БЪЛГАРСКА АКАДЕМИЯ НА НАУКИТЕ • BULGARIAN ACADEMY OF SCIENCES

ГЕОХИМИЯ, МИНЕРАЛОГИЯ И ПЕТРОЛОГИЯ • 42 • СОФИЯ • 2005
GEOCHEMISTRY, MINERALOGY AND PETROLOGY • 42 • SOFIA • 2005

The isolated plutons in Hurd Peninsula, Livingston Island, Antarctica: Petrological and geochronological evidences of their affiliations to Barnard Point Batholith

Borislav K. Kamenov, Xiangshen Zheng, Dimo Dimov, Christo Pimpirev

Abstract. South-east Livingston Island is dominantly composed of plutonic rocks, among them Barnard Point Batholith being of Eocene age. Several small plutonic bodies are exposed on the eastern side of Hurd Peninsula not very far from the batholith. They have been considered for a long time as related genetically with it, but unanimous evidence for such affiliations is still not published. The new petrographic and geochemical studies on the stocks exposed at the nunataks Moores Peak, Cerro Mirador, Dell Castillo, Willan and Pliska reveal that the main rock varieties are diorite, quartz-diorite and granodiorite, similar to those of the batholith.

Typical geochemical fingerprints of subduction-related processes (*LILE* enrichment, *HFSE* depletion compared to *LREE*) are observed and they are correlated to igneous rocks from other outcrops in the Hurd Peninsula. The calc-alkaline affinity of the magmas is not very different from the trend of samples from the volcanics of the Mount Bowles Formation, but at the same time it is also characteristic feature of the Barnard Point tonalite as well. All samples from the stocks studied fall in the medium-potassium series. Whole-rock and mineral compositions are compatible with processes of crystal differentiation and magma mixing responsible for the rock variability.

The age constraints on the emplacement of the stocks are given by Ar-Ar isotope analyses (whole-rock and monomineral). The new-obtained dating is in the range 45-50 Ma, thus coinciding perfectly with the published already isotopic age of the Barnard Point tonalite of 46 Ma. This is also the age of one of the well-spread dyke populations in Livingston Island. The new precise dating and the general geochemical correlation support more firmly that all plutonic exposures along the eastern end of Hurd Peninsula are really apophyses of the larger Barnard Point Batholith.

Key words: Livingston Island, Antarctic plutons, rock-forming mineralogy, geochemistry, $^{40}Ar/^{39}Ar$ dating
Addresses: B.K. Kamenov, D. Dimov and C. Pimpirev – Faculty of Geology and Geography, Sofia University, 1000 Sofia, Bulgaria; E-mail: Kamenov@gea.uni-sofia.bg; X. Zheng - Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, People's Republic of China

Каменов, Б.К., К. Зенг, Д. Димов, Х. Пимпирев. 2005. Изолираните плутони от п-ов Хърд, о-в Ливингстън, Антарктида: Петроложки и геохроноложки доказателства за принадлежността им към батолита Бърнард Пойнт. *Геохим., минерал. и петрол.*, **42**, 67-86.

Резюме. Югоизточната част на остров Ливингстън е изградена главно от плутонични скали. Между тях е и еоценския по възраст батолит Бърнард Пойнт. Няколко малки плутонични тела са разкрити от източната страна на полуостров Хърд, недалеч от батолита. От дълго време те са били считани за генетично свързани с него, но недвусмислени доказателства за такава принадлежност все още не са публикувани. Новите петрографски и геохимични изследвания върху разкритите щокове при нунатаците Мурес Пик, Серо Мирадор, Дел Кастильо, Уилън и Плиска разкриват, че главните им скални разновидности са диорит, кварцдиорит и гранодиорит, аналогични на скалите на батолита.

Наблюдаваните типични геохимични особености, свързани със субдукция (обогатяване на елементите *LIL*, изтощаване на елементите *HFS* по отношение на *LRE* елементи) са съпоставени с тези на магматични скали от други разкрития в полуостров Хърд. Калциево-алкалният афинитет на магмите не е много по-различен от тенденцията на пробите от формацията Маунт Боулес. Едновременно с това той е и характерна особеност на скалите от тоналитовия батолит Бърнард Пойнт. Всички проби от изучените щокове попадат в среднокалиевата серия. Скалните и минерални анализи подкрепят наличието на процеси на кристално фракциониране и на магмено смесване, предизвикали скалното разнообразие.

Обосновките за възрастта на внедряване на щоковете са изведени от Ar-Ar анализи (общи скални проби и мономинерални фракции). Новополучените датировки са в обхвата 45-50 Ма, което е отлично съвпадение с вече публикуваната възраст на тоналита от батолита Бърнард Пойнт - 46 Ма. Такава е също така и възрастта на една от широко разпространените в остров Ливингстън дайкови групи. Новата точна датировка и общата геохимична корелация подкрепят по-уверено идеята, че всички плутонични разкрития от източния край на полуостров Хърд са наистина апофизи на големия батолит Бърнард Пойнт.

Introduction

Livingston Island contains locally well-exposed small plutonic outcrops along the eastern coast of Hurd Peninsula. They are emplaced into the volcanic sequence, known as Mount Bowles Formation (Smellie et al., 1984) assumed to be Cretaceous on the basis of regional correlations (Smellie et al., 1995). All these small stocks were interpreted as apophyses of the larger Barnard Point Batholith (Hobbs, 1968; Caminos et al., 1973; Willan, 1994; Smellie et al., 1996; Kamenov, 1997), but weighty arguments in favour of this idea were not advanced up to now. Published petrological and geochronological correlations with the located at a short distance batholith are lacking. In spite of the mentioning of these small bodies in papers of Pallas et al. (1992, Fig. 12), Willan (1994, Fig. 10), Kamenov and Monchev (1996, Fig. 1) no mineralogical and geochemical details are available for the most of them.

The only one K-Ar dating of Willan Nunatak exposure (Smellie et al., 1995, 43.4 Ma) was assigned to the likely emplacement age of the other plutonic bodies. This age was compared to those of tonalite from Barnard Point (Smellie et al., 1984, 46±2 Ma, K-Ar) and of granodiorite from Noel Hill of King George Island (Smellie et al., 1984, 47±1 Ma). Stratigraphically all these K-Ar ages would signify an Eocene age. Nearly similar K-Ar age was reported for granodiorite from Cerro Mirador Nunatak (Kamenov, Monchev, 1996, 40 ±2 Ma). Precise determination of the emplacement age of the other plutonic bodies with more reliable methods is not known. As glaciers and ice sheets throughout the island are currently being subjected to protracted reduction, new clean exposures have been revealed, and a reassessment of the map of this part of the Hurd Peninsula was unavoidable.

In this paper, the petrology of the several small stocks exposed at the nunataks Cerro Mirador, Dell Castillo, Willan, Moores Peak and Pliska is revised and filled out with new geochemical analyses of the rocks and with the first published chemical composition of their rock-forming minerals. The new-obtained data and correlations would be of help in every attempt to explain the peculiarities of this magmatism. The center is on the elucidation of the chemical variation of the rocks, which will enable the research workers to arrive at a common nomenclature and deeper under-standing of the petrogenesis of the Eocene magmatism in the island. We present unpublished new whole-rock and mineral precise Ar-Ar dating of samples from a subvolcanic body at Moores Peak and at Cerro Mirador stock with the purpose to confirm or reject the ongoing interpretations.

Geological background

The South Shetland Islands are a fragment of the Antarctic Peninsula Mesozoic to Cenozoic magmatic arc that lies above a continental basement. The evolution of the arc is controlled by the subduction of the proto-Pacific oceanic

Fig. 1. View to the Barnard Point Batholith across the False Bay. An outcrop of Cerro Mirador Stock - in the lower right part of the photo

Фиг. 1. Поглед към батолита Бърнард Пойнт на другата страна на Фолс Бей. Разкритие на щока Серо Мирадор – в долната дясна част на снимката

crust beneath Lesser Antarctica (Storey, Garett, 1985; Smellie et al., 1995). The second largest of the archipelago Livingston Island hosts several of the main geological units of the Antarctic Peninsula region – fore-arc basin, magmatic arc and extension-related back-arc volcanics (Storey et al., 1996; Kamenov, 2004).

The Miers Bluff Formation (Willan et al., 1994) makes up most of Hurd Peninsula. It consists of a NW- dipping, open-folded and mostly overturned turbiditic sequence (Hobbs, 1968; Smellie et al., 1984; Tokarski et al., 1997; Smellie et al., 1995). The depositional age of the formation is not universally accepted. Late Paleozoic (Grikurov et al., 1970), Early Triassic (Smellie et al., 1984; Willan et al., 1994), Late Triassic (Onuyang et al., 2000), Early Jurassic (Herve et al., 1991) or Late Cretaceous (Stoykova et al., 2002; Pimpirev et al., 2004) ages were substantiated on different grounds.

The Mesozoic to Cenozoic magmatic arc (Thomson et al., 1983) consists both of calc-alkaline plutonic rocks (parts of the Antarctic Peninsula Batholith, Leat et al., 1995) and volcanic and volcanoclastic rocks (assigned to the Antarctic Peninsula Volcanic Group - APVG, Gledhill et al., 1982; Thompson, 1982). The plutons are of Late Cretaceous age (Kamenov, 1997) and of Eocene age (Smellie et al., 1995, 1996) and the volcanic exposures yielded discrepant results – 111-40 Ma, the prevailing dating being within the Eocene epoch. The volcanic exposures in Hurd Peninsula are known as Mount Bowles Formation.

The possibility that the K-Ar system of the dated as Eocene volcanic samples have been thermally reset is not to be excluded.

Extension-related mafic volcanics and dykes (Oligocene to Recent) are related to the opening of the Bransfield Strait back-arc basin (Keller et al., 1991; Smellie, 2001; Kamenov, 2004). These rocks outcropped at northeastern Livingston Island are known as Inott Point Formation (Hobbs, 1968; Smellie et al., 1984).

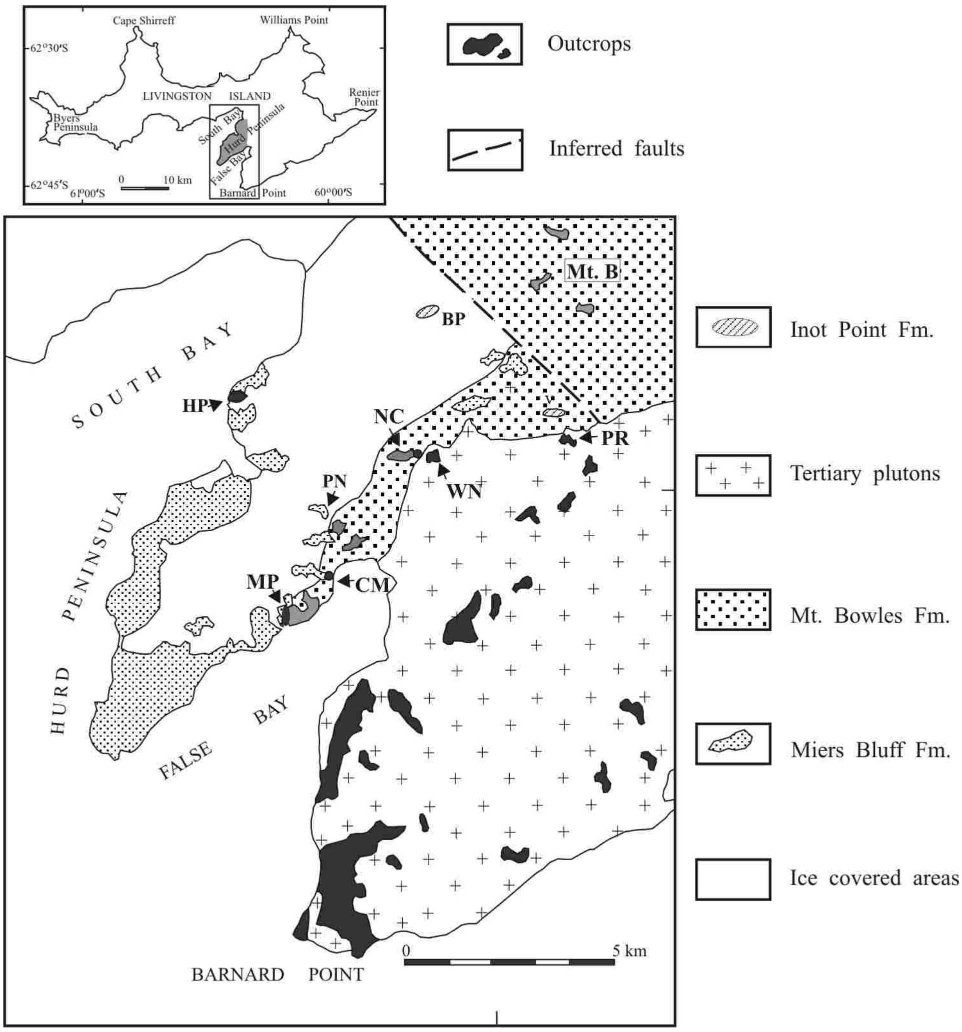


Fig. 2. Simplified sketch map showing the location of the exposures of the plutonic stocks in Hurd Peninsula. MP – Moores Peak, CM – Cerro Mirador, PN – Napier Peak, NC – Nunatak Dell Castillo, WN – Willan Nunatak, PR – Pliska Range, BP – Burdic Peak, Mt B – Mount Bowles, HP – Hesperides Point pluton

The tonalite pluton on Barnard Point on the southeastern Livingston Island has a gabbroic and dioritic petrographic composition passing inwards to tonalite and minor grano-diorite (Smellie et al., 1984; Armstrong, Willan, 1996). A sample from Mac Kay Peak is dated Eocene in age (whole-rock Rb-Sr age is 46 ± 2 Ma). The several small hypabyssal intrusions emplaced along the northwestern coast of the False Bay in Hurd Peninsula are only some 1-3 km away from the northwestern exposures of the Barnard Point Batholith and they are intruded either in the rocks of the Miers Bluff Formation, or in the rocks of the Bowles Formation. Certain new K-Ar dating have come to light recently for two of these stock-like small plutonic bodies and they coincided within the boundaries of Eocene age, like the ones obtained from the Barnard Point Batholiths (Kamenov, Monchev, 1996; Smellie et al., 1995).

Geology and petrography

1. Moores Peak

Moores Peak is one of the expressive nunataks within the southeastern part of Hurd Peninsula. It was Hobbs (1968) who made the first mention of some volcanic rocks exposed in the hill Moores. Willan (1994) describing the mineralized veins in the Hurd Peninsula published a geological sketch-map where in addition to outcrops of the Mount Bowles Formation plotted a small hypabyssal plutonic body supposed to consist of tonalite. In a paper devoted to the volcanic sequences from the central part of Livingston Island Smellie et al. (1996) presumed that all volcanic rocks of Mount Bowles Formation have been affected by a thermal event caused by the intrusion of the Barnard Point Batholith. No any geochemical or geochronological data for the plutonic body are given there.

The exposed rocks in the nunatak are referred to the Miers Bluff Formation (Moores Peak breccias member) and to the Mount Bowless Formation.

The subvolcanic pluton emplaced within the volcanics is made up by two united in their northern parts elongated bodies, orientated in N-S direction. They could be traced in the exposed area to nearly 200 m. The rocks are composed of equigranular and mesocratic fine-grained to medium-grained gabbro and diorite. The dark-grey colour on fresh surface is gradually passing into light green in the hydrothermally altered paths of the rock. The following petrographical varieties are discriminated: weakly porphyroid quartz-bearing microgabbro, quartz-bearing pyroxene-hornblende diorite and hornblende diorite. The hypidiomorphic granular texture is characteristic for the central parts of the magmatic body, but sometimes intersertal and even granohyric textures are observed in its marginal parts. The porphyry minerals are clinopyroxene, amphibole and plagioclase.

Clinopyroxene is partly preserved from the hydrothermal processes. It is replaced irregularly by chlorite, epidote, calcite or actinolite. A rather short range of compositions in Ca-Fe-Mg space (Morimoto, 1988) is revealed (Table 1). The wollastonite component (Wo) is between 41.5 and 47.2 and most of the porphyry pyroxenes are auguites. The ratio Mg# is average 72 in the cores (range 67.7-75.6) and 70 in the rims (range 69-73). The outer zones are usually with lower values of Mg#. A reverse zoning also occurs in some of the larger grains in addition to the usually normal one, but the range of the zoning differences is short.

Plagioclase. The prevailing part of the central and intermediate zones (Table 2) of the euhedral plagioclase laths in the microgabbro is not zoned (An_{60-63}) and only the relatively thin rims show very low anorthite composition (An_{22-25}). The plagioclase composition in the middle parts of the laths is sometimes An_{48-50}. Frequently the plagioclase is stained with chlorite, and rarely with prehnite, scapolite and epidote. Most of the plagioclases are overfilled with microinclusions of brown hornblende and magnetite.

Table 1. *Chemical composition of selected clinopyroxenes from plutonic bodies around False Bay, Livingston Island*
Таблица 1. *Химичен състав на избрани клинопироксени от плутонични тела около Фолс Бей, о-в Ливингстън*

Stock	Peak Moores								Cerro Mirador		
Point	31CPx c	32CPx r	33CPx c	34CPx r	3CPx c	4CPx r	13CPx c	14CPx r	28CPx c	30CPx c	29CPx c
Sample	PM-67				PM-31				CM-5D		
Rock	Microdiorite				Potassium trachybasalt				Basalt-dyke		
SiO_2	50.46	53.45	52.22	52.12	52.24	51.76	49.73	51.28	51.61	52.71	51.36
TiO_2	0.00	0.00	0.19	0.20	0.25	0.11	0.26	0.34	0.29	0.20	0.23
Al_2O_3	3.34	2.29	2.22	1.79	4.75	4.49	5.75	3.43	5.02	3.02	5.01
Cr_2O_3	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.38	0.27
FeOt	11.67	10.30	8.06	10.31	6.94	6.71	7.58	9.45	5.49	6.71	6.77
MnO	0.55	0.30	0.43	0.41	0.09	0.27	0.08	0.38	0.14	0.13	0.09
MgO	13.59	15.14	13.88	12.93	16.67	15.62	15.18	15.62	15.86	16.27	15.92
CaO	19.95	17.85	22.95	22.24	18.64	20.52	20.29	19.03	20.46	21.22	21.04
Na_2O	0.35	0.00	0.00	0.51	0.00	0.38	0.76	0.40	0.00	0.00	0.00
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	99.91	99.40	99.95	100.51	99.68	99.73	99.93	100.10	99.40	100.26	100.69
Wo%	39.6	45.0	39.9	37.4	49.2	37.8	44.8	45.3	43.6	43.1	43.3
En %	41.5	37.9	47.2	46.0	39.4	47.3	42.8	39.4	47.3	46.3	45.9
Fs %	18.9	17.0	12.9	16.6	11.4	14.9	12.4	15.2	9.1	10.6	10.8
Mg #	67.7	72.6	75.6	69.3	81.2	71.8	78.3	74.8	83.8	81.3	80.9

c – core, r – rim
c – ядро, r – периферия

The anorthite composition of the central plagioclase cores in the diorites is fluctuating between An_{51} and An_{55}. The outer zones in part of the complex twinned plagioclases is An_{40-43} in the larger grains, but in the smaller ones the rims are formed after a magmatic corrosion and their composition reach to An_{22-25}. The presence of some intermediate zones overgrown by sharply more basic plagioclases in the diorites is a specific feature indicating not only rapid change in the crystallization environment, but also the inflow of a mafic pulse of gabbro magma and magma-mixing process.

Amphibole is typical minor constituent for the quartz-bearing varieties where it occurs instead of clinopyroxene. All analyzed amphiboles (Table 3) are of the calcic group. According to Leake et al. (1997) the amphiboles are high-Si magnesio-hornblendes. The elongated anhedral prismatic crystals are brownish-green (along the Z axis of the indicatrice) and pale-beige (along the axis X). The ratio Mg# of the amphiboles is lower in comparison with this ratio in the clinopyroxenes (the average is 65). The replacement of the magnesio hornblendes by fibrous actinolite is often observed. The partly chloritized amphibole crystals are probably postmagmatic in origin and their ratio Mg# is 52-60.

The hollocrystalline *groundmass* consists of clinopyroxene, plagioclase, magnetite, and quartz or of granophyric quartz-feldspar mosaic with well-developed finger-like inter-growths. Usually the groundmass is altered to a great extent.

Minor constituents taken as a whole are less than 5%. They include quartz, K-feldspar, magnetite. Accessory minerlas are apatite, titanite, anatase, zircon. The secondary minerals comprise epidote, chlorite, leucoxene,

Table 2. *Chemical composition of selected plagioclases from plutonic bodies around False Bay, Livingston Island*
Таблица 2. *Химичен състав на избрани плагиоклази от плутонични тела около Фолс Бей, остров Ливингстън*

Stock	Pliska			Peak Moores			Cerro Mirador		
Point	13Pl-c	16Pl-c	15Pl-r	28Pl-c	29Pl-i	30Pl-r	31Pl-c	30Pl-r	25Pl-r
Sample	Pl/1			PM-67			CM-5D		
Rock	Quartz diorite			Microdiorite			Basalt - dyke		
SiO_2	54.27	54.21	59.12	54.03	52.26	61.36	47.58	57.96	57.97
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.09	0.06
Al_2O_3	29.46	28.79	25.05	28.30	29.49	23.82	32.35	26.05	26.59
FeOt	0.26	0.13	0.15	0.55	0.74	0.28	0.64	0.54	0.55
MnO	0.10	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00
MgO	0.29	0.65	0.77	0.00	0.22	0.00	0.00	0.00	0.00
CaO	10.44	9.73	6.03	10.69	11.78	4.59	17.90	9.42	7.97
Na_2O	5.26	6.12	8.37	5.42	4.66	9.27	1.47	5.62	6.50
K_2O	0.03	0.30	0.39	0.30	0.69	0.12	0.00	0.18	0.13
Total	100.11	99.93	99.88	99.38	99.84	99.44	100.07	99.86	99.77
An %	52.1	44.5	27.9	51.2	56.0	21.4	87.1	47.5	40.0
Ab %	47.9	53.5	70.2	47.0	40.1	77.9	12.9	51.4	0.8
Or %	0.0	2.0	1.9	1.8	3.9	0.7	0.0	1.1	59.1

c- core, i - intermediate zone of the crystal, r - rim
c - ядро, i - междинна зона, r - периферия на кристала

calcite, prehnite, scapolite, and clay minerals. Copper and iron hydroxides are disseminated close to the hydrothermal quartz veinlets cutting the altered rocks.

Dark-grey, nearly black and usually aphanitic dykes with massive structure cut the subvolcanic body of Moores Peak. Sometimes rare phenocrysts 1-3 mm in size of euhedral clinopyroxene and zonal plagioclase are observed. The matrix is fine-grained and consists of clear short plagioclase laths, frequent anhedral clinopyroxene and magnetite. The intersertal and micro-granular textures are characteristic. The mafic minerals are chloritized, and there occur also secondary actinolite, leucoxene, epidote and abundant Fe-oxide aggregates. The petrographic nomenclature of the dykes is potassium-trachybasalt, according to the new-obtained silicate analyses.

2. The plutonic bodies near to Pliska Peak and nunataks Willan and Dell Castillo

The plutonic stocks around the nunataks Willan and Dell Castillo were objects of casual mention by Hobbs (1968), Smellie et al. (1984, 1995), Willan (1994), but the petrographical information for them is poor and imperfect. The role of these rocks in the general geodynamic evolution of the island is not explained and with the exemption of the nunatak Willan, their age is not supported by isotopic studies. Together with the exposures around Pliska Peak all these outcrops have been targets of the Bulgarian geological teams since 1993.

The stocks comprise mainly biotite-hornblende quartz-diorite, medium-grained and equigranular in structure. Granitic texture is the most frequently observed. The principal rock-

Table 3. *Chemical composition of selected mafic minerals from plutonic bodies around False Bay, Livingston Island*
Таблица 3. *Химичен състав на избрани мафични минерали от плутонични тела около Фолс Бей, остров Ливингстън*

Stocks	Cerro Mirador					Pliska			Peak Moores		Pliska			
Mineral	Amphiboles									Magnetite	Ilmenite	Spinel	Biotites	
Sample	CM-59					P/1			P-67		P/2			
Rock	Basalt dyke					Quartz-diorite			Microdiorite		Quartz-diorite			
Point	$30Hb^{I}$-c	Hb^{I}-r	$34Hb^{II}$-c	$28Hb^{I}$-r	$36Hb^{II}$-r	5Hb-c	3Hb-c	1-Hb-c	35Hb-c	1Mt-c	2Ilm-c	1Sp	1Bt-c	2Bt-c
SiO_2	44.58	46.03	51.47	46.37	52.79	49.69	49.20	47.74	52.11	0.86	3.29	1.49	37.01	37.00
TiO_2	2.13	1.59	0.09	1.52	0.30	0.03	0.06	0.06	0.00	0.95	48.32	2.94	0.23	0.22
Al_2O_3	11.18	8.26	5.21	9.12	3.25	5.26	5.61	6.39	3.02	0.00	1.45	4.04	14.75	14.41
Cr_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.36	0.00	0.00	0.26	12.95	0.00	0.00
FeOt	13.62	15.02	13.55	16.67	17.55	13.62	14.21	14.15	14.76	92.20	44.83	76.23	20.01	18.66
MnO	0.36	0.26	0.47	0.28	0.56	0.80	0.72	0.59	0.46	0.00	0.00	0.33	0.00	0.34
MgO	14.03	13.47	16.16	13.17	13.27	15.26	15.74	14.92	15.14	0.00	0.00	1.80	13.36	14.05
CaO	10.21	10.76	10.80	9.96	10.28	11.60	11.32	11.26	11.88	1.01	0.79	0.26	0.00	0.00
Na_2O	2.19	2.38	0.00	1.01	0.00	1.36	1.20	1.62	0.61	0.00	0.00	0.00	0.00	0.64
K_2O	0.26	0.24	0.16	0.28	0.20	0.44	0.50	0.43	0.06	0.00	0.00	0.00	10.56	10.21
LOI	1.44	1.99	2.09	1.62	1.80	1.94	1.44	2.18	1.92	-	-	-	4.08	4.47
Total	98.56	98.01	97.91	98.38	98.20	98.06	98.56	97.82	98.08	95.02	98.94	100.07	95.92	95.53
Mg #	65.0	61.7	68.2	58.7	57.6	74.4	72.1	69.3	76.6	-	-	-	54.3	57.3

c – core, r – rim
c – ядро, r – периферия

forming minerals are plagioclase and quartz and the minor ones include amphibole, biotite and K-feldspar. The accessories are titanite, apatite, magnetite, zircon, anatase. The early-crystallized mineral association is composed by fine-grained and euhedral zircon, apatite^{I}, magnetite^{I}, plagioclase^{I} (1st generation). The main mineral association comprise amphibole, plagioclase^{II}, anatase, apatite^{II}, magnetite^{II} (2nd generation). The late-crystallized minerals are plagioclase^{III}, titanite, biotite, quartz, and K-feldspar. Epidote, chlorite (pycnochlorite type), zeolites and sericite replacements are common.

Plagioclase (60-75 vol.%) is with patchy extinction, cracked and sometimes replaced by a thin net of sericite. The core (Pl^{I}) is corroded and unevenly replaced by the intermediate zones (Pl^{II}) while the rim is distinctly with an abrupt transition to the last plagioclase generation (Pl^{III}). Frequently the normal zoning is as follows: cores (Pl^{I} - An_{46-56}), intermediate zones (Pl^{II} - An_{35-49}) and rims (Pl^{III} - An_{26-28}). The intermediate plagioclase zones may show several oscillations between An_{35} and An_{45}. The outer plagioclase zones contain euhedral inclusions of very small amphibole grains, clinopyroxene, ilmenite and rarely apatite^{I} and magnetite^{I} arranged along the zones of crystal growth. Reverse zoning is also observed in some of the plagioclase crystals. Micromyrmekite structures occur at the contacts of plagioclase with K-feldspar and quartz.

Quartz (less than 5-10 vol.%) is predominantly fine-grained.

Amphiboles (8-10 %) are assigned to the edenite and magnesio-hornblende species. The ratio Mg# is 72-75 in the larger crystals and 69-75 in the smaller ones. Al_2O_3 (wt. %) is average 6 %. Weak zoning from the cores (Mg# 74) to the rimes (Mg#72) is revealed. The oxidation degree ranges 0.18-0.30. The mineral inclusions within the amphibole crystals are plagioclase, anatas, magnetite^{I}, and titanite.

K-feldspar (2-3 %) is rarely observed and it is orthoclase type having over 70 % Or. The chemical composition from one analysis is $An_0Or_{92.5}Ab_{6.5}Cn_{0.9}$.

Biotite (3-5 %) is brown and has an average ratio Mg# 56 (range 54-58).

Magnetite (2-4 %) is Ti-poor variety.

Cr-bearing spinel is observed very rarely. *Ilmenite* (TiO_2 48-49 wt.%) is exceptionally scarce accessory mineral. Sometimes it is coated by ilmeno-rutile and rutile.

The two and more populations of plagioclase, some of which show zoning reversals, overgrown dissolution surfaces, sieve-textured zones or cores, intergrowths with other grains, or polycrystalline clots with mafic crystals provide evidence for multi-stage thermal and ascent histories, generally evolving magma-mixing and remobilisation of stalled crystallizing batches (Singer et al., 1995).

3. *The stock at Cerro Mirador Nunatak.*

The nunatak Cerro Mirador is situated in the southeastern part of Hurd Peninsula and offers a plutonic exposure just next to the coast of False Bay. A small stock-like plutonic body cuts the weakly metamorphosed sandstones of the Miers Bluff Formation. The visible size of this body beneath the snow cover is 400 x 480 m. The plutonic rocks were described in some of the regional geological studies (Caminos et al., 1973; Willan, 1994; Smellie et al., 1984, 1995) as tonalites. The Tertiary age of the pluton was accepted without any radioisotope evidences. No published chemical analyses are available and the petrographical nomenclature was not supported in these publications.

Two fine-grained and equigranular, grey in colour varieties, partly hydrothermally altered, compose the stock. The mesocratic variety is classified as biotite-hornblende quartz-diorite. The leucocratic one is hornblende-biotite microgranodiorite and forms separate vein-like irregular areas within the quartz-diorite. Aplitic veins cut all other magmatic rocks. The rocks have a granular dioritic texture. The structure is massive.

The principle minerals are plagioclase and quartz while the minor ones comprise biotite, amphibole, and K-feldspar. In additions to the usual accessories, allanite occurs in the rocks. The secondary minerals are nearly the same as in the other above-described stocks. Plagioclase is andesine type and sometimes is patchy-zoned. The alteration is unevenly developed and most of the plagioclase grains are nearly entirely replaced by epidote, zoisite, albite, chlorite or sericite. Quartz is with a wavy extinction and of different grain size. Biotite is brownish-green, with fine-grained flakes and often with threadbare ends of its crystals. K-feldspar is microperthitic orthoclase. Thin chlorite and epidote veinlets cut the rocks. The secondary leucoxene and allanite are very well presented in the altered areas.

Geochemistry

A selection of new whole-rock analyses of representative samples from relatively fresh rocks of the stocks (Table 4) plotted on the TAS-diagramme (LeMaitre et al., 1989) is demonstrated in Fig. 3A. There the outline of all analyzed plutonic rocks from Hurd Peninsula is shown also for correlation purpose. The field of the plutonic rocks from Hurd Peninsula is composed of the chemical analyses from the Hesperides Point Pluton K-Ar dated as Late Cretaceous and of several available from the literature (Smellie et al., 1984) analyses from the Eocene in age Barnard Point Batholith. It is clear that several clusters of analyses are formed corresponding to the following plutonic stocks: Moores Peak, Cerro Mirador and a common set of the samples from Pliska Peak and Nunatak del Castillo. All these clusters are emplaced generally in the same chemical trend. The analyses from Moores Peak are located partly in the most basic end of the general plutonic trend, but they also extend the variation to still further primitive compositions. In contrast the Cerro Mirador analyses fall in the most evolved part of the field of the Hurd Peninsula plutonic field.

The large variations in SiO_2 range, together with the presence of magnetite, titanite, amphibole and apatite inclusions in biotite flakes are in support for I-type geochemical characteristics. All rocks are metaluminous and comprise Si-oversaturated varieties. The studied samples belong to a calc-alkaline medium-K series related to arc magmatism (Fig. 3 B). The same series is typical also for the volcanics from the Mount Bowles Formation (Table 5).

The characteristic trace-element features of representative samples are demonstrated in Fig. 4 as a series of multi-element plots normalized to average tholeiitic N-MORB. Pointing out that only a few variables carry most of the discrimination power, we chose for the list and sequence of the highly incompatible elements the approach of Pearce (1996). Fig. 4 shows the typical patterns that result when these most discriminatory elements are plotted for some type examples for comparison. All patterns coincide perfectly with a volcanic-arc setting. The key feature is the significant Nb negative anomaly with respect to Th and Ce. The absolute depletion relative to N-MORB of Ti and Y is characteristic for this setting also. The MORB-normalized patterns of the selected samples from the plutonic stocks (Fig. 4A) are very much alike the patterns from the Late Cretaceous Hesperides Point Pluton (Fig. 4B) and from the assumed to be of Late Cretaceous age Mount Bowles Formation (Fig. 4C). Even the Quaternary extentional basalts of Inott Point Formation (Fig. 4D) do not exhibit any essential divergence in their geochemical distributions. It is evident that the similarity between the Late Cretaceous magmatic products (Fig. 4B,C) and the plutonic rocks from the nunataks around False Bay hardly could contribute to the idea of their coeval age. The prolonged subduction history of the Antarctic Peninsula area and of the South Shetland Islands particularly from the Late Triassic to Tertiary is suggestive of many episodes of magma and fluid contributions to the mantle magma source. As a result, this source has been enriched in *LILE* and has produced similar volcanic-arc geochemical affinity of the magmas, even in the back-arc setting of the Quaternary.

In terms of incompatible trace element ratios the plutonic rocks from the studied stocks exhibit some faint resemblance to an OIB source. In the Rb/Nb *vs.* Ba/Nb plot

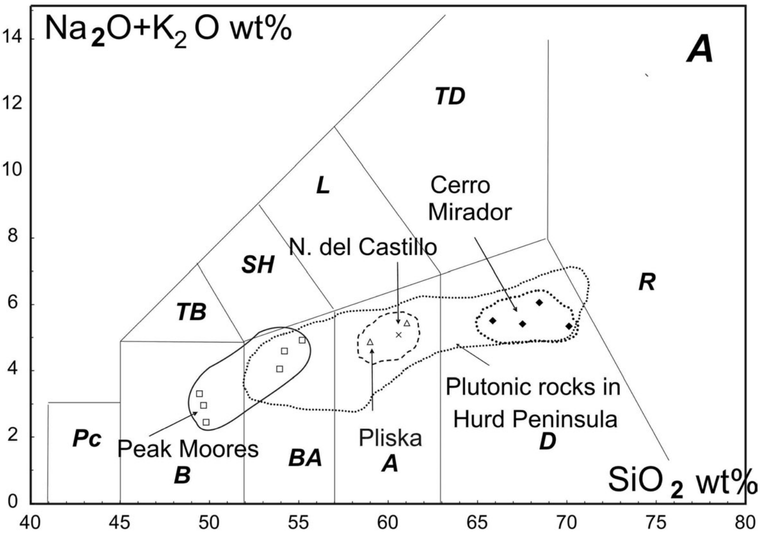
Table 4. *Representative chemical analyses of rocks from the Tertiary plutonic stocks around False Bay, Livingston Island (major oxides in wt. %, trace elements in ppm)*

Таблица 4. *Представителни химични анализи на скали от терциерните плутонични щокове около Фолс Бей, о-в Ливингстън (главните оксиди в тегловни %, елементите-следи в ppm)*

Stock	Cerro Mirador				Willan Nunatak	N.del Castillo	Pliska	Peak Moores	
Sample	CM-1	CM-2	CM-3	CMS	W-243	NC-11	Pl/1	PM-65	PM-67
Rock	Quartz diorite			Gd	Quartz diorite			Diorite	
SiO_2	65.90	67.30	68.70	65.20	60.90	60.01	58.81	53.21	54.23
TiO_2	0.68	0.69	0.68	0.50	0.51	0.61	0.67	1.10	0.82
Al_2O_3	13.94	15.03	13.78	13.92	16.19	16.63	16.50	17.00	17.18
Fe_2O_3	6.45*	5.78*	5.69*	2.76	3.29	2.59	3.88	3.00	2.46
FeO	-	-	-	4.47	3.32	3.65	3.73	5.91	5.36
MnO	0.11	0.12	0.13	0.13	0.13	0.17	0.13	0.17	0.15
MgO	1.43	1.35	1.36	2.70	3.00	3.31	3.48	4.97	5.91
CaO	3.63	1.89	2.23	3.71	6.85	6.96	7.62	7.91	6.90
Na_2O	3.20	3.44	3.96	2.69	4.19	3.62	3.77	3.10	3.04
K_2O	2.08	2.52	1.27	2.76	1.24	1.42	1.09	1.40	1.80
P_2O_5	0.18	0.19	0.18	0.13	0.13	0.06	0.16	0.39	0.31
H_2O^-	0.28	0.27	0.66	0.09	0.12	0.03	0.07	0.15	0.15
LOI	0.82	0.96	1.04	0.50	0.55	0.56	0.46	1.52	1.35
Total	98.70	99.54	99.68	99.79	100.42	99.63	100.23	99.83	99.76
Cr	513	456	275	88	49	20	45	101	119
Ni	21.7	18.6	20	40	11	13	10	39	51
Co	10.4	8.6	6	16	12	15	16	18	20
V	102	83	64	40	130	70	140	-	151
Rb	66	58	65	87	12	26	20	38	36
Ba	412	561	336	480	430	322	280	-	288
Sr	249	278	191	264	591	625	599	-	452
Zr	204	193	244	348	146	161	134	-	150
Y	27.7	26.5	65	45	25	27	26	-	21
Nb	7.2	7.2	8	17	8	3	9	-	12
Th	9.3	9.3	-	10	-	11.2	-	-	6
Ce	54.2	55.8	22.6	-	-	32.5	-	-	33

* Fe_2O_3 as total oxides. The major oxides are analysed by XRF in the EUROTEST Co, Sofia by the analysts R. Deligeorgieva and A. Raicheva (samples CM-1, CM-2 and CM-3) and by wet silicate method in the Geochemical Laboratory of Sofia University, Faculty of Geology and Geography by the analysts E. Landjeva and T. Kurteva (the rest of the samples). The trace elements are analyzed by ICP-MS method in ETH, Zurich on the Excimer Laser Ablation (Elan 6000) on pellets (samples CM-1 and CM-2) and by XRF in the EUROTEST Co. The trace elements of sample PM-65 are obtained by Atomic Absorption Analyses only. Rock abbreviations: Gd – granodiorite. Rock nomenclature after LeMaitre et al. (1989)

* Fe_2O_3 като сумарно. Главните оксиди са анализирани чрез РФА в ЕВРОТЕСТ Со, София от аналитиците Р. Делигеоргиева и А. Райчева (проби СМ-1 и СМ-2) и чрез мокър силикатен анализ в Геохимичната лаборатория на Софийския университет, Геолого-географски факултет от аналитиците Е. Ланджева и Т. Куртева (останалите проби). Елементите-следи са анализирани по метода ICP-MS в ETH, гр. Цюрих на апарат Excimer Laser Ablation (Elan 6000) върху пелети (проби СМ-1 и СМ-2) и чрез РФА в ЕВРОТЕСТ Со. Елементите-следи на проба РМ-65 са получени само от Атомна абсорбция. Съкращения за скалите: Gd – гранодиорит. Скалната номенклатура е по LeMaitre et al. (1989)



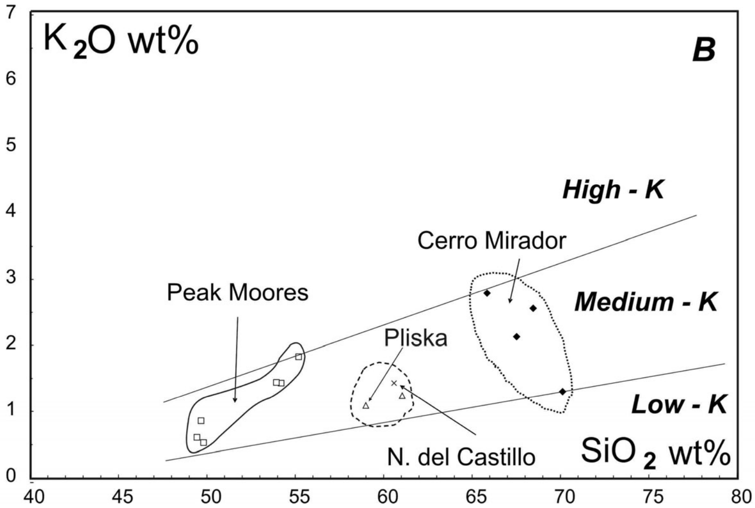


Fig. 3A) Samples from the studied plutonic stocks in Livingston Island on the plot SiO_2 *vs.* (Na_2O + K_2O) after LeMaitre (1989). The fields of all Hurd Peninsula plutonic rocks and of the extensional Quaternary basalts (Kamenov, 2004) are for comparison. B) SiO_2 *vs.* K_2O plot (after LeMaitre, 1989)

Фиг. 3A) Проби от плутоничните скали на щоковете около Фолс Бей в диаграмата SiO_2 *vs.* (Na_2O + K_2O) по LeMaitre (1989). Полетата на всички плутонични скали от полуостров Хърд и на екстензионните кватернерни базалти (Kamenov, 2004) са дадени за сравнение. B) Диаграма SiO_2 *vs.* K_2O plot (по LeMaitre, 1989)

(Fig. 5A) the analyzed samples from the stocks are located between the points for average crust materials and EMI OIB source (Weaver, 1991), like the cases in the Late Cretaceous (?) volcanic rocks of Mount Bowless Formation and the Hesperides Point pluton samples are (Kamenov, 1997). The higher ratio Rb/Nb of the samples from the stocks distinguish them from the extensional Quaternary basalts from Bransfield Strait (Kamenov, 2004). The crustal

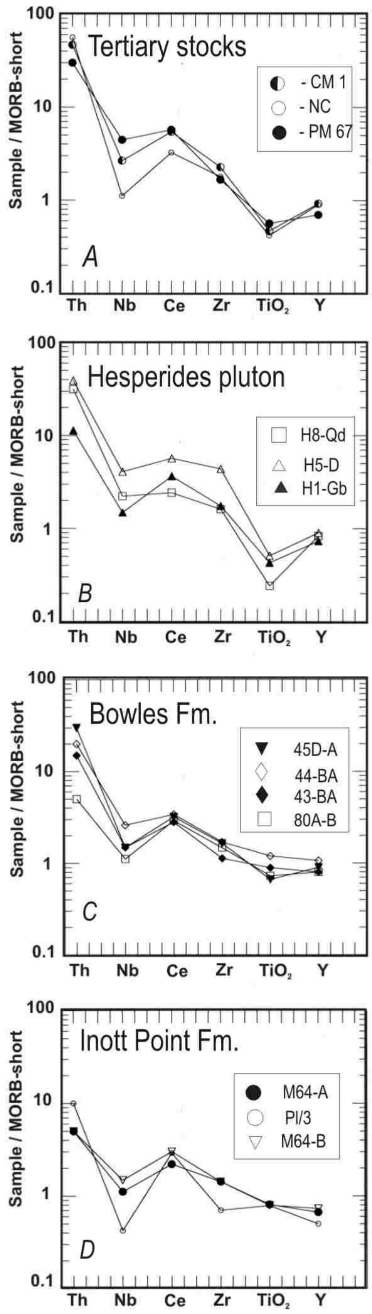


Fig. 4. MORB-normalized trace element patterns (Pearce, 1996) for the studied stocks (A), compared to data from: Hesperides Point Pluton (Kamenov, 1997) (B), Mount Bowless Formation (Smellie et al., 1995) (C), and Quaternary basalts in Livingston Island (Kamenov, 2004) (D)

Table 5. *Representative new chemical analyses from the Bowles Formation volcanic rocks in Peak Moores around False Bay, Livingston Island (major oxides in wt. %, trace elements in ppm)*

Таблица 5. *Представителни нови химични анализи на вулкански скали от формацията Боулес от Пик Мурес около Фолс Бей, о-в Ливингстън (главните оксиди в тегловни %, а елементите-следи в ppm)*

Site	Peak Moores				
Sample	54-A	51	52	53	PM-31
Rock	B	B	BA	B	KTB
SiO_2	48.79	48.69	52.88	48.55	47.78
TiO_2	0.66	0.74	0.63	0.58	0.80
Al_2O_3	17.37	17.09	16.52	17.18	16.95
Fe_2O_3	4.15	6.37	4.37	4.96	278
FeO	6.09	4.19	6.74	6.13	6.37
MnO	0.17	0.19	0.17	0.18	0.17
MgO	7.48	7.47	5.55	7.51	7.68
CaO	10.69	10.36	7.10	9.66	9.92
Na_2O	1.88	2.66	2.56	2.05	1.94
K_2O	0.52	0.60	1.41	0.84	4.18
P_2O_5	0.15	0.12	0.09	0.11	0.24
H_2O-	0.19	0.18	0.17	0.17	0.13
LOI	1.62	1.75	1.44	1.87	1.85
Total	99.76	100.41	99.66	99.79	100.79
Cr	160	130	220	170	123
Ni	48	41	55	48	43
Co	34	30	38	46	29
Rb	4	4	24	11	14

Rock abbreviations: B – basalt, BA – basaltic andesite, KTB – potassium trachybasalt. Wet silicate analyses and Atomic Absorption Analyses – Sofia University, Geochemical Laboratory, Faculty of Geology and Geography

Съкращения за скалите: B – базалт, BA – андезитобазалт, KTB – калиев трахибазалт. Мокрите силикатни анализи и атомно-абсорбционния анализ – Софийски университет, Геохимична лаборатория, Геолого-географски факултет

Фиг. 4. MORB-нормализирани модели (Pearce, 1996) за проби от изучените щокове (A), сравнени с данни от плутона Есперидес Пойнт (Kamenov, 1997) (B), формацията Маунт Боулес (Smellie et al., 1996) (C) и кватернерните базалти от о-в Ливингстън (Kamenov, 2004) (D)

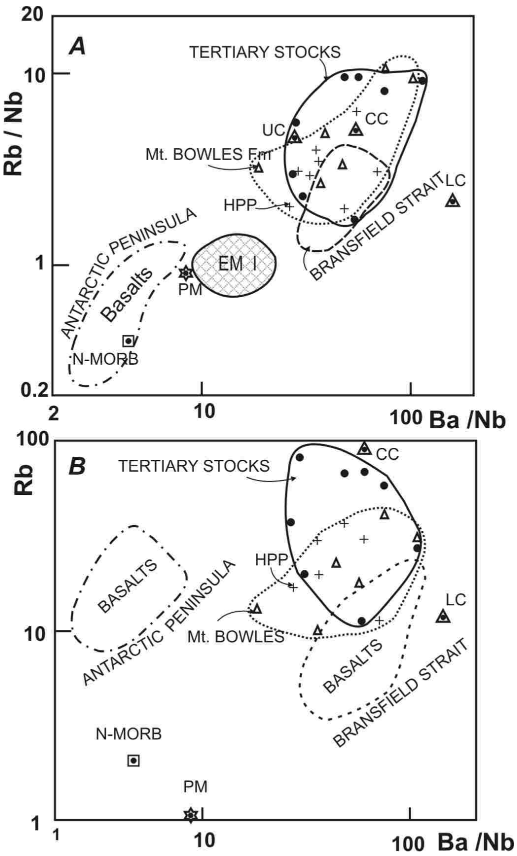


Fig. 5. Trace element variation diagrammes for Hurd Peninsula stocks (filled circles) compared to samples from the Quaternary basalts from the Antarctic Peninsula (outline after Hole et al., 1993), Bransfield Strait area (outline after Kamenov, 2004), Mount Bowless Formation (empty triangles, outline after Smellie et al., 1995) and Hesperides Point Pluton (crosses, HPP, Kamenov, 1997); A, Rb/Nb *vs.* Ba/Nb plot and B, Rb *vs.* Ba/Nb plot. Continental crust (CC), upper crust (UC), lower crust (LC) – after Weaver, Tarney (1984), the field of EM I – after Weaver (1991), N-MORB – after Saunders, Tarney (1984), Antarctic Peninsula basalts – after Hole et al. (1993)

Фиг. 5. Вариационни диаграми за отношения на елементи-следи в проби от щоковете на полуостров Хърд (черни точки) сравнени с проби от кватернерните базалти от Антарктическия полуостров (полето е от Hole et al., 1993), формацията Маунт Боулес (кухи триъгълници и поле от Smellie et al., 1995), от Пролива на Бренсфийлд (полето е от Kamenov, 2004) и с проби от плутона Есперидес Поинт (кръстчета, HPP, Kamenov, 1997). А) Диаграма Rb/Nb *vs.* Ba/Nb. В) Диаграма Rb *vs.* Ba/Nb. Средните състави на континенталната кора (CC), горната кора (UC), долната кора (LC) са от Weaver, Tarney (1984), на N-MORB- от Saunders, Tarney (1984), а полето на EM I – от Weaver (1991)

contamination of the mantle source was probable because the samples fall close to the average continental crust (Weaver, Tarney, 1984).

The geochemical differences between the magmatic complexes in Hurd Peninsula are expressed more distinctly on the plot Rb *vs.* Ba/Nb (Fig. 5B). The stocks around False Bay are notable for their higher Rb contents in their samples and with their closer position to the average continental crust.

Chondrite-normalized *REE* patterns for representative samples from one of the stocks (Cerro Mirador Nunatak) are in accord with an enriched mantle source (Fig. 6). The patterns resemble those of the typical island-arc calc-alkaline rocks with moderately *LREE*-enriched and *HREE*-depleted distributions. No any difference in the enrichment degree between the middle- and the heavy *REE*-normalized values are revealed. The very weak negative Eu-anomaly is in contrast to the lack of whatever Eu anomalies in the Hesperides Point pluton, for example. This feature points to the probable involvement of plagioclase in the fractionation history of the magma. The both samples from Cerro Mirador stock are with different degree of postmagmatic alteration, but it is evident that their patterns are not the least bit influenced by the secondary processes and they are really indicative for the primary geochemistry of the rocks.

Geochronology

A rather wide range may be possible for the studied rocks in the stocks in Hurd Peninsula, according to analogy with the dated hypabyssal intrusions and volcanic sequences in the island. Whereas the volcanics of the Mount Bowles Formation are assumed to be Cretaceous ($^{40}Ar/^{39}Ar$ isochron data of 111-106 Ma, Zheng et al., 1997) and the Hesperides Point Pluton was dated 73 Ma (K-Ar, Kamenov, 1997), the

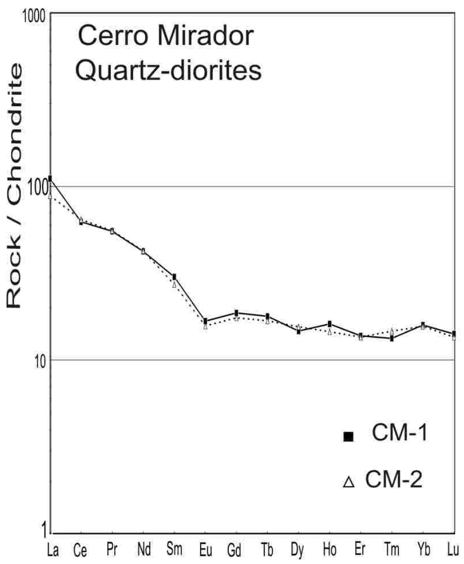


Fig. 6. Chondrite-normalized patterns for selected samples from Cerro Mirador stock. Qd – quartz-diorite

Фиг. 6. Хондрит-нормализирани модели на избрани проби от щока Серо Мирадор. Qd – кварцдиорит

tonalite at Barnard Point in the mountainous area in the southeastern end of the island is of Eocene age (46 Ma, Smellie et al., 1996). All small plutonic exposures on the eastern side of Hurd Peninsula are adjacent to the Barnard Point Batholith, but direct field relationships are not available because of the thick snow cover. The paucity of reliable age information for these small plutonic stocks could be surmounted partly by our attempt to present new Ar-Ar results.

The analyses for $^{40}Ar/^{39}Ar$ step-heating age were carried at the Institute of Geology and Geophysics, Chinese Academy of Sciences, by the analyst H. Sang, following the procedure described by Hu et al. (1985). A high frequency oven was used to heat the samples for 20 minutes in each step. Apparent ages were corrected for mass discrimination, memory effect, interference of K and Ca to the Ar isotope, and ^{37}Ar radioactive decay. A half-life of 35.1 days was adopted to correct the radioactive decay of ^{37}Ar. Uncertainty is quoted at one sigma and does not include the calculated J-factor error.

The $^{40}Ar/^{39}Ar$ incremental heating results carried out on 2 samples are presented with their age spectra and $^{40}Ar/^{36}Ar$-$^{39}Ar/^{36}Ar$ and $^{36}Ar/^{40}Ar$–$^{39}Ar/^{40}Ar$ isochrons (Fig. 7, 8, 9). Sample 67/PM was collected from the northern part of Moores Peak Nunatak (see Fig. 2). It is slightly hydrothermally altered quartz-bearing diorite with porphyroid structure. The mafic minerals are clinopyroxene and hornblende. Chlorite, prehnite, scapolite and epidote occur amongst the rare secondary minerals. The pronounced plateau (Fig. 7) over large portions of its spectra (steps 3-7) yields an age of 43.34 ± 0.86 Ma. This age is supported by $^{40}Ar/^{36}Ar$–$^{39}Ar/^{36}Ar$ isochron calculations that yield an isochron age of 45 ± 3 Ma and by $^{36}Ar/^{40}Ar$–$^{39}Ar/^{40}Ar$ isochron using only five full fusion steps and yielding an age of 45 ± 3.8 Ma. Having in mind that the initial $^{40}Ar/^{36}Ar$ ratio is different to that of the atmospheric value (295.5) and the rather high MSWD values probably due to the weak alteration of the sample, we prefer to rely more confidently to the plateau age of around 43.3 Ma.

Sample BB/1 was taken from Cerro Mirador Nunatak. It is even-grained and coarse-grained, grey in colour biotite granodiorite. Hornblende occurs also rarely in the mafic mineral assemblage. Minor constituents are quartz and K-feldspar. Secondary minerals are sericite and chlorite. To obtain better results we separated and measured monomineral fractions of biotite (BB1-B) and feldspar (BB1-F). A plateau age of 49.99 ± 0.88 Ma was obtained on the biotite fraction, excluding the older ages of the first and last three steps (Fig. 8). The released ^{39}Ar is sufficiently high compared to the totally released. This age is confirmed by the isochron calculations of $^{36}Ar/^{40}Ar$ *vs.* $^{39}Ar/^{36}Ar$ and $^{36}Ar/^{40}Ar$ *vs.* $^{39}Ar/^{40}Ar$. The yielded ages are 50.6 ± 1.2 Ma and 50.6 Ma ± 1.2 Ma respectively. The MSWD values of these isochrones are acceptable (4.5 and 9.7) and an age of around 50 Ma should be well constrained.

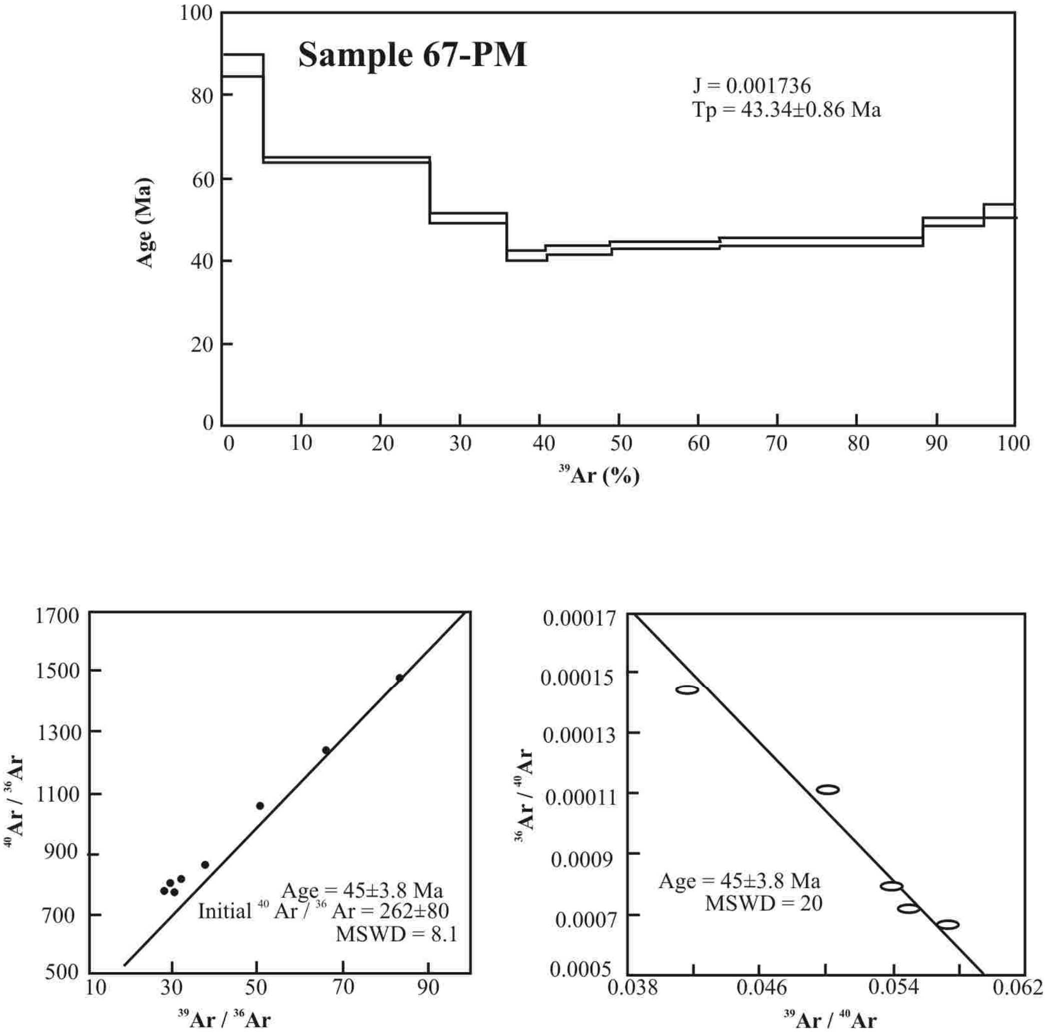


Fig. 7. $^{40}Ar/^{39}Ar$ age spectra and $^{40}Ar/^{36}Ar$–$^{39}Ar/^{36}Ar$ isochrons of sample 67/PM (gabbrodiorite from Moores Peak)

Fig. 7. $^{40}Ar/^{39}Ar$ спектри и $^{40}Ar/^{36}Ar$–$^{39}Ar/^{36}Ar$ изохрони за образец 67/PM (габродиорит от Мурес Пик)

The Ar-Ar results on the feldspar separate (sample BB1-F) are shown on the Fig. 9. The plateau age of 42.15 ± 0.62 Ma is younger than that of the biotite, but the support from the isochrones is more confident – 44.9 ± 2.3 Ma and 44.9 ± 2.3 Ma. The MSWD values of the isochrones are rather high – 43 and 85 and we use the dating of the feldspar fraction only to confirm once more the Eocene age of the stock studied.

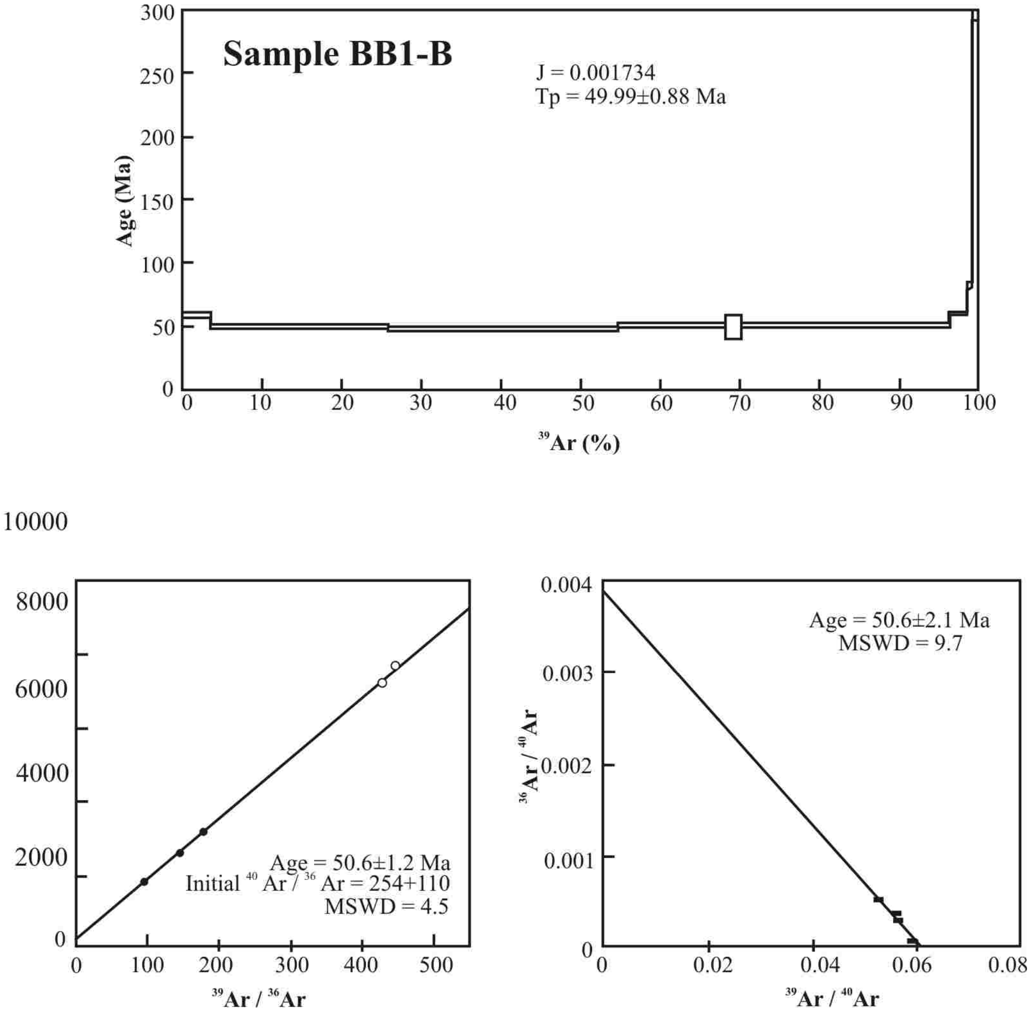


Fig. 8. $^{40}Ar/^{39}Ar$ age spectra and $^{40}Ar/^{36}Ar–^{39}Ar/^{36}Ar$ isochrons of sample BB1-B (biotite from granodiorite of the Cerro Mirador)

Fig. 8. $^{40}Ar/^{39}Ar$ спектри и $^{40}Ar/^{36}Ar–^{39}Ar/^{36}Ar$ изохрони на образец BB1-B (биотит от гранодиорита на Серро Мирадор)

Conclusions

Comparing the present results for the both stocks fluctuating between 45 and 50 Ma with the published already age of the Barnard Point Batholith of 46 Ma and with the age of the Willan Nunatak stock (43.3 Ma, Smellie et al., 1995) we could support more firmly that all studied small plutonic exposures along the eastern side of the Hurd Peninsula are really apophyses of the larger Barnard Point Batholith. Such a conclusion is already well grounded also with the geochemical correlations made here. This Eocene in age episode of plutonic activity is wide-spread everywhere in the South Shetland Islands, to mention only the dykes in Livingston Island with 42-45 Ma Zheng et al., 2003), which are obviously genetically related to this magmatism.

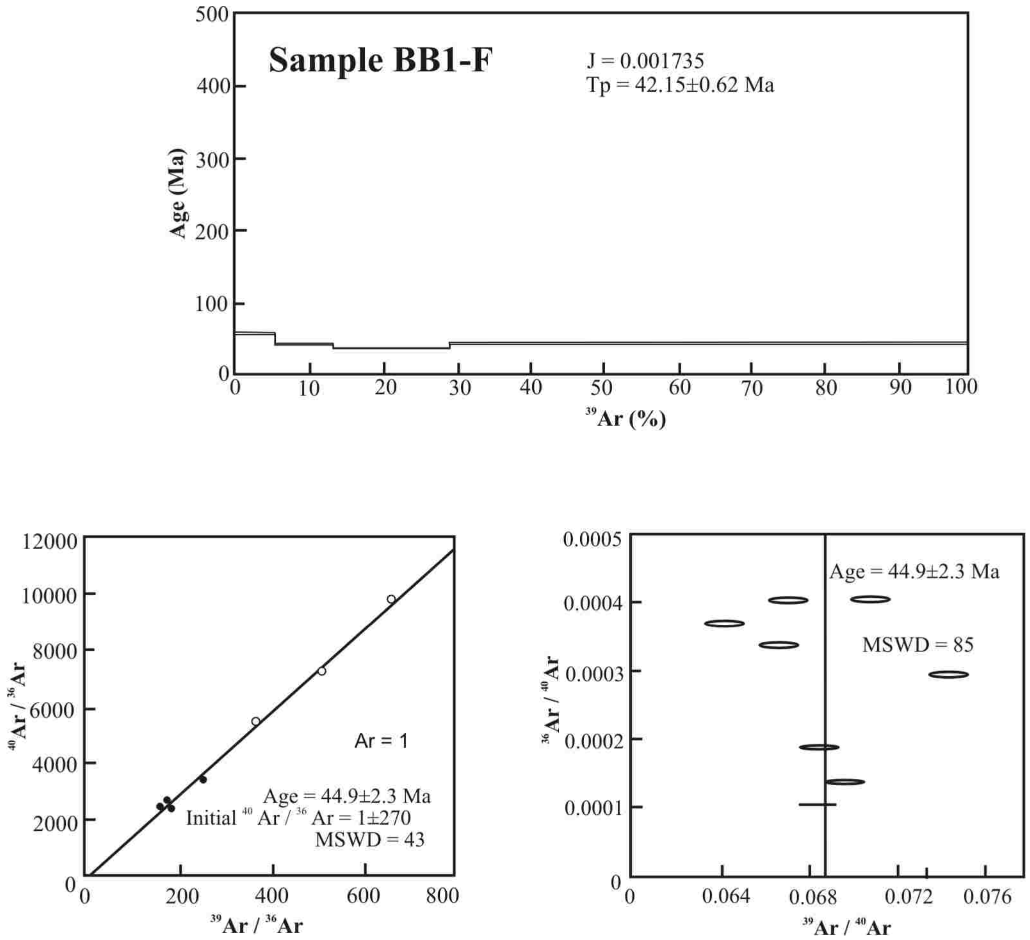


Fig. 9. $^{40}Ar/^{39}Ar$ age spectra and $^{40}Ar/^{36}Ar–^{39}Ar/^{36}Ar$ isochrons of sample BB1-F (K- feldspar from the same granodiorite)
Fig. 9. $^{40}Ar/^{39}Ar$ спектри и $^{40}Ar/^{36}Ar–^{39}Ar/^{36}Ar$ изохрони на образец BB1-F (калиев фелдшпат от същия гранодиорит)

The new petrological, geochemical and radiometric results for the stocks under study should provide a better understanding of the arc-building process in the Livingston Island, but also impose the necessity the attention to be drawn on the closer searching study of the petrology and geochemistry of the batholith itself.

Acknowledgements: The study is part of the Project *Complex geological, geochemical and ecosystem research in the area of the Bulgarian Antarctic Base “St. Kliment Ohridsky”* sponsored by the Bulgarian Ministry of the Environment and Water. The Bulgarian Antarctic Institute logistically supported the fieldwork. The authors acknowledge the Spanish Antarctic Programme for transport to Antarctica. The help of E. Genova (Sofia University) for drawing some of the figures is appreciated.

References

Armstrong, D.C., R.C.R. Willan. 1996. Ortho-magmatic quartz and post-magmatic carbonate veins in a reported porphyry copper deposit, Andean Intrusive Suite, Livingston Island, South Shetland Islands. *Mineral. Deposita*, **31**, 290-306.

Caminos, R., H.G. Marchese, A.C. Massabie, J.R. Morelli, C.A. Rinaldi, J.P. Spekermann. 1973. Geologia del sector noroccidental de la Peninsula Hurd, Isla Livingston, Shetland del Sur, Antartida Argentina. *Contrib. Inst. Antartico Argentina,* **162**, 32 p.

Gledhill, A., D.C. Rex, P.W.G. Tanner. 1982. Rb-Sr and K-Ar geochronology of rocks from the Antarctic Peninsula between Anvers Island and Marguerite Bay. In: C. Craddock (Ed.), *Antarctic Geoscience, Univ. Wisconsin Press*, 315-323.

Grikurov, G.E., A.Y. Krylov, M.M. Polyakov, Y.N. Tsovbin. 1970. Age of rocks in the northern part of Antarctic Peninsula and on the South Shetland Islands (K-Ar data). *Bull. Soviet Antarctic Expedit.,* **80**, 30-39 (in Russian).

Hervé, F., W. Loske, H. Miller, R.J. Pankhurst. 1991. Chronology of provenance, deposition and metamorphism of deformed fore-arc sequence, Southern Scotia arc. In: M.R.A. Thomson, J.A. Crame, J.W. Thomson (Eds.), *Geological Evolution of Antarctica*, Cambridge Univ. Press, Cambridge, 429-435.

Hobbs, G. J. 1968. The geology of the South Shetland Islands: IV. The geology of Livingston Island. *British Antarctic Surv. Sci. Reports*, **47**, 34 p.

Hole, M.J., P.D. Kempton, I.L. Millar. 1993. Trace-element and isotopic characteristics of small-degree melts of the asthenosphere: Evidence from the alkalic basalts of the Antarctic Peninsula. *Chem. Geol*., **109**, 51-68.

Hu, S.L., S.S. Wang, H.Q. Sang. 1985. An application of the fast-neutron activation dating technique to approach the age of early emplacement of Jiuling granodiorite intrusion of Jiangxi province. *Acta Petrol. Sinica*, **1**, 29-34.

Kamenov, B.K. 1997. Geochemistry and petrology of the Hesperides Point Intrusion, Hurd Peninsula, Livingston Island. In: C. Ricci (Ed.), *Geological Evolution and Processes*. *Terra Antarctica*, Siena, 341-352.

Kamenov, B.K. 2004. The olivine basalts from Livingston Island, West Antarctica: Petrology and geochemical comparisons. *Geochem. Mineral. Petrol.* **41**, Sofia, 71-98.

Kamenov, B.K., P. Monchev. 1996. New age constraints for Hesperides Point Pluton and Mirador Stock, Central Livingston, Antarctica. *C. R. Acad. bulg. Sci*., **49,** 11/12, 65-68.

Keller, R.A., M.R. Fisk, W.M. White, K. Birkenmajer. 1991. Isotopic and trace element constraints on mixing and melting models of marginal basin formations, Bransfield Strait, Antarctica. *Earth Planet. Sci. Lett.*, **111**, 287-303.

Leake B.E., A.R. Wooley, C.E.S. Arps., W.D. Birch, M.C. Gilbert, F.C. Hawthorn, A. Kato, H..J. Kisch, V.G. Krivovichev, K. Linthout, J. Laird, J. Mandarino, W.K. Maresh, E.H. Nickel, N.M.S Rock, J.C. Schumaher., D.C. Smith, N.C.N. Stephenson, L. Ungaretti, G. Youzhi. 1997. Nomenclature of amphiboles. Report of the Subcommittee on Amphiboles of the International Mineralogical Association, Commission on new minerals and mineral names. *European J. Mineral.*, **9**, 623-651.

Leat, P.T., J.H. Scarrow, I.L. Millar. 1995. On the Antarctic Peninsula Batholith. *Geol. Mag.*, **132**, 399-412.

LeMaitre, R.W. (Ed.). 1989. *A Classification of Igneous Rocks and Glossary of Terms. Recommendations of the UUGS Subcommission on the systematics of igneous rocks.* Oxford, Blackwell, 193 p.

Morimoto, N. 1988. Nomenclature of pyroxenes. *Forschr. Mineral*., **66**, 2, 237-252.

Ouyang, S., X. Deng, Y. Shen, X. Zheng, X. Liu. 2000. Late Triassic plant microfossils from Miers Bluf Formation of Livingston Island, South Shetland Islands. *Antarctic Science*, **12** ,2, 217-228.

Pallàs, R., J.A. Muñoz, F. Sabat. 1992. Éstratigrafia de la Formación Miers Bluff, Isla Livingston, Islas Shetland del Sur. In: J. Lopez-Martinez (Ed.), *Geologia de la Antártida Occidental*. Simposios T3, III Congr. Latinoamericano de Geologia, Salamanca: España, 1992, 105-115.

Pearce, J.A. 1996. A user's guide to basalt discrimination diagrams. In: D.A. Wyman (Ed.), *Trace Element Geochemistry of Volcanic Rocks: Applications for Massive Sulphide Exploration*. Geol. Assoc. Canada, Short Course Notes, **12**, 79-113.

Pimpirev, C., D. Dimov, M. Ivanov, K. Stoykova. 2004. New paleontological evidences for a Late Cretaceous age of the Miers Bluff Formation (Livingston Island, South Shetland Islands). *Proceed. IXth Intern. Symp. Antarctic Earth Sci.*, Berlin, Springer (in press).

Saunders, A.D., J. Tarney. 1984. Geochemical characteristics of basaltic volcanism within back-arc basins. In: B.P. Kokelaar, M.F. Howels

(Eds.), *Marginal Basin Geology, Geol. Soc. London, Sp. Publ.,* **16**, 59-76.

Singer, B.S., M.A. Dungan, G.D. Layene. 1995. Textures and Sr, Ba, Mg, Fe, K, and Ti compositional profiles in volcanic plagioclase: Clues to the dynamics of calc-alkaline magma chambers. *Amer. Mineral*., **80**, 776-798.

Smellie, J.L. 2001. Lithostratigraphy and volcanic evolution of Deception Island, South Shetland Islands. *Antarctic Sci.*, **13**, 188-209.

Smellie J.L., R.J. Pankhurst, M.R.A. Thomson, R.E.S. Davies. 1984. The geology of the South Shetland Islands: VI. Stratigraphy, geochemistry and evolution. *British Antarctic Surv. Bull.,* **87**, 85 p.

Smellie, J.L., M. Liesa, J.A. Munoz, F. Sabat, R. Pallas, R.C.R. Willan. 1995. Lithostratigraphy of volcanic and sedimentary sequences in central Livingston Island, South Shetland Islands. *Antarctic Sci.,* **7**, 1, 99-113.

Smellie, J.L., R. Pallas, F. Sabat, X. Zheng. 1996. Age and correlation of volcanism in central Livingston Island, South Shetland Islands: K-Ar and geochemical constraints. *J. South Amer. Earth Sci.*, **9**, 3/4, 265-272.

Storey, B.C., S.W. Garett. 1985. Crustal growth of the Antarctic Peninsula by accretion, magmatism and extension. *Geol. Mag.,* **122**, 5-14.

Stoykova, K., C. Pimpirev, D. Dimov. 2002. Calcareous nannofossils from the Miers Bluff Formation (Livingston Island, South Shetland Islands, Antarctica): First evidence for a Late Cretaceous age. *J. Nannoplankton Res*., **24,** 2, (9th INA Conference, Parma, Abstracts and Programme), 166-167.

Thompson, R.N. 1982. Magmatism of the British Tertiary Volcanic Province. *Scott. J. Geol*., **18**, 49-107.

Tomson, M.R.A., R.J.Pankhurst, P.D. Clarkson. 1983. The Antarctic Peninsula: A late Mesozoic-Cenozoic arc (Review). In: R.L. Oliver, P.R. James, J.B. Jago (Eds.), *Antarctic Earth Sci.* Australian Acad. Sci., Canberra, 289-294.

Tokarski, A.K., A. Swierczewska, M. Doctor. 1997. Miers Bluf Formation, Livingston Island (South Shetland Islands): Diagenesis/metamorphism and early stage of structural development. In: *The Antarctic Region: Geological Evolution and Progress*, 409-416.

Weaver, B.L. 1991. The origin of ocean island basalts end-member compositions: Trace element and isotopic constraints. *Earth Planet. Sci. Lett*., 382-397.

Weaver, B.L., J. Tarney. 1984. Empirical approach to estimating the composition of the continental crust. *Nature*, **310**, 575-577.

Willan, R.C.R. 1994. Structural setting and timing of hydrothermal veins and breccias on Hurd Peninsula, Livingston Island, South Shetland Islands: A possible volcanic-epithermal system in deformed turbidites. *Geol. Mag*., **131**, 4, 465-483.

Willan R.C.R., R.J. Pankhurst, F. Herve. 1994. A probable Early Triassic age for the Miers Bluff Formation, Livingston Island, South Shetland Islands. *Antarctic Sci.,* **6**, 401-408.

Zheng, X., H. Shilling, J. Liu. 1997. New ^{40}Ar/39Ar age evidence for the Cretaceous volcanic rocks of the Mount Bowles Formation in Livingston Island, South Shetland Islands. *Chinese J. Polar Sci.*, **8**, 2, 89-95.

Accepted June 28, 2005
Приета на 28.06.2005 г.