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The olivine basalts from Livingston Island, West Antarctica: Petrology and geochemical comparisons

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Abstract. Late Cenozoic mafic alkaline volcanic rocks occur throughout the entire Pacific coast of West Antarctica, including in some of the islands adjacent or within the Bransfield Strait. Amongst them, Livingston Island is the least well-known, particularly in respect to mineralogy, petrology and geochemistry of the sparse manifestations of this type rocks, known as Inott Point Formation. The petrographic and geochemical aspects of old and new-discovered outcrops of primitive volcanic rocks are described. The new chemical analyses specify the nomenclature as low-Ti undersaturated olivine basalts mainly, and hawaiites rarely.

Comparisons with the trace element characteristics of the similar rocks from the islands Greenwich, Penguin, Deception and Bridgemen revealed common features: high *LILE/HFSE* ratios (e.g. Ba/Zr 1.4-2.2; Ba/Nb 42-67; Rb/Nb 2.7-4; Ce/Nb 2.5-10; Th/Nb 0.25- 0.90; K/Zr 39-67 etc.). These ratios are opposite to the low *LILE/HFSE* ratios in the alkalic provinces in Antarctic Peninsula (AP) and in Marie Byrd Land (MBL). The generally low absolute abundances of *HFSE* in all within and around the Bransfield Strait alkaline basalts and the high Zr/Nb (19-43) and Sr/Nb (>100) ratios are in contrast to such ratios in AP and MBL exposures. Higher degree of melting and variable interaction with the continental lithosphere is probably responsible for the geochemical differences with the alkaline basalts from the other provinces in West Antarctica. The regional geochemical *LILE* differences between MBL and AP substantiate the conclusion that they were derived from different source regions. Alkaline basalts from cratonic flood basalts in Patagonia and from the Atlantic Ocean island Ascension were used for correlation and their geochemistry is similar to plume-related MBL basalts.

In spite of the extensional setting in the back-arc rift of Bransfield Strait, the studied alkaline basalts bear most of arc trace element signatures. New subdivision of the alkaline basalt provinces in West Antarctica is proposed. To the AP province, known to be derived from MORB-source asthenosphere in slab-window setting and to the MBL one, related to a deep mantle plume, we may add another one specific province, namely Bransfield Strait extensional one with alkaline basalts bearing traces of a lithospheric contamination and subduction-related geochemical signature.

Key words: alkaline rocks, rock-forming mineralogy, geochemistry, petrology, magma sources and settings
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Резюме. По целия тихоокеански бряг на Западна Антарктида, включително и в някои от островите, съседни на или всред Протока на Бренсфийлд се срещат къснонеозойски мафични алкални вулкански скали. Остров Ливингстън е най-малко изучен между тези острови, особено по отношение на минералогията, петрологията и геохимията на оскъдните прояви на този тип скали, които тук са известни като Формацията Инот Пойнт. В работата са описани петрографските и геохимични характеристики на известни и новооткрити разкрития на тези примитивни вулкански скали. Новите химични анализи уточняват наименованията на скалите главно като нискотитанови ненаситени оливинови базалти и по-рядко като хавайити.

Сравненията с елементите-следи на аналогични скали от островите Грийнуич, Пенгуин, Дисепшън и Бриджмен разкриват общи особености – високи отношения *LILE/HFSE* (например, Ba/Zr 1.4-2.2; Ba/Nb 42-67; Rb/Nb 2.7-4; Ce/Nb 2.5-10; Th/Nb 0.25- 0.90; K/Zr 39-67, и т.н.). Тези отношения са противоположни на ниските отношения *LILE/HFSE* в алкалните провинции на Антарктическия полуостров (АР) и на Земята на Мери Бърд (MBL). Общо взето, ниските абсолютни количества на *HFSE* във всички алкални базалти от района на Протока Бренсфийлд и високите отношения Zr/Nb (19-43) и Sr/Nb (>100) са коренно различни от тези в AP и MBL По-високата степен на топене и променливите взаимодействия с континенталната литосфера са вероятната причина за геохимичните различия с алкалните базалти от другите провинции на Западна Анатрктида. Регионалните геохимични различия в елементите *LIL* между MBL и AP обосновават заключението, че те са произлезли от различни източници на топене. Алкални базалти от кратонните плато-базалти в Патагония и от атлантическия остров Възнесение са използвани за сравнение и тяхната геохимия е подобна на свързаните с мантийна струя базалти на MBL.

Независимо от екстензионната обстановка в заддъговия рифт на Протока на Бренсфийлд, алкалните базалти носят много от дъговите характеристики на елементите си следи. Предлага се ново подразделяне на алкалнобазалтовите провинции в Западна Антарктида. Ние добавяме към провинцията на AP, произлязла от един астеносферен MORB източник в обстановка на скъсване на субдуцираната пластина и към провинцията на MBL, свързвана с дълбока мантийна струя и една друга характерна провинция, а именно тази на Протока на Бренсфийлд – екстензионна, с алкални базалти, носещи следи от замърсяване с литосферен материал и с геохимична характеристика, свързана със субдукция.

Introduction

Cenozoic alkaline basalts are widespread throughout the entire Pacific coast of West Antarctica. Strong compositional similarities are found between all outcrops, in spite of the fact that this volcanism is sparsely distributed and episodic. The tectonic significance of the Late Cenozoic magmatic activity has not been fully explained, but some of the alkali volcanic rocks have been related to the inception of extension following the cessation of subduction at the Pacific margin (Barker, 1982). The early Mesozoic to Recent subduction at the Pacific margin of the Antarctic Peninsula gradually has ceased progressively northeastwards after a series of ridge crest-trench collisions (Cande et al., 1982). Only off the South Shetland Islands might very slow subduction be continuing at present to open the back-arc basin in the Bransfield Strait. This opening had occurred during the last 2 Ma (Weaver et al., 1979) and is marked with a series of submarine volcanoes developed in association with the Bransfield Rift Basin. Some of the volcanoes emerged above sea level to form the islands Deception, Penguin and Bridgeman (Gonzalez-Ferran, 1972, 1987), representing the top of stratovolcanoes formed during Pleistocene-Recent times.

Fresh lava and pyroclastic deposits of Quaternary age are known also on some spots in Livingston Island and in Greenwich Island (Smellie et al., 1984). The extensive snow coverage is a serious obstacle to examine the sparse volcanic activity on these islands and every new piece of petrological and geochemical knowledge would add important clues to the petrogenetic and tectonic interpretations of the area. Within this belt of alkaline magmatism, Livingston Island is the least well-known, particularly in respect to its petrology, notwithstanding that the South Shetland magmas are unique in the region with their combination of features found in alkaline and some mature arc settings. Their mantle sources seem to have been chemically modified by subduction processes and that is why they are chemically ambiguous.

This paper sets out to incorporate some new whole-rock analyses, trace-element data and rock-forming mineral chemistry obtained from old and new-discovered outcrops in Livingston Island into the published data sets. In order to allow comparison to other alkaline basalt provinces, the study combines these new data with a review of published data. We aim to assess more fully the outcrops with the hope that the new-obtained data and correlations could help in every attempt to explain this magmatism. The purposes of this mainly geochemical oriented study are: 1) to determine the specific geochemical characteristics of the basalts from the known and new outcrops in the island; 2) to compare lavas erupted in Livingston Island with lavas from nearby volcanoes in the Bransfield Strait and to some alkaline Quaternary provinces in West Antarctica and in the adjacent areas; 3) to add new arguments in understanding the petrogenesis of basaltic lavas in the region of West Antarctica.

Geological background

Livingston Island is one of the places along the Pacific coast of the West Antarctica known to host 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).

The oldest unit is the Miers Bluff Formation (Hobbs, 1968), supposed for a long time to be an important part of the fore arc basin. It makes up most of Hurd Peninsula. The depositional age of the formation is debatable – Late Paleozoic (Grikurov et al., 1968), Early Triassic (Smellie et al., 1984; Willan et al., 1994; Tokarski et al., 1997), Late Triassic (Ouyang et al., 2000) or Early Jurassic (Herve et al., 1991). Recently nannofossils have been recovered from the rocks (Stoykova et al., 2002; Pimpirev et al., 2004) and the age was assigned to Late Cretaceous. The tectonic setting is equivocal and not well understood.

The Mesozoic and Cenozoic Magmatic Arc (Thomson et al., 1983) is represented by calc-alkaline plutonic and volcanic exposures, thought to be parts of the Antarctic Peninsula Batholith (Leat et al., 1995; Zheng et al., 1995) and the Antarctic Peninsula Volcanic Group (Thompson, 1982). The plutons are of Late Cretaceous (Kamenov, Monchev, 1996; Kamenov, 1997) and of Eocene age (Smellie et al., 1995; 1996). Late Cretaceous age is obtained for some of the volcanic successions (Smellie et al., 1996; Zheng et al., 1996), but K-Ar ages of 35-45 Ma (Smellie et al., 1996) are published too and probably they show the effect of a thermal event caused by the late intrusions. Numerous mafic dykes cut all these igneous and sedimentary complexes and their emplacement spans the range of 79-31 Ma (Zheng et al., 2002).

The late extension stage (Oligocene-Recent) is related to the opening of the Bransfield Strait back-arc basin, which is also alternatively considered recently as a rifted ensialic marginal basin setting (Keller et al., 1991; Smellie, 2001). The rocks of this stage are observed at northeastern Livingston Island (Fig. 1) and they are known as the Inott Point Formation. The lavas and lapilli-tuff units of alkaline affinity (Smellie et al., 1984; 1995; 1996) were K-Ar dated at four widely separated localities and yielded Pleistocene-recent ages (≤ 1Ma, Smellie et al., 1996). The lavas may overlie the Miers Bluff Formation at Gleaner Heights, but no contacts are exposed. The volcano Micky is a new well-preserved exposure of fresh basaltic lavas, palagonitic tuffs and lapili, located northwest of Burdick Peak. Some pillow lava fragments were obviously produced by eruption inside the ice. The subglacial conditions are observed also in another exposure southeast of Burdick Peak, where red scoria is found as well, thus suggesting subareal deposition in addition to the shallow water pillow lavas. Only 2 chemical analyses were available in the literature – one from the outcrop southeast of Burdick Peak and other from Samuel Peak from the eastern part of the island, not very far from Inott Point (Smellie et al., 1984; 1996). Recently Veit (2002) presented several new analyses taken out from the area around Burdick Peak. The field observations and sampling for the present paper were undertaken during several Bulgarian Antarctic expeditions, starting from 1992/1993 season.

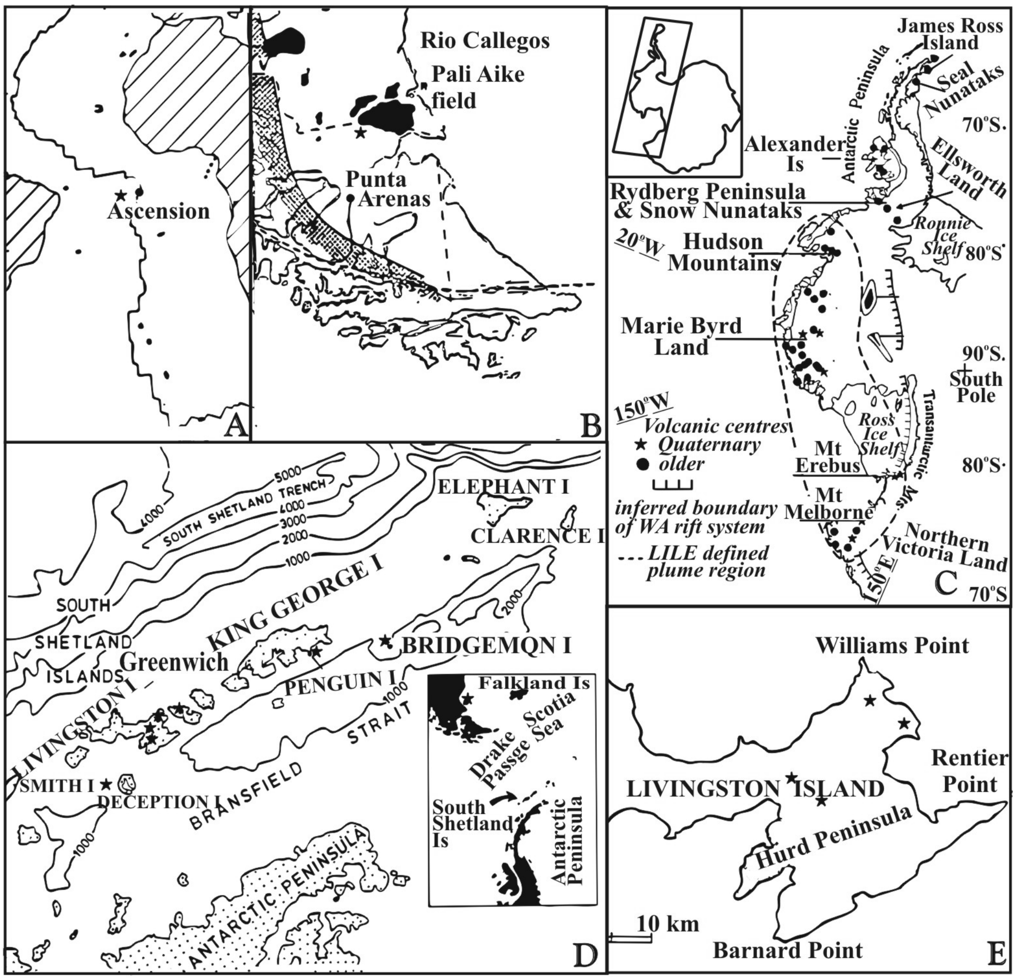


Fig. 1. Sketch maps showing the location of the exposures of alkali basalts mentioned in the text: Ascension Island (A); Pali-Aike volcanic field in Patagonia. Eastern limit of Cenozoic arc-cross-hatched strip (B); Cenozoic alkaline volcanic rocks in Marie Byrd Land and in Antarctic Peninsula (C); South Shetland Islands and Bransfield Strait with batimetry (D); main outcrops (stars) in Livingston Island, Inott Point Formation (E). Maps of Weaver (1991), Weaver et al. (1979, 1987), Stern et al. (1990), Hole, LeMasurier (1994) are used in this compilation

Фиг. 1. Схематични карти, показващи мястото на разкритията от алкални базалти, споменавани в текста: Остров Възнесение (A); вулканското поле Пали-Айке в Патагония. Източната граница на неозойската дъга – ивицата с кръстосана щриховка (B); неозойски алкални вулкански скали в Земята на Мери Бърд и в Антарктическия полуостров (C); архипелагът на Южношетландските острови и Протока на Бренсфийлд с батиметрията (D); главните разкрития (звездички) в остров Ливингстън, Формацията Инот Пойнт (E). В компилацията са използвани карти на Weaver (1991), Weaver et al. (1979, 1987), Stern et al. (1990), Hole, LeMasurier (1994)

The lava rocks at the Mount Plymouth in Greenwich Island are lithologically and geochemically comparable with the ones from Inott Formation in Livingston Island (Weaver et al., 1979).

Representative samples of alkaline volcanic rocks from the islands Deception (Baker et al., 1975; Smellie, 1990; 2002), Bridgman and Penguin (Gonzalez-Ferran, Katsui, 1970; Gonzalez-Ferran, 1972) were studied (Weaver et al., 1979) to provide information on the nature of magmatism associated with the initial stages of back-arc spreading. The islands Deception and Bridgeman are situated close to the axes of spreading, whereas Penguin Island lies slightly to the north of these axes. All these exposures, including the ones from Livingston Island are in general not very much unlike the outcrops in Mary Byrd Land (LeMasurier, 1972; LeMasurier, Rex, 1991), Alexander Island (Hole et al., 1991), Antarctic Peninsula (Gonzalez-Ferran, 1983,1985; Smellie, 1981; 1987; Smellie et al., 1988; Hole, 1988; Hole et al., 1993), Seal Nunataks (Hole, 1990) and James Ross Island (Baker et al., 1973). Some chemical and isotopic data for the Quaternary basalts of Bransfield Strait are published (Keller et al., 1991) and it is known that their range of $^{87}Sr/^{86}Sr$ is between 0.7030 and 0.7036, εNd being between 4.7 and 7.4 (Futa, LeMasurier, 1983). Limited number of Pb-isotopic results reveals rather restricted range of the ratios $^{206}Pb/^{204}Pb$ (18.74-18.76), $^{207}Pb/^{204}Pb$ (15.60-15.62) and $^{208}Pb/^{204}Pb$ (38.50-38.56).

The Quaternary alkaline basalts of the Patagonian plateau lavas of southernmost South America in Pali-Aike volcanic field (Munoz, Stern, 1989; Stern et al., 1990; Skewes, Stern, 1979) were chosen also for comparisons with the Livingston Island extensional basalts as well as the alkaline basalts from one typical ocean island, namely Ascension Island in the South Atlantic (Harris, 1983; Weaver et al., 1987). The author visited briefly the occurrences in Ascension Island, Deception Island and in Pali-Aike field, Patagonia in 1988 and 1994 and carried out field work in Alexander Island, Antarctic Peninsula alkaline province in 1989, but all comparative geochemical data from these localities are taken from the published literature.

Petrography

The lavas in Livingston Island are black in colour and very fresh olivine-basalts predominantly and rarely havaiites. The highly porphyritic varieties are seldom observed and the aphyric and subporphyric rocks are most common. The porphyritic basalt contains 15-17% phenocrysts by volume. Lavas in the exposure around the elevation 443 m. a.s.l. comprise typically 5-8% clinopyroxene crystals, 4-7% plagioclase phenocrysts and 3-4% rounded or embayed olivine grains. The groundmass is fine-grained intergranular in texture, formed by elongated tiny plagioclase laths (50-60%), isometric olivine grains (2-3%), clinopyroxene (≈20%) and magnetite (≈10%) microliths and a few chlorite flakes developed partly on the brown volcanic glass (≈5-10%). Intersertal textures are also present. Havaiites show trachytic textures. The average size of the plagioclase laths in the groundmass is 0.25 × 0.003 mm.

Clinopyroxene phenocrysts (Table 1) have average size 0.80 × 0.50 mm, the largest in the thin sections size being 1.75 × 1.10 mm. The wollastonite component (Wo) is between 44 and 51% (the average composition is Wo_{49}) and this determines the clinopyroxenes as diopside. The extinction angle c/Z = 43-50°. Hourglass structure and oscillatory zoning are often observed. Chemically zoned pyroxenes have cores with average $Wo_{49.5}$ in the cores and $Wo_{51.5}$ in the rims. The increasing of the Ca to the rims is related to the increase in alkalinity during the crystallization. The ratio Mg# is average 81 (range 78-83) in the cores and 76 (range 74-77) in the rims. This parameter confirms the marked enrichment not only in Ca (usually Al and Ti, too), but also in Fe/Mg ratio.

Olivine microphenocrysts are chemically zoned having Mg-rich cores and slightly more

Table 1. *Chemical composition of selected phenocrysts of mafic minerals*
Таблица 1. *Химичен състав на избрани порфири от мафични минерали*

Mineral	Clinopyroxene			
Rock	Olivine basalts		Hawaiite	
SiO_2	50.97	52.44	49.18	47.91
TiO_2	0.28	0.25	0.62	0.95
Al_2O_3	4.92	5.09	7.89	7.45
Cr_2O_3	0.26	0.18	0.16	0.22
NiO	-	-	-	-
FeOt	6.13	5.09	6.41	7.81
MnO	0.00	0.00	0.00	0.00
MgO	15.86	16.34	14.39	12.55
CaO	21.41	20.80	21.53	23.19
Na_2O	0.00	0.00	0.00	0.00
K_2O	0.00	0.00	0.00	0.00
Total	99.83	99.82	100.18	100.08
Na	0.00	0.00	0.00	0.00
Ca	0.84	0.81	0.85	0.93
Mn	0.00	0.00	0.00	0.00
Fe^{2+}	0.16	0.15	0.15	0.07
Mg	0.00	0.04	0.00	0.00
M2	1.00	1.00	1.00	1.00
Fe^{2+}	0.03	0.00	0.05	0.17
Mg	0.87	0.84	0.79	0.70
Ti	0.01	0.01	0.02	0.03
Cr	0.01	0.01	0.00	0.01
Al	0.09	0.12	0.15	0.12
M1	1.01	0.98	1.01	1.03
Al	0.12	0.10	0.19	0.21
Si	1.88	1.90	1.81	1.79
T	2.00	2.00	2.00	2.00
Mg #	81.7	86.4	79.8	74.5
Wo	45.2	44.0	46.2	49.7
En	44.8	47.8	42.9	37.4
Fs	10.0	8.2	10.9	12.8

Mineral	Olivine			
Rock	Olivine basalt		Hawaiite	
SiO_2	39.44	39.11	40.58	38.17
TiO_2	0.00	0.08	0.09	0.00
Al_2O_3	0.68	0.67	1.03	0.60
Cr_2O_3	-	-	-	-
NiO	0.00	0.21	0.28	0.00
FeOt	16.56	15.30	13.19	24.22
MnO	0.28	0.31	0.52	0.53
MgO	42.36	43.46	43.62	36.10
CaO	0.27	0.08	0.14	0.36
Na_2O	0.00	0.00	0.00	0.00
K_2O	0.00	0.00	0.00	0.00
Total	100.53	99.22	99.45	99.98
Si	1.00	0.99	1.01	1.00
Al	0.00	0.01	0.00	0.00
T	1.00	1.00	1.01	1.00
Al	0.02	0.01	0.03	0.02
Ti	0.00	0.00	0.00	0.00
Ni	0.00	0.00	0.01	0.00
Fe	0.35	0.32	0.28	0.53
Mn	0.01	0.01	0.01	0.01
Mg	1.60	1.64	1.63	1.41
Ca	0.01	0.00	0.00	0.01
Na	0.00	0.00	0.00	0.00
Total	1.99	1.98	1.99	1.98
Fo %	82.0	83.7	85.3	72.7

Chemical analyses made on JEOL JCM 35CF electron microprobe with Tracor Northern TN-2000 system in the EUROTEST Co, Sofia. Operating conditions: 15 kV accelerating voltage, counting times 100 s and sample current 2.10^{-9}A; Mg# =100Mg/Mg+Fe (*apfu*)

Fe-rich rims. The compositional range (Table 2) for the grains of average size 0.35 × 0.10 mm is Fo_{83-86} in the cores and Fo_{82-83} in the rims. The smaller grains of average size 0.15 × 0.10 mm have a composition Fo_{80-82}. The maximum range of composition encountered in a single crystal is Fo_{85-73} in havaiite. Within this range olivine phenocrysts show a limited but distinct trend of Ca-enrichment from 0.14 wt.% to 0.36 wt.%. This may be interpreted as a response to decreasing pressure during crystallization.

Plagioclase phenocrysts in the range An_{80-87} have been determined (Table 3). The average size is 0.24 × 0.09 mm and the maximum in the thin sections studied is 0.62 × 0.19 mm. A seriate gradation of the grain-size into the groundmass is typical. Most crystals are normally zoned having calcic cores (An_{87-76}) progressing to more sodic rims (An_{60}). A reverse zoning is also observed in some of the larger grains – An_{81} in the cores and An_{84} in the rims. Plagioclase microliths in the groundmass (size 0.15 × 0.03 mm) have compositions in the range An_{50-55}. Olivine and clinopyroxene participate also in the groundmass.

Microphenocrysts of *magnetite* and *ilmenite* coexist in the basalts. *Chromite* grains are present as intergranular rare small crystals in more Mg-rich variety of the olivine basalt rock.

Table 2. *Chemical composition of selected plagioclases*
Таблица 2. *Химичен състав на избрани плагиоклази*

Rock	Olivine basalt			Hawaiite	
Notes	core	core	core	core	rim
SiO_2	47.85	47.74	47.40	49.53	55.16
TiO_2	0.07	0.00	0.00	0.00	0.06
Al_2O_3	33.52	33.16	33.05	30.15	27.66
FeO	0.63	0.70	0.78	0.64	0.90
MnO	0.00	0.00	0.10	0.00	0.11
MgO	0.00	0.00	0.00	0.00	0.00
CaO	16.23	16.04	16.45	15.90	11.64
Na_2O	1.39	1.99	1.70	2.75	4.41
K_2O	0.00	0.10	0.06	0.14	0.00
Total	99.69	99.73	99.54	99.11	99.94
Na	0.12	0.18	0.15	0.25	0.39
K	0.00	0.01	0.00	0.01	0.00
Ca	0.80	0.79	0.81	0.79	0.56
Mn	0.00	0.00	0.00	0.00	0.00
Mg	0.00	0.00	0.00	0.00	0.00
X	0.92	0.98	0.96	1.05	0.95
Si	2.20	2.20	2.19	2.29	2.49
Al	1.81	1.80	1.80	1.65	1.47
Ti	0.00	0.00	0.00	0.00	0.00
Fe	0.02	0.03	0.03	0.02	0.03
Z	4.03	4.03	4.02	3.96	3.99
X+Z	4.95	5.01	4.98	5.01	4.94
An %	86.9	80.6	84.4	75.2	58.9
Ab %	13.1	18.4	15.6	23.8	41.1
Or %	0.0	1.0	0.0	1.0	0.0

The alteration is unusually slight in most of the specimens. It consists of serpentine and bowlingite rare replacements of olivine and chlorite in the groundmass. The yellow-orange glass in the tuffs is palagonitized.

Geochemistry

Major oxides

Basalts from Inott Point Formation are not very much variable in major oxide composition (Table 4), e.g., SiO_2 46-50%, Al_2O_3 16-18%, TiO_2 1.0-1.3%. MgO varies from 5 to 11% with > 80% of samples having over 6% MgO and > 100 ppm Cr (max. to 594 ppm). The samples do not define a single coherent trend on MgO variation diagrams. Samples are mainly undersaturated low-Ti olivine basalts (up to 6% normative nepheline) to slightly Si-saturated (less than 4% normative quartz). The majority of samples plot beneath the dividing line between saturated and undersaturated rocks with a few samples above this line (Fig. 2a). Based on the classification TAS plot of LeMaitre (1989) the samples are assigned to olivine basalts and hawaiites. The analyzed samples are relatively primitive and therefore the effects of high-level fractional crystallization are insignificant. It means that there is no need for screening and reduction of the set, when the primary geochemical peculiarities are considered. The element variations are consistent with limitted low-pressure crystal fractionation involving olivine - calcic plagioclase - clinopyroxene.

A close similarity is found between the Inott Point Formation samples and the alkaline basalts from Penguin and Greenwich (Weaver et al., 1979) islands, situated in Bransfield Strait area. The common field of these volcanic samples is located on the most primitive end of the chemical range of all magmatic rocks in Hurd Peninsula. It seems that the Quaternary basalts from the islands Bridgeman and Deception (Baker et al., 1975) are more evolved than the lavas from the same age from Livingston Island. In contrast to other Quaternary basalts in Bransfield Strait, which are all basaltic to basaltic andesitic, Deception Island contains a wide range of compositions extending from basalt to dacite. The trend of the Deception Island compositions lies close to and just above the dividing line between the transitional and saturated rocks.

All studied rocks belong basically to a calc-alkaline medium-K series related to arc magmatism (Fig. 2b). The same series is typical for the other Quaternary volcanic rocks from the islands Deception, Bridgeman, Penguin and Greenwich.

Trace element characteristics

General features

The general trace element characteristics of representative samples from the new exposures

Table 3. *Representative analyses of rocks (major oxides in wt.% and CIPW norms)*
Таблица 3. *Представителни анализи на скали (главни оксиди в тегл.% и CIPW норми)*

Sample	М-64/А	М-64/Б	М-64/Г	П/3	П/2
Rock	basalt	basalt	hawaiite	basalt	basalt
SiO_2	48.78	49.02	49.00	45.66	45.71
TiO_2	1.17	1.15	1.08	1.14	1.30
Al_2O_3	17.56	17.50	17.71	15.78	15.89
Fe_2O_3	3.40	3.10	3.05	8.11	3.46
FeO	6.55	5.98	6.23	2.55	6.94
MnO	0.17	0.16	0.17	0.17	0.17
MgO	6.81	7.01	6.50	11.90	11.90
CaO	10.93	11.21	11.30	11.35	11.11
Na_2O	3.84	4.25	4.22	2.54	2.60
K_2O	0.60	0.68	0.91	0.95	0.46
P_2O_5	0.23	0.20	0.20	0.19	0.20
H_2O-	0.05	0.11	0.02	0.02	0.13
Total	100.09	100.37	100.39	100.36	99.87
Q	0	0	0	0	0
Or	3.55	4.02	5.38	5.61	2.72
Ab	26.26	23.85	22.20	15.87	16.37
An	28.92	26.68	26.71	28.86	30.34
Ne	3.38	6.56	7.31	3.04	3.05
Wo/Di	9.94	11.54	11.71	10.94	9.80
En/Di	6.41	7.69	7.50	9.46	7.02
Fs/Di	2.87	3.00	3.45	0	1.90
Fo	7.39	6.84	6.09	14.40	15.85
Fa	3.65	2.94	3.08	0	4.74
Mt	4.93	4.50	4.42	5.46	5.02
Hem	0	0	0	4.35	0
Il	2.22	2.18	2.05	2.17	2.47
Ap	0.54	0.47	0.47	0.45	0.47
Total	100.06	100.30	100.40	100.60	99.75
DI	33.18	34.43	34.89	24.53	22.13
CI	37.41	38.69	38.30	46.51	46.80
N-An%	50.73	49.33	50.51	62.22	62.74

Wet silicate analyses, performed in the Geochemical Laboratory of the Sofia Univesrsity by the analysts E. Landgeva and T. Kurteva. The rocks are named by the TAS-systematics of LeMaitre et al. (1989). Samples П-3 and П-2 are dykes cutting the plutonic exposures around Mount Pliska and referred to the same Inott Point Formation

Скалите са анализирани по мокър класически способ в геохимичната лаборатория на Софийския университет от аналитиците Е. Ланджева и Т. Куртева. Номенклатурата на скалите е по TAS-класификацията на LeMaitre et al. (1989). Пробите П-3 и П-2 са дайки, сечащи плутоничните разкрития около връх Плиска и се отнасят към същата формация Инот Поинт

of basalts in Livingston Island are shown in Fig. 3A as a series of multi-element plots normalized to average N-MORB of Pearce (1983). All patterns are typically enriched in *LILE* and depleted in the *HFS* elements Ti, Y and Cr. The clear negative absolute (in relation to MORB) and relative (regarded to the adjacent Ce and Th normalized values) anomalies for Nb are geochemical island-arc characteristics of the subduction-related magmas, which like the bulk continental crust itself (Taylor, McLennan, 1981) are strongly depleted in Nb

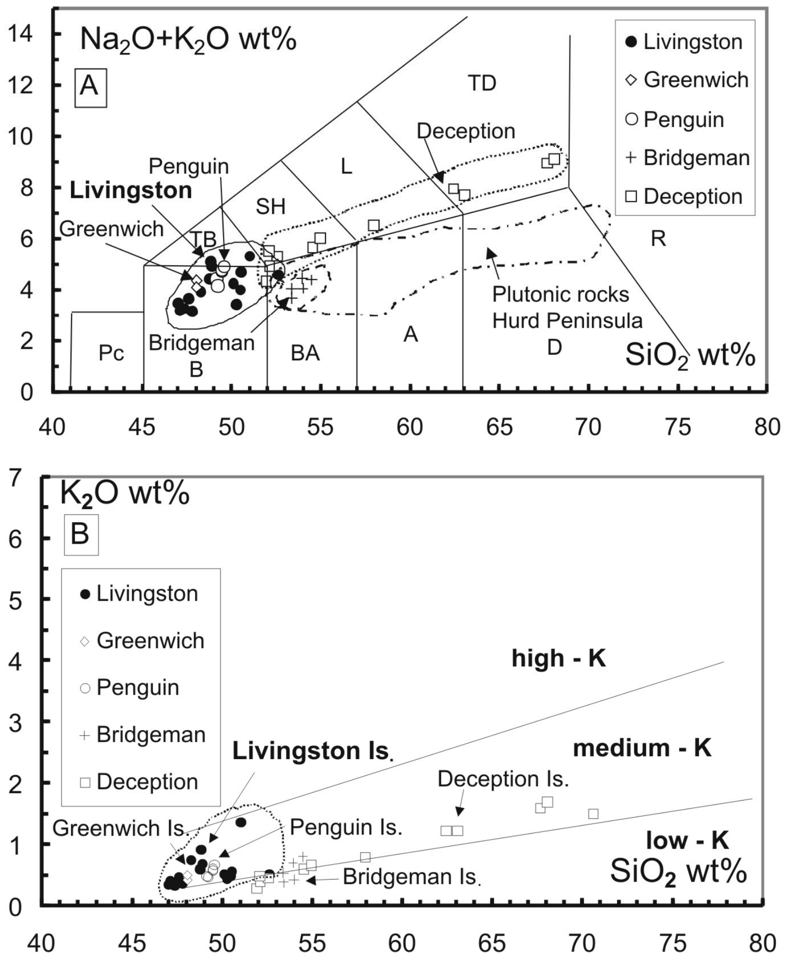


Fig. 2A) Quaternary basalts from the areas in Bransfield Strait and adjacent islands in South Shetland Islands in the plot SiO_2 *vs.* (Na_2O + K_2O) after LeMaitre (1989). Fields of all Hurd Peninsula, Livingston Island plutonic rocks, of Deception Island volcanic rocks (Baker et al., 1975), Bridgeman Island basalts (Gonzalez-Ferran, Katsui, 1970; Weaver et al., 1979) are for comparison with the field for Livingston Island alkaline basalts (unpublished and from Smellie et al., 1984), Greenwich Island (Smellie et al., 1984), Penguin Island (Weaver et al., 1979). B) SiO_2 *vs.* K_2O plot after LeMaitre (1989). The same reference sources are used

Фиг. 2A) Алкални базалти от района на Протока Бренсфийлд и съседните острови в Архипелага на Южношетландските острови в диаграмата SiO_2 *vs.* (Na_2O + K_2O) по LeMaitre (1989). Полетата на всички плутонични скали от полуостров Хърд, остров Ливингстън, на вулканските скали от остров Дисепшън (Baker et al., 1975), на алкални базалти от остров Бриджмен (Gonzalez-Ferran, Katsui, 1970; Weaver et al., 1979) са за сравнение с полето за алкалните базалти от остров Ливингстън (непубликувани и от Smellie et al., 1984), остров Грийнуич (Smellie et al., 1984), остров Пенгуин (Weaver et al., 1979). B) Диаграма SiO_2 *vs.* K_2O по LeMaitre (1989). Използвани са същите литературни източници

Table 4. *Trace elements in some selected bulk rock samples*
Таблица 4. *Съдържания на елементи-следи в някои избрани скални проби*

Sample	Cr	Ni	Th	Rb	Ce	Ba	Sr	Zr	V	Nb	Y
М-64/а	98	35	1	8	22	190	568	128	240	3	20
М-64/б	117	35	1	12	30	180	544	128	170	4	22
М-64/г	96	37	2	12	14	200	575	129	270	3	22
П-2	590	180	1	8	15	90	420	55	292	3	18
П-3	450	206	2	12	29	129	530	63	285	2	15

Analytical method: X-ray fluorescence (EUROTEST Co, Sofia) with exception of Ni determined by atomic absorption in the Geochemical Laboratory of Sofia University
Аналитичен метод: рентгено-флуоресцентен (EUROTEST Co, София), с изключение на Ni, определян чрез атомна абсорбция в Геохимическата лаборатория на Софийския университет

relative to the other highly-incompatible trace elements (e.g., Saunders et al., 1980; Thompson et al., 1984). The pattern resembles the one for the transitional basalts in the ocean arcs (Pearce, 1983). The shown for comparison patterns for the representative samples from Penguin Island (Fig. 3B), and Bridgeman Island (Fig. 3C) using the data from Weaver et al. (1979) are with similar peculiarities and also suggest subduction-related affinity of their magmas. The ratio Ce_N/Y_N = 1.5-3.7 in the Inott Point Fm. basalts coincides with Ce_N/Y_N range in the basalts from the islands within Bransfield Strait (1.2-4.6).

Quite different are the patterns of the MORB-normalized trace-element distributions for selected alkaline basalts from Patagonia (data source: Stern et al., 1990) shown in Fig. 3D. In general they exhibit similar trace-element abundances to ocean-island basalts (OIB) and some continental alkaline basalts with low *LILE/HFSE* ratios. The high absolute negative Nb anomaly, which is a feature of arc magmas, does not exist. The spidergrams have the humped profiles, similar to oceanic island tholeiites. It is interesting that the N-MORB-normalized diagramme of the Deception Island (Smellie, 2002) reveals some similarities with the one for Patagonia samples. Variable Ce_N/Y_N ratios (4.4-8.8), but relatively consistent abundances of *HFSE* are suggestive of residual garnet during partial melting. Typical within-plate basalt patterns (WPB) of the MORB-normalized multi-element plots are reported for Antarctic Peninsula alkaline basalts (Hole, LeMasurier, 1994), St. Helena (Chaffey et al., 1989), Ascension Island (Weaver et al., 1987), Baja California, Mexico (Storey et al., 1989), etc.

HFSE fractionation as indicators of partial melting

The absolute abundances of Y (14-22 ppm) in the samples from Livingston Island are nearly constant and always <1 in their MORB-normalized values, which also supports the idea of presence of residual garnet in the mantle source, giving a minimum depth of origin of the magma around 80 km. Nearly the same range of Y is observed in the basalts from Penguin Island (10-13 ppm), Greenwich Island (12-14 ppm), Bridgeman Island (9-11 ppm). In contrast, the alkaline basalts from Alexander Island (23-26 ppm), Seal Nunataks (21-27 ppm), Patagonia cratonic basalts (20-24 ppm) and Ascension Island (34-47 ppm) have higher absolute Y abundances.

All analyzed samples from Livingston Island have less than 8000 ppm Ti (range 5454-7012 ppm) similar to the Ti abundances in the other Bransfield Strait basalts. On a plot of Zr/Nb ratio versus Ti (Fig. 4A) two clusters are distinguished. The low-Ti and high Zr/Nb alkaline basalts of the Bransfield Strait province, including the outcrops in Livingston Island are clearly distinguished from the high-Ti and low Zr/Nb alkaline basalts from the provinces in Antarctic Peninsula (Alexander Island and Seal Nunataks), Patagonia flood basalts and Ascension within-plate ocean-island basalts.

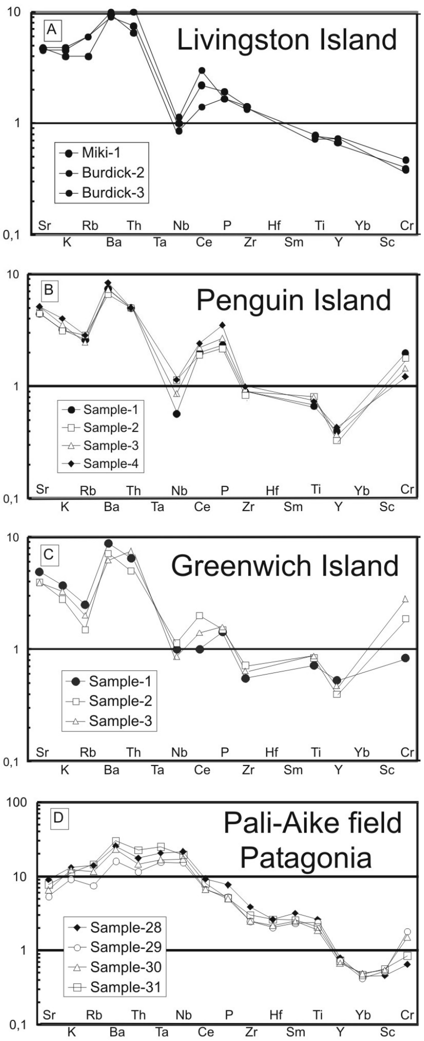
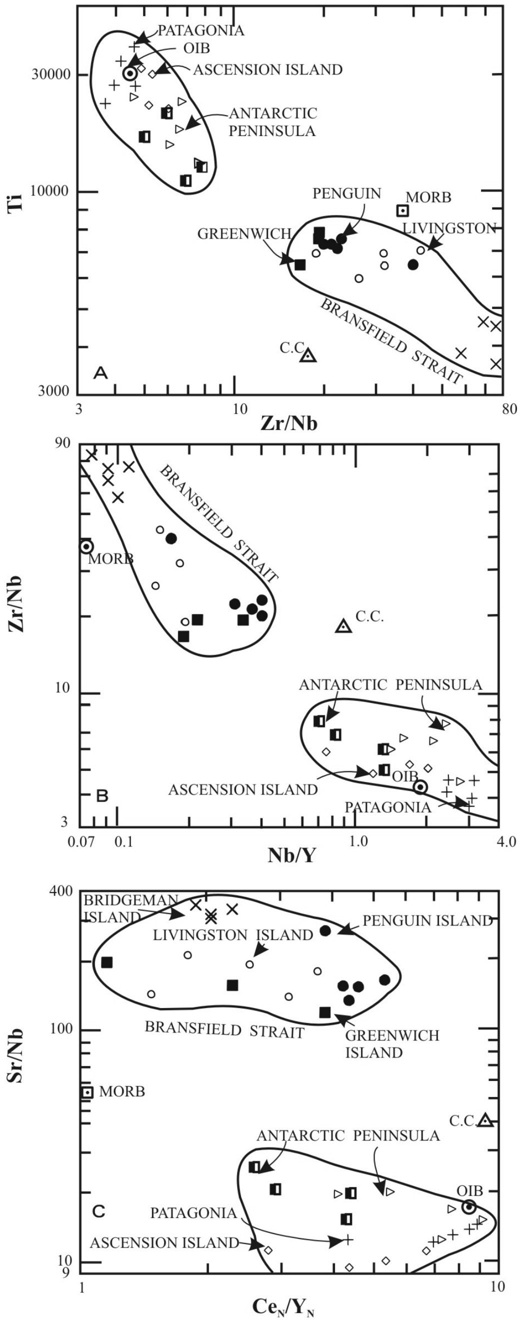


Fig. 3. Selected MORB-normalized trace-element patterns for samples from Livingston Island (A), compared to data from Penguin Island (Weaver et al., 1979) (B), Bridgeman Island (Weaver et al., 1979) (C), and Patagonia Pali-Aike volcanic field (Stern et al., 1990) (D)

Фиг. 3. Избрани MORB-нормализирани разпределения за проби от остров Ливингстън (A) сравнени с данни от островите Пенгуин (Weaver et al., 1979) (B), Бриджмен (Weaver et al., 1979) (C) и вулканското поле Пали-Айке в Патагония (Stern et al., 1990) (D)

The relative abundances of the *HFSE* of Inott Point basalts differ essentially from those of Antarctic Peninsula and Marie Byrd Land (MBL). For instance, the total range in Zr/Nb is between 19 and 43 (average 33) for Inott Point basalts, but for the Antarctic Peninsula this ratio is as low as 2.9-9.0 (average 6), according to Hole (1990) and Hole et al. (1993). Nearly the same range of this ratio is known for MBL basalts (3.1-9.2, average 4.5 - LeMasurier, Rex, 1991; Hole, LeMasurier, 1994). Similar overlapping ranges of the low ratios are reported for cratonic basalts in Patagonia (3.7-4.7, average 4.2 - Stern et al., 1990) and in the ocean island basalts of Ascension Island (Weaver et al., 1987). In contrast, the majority of the inter-element ratios of the HFSE cover similar ranges for the basalts from the volcanoes within and around the Bransfield Strait. For example, the total range of Zr/Nb for Penguin Island is as high as 20-40 (average 26), for Greenwich Island it is 39-77 (average 30) and for Bridgeman Island – 58-76 (average 70), calculated from the published data (Weaver, 1979). The high Zr/Nb ratios in the basalts from the province around Bransfield Strait are due mainly to the very low Nb absolute abundances in these basalts (2-5 ppm). By contrast, samples from Alexander Island (Hole et al., 1991) and from Seal Nunataks (Hole, 1990; Hole et al., 1993; Hole, LeMasurier, 1994) have a total range in Nb abundances between 12 and 80 ppm and this range is comparable to the range in Marie Byrd Land basalts (31-91 - Hole, LeMasurier, 1994), similar to the range in alkaline basalts from Patagonia (50-75 - Stern et al., 1990) and from Ascension Island (35-68 - Weaver et al., 1987). The unusual low absolute abundances of Nb in the basalts from Livingston Island and in the islands within the Bransfield back-arc rift are even lower than in the subduction-related Tertiary lavas from Antarctic Peninsula (2-14 - Saunders et al., 1980).

All primitive alkaline basalts, regardless of geographical location, exhibit strong relationship between the degree of partial melting (La_N/Yb_N, Ce_N/Y_N, Nb/Y etc. as indexes of the extent of melting) and the ratios Ti/Nb, Zr/Nb,



Фиг. 4A) Zr/Nb *vs.* Ti plot for Livingston Island samples (open circles) compared to samples from the islands Penguin (filled circles), Greenwich (filled squares), Bridgeman (×) in Bransfield Strait area and to samples from Antarctic Peninsula (open triangles, Alexander Island and half-filled squares, Seal Nunataks), Ascension Island (diamonds, Weaver et al., 1987) and Patagonian Pali-Aike volcanic rocks (crosses). The other sources are as in the Fig. 3. Data for N-type MORB is from Saunders and Tarney (1984), and for average continental crust (C.C.) - from Weaver and Tarney (1984). B) Zr/Nb *vs.* Nb/Y plot for the same samples. OIB – from Sun (1980). C) Sr/Nb *vs.* Ce_N/Y_N plot for the same samples. Chondrite-normalization factors - from Sun and McDonough (1989). The average continental crust (C.C.), N-MORB and OIB values – as in Fig. 4A

Фиг. 4A) Диаграма Zr/Nb *vs.* Ti за образци от остров Ливингстън (празни кръгчета), сравнени с проби от островите Пенгуин (плътни кръгчета), Грийнуич (запълнени квадрати), Бриджмен (хиксове) от района на протока Бренсфийлд и с проби от Антарктическия полуостров (остров Александър – празни триъгълници и Нунатаците Сийл – полузапълнени квадрати), остров Възнесение (Weaver et al., 1987 - ромбове) и проби от вулканското поле Пали-Айке в Патагония (кръстчета). Другите източници са както на фиг. 3. Данните за типа N- MORB са от Saunders, Tarney (1984), а за средната континентална кора (C.C.) – от Weaver, Tarney (1984). B) Диаграма Zr/Nb *vs.* Nb/Y за същите проби. Океанско-островните базалти (OIB) са по Sun (1980). C) Диаграма Sr/Nb *vs.* Ce_N/Y_N за същите проби. Нормализацията е по хондрита на Sun, McDonough (1989). Средната континентална кора (C.C.), N-MORB и OIB – както на фиг. 4A

Sr/Nb, Ti/Zr and P/Nb (Clague, Frey, 1982; Weaver et al., 1987; Latin et al., 1990). Such *HFSE* fractionation is considered to be a function of the amount of residual clinopyroxene and garnet at low degrees of melting, as distribution coefficients for Nb are lower than the most of the other *HFSE* in mantle clinopyroxenes and garnets (Greenough, 1988). The finding of such negative correlations should suggest that the observed relative fractionation of these *HFS*-elements is a function of degree of partial melting rather than source-region heterogeneity. Inter-element ratios involving only the *HFSE* are therefore not reliable indicators of the composition of the mantle source region for undersaturated alkaline basalts (Hole, LeMasurier, 1994). The negative correlations between Zr/Nb and Nb/Y ratio are demonstrated in Fig. 4B as an example. The field of the high Zr/Nb- and low Nb/Y-basalts comprise the samples from Livingston Island, Penguin Island, Greenwich Island and Bridgeman Island and is located between the N-MORB and the average continental crust. The second high Nb/Y- and low Zr/Nb-field covers the samples from Alexander Island, Seal Nunataks, Patagonia flood basalts and the ocean island Ascension. A MORB-source contaminated with continental crust materials during the subduction process is hence probable for the Bransfield alkaline magmas and a specific OIB source, probably mixed to some degree with crust materials does not contradict to the derivation of the Antarctic Peninsula, Patagonia and Ascension Island basaltic magmas from enriched mantle. The main reasons for the essential geochemical differences between the both groups of alkaline basalts should be the higher melting degree for the first group, including the Livingston Island samples and the lower melting degree of melting for the second group, consisting of within-plate basalts. Similar are the relationships in the plots Ti/Nb *vs.* Nb/Y, Sr/Nb *vs.* Nb/Y (not shown here).

The both groups of alkaline basalts are distinguished perfectly on the plot Ce_N/Y_N *vs* Sr/Nb (Fig. 4C), where we used the ratio Ce_N/Y_N as an indicator for melting degree. Y does not precisely behave like Yb, but acts rather more like middle-*REE*. The Livingston Island alkaline basalts fall in the group of the high Sr/Nb ratios (>100) showing higher degrees of melting together with the similar basalts from the islands Penguin, Greenwich and Bridgeman in contrast to the samples from Alexander Island, Seal Nunataks, Patagonia and Ascension Island, showing lower Sr/Nb ratios (<30) and lower melting degrees.

Fractionation of the LILE and magma sources

LIL-elements may also be fractionated significantly during low degree of partial melting. Relative compatibility of K and the generation of low K/*LILE* and K/*HFSE* are generally considered to be the result of residual hydrous phases in the source of these magmas (Hole, LeMasurier, 1994). On plots involving an index of degree of partial melting like Nb/Y vs. K/Ba and K/Rb (e.g., Fig. 5A), all the analyzed basalts from Inott Point Formation cover nearly similar ranges in Nb/Y with samples from Penguin Island and Greenwich Island, but differ with the samples from Antarctic Peninsula, Patagonia and Ascension Island. The lower alkalinity of the Inott Point Fm. basalts (lower ratios Nb/Y meaning also higher melting degree) is combined on the plot with one of the lowers ratios K/Ba (26-38, average 32) typical also for Penguin (27-32; average 30) and Greenwich islands (24-33, average 27.9). The basalts from Bridgeman Island differ from the Livingston Island in the still lower ratio Nb/Y (higher degree of melting) and in the significantly higher ratios K/Ba (51-59, average 55). Mixing and melting modeling for the Bransfield Strait lavas using isotope data (Keller et al., 1991) also suggest that the on-axis lavas (Bridgman Island, Deception Island and submarine volcanoes aligned on the axis of rifting) are products of more melting than the off-axis lavas (e.g., Penguin Island).

The variations in K/Ba ratios in the group of samples from Antarctic Peninsula, Ascension Island and Patagonia cover a broad range of values, which are independent of Nb/Y and therefore these are regional variations unlikely to be simply an artifact of degree of partial melting. The average K/Ba in Antarctic Peninsula is 78 at range of 49-134 (Hole, LeMasurier, 1994). The average K/Ba in Marie Byrd Land is 27 (range 14-40) and as it is seen on the Fig. 5A it is very close to the average continental crust and average OIB (Weaver et al., 1987). The K/Ba ratios of the Patagonia and of Ascension Island alkaline basalts are not very much unlike to the Marie Byrd Land samples. These regional trace element variations must be a result of generating the basalts from different portions of their source (Hart, 1988; Hickey et al., 1986) and/or variable interaction with the continental litho-

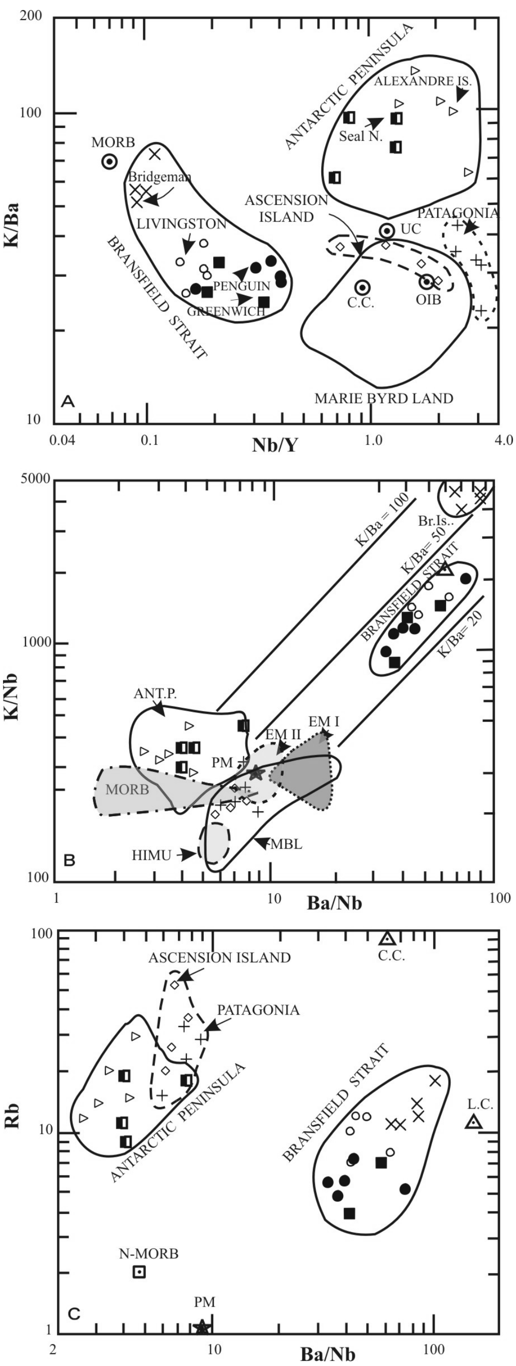


Fig. 5. Trace element variation diagrams for Livingston Island samples compared to samples from Bransfield Strait area and to Antarctic Peninsula, Marie Byrd Land (the field of Marie Byrd Land (MBL) is from LeMasurier and Rex, 1991), Ascension Island and Patagonia samples. A) K/Ba *vs.* Nb/Y plot. Data sources and average MORB, C.C. and OIB are as in Fig. 4. Upper continetal crust (UC) - from Taylor and McLennan, 1981, lower crust (LC) - from Weaver and Tarney (1984). B) Ba/Nb *vs.* K/Nb plot. The average compositions EMI, EMII and HIMU OIB are from Weaver (1991) and Hole and LeMasurier (1994). The field for MORB is from Hofmann et al. (1986) and from Hofman and White (1983). Star, primordial mantle of Weaver (1991). C) Rb *vs.* Ba/Nb plot. All data sources and average reference points are as in Figs. 4 and 5. Field for MBL from Hole and LeMasurier (1994)

Фиг. 5. Вариационни диаграми за отношения на елементи-следи в проби от остров Ливингстън, сравнени с проби от островите около Протока на Бренсфийлд (Пенгуин, Грийнуич, Бриджмен) и с проби от Антарктическия полуостров, Земята на Мери Бърд (полето е от LeMasurier, Rex, 1991), остров Възнесение и вулканското поле Пали-Айке в Патагония. A) Диаграма K/Ba *vs.* Nb/Y. Източниците и средните MORB, континентална кора (C.C.) and OIB са както на фиг. 4. Горната кора (UC) е от Taylor, McLennan (1981), долната кора (LC) - от Weaver, Tarney (1984). B) Диаграма Ba/Nb *vs.* K/Nb. Средните състави на EMI, EMII and HIMU OIB са от Weaver, (1991) и от Hole, LeMasurier (1994). Полето на MORB е от Hofmann et al. (1986) и от Hofman and White (1983). Изначалната мантия (звезда) е по Weaver (1991). C) Диаграма Rb *vs.* Ba/Nb. Всички символи и литературни източници са както на фиг. 4 и 5

sphere as Hole and LeMasurier (1994) assumed for the case of Marie Byrd Land and Antarctic Peninsula. For the Bransfield back-arc rift the role of the degree of partial melting in forming this ratio seems more plausible. The positive correlation between the ratios K/Rb and Nb/Y found in the basalts from Bransfield back-arc rift supports such a conclusion.

Asthenospheric heterogeneity

Similar arguments apply to variations K/Nb and Ba/Nb throughout basalts from Bransfield Strait region and from the Antarctic Peninsula and Marie Byrd Land (Hole, LeMasurier,

1994) shown in Fig. 5B. Ratio plots of highly incompatible elements minimize the effects of inter-element fractionation, such that for elements with identical bulk distribution coefficients (D), ratios should not change during partial melting or fractionation crystallization. The first and most impressive feature of this diagram is the clear separation of the samples from Livingston Island and from Bransfield Strait region and of the Antarctic Peninsula, Patagonia and Ascension Island samples into two clusters. The Inott Point Fm. basalts (as well as the basalts from the islands in the Bransfield Strait) have considerably higher Ba/Nb, K/Nb, K/Rb, K/Zr, Th/Nb and Rb/Nb than the Antarctic Peninsula basalts. Basalts from the Marie Byrd Land, Patagonia and Ascension Island show lower K/Nb and higher Ba/Nb, but nearly the same K/Ba ratios (mostly between 20 and 40) just as these ratios in Bransfield Strait region are. The difference between the Bransfield Strait and these regions is in the fact that the former are close to the average crust point (Taylor, McLennan, 1981), and the last ones – to the HIMU and EMII OIB fields (Weaver, 1991). The Antarctic Peninsula samples form the continuation of the MORB array to higher K/Nb, but similar K/Ba ratios, whereas the MBL basalts overlap with the array defined by plume-related OIBs. The proximity of the cluster of samples from Bransfield rift, confirms that a subduction-influenced source was involved into the composition of their magmas. The significant differences in K/Nb and K/Ba ratios between Marie Byrd Land and Antarctic Peninsula require that they were derived from different and isolated source regions. Hole et al. (1993) support the hypothesis that Antarctic Peninsula Quaternary basalts could simply represent small degree melts of MORB-source asthenosphere and the data of MBL are consistent with their derivation from plume source (Hofmann, White, 1982; Storey et al., 1988). This is the reason these data to fall close to OIBs source. LeMasurier and Rex (1991) and Hole and LeMasurier (1994) suggested also a mantle plume source for MBL basalts. Looking on the distribution of the data from Patagonia flood basalts and from Ascension Island, which we used for comparison in Fig. 5B, the same conclusions are possibly valid for them. Conversely, a lithospheric involvement in the basalt genesis is a characteristic of the Bransfield Strait basalts and a subarc source region contamination might affected their mantle source.

In spite of the fact that the Antarctic Peninsula region is characterized by unusually low absolute abundances of Rb (12-30 ppm for Alexander Island and 9-19 ppm for Seal Nunataks, Hole et al., 1993) the alkaline basalts of Livingston Island contain still lower abundances of Rb – 8-12 ppm. These values come into line with the abundances in the basalts from the other back-arc rift islands in the Bransfield Strait. For example, Penguin Island basalts have 5-7 ppm Rb, Greenwich Island ones – 3-7 and Bridgeman – 6-7. The absolute Rb abundances are nearly two times higher in Antarctic Peninsula, MBL basalts and the Ascension and Patagonia alkali basalts (Fig. 5C - Rb *vs* Ba/Nb) - features that are independent of absolute and low abundances of K_2O or SiO_2. The successive subduction of ridge crest-trench collision episodes along the west margin of the Antarctic Peninsula and a relatively juvenile lithosphere (Barker, 1982; Larter, Barker, 1991) should explain the depleted Rb abundances.

Interactions with continental lithosphere

The relative abundances of K, Rb and Ba in Livingston Island basalts are compared in Fig. 6A to materials comprising subducted oceanic crust, i.e., fresh and altered MORB, taken from "Nasca" plate, constructed by Hickey-Vargas et al.(1989) with the data of Thompson et al. (1976), Staudigel et al. (1980).The pelagic sediments (Hole et al., 1984; Morris, Hart, 1983; Stern and Ito, 1983), continental crust (Taylor, Mc Lennan, 1981) and the enriched oceanic mantle are inferred from Morris and Hart (1983). The lavas from Livingston Island have K/Rb ratios in the range 380-630 (the average is 510), while the basalts from Antarctic Peninsula have these ratios in the

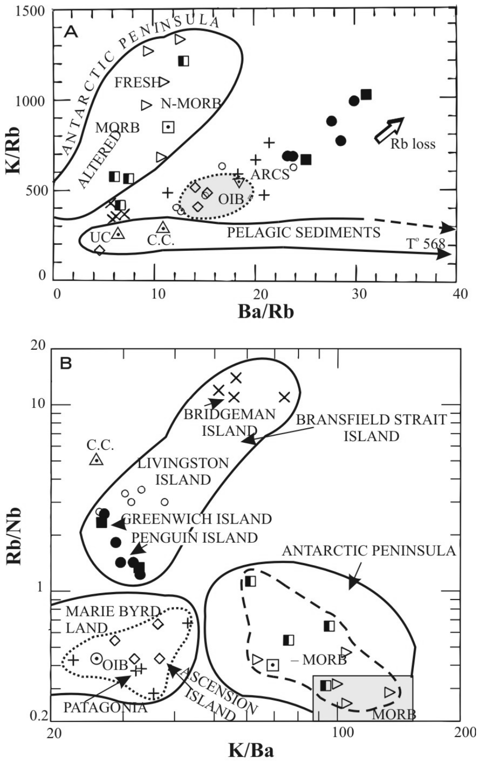


Fig. 6. Trace element variation diagrams for Livingston Island samples compared to samples from the islands within Bransfield Strait area (Penguin, Greenwich, Bridgeman) and to samples from Alexander Island, Seal Nunataks, Ascension Island and Pali-Aike volcanic field, Patagonia. A) K/Rb *vs.* Ba/Rb plot. Fresh and altered MORB, pelagic sediments, OIB and continental crust (average crust, C.C. and average upper crust, UC) are projected on the plot for comparison. MORB field is taken from Hickey-Vargas et al. (1989) and the field for pelagic sediments is constructed with data from Hole et al. (1984), Morris, Hart (1983) and Stern, Ito (1983). OIB field is constructed with the averages of Morris, Hart (1983). The average continental crust (C.C.) is from Weaver, Tarney (1984) and the average of the upper crust (UC) is of Taylor and McLennan (1981). B) Rb/Nb *vs.* K/Ba plot. Fields for Antarctic Peninsula and Marie Byrd Land are from Hole, LeMasurier (1994). The samples for comparison in this study are outlined with dashed line. MORB field is from Ito et al. (1989). The average N-MORB, OIB, continental crust and the other sources and all other symbols are as for Fig. 4

Фиг. 6. Вариационни диаграми за елементи-следи за проби от остров Ливингстън, сравнени с проби от островите всред Протока на Бренсфийлд (Пенгуин, Грийнуич, Бриджмен) и с проби от остров Александър, Нунатаците Сийл, остров Възнесение, вулканското поле Пали-Айке в Патагония. А) Диаграма K/Rb *vs.* Ba/Rb. Свежите и променени MORB, пелагичните седименти и континенталната кора (средна кора, C.C. и средна горна кора, UC) са поставени за сравнение. MORB полето е взето от Hickey-Vargas et al. (1989), а полето за пелагичните седименти е конструирано с данни от Hole et al. (1984), Morris, Hart (1983) and Stern, Ito (1983). Полето OIB е конструирано със средните значения от Morris, Hart (1983). Средната континентална кора е от Weaver, Tarney (1984), а средната горна кора (UC) е от Taylor, McLennan (1981). B). Диаграма Rb/Nb *vs.* K/Ba. Полетата за Антарктическия полуостров и Земята на Мери Бърд са от Hole, LeMasurier (1994). Използваните в това изследване проби за сравнение са очертани с щрихирана линия. Полето MORB е от Ito et al. (1989). Средните типове N-MORB, OIB, континентална кора и другите литературни източници и символи са както на фиг. 4

range 500-1750 and the lavas from Marie Byrd Land – 250-550 (Hole et al., 1993). The samples from Inott Point Fm. fall in an area where mixture of altered MORB and sediments (i.e., subducted oceanic crust), continental crust and OIB field (i.e., enriched oceanic mantle) overlap. In this respect they are similar to Ascension Island basalts and close to Patagonia flood basalts, derived from an enriched mantle. The possible contamination of the mantle source by rich in Ba and Pb pelagic sediments is well supported by the study of Keller et al. (1991) confirming that the Pb-isotope signature of the basalts is dominated by the subducted sediments. A typical feature of the Penguin Island, as well as of the Greenwich Island basalts, is that they do not overlap with fresh or altered MORB, pelagic sediment or OIB mantle, nor do they form mixing trends between these end-members (Fig. 6A). Trends for Penguin and Greenwich basalts are more explicable by loss of Rb relative to K and Ba from the subducted crust as a whole. The variations in alkali elements during the dehydratation of the subducted crust and the preferential loss of Rb could control their high K/Rb ratios and the correlation with Ba/Rb (Tatsumi et al., 1986). The long history of subduction and arc volcanism in the South Shetland Islands provides ample opportunity for migration of slab-derived fluids through the mantle wedge, resulting in depletion of Rb in the residual mantle. In order to explain these features we appeal to heterogeneity in one of the proposed sources of the magmas. Possibly, fluids expelled from certain sections of the oceanic subducting plate vary in their alkali element abundances. These fluids generate batches of magma that bear these geochemical differences, in addition to variations that result from the amount of fluid incorporated and the extent of melting. In this case, pooling and mixing beneath the large, long-lived volcanic centers homogenize the variations in individual magma batches. Based on the geochemical data only we cannot differentiate between heterogeneity in the subcontinental lithosphere mantle or of the slab-derived fluids as a source for the unique features of the Penguin and Greenwich basalts. A striking difference between within-plate basalts in Bransfield Strait, Ascension Island and Patagonia is the location of Antarctic Peninsula basalts in this Fig. 6A. The last ones form a field, entirely within the MORB source of their magmas.

In terms of incompatible trace element ratios the Livingston Island and Penguin basalts exhibit some similarities with ocean-island basalts sources OIB (Fig. 6B). Rb/Nb ratios extend to higher values than for the MORB and are close to the continental crust values. The range of Rb/Nb in Inott Point Fm. basalts is 2.7-4.0 (average 3.3) and it is a bit higher than in the Penguin and Greenwich islands altogether – 1.2-2.6 (average 1.6), but clearly lower than in the Bridgeman Island on-axis basalts – 11-14 (average 12). All the so-called “Bransfield Strait” basalts form an elongated common field, characterized with the high Rb/Nb ratios like in the volcanic arcs (average 33.1 - Morris, Hart, 1983). The close location to the average crust gives a hint to the suggestion that Inott point samples and their neighboring Bransfield occurrences have sources of back-arc extensional settings strongly influenced by the subduction process. The two fields of samples with low Rb/Nb ratios comprise from one side Marie Byrd Land (Rb/Nb 0.2-0.9), Patagonia (Rb/Nb 0.3-0.7, average 0.4) and Ascension Island basalts (Rb/Nb 0.42-1.4), which are low K/Ba plume-related enriched WPB and Antarctic Peninsula high K/Ba basalts from the other side (Rb/Nb 0.3-1.2), explained as small-degree melts of the asthenosphere in a slab-window setting (Hole, LeMasurier, 1994). The first group of the low Rb/Nb basalts is close to/or within the range of the OIB field, but the second group of low Rb/Nb basalts is close or within the MORB source. Nearly the same geochemical differences are revealed in Fig. 7A (Rb/Nb *vs.* Ba/Nb) and in Fig. 7B (Ba/Th *vs*. Rb/Nb). In the Rb/Nb *vs*. Ba/Nb plot of Fig. 7A EMI OIB is distinct from HIMU OIB and partly from EMII OIB. The field of high Rb/Nb and high Ba/Nb ratios comprises all alkaline basalts from Livingston Island, Penguin Island and Greenwich Island and it is located between the points for average crust materials and EMI OIB source, as the field of alkaline basalts from Antarctic Peninsula, Patagonia and Ascension Island overlaps HIMU OIB, N-MORB, Primordial Mantle and EMII OIB. EMI OIB are effectively discriminated from HIMU OIB in terms of the trace element ratios Ba/Th and Rb/Nb in Fig. 7B. The enhanced *LILE/HFSE* ratios in EMI OIB relative to HIMU OIB are reflected by the lack of relative Nb enrichment in the spidergrams for EMI OIB (Weaver, 1991) and in this respect there is a distant similarity with this peculiarity in the spidergrams of the Livingston Island basalts (Fig. 3A). A combination between EMI OIB and continental crust sources is plausible for the alkaline basalts from the Bransfield Strait area, but the Antarctic Peninsula basalts seems to originated from HIMU OIB source without significant crustal contamination. In addition EMI OIB also display enrichment in Ba relative to other *LIL* elements, leading to high

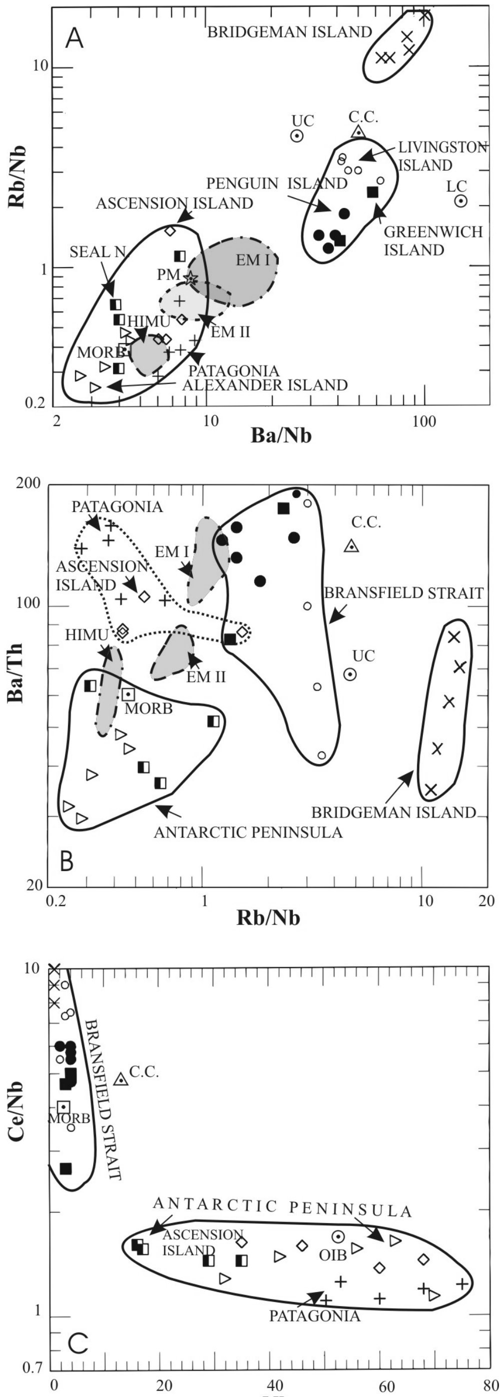


Fig. 7. Trace element variation diagrams for Livingston Island samples compared to samples from the islands within Bransfield Strait area (Penguin, Greenwich, Bridgeman) and to samples from Alexander Island, Seal Nunataks, Ascension Island and Pali-Aike volcanic field, Patagonia. A) Rb/Nb *vs.* Ba/Nb plot. B) Ba/Th *vs.* Rb/Nb plot. C) Nb *vs.* Ce/Nb plot. Symbols, mantle source fields, average crust and MORB points and data sources are as for Fig. 4 and Fig. 5. Note the increase in Ce/Nb with decreasing Nb, which is probably a function of asthenosphere-lithosphere interaction

Фиг. 7. Вариационни диаграми за елементи-следи за проби от остров Ливингстън, сравнени с проби от островите всред Протока на Бренсфийлд (Пенгуин, Грийнуич, Бриджмен) и с проби от остров Александър, Нунатаците Сийл, остров Възнесение, вулканското поле Пали-Айке в Патагония. A) Диаграма Rb/Nb *vs.* Ba/Nb. B) Диаграма Ba/Th *vs.* Rb/Nb. C) Диаграма Nb *vs.* Ce/Nb. Символите, полетата за мантийните източници, средните точки за кората и MORB и литературните източници са както във фиг. 4 и фиг. 5. Отбележете увеличаването на Ce/Nb с намаляването на Nb, което вероятно зависи от взаимодействието между астеносферата и литосферата

Ba/Th and Ba/Rb ratios and development of a characteristic positive Ba anomaly on the MORB-normalized spidergrams in the alkaline basalts from Bransfield Strait area. The separation of Bridgeman Island samples from the field of the other islands within the Bransfield Strait is probably due to crystal fractionation effect.

The Inott Point basalts exhibit considerable broad range in Ba/Th ratios and form a field overlapping partly with the composition of EMI and EMII sources. Penguin and Greenwich islands basalts are also close or overlapping with the composition of EM-I. The same is valid for Ascension Island and to the certain degree for Patagonia. The Antarctic Peninsula basalts delineate a field overlapping with the composition of MORB in plots involving K, Ba and Th, but have more similarities to OIB on plots involving *HFSE*. Therefore, the Antarctic Peninsula basalts cannot easily be reconciled with a simple origin by melting of MORB-source material, but they would be consistent with derivation from a

HIMU-OIB type source. According to Hole et al. (1993) they are similar to HIMU basalts in their Sr and Nd-isotopes and like MORB in their Pb-isotope and some incompatible trace elements ratios.

Ba/Zr ratios in Inott Point alkali basalts are as high as 1.4-2.2. Comparisons with the other volcanic islands within the Bransfield Strait area (data from Weaver et al., 1979) show that this ratio cover nearly the same range in Penguin Island (1.65-1.85), Greenwich Island (1.9-3.5) and Bridgeman Island (1.0-1.25). All these ratios fall within the range of the orogenic basalts in Antarctic Peninsula (1.4 -2.2, Saunders et al., 1980) and they differ essentially from the Ba/Zr ratio in the Antarctic Peninsula alkaline basalts (0.4-1.2 - Hole et al., 1993).

The study of the ratio K/Zr reveals similar relationships, having the range 39-67 in Livingston Island alkaline basalts. This ratio differs from N-MORB value (9.4 - Saunders, Tarney, 1984; Sun, 1980), but is close to Lower Crust K/Zr ratio (41 - Weaver, Tarney, 1984) and a continental crust contamination could be assumed for the source of the alkaline basalts in Livingston Island and in the similar basalts from the islands within the Bransfield Strait.

The significance of the slab-derived components

The inter-volcano differences are especially evident in the ratios *LILE/HFSE.* We have already traced the Rb/Nb (Fig. 6B, Fig. 7A, B) ratios, which are high for Livingston Island basalts and for the lavas in the volcanoes within the Bransfield Strait and low for the Antarctic Peninsula, Marie Byrd Land, Patagonia and Ascension Island. The range of Ba/Nb (Figs. 5B, C and 7A) in the Livingston Island basalts is 42-67 (average 52). These values are 33-74 for the Penguin Island, 36-58 for the Greenwich Island and 70-86 for the Bridgeman Island. Antarctic Peninsula samples have the range 2.5-9.0 (Hole et al., 1993) and MBL – 6-18 (Hole, LeMasurier, 1994). Nearly similar is the range of Ba/Nb in Patagonia and in Ascension Island (6-9). The high Ba/Nb ratios are due mainly of the low absolute abundances of Nb. The absolute Ba abundances in the Inott Point Fm. basalts are in the range 85-200 ppm (average 156 ppm). In this respect only the basalts of Alexander Island (113-320 ppm) and of Seal Nunataks (66-141 ppm) have similar absolute Ba abundances. All other basalts from the islands within Bransfield Strait cover rather broad range of their absolute Ba abundances, but nevertheless their Ba/Nb ratios are high.

The K/Nb (Fig. 5B) and the Ce/Nb (over 2.5 in back-arc occurrences and less than 1.5 in the asthenosphere-enriched mantle sources) ratios reveal similar peculiarities – high ratios in all samples from the Bransfield Strait volcanoes and low ratios in OIB mantle sources of Antarctic Peninsula, Patagonia and Ascension Island samples.

A plot of Nb *vs*. Ce/Nb (Fig. 7C) shows that basalts from Bransfield Strait volcanoes exhibit increasing Ce/Nb ratios with decreasing Nb abundances. In contrast, the majority of samples of alkali basalts from West Antarctica and from Patagonia and Ascension Island have Ce/Nb either within the range of/or slightly lower than OIB. These low *LILE/HFSE* ratios, coupled with markedly unradiogenic Sr-, but radiogenic Nd-isotope ratios for all analyzed samples from West Antarctica (Hole, LeMasurier, 1994) suggest that only extremely minor interaction with the continental lithosphere can have occurred in this region. Therefore, all the analysed basalts from Bransfield Strait region, including the Livingston Island ones, must predominantly contain a significant contribution from a subduction-enriched mantle.

Geodynamic setting

A display of alkaline basalt compositions from Livingston Island (Fig. 8A) on Ti/100 – Zr - 3*Y discrimination plot (Pearce, Cann, 1973) classifies almost all samples as within-plate basalts (OIB and CFB) and a small part of them as calc-alkaline basalts. The Ti – Zr - Y *HFSE* relationships do not distinguish Living-

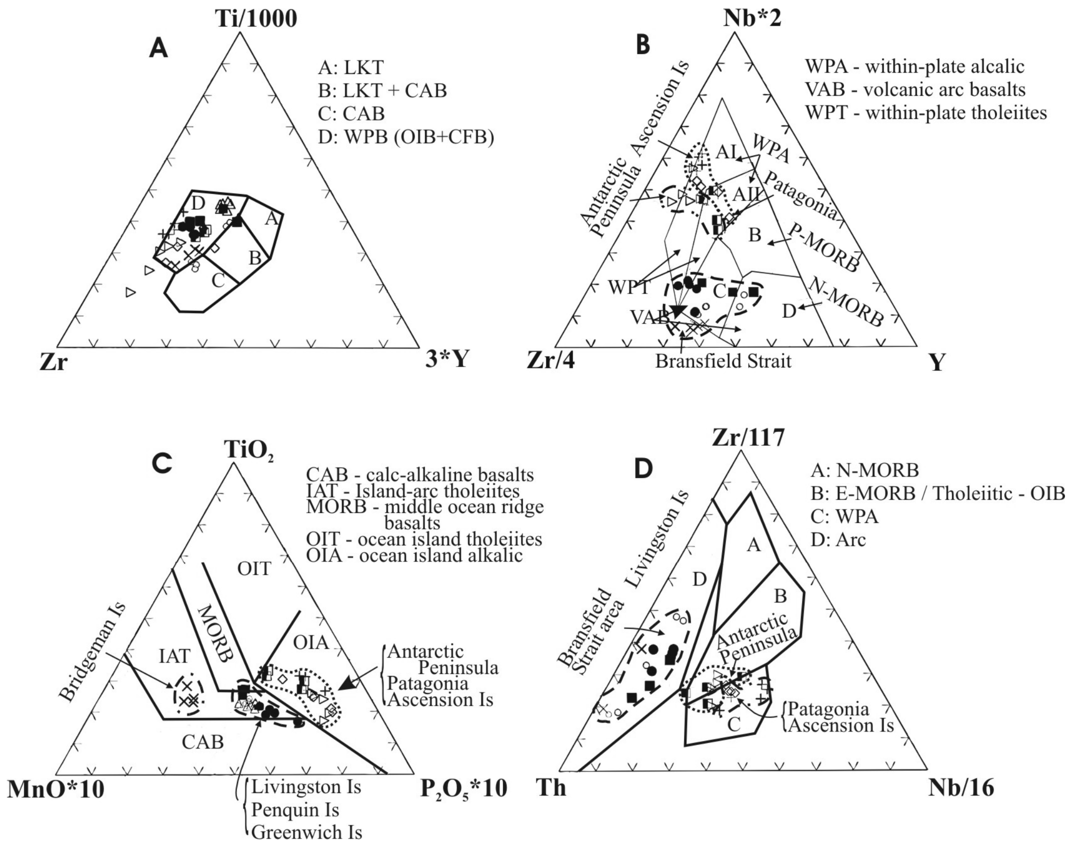


Fig. 8. Discrimination diagrams for Livingston Island samples compared to samples from the islands within Bransfield Strait area (Penguin, Greenwich, Bridgeman) and to samples from Alexander Island, Seal Nunataks, Ascension Island and Pali-Aike volcanic field and Patagonia (A-D). A) Zr-Ti/100-3*Y diagram (Pearce, Cann, 1973). B) Zr/4-Nb*2-Y diagram (Meshede, 1986). C) MnO*10-TiO_2-P_2O_5*10 diagram (Mullen, 1983). D) Th-Zr/117-Nb/16 diagram (Wood, 1980). Symbols and data sources as in for Fig. 4

Фиг. 8. Дискриминантни диаграми за проби от остров Ливингстън, сравнени с проби от островите в Протока Бренсфийлд (Пенгуин, Грийнуич и Бриджмен) и с проби от остров Александър, Нунатаците Сийл, остров Възнесение и вулканското поле Пали-Айке в Патагония (A-D). A) Диаграма Zr-Ti/100-3*Y (Pearce, Cann, 1973). B) Диаграма Zr/4-Nb*2-Y (Meshede, 1986). C) Диаграма MnO*10-TiO_2-P_2O_5*10 (Mullen, 1983). D) Диаграма Th-Zr/117-Nb/16 (Wood, 1980). Символите и литературните източници са както във фиг. 4

ston samples neither from the basalts for comparison from the islands Greenwich, Penguin and Bridgeman (Weaver et al., 1979; Saunders, Tarney, 1979), nor from the alkaline basalts from Antarctic Peninsula (Smellie et al., 1988; Hole et al., 1993) and from Ascension Island (Weaver et al., 1987), thought to be typical OIB. Even the alkaline basalts from Patagonia (volcanic field Pali-Aike, Stern et al., 1990) proved to be continental flood basalts (CFB) fall in this common field. The applied Nb*2 – Zr/4 – Y discrimination plot (Meshede, 1986) differ the samples from Livingston Island from the ones from Alexander Island, Seal Nunataks, Ascension Island and Pali-Aike volcanic field in Patagonia (Fig. 8B). The Livingston Island samples are mainly in the field C (VAB) and partly - in D (N-MORB).

The samples from Penguin Island occupy mainly the fields AI and AII (WPA) and partly – C (VAB). Greenwich Island samples are placed in the field C (VAB) and only one sample occupies the field D (N-MORB). Bridgeman Island samples fall close to and in the field C (VAB). In contrast, all the samples from Patagonia CFB, Ascension OIB, Alexander Island and Seal Nunataks plot in the within-plate alkali volcanic rocks. The result of applied discrimination using the minor oxides TiO_2, MnO and P_2O_5 (Mullen, 1983) refer all samples from the islands Livingston, Penguin, Greenwich and Bridgeman in the delineation of the island-arc tholeiites (IAT). The same plot (Fig. 8C) classifies the samples from Alexander Island, Seal Nunataks, Patagonia and Ascension Island as ocean-island alkali rocks (OIA). The only one fully satisfactory discrimination for the case is the Th - Zr/117 - Nb/16 plot (Fig. 8D) of Wood (1980). Note that in the Fig. 8D high Th contents of the alkaline basalts exposed in and around Bransfield Strait causes them to plot in the arc field, despite some of their above-stated MORB-like *HFSE* characteristics (Saunders et al., 1988). Different place occupy the samples from Antarctic Peninsula. They fall mainly in the field of E-MORB/OIB) and partly in the field C of the alkaline within-plate rocks (WPA), while the samples from Patagonia and Ascension Island are placed entirely in the last field.

The mildly alkaline basalts in Livingston Island show rather high Th/Nb ratios (0.25-0.90) comparable also to Th/Nb in the other islands within the Bransfield Strait (Weaver, 1979), but not to the Antarctic Peninsula alkali basalts (0.06-0.15 - Hole et al., 1993), Patagonia ones (0.04-0.08 - Stern et al., 1990), Ascension Island ones (0.070-0.08 - Weaver et al., 1987). Th is commonly considered as a reliable indicator of igneous *LILE* characteristics. The high Th/Nb values (Fig. 9A, B), shown also by some of the positive Th spikes in the MORB-normalized plots (Fig. 3), indicate that *LILEs* are enriched over *REEs* and *HFSEs*. This is valid for samples from Livingston Island, Penguin, Bridgeman and Greenwich islands having trace element signatures (high Th/Nb as in Fig. 8C) that are almost identical to those forming in modern intra-oceanic arcs (Stern et al., 1995a). Following current practices of subdividing modern ocean-floor basalts using the ratios of the immobile trace elements (Le Roex, 1987) the basalts in Bransfield Strait area with high Th/Nb are thought to be derived, in part, from metasomatized arc mantle similar to that which produced the arc basalts (Stern et al., 1995b). The interactions with continental lithosphere are evident in Fig. 9 where the samples lie between the average continental crust and N-MORB. The alkaline basalts from Antarctic Peninsula occupy the transitional field between arc-derived and non-arc ones, the Seal Nunataks samples being closer to the arc settings. As far as Patagonia and Ascension Island basalts are concerned, they resemble modern transitional and plume MORBs (Stern et al., 1995b) with slightly enriched Nb/Y ratio, lower Zr/Nb and lower Th/Nb (Fig. 9). The last alkaline basalts fall in E-MORB and OIBs delineations in the Fig. 9. The revealed geochemical peculiarities are similar to those of many intra-oceanic back-arc basin settings (e.g., Tarney et al., 1981; Sinton, Fryer, 1987; Saunders, Tarney, 1979, 1984, 1991) like the modern-day Mariana Trough or Lau Basin. A wide range of rock types have erupted in these basins, including N-MORBs, MORBs with arc signature (i.e., BABBs), OIBs and also arc tholeiites (Hawkins, Melhior, 1985; Sinton, Fryer, 1987; Price et al., 1990; Faloon et al., 1992; Ewart et al., 1994; Pearce et al., 1994).

The results from the application of some discrimination plots reveal that they are equivocal. The source of the alkali magmas in the islands in Bransfield Strait area was probably complex and transitional. VAB mainly, but also WPB and even a little N-MORB characteristics appear out of the geochemistry of the basalts.

Generation of high *LILE/HFSE* in the subcontinental mantle is a consequence of subduction-related magmatism (Hole, LeMasurier, 1994), and it is recognized that such process is extremely important in determining the geo-

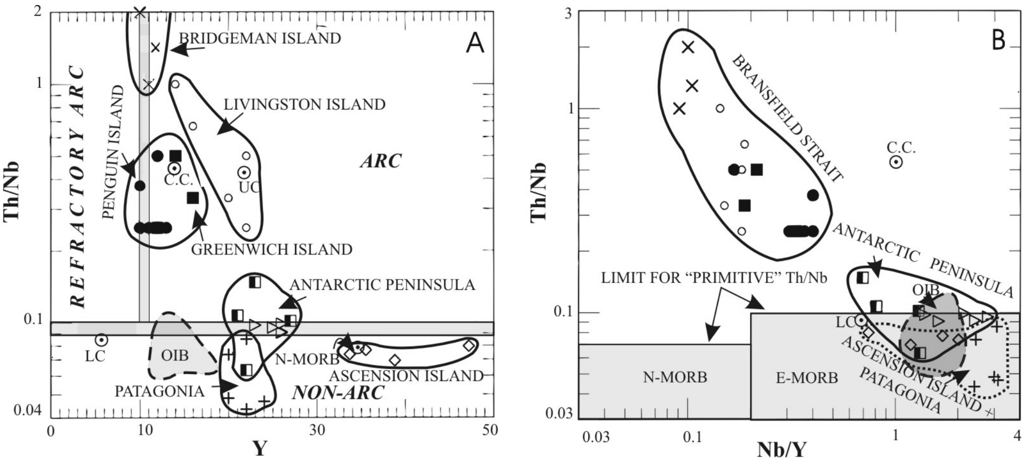


Fig. 9. Trace element variation diagrams for arc and ocean-floor assemblages of alkaline basalts in West Antarctica. A) Y *vs.* Th/Nb (modified from Syme et al., 1999). Rocks with an arc signature have Th/Nb> 0.1. B) Nb/Y *vs.* Th/Nb. The fields for N- and E-type MORBs from Stern et al. (1995b). Average continental crust, upper crust, lower crust, average N-MORB, OIB field, sample symbols and data sources for comparison are as in Fig. 4 and Fig. 5

Фиг. 9. Вариационни диаграми за елементи-следи от дъгови и океанско-дънни асоциации в Западна Антарктика. A) Диаграма Y *vs.* Th/Nb (видоизменена от Syme et al., 1999). Скали с характеристика на дъгова обстановка имат Th/Nb> 0.1. B) Диаграма Nb/Y *vs.* Th/Nb. Полетата за типовете N- и E- MORB са по Stern et al. (1995b). Средните значения за континенталната кора, горната кора, долната кора, точката N-MORB и полето OIB, както и символите и литературните източници на пробите за сравнение са както във фиг. 4 и фиг. 5

chemical (isotopic as well) evolution of this subcontinental mantle source (Kay, 1980; 1984). Usually the interaction between asthenosphere-derived magmas and lithosphere that has been geochemically modified by subduction processes should be a quick event and the modification of the trace element ratios by the same process should be effected easily. Stern et al. (1990) noted that the apparent lack of an "old" lithospheric isotope signature in flood basalts of Patagonia, which were erupted through lithosphere similar in age to that of West Antarctica, is simply because the asthenosphere and the lowermost lithosphere were isochemical.

The main inference out of the above-stated considerations is that the observed geochemical differences between the Quaternary basaltic rocks of the Antarctic Peninsula and of the Bransfield Strait region must be due to tapping of geochemically distinct domains within the asthenosphere and the stronger lithospheric contamination of the source of the last region basalts, comprising the Inott Point Fm. in Livingston Island. The geochemistry of the volcanoes of Bransfield Strait area displays several unusual features, some of which are indicative of island arc magmatism and others, which are more typical of ocean floor basalts. The nearly identical radio-isotopic ages of the basalts outcropped within the area and close to Bransfield Strait area (Keller et al., 1991), the dual characteristics of MORB-like major element geochemistry and the arc-element signature (e.g., lower TiO_2 and higher Th/Nb ratios: Fig. 4A, Fig. 9) and the characteristics of basalts in modern intra-oceanic back-arc basins (Tarney et al., 1981; Sinton, Fryer, 1987) are suggestive that these alkaline basalts bear most of their arc trace-element features, because they are adjacent to the South Shetland magmatic arc, in spite of the extensional setting in the back-arc rift of Bransfield Strait.

Conclusions

1. On the basis of new-described exposures and new chemical analyses the petrographic diversity of the Quaternary basalts from Livingston Island was defined more accurately. Olivine basalts and hawaiites are the main rocks. Compositional variations in the main rock-forming minerals are published for the first time.
2. The alkaline basalts of Livingston Island have trace-element characteristics that are comparable with the basalts from the islands within of the Bransfield Strait back-arc rift and they differ clearly from most other West Antarctic basalts. The rocks exhibit high *LILE/HFSE* ratios (e.g. Ba/Zr 1.4-2.2; Ba/Nb 42-67; Rb/Nb 2.7-4; Ce/Nb 2.5-10; Th/Nb 0.25-0.90, K/Zr 39-67, etc.) in contrast to the low *LILE/HFSE* ratios in Antarctic Peninsula and in Marie Byrd Land alkaline basalts.
3. Trace element characteristics indicate that all within/or around Bransfield Strait basalts, including the ones from Livingston Island, have low absolute abundances of the *HFSE* (Ti, Y, Nb, Zr, P etc.). The fractionation of the *HFSE* in these rocks is mainly a function of partial melting degree, which is higher than in the alkaline basalts in Antarctic Peninsula and Marie Byrd Land provinces. Relatively high Zr/Nb (19-43) and Sr/Nb (>100) ratios are typical for the Livingston Island alkaline basalts and the basalts from the neighbouring islands in Bransfield Strait area. The low Nb/Y ratios are explained by the higher degrees of melting.
4. The *LILE* variations in the alkali basalts from Livingston Island (e.g., K/Ba 26-38 and K/Rb 380-630) cover nearly the same ranges as in the other volcanic islands within the Bransfield Strait area. These *LILE* variations differ greatly from the absolute and relative *LILE* abundances in the Antarctic Peninsula and Marie Byrd Land alkaline provinces. We conclude that the regional trace element variations observed in the basalts from Livingston Island and on the other islands within the Bransfield Strait area are a result of their generation from different portions of the asthenosphere and mainly of the variable interaction with the continental lithosphere. The lithospheric involvement in alkaline basalt genesis is a characteristic of the Bransfield Strait basalts and a subarc source region contamination might have affected their mantle source. The *LIL* trace element ratio differences between Marie Byrd Land and Antarctic Peninsula require that they were derived from different and isolated source regions. The Antarctic Peninsula samples, occupying the fields close to OIBs sources on the most plots could simply represent a low degree melts of shallow convecting MORB-source or HIMU OIB asthenosphere beneath the Peninsula (Hole et al., 1993), as the data from MBL are consistent with their derivation from the plume-related source (LeMasurier, Rex, 1991; Hole, LeMasurier, 1994).
5. Alkaline basalts from Patagonia flood basalts and from Ascension Island, which we used for comparison in some of the plots, are quite similar to those in Marie Byrd Land in their trace element characteristics and the conclusion for a plume OIB source is valid for them.
6. The unique tectono-magmatic regime, which developed within the Bransfield Strait rift, bears a strange combination of subduction-related volcanic arc characteristics and extensional within-plate setting. The melts of the altered MORB, contaminated with continental crust materials recycled into the upper mantle were obviously responsible for the geochemical peculiarities of the alkaline basalts, not only in the Livingston Island, but also occurring in the adjacent volcanic islands Penguin, Greenwich and Bridgeman.
7. The West Antarctic alkaline basalts can be subdivided not into two provinces, as Hole et al. (1993) proposed, but into three, based on the absolute and relative abundances of the trace elements: (1) Bransfield Strait province with alkaline basalts, bearing traces of lithospheric contamination and subduction-related magmatism; (2) Antarctic Peninsula province with alkaline basalts derived from MORB-source asthenosphere in slab-window setting and (3) Marie Byrd Land alkaline

basalts related to a deep-seated mantle plume (Hole, LeMasurier, 1994). The study of the isotope variations in the new-defined Bransfield alkaline basalt province would confirm better such division.

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References

Baker, P.E., O. Gonzalez-Ferran, M. Vergara. 1973. Paulet Island and the James Ross Island Volcanic Group. *British Antarct. Surv. Bull.*, *Sci. Rep.*, **32**, 89-95.

Baker, P.E., M.A. McReath, M.R. Harvey, M.J. Roobol, T.G. Davies. 1975. The geology of the South Shetland Islands: V. Volcanic eruption of Deception Island. *British Antarct. Surv., Sci. Rep.*, **78**, 81 p.

Barker, P.F. 1982. The Cenozoic subduction history of the Pacific margin of the Antartic Peninsula: ridge crest-trench interactions. *J. Geol. Soc. London*, **139**, 789-801.

Cande, S.C., E.M. Herron, B.R. Hall. 1982. The Early Cenozoic tectonic history of the southeast Pacific. *Earth Planet. Sci. Lett.*, 57 (1), 63-74.

Chaffey, D.J., R.A. Cliff, B.M. Wilson. 1989. Characterization of the St. Helena magma source. In: A.D. Saunders, M.J. Norry (Eds.). *Magmatism in Ocean Basins*. Geol. Soc. London, Spec. Publ. **42**, 257-276.

Clague, D.A., F.A. Frey. 1982. Petrology and trace element geochemistry of the Honolulu volcanics: implications for the oceanic mantle below Hawaii. *J. Petrol.*, **23**, 447-504.

Ewart, A., W.B. Bryan, B.W. Chappel, R.L. Rudnick. 1994. Regional geochemistry of the Lau-Tonga arc and back-arc systems. *Proceed. Ocean Drilling Program, Scientific Results*, **135**, 385-485.

Faloon, T.J., A. Malahoff, L.P. Zonensthain, Y. Bogdanov. 1992. Petrology and geochemistry of back-arc basin basalts from Lau Basin, spreading ridges at 15^o, 18^o and 19^o. *Contrib. Mineral. Petrol.*, **47**, 1-35.

Futa, K., W.E. Masurier. 1983. Nd and Sr isotopic studies of Cenozoic mafic lavas from West Antarcica: Another source for continental alkali basalts. *Contrib. Mineral. Petrol.*, **83**, 38-44.

Gonzalez-Ferran, O. 1972. Distribution, migration and tectonic control of Upper Cenozoic volcanism in West Antarctica and South America. In: R.J. Adie (Ed.). *Antarctic Geology and Geophysics*. Universitetforlagen, Oslo, 173-180.

Gonzalez-Ferran, O. 1983. The Seal Nunataks: An active volcanic group on the Larsen Ice Shelf, West Antarctica. In: R.L. Oliver, P.R. James, J.B. Jago (Eds.). *Antarctic Earth Science*. Australian Acad. Sci., Canberra, 334-346.

Gonzalez-Ferran, O. 1985. Volcanic and tectonic evolution of the northern Antarctic Peninsula-Late Cenozoic to Recent. *Tectonophys.,* **114**, 389-409.

Gonzalez-Ferran, O. 1987. The Bransfield and its active volcanism. In: M.R.A. Thomson, J.A. Crame, J.W. Thomson (Eds). *Geological Evolution of Antarctica*, Cambridge Univ. Press, Cambridge, 505-509.

Gonzalez-Ferran, O., Y. Katsui. 1970. Estudio integral del volcanismo cenozoico superior de las Islas Shetland del Sur, Antarctica. *Serie Sientifica, Instituto Antarctico Chileno,* **1** (2), 123-174.

Greenough, J.D. 1988. Minor ohases in the Earth's mantle: evidence from trace- and minor-element patterns in primitive alkaline magmas. *Chem. Geol.*, **69**, 177-192.

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 Expeditions*, **80**, 30-39 (in Russian).

Harris, C. 1983. The petrology of lavas and associated plutonic inclusions of Ascension Island. *J. Petrol.*, **24**, 424-470.

Hart, S.R. 1988. Heterogeneous mantle domains: Signatures, genesis and mixing chronologies. *Earth Planet. Sci. Lett.,* **90,** 273-296.

Hawkins, J.W., J.T. Melhior. 1985. Petrology of Mariana Trough and Lau Basin basalts. *J. Geophys. Res.*, **90**, 11431-11468.

Herve 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.

Hickey, R.L., F.A. Frey, D.C. Gerlach, L. Lopez-Escobar. 1986. Multiple sources for basaltic arc rocks from the southern volcanic zone of the Andes (34°-41° S): Trace element and isotopic evidence for contributions from subducted oceanic crust, mantle and continental crust. *J. Geophys. Res*., **91**, 5693-5983.

Hickey-Vargas, R., H.M. Roa, L. Lopez-Escobar, F.A. Frey. 1989. Geochemical variations in Andean basaltic and silicic lavas from the Villarrica-Lanin volcanic chain (39.5° S): An evaluation of source heterogeneity, fractional crystallization and crustal assimilation. *Contrib. Mineral. Petrol*., **103**, 361-386.

Hobbs, G.J. 1968. The geology of the South Shetland Islands, IV. The geology of Livingston Island. *British Antarct. Surv., Sci. Rep*., **47**, 1-34.

Hofmann, A.W., W.M. White. 1982. Mantle plumes from ancient oceanic crust. *Earth Planet. Sci. Lett*., **57**, 421-436.

Hofmann, A.W., W.M. White. 1983. Ba, Rb and Cs in the Earth's mantle. *Z. Nat*., **38a**, 256-266.

Hofmann, A.W., K.P. Jochum, M. Seufert, W.M. White. 1986. Nb and Pb in oceanic basalts: New constraints on mantle evolution. *Earth Planet. Sci. Lett*., **79**, 33-45.

Hole, M.J. 1988. Post-subduction alkaline volcanism along the Antarctic Peninsula. *J. Geol. Soc. Lond*., **145**, 985-988.

Hole, M.J. 1990. Geochemical evolution of Pliocene-Recent post-subduction alkalic basalts from Seal Nunataks Antarctic Peninsula. *J. Volcan. Geotherm. Res*., **40**, 149-167.

Hole, M.J., W.E. LeMasurier. 1994. Tectonic control on the geochemical composition of Cenozoic, mafic alkaline volcanic rocks from West Antarctica. *Contrib. Mineral. Petrol*., **117**, 187-202.

Hole, M.J., A.D. Saunders, G.F. Marriner, J. Tarney. 1984. Subduction of pelagic sediments: Implications for the origin of Ce-anomalous basalts from the Mariana Islands. *J. Geol. Soc*., *London*, **141**, 453-472.

Hole, M.J., J.L. Smellie, G.F. Marriner. 1991. Geochemistry and tectonic setting of Cenozoic alkaline basalts from Alexander Island, southwest Antarctic Peninsula. In: M.R.A. Thomson, J.A. Crame J.W. Thomson (Eds.). *Geological Evolution of Antarctica*, Cambridge Univ. Press, Cambridge, 521-526.

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.

Ito, E., W.M. White, C. Gopel. 1989. The O, Sr, Nd and Pb isotope geochemistry of MORB. *Chem. Geol.*, **62**, 157-176.

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., 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.

Kay, R.W. 1980. Volcanic arc magmas: Implications of a melting-mixing model for element recycling in the crust-upper mantle system. *J. Geol*., **81**, 653-682.

Kay, R.W. 1984. Elemental abundances relevant to the identification of magma sources. *Phyl. Trans. Roy. Soc. London,* **A31**0, 535-547.

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.

Latin, D.M., J.E. Dixon, J.G. Fitton. 1990. Rift-related magmatism in the North Sea basin. In: D.J. Blundell, A.D. Gibbs (Eds.). *Tectonic Evolution of the North Sea Rifts*. Oxford Sci. Publ., Oxford, Clarendon Press, 102-144.

Larter, R.D., P.F. Barker. 1991. Effects of ridge-crest trench interaction on Antarctic – Phoenix spreading: forces on a young subducting plate. *J. Geoph. Res*., 96, 19583-19607.

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 IUGS Subcommission on the systematics of igneous rocks. Oxford, Blackwell, 193 pp.

LeMasurier, W.E. 1972. Volcanic record of Cenozoic glacial history of Marie Byrd Land. In: R.J. Adie (Ed.). *Antarctic Geology and Geophysics*. Universitetforlaget, Oslo, 251-260.

LeMasurier, W.E., D.C. Rex. 1991. The Marie Byrd Land volcanic province and its relation to the Cenozoic West Antarctic rift system. In: R.J.

Tingey (Ed.). *The Geology of Antarctica*. Oxford, Clarendon Press, 249-284.

Le Roex, A.P., 1987. Source regions of mid-ocean ridge basalts: evidence for enrichment processes. In: M.A. Menzies, C.J. Hawkesworth (Eds.). *Mantle Metasomatism*. N.Y., Academic Press, 389-422.

Meshede, M. 1986. A method of discriminating between different types of mid-ocean ridge basalts and continental tholeiites with Nb-Zr-Y diagram. *Chem. Geol*., 56, 207-218.

Morris, J.D., S.R. Hart. 1983. Isotopic and incompatible element constraints on the genesis of island arc volcanics, Cold Bay and Amak Island, Aleutians. *Geochim. Cosmochim. Acta*, **47**, 2015-2030.

Mullen, E.D. 1983. $MnO/TiO_2/P_2O_5$: a minor element discriminant for basaltic rocks of oceanic environments and its implications for petrogenesis. *Earth Planet. Sci. Lett*., **62**, 53-62.

Munoz, J., C.R. Stern. 1989. Alkaline magmatism within the segments 38^o and 39^o S. *J. South Am. Earth Sci.*, **1**, 147-161.

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.

Pearce, J.A. 1983. Role of sub-continental lithosphere in magma genesis at active continental margins. In: C.J. Hawkesworth, M.J. Norry (Eds.). *Continental Basalts and Mantle Xenoliths*, Shiva, Orpington, 230-249.

Pearce, J.A., J.R. Cann. 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses. *Earth Planet. Sci. Lett.*, **19**, 290-300.

Pearce, J.A., M. Ernewein, S.H. Bloomer, L.M. Parson, B.J. Murton, L.E. Johnson. 1994. Geochemistry of Lau Basin volcanic rocks. In: J.L. Smellie (Ed.). *Volcanism Associated with Extension at Consuming Plate Margins*, 81, 53-75.

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. of the IXth International Symposium Antarctic Earth Sciences*, Berlin, Springer Verlag (in press).

Price, R.C., L.E. Johnson, A.J. Crawford. 1990. Basalts of the North Fiji Basin: The generation of back-arc basin magmas by mixing of depleted and enriched mantle sources. *Contrib. Mineral. Petrol*., **105**, 106-121.

Saunders, A.D., J. Tarney. 1979. The geochemistry of basalts from a back-arc spreading center in the East Scotia Sea. *Geochim. Cosmochim. Acta*, **43**, 555-572.

Saunders, A.D., J. Tarney, 1984. Geochemical characteristics of basaltic volcanism within back-arc basins. In: B.P. Kokelaar, M.F. Howells (Eds.). *Marginal Basin Geology,* Geol. Soc. London, Sp. Publ.,**16,** 59-76.

Saunders, A.D., J. Tarney, 1991. Back-arc basins. In: B.P. Kokelaar, M.F. Howels (Eds.). *Marginal basin geology*. Blackwell Scientific Publications, Oxford, U.K., 69-86.

Saunders, A.D., J. Tarney, S.D. Weaver. 1980. Transverse geochemical variations across the Antarctic Peninsula: Implications for the genesis of calc-alkaline magmas. *Earth Planet. Sci. Lett*., **46**, 344-360.

Saunders, A.D., M.J. Norry, J. Tarney. 1988. Origin of MORB and chemically depleted mantle reservoirs: Trace element constraints. *J. Petrol., Lithosphere Iss*., 415-445.

Sinton, J.M., P.A. Fryer. 1987. Mariana Trough lavas from 18^{o}N: Implications for the origin of back-arc basin basalts. *J. Geophys. Res*., **92**, 12782-12802.

Skewes, M.A., C.R. Stern. 1979. Petrology and geochemistry of alkali basalts and ultramafic inclusions from the Pali-Aike volcanic field in southern Chile and the origin of the Patagonian plateau lavas. *J. Volcan. Geotherm. Res*., **6**, 3-25.

Smellie, J.L. 1981. A complete arc-trench system recognized in Gondwana sequences of the Antarctic Peninsula region. *Geol. Mag*., **118**, 139-159.

Smellie, J.L. 1987. Geochemistry and tectonic setting of alkaline volcanic rocks in the Antarctic Peninsula: A review. *J. Volcan. Geotherm. Res*., **32**, 1-3, 269-285.

Smellie, J.L. 1990. Graham Land and South Shetland Islands: Summary. In: W.E. LeMasurier, J.W. Thomson (Eds.). *Volcanoes of the Antarctic Plate and Southern Oceans*, Am. Geophys. Union, Antarctic Research Series, **48**, Washigton, D.C., 487 p.

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

Smellie, J.L. 2002. The 1969 subglacial eruption of Deception Island (Antarctica): events and processes during an eruption beneath a thin glacier and implications for volcanic hazards. In: J.L. Smellie, M.G. Chapman (Eds.). *Volcano-Ice*

Interaction on Earth and Mars. Spec. Publ., Geol. Soc. London, № **202**, 59-79.

Smellie, J.L., R.J. Pankhurst, M.R. Thomson, R.E.S. Davies. 1984. The geology of the South Shetland Islands: VI. Stratigraphy, geochemistry and evolution. *British Antarct. Surv. Bull*., **87**, 1-85.

Smellie, J.L., R.J. Pankhurst, M.J. Hole. 1988. Age, distributions of late Cenozoic and eruptive conditions of late Cenozoic alkaline volcanism in the Antarctic Peninsula and eastern Elsworth Land: Review. *British Antarct. Surv. Bull*., **80**, 21-49.

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

Smellie, J.L., R. Pallàs, F. Sabàt, X. Zheng. 1996. Age and correlation of volcanism in central Livingston Island, South Shetland Islands: K-Ar and geochemical constraints. *J. South Am. Earth Sci*., **9**, 265-272.

Smellie, J.L., J. Lopez-Martinez, R.K. Headland, F. Hernandez-Cifuentes, A. Maestro, I.L. Millar, J. Rey, E. Serrano, L. Somoza, J.W. Thomson. 2002. *Geology and Geomorphology of Deception Island.* Supplementary text with accompanying maps. BAS GEOMAP Series, Sheets 6-A and 6-B, 1:25 000. Cambridge, British Antarctic Survey, 77 p.

Staudigel, H., F.A. Frey, S.R. Hart. 1980. Incompatible trace element geochemistry and $^{87}Sr/^{86}Sr$ in basalts and corresponding glasses and palagonites. In: T. Donelly, J. Francheteau (Eds.). *Initial Repts, DSDP Leg 53*, US Gov. Printing Office, Washington D.C., 1137-1144.

Stern, R.J., E. Ito. 1983. Trace element and isotopic constraints on the source of magmas in the active volcano and Mariana Island arcs, western Pacific. *J. Volcan. Geotherm. Res*., **18**, 461-482.

Stern, C.R., F.A. Frey, K. Futa, R.E. Zartman, Z. Peng, T.K. Kyser. 1990. Trace-element and Sr, Nd, Pb, and O isotopic composition of Pliocene and Quaternary alkali basalts of the Patagonian Plateau lavas of southernmost South America. *Contrib. Mineral. Petrol.,* **104**, 294-308.

Stern, R.A., E.C. Syme, A.H. Bailes, S.B. Lucas. 1995a. Paleoproterozoic (1.86-1.90 Ga) arc volcanism in the Flin Flon belt, Trans-Hudson Orogen, Canada. *Contrib. Mineral. Petrol*., **119**, 117-141.

Stern, R.A., E.C. Syme, S.B. Lucas. 1995b. Geochemistry of 1.9 Ga MORB- and OIB-like basalts from the Amisk collage, Flin Flon belt, Canada: Evidence for an intra-oceanic origin. *Geochim. Cosmoshim. Acta,* **59**, 3131-3154.

Storey, M., A.D. Saunders, J. Tarney, P.T. Leat, M.F. Thirlwall, R.N. Thompson, M.A. Menzies, G.F. Marriner. 1988. Geochemical evidence for plume-mantle interactions beneath Kerguelen and Heard Islands, Indian Ocean. *Nature*, **336**, 371-374.

Storey, M., G. Rogers, A.D. Saunders, D. Terrell. 1989. San Quintin volcanic field, Baia California, Mexico: "Within-plate" magmatism following ridge subduction. *Terra Nova*, **1**, 195-202.

Storey, B.C., A.P.M. Vaugham, I.L. Millar. 1996. Geodynamic evolution of the Antarctic Peninsula during Mesozoic times and its bearing on Weddell Sea history. In: B.C. Storey, E.C King, R.A. Livermore (Eds.). *Weddell Sea Tectonics and Gondwana Break-up*. Geol. Soc. London, Sp. Pub. 68, 149-164.

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.

Sun, S.S. 1980. Lead isotopic study of young volcanic rocks from mid-ocean ridges, ocean islands and island arcs. *Phil. Trans. Roy. Soc. London*, Series A, **297**, 409-445.

Sun, S.S., W.F. McDonough. 1989. Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. In: A.D. Saunders, M.J. Norry (Eds.). *Magmatism in the Ocean Basins*. Spec. Publ., Geol. Soc. London, **42**, 313-345.

Syme, E.C., S.B. Lucas, A.H. Bailes, R.A. Stern. 1999. Contrasting arc and MORB-like assemblages in the Paleoproterozoic Flin Flon Belt, Manitoba, and the role of intra-arc extension in localizing volcanic-hosted massive sulphide deposits. *Can. J. Earth Sci.,* 36, 1767-1788.

Tarney, J., A.D. Saunders, D.P. Mattey, D.A. Wood, N.G. Marsh. 1981. Geochemical aspects of back-arc spreading in the Scotia Sea and Western Pacific. *Phil. Trans. Roy. Soc. London,* Series A, **300**, 263-285.

Tatsumi, Y., D.L. Hamilton, R.W. Nesbitt. 1986. Chemical characteristics of fluid phase released from a subducted lithosphere and origin of arc magmas: evidence from high-pressure experiments and natural rocks. *J. Volcan. Geotherm. Res*., **29**, 293-309.

Taylor, S.R., S.M. Mc Lennan. 1981. The composition and evolution of the continental crust, rare earth evidence from sedimentary rocks. *Phil. Trans. Roy. Soc. London*, Series **A, 301**, 381-399.

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

Thompson, G., W.B. Bryan, F.A. Frey, J.S. Dickes, C.J. Suen. 1976. Petrology and geochemistry of basalts from DSDP Leg 34, Nasca Plate. In: In: R.S. Yeats, S.R. Hart (Eds.). *Initial Reports of the Deep Sea Drilling Project, Leg 34*. US Gov. Printing Office, Washington, D.C., 215-226.

Thompson, R.N., M.A. Morrison, G.L. Hendry, S.J. Parry. 1984. An assessment of the relative roles of crust and mantle in magma genesis: an elemental approach. *Phil. Trans. Roy. Soc. London*, Series **A, 310**, 549-590.

Thomson, 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 Science*. Australian Academy of Science, Canberra, 289-294.

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

Veit, A. 2002. Volcanology and geochemistry of Pliocene to Recent volcanics on both sides of the Bransfield Strair/West Antarctica. *Reports on Polar and Marine Research.* Alfred Wagener Institute for Polar and Marine Research, Bremerhaven, 420, 177, http://www.awi-bremerhaven.de/BIB/BerPolarforsch/BerPolarforsch2002420.pdf.

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.

Weaver, B.L., A.D. Saunders, R.J. Pankhurst, J. Tarney. 1979. A geochemical study of magmatism associated with the initial stages of back-arc spreading: The Quaternary volcanics of Bransfield Strait, from South Shetland Islands. *Contrib. Mineral. Petrol*., **68**,151-169.

Weaver, B.L., D.A. Wood, J. Tarney, J.L. Joron. 1987. Geochemistry of ocean island basalts from the South Atlantic: Ascension, Bouvet, St. Elena, Gough and Tristan da Cunha. In: J.G. Fitton, B.C.J. Upton (Eds.). *Alkaline Igneous Rocks*, Spec. Publ., Geol. Soc. London, **30**, 253-267.

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

Wood, D.A. 1980. The application of a Th-Hf-Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province. *Earth Planet. Sci. Lett*., **50**, 11-30.

Zheng, X., F. Sabat, J.M. Casas, R. Pallas. 1995. Petrochemistry of the Mesozoic-Cenozoic volcanic rocks from the central part of Livingston Island, West Antarctica. *Antarctic Research* (Chinese edition), **7**(2), 1-17 (in Chinese with English summary).

Zheng, X., F. Sabat, J.L. Smellie. 1996. Mesozoic-Cenozoic volcanism on Livingston Island, South Shetland Islands, Antarctica: Geochemical evidences for multiple magma generation processes. *Korean Journal of Polar Research*, **7**(1/2), 35-45.

Zheng, X., B.K. Kamenov, H. Sang, P. Monchev. 2002. New radiometric dating of the dykes from the Hurd Peninsula, Livingston Island, South Shetland Islands. *J. South Am. Earth Sci*., **15**, 925-934.

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