

New $^{40}\text{Ar}/^{39}\text{Ar}$ age evidence for the Cretaceous volcanic rocks of the Mount Bowles Formation in Livingston Island, South Shetland Islands*

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Abstract The age of the volcanic rocks of the Mount Bowles Formation (MBF) on the eastern part of Livingston Island, South Shetland Islands, Antarctica is redetermined by using $^{40}\text{Ar}/^{39}\text{Ar}$ and laser microarea isochron age dating method with a continuous laser system and mass spectrometer. The isochron ages of an andesite sample and a basaltic andesite sample are (105.62 ± 2.11) Ma and (111.48 ± 2.23) Ma with the $^{40}\text{Ar}/^{36}\text{Ar}$ initial ratios of 295.3 and 294.6 respectively, being almost the same as the atmospheric value, which proves that there exists no excess argon in these rocks. The $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of an aplite sample is (96.7 ± 1.6) Ma and the calculated isochron age is 96.6 Ma, which indicates that the aplite occurred after lava eruption. These data suggest that the MBF volcanic rocks were formed during Cretaceous.

Key words Mount Bowles Formation, $^{40}\text{Ar}/^{39}\text{Ar}$ age dating, Livingston Island, Antarctica.

1 Introduction

The volcanic rocks of the Mount Bowles Formation (MBF, Smellie *et al.* 1995) outcrop mainly in the north of Hurd Peninsula on the eastern part of Livingston Island, South Shetland Islands (Fig. 1). Because the MBF sequence is relatively strongly deformed and metamorphosed, and some Tertiary tonalitic intrusives occurred nearby, it was much difficult to date the age of the volcanic rocks with K-Ar dilution method. But by using $^{40}\text{Ar}/^{39}\text{Ar}$ and laser microarea isochron age dating techniques the age of the volcanic rocks in the studied area is precisely determined.

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2 Geological background

The oldest strata on Livingston Island comprise the strongly deformed turbidites, which are essentially restricted to Hurd Peninsula and were probably deposited between late Carboniferous and early Jurassic. They are generally considered as the representative of the Paleozoic basement in South Shetland Islands (Smellie *et al.* 1984, 1995; Hervé *et al.* 1991; Arche *et al.* 1992a, 1992b). Volcanic activities occurred widely in Livingston Island during the Cretaceous and lasted to Quaternary, and thus became a part of the South Shetland magmatic arc (Smellie *et al.* 1984). Previous studies show that the volcanic rocks in Byers Peninsula on the west of the island, were formed about 128 Ma to 90 Ma ago (Pankhurst *et al.* 1980), the rocks exposed at Cape Shirreff have an age of about 90 Ma, and in the middle part of the Hannah Point volcanic section the rocks are formed nearly 88 Ma ago (Smellie *et al.* 1996). In late Cretaceous dolerite sills (74–79 Ma) were developed (Smellie *et al.* 1984, 1996). Eocene tonalitic batholith and other small bodies intruded into Cretaceous volcanic strata (Grikurov *et al.* 1970; Dalziel *et al.* 1973; Smellie *et al.* 1984, 1996). Pleistocene to Recent volcanics were limited in distribution, being seen only on the northeastern part of Livingston Island (Hobbs 1968; Smellie 1990; Smellie *et al.* 1984, 1995, 1996).

The volcanic rocks of the MBF exposed on the central Livingston consist of

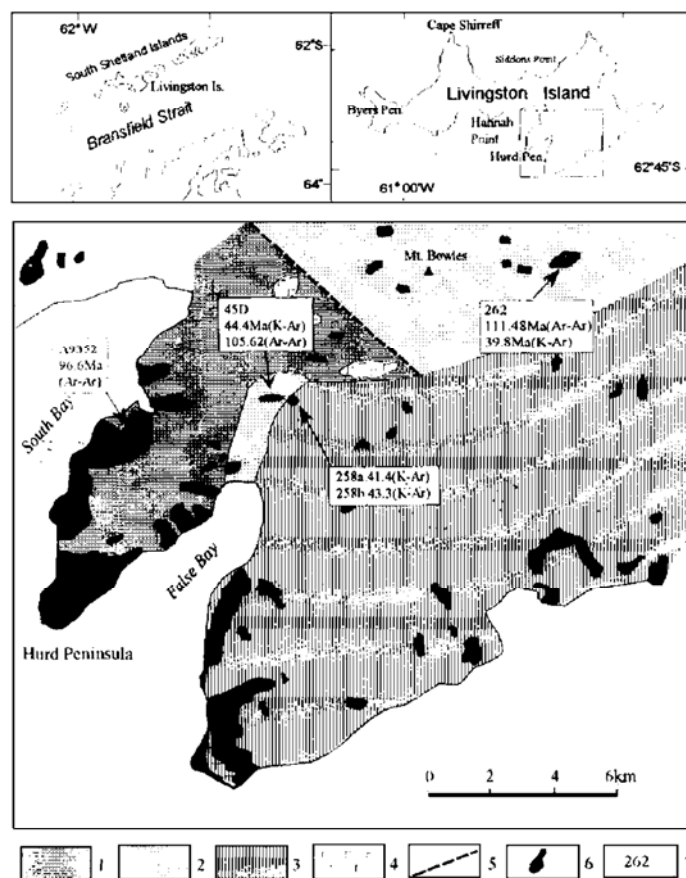


Fig. 1. Geographic setting and geological sketch map of the studied area of Livingston Island (after Smellie *et al.* 1995, Fig. 1; modified by authors.). 1. Paleozoic base; 2. Mount Bowles Formation; 3. Intrusives; 4. Quaternary volcanic rocks; 5. Inferred fault; 6. Outcrop; 7. Sample location.

basalt, basaltic andesite, andesite lavas, pyroclastics and some hypabyssal intrusives. The Mount Bowles massif is comprised of andesitic or basaltic lavas, doleritic dykes and few clastic rocks (Smellie *et al.* 1995). These rocks are frequently altered. The primary texture was largely destroyed and the groundmass is extensively replaced by chlorite, biotite, epidote, and oxide minerals. Plagioclase phenocryst is generally replaced by albite, or by some combination of sericite, epidote and magnetite with actinolite, chlorite or biotite infilled along cleavages. Pyroxene is rimmed or replaced by amphibole, chlorite and minor carbonate. The MBF has been correlated with the Antarctic Peninsula Volcanic Group (Smellie *et al.* 1995) and its eruptive age is assumed to be Cretaceous by analogy. Besides two ages (35.0 Ma and 44 Ma) obtained with K-Ar dilution method by Smellie *et al.* (1996), however, there was still no believable isotopic ages published until this study.

3 Analytical method

Sample 45D and 262 were collected by Dr. Sábát in 1992 from the outcrops near the Willan Nunatak and in the east of Mount Bowles of Livingston Island respectively (Fig. 1). 45D is a porphyritic andesite containing a lot of plagioclase phenocrysts, altered pyroxene and some opaque oxide phenocrysts. Sample 262 is a basaltic andesite with cryptocrystalline texture. These two samples are much fresher than other rocks from the same area, the original, igneous textures are mostly preserved, the primary minerals are only partly recrystallised to a secondary assemblage. Sample A9352 was taken from an aplitic vein near the Spanish Base in the east coast of Hurd peninsula by Dr. Liu in 1993.

The $^{40}\text{Ar}/^{39}\text{Ar}$ isochron ages of 45D and 262 are determined by a continuous laser system and mass spectrometer (Table 1). This method has been described in detail by Hu *et al.* (1995).

Table 1. $^{40}\text{Ar}/^{39}\text{Ar}$ isochron data of 262 basaltic andesite and 45D andesite

Sample	H. Tem. / °C	^{39}Ar / %	^{40}Ar / %	$^{40}\text{Ar}^*$ / %	$^{40}\text{Ar}/^{36}\text{Ar}$	$^{39}\text{Ar}/^{36}\text{Ar}$	Apparent Age/Ma
262(1)	1500	100	100	6.30	315.36	7.6815	118.95 ± 12.01
262(2)	1500	100	100	3.40	305.89	5.5516	86.84 ± 3.65
262(3)	1500	100	100	4.10	308.15	4.8004	121.11 ± 4.25
262(4)	1500	100	100	4.66	309.93	7.1629	93.35 ± 3.79
45D(1)	1500	100	100	1.02	298.55	1.4702	96.07 ± 10.53
45D(2)	1500	100	100	1.42	299.77	1.8434	106.90 ± 5.19
45D(3)	1500	100	100	1.41	299.72	1.9762	98.80 ± 13.84
45D(4)	1500	100	100	10.36	329.69	15.028	105.05 ± 1.12

H. Tem. : heat temperature.

Nd:YAG solid laser generator was used as a heat source, which outputs coherent laser beam of near-infrared radiation with 1064 nm wavelength and 250 μm in diameter. When the current in the krypton lamp of krypton pump was continuously regulated up to 14 A, a laser beam would be produced with enough energy to melt the sample instantaneously. A He-Ne collimated laser which is a low energy (1 mV) visible light with 632 nm wavelength was used to guide the invisible Nd:YAG laser beam through the glass window over the sample stage of microscope to focus the sur-

face of the sample on the stage. The sample prepared as a polished section with 6 mm \times 6 mm \times 2 mm was irradiated for 50 h in the E-5 passage at the center of the reactor. The total flux of fast neutron is 1.8×10^{18} n/cm². The K-Ar standard biotite sample with the age of 132 Ma from Zhoukoudian, Beijing was used as the monitor of neutron flux. After radioactive cooling, the sample was put in a pan on the object stage of microscope which is adjustable in X-Y-Z directions. The rim of sample pan is connected by a corrugated pipe to an ultravacuum system (10^{-7} Pa), a Zr-Al getter purified system. 4 microareas of the sample were chosen for melting separately and the released and purified gas was inputted into MM-1200 mass spectrometer. The peak values of argon isotopes were measured with a 17 cascade Cu-Be high gain electronic multiplier. The constant $\lambda_{40K} = 5.543 \times 10^{-10}/a$ (Steiger and Jäger, 1977) is adopted for age calculation and the error of age is 1σ .

A9352 was measured with ⁴⁰Ar/³⁹Ar age step heating method. The sample was ground into 60–80 mesh, wrapped with an aluminum foil and sealed hermetically in a quartz ampoule together with the monitor sample for neutron flux. The monitor samples include ZBJ hornblende of (132.8 ± 3.1) Ma age, ZBH-25 biotite of (132.7 ± 2.8) Ma and international standard sample BSP-1 hornblende (2060 ± 17.5) Ma. K₂SO₄ and CaF₂ were used in experiment to correct K and Ca interfering Ar isotopes. Then, the sample was put in the H4 channel of 49-2 Reactor for 4490 min irradiating with instantaneous fast neutron flux (0.6×10^{13} n/(cm²s)), i.e, the total amount of the integrated fast neutron flux is 1.43×10^{18} n/cm². The cadmium foil with 0.5 mm in thickness was used as a shield to prevent the interference of slow neutron. After cooling to the safe dosage, the irradiated sample was put in an Ar-extraction system to carry out stepping analysis. A high-frequency oven was used for heating sample with each step of 20 min. The extracted argon was purified by CuO and sponge titanium and then, introduced directly to RAG-10 mass spectrometer for argon isotope analysis. Apparent ages were corrected of mass discrimination, memory effect, K and Ca interfering Ar isotope and ³⁷Ar radioactive decay. The measured correction factors of K and Ca interfering Ar isotope are $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}} = 7.15 \times 10^{-3}$; $(^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 2.64 \times 10^{-4}$; $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{Ca}} = 6.87 \times 10^{-4}$ (Hu *et al.* 1985). A half life of 35.1 d was adopted to correct the radioactive decay of ³⁷Ar. Nine temperature steps were performed on A9352 andesite sample and the Ar isotopic data and the age spectrum are shown in Table 2 and on Fig. 3.

4 Discussion

4.1 Laser microarea isochron age on samples 45D and 262

The four full fusion ⁴⁰Ar/³⁹Ar apparent ages, measured with one laser probe on 262 basaltic andesite sample vary from 121.11 Ma to 86.84 Ma (Table 1). An isochron line with much high goodness of fit was obtained by plotting the isotope ratios (⁴⁰Ar/³⁶Ar-³⁹Ar/³⁶Ar) of the 4 points (Fig. 2a) and an isochron age of $(111.48 \pm$

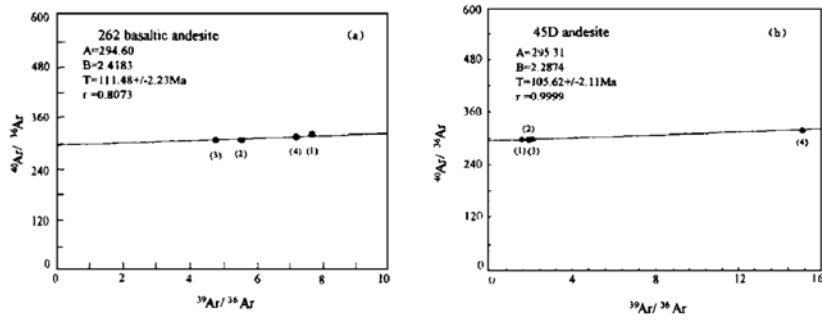


Fig. 2. $^{40}\text{Ar}/^{36}\text{Ar}$ - $^{39}\text{Ar}/^{36}\text{Ar}$ isochron of 262 basaltic andesite (a) and 45D andesite (b).

2.23) Ma was calculated from the equation $t=1/\lambda \ln(1+J \cdot ^{40}\text{Ar}^*/^{39}\text{Ar})$. This age is within above 4 apparent ages, while the initial ratio of $^{40}\text{Ar}/^{36}\text{Ar}$ (294.6) is almost the same as the atmospheric value (295.5). The four full fusion $^{40}\text{Ar}/^{39}\text{Ar}$ apparent ages of 45D andesite sample are more equivalent than that of 262 sample, only from 106.9 Ma to 96.07 Ma (Table 1) and the four points of $^{40}\text{Ar}/^{36}\text{Ar}$ - $^{39}\text{Ar}/^{36}\text{Ar}$ ratio fall on the same straight line with $r=0.9999$ (Fig. 2b). The calculated isochron age is (105.62 ± 2.11) Ma, comparable with each apparent ages and the isochron age of 262 sample. The initial ratio of $^{40}\text{Ar}/^{36}\text{Ar}$ of 295.31 also equals to the atmospheric value. These results imply that the 262 basaltic andesite and 45D andesite might not contain any excess argon and the isochron age would be more desirable than K-Ar dilution age in explaining the volcanic activities. Therefore we consider that both 262 basaltic andesite (111.48 ± 2.23) Ma and 45D andesite (105.62 ± 2.11) Ma were formed in Cretaceous.

4.2 $^{40}\text{Ar}/^{39}\text{Ar}$ step heating data on sample A9352

The apparent age of the lowest temperature is meaningless geologically because the sample is effected by nuclear recoil in irradiation and alteration. The apparent age of the high temperature is also of no importance because of the high background contribution of apparatus. From Table 2 and Fig. 3a, a plateau age of (96.7 ± 1.6) Ma was obtained by calculating the apparent ages from step 3 to step 6 and the released ^{39}Ar is 73.48% of the total released. Furthermore, $^{40}\text{Ar}/^{36}\text{Ar}$ - $^{39}\text{Ar}/^{36}\text{Ar}$ isochron calculation was made by using

Table 2. Argon isotopic data of A9352 andesite

$J=0.01726$; $W=0.30g$

Step	Tem. /C	$(\frac{^{40}\text{Ar}}{^{39}\text{Ar}})_m$	$(\frac{^{36}\text{Ar}}{^{39}\text{Ar}})_m$	$(\frac{^{37}\text{Ar}}{^{39}\text{Ar}})_m$	$(\frac{^{38}\text{Ar}}{^{39}\text{Ar}})_m$	$^{39}\text{Ar}_K$ / 10^{-12} mol	$(\frac{^{40}\text{Ar}^*}{^{39}\text{Ar}_K})$ / $\pm 1\sigma$	$(^{39}\text{Ar}_K)$ /%	Apparent age $t \pm 1\sigma$ /Ma
1	460	5.826	0.0178	21.980	0.227	4.49	2.34 ± 0.18	5.13	71.4 ± 5.6
2	640	13.296	0.0386	8.366	2.205	0.62	2.59 ± 0.42	0.71	78.9 ± 12.6
3	760	3.594	0.00115	0.208	0.0526	26.88	3.27 ± 0.11	30.7	98.9 ± 3.5
4	860	5.619	0.0081	0.114	0.552	2.94	3.24 ± 0.18	3.36	98.2 ± 5.3
5	960	3.418	0.00171	1.285	0.0564	32.76	3.07 ± 0.11	37.42	93.3 ± 3.2
6	1150	5.50	0.00794	1.461	0.548	1.76	3.28 ± 0.17	2.00	99.2 ± 5.2
7	1250	15.763	0.00452	27.671	0.180	2.48	4.70 ± 0.50	2.83	140.7 ± 14.4
8	1450	17.207	0.0316	0.580	2.973	15.54	7.95 ± 0.54	17.75	231.9 ± 15.1
9	1550	215.79	0.719	129.165	18.421	0.08	15.65 ± 2.27	0.09	431.5 ± 55.8

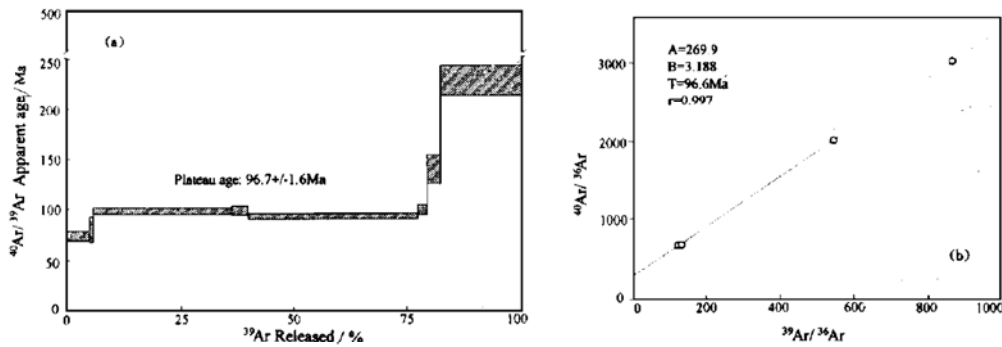


Fig. 3. $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum (a) and $^{40}\text{Ar}/^{36}\text{Ar}$ - $^{39}\text{Ar}/^{36}\text{Ar}$ isochron (b) of A9352 aplite.

the Ar isotopic ratios of above mentioned 4 steps of the plateau age. The $^{40}\text{Ar}/^{36}\text{Ar}$ initial ratio is 269.9 slightly lower than the atmospheric value (295.5), and the isochron age of 96.6 Ma (Fig. 3b) is the same as the plateau age of the sample. So, it is even more applicable to take the isochron age as the emplacement age of this sample.

5 Conclusions

The four fusion $^{40}\text{Ar}/^{39}\text{Ar}$ apparent ages by laser-mass spectrometer of 45D andesite vary from 107 Ma to 96 Ma and that of 262 basaltic andesite are from 121 Ma to 87 Ma, which are compatible to each other. The calculated isochron ages of the two samples are (105.62 ± 2.11) Ma and (111.48 ± 2.23) Ma, respectively. The $^{40}\text{Ar}/^{36}\text{Ar}$ initial ratio of the samples is equal to the atmospheric value, which indicates that there should be no excess argon existing in the studied samples and the isochron ages obtained from this study should be the real emplacement ages of these rocks.

The $^{40}\text{Ar}/^{39}\text{Ar}$ isochron age of 9352 aplite is 96.6 Ma, which is again the emplacement age. The $^{40}\text{Ar}/^{36}\text{Ar}$ initial ratio of this sample is equal to 91% of the atmospheric value and the isochron age is the same as the plateau age, therefore, it can be believed that the A9352 aplite was formed in Cretaceous, compatible with 45D andesite and 262 basaltic andesite. However, the age of aplite A9352, lower than those of the measured lavas, suggests that the intrusive rock was also successive to the main volcanic activity.

Smellie *et al.* (1996) interpreted the Eocene-Oligocene K-Ar ages of 45D and 262 samples as reset ages, which were related to the emplacement and cooling of a nearby Eocene tonalite pluton. These new $^{40}\text{Ar}/^{39}\text{Ar}$ ages are different from previous K-Ar ages (Smellie *et al.* 1996), and, combining with field relationship, provide that the volcanic rocks of MBF do erupted in Cretaceous as suggested by Smellie *et al.* (1996).

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References

- Arche A, Lòpez-Martínez J, Marfil R (1992a): Petrofacies and provenance of the oldest rocks in Livingston Island, South Shetland Islands. In: *Geología de la Antártida Occidental*. Salamanca; III Congreso Geológico de España y VIII Congreso Latinoamericano de Geología, Ed. by Lòpez-Martínez J, 93 – 104.
- Arche A, Lòpez-Martínez J, Martí nez de Pison E (1992b): Sedimentology of the Miers Bluff Formation, Livingston Island, South Shetlands. In: *Recent Progress in Antarctic Earth Science*, Ed. by Yoshida Y, Kamnumaet K, Shiraishi K, Tokyo, Terra Scientific Publishing Company, 357 – 362.
- Dalziel IWD, Kingfield R, Lowrie W, Opdyke ND (1973): Paleomagnetic data from the southernmost Andes and the Antarctic Andes. In: *Implications of Continent Drift to the Earth Sciences*, Ed. by Tarling DH & Runkorn SK, New York, Academic Press, 87 – 101.
- Grikurov GE, Krylov AYa, Polyakov MM, Tsovbnun YaN (1970): *Vozrast porod v Severnoi chasti Antarkticheskogo poluostrova i na Yuzhnykh Shetlandskikh ostrovakh (po dannym kaliargonovogo metoda)*. *Informatsionnyy Byulleten' Sovetskoy Antarkticheskoy Ekspeditsii.*, 80:30 – 33. (Age of rocks in the northern part of the Antarctic Peninsula and on the South Shetland Islands (according to Potassium-Argon data), *Information Bulletin, Soviet Antarctic Expedition*, 80, 61 – 63.)
- Hervé F, Loske W, Miller H, Pankhurst RJ (1991): Chronology of provenance, deposition and metamorphism of deformed fore-arc sequences, southern Scotia arc. In: *Geological Evolution of Antarctica*, Ed. by Thomson MRA, Crame JA & Thomson JW, Cambridge, Cambridge University Press, 429 – 435.
- Hobbs GJ (1968): The geology of the South Shetland Islands; IV. The geology of Livingston Island. *Brit. Antarctic Surv. Sci. Rep.*, 49:34.
- Hu SL, Wang SS, Sang HQ, Qiu J (1985): An application of the fast-neutron activation dating technique to approach the age of early emplacement of Jiuling granodiorite intrusion of Jiangxi province. *Acta Petrologica Sinica*, 1(3): 29 – 34.
- Hu SL, Zheng XS, Dai DM, Pu ZP (1995): $^{40}\text{Ar}/^{39}\text{Ar}$ isochron dating on a microarea scale of A635 basalt from the northern coast of King George Island, Antarctica by using a continuous laser system and a mass spectrometer. *Chinese Science Bulletin*, 40(16): 1495 – 1496.
- Pankhurst RJ, Weaver SD, Brook M, Saunders AD (1980): K-Ar chronology of Byers Peninsula, Livingston Island, South Shetlands. *Brit. Antarctic Surv. Bull.*, 40:277 – 282.
- Smellie JL (1990): Graham Land and South Shetland Islands; Summary. In: *Volcanoes of the Antarctic plate and Southern oceans*, Ed. by LeMasurier WE & Thomson JW, Antarctic Research Series, 48: 303 – 312, Washington D. C. : American Geophysical Union.
- Smellie JL, Liesa M, Muñoz JA, Sàbat F, Pallàs R, Willam RCR (1995): Lithostratigraphy of volcanic and sedimentary sequences in central Livingston Island, South Shetland Islands. *Antarctic Science*, 7 (1): 99 – 113.
- Smellie JL, Pallàs R, Sàbat F, Zheng XS (1996): Age and correlation of volcanism in central Livingston Island, South Shetland Islands: K-Ar geochemical constraints. *J. South Am. Earth Sci.*, 9(3/4): 265 – 272.
- Smellie JL, Pankhurst RJ, Thomson MRA, Davies RES (1984): The geology of the South Shetland Islands; VI. Stratigraphy, Geochemistry and evolution, Cambridge, *Brit. Antarctic Surv. Sci. Rep.*, 87:85.
- Steiger RH, Jäger (1977): Subcommittee on Geochronology: Convention on the use of decay constants in geo and cosmochronology. *Earth Planet. Sci. Lett.*, 36:359 – 362.