

A Holocene palaeoenvironmental study of a sediment core from Ile de la Possession, Iles Crozet, sub-Antarctica

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Abstract: Ile de la Possession is one of the few islands in the southern Indian Ocean, making the island a valuable place to reconstruct past environmental and climatic changes. In this study a peat sediment core was analysed to reconstruct the changes that occurred before, during and after the eruption of the Morne Rouge (10 000–5500 ¹⁴C yr BP) volcano. In addition to sedimentological analyses, diatom communities were used to reconstruct humidity and altitude, based on existing transfer functions. Radiocarbon dating of a tephra layer showed that the Morne Rouge volcano erupted between 6700–6600 cal. yr BP, giving a much more precise time scale for this event. The eruption was preceded by a tsunami flooding, indicated by the high numbers of marine diatoms found immediately before the tephra layer. After the eruption pioneer diatom species recolonized the coring site. Evidence is presented of the late climatic optimum around 3050 cal. yr BP, preceded by a cooling event until 6600 cal. yr BP. Nutrient input from elephant seals and wandering albatrosses obscured the climate signal for the last 600 cal yr BP.

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Introduction

Although the Southern Hemisphere oceans play a key role in global climate change (Hodgson & Sime 2010), relatively few palaeoclimate records exist from there in comparison to the Northern Hemisphere (Pahnke & Sachs 2006). The Southern Hemisphere palaeo-reconstruction database (NOAA Paleoclimatology Program <http://www.ncdc.noaa.gov/paleo/recons.html>, accessed 4 April 2010) consists mainly of studies on deep sea sediment cores (Stott *et al.* 2007). The few terrestrial Holocene records of the Antarctic region are mainly concentrated in East Antarctica (Verleyen *et al.* 2010), the Antarctic Peninsula (Bentley *et al.* 2009), the maritime Antarctic and sub-Antarctic islands (e.g. Jones *et al.* 2000, Van der Putten *et al.* 2004) and are reviewed by Ingólfsson *et al.* (1998) and Hodgson *et al.* (2004). In the southern Indian Ocean sector, terrestrial Holocene palaeoecological data are scarce and restricted to a few climate reconstructions of the Iles Kerguelen mainly focusing on palynological data (Bellair-Roche & Delibrias 1967, Young & Schofield 1973, Larson 1974, Bellair-Roche 1976a, 1976b). Only three studies are known from Ile de la Possession (Iles Crozet). In 1972, Bellair-Roche reported a sequence of undated warmer and cooler events based on pollen and botanical macro remains in a peat core of the Vallée des Branloires. Vincke (2006) investigated the sub fossil testate amoebae assemblages in a peat core from the same valley. The studied core, however, did not represent a complete sequence, due to a gap of more than 4500 years between 5400 and 700 ¹⁴C yr BP. Finally,

Van der Putten *et al.* (2008) investigated a 6200 cal. yr BP old peat core from the Morne Rouge volcano crater based on moss remains, diatoms and geochemistry.

Despite the important information provided by these environmental reconstructions on Ile de la Possession, none of them reported on the impact of the most recent eruption of the Morne Rouge volcano. Moreover, the exact date of this eruption was only roughly estimated to have occurred somewhere between 10 000 and 5800 ¹⁴C yr BP (Giret *et al.* 2003, Van der Putten *et al.* 2008). The aim of the present study was therefore to carry out a high-resolution environmental reconstruction before, during and after the eruption event. Environmental and climatic changes in the terrestrial environment were inferred from sedimentological and diatom-based proxies and applying previously developed diatom transfer functions for moisture and temperature (Van de Vijver & Beyens 1999, Gremmen *et al.* 2007).

Site description

The Iles Crozet (45°48'–46°26'S, 50°14'–52°15'E) is a group of five small volcanic islands located in the southern Indian Ocean, north of the Polar Front at about 2400 km south-east of the South African coast (Fig. 1). The islands have a cold oceanic climate with a mean annual air temperature of about 5°C and an annual precipitation usually exceeding 2400 mm, mostly in the form of rain, snow and mist. Strong winds, coming from the west and north-west sweep the

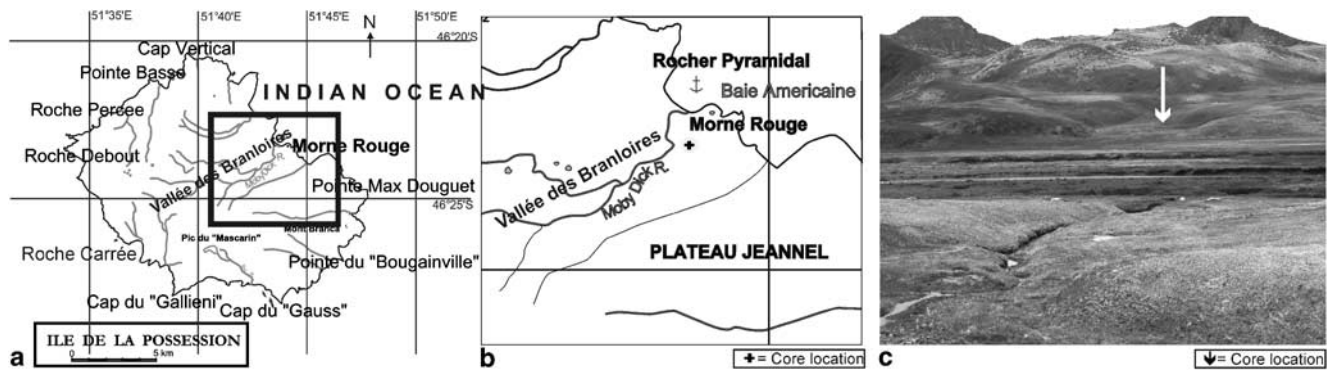


Fig. 1. a. Map of Ile de la Possession with b. detail of the coring location, and c. a site photograph.

islands (records from the east coast of Ile de la Possession) (Frenot 1986). Ile de la Possession is the largest island (146 km²) of the Iles Crozet (Fig. 1a). Its last volcanic phase (Phase V) occurred during the past 10 000 ¹⁴C yr BP (Giret *et al.* 2003, Van der Putten *et al.* 2008) forming several cones on the island such as Morne Rouge (116 m), Mont Branca (383 m) and Mont des Cratères (700 m).

The eastern part of the island is characterized by several larger valleys, probably of glacial origin (such as Vallée des Branloires, Vallée de la Hébé, Baie du Petit Caporal), intercepted by plateaus with steep slopes. In contrast, the western part of Ile de la Possession has a totally different topography with mountain ranging up to 934 m altitude (Frenot 1986).

The vegetation consists of 22 vascular plants (Frenot 1986) including four ferns and two *Lycopodium* species. Apart from this native flora, more than 60 introduced species have been recorded on the island (Frenot *et al.* 2001), most of them only near the permanent base Alfred Faure and several cabins on the island. Furthermore, more than 100 bryophyte species have been observed although *Sphagnum* species are completely absent (Van de Vijver *et al.* 2002). The climatic conditions favour extensive peat formation at low altitudes.

Material and methods

Coring

During the summer of 2004–05, a 203 cm long sediment core was sampled on the south-western slope of the Morne Rouge volcano located at the end of the Vallée des Branloires, close to the Indian Ocean (Frenot 1986). The volcano (max. altitude 116 m) is characterized by steep cliffs bordering the ocean and a gentle slope towards the Vallée des Branloires. The latter slope is composed of several depressions and ridges. The coring site (46°23'35.45"S–51°48'28.85"E) (Fig. 1b) was chosen in one of these small, slightly elevated side depressions at an altitude of 12 m since the latter was probably created following the volcanic eruption and thus most probably would contain evidence of this eruption. The depression is formed by

a 10 m wide, 150 m long and very gentle slope down valley in a NNW–SE direction. It is bordered by relatively high, vegetated ridges. The depression was vegetated with semi-wet tundra dominated by *Sanionia uncinata* (Hedw.) Loeske and *Agrostis magellanica* Lam. (Vincke 2006). The sediment core was sampled by pushing a 10 cm diameter PVC tube into the soil. The resulting core was subdivided into three sections for shipping. In the laboratory, these sections were split lengthwise followed by a description of the core lithostratigraphy. One-half of the core was sliced into 1 cm thick samples. Every three slices a sample was selected, resulting in a total of 73 samples available to be processed for diatom, bulk density and Loss-on-Ignition analyses.

Radiometric dating

Ten samples for AMS ¹⁴C dating were taken near stratigraphical boundaries. The ¹⁴C analysis was done by the Royal Institute for the study and conservation of Belgium's Artistic Heritage (KIKIRPA) in Brussels. Calibration of the radiocarbon dates was performed using Oxcal v4.1.7 (Bronk-Ramsey 2009) and the Southern Hemisphere Atmospheric Data (McCormac *et al.* 2004). The methods for the radiocarbon dating were explained in Van der Putten *et al.* (2004).

Bulk density and Loss-On-Ignition (LOI)

Seventy-one samples were selected for bulk density analysis, but only 52 were actually analysed due to the difficulty of taking samples of a fixed volume from a stony layer and problems of getting samples of wet fibrous peat that compacted during sampling.

Samples for bulk density analysis and Loss-On-Ignition were taken with a corer of 0.5 cm³ and treated following Last & Smol (2001).

Diatom analysis

Diatoms are one of the most abundant algal groups in the Antarctic Region, both in number of species and individuals.

Table I. Results of the radiometric dating. Bulk sediments were used for the radiometric analyses.

Code	Depth below surface (cm)	Radiocarbon date yr BP	Calibrated date yr BP	Mean calibrated date yr BP
KIA-31345	44	240 ± 45	1σ 148–219 2σ 135–324	184
KIA-31347	83	680 ± 25	1σ 561–605 2σ 558–654	583
KIA-31348	133	1470 ± 40	1σ 1293–1345 2σ 1277–1390	1319
KIA-31346	141	1270 ± 30	1σ 1078–1175 2σ 1059–1187	1127
KIA-31332	152	2980 ± 30	1σ 3002–3084 2σ 2961–3210	3043
KIA-31356	159	4265 ± 35	1σ 4702–4760 2σ 4616–4767	4731
KIA-31361	168	5840 ± 40	1σ 6533–6652 2σ 6467–6678	6593
KIA-31330	190	5965 ± 40	1σ 6673–6757 2σ 6638–6859	6715
KIA-31355	197	6110 ± 40	1σ 6849–6972 2σ 6779–7020	6911

Compared to the diatom flora on larger landmasses, the non-marine diatom composition on Ile de la Possession is rather species-poor with less than 250 species known (Van de Vijver *et al.* 2002). Nevertheless, they have been found in almost all habitat types present on the island. Specialized diatom species that are able to tolerate different extreme environmental conditions (e.g. drought, limited nutrient levels, pH changes), allow this group to be excellent indicators of palaeo-environmental changes and, because of their silica exoskeleton, they are usually well-preserved in sediment and peat records (Stoermer & Smol 1999).

Seventy-three samples were processed for diatom analysis. The samples were dried in an oven at 36°C for 24 h. Approximately 0.5 g of dried material of each sample was subsequently prepared following Van der Werff (1955). *Lycopodium* spores (Stockmarr 1971) were added to estimate total diatom concentration expressed as valves per gramme dry sediment (VGS). Cleaned diatom valves were mounted in Naphrax[®]. In each sample a total of 500 diatom valves were counted on random transects using an Olympus BX 51 microscope equipped with Differential Interference Contrast optics (DIC-Nomarski). Broken valves and fragments were counted following the methods described in Beyens & Denys (1982).

Correspondence Analysis (CA) was used to explore patterns in the data. The resulting ordinations were used to define zones in the sediment core on the basis of changes in their diatom species assemblages. Only species occurring with an abundance of 1% in at least two samples were used in the study. Statistical analysis was performed using CANOCO

version 4.0 (ter Braak & Šmilauer 1998). Multivariate techniques worked with in this study are described in Jongman *et al.* (1995). Shannon-Wiener diversity (log-based) was calculated in R2.10.1 (R Development Core Team 2009).

The environmental reconstruction relied partly on previously developed transfer functions based on existing knowledge of the modern ecology of diatoms on Ile de la Possession and its neighbouring islands in the southern Indian Ocean in relation to soil moisture (Van de Vijver & Beyens 1999) and temperature (Gremmen *et al.* 2007).

The moisture scale of Jung (1936) was used. This is an eight-point exponential moisture scale ranging from I (submerged) to VIII (completely dry), used to determine the moisture content of mosses. Although this moisture scale was qualitative, these moisture classes have been related to percentage moisture equivalents (Meisterfeld 1977). A transfer function for altitude, convertible into temperature, was developed in Gremmen *et al.* (2007) using the following formula: temperature = 8.263 – 0.0082*altitude.

Results

Radiometric dating

The results of the ¹⁴C dating showed an almost undisturbed stratigraphical sequence (Table I). One inversion occurred at 141 cm depth (1270 ± 30 ¹⁴C yr BP); probably due to insufficient carbon in sample 133 (1470 ± 40 ¹⁴C yr BP) (Mark van Strydonck, personal communication 2010). So this sample was not used in further analyses. The sedimentation

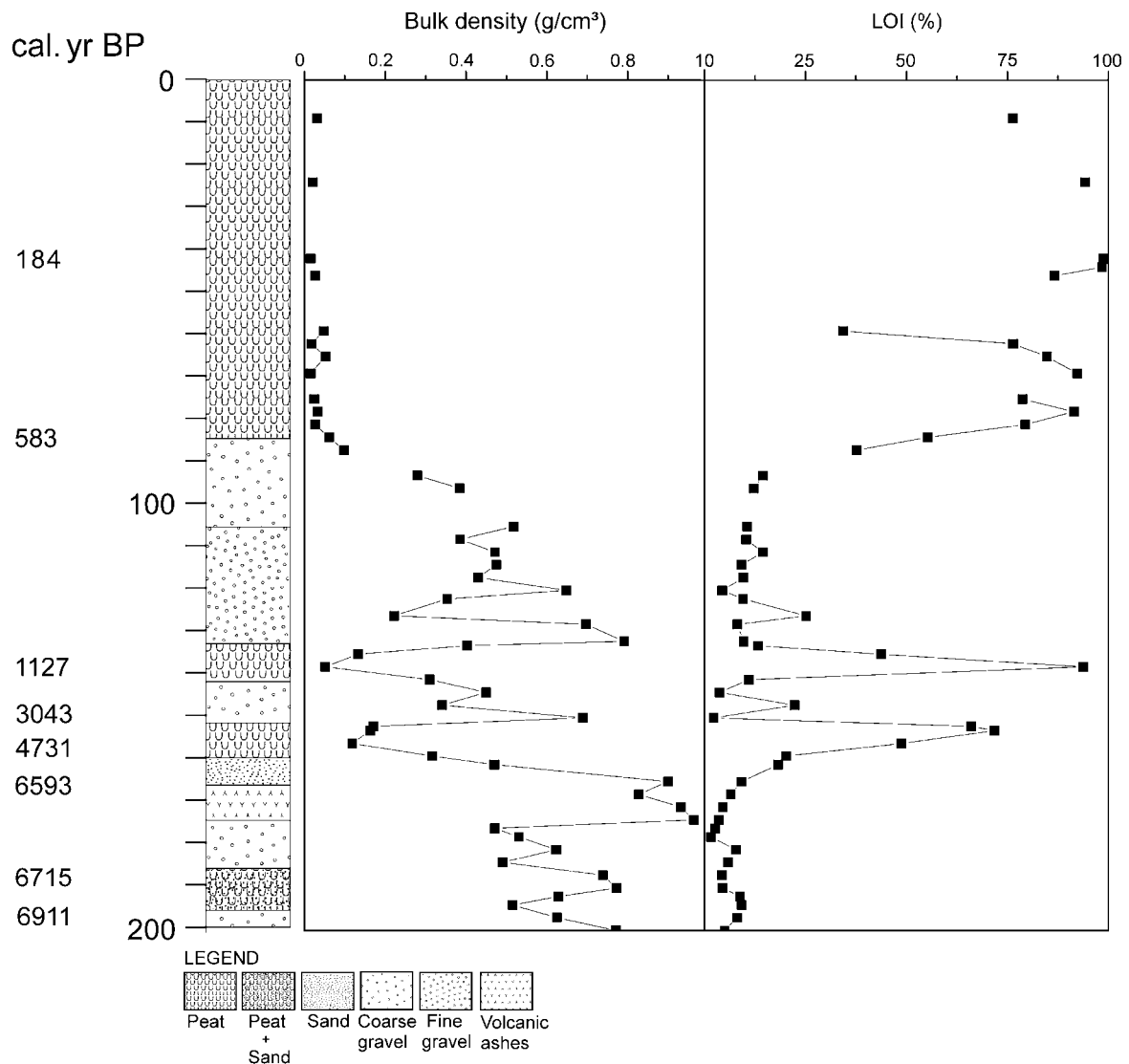


Fig. 2. Results of the different lithostratigraphical analyses. Showing (from left to right) the radiocarbon dating, sediment stratigraphy, bulk density and Loss-on-Ignition values.

rate was not uniformly changing from 0.006 cm yr^{-1} between $5840 \pm 40 \text{ }^{14}\text{C yr BP}$ and $1270 \pm 30 \text{ }^{14}\text{C yr BP}$ and one of 0.1 cm yr^{-1} over the last $1270 \pm 30 \text{ }^{14}\text{C yr BP}$.

Lithostratigraphic analysis

The deepest part of the core was made up of a coarse gravel and sandy peat layer with very little organic matter ($\pm 6.5\%$) (Fig. 2). A 7 cm thick layer of very fine-grained black tephra (volcanic ashes) was found between 174–166 cm and had the highest bulk density (max. 0.9 g cm^{-3}). Two very small organic peat layers (160–153 cm and 143–134 cm), separated by inorganic layers of sand and coarser gravel, were recognized from their high organic matter content of 75% and 90% respectively. A thick layer of gravel (134–85 cm) was subdivided into a fine-grained lower part (134–105 cm) and a

coarser fraction above (105–85 cm). The uppermost 85 cm of the core consisted almost entirely of homogenous peat containing a large amount of non-decomposed plant litter (mainly grasses and bryophytes) with an organic matter content of 80–90% and a bulk density of $0.01\text{--}0.05 \text{ g cm}^{-3}$.

Diatom record

In 67 of the 71 samples counted, an abundant and well-preserved diatom flora was found. Four samples yielded insufficient diatoms (at depths of 200 cm and 174–168 cm) for counting. In total, 175 different taxa (including species, varieties and forms), belonging to 74 genera were observed. Although most taxa were considered to be typical freshwater taxa, 47 taxa (representing 12 genera) were identified as marine species.

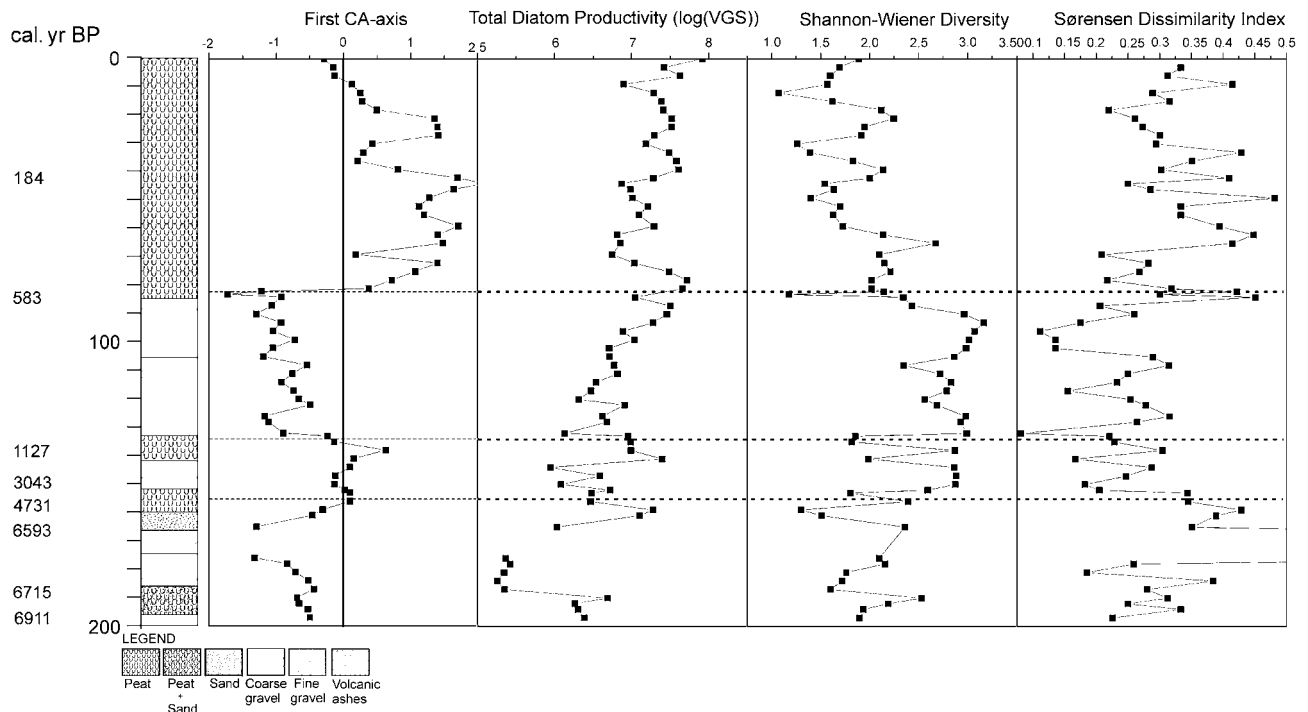


Fig. 4. Results of the Correspondence Analysis (CA), Total Diatom Productivity, Shannon Wiener Diversity and Sørensen Dissimilarity Index. The dotted lines indicate the four MRDZ.

The results of the first CA-axis suggested that the core could be subdivided into four distinct diatom zones (Morne Rouge Diatom Zones, MRDZ) (Figs 3 & 4).

MRDZ 1 (203–156 cm, *c.* 6900–4731 cal. yr BP) was characterized by high abundances of *Diadesmis ingeae* Van de Vijver (7–71%), *Eunotia paludosa* Grunow var. *paludosa* (1–20%), *Pinnularia pisciculus* Ehrenberg sensu Van de Vijver *et al.* (2002a) (0–15%), *P. borealis* var. *scalaris* (Ehrenberg) Rabenhorst (0–13%) and *Psammothidium germainii* (Manguin) Sabbe (0–5%). Several other taxa played a minor role such as *Psammothidium investians* (Carter) Bukhtiyarova (0–6%), *Pinnularia cf. divergentissima* Grunow (0–11%) and *P. obscura* Krasske (0–36%). At 175 cm, the proportion of marine taxa increased dramatically to almost 37%. No diatoms were present in the tephra layer between 174 and 166 cm. Immediately after this tephra layer, *Pinnularia obscura* occurred at its highest abundance (36%). Both Total Diatom Productivity (TDP) (min. 5.25 log(VGS)) and Sørensen Dissimilarity Index (SDI) (min. 0.18) increased above the tephra layer (TDP max. 7.27 log(VGS); SDI max. 0.43), while Shannon diversity values declined from 2.5 to 1.3 (mean 2.25). The reconstructed moisture values indicated a moist (*F*-value 4.75) to relatively dry environment (*F*-value 7.41) while the reconstructed temperature pointed towards a rather cold environment (mean 5.9°C) (Fig. 5).

MRDZ 2 (156–134 cm, *c.* 4731–1127 cal. yr BP) had a high taxon diversity. *Diadesmis ingeae* dominated still (15–61%)

while the other taxa of MRDZ1 gradually disappeared. *Chamaepinnularia australomediocris* (Lange-Bertalot & Schmidt) Van de Vijver (1–11%) and *Adlafia bryophila* (Petersen) Lange-Bertalot (0–5%) were subdominant. Several species such as *Frankophila maillardii* (Le Cohu) Lange-Bertalot (0–10%), *Planothidium lanceolatum* (Brébisson) Lange-Bertalot (2–12%), *Pinnularia angliciformis* Van de Vijver & Beyens (0–11%) and *Pinnularia carteri* Krammer (0–10%) were present for the first time (Fig. 3). Compared to the previous zone, TDP and Shannon-Wiener diversity tended to be higher (mean TDP MRDZ 1: 6.1 log (VGS) vs mean TDP MRDZ2: 6.63 log (VGS); Shannon-Wiener diversity: mean 2.35) (Fig. 4). The SDI decreased (mean MRDZ1 0.43 vs mean MRDZ2 0.26). The reconstructed temperature was slightly lower (mean 5.5°C) and the environment became more humid (*F*-value 4.72) (Fig. 5).

In MRDZ 3 (134–83 cm, *c.* 1127–583 cal. yr BP) *Diadesmis ingeae* remained consistently present in high abundances (1–61%), while the composition differed from the previous zone by the occurrence of *Psammothidium investians* (0.2–10%), *P. germainii* (0–5%), *Pinnularia cf. divergentissima* (1–8%) and *Chamaepinnularia australomediocris* (0–10%). Towards the end of this zone, *Sellaphora seminulum* (Grunow) Mann (1–42%) became more important (Fig. 3). Total diatom productivity (ranging from 6.12 to 7.5) gradually increased towards the end of this zone. Both species diversity and SDI, followed the same trend as in MRDZ 2, respectively increasing

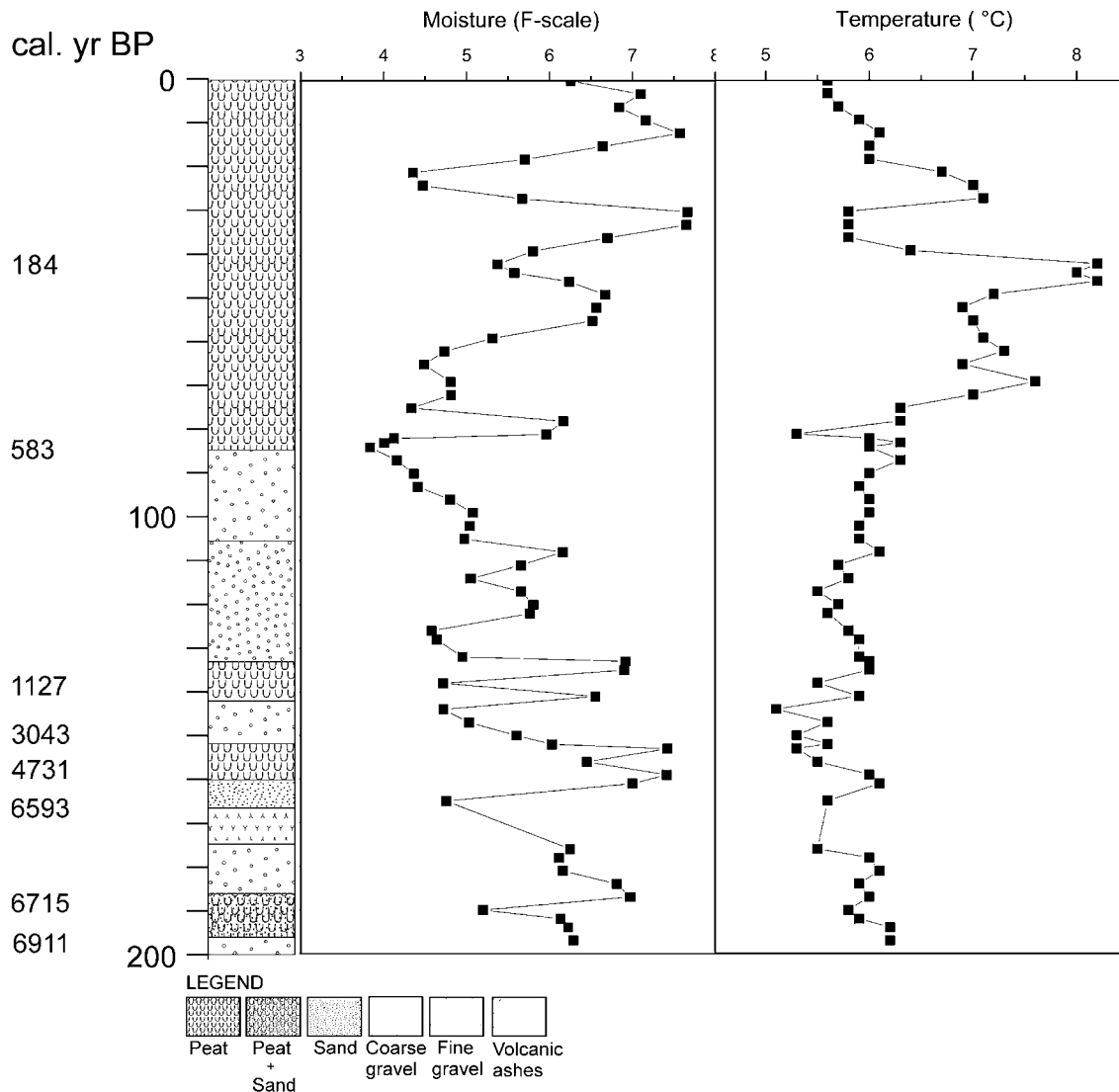


Fig. 5. Reconstructions of temperature and humidity. The dotted lines indicate the four MRDZ.

(mean 2.76) and decreasing (mean 0.24) (Fig. 4). The moisture level reached its lowest values (F -value 3.8) while the reconstructed temperature slightly increased (mean 5.9°C) pointing to slightly warmer, wetter conditions (Fig. 5).

The base of the fourth zone, MRDZ 4 (83–0 cm, *c.* 583 cal. yr BP to present), was characterized by high abundances of *Sellaphora seminulum* (68%), *Pinnularia angliciformis* (10%), *Frankophila maillardii* (20%) and *Pinnularia acidicola* Van de Vijver & Le Cohu (20%). The proportion of *Diademesma ingeae* (0.2%) decreased significantly at the beginning of this zone but returned to higher values (65%) after the decline of the above-mentioned taxa. Around 76 cm, the diatom composition changed markedly. Taxa such as *Pinnularia subantarctica* var. *elongata* (Manguin) Van de Vijver & Le Cohu (1–53%), *P. carteri* (0–20%), *P. crozetii* Van de Vijver & Le Cohu (0–35%), *Stauroneis kriegei* Patrick (0–6%)

and *Gomphonema subantarcticum* Van de Vijver & Beyens (0–17%) replaced all taxa from the previous zone. *Planothidium lanceolatum* showed two isolated peaks, one at a depth of 75 cm (35%) and another one at a depth of 24 cm (39%) (Fig. 3). The TDP remained at the high level (mean 7.3 log (VGS)) reached at the end of the previous zone (Fig. 4). Shannon-Wiener diversity values were the lowest in this zone (mean 1.8) and SDI raised again (mean 0.32). Both reconstructed moisture and temperature showed a fluctuating pattern (Fig. 5). The first part of this zone was characterized by wetter, warmer conditions. Near the middle of this zone, the moisture started to decrease as expressed by higher F -values (F -value max. 7.7) whereas the reconstructed temperature reached its highest values (8.2°C). Towards the end of this zone, values approached currently prevailing conditions.

Discussion

The reconstruction of the palaeo-events at the coring site reveals several environmental changes that are on one hand strongly impacted by multiple local influences and on the other hand might reflect regional climatic changes. The results could only be compared with three previous studies from the Iles Crozet. The diatom-based reconstruction of the peat cores reported in Van de Vijver (1999) are based on a non-revised taxonomy (prior to 2000) making that comparison with later studies can only be based on the interpretation. The oldest parts in Vincke (2006), analysed in a core taken at 500 m southwards from the Morne Rouge volcano, spanning from 8400 ¹⁴C yr BP to around 5400 ¹⁴C yr BP. Although a tephra layer was not reported, a recent reanalysis of the core indicated a small (5 mm wide) tephra layer (Van de Vijver, personal observation). The core analysed in Van der Putten *et al.* (2008), was taken in the centre of the Morne Rouge crater spanning about 6400 cal. yr BP. On the nearby Iles Kerguelen, Frenot *et al.* (1997) reported several climatic changes as indicated by the retreat of a glacier on the island.

Based on the obtained results and a comparison with the regional studies, the main features of our palaeoenvironmental reconstruction are described below.

Morne Rouge volcano eruption

The oldest records in the Morne Rouge sediment core (c. 6900 cal. yr BP) point to the presence of a rather acid, dry environment dominated by a dry moss tundra, presenting similar conditions to the present situation at Vallée des Branloires. The dominance of taxa such as *Diadsmis ingeae*, *Eunotia paludosa* var. *paludosa*, *Pinnularia pisciculus*, *Pinnularia borealis* var. *scalaris* and *Psammothidium germainii* clearly confirm this observation (Van de Vijver *et al.* 2002). The short appearance of *Adlafia bryophila* and *Chamaepinnularia australomediocris*, both favouring semi-wet, nutrient-poor conditions, is probably the result of the inflow of hillslope material onto the coring site, as is also confirmed by a higher amount of coarse gravel in the core.

The sudden increase in the relative abundance of marine valves, right before the occurrence of a 7 cm thick tephra layer, indicates the beginning of a dramatic event that took place at the coring site. Dominant genera include *Cocconeis*, *Fragilariopsis* and *Thalassiosira*. While the first is a typical epiphytic genus, the latter two are known for their pelagic life form within the Polar Front Zone (Medlin & Priddle 1990, Crosta *et al.* 2005). Considering the large diversity of marine taxa (47 out of 175), the high proportion present during only a very short period, the good preservation of the valves and the almost complete absence of marine valves in the rest of the core, passive wind-driven transport should be excluded. More probably, the presence of the tephra layer, points to a sudden subaqueous volcanic eruption (Gerald Ernst, personal communication 2010) of the Morne Rouge volcano between

6715 ± 42 and 6593 ± 60 cal. yr BP. Our interpretation is that the volcanic eruption caused a sudden flooding of the coring area by seawater. It is well known that eruptions of subaqueous volcanoes can generate tsunami waves (Egorov 2007) and at the relatively low altitude of the coring site on the Morne Rouge volcano (12 m a.s.l.) the link to such a tsunami wave is highly likely. Then, the homogeneous tephra layer was probably deposited during a single eruption, as no diatom remains were found (depths 168, 171, 174 cm). Giret *et al.* (2003) and Van der Putten *et al.* (2008) stated that the last (Strombolian) volcanic phase (phase V) on Ile de la Possession (including the formation of Morne Rouge, Mont Branca and Mont des Cratères) took place between 10 000 and 5800 ¹⁴C yr BP. Our data now constrain the Morne Rouge volcanic eruption to the period c. 6700–6600 cal. yr BP. The palaeo-reconstruction in Van der Putten *et al.* (2008), based on three cores taken in the lake located in the crater, starts at 6485 cal. yr BP, and corresponds to the end of the volcanic eruption, as inferred from our data. Based on the presence of the tephra layer, the absence of raised beaches (Van de Vijver, personal observation) in the area and the absence of evidence in the diatom data for a more long-lasting marine event at the coring site, a relative sea level change at that period can be excluded. Moreover, data from other Antarctic localities place relative sea level rises much earlier in time (Verleyen *et al.* 2005).

Mid-Holocene cooling event

After the volcanic eruption, sedimentation rates declined and less than 30 cm was deposited over more than 4000 years. The tephra was rapidly colonized by *Pinnularia obscura*, a pioneer species (Krammer 2000). Several diatom species, present before the volcanic eruption, reappeared at the coring site, indicating a gradual re-establishment of the dry moss tundra. The overall dominance of *Diadsmis ingeae* (up to 70%), typical for very dry, terrestrial circumstances (Van de Vijver *et al.* 2002) and the lack of a high sedimentation rate is interpreted as the result of a dry, cooler, less productive period. This finding is consistent with some studies, based on both marine and terrestrial evidence, which suggest that there was a cooling in the Southern Hemisphere between 6000 and 3000 cal. yr BP. For example, in the terrestrial record of Van der Putten *et al.* (2008) a period of lower biological production is observed, similar to our results, pointing towards a colder (and/or wetter) climate from c. 5560 cal. yr BP. Two terrestrial studies from the neighbouring Iles Kerguelen show evidence for a colder period (Bellair-Roche 1976a, Young & Schofield 1973) whereas on the sub-Antarctic Campbell Island (located between New Zealand and the Antarctic Continent) a cool period was recorded based on pollen data (McGlone *et al.* 2010). Nielsen *et al.* (2004) concluded from the analysis of their Holocene marine cores in the South Atlantic sector of the Southern Ocean, that a cooler period occurred between 6000 and 3000 cal. yr BP.

Late Holocene warm period

Around 3050 cal. yr BP, the increase in diatom diversity caused by a sudden appearance of a high number of taxa indicates a major shift in environmental conditions, probably caused by changing climatic circumstances. The diatom record points to wetter and even warmer conditions, as taxa such as *Chamaepinnularia australomediocris*, *Frankophila maillardii*, *Adlafia bryophila* and *Planothidium lanceolatum* (Van de Vijver *et al.* 2002, Gremmen *et al.* 2007) start to dominate the flora. The occurrence of several zones of gravel and fine-grained material, resulting in a sudden decrease of organic matter and an increase of bulk density may be the result of wetter and/or windier climatic conditions at the island. Van der Putten *et al.* (2008) found a similar signal with wetter conditions around the same time in the Morne Rouge lake sediments although they related these conditions more to an intensification of the Southern westerlies and less to a more global warming. Evidence of a warmer period between 2400–2190 ^{14}C yr BP was also found in Van de Vijver (1999). The short but distinct occurrences of *Fragilaria* s.l. and *Frankophila maillardii*, known to prefer almost exclusively lotic conditions on the sub-Antarctic islands (Van de Vijver & Beyens 1999, Van de Vijver *et al.* 2001) supports the hypothesis of temporary increased erosion and slow run-off towards the coring site. These results may correspond to a more general late Holocene climatic optimum, reported from several locations in the sub-Antarctic region. On nearby Kerguelen, glaciers retreated between 2400 and 1000 cal. yr BP, probably indicating a warming period (Frenot *et al.* 1997). McGlone *et al.* (2010) found a similar warming trend from c. 1700–700 cal. yr BP on Campbell Island. In the Antarctic Peninsula Region, Jones *et al.* (2000) and Hodgson & Convey (2005) described a warmer, more productive period based on pollen and diatom results lasting until c. 1400 cal. yr BP followed by a cooling event. Many studies from the Antarctic Continent report the occurrence of a warmer period between 4000 and 2000 cal. yr BP inferred from various ice, marine and lake cores but a distinct neoglacial cooling starting around 2000 cal. yr BP (Verleyen *et al.* 2010).

Past 600 years

Around 600 cal. yr BP, *D. ingeae* gradually disappears and the subsequent dominance of *Sellaphora seminulum*, *Pinnularia angliciformis*, *P. acidicola* and *Psammothidium investians* points to the presence of wet soil with an increase in nutrients. It is, however, not entirely clear whether this increase is the result of a climatic change followed by a higher productivity or the result of an increased input of nutrients by marine mammals and/or birds. In elephant seal wallow areas, several of these species dominate the diatom flora (Van de Vijver *et al.* 2002). Elephant seals can nowadays still be found on the small plateaus on the Morne Rouge slopes during their moulting period and their influence of the soil is very distinct (Van de Vijver, personal observation). Analysis of peat cores taken in

the southern part of the Vallée des Branloires where elephant seals are absent, might clarify this problem (Van de Vijver, unpublished results). The marked increase of *S. seminulum* in combination with an almost complete absence of more terrestrial species such as *D. ingeae*, *P. obscura* and the different *Psammothidium* species near the end of this period reflects much wetter conditions that abruptly come to an end.

During the last 400 cal. yr BP, the diatom evidence probably reflects very local biotic influence, obscuring the climatic signal. Moravcová *et al.* (2009) found a comparable diatom composition near occupied wandering albatross (*Diomedea exulans*) nests at different nesting sites on Ile de la Possession. It is possible that the coring site was used by one or more wandering albatross pairs as a nesting ground, altering significantly the environmental conditions at this site. Nowadays, several nests of wandering albatrosses are still present on the slopes of the Morne Rouge (Van de Vijver, personal observation) but there is no visual evidence of large ancient albatross nesting grounds on the site making it very likely that the influence was limited to the proximity of a single nesting pair that did not continuously impact the site since the taxa preferring higher nutrient conditions, such as *Pinnularia subantarctica* var. *elongata*, *Pinnularia carteri*, *Stauroneis kriegeri* and *Gomphonema subantarcticum*, alternate with *D. ingeae*, known to avoid enriched soils (Moravcová *et al.* 2009). The biotic influence by other animals can be excluded. Although *Planothidium lanceolatum* was often found in soils near penguin rookeries, the topography of the site does not support the presence of large numbers of penguins since they use bare ground, sandy beaches or rocky slopes to incubate their eggs (Boersma 2008). The very low number of *P. angliciformis* typically present in elephant seal wallows and the absence of other typical wallow species such as *Sellaphora seminulum* and *Staurosirella pinnata* (Ehrenberg) Williams & Round (Van de Vijver *et al.* 2002), do not indicate large elephant seal numbers.

Around 100 cal. yr BP ago, the importance of the nutrient-rich diatom community declined with many species disappearing being replaced by more aerophilic, oligotrophic species reflecting the present-day diatom community typical for dry, peaty valley slopes in the Vallée des Branloires.

Conclusion

The present study reconstructed several major environmental changes on Ile de la Possession during the past 7000 years. A tephra layer, containing no diatoms, constrains the eruption of the Morne Rouge volcano between 6700–6600 cal. yr BP. The presence of a marine diatom rich layer just below the tephra is interpreted as a marine flooding event associated with the volcanic eruption. Sediments on top of the tephra layer indicate a gradual recolonization signal by terrestrial diatoms.

Using transfer functions for temperature and moisture, evidence is presented of the late climatic optimum

around 3050 cal. yr BP, preceded by a cooling event until 6600 cal. yr BP. The reconstruction of the past 600 cal. yr BP has been obscured by an increased biotic impact of both elephant seals and wandering albatrosses.

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