

The geology and age of Peter I Øy, Antarctica

TORE PRESTVIK and ROBERT A. DUNCAN



Prestvik, T. & Duncan, R. A.: The Geology and Age of Peter I Øy, Antarctica. *Polar Research* 9(1), 89–98.

The island Peter I Øy is located in the Bellinghousen Sea 400 km off the coast of West Antarctica. It is situated at the transition between oceanic and continental crust close to a former transform fault, the Tharp fracture zone. The island is completely volcanic, consisting of predominantly alkali basalt and hawaiite and some more evolved rocks. Sampling done by the *Aurora* expedition in 1987 has made dating and detailed petrological studies possible. The island appears to be much younger (<0.5 Ma) than previously believed. However, the volcanic activity responsible for this oceanic island may have lasted for 10–20 Ma. Volcanic activity at the island thus took place at the same time as post-subduction rift-related volcanism took place along the Antarctic Peninsula and in Marie Byrd Land. However, the petrologic data indicate that this may be coincidental and that the Peter I Øy activity is independent and related to transtensional rifting along the Tharp fracture zone.

Tore Prestvik, Department of Geology and Mineral Resources Engineering, University of Trondheim, N-7034 Trondheim, Norway; Robert A. Duncan, College of Oceanography, Oregon State University, Corvallis, Oregon 97331, USA.

Introduction

Peter I Øy is located at 68°50'S, 98°35'W in the Bellinghousen Sea approximately 400 km north-east of Eights Coast, West-Antarctica (Fig. 1). The island was discovered and named by the Russian *von Bellinghousen* expedition in 1821. It became Norwegian territory after the first landing was made by the *Norvegia* expedition in 1929. The most comprehensive reports on early expeditions to the island can be found in the papers by Broch (1927), Johnson (1966), and Bastien & Craddock (1976a).

The Norwegian *Aurora* expedition visited Peter I Øy from 23 January to 2 February 1987 under very good weather and ice conditions (Fig. 2). The present account, which is based on samples collected during this expedition, reports new geochronological data and gives a review of the geology of this remote island. Detailed petrological and geochemical descriptions will be published elsewhere (Prestvik et al. 1990).

Whereas the samples described by Broch (1927) were all dredged off the island, and the samples examined by Bastien & Craddock (1976a) came from one locality on the western coast, the *Aurora* collection comprises material from five different locations on the island (Fig. 3): (1) Framnæsodden and (2) Kapp Ingrid/Norvegiabukta on

the western coast, (3) Tvisteinen and (4) Auroraholmen in the north, and (5) Michajlovodden on the eastern coast of the island. The *Aurora* collection contains various types of basalts. In addition to this material Prestvik et al. (1990) reexamined the dredged *Odd-I* collection (Broch 1927), and three of these samples were included in their study. Because no geologists participated in the *Aurora* expedition, some of the geological features and field relations described here are based on previously published information.

Tectonic setting and geologic history

Peter I Øy is 19 × 13 km in N-S/E-W directions, it reaches 1640 m above sea level (Fig. 3) and covers an area of approximately 154 km² (Norsk Polarinstitutt 1988). It is the surface part of a huge volcanic structure rising from about 4,000 m below sea level between the South Pacific ocean floor and the upper continental rise of the Antarctic continent (Tucholke & Houtz 1976; Kimura 1982). Peter I Øy thus classifies as an oceanic island. It is not known with certainty whether the volcanic structure represents Hawaiian type within-plate activity, or if it is related to "leakage" along zones of tectonic weakness, such as a trans-

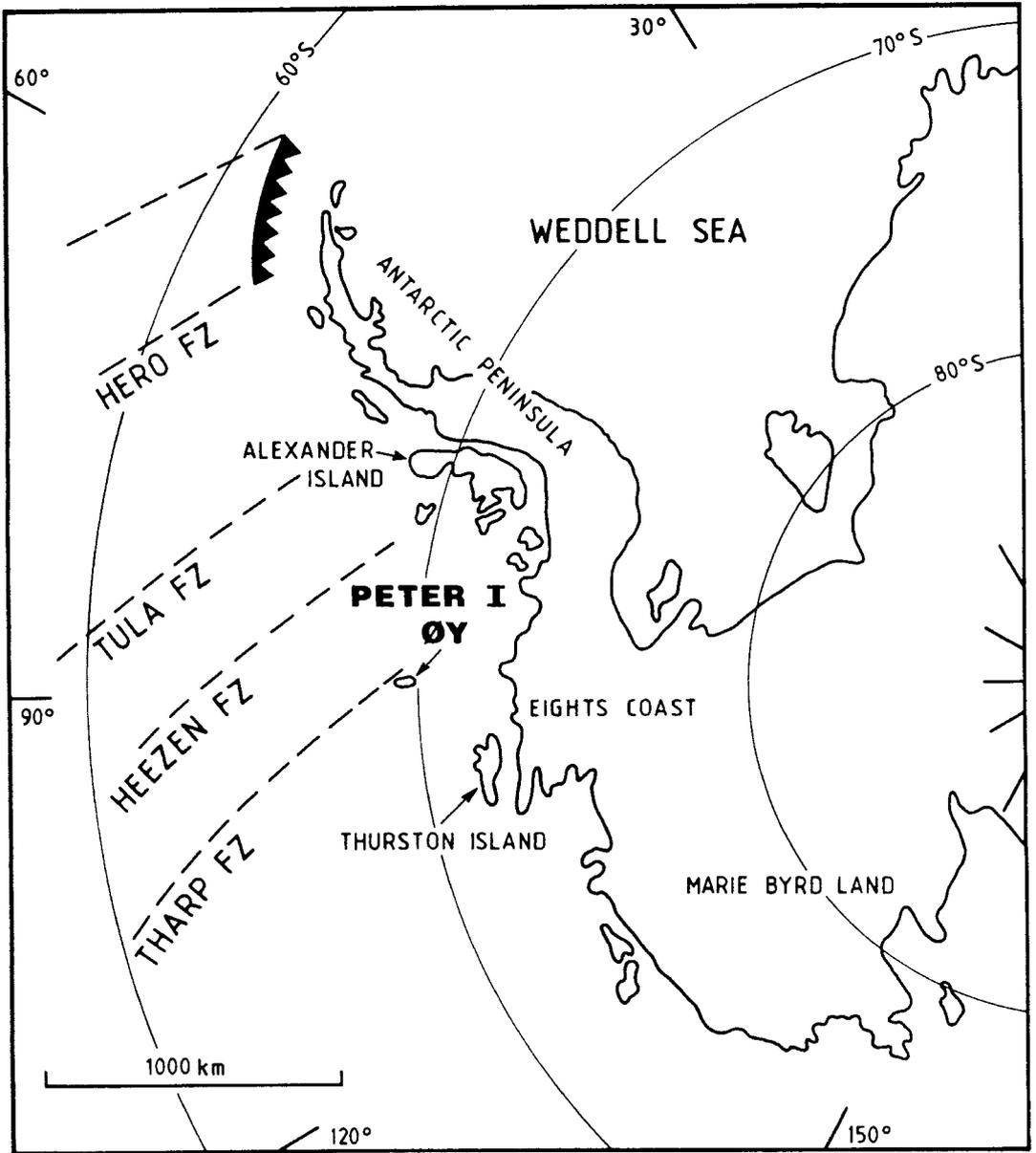


Fig. 1. Location map of Peter I Øy with major tectonic features of the southeasternmost Pacific indicated.

form fault. Herron & Tucholke (1976) found that Peter I Øy was located close to a former transform fault or fracture zone, although its relation to the tectonic history of the South Pacific in the area was not fully understood then. However, on the basis of several more recent reports (Weissel et al. 1977; Barker 1982; Cande et al. 1982; Kimura

1982; Stock & Molnar 1987), it seems well-established that this part of the continental margin of West Antarctica was a collisional plate boundary during most of the Cretaceous and into early Tertiary. At that time oceanic crust formed at an oceanic ridge which is now subducted beneath the continental crust of West Antarctica. Between

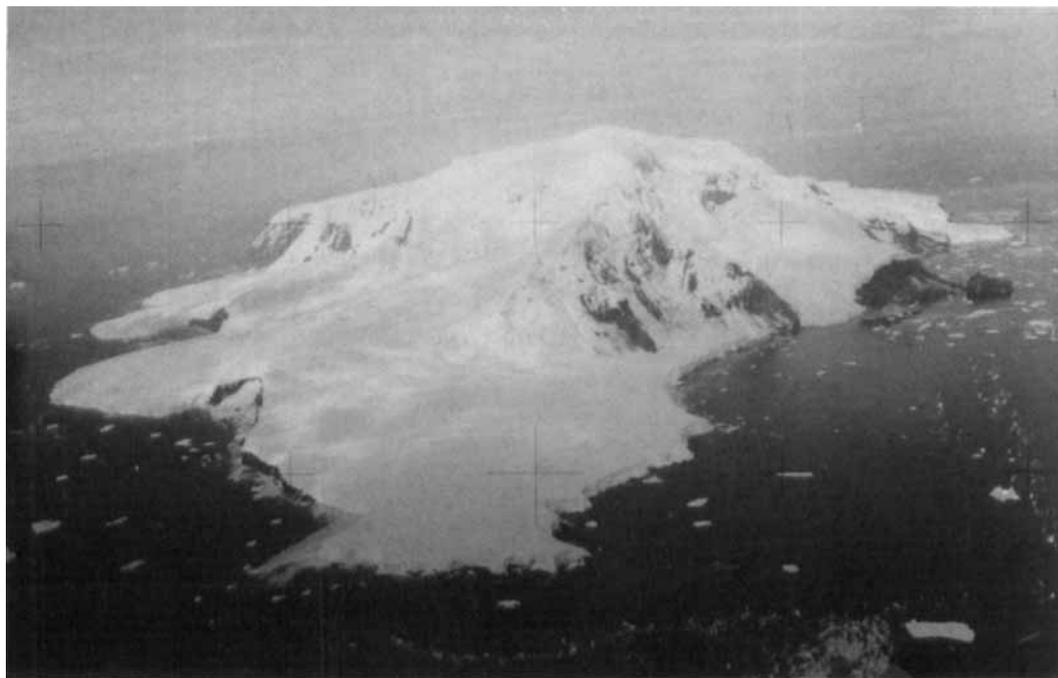


Fig. 2. Aerial view of Peter I Øy from the north (Photo: Norsk Polarinstitut).

the Tharp (Peter I fracture zone of Kimura 1982) and Tula fracture zones (Fig. 1), this subduction stopped some time in the Middle Eocene (Weissel et al. 1977; Barker 1982; Cande et al. 1982). Kimura (1982) reported the existence of trench and fore-arc basin sediment complexes within the continental rise/slope part of the presently passive oceanic/continental margin. From this evidence it can be inferred that Peter I Øy is situated on oceanic crust covered with 1.5–2 km of various kinds of sediments.

The age of Peter I Øy has not been known in detail, because only one K/Ar date (12.5 ± 1.5 Ma) of a basaltic lava from the island has been published (Bastien & Craddock 1976a). This age determination indicates that the volcanism of this area may have started back in Early Miocene or Late Oligocene. Our new K/Ar measurements of Peter I Øy rocks indicate, however, that the activity responsible for the rocks at the surface is much younger, <0.5 Ma (see below). The volume of the total volcanic cone above the seafloor can be estimated on the basis of bathymetric data (Bastien & Craddock 1976a) to be about $2,900 \text{ km}^3$. Because eruption rates are unknown, it is difficult to estimate when

the Peter I Øy volcanism started. However, if we as an example select eruption rates 10–20% of those of the very productive Hawaiian plume (Clague & Dalrymple 1987), the building up of the Peter I Øy cone may have started 10–20 Ma before present time. (Higher or larger rates expand the age range on the lower and higher sides of this estimate respectively). Based on this estimate, the volcanic activity of the Peter I Øy area thus coincides more or less completely with the rift-related volcanism in Marie Byrd Land and Eights Coast (LeMasurier & Rex 1982) and along the Antarctic Peninsula (Smellie et al. 1988).

Geological features and petrology

Broch (1927) described the samples dredged off Peter I Øy during the *Odd I* expedition, and Holtedahl (1935) made some points on the geology on the basis of photographs and samples taken during the *Norvegia* expedition in 1929. Accounts of the geology have also been given by Johnson (1966) and Bastien & Craddock (1976a, b), and Rowley (1989) has reviewed the geology of the island. The most comprehensive

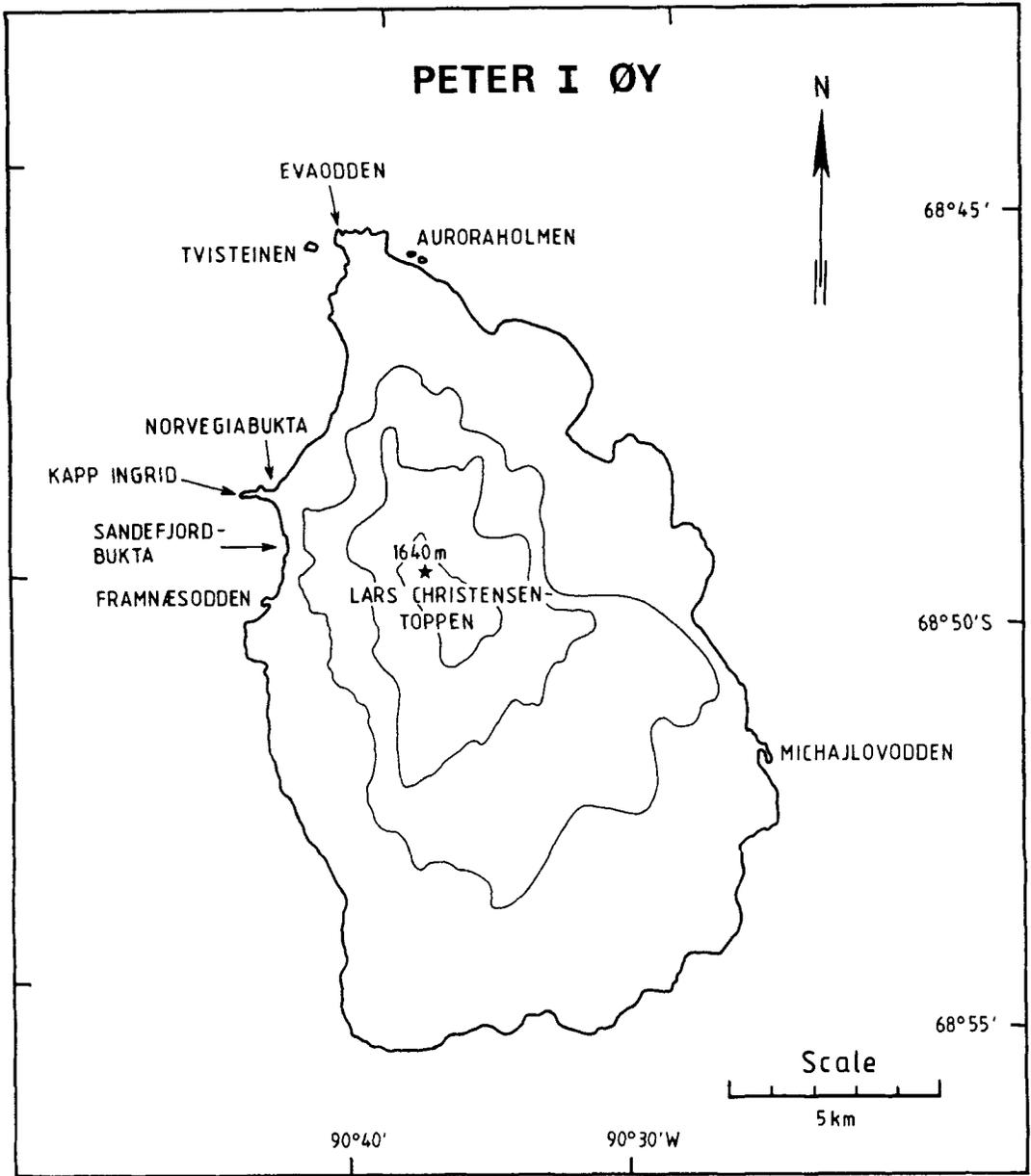


Fig. 3. Sketch map of Peter I Øy showing sample locations (Norsk Polarinstitut 1988, modified).

contributions are those of Broch (1927), Bastien & Craddock (1976a), and Prestvik et al. (1990).

Broch (1927) described in great detail the petrography of 175 rock samples dredged close to the western coast of the island. The material collected in Norvegiabukta during the *Burton Island* expedition in 1960 (Craddock & Hubbard 1961; Bastien & Craddock 1976a) comprises 29

samples. Thirteen of these are basalts, the rest are trachyandesites (trachyte according to Prestvik et al. 1990). One of the basalts and most of the trachyandesites (trachytes) have inclusions of gabbro/diorite (Bastien & Craddock 1976a). These authors described the geology at Norvegiabukta as made up of interbedded flows of basalt and more siliceous (trachyte) lava. These

are intruded by dikes and small stocks. Plug-like masses of basalt were described from Evaodden in the north, from Kapp Ingrid, and from the southeast corner of Sandefjordbukta (Framnæsodden). Broch (1927) also described xenolithic material in trachyandesite (trachyte) from Norvegiabukta, and he inferred (p. 34) the existence of a light-colored intrusion within the flow sequence at Kapp Ingrid.

On the basis of excellent photographs taken from helicopter during the *Aurora* expedition, we are adding the following information on geological features:

At least 95% of the island is covered by permanent ice and snow. A flat summit area (Fig. 3) indicates the presence of a summit crater. The exposed cliffs along the northern part of the west coast present a considerable section through the volcanic pile of the island. There lava flows, flow units, fragmental rocks (probably hyaloclastites) and dikes are well-exposed in cliffs reaching from sea-level and up to about 400 m. The asymmetrical shape of the island, with the assumed crater closer to the west coast, indicates that the lowermost lavas exposed along the western coast could represent some of the oldest activity of



Fig. 4. Thin lava flows or flow units at the Kapp Ingrid promontory. The uppermost section appears to contain fragmental (pyroclastic) material. The summit reaches 163 m above sea-level. (Photo: Norsk Polarinstitutt).

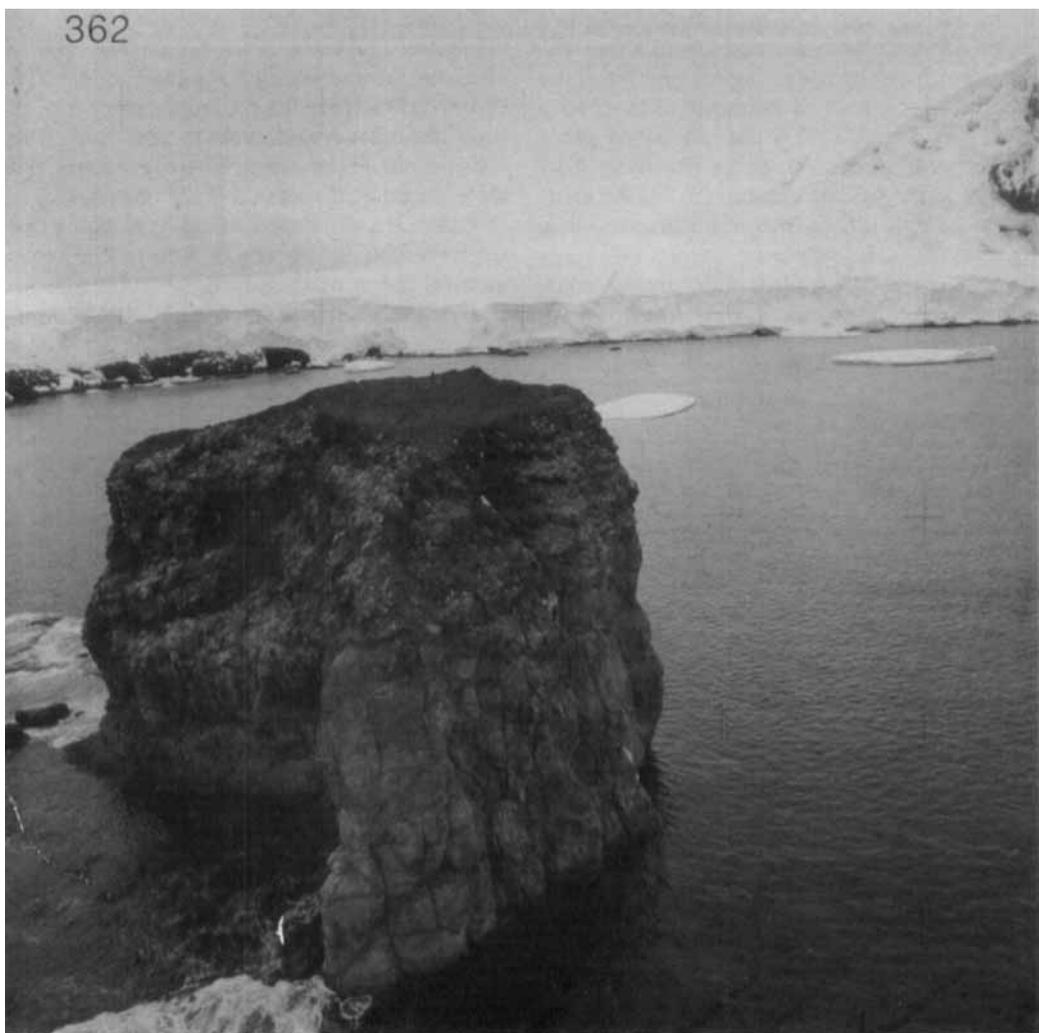


Fig. 5. The islet of Tvisteinen. Massive basalt is capped by thin flow units. The top of the islet is 49 m above sea-level. (Photo: Norsk Polarinstittutt).

the island. The best exposures appear to be at Framnæsodden, Kapp Ingrid and at Norvegiabukta (Fig. 3). Photographs show massive lava overlaid by thin lava flows or flow units (Fig. 4) at both Framnæsodden and at the outer part of the promontory Kapp Ingrid. Pictures of the small islet Tvisteinen in the very north of the island (Fig. 3) leave a similar impression: thin lava flows occur on top of much thicker dense lava flows (Fig. 5). It is possible that the dense lavas are more resistant to abrasion and that their presence at these locations is the reason why Kapp Ingrid and Framnæsodden still exist as promontories. However, at Norvegiabukta Kapp Ingrid is almost

cut off from the mainland, and it is probable that Kapp Ingrid in the future will be separated from the rest of the island. Tvisteinen (Fig. 3) may represent a remnant of such a promontory in the north (from Evaodden) because abrasion has reached a more advanced stage there.

Prestvik et al. (1990) described the petrology and geochemistry of Peter I Øy on the basis of the *Aurora* collection and on reexamination of a few samples of the *Odd I* collection. Analytical data of representative samples are presented in Table 1. The results of Prestvik et al. (1990) may be summarized as follows:

The rocks of the island are predominantly alkali

Table 1. Major (in wt.%) and trace element (in ppm) data for representative Peter I Øy samples.

	PI-2 alk. basalt	PI-4 alk. basalt	PI-13 alk. basalt	I-19 benmoreite	I-13 trachyte
SiO ₂	47.64	46.32	49.22	57.22	62.18
TiO ₂	3.32	3.72	3.10	2.32	0.87
Al ₂ O ₃	13.67	13.37	14.71	15.01	16.90
Fe ₂ O ₃	2.25	2.45	2.31		
FeO	9.36	9.43	9.00	*8.36	*4.81
MnO	0.14	0.15	0.14	0.10	0.05
MgO	8.81	8.88	6.12	3.65	1.38
CaO	9.04	9.10	9.20	5.35	2.50
Na ₂ O	3.32	3.76	3.35	4.86	7.55
K ₂ O	1.23	1.37	0.93	2.84	3.58
P ₂ O ₅	0.61	0.62	0.49	0.44	0.22
LOI	0.78	0.63	1.69	0.70	0.53
Total	100.17	99.80	100.26	100.85	100.57
Ba	291	311	212	432	618
Rb	21.4	22.3	22.4	66.8	66.5
Sr	714	736	550	573	1,125
Zr	279	287	219	453	548
Y	30.1	29.7	29.5	31.7	15.2
Nb	48	44	29	48	95
Sc	19.7	21.1	22.0	11.4	3.1
Cr	281	350	155	97	21
Ni	229	228	99	84	13
Co	47	57	44	31	<3.6
V	177	187	175	123	38
La	37.1	39.1	28.0	54.5	73.5
Ce	101	113	94	117	159
Nd	41.6	42.9	31.2	45.8	66.9
Sm	9.2	9.5	7.7	9.4	10.6
Eu	2.76	3.14	2.84	2.79	3.15
Gd	6.79	5.33	4.73	n.d.	n.d.
Tb	0.88	0.81	1.01	1.06	0.77
Yb	1.08	1.13	1.33	1.56	0.52
Lu	0.13	0.12	0.20	0.22	0.07
Ta	3.1	3.36	2.31	3.76	6.65
Hf	5.6	6.87	5.03	10.84	13.13
Th	<1.8	2.93	2.57	14.49	15.19
U	0.86	0.77	1.14	3.35	4.26

* = Total Fe as FeO.

n.d. = not determined.

basalt and hawaiite, some benmoreite and trachyte. The basic rocks typically contain phenocrysts of olivine, minor diopsidic augite, and in one sample plagioclase. Small xenoliths in basalt comprise mantle-type spinel lherzolite, cumulate clinopyroxenite and gabbro and colourless felsic inclusions that consist of medium-grained, strained quartz, plagioclase, and abundant colourless glass. Chemically, the basic rocks are characterized by rather high MgO (7.8–10.2 wt.%) and TiO₂ (3.1–3.7 wt.%) and relatively low CaO (8.4–9.5 wt.%) contents. They have steep REE patterns [(La/Yb)_N = 20] with

HREE only 5x chondrite. Y and Sc are almost constant at relatively low levels. Compatible trace elements such as Ni and Cr show considerable variation (190–300 and 150–470 ppm resp.), whereas V shows only little variation. Sr and Nd isotope ratios vary slightly with ⁸⁷Sr/⁸⁶Sr averaging 0.70388 and ¹⁴³Nd/¹⁴⁴Nd 0.51277, both typical for ocean island volcanism. Lead isotope ratios are consistently high in basalts; ²⁰⁶Pb/²⁰⁴Pb = 19.194, ²⁰⁷Pb/²⁰⁴Pb = 15.728, and ²⁰⁸Pb/²⁰⁴Pb = 39.290, whereas benmoreite is somewhat less radiogenic. Oxygen isotope analyses average δ¹⁸O = +6.0‰. Incompatible trace elements vary

by a factor of 1.5–2.0 within the range of the basic rocks. It is proposed that the incompatible trace element variations represent different degrees (7–15%) of partial melting, and that these melts were later modified by minor olivine and spinel fractionation. The very small variation in Y (and Sc) and the very fractionated REE pattern indicate that the source had a Y and HREE-rich residual phase, most probably garnet. Furthermore, on the basis of chemical composition and available experimental data (Falloon & Green 1988), Prestvik et al. (1990) suggested that the source was slightly hydrous and that melting took place at 1.8–2.0 GPa. Trachyte was derived by multiphase fractionation of *ne*-normative basalts, and benmoreite from *hy*-normative parental liquids.

Geochronology

K-Ar analyses were performed to determine the age and duration of volcanic activity at Peter I Øy. Samples were selected to cover the widest possible geographic distribution, and from the freshest material available. All samples chosen for age determinations were basaltic and contained small amounts of olivine phenocrysts. These rocks were massive, well-crystallized and completely fresh. Any small xenocrystic material

was avoided because of the possibility of inherited mantle argon.

Samples were first crushed and sieved to obtain the 0.5 to 1 mm size fraction; any surface weathering, saw marks or xenocrystic material was removed. The crushed material was washed in distilled water to remove dust and then dried. These samples were then split into two aliquots, one for K-analysis by atomic absorption spectrophotometry and the other for Ar-analysis by mass spectrometry.

From 3 to 5 g of the crushed fraction of each sample was loaded in a suspended Mo-crucible in the argon extraction line and baked overnight at 180°C to achieve high vacuum ($\sim 10^{-6}$ Pa). The samples were fused by radio frequency heating of the crucibles and active gases were gettered over hot Ti-TiO₂ metal sponge. The isotopic composition of argon (⁴⁰Ar, ³⁶Ar) was then measured with an AEI MS-10S mass spectrometer. Because of the expected young ages and low amounts of radiogenic argon, several special analytical procedures were adopted, following Cassagnol & Gillot (1982). First, the usual addition of a known quantity of ³⁸Ar to calibrate sensitivity was eliminated because of small amounts of ⁴⁰Ar and ³⁶Ar in the spike; sensitivity was determined from the long-term measurement of conventional, spiked analyses which showed only a 1–2% variation in ³⁸Ar peak heights. Secondly, pipetted aliquots of

Table 2. K-Ar determinations for basalts from Peter I Øy.

Sample	Location	K content (wt.%)	Radiogenic ⁴⁰ Ar ($\times 10^{-12}$ mol/g)	Radiogenic ⁴⁰ Ar/total ⁴⁰ Ar	Age* $\pm 1\sigma$ (ka)
PI-2	North beach at Kapp Ingrid; massive lava	1.117	0.21433	0.036	111 \pm 36
PI-7	Norvegiabukta; massive lava	1.291	0.39812	0.068	178 \pm 20
PI-13	Michajlovodden; grey lava	1.223	0.61848	0.062	292 \pm 49
PI-15	Auroraholmen; grey lava with rare peridotite xenoliths	1.241	0.51768	0.052	229 \pm 13
PI-23	North beach at Kapp Ingrid; massive lava	1.164	0.66084	0.052	327 \pm 88

* ages calculated using the following decay constants: $\lambda_r = 0.581 \times 10^{-10}/a$; $\lambda_\beta = 4.962 \times 10^{-10}/a$; $^{40}\text{K}/\text{K} = 1.167 \times 10^{-4}$ mol/mol.

The K-Ar determinations were performed at Oregon State University, USA.

air argon were routinely measured both before and after each sample analysis in order to obtain the most precise correction for atmospheric ^{40}Ar as possible. Proportions of radiogenic ^{40}Ar as small as a few tenths of one percent of the total ^{40}Ar signal were, thus, detectable and reproducible (Levi et al. 1990; Gillot & Nativel 1989).

Measured ages fall in the range from 100,000 to 300,000 years (Table 2) for these basaltic rocks. Analytical uncertainties (1σ) vary from 6 to 32% of the measured age, depending on the proportion of radiogenic ^{40}Ar . There is no apparent spatial variation in ages: samples from the eastern (PI-13) and northern (PI-15) coasts fall in the same range as the three basalts from the Kapp Ingrid section (PI-2, PI-7, and PI-23). Hence, the island was built up above sea-level in late Pleistocene time, probably entirely within the Brunhes epoch of normal magnetic polarity.

Summary

The rocks of Peter I Øy are generally of the same type and age as those outcropping in extensional regimes on the nearby continent, and these occurrences may therefore be related to each other in some way. However, the Peter I Øy rocks are considerably more radiogenic in Sr and less in Nd than the rocks of the Antarctic Peninsula and Marie Byrd Land which have MORB-type isotope characteristics. According to Prestvik et al. (1990) possible explanations are that Peter I Øy represents separate asthenospheric hot spot activity, or is connected to transtensional rifting along the old fractures of the Tharp fracture zone as subduction ceased in Early Tertiary.

The previously reported K-Ar age of 12.5 ± 1.5 Ma for a basalt from Kapp Ingrid/Norvegiabukta (Bastien & Craddock, 1976a) appears to be erroneously old, perhaps because of unrecognized xenolithic material in the analyzed sample. On the basis of the unmodified form of the higher parts of the island, Rowley (1989) concluded that at least parts of the volcano were relatively young, probably Holocene. Holtedahl (1935) interpreted incisions at higher levels as raised shorelines. Such uplift could be the result of isostatic adjustment after partial deglaciation and thus be a relatively young feature. This uplift could also be a reflection of hot lithosphere in the area, indicating that magmatic activity is still taking place. In areas where the magmatic activity

has stopped, lithospheric *subsidence* is the normal process.

Acknowledgements. – We thank the Norwegian Polar Research Institute and the scientific crew on the *Aurora* expedition for collecting the samples on Peter I Øy. We thank R. Keller for sample preparation and K-analyses in support of the age determinations. A grant from Roald Amundsens Minnefond is gratefully acknowledged. Comments by two anonymous reviewers improved the manuscript. This paper is Publication No. 103 of the Norwegian Antarctic Research Expeditions (1987).

References

- Barker, P. F. 1982: The Cenozoic subduction history of the Pacific margin of the Antarctic Peninsula: ridge crest-trench interactions. *J. Geol. Soc. London* 139, 787–801.
- Bastien, T. W. & Craddock, C. 1976a: The geology of Peter I Island. *Initial Reports of the Deep Sea Drilling Project XXXV*, 341–357.
- Bastien, T. W. & Craddock, C. 1976b: Igneous rocks of Peter I Island. *Antarctic Journal* 11, 267–269.
- Broch, O. A. 1927: Gesteine von der Peter I-Insel, West Antarktis. *Avh. Norske Vid. Akad., Mat. Naturv. Kl. No. 9*, 1–41.
- Cande, S. C., Herron, E. M. & Hall, B. R. 1982: The early Cenozoic tectonic history of the southeast Pacific. *Earth Planet. Sci. Letters* 57, 63–74.
- Cassignol, C. & Gillot, P.-Y. 1982: Range and effectiveness of unspiked potassium-argon dating: Experimental groundwork and applications. Pp. 159–179 in Odin, G. S. (ed.): *Numerical Dating and Stratigraphy*. John Wiley & Sons, New York.
- Clague, D. A. & Dalrymple, G. B. 1987: The Hawaiian-Emperor volcanic chain. Part I Geologic evolution. Pp. 5–54 in Decker, R. W., Wright, T. & Stauffer, P. H. (eds.): *Volcanism in Hawaii Vol. 1. USGS Prof. Paper* 1350.
- Craddock, C. & Hubbard, H. A. 1961: Preliminary report on the 1960 U.S. expedition to the Bellinghausen Sea, Antarctica. *Science* 133, 886–887.
- Falloon, T. J. & Green, D. H. 1988: Anhydrous partial melting of peridotite from 8 to 35 kb and the petrogenesis of MORB. *J. Petrol., Special Lithosphere Issue*, 379–414.
- Gillot, P.-Y. & Nativel, P. 1989: Eruptive history of the Piton de la Fournaise volcano, Reunion Island, Indian Ocean. *J. Volcanol. Geotherm. Res.* 36, 53–66.
- Herron, E. & Tucholke, B. E. 1976: Sea-floor magnetic patterns and basement structure in the southeastern Pacific. *Initial Reports of the Deep Sea Drilling Project XXXV*, 263–278.
- Holtedahl, O. 1935: On the geology and physiography of some Antarctic and sub-Antarctic islands. *Scientific Results of the Norwegian Antarctic Expeditions 1929, No. 3*, 83–88.
- Johnson, G. L. 1966: Peter I Island. *Norsk Polarinst. Årbok* 1965, 85–93.
- Kimura, K. 1982: Geological and geophysical survey in the Bellinghausen Basin, off Antarctica. *Antarctic Record* No. 75, 12–24. National Institute of Polar Research, Tokyo.
- LeMasurier, W. E. & Rex, D. C. 1982: Volcanic record of Cenozoic glacial history in Marie Byrd Land and Western Ellsworth Land: Revised chronology and evaluation of tectonic factors. Pp. 725–734 in Craddock, C. (ed.): *Antarctic Geoscience*. The University of Wisconsin Press, Madison.
- Levi, S., Audunsson, H., Duncan, R. A., Kristjansson, L.,

- Gillot., P.-Y. & Jakobsson, S. K. 1990: Late Pleistocene geomagnetic excursion in Icelandic lavas: Confirmation of the Laschamp excursion. *Earth Planet. Sci. Letters* 96, 443–457.
- Norsk Polarinstitutt 1988: Peter I. Øy. *Topographic map, scale 1:50,000*. Oslo.
- Prestvik, T., Barnes, C. G., Sundvoll, B. & Duncan, R. A. 1990: Petrology of Peter I Øy (Peter I Island), West Antarctica. *J. Volcanol. Geothermal Res.* 44, 315–338.
- Rowley, P. D. 1989: F.11. Peter I Island. Pp. 63–67 in LeMasurier, W. E. and Thomson, J. (eds.): *Volcanoes of the Antarctic Plate*. American Geophysical Union.
- Smellie, J. L., Pankhurst, R. J., Hole, M. J. & Thomson, J. W. 1988: Age, distribution and eruptive conditions of late Cenozoic alkaline volcanism in the Antarctic Peninsula and eastern Ellsworth Land. *Brit. Antarctic Surv. Bull.* 80, 21–49.
- Stock, J. & Molnar, P. 1987: Revised history of early Tertiary plate motion in the south-west Pacific. *Nature* 325, 495–499.
- Tucholke, B. E. & Houtz, R. E. 1976: Sedimentary framework of the Bellinghausen Basin from seismic profiler data. *Initial Reports of the Deep Sea Drilling Project XXXV*, 197–227.
- Weissel, J. K., Hayes, D. E. & Herron, E. 1977: Plate tectonic synthesis: The displacements between Australia, New Zealand and Antarctica since the Late Cretaceous. *Mar. Geol.* 25, 231–277.