Berichte zur Polar- und Meeresforschung

571
2008

Reports on Polar and Marine Research

The Antarctic ecosystem of Potter Cove, King-George Island (Isla 25 de Mayo)

Synopsis of research performed 1999-2006 at the Dallmann Laboratory and Jubany Station

Edited by Christian Wiencke, Gustavo A. Ferreyra, Doris Abele and Sergio Marenssi

HELMHOLTZ GEMEINSCHAFT

ALFRED-WEGENER-INSTITUT FÜR
POLAR- UND MEERESFORSCHUNG
In der Helmholtz-Gemeinschaft
D-27570 BREMERHAVEN
Bundesrepublik Deutschland

ISSN 1618 - 3193

Geology, tectonics and Ar-Ar ages of the magmatic dykes from Potter Peninsula (King George Island, South Shetland Islands)

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Introduction

Potter Peninsula is located at the southernmost extreme of King George Island (Fig. 1), stretching from 58°35.0' to 58°41.0' W and from 62°13.9' to 62°15.7' S. The unglaciated area comprises approx. 6 km^2, bordered by the Warszawa Icefield to the NE, Bransfield Strait to the SE, Maxwell Bay to the SW and Potter Cove to the NW.

Like in large parts of King George Island, the morphology on Potter Peninsula is predominantly characterized by a glacial landscape with offshore abrasion platforms, partly steep cliffs along the coast, and a rather smooth, hilly countryside in the interior. The most prominent morphological feature is Three Brothers Hill (196 m), a well known andesitic plug showing conspicuous columnar jointing (Fig. 2). It marks the final stage of activity of a Paleogene volcano, whose eruption products (lava flows and pyroclastic rocks) in combination with hypabyssal intrusions related to the volcanism, constitute most of the lithology observed on Potter Peninsula.

Among the first who carried out geological work in that area were FERGUSON [1921] and TYRELL [1921], who supplied short descriptions of the volcanic sequence. Later on, HAWKES [1961], BARTON [1961, 1965], SMELLIE et al. [1984] and BIRKENMAJER [1998] published more detailed geological and petrographic information, SMELLIE et al. [1984] also geochronological and geochemical data. Geological drafts and sketch maps of Potter Peninsula have been published by FOURCADE [1960], GONZÁLEZ-FERRAN & KATSUI [1970] and BIRKENMAJER [1998].

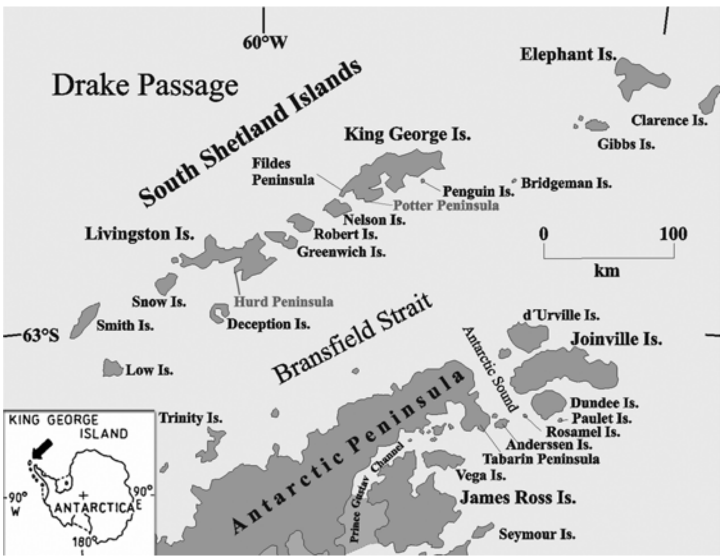


Fig. 1: The location of Potter Peninsula in the South Shetland Islands archipelago. Modified after VEIT (2002).

Geological frame

Potter Peninsula forms part of the downthrown Warszawa Block [BIRKENMAJER 1998]. The volcanic sequence cropping out here belongs to the King George Island Supergroup, with an observed local minimum thickness of approx. 90m [KRAUS 2005].

According to SMELLIE et al. [1984], the sequence can be referred to as part of the Fildes Formation introduced by these authors. Geochronological data from Potter Peninsula were published by WATTS [1982], who reports an Ypresian age (K-Ar, 50.6 ± 0.7 Ma) for Three Brothers Hill and Thanetian to Ypresian ages (57.9 ± 0.8 to 49.1 ± 0.9 Ma) for three andesitic lava flows. SMELLIE et al. [1984] obtained Ypresian to Lutetian K-Ar ages (49 ± 1 to 42 ± 1 Ma) for 6 basaltic to andesitic lava flows and hypabyssal intrusions, among them a Lutetian age (47 ± 1 Ma) for Three Brothers Hill.

Fig. 2: View towards SW to Three Brothers Hill (196 m), an Eocene andesitic plug showing prominent columnar jointing.

Three volcanic centers contributed to the volcanic sequence cropping out in the area: the former position of a stratovolcano is marked by the Three Brothers Hill plug, measuring about 500 m in diameter. Nearby Florence Nunatak, piercing the Warszawa Icefield about 4.7 km to the NE of Three Brothers Hill, is also a plug and marks the location of another extinct volcanic center. It is of basaltic andesitic composition and, like Three Brothers Hill, strongly columnar jointed. The remnants of a third but smaller stratovolcano are located at Stranger Point (Fig. 3). Today, this stratocone is completely eroded and only the reminders of the two feeding vents and the eruption products are left.

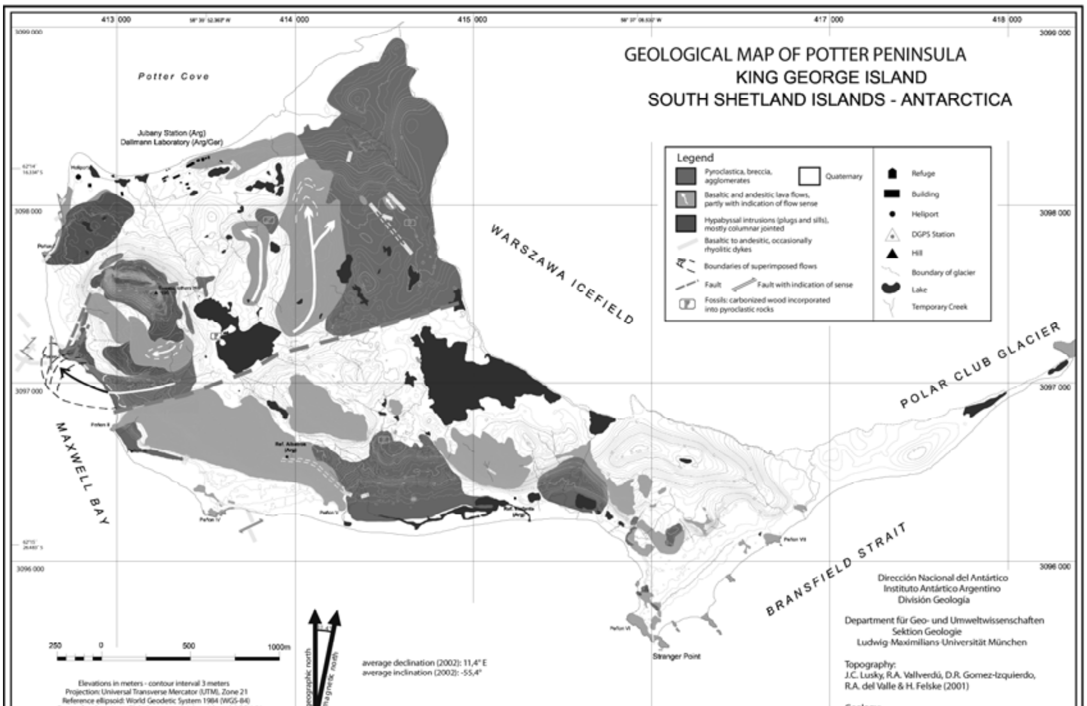


Fig. 3: Topographic and geological map of Potter Peninsula (King George Island, South Shetland Islands). Dyke thickness not scale appropriate. For high resolution color version please see: http://doi.pangaea.de/10.1594/PANGAEA.667386

The same applies to the Three Brothers Hill volcanic complex, which is eroded down to its deepest levels. Thus, the stratigraphically deepest units from the initial phase of volcanic activity are cropping out in some parts [KRAUS et al. 2000]. The lithology on Potter Peninsula comprises lava flows (~50%), pyroclastic rocks (ash-fallout, pyroclastic flow deposits, volcanic breccia and agglomerates, ~30%) and hypabyssal intrusions (dykes, sills and small subvolcanic intrusive bodies, ~20%).

Block faulting and subsequent tilting is evident everywhere on Potter Peninsula, though the individual blocks are tilted no more than 10-20° and without a prevailing direction. The prominent, NE-SW running fault separating Potter Peninsula in a northwestern and a southeastern sector was probably created during Late Cenozoic block faulting.

The dykes on Potter Peninsula

26 dykes crop out on Potter Peninsula, featuring a thickness between 30 cm and 10 m (average 3.68 m). They are far more abundant in the northwestern sector of the peninsula than in the SE towards Stranger Point (Fig. 3). Most

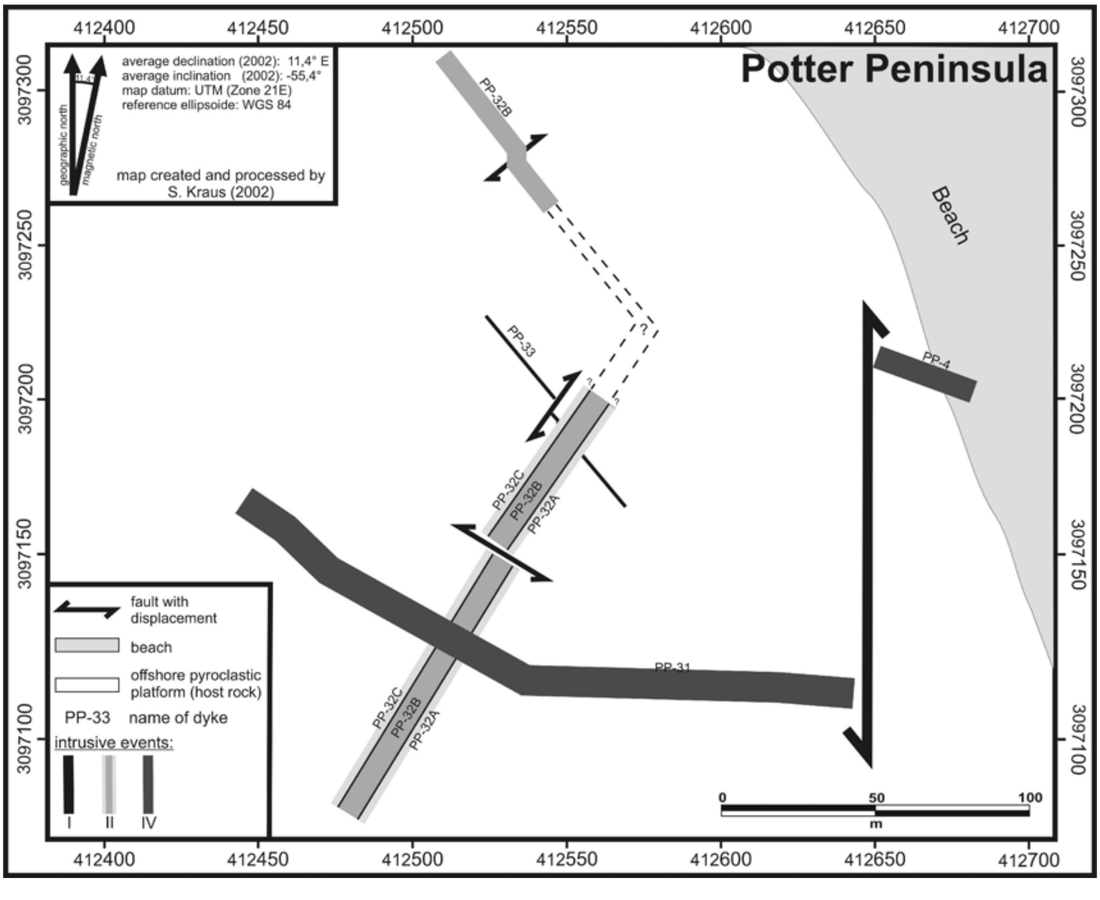


Fig. 4: Dyke system mapped at the western side of Potter Peninsula (Fig. 3). The system is located offshore, cutting an abrasion platform consisting of pyroclastic rocks. Accessibility is restricted to days with extremely low tide. The system comprises 5 dykes taking directions corresponding to intrusive events I, II and IV as determined on Hurd Peninsula, Livingston Island [KRAUS 2005]. Event III from Hurd Peninsula is not represented here. Note the multiple intrusion comprising dyke PP-32B (rhyolite, 7.6 m thick) flanked by two thin basaltic andesitic dykes (PP-32A and PP-32C, 1.0 - 1.2 m thick). Ar-Ar age determinations yielded same ages (Lutetian, approx. 46 Ma) for all dykes of the system, suggesting that the dykes intruded within a very short time, using different tectonic directions.

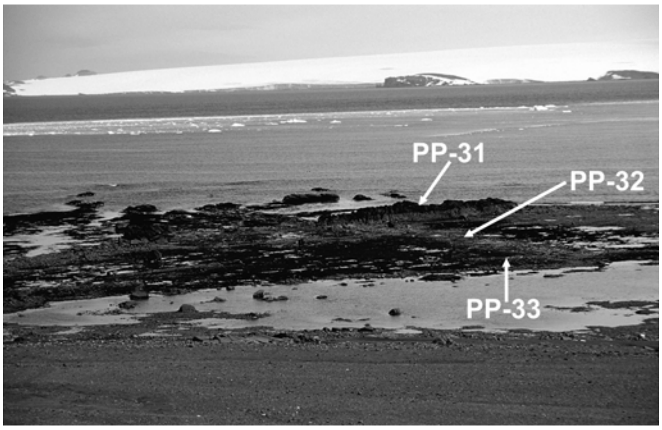


Fig. 5: View towards SW to the dyke system located offshore Potter Peninsula, cutting a pyroclastic platform. Barton Peninsula in the background.

of them are single, isolated dykes cutting the stratiform volcanic sequence, and can be traced from several meters length to up to 200 m (with interruptions). Like on adjacent Barton Peninsula, the only existing outcrop of a coherent dyke system allowing the observation of relative age relationships is an offshore pyroclastic abrasion platform near Peñón I (Fig. 3, 4 and 5). It is pierced by 5 dykes (some of them zigzagging), part of them forming a multiple intrusion (Fig. 4). The dykes are offset by three sets of faults. The oldest is dextral and strikes approx. 35-45°, the second sinistral striking approx. 120° and the third set is also sinistral, running exactly N-S (0° strike).

Most of the dykes are inconspicuous concerning their main characteristics and general appearance. The vast majority are of basaltic to andesitic composition, with mineralogies typical for a subduction related calc-alkaline suite. However, two outcrops deserve special attention, due to their unique appearance and features.

An especially spectacular example is an andesitic dyke cropping out in the northern part of Potter Peninsula near the border of Warszawa Icefield (414533 / 3098052, UTM, WGS 84, Zone 21E). Its orientation is 136/64 NE, featuring a thickness about 4 m; it can be traced over a length of approx. 60 m along a ditch approx. 1.8 m deep (Fig. 6). Here, the extensive pyroclastic rock sequence borders a small basaltic lava flow (Fig. 3). The dyke has intruded along this border between the two units. At approx. 150 m distance from the icefield, the dyke is located within an area from which the glacier retired only during the last 40 years. Thus, the ditch most probably represents the bed of a melt water creek which has fallen dry meanwhile. The water ran along the border between the dyke and the pyroclastic host rock, removing only the latter because of its lower resistance against erosion, thus

Fig. 6: About 60 m long ditch representing the bed of a meltwater creek now fallen dry. The left wall of the ditch is the outer surface of dyke PP-9. View towards NW.

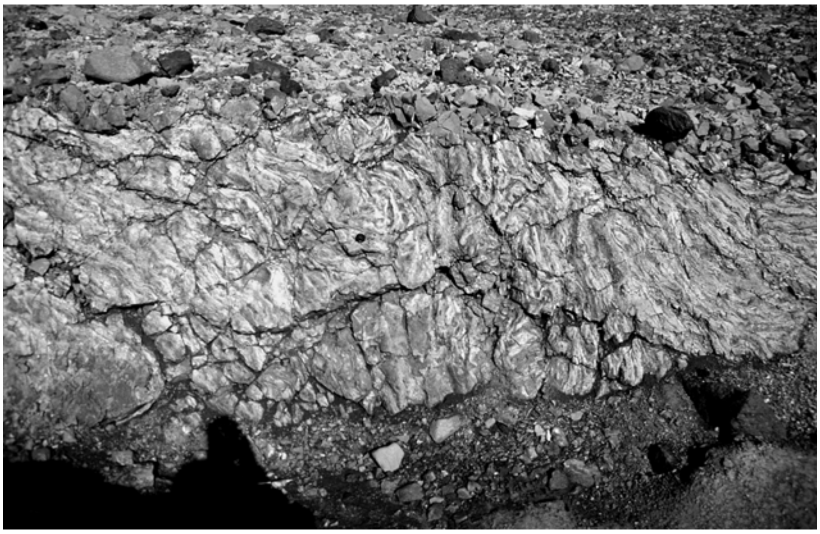


Fig. 7: Bulging structures on the outer surface of dyke PP-9, reflecting clearly the movement of the magma during intrusion. The dyke's chilled margin is greenish, fragments of the pyroclastic host rock baked onto the surface of the dyke are brownish. The ditch is approx. 1.5 m deep.

laying open the outer wall of the dyke over a length of approx. 60 m (Fig. 6).

Its appearance is characterized by bulging, more seldom globular structures and redbrown to greenish schlieren (Fig. 7). The bulges reflect clearly the magma's movement while intruding the fissure, mostly in a vertical but sometimes also subhorizontal direction. The color of the redbrown areas is due to fragments of the northeasterly lying pyroclastic host rock being baked onto the surface of the dyke, the greenish schlieren mark the chilled margin of the dyke itself, to a great extent consisting of secondary minerals like chlorite. Fragments of the pyroclastics are sometimes lined up in a string, also demonstrating the movement of the magma (Fig. 7). The dyke's approx. 4-5 cm thick chilled margin consists of a schlieren-like melange of greenish dyke- and redbrown pyroclastic material. Sometimes flame-structured amygdales of up to cm-size occur within this zone, often filled with a microcrystalline mineral of deep orange color, possibly zeolite. Within small geodes, this mineral sometimes forms dodecahedrons of up to 1 mm diameter. Further towards the dyke's interior, the color of the dyke rock changes to brownish-grey, then to grey. Small pores (< 1 mm) are aligned parallel to the dyke's outer wall and filled with calcite. They are aligned according to the orientation of the aforementioned bulges and thus reflect the magma's movements also in the dyke's interior. At about 15 cm distance from the dyke's surface, another zone of up to 1 cm big amygdales is visible, also partly filled with calcite. The bulk rock of the dyke consists of a light-grey, dense matrix hosting phenocrysts like pyroxene (up to 1.5 mm, euhedral, greenish), plagioclase (up to 2 mm, euhedral, whitish) and opaque minerals. Scarce amygdales of up to 2 cm diameter and irregular form are filled with chlorite and/or calcite.

A second outcrop is well worth mentioning, consisting of a multiple intrusion comprising three dykes. The outcrop is located at the shore SW of the Heliport (412683 / 3097998, UTM, WGS 84, Zone 21E), close to and possibly related to the dyke system shown in Fig. 4. A yellowish, rhyolitic dyke is sandwiched between two dykes of basaltic andesitic composition (Fig. 8), the orientation is 30/84 SE. The rhyolitic dyke is 4 m thick, shows tight cleaving and a smooth surface with small pores (mm-range) and single feldspar grains (< 0.5 mm). The rhyolite reacts with HCl, indicating presence of calcite; it bears accessory, mostly cubic pyrite (< 0.5 mm). The alteration rim is yellowish, 3-4 cm thick, and changes its color towards the fresher interior to grey-whitish. The contact with the two enclosing basaltic andesitic dykes is not sharp, but a rather blurry, approx. 2-3 cm (max. 5 cm) wide transition zone showing a schlieren-like intermingling of the two magmas. Pyrite cubes (< 0.5 mm) appear more frequently in the vicinity of the contact but are restricted to the rhyolitic dyke. Pores, too, become more frequent towards the contact, indicating a stronger degassing towards the rim.

Each of the two flanking dykes (Fig. 8) is 1.6 m thick. Their contacts to the rhyolitic dyke exhibit sometimes a fine-grained darker banding about 1 cm thick but without glass. Mostly this margin is rather vague and in some parts missing, instead the aforementioned intermingling of the two magmas is prevailing. Plagioclase crystals are aligned parallel to the contact and sometimes arranged in a tile-like pattern. Like the rhyolitic dyke between them, these two flanking dykes are lacking a chilled margin at the contact with their acidic counterpart, being a strong hint on contemporaneous intrusion.

About 60 m to the S (412679 / 3097935, UTM, WGS 84, Zone 21E), a very similar situation occurs. Here, the orientation of the dykes is 50/80 NW, the rhyolitic dyke is only 3 m thick and the basaltic andesitic dykes each 1.6 m. A small, NW-SE running fault has cut and brecciated the dyke system.

At both outcrops, the rhyolitic dyke morphologically steps backward relative to the flanking ones and is also stronger jointed. This latter effect may be due to the considerable differences in acidity, resulting in a lower resistance against brittle failure of the rhyolite as compared to the basaltic andesite.

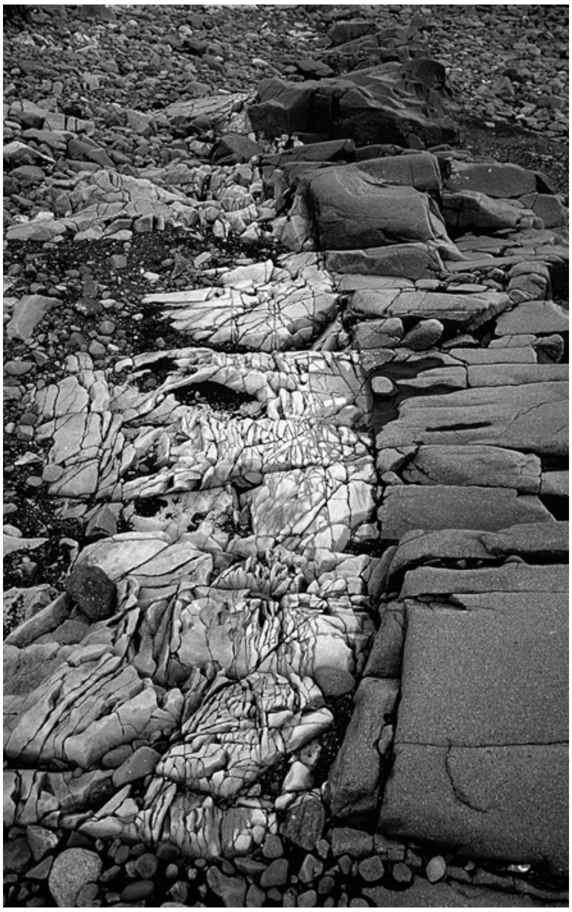


Fig. 8: A multiple intrusion, reflecting bimodal volcanism and maybe also bimodal flow. A rhyolitic dyke (left side) is sandwiched symmetrically between two 1.6 m thick basaltic andesitic dykes (one of them at the right side).

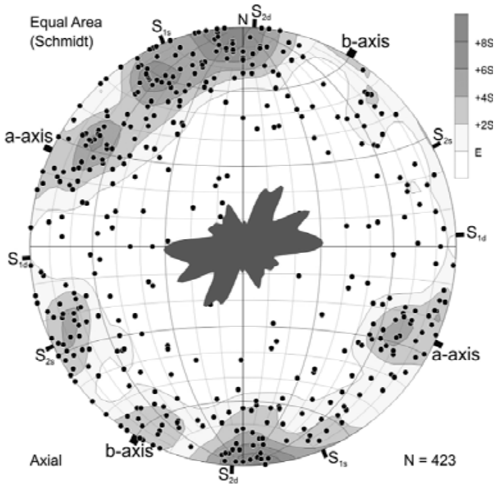
Two more outcrops on Potter Peninsula show the same situation of a rhyolitic dyke sandwiched symmetrically between two basaltic andesitic dykes (412529 / 3097149, UTM, WGS 84, Zone 21E and 413381 / 3096562, UTM, WGS 84, Zone 21E). The unique character of these outcrops has to be emphasized, because this type of multiple dyke intrusion has not been reported from anywhere else on the South Shetland Islands up to now.

Concerning the development of these remarkable intrusions, one explanation might be that the rhyolitic dykes intruded first, followed by tearing of the contacts to the wall rock during cooling. Subsequent intrusion of the basaltic andesitic magma might have occurred along these newly formed planes, accompanied by intermingling with the still not completely crystallized rhyolite. However, to our opinion this theory is not satisfying concerning the missing chilled margins of the rhyolitic dyke and the schlieren-like intermingling of the two magmas, as especially the contacts of the rhyolite to the host rock should have cooled rapidly. Moreover, the outer surfaces of a dyke do often carry fragments of the host rock baked onto them (Fig. 7). According to the above theory, such fragments should be found along the contact between the rhyolite and the flanking basaltic andesitic dykes. However, this has not been observed at any of the outcrops.

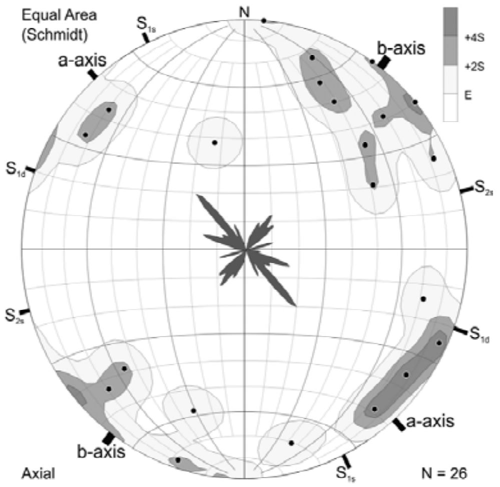
A more comprehensive and maybe promising but yet unproven theory is bimodal flow [McClarren 2003], requiring the contemporaneous intrusion of the crack by two types of magma, one of high viscosity and the other of low. The rhyolitic magma may have originated from the mush-zone of a differentiated magma chamber, whereas the basaltic andesitic material might have come from the chamber interior, both being pulled out through a crack in the chamber wall. When entering the fissure, the magma flow is probably rather chaotic, but the higher viscous magma (rhyolite) should, according to theory, soon become surrounded/sandwiched by the lower viscous, more basic material. Because of the much higher viscosity of the rhyolitic magma, mixing is rather unlikely. This phenomenon is well known to the petroleum industry, injecting water into oil pipelines in order to speed up the oil flow. In case of the dyke, the consequence would be that only the lower viscous (and hotter) magma is touching the host rock, whereas the rhyolitic magma remains insulated and does therefore suffer neither friction (which would lead to a slowdown) nor cooling. In other words, the more basic magma acts like a lubricant for the acid one. This process might allow a highly viscous rhyolitic magma to travel much longer distances than without presence of the more basic counterpart [McClarren 2003].

This second explanation appears plausible in this case, because the aforementioned schlieren-like intermingling and the missing chilled margins along the contacts between the basaltic andesitic and the rhyolitic dyke argue against a temporal gap between the intrusion of the two melts but instead for a contemporaneous one. Moreover, the position of the rhyolite sandwiched *between* the two basaltic andesitic dykes corresponds well to the above mentioned theory of the lower viscous magma acting like a lubricant, with the rhyolite placed in between. However, this theory is not without weaknesses. In contrast to the mechanism observed in petroleum pipelines, it requires the contemporaneous injection of two liquids not only highly diverse in chemical composition but also in temperature. The difference should be several hundreds of degrees Celsius, and the question is what effect this might have during flow concerning the interaction of the two magma types. Another question is, if the conditions within a magma chamber really allow the contemporaneous injection of two such different magma types into a crack.

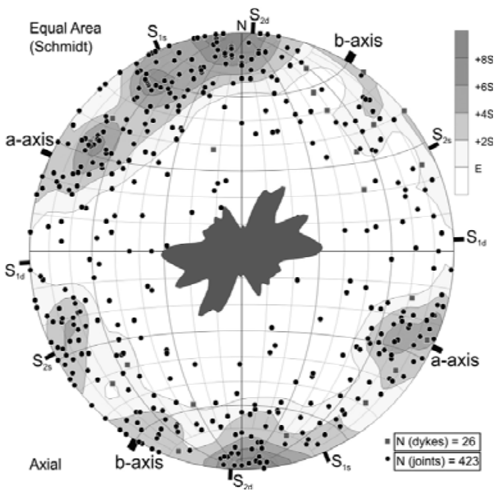
At least the occurrence of bimodal volcanism is indicated by the observed situation at the four outcrops, and probably related to the magma chamber which has fed Three Brothers Hill volcano. This assumption is supported by the relatively low distance (not more than 1 km) of all four outcrops to Three Brothers Hill (Fig. 3), furthermore by parallel trends displayed in certain geochemical diagrams [Kraus 2005].



Abbr.	Explanation (with average strike)
b-axis	37°
a-axis	138°
S_{1d}	dextral first order shear direction: 110°
S_{1s}	sinistral first order shear direction: 154°
S_{2s}	sinistral second order shear direction: 75°



Abbr.	Explanation (with average strike)
b-axis	30°
a-axis	116°
S_{1d}	dextral first order shear direction: 87°
S_{1s}	sinistral first order shear direction: 157°
S_{2d}	dextral second order shear direction: 3°
S_{2s}	sinistral second order shear direction: 62°



Abbr.	Explanation (with average strike)
b-axis	30°
a-axis	116°
S_{1d}	dextral first order shear direction: 87°
S_{1s}	sinistral first order shear direction: 158°
S_{2d}	dextral second order shear direction: 3°
S_{2s}	sinistral second order shear direction: 63°

Fig. 9: Schmidt Net showing all joints measured on Potter Peninsula (A), the orientation of the investigated dykes (B) and a compilation of all tectonic data (C). Cooling joints within the dykes have not been plotted. The tables to the right of the stereograms summarize the principal tectonic directions of the respective net. For contouring, the Gaussian method 'K=100' has been applied. This method gives an expected count E, that is the same as the conventional 1% counting circle. The mean, or expected, value E is the count that should arise in each counting model if the data set was uniformly distributed. The weighting curve has a width at half-height of 8.1°. The contour levels are in multiples of s (standard deviation) above (or below) E. Poles to planes.

Tectonics

Due to the lack of folding visible in the field, no folding axis could be determined on Potter Peninsula. However, structural data obtained during extensive field work carried out on the sedimentary Miers Bluff Formation at Hurd Peninsula (Livingston Island) revealed a NNE-SSW striking folding axis and associated first and second order sinistral and dextral shear directions [KRAUS 2005].

The very similar pattern found on Potter Peninsula as compared to Hurd Peninsula in our opinion justifies the asignation of the different tectonic directions (Fig. 9) assuming a stress field similar as on Hurd Peninsula. A thus inferred b-axis strikes 30° and the corresponding a-axis 116°.

423 joints measured on Potter Peninsula, predominantly within the pyroclastic rocks and the dykes (cooling joints eliminated), reflect ac-planes oriented 116/87 NE, a dextral first order shear plane at 87/90 N (S_{1d}), a sinistral first order shear plane at 158/79 NE (S_{1s}), a dextral second order shear plane at 3/78 E (S_{2d}) and a sinistral second order shear plane at 63/80 SE (S_{2s}). All these directions correspond unexpectedly well with the stress regime determined on Hurd Peninsula (Livingston Island). Concerning the ac-, S_{1d}- and S_{2d}-directions, differences in strike are no more than 5°, whereas the sinistral first and second order shear directions deviate 13-14° from the corresponding values on Hurd Peninsula.

However, the average orientation of the dykes on Potter Peninsula deviates much stronger from the directions shown by the joints as well as from the directions observed on Hurd Peninsula. The Potter Peninsula dykes suggest a b-axis striking 37° and an a-axis oriented at 138° (Fig. 9), the latter deviating 22° clockwise from the corresponding direction as deduced from the joints. The same applies to S_{1d} (23° difference clockwise), and only S_{1s} is close to the direction shown by the joints (difference of 4° clockwise). At present, no convincing explanation can be presented for the differing behavior of the dykes.

Ar-Ar ages of the dykes

$^{40}Ar/^{39}Ar$ datings were performed on plagioclase separates of 5 dykes from Potter Peninsula. Sample preparation was carried out partly in Munich (Germany), partly at Stanford University (California, USA). Here, the measurements were carried out applying the stepwise heating technique. Sample preparation and the applied technique are described in detail by KRAUS [2005, the full datasets including all age spectra may be downloaded from http://edoc.ub.uni-muenchen.de/archive/00003827/). The coordination of the isotope derived ages to the geological time scale follows the International Stratigraphic Chart pub-

Table 1: Ar-Ar ages and other data of five dykes from Potter Peninsula. The close-lying ages reflect an intense, but short intrusive phase during the Lutetian. For further details and $^{39}Ar/^{40}Ar$ vs. $^{36}Ar/^{40}Ar$ isochron diagrams see KRAUS [2005].

Sample #	latitude (UTM, WGS84)	longitude	strike	dip	thickness	lithology	LOI (wt%)	Ar-Ar age (Ma)	MSWD
PP-32B	412529	3097149	35	76SE	7.6 m	rhyolite	4.08	**45.7** ± 1.2	184
PP-33	412546	3097200	140	60SW	0.7 m	trachyandesite	5.76	**46.43** ± 0.56	1.6
PP-11	414308	3098266	15	72W	4.0 m	andesite	3.05	**46.61** ± 0.37	5.8
PP-31B	412514	3097131	110	71N	6.2 m	basaltic andesite	2.76	**46.98** ± 0.62	10.6
PP-32C	412529	3097149	35	76SE	1.0 m	andesite	2.35	**47.19** ± 0.50	0.61

lished by the IUGS International Commission on Stratigraphy (ICS, website: www.stratigraphy.org).

A first order observation is the narrow time interval covered by the ages (Table 1). Dyke intrusion on Potter Peninsula seems to have been restricted to a short time between approx. 48 and 45 Ma during the Lutetian. A second order observation is that the dykes, without correlation to the ages, intruded along different tectonic directions. The two observations argue strongly for a short-lived, intense intrusive event producing dykes which took different directions, but all belonging to the same tectonic stress field. This means that the tectonic parameters changed only very slightly during dyke intrusion, but the overall stress conditions remained the same, an observation that has found to be true for the whole archipelago and for an even much longer period [KRAUS 2005].
The good correlation of these data with the ages published for the Three Brothers Hill plug indicates that dyke intrusion on Potter Peninsula was related to the volcano's final phase of activity, as was the formation of the plug.

Conclusions

1. Magmatic dykes are more abundant in the northwestern part of Potter Peninsula and around Three Brothers Hill than in the eastern part of the area.
2. All dykes belong to a calc-alkaline, subduction related suite, with lithologies ranging from basalts to rhyolites, but with andesites prevailing.
3. The time during which intrusion took place seems to have been restricted to a narrow interval between 47.2 ± 0.5 and 45.7 ± 1.2 Ma (Lutetian).
4. Dyke intrusion was most probably related to the final phase of activity of Three Brothers Hill volcano, an assumption strongly supported by the very similar ages published for the Three Brothers Hill plug, which marks the end of activity of the volcano.
5. A spectacular multiple intrusion (a rhyolitic dyke flanked by two basic ones) forms part of a dyke system piercing an offshore pyroclastic platform west of Three Brothers Hill.
6. The joint directions used by the dykes indicate a stable tectonic stress field during the complete time of intrusive activity, because all directions can be interpreted as belonging to the same tectonic regime. The use of different directions indicates that slight changes of the overall tectonic parameters led to different preferred directions, but within the same stress field. At least three different intrusive events are evident on Potter Peninsula.
7. Analysis of the structural data of the dykes and their host rocks shows, that the tectonic stress field prevalent on Potter Peninsula was very similar as in other parts of the archipelago (e.g. Hurd Peninsula, Livingston Island), and that only minor changes of this stress field occurred during the time of dyke emplacement.

Acknowledgements

We thank the German Science Foundation (DFG) for funding the project (project number MI 120/41-1). Logistic support was kindly provided by the Alfred-Wegener-Institut (AWI Bremerhaven, Germany) and the Instituto Antártico Argentino (Buenos Aires, Argentina).

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Appendix: SCAR accepted, Argentine and Chilean place names mentioned in the text.

SCAR accepted names	Argentine names	Chilean names
Bransfield Strait	Mar de la Flota	Estrecho Bransfield
South Shetland Islands	Islas Shetland del Sur	Islas Shetland del Sur
King George Island	Isla 25 de Mayo	Isla Rey Jórge
Livingston Island	Isla Livingston	Isla Livingston
Florence Nunatak	Yamana Nunatak	Florence Nunatak