The geology and age of Peter I Øy, Antarctica

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The island Peter I Øy is located in the Bellinghausen 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.

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Introduction

Peter I Øy is located at 68°50'S, 98°35'W in the Bellinghausen Sea approximately 400 km northeast of Eight Coast, West-Antarctica (Fig. 1). The island was discovered and named by the Russian von Bellinghausen 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) Framnesodden and (2) Kapp Ingrid/Norvegiabukta on the western coast, (3) Twisteinen and (4) Auroralholmen 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-
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
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 km³. 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
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 (Framnesodden). 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 Polarinstittu).
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 1 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
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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 | L-19 benmoreite | L-13 trachyte |
|--------------|-----------------|-----------------|------------------|-----------------|--------------|
| SiO₂         | 47.64           | 46.32           | 49.22            | 57.22           | 62.18        |
| TiO₂         | 3.32            | 3.72            | 3.10             | 2.32            | 0.87         |
| Al₂O₃        | 13.67           | 13.37           | 14.71            | 15.01           | 16.90        |
| Fe₂O₃        | 2.25            | 2.45            | 2.31             |                 |              |
| FeO          | 9.36            | 9.43            | 9.00             | 9.36            |              |
| 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         |
| Na₂O         | 3.32            | 3.76            | 3.35             | 4.86            | 7.55         |
| K₂O          | 1.23            | 1.37            | 0.93             | 2.84            | 3.58         |
| P₂O₅         | 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       |

| Element | PI-2 | PI-4 | PI-13 | L-19 | L-13 |
|---------|------|------|-------|------|------|
| Ba      | 291  |      | 212   | 432  |      |
| Rb      | 21.4 | 22.3 | 22.4  | 66.8 |      |
| 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   |      |
| Ni      | 229  | 228  | 44    | 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 diopside 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 (~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 Cassignol & Gillot (1982). First, the usual addition of a known quantity of 36Ar 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 "Ar peak heights. Secondly, pipetted aliquots of

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

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

* ages calculated using the following decay constants: λ0 = 0.581 x 10^-10/a; λ0 = 4.962 x 10^-10/a; 40K/K = 1.167 x 10^-4 mol/mol.

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

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