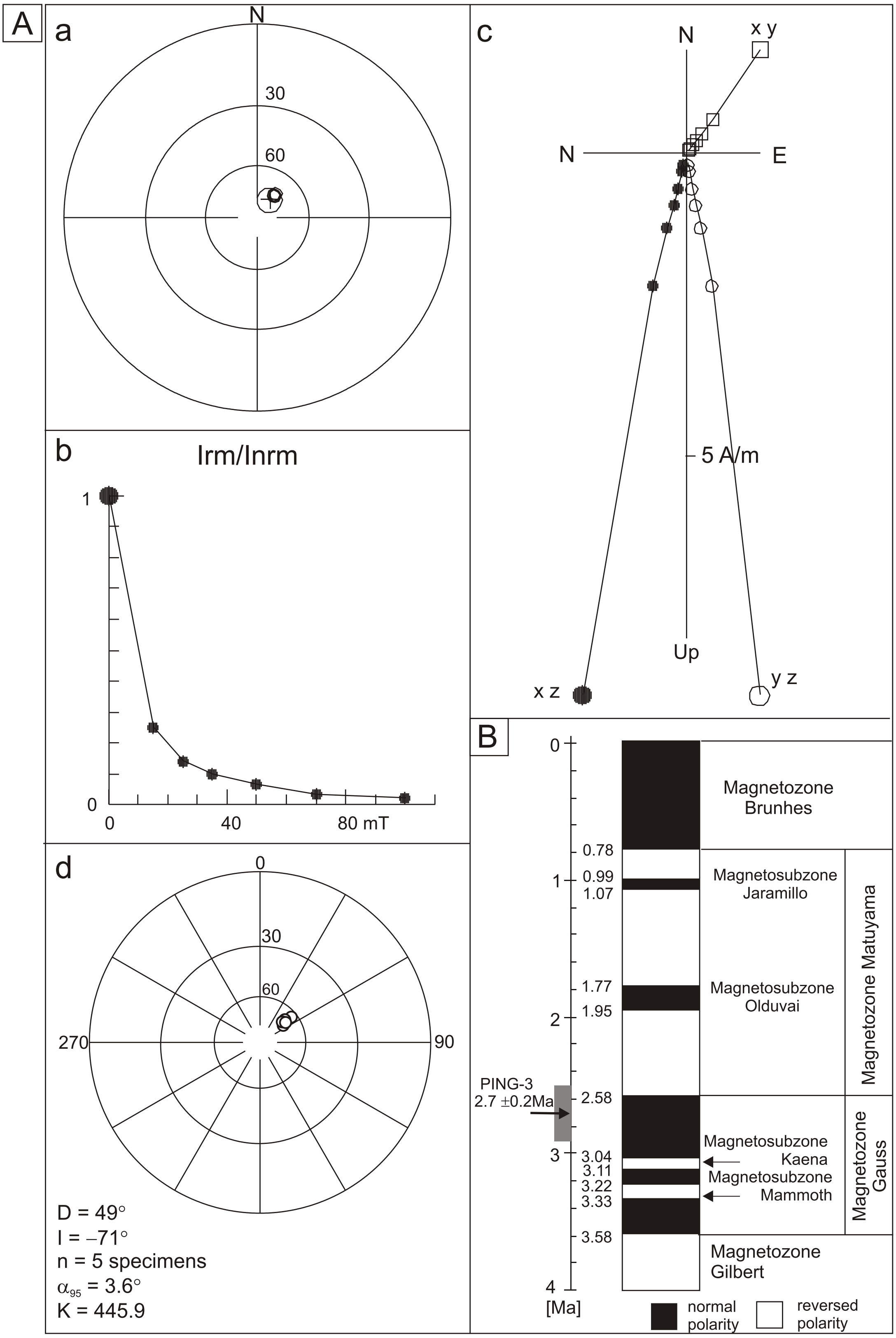


Fig. 5A – typical demagnetisation characteristics of the studied basaltic sample from the Penguin Island;
B – correlation of obtained normal magnetic polarity and Ar-Ar isotope age to the GPTS (Gradstein *et al*., 2004)

a – stereographic projection of demagnetisation path; b – intensity decay curve; c – orthogonal plot; d – stereographic projection of line fit palaeomagnetic directions isolated from particular specimens with parameters of mean direction (D, I – mean declination and inclination; α_{95}, K – Fisher's statistics parameters, n – number of specimens; Irm – intensity of remanent magnetisation, Inrm – initial intensity of remanent magnetisation; open (closed) symbols denote upward (downward) pointing inclinations nic processes that accompanied the opening of Bransfield Strait took place in the middle Pliocene.

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