A palaeoenvironmental study of a peat sequence from Iles Kerguelen (49°S, Indian Ocean) for the Last Deglaciation based on pollen analysis

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Cover Picture: Cyriel Verbruggen walking towards P12. Photo: Nathalie Van der Putten.

Abstract

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Abstract: In recent years, the Southern Hemisphere (SH) and the vast Southern Ocean (SO) have gained awareness and importance within the scientific community in relation to global climate change and the global CO_2 cycle, particularly since the Last Glacial Maximum (LGM) and into the Holocene. It is believed that the Southern Hemisphere Westerlies (SHW) play a key role in regulating climate change in the mid-to-high latitudes of the SH, thus reconstructing the SHW latitudinal positioning since the LGM has been crucial. However, terrestrial records of the mid-to-high latitudes are sparse. Most of the evidence is generally constrained to southern South America and New Zealand, and at times reveals contradictory results. Scientists have been trying to obtain a clearer picture of shifts in the SHW in the mid-to-high latitudes through analyzing terrestrial records from the island groups that make up the sub-Antarctic region. Here, a c.14000 cal yr BP terrestrial record from Port Douzieme (P12) at Iles Kerguelen (49°S) is analyzed using a multi-proxy approach (lithostratigraphy, magnetic susceptibility, loss on ignition, and pollen). The P12 record reveals clear changes since c.14000 cal yr BP, at which time a sparsely vegetated environment existed, dominated by grasses (Poaceae). Then, the wind tolerant, cushion plant *Azorella selago* became a much more influential species by c.13600, coinciding with the presence of lacustrine-type-sediments, suggesting windier and wetter conditions. By c.12900 cal yr BP the lowland species *Acaena magellanica* suddenly expanded, becoming the dominant species and coinciding with the end of the Antarctic Cold Reversal (ACR). Finally, at c.11200 cal yr BP the species *Uncinia compacta* and *Blechnum penna-marina* appear in the pollen record, suggesting much warmer conditions on the Kerguelen archipelago. The record from P12 was compared with a previous study done by Van der Putten et al. (submitted) at the Estacade site in the Kerguelen archipelago, approximately 50 km northeast of the P12 site. The pollen record from the Estacade site shows a similar vegetation history as the record from P12 for the Kerguelen archipelago. At the Estacade site, Poaceae is prominent between c.16000-13650 cal yr BP, followed by a period of dominance by the wind tolerant species *Azorella selago* and *Lyallia kerguelensis* at 13650 cal yr BP. At around 11200 cal yr BP the lowland species *Acaena magellanica* and *Uncinia compacta* expanded. Additionally, the pollen record from P12 reveals a higher influence of the SHW at about 13600 cal yr BP, when a great diversity in long distance pollen grains is recorded, coinciding with the expansion of the wind tolerant species *Azorella selago*, as well as the presence of lacustrine-type-sediments at both the Estacade site and P12.

Keywords: Antarctic Cold Reversal, Southern Hemisphere Westerlies, sub-Antarctic, Iles Kerguelen, pollen.

Supervisor(s): Nathalie Van der Putten, Mats Rundgren, Svante Björck and Cyriel Verbruggen (Gent University, Belgium)

Subject: Quaternary Geology

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Svensk abstracttitel

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Sammanfattning: Under de senaste åren har södra halvklotet och den vidsträckta Södra oceanen fått ökad uppmärksamhet och betydelse inom det vetenskapliga samfundet med avseende på globala klimatförändringar och den globala CO_2-cykeln, särskilt vad gäller förhållandena under senaste istidsmaximum (*Last Glacial Maximum*, LGM) och holocen. Man menar att Västvindbältet på södra halvklotet (*Southern Hemisphere Westerlies*, SHW) spelar en viktig roll i regleringen av klimatförändringar på mellan- och höga breddgrader på SH. Därmed har det varit av avgörande betydelse att rekonstruera det latitudinella läget av SHW sedan LGM, men kontinentala klimatarkiv från mellan- och höga breddgrader är sällsynta. Merparten av data begränsas till södra Sydamerika och Nya Zeeland, och dessa ger ibland motsägelsefulla resultat. Forskare har försökt att få en tydligare bild av förändringarna av SHW på mellan- och höga breddgrader genom att analysera kontinentala arkiv från de ögrupper som utgör den Subantarktiska regionen. Här presenteras resultaten från en multi-proxy-undersökning (litostratigrafi, magnetisk susceptibilitet, glödförlust, och pollen) av en ca 14000 år gammal kontinental lagerföljd från Port Douzieme (P12) på Kerguelen-öarna (49 °S). Dessa visar på tydliga förändringar sedan ca 14000 cal yr BP, då området kännetecknades av ett glest vegetationstäcke dominerat av gräs (Poaceae). Betydelsen av den vindtoleranta, kuddformiga växten *Azorella selago* ökade för ca 13600 år sedan samtidigt som vattenavsatta sediment börjar uppträda, vilket tyder på blåsigare och blötare förhållanden. Omkring 12900 cal yr BP expanderade plötsligt *Acaena magellanica* som idag förekommer i öns låglandsområden, och denna art blev därefter dominerande. Förändringen sammanfaller med slutet av Antarctic Cold Reversal (ACR). Slutligen, vid ca 11200 cal yr BP uppträder arterna *Uncinia compacta* och *Blechnum penna-marina* för första gången i pollendata, vilket tyder på betydligt varmare förhållanden i Kerguelen-arkipelagen. Resultaten från P12 jämfördes med en tidigare studie utförd av Van der Putten (*submitted*) på lokalen Estacade i Kerguelen-arkipelagen, ca 50 km nordost om P12. Den vegetationshistoria som pollenanalysen från Estacade visar för Kerguelen-arkipelagen liknar den som ses i data från P12. På Estacade-lokalen är Poaceae framträdande mellan ca 16000 och 13650 cal yr BP, följt av en period med dominans av de vindtoleranta arterna *Azorella selago* och *Lyallia kerguelensis* ca 13650 cal yr BP. Omkring 11200 cal yr BP expanderade låglandsarterna *Acaena magellanica* och *Uncinia compacta*. Pollenanalysen av P12 visar därutöver en ökad påverkan av SHW från ca 13600 cal yr BP, då ett stort antal pollentyper transporterade över stora avstånd påträffas, vilket sammanfaller med expansionen av den vindtoleranta arten *Azorella selago* samt förekomsten av vattenavsatta sediment både vid Estacade och P12.

Nyckelord: pollen, Södra oceanen , Iles Kerguelen, Southern Hemisphere Westerlies, Subantarktiska regionen.

Handledare: Nathalie Van der Putten, Mats Rundgren, Svante Björck and Cyriel Verbruggen (Gent University, Belgium)

Ämnesinriktning: Kvartärgeologi.

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1 Introduction

The last two hundred and fifty years have been characterized by the dramatic increase of greenhouse gases due to the industrial capabilities and economic ambitions of humans. The continued input of greenhouse gases into the atmosphere, has led mankind to a turning point in both its existence and intellectual capabilities to resolve what may be the biggest threat to the human race, i.e. climate change.

Recently, the topic of climate change has acquired large momentum both in the scientific community and among society. The on-going man-induced climate change is likely to affect sensitive ecosystems such as the Arctic and coral reefs, as well as, disrupt the global economy and world peace due to a shortage of goods and extreme weather events (IPCC, 2014). It is therefore, important to understand key mechanisms behind this on-going phenomenon. It is specifically important to estimate what effects will be derived by the ongoing global warming on sensitive ecosystems, such as the Arctic and the Antarctic, and how will the disruption of these regions exert alterations on the world's oceans, the atmospheric circulation, and bio-diversity. One way to predict possible scenarios related to climate change in the future is to look back in time. For example, the fossil record can be a reliable source of information to deduce paleoecological and paleoenvironmental changes in response to climate change. These natural archives can yield information about mass migration or the favoring of a species in a certain ecological niche due to climate disruptions (Willis et al, 2010).

It is for this reason that research in these sensitive regions (both the Arctic and the Antarctic) has intensified in the last decade. It is known that the mid-to- high latitudes of both hemispheres are important regions in terms of the global climate system, and its feedback mechanisms, relating to the waxing and waning of ice sheets, changes in deep water formation and oceanic fronts to name a few. However, data from these key latitudes in the Southern Hemisphere (SH) are still scarce in comparison with the amount of available data in the Northern Hemisphere (NH), partly due to the lack of land at the Southern mid-high latitudes (Fig. 1).

Recent studies have indicated, mainly based on ice core records from Greenland and Antarctica, an asynchronous evolution of temperature between the two hemispheres during the last ice age and the glacial-interglacial transition. Evidence from the Greenland ice core records revealed that the NH suddenly plunged back to cold conditions during an event known as the Younger Dryas (YD)12900-11700 cal yr BP. The latter followed an abrupt warming event known as Bolling/Allerod interstadial 14700-12900 cal yr BP (e.g. Lowe et al., 2008). However, evidence from the SH ice core records revealed that during this time period, the temperature changes over Antarctica were more gradual and anti-phased in comparison with the NH. For example, while the North Atlantic region was experiencing cold conditions during YD, the Antarctic continent was warming. This mechanism is referred to as the 'Bipolar See-Saw' (e.g. Broecker, 1998; Stenni et al., 2011). However, not all ice core records show this asynchronous climatic behavior. An ice core record retrieved from the Taylor Dome, in the Ross Sea sector of Antarctica revealed temperature changes that were in phase with the temperature changes in the NH during the last glacial-interglacial transition (Steig et al., 1998), but the integrity of this hypothesis has been questioned by Stenni et al. (2011) due to errors in the chronology of the Taylor Dome ice core. However, overall most records in the SH show a distinct anti-phased pattern between the NH and the SH (e.g. Anderson et al., 2009)

The consensus within the scientific community suggests that deglacial warming started in Antarctica at roughly 18350 cal yr BP, culminating in the Antarctic Isotope Maximum 1 (AM1, Stenni et al., 2011). This warming trend was followed by a return to colder conditions, which is known as the Antarctic Cold Reversal (ACR) covering the period about 14650-12900 cal yr BP (e.g. Stenni et al., 2001). At the end of the ACR, warming resumed and continued into the Holocene. Evidence obtained from the EPICA Dome C in Antarctica, based on deuterium excess revealed cooling that took place in the South Indian Ocean (moisture source area for the EPICA Dome C ice core record) (Fig.1). It was proposed to take place about

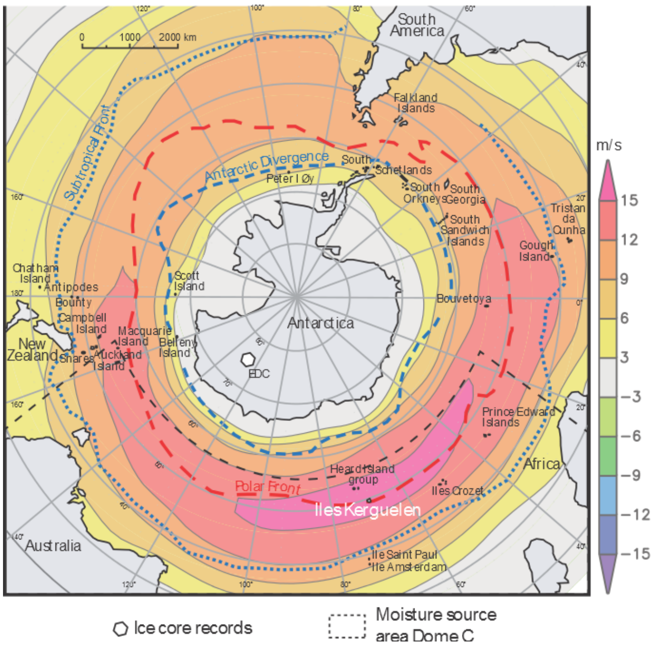


Fig. 1. Map of the Southern Hemisphere mid-to-high latitudes. Location of Iles Kerguelen marked (white bold italics). Sites and areas mentioned in text: Epica Dome C ice record (EDC), Moisture source area Dome C (dashed black lines). Oceanic fronts and mean annual zonal winds (m/s) at 850 mb averaged for the period 1979-2009 based on (NCEP CFSR). Map adapted from Van der Putten et al., (submitted)

900-800 years later than the ACR. This event is known as the Oceanic Cold Reversal (OCR) (Stenni et al., 2001). However, it is still debated whether the evidence retrieved from EPICA Dome C reflects changes in sea surface temperature at the source area, or a shift of the moisture source due to a change in atmospheric circulation (Stenni et al., 2011).

During the past few decades, there has been increasing interest to reconstruct paleoenvironmental and paleaoclimatic changes at key latitudes (mid to high latitudes) of the SH. Nevertheless, the majority of this region is governed by the extensive Southern Ocean (SO), thus limiting most of the existing terrestrial records to Southern South America and New Zealand (Fig. 1). Deep sea records are frequently used to reconstruct changes in sea surface temperature, past ocean circulation, as well as, atmospheric circulation in these regions (e.g. Anderson et al., 2009). However, deep sea records, are sometimes problematic due to their low sedimentation rates, providing low resolution records. Marine records can also be problematic when constraining an age range for a specific period, or sequence of events, as one always has to keep in mind the reservoir age of sea water, which varies regionally and also in time (Siegenthaler et al., 1980; Lougheed et al., 2013).

Researchers have been focusing on a mechanism that is believed to be a key player in the evolution of the climate in the SH, as well as its involvement in the global overturning circulation, known as the Southern Hemisphere Westerlies (SHW). The SHW are a wind belt blowing from west to east around the Antarctic continent situated between the latitudes of 30-60°S (Fig.1). This wind belt is a prominent driving force of the of the Antarctic Circumpolar Current (ACC) (Chevaillaz et al., 2013), and in consequence of the global ocean circulation, resulting in the mixing of salt and heat, and in nutrient transport around the globe (e.g. Toggweiler and Samuels, 1995). The SHW are the result of temperature gradients between the equator and the poles, and govern the mid-latitude weather and climate. The SH is characterized by the SO with little continental land mass (except for South America) resulting in a strong and nearly undisturbed SHW wind belt. Reconstructing the latitudinal position and intensity of the SHW is key in understanding the past global climate evolution. Evidence suggests that the SHW played a prominent role in driving glacial-interglacial changes, due to their involvement in the sequestration of CO_2 in the oceans and subsequent ventilation of CO_2 in to the atmosphere (e.g. Anderson et al., 2009; Toggweiler et al., 2006; Kohfeld et al., 2013). It has been postulated that the location of the SHW was different in the past in comparison with their current location. Researchers have been specifically focusing on changes in the position of the SHW since the Last Glacial Maximum (LGM 19000-23000 cal yr BP) and up to the Holocene, as well as, on possible climate change signals relating to this phenomenon. Recent modeling studies have shown that during the LGM the westerlies were situated 7-10° north of their current location (e.g., Anderson and Burckle, 2009). In turn, the SHW acted as a feedback mechanism, reducing the release of CO_2 to the atmosphere, bringing cooler conditions to the southern mid-high latitudes (Fig. 1) (Toggweiler et al., 2006). The opposite process is hypothesized during the post-LGM climate warming. The SHW moved south, closer to the Antarctic divergence, resulting in intensified upwelling and the release of CO_2 to the atmosphere (Toggweiler et al., 2006). However, a recent compilation of existing data on the LGM position of the SHW has resulted in various contradictory views. In consequence, the position and intensity of the SHW from the LGM onwards is still a matter of intense debate (Kohfeld et al., 2013).

There have been several attempts to reconstruct latitudinal shifts of the SHW since the LGM using terrestrial archives. Palaeo-SHW reconstructions are primarily based on precipitation/moisture proxies and their expected positive correlation to wind intensity. The following paragraphs summarize existing studies on past changes in intensity and/or latitudinal shifts of the SHW. In a study including a high resolution pollen and charcoal record in the Chilean Lake District (41°S) Moreno et al., (1999), reports an equator-ward shift and intensification of the SHW during the LGM, based on findings of pollen representative for Magellanic Moorland, an ecosystem occuring in areas highly influenced by the SHW today, in the southernmost part of South America between 48 and 56°S. A pole-ward shift of the SHW is inferred when the Magellanic Moorland flora disappears from the pollen record at approximately 13000 ^{14}C yr BP.

Björck et al. (2012) analyzed aeolian sand influx, pollen, loss on ignition, humification, geomagnetic properties, as well as bulk density on a 14000 year old peat record from Islas de Los Estados (54°S), Tierra del Fuego. The authors reported multiple positional changes of the SHW, starting with changes at 13600-13300 cal BP when data suggests a high intensity of the SHW, partly corresponding to the ACR. At approximately 12200 cal BP the authors report a pole-ward shift of the SHW, to a latitude south of Tierra del Fuego bringing favorable conditions to Islas de los Estados during the YD cold period in the North Atlantic. Then at 10000 cal BP the SHW return to the latitudes of Tierra del Fuego, reaching a Holocene maximum in SHW intensity between 4500 and 3500 cal BP.

A 16000 yr old peat sequence from Iles Kerguelen (49°S), in the Southern Indian Ocean was investigated using a multi-proxy approach, including pollen and plant macrofossils, geochemical and geomagnetic properties (Van der Putten et al. submitted). They report the onset of wetter and windier conditions at approximately 13650 cal yr BP associated with a strengthening of the SHW at Iles Kerguelen. These conditions are then followed by less windy and relatively drier/warmer conditions suggesting less intense

SHW influence, associated with the end of the ACR and a possible southward shift of the core of the wind belt to a position south of the Kerguelen Archipelago (Fig. 1). Then from 11650 cal yr BP the record indicates more favorable conditions, related to the Holocene Climatic Optimum. An interesting pollen record is displayed in this study. The record shows a dominance of Poaceae at around 16,000-13,650 cal yr BP, after which *Azorella selago* and *Lyallia kerguelensis* become prominent. Finally, around 11,650 cal yr BP an expansion of *Aceana magellanica* is observed.

More studies are needed at these key latitudes, especially studies that use proxies directly or indirectly associated with atmospheric and climatic changes. This would allow us (1) to further understand key processes that govern climate in this region and (2) allow to test different hypotheses related to the regional and global climatic evolution since the LGM.

1.1 Aim of study

The aim of this thesis is to conduct a multi-proxy study on a ~15,000 year old sedimentary sequence from Port Douzieme (P12), Iles Kerguelen. This sedimentary sequence was recovered during the same expedition as the Estacade peat record (Van der Putten et al., submitted). Prior to this study, there has been only one paleoecological/botanical study performed at P12, a palynological study by Young and Schofield (1973) on two peat sequences sampled in stream cuts along the south coast of the Golfe de Morbihan revealed a basal radiocarbon date of 11010 ± 160 ^{14}C yr BP for the site near Port Douzième (core 2 in Young and Schofield, 1973) on the Presqu'île Ronarch (Fig. 3). The authors stated that "buried soils below the bottom of core 2 were not sampled because of seepage problems" (page 311). Based on the pre-Holocene basal date together with the indication of deposits beneath the sequence of Young and Schofield (1973), it was decided to revisit the area of Port Douzième. This multy-proxi study includes loss-on-ignition (LOI), Magnetic Susceptibility (MS), and pollen analysis with special attention for long distance pollen. This thesis project intends to answer the following important questions:

(1) When do significant pollen assemblage changes occur?

(2) What do these changes together with the lithology of the sediments, the LOI results, as well as, the MS measurements, tell us about the local environmental changes at the P12 site?

(3) Is the pollen stratigraphy found in the P12 core similar to the Estacade pollen stratigraphy?

(4) What do the results tell us about regional climate conditions on the archipelago?

(5) Can we deduce changes in intensity and/or latitudinal shifts of the SHW based on the data resulting from this study?

1.2 Background to the study area

1.2.1 The sub-Antarctic zone

In the vast Southern Ocean (SO), we find the sub-Antarctic zone. The sub-Antarctic is a region situated

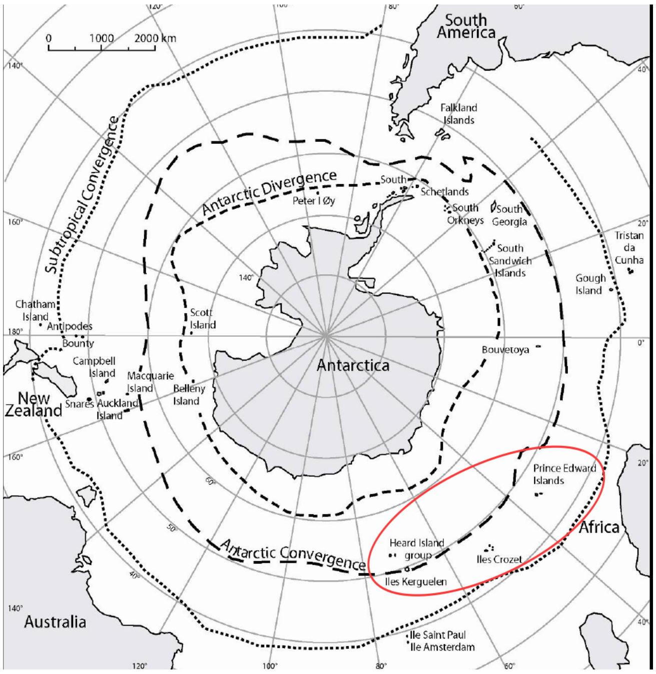


Fig. 2. The southern hemisphere and the sub-antarctic, showing islands mentioned in text. Islands of the South Indian Ocean Province encircled in red. Map adapted from Van der Putten. (2008)

approximately between 46° and 60° S , between the Polar Front (PF) and the Subtropical Front (STF) (Fig. 2). The term sub-Antarctic was first used by Ludwig in 1898 (Van der Putten. 2008).

Thereafter, researches from different scientific disciplines attempted to subdivide the high and mid southern latitudes into regions or zones, based on biological, geographical, oceanic and climatic characteristics (Van der Putten, 2008). Therefore, the definition or delineation of the sub-Antarctic has varied since the end of the 19th century. However, the most widely accepted delineation of the sub-Antarctic zone is based on botanical or biological characteristics (Van der Putten et al., 2010; Bergstrom et al., 2006). No major continental masses are present in the sub-Antarctic, as this region is exclusively made up of islands: South Georgia in the south Atlantic, Prince Edward Islands, Iles Crozet, Iles Kerguelen and the Heard Island Group in the south Indian and Macquarie Island in the south Pacific Ocean (Fig. 2). All of the islands are characterized by an oceanic climate, with annual mean temperatures ranging from 4.5° to 6°C, with the exception of South Georgia (2°C) and Heard Island Group (1.2°C) due to their geographical positioning south of the PF

(Van der Putten. 2008). The total annual precipitation in the sub-Antarctic is at least 800 mm but it is mostly much higher (Van der Putten, 2008). The sub-Antarctic can be grouped into three major provinces based on differences in botany, which will be described in detail in section 1.2.3 Sub-Antarctic provinces. The three major provinces are the South Atlantic, South Pacific, and South Indian Ocean Province (Van der Putten et al., 2010).

1.2.2 Vegetation of the sub-Antarctic

The flora of the sub-Antarctic is very limited, as the variety of species is very low in relation with other regions of the globe. The flora is characterized by closed phanerogamic communities and bryophytes (mosses and liverworths) play an important role in the sub-Antarctic vegetation. No trees are present on the islands. The flora is made up of woody herbs, forbs, and cryptograms. Extensive peat deposits can be found on the lowlands of the islands, while exposed areas are dominated by a fellfield vegetation (Van der Putten. 2008). The typical 'sub-Antarctic Island Species' are *Blechnum penna-marina, Acaena magellanica, Callitriche antarctica, Ranunculus biternatus, and Juncus scheuchzerioides*. These species are found on all of the islands except on the Heard Island Group (Van der Putten, 2008).

1.2.3 Sub-Antarctic provinces

It was previously mentioned that the sub-Antarctic zone is further divided into three major provinces based on botanical differences. The three major provinces are the South Atlantic Province, South Pacific Province, and the South Indian Ocean Province. However, in this section, we will focus on the South Indian Ocean Province, also known as the Kerguelen Phtyogeographic Province since Iles Kerguelen is part of this zone (Fig. 2).

1.2.4 South Indian Ocean Province (Fig. 2)

There are five main vegetation types in the South Indian Ocean Province (Van der Putten et al., 2012). However, this is a generalization and not all vegetation types occur in the same settings and/or are not common on all of the islands (Van der Putten et al.,2012). The first vegetation type is strongly influenced by sea salt-spray and is characterized by the species *Crassula moschata,* and *Leptinella plumosa* . Therefore, this community is typically found on the coastline. The second type is usually found in all types of terrains, and environments. *Acaena magellanica* is the prominent species of this group. This vegetation type typically occurs on sites with lateral water flow or down sloping water flow (Van der Putten et al., 2012).

The third type is commonly found on well drained sloping terrains. The most important species associated with this type of vegetation is the fern *Blechnum penna-marina* (Van der Putten. 2008). The fourth type consists of mire vegetation, where thick peat deposits can be found. The dominant species in this type of vegetation is *Juncus scheuchzerioides.* However, the species *Ranunculus biternatus* along with bryophytes can be found around small pond and lakes (Van der Putten. 2008). The fifth type is the so-called fellfield community, which is commonly found at higher altitudes in exposed areas. The most prominant species in this type of vegetation is the wind tolerable cushion plant *Azorella selago* together with several moss species (Van der Putten. 2012).

1.2.5 Palynology of the sub-Antarctic

Palynological studies in the sub-Antarctic are still scarce in comparison to the amount of studies carried out in other parts of the world. For Iles Kergulen we can refer to the studies of e.g. Schalke and van Zienderen Bakker (1967), Bellair (1967), Young and Scholfield (1973). The first palynological studies attempted to demonstrate post-LGM Holocene vegetational and climate change on the sub-Antarctic islands, but as pointed out by Van der Putten et al. (2012) (see also Barrow, 1978 for South Georgia), identifying climate-change from pollen data in the sub-Antarctic islands is not straightforward, especially when relying on palynological data only. In contrast to the palaeobotanical evolution at similar latitudes in the Northern Hemisphere, clear biozonations are absent in the pollen diagram from the sub-Antarctic, at least in the Holocene.

The general principle used to deduce environmental change on the sub-Antarctic Islands, has been based on relative changes observed on the pollen record. The appearance of the 'upland' species, *Azorella selago* in the pollen record, would suggest colder conditions, as this 'upland' community is typically found on wind exposed areas. The presence of 'low land' species such as *Acaena magellanica, Uncinia compacta, Gallium antarcticum,* together with *Lycopodium spp.*, in the pollen record, suggests warmer or more sheltered conditions (e.g. Young and Schofield, 1973). However, Van der Putten et al., (2012) has questioned whether one can infer climate change in this region based on this principle. The authors claim that at least for the Holocene, this principle may be flawed, as the authors see no direct evidence between the presence of *Azorella selago* pollen, and colder conditions, as well as, the presence of *Acaena magellanica, Uncinia compacta, Gallium antarcticum,* and *Lycopodium spp.* pollen, with warmer conditions. The question still remains whether this principle can be used for the Last Termination (Van der Putten et al., 2012).

1.2.6 Regional pollen transport in the sub-Antarctic

Palynological studies in poorly vegetated, windy environments such as the sub-Antarctic, are to be approached differently than studies carried out on densely vegetated continental landmasses of the Southern and Northern Hemispheres. In general, pollen grains tend to be evenly dispersed by wind 10 to 1000 m away from their source (Seppä, 2006). However, an interesting issue in the sub-Antarctic islands, is the large distances that the pollen grains are able to travel due to the intensity of the SHW wind and the high amount of precipitation. Palynologists working in these harsh environments, need to be careful, as the pollen record retrieved from a certain site can be misinterpreted, resulting in erroneous vegetation history of the site or region.

Thus, site selection for palynological studies is critical. In the largely vegetated continental land masses of the Northern and Southern hemispheres, pollen records retrieved from small open areas, surrounded by dense vegetation, or small lakes that are < 50 m in radius, are representative of local vegetation changes. While, pollen records retrieved from larger lakes > 250 m in radius are more representative of regional vegetation changes (Seppä, 2006).

However, in the poorly vegetated sub-Antarctic islands, a small lake or small valley, would be an optimal site to reconstruct past vegetation changes within a region of a couple of kilometers around the site (Seppä, 2006).

1.2.7 Evidence of long distance pollen transport in the sub-Antarctic

Several studies have used the presence of exotic, long distance pollen to infer atmospheric changes, or latitudinal changes of the SHW. Scott and van Zinderen Bakker (1985) reported the presence of both South African and South American pollen taxa peat profiles as well as surface samples in Marion Island. Björck et al. (1993) working in the South Shetland Islands suggested increased influence of northern air masses at about 4000-3300 BP. This assumption was based on the findings of long distance pollen grains from Southern South America; *Nothofagus, Ulmaceae, Chenopodiacea.* Recently, Strother et al., 2015 reported the presence of long distance pollen grains (e.g. *Nothofagus, Podocarpaceae,* Ephedra) in a pollen record from South Georgia Island. The intensity and/or latitudinal position of the SHW were induced based on their results.

1.2.8 Iles Kerguelen geography and climate

Situated in the South Indian Ocean, in the core of the SHW, the Kerguelen archipelago (49°-69° S) (Fig. 3), is a French island group. It is the largest land mass in the sub-Antarctic. The main island has a surface area of approximately 7200 km^2 and is surrounded by numerous small islands. The highest peak on the Kergulen archipelago is the Mont Ross volcano, with an altitude of 1850 m above sea level (Fig. 3). The archipelago has high mean annual precipitation values due to its position in the core of the SHW, but these differ on the western and eastern part of the archipelago due to an orographic effect; annual precipitation on the mountainous western part is approximately 3200 mm,

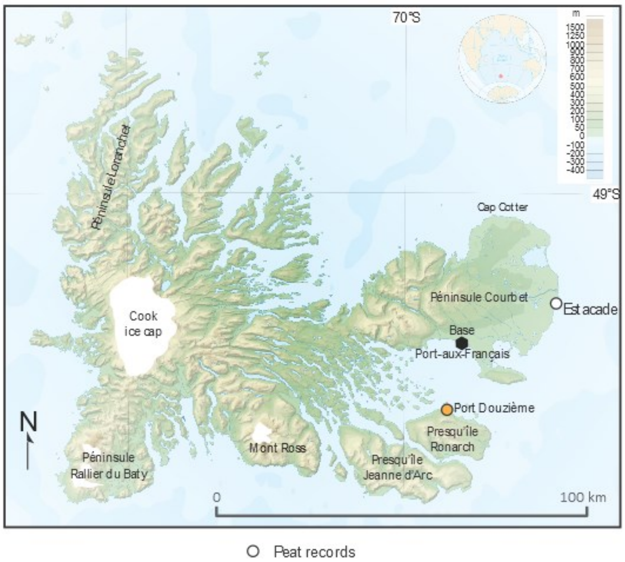


Fig. 3. The Kerguelen archipelago, with location of Port Douzieme and the Estacade sites. Van der Putten et al., (submitted).

while on the eastern part precipitation only attains 800 mm. Mean wind velocity is approximately10 m/s (Frenot et al., 2001).

1.2.9 Geology

The vast majority of the exposed bedrock is made up of flood basalts (approximately 85%), the remaining 15% is made up by plutonic rocks and Quaternary deposits. The minimum age estimated for the formation of the Kerguelen archipelago is estimated to be about 39 Myrs (Frey et al., 2000). The mean elevation is roughly 800 m, with the western part containing the most rugged terrain while the eastern part is generally flat.

Currently 12% of the archipelago is covered by ice, the main source of ice being the Cook ice cap with its small outlet glaciers (Fig. 3). U-shaped valleys, glacially eroded sediments and landforms are prominent features on the archipelago, suggesting that at some point in time, the extent of glaciers and ice cover must have been much greater than the current one. However, the extent of past ice cover is still a matter of debate specifically related to the ice cover during the LGM (e.g. Nougier, 1970; Hall, 1984).

1.2.10 Endemism on Kerguelen

There are five endemic species found in the South Indian Ocean Province (Fig. 2) (*Poa kerguelensis, Colobanthus kerguelensis, Pringlea antiscorbutica, Lyallia kerguelensis,* and *Ranunculus moseleyi*). *Lyallia kerguelensis* is strictly endemic to the Kerguelen archipelago (Fig. 3) (Wagstaff and Hennion, 2007).

The origin of the sub-Antarctic flora has puzzled scientists for many years. Two main hypotheses have been put forward in order to explain their origin; post-glacial colonization, or pre-glacial survivors (e.g.

Wace, 1965; Van der Putten et al., 2010).

Two species in the south Indian Ocean Province have attracted attention amongst scientists; the endemic species of the Kerguelen archipelago *Lyallia kergulensis* and the so-called 'Kerguelen cabbage' *Pringlea antiscorbutica*. Lineage and botanical studies suggested that the species *Lyallia kergulensis* has remained isolated for thousands of years, with a possible link to a species that was once widely distributed on the Antarctic Continent before major glaciation took place (Wagstaff and Hennion, 2007). On the other hand, the Brassicaceae species *Pringlea antiscorbutica* has been related to a South American ancestor. Lineage studies have suggested divergence from the South American ancestor at approximately 7.7-2.6 Ma ago (Bartish et al., 2012). However, the dispersal route of this species still remains a topic of discussion.

1.2.11 Presqu'ile Ronarch

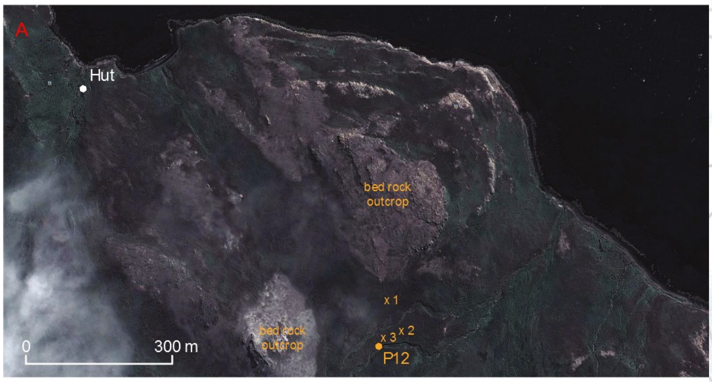
The geology of Iles Kerguelen is characterised by flood basalts, stacked on top of each other, creating a relief shaped as stairs. The central part of the Presqu'île Ronarch is mountainous and reaches to an altitude of 937 m asl (Mt Wyville). In the northern part of the Presqu'île the landscape is dominated by two eroded basaltic outcrops: Le Pouce (744 m asl) and Le Pain de Sucre (593 m asl) (Fig. 4B). When descending towards the northern coastline, the relief shows the characteristic stepwise flood basalts. At lower altitudes, the flat areas in between the stairs are covered by peat deposits as precipitation and seepage water is retained. Sometimes these flat areas with peat deposits form the catchment for relatively small streams that are today erosive and cut through peat deposits, as is the case in the area around Port Douzième (Fig. 4A).

2 Methods

2.1 Fieldwork

The site at Port Douzieme (P12) was cored during the November 2006 - January 2007 expedition to the Kerguelen archipelago. The Author of this thesis was not involved in this expedition. The coring was done by Nathalie Van der Putten, Cyriel Verbruggen, and Bart Klinck (Fig. 5). First the area was prospected with hand coring equipment, using a 4 cm diameter gauge, an excellent tool for coring peat deposits, in order to survey the thickness of the deposits and detect continuous organic sequences suitable for palaeoenvironmental research. Peat deposits situated on the flat areas in between the basaltic stairs attained depths of about 2-3 m. To the East of the hut (Fig. 4A) a vertical section of about 4.5 m high was found to be eroded by a small stream. The left bank of this channel is built up by organic deposits until about 1.5 to 0.5 m from the top. The overlaying sediments consist of small stones, gravel and mud and are clearly visible along the gully becoming less thick more downstream (Fig. 5). Prospection with the gauge at sites 1, 2 and 3 (Fig. 4A) revealed a thickness of organic/peat deposits of 1, 1.5 and 6 m respectively. Prospection below the stream bed showed another c. 2 m of mixed organic deposits. The section was sampled by cutting out

Fig. 5. P12 site inspection by Nathalie Van der Putten, Cyriel Verbruggen, and Bart Klinck. Photo by.: Nathalie Van der Putten



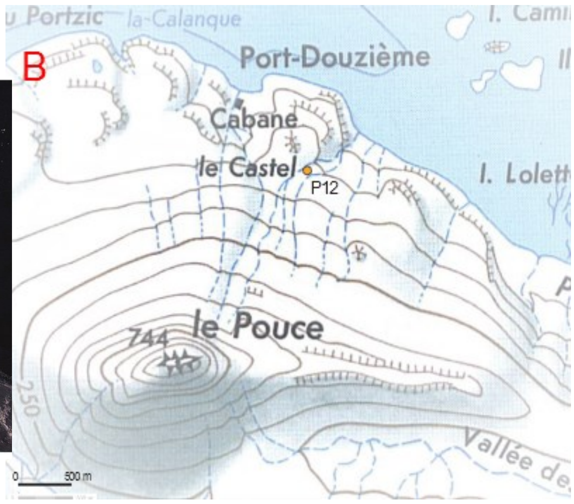


Fig. 4: (A) Satellite view of Port-Douzieme and different locations near the site.(google maps) *(B)* Topographic map of P12. (geoportail)

blocks. The deposits beneath the stream were sampled using two 11 cm diameter PVC tubes, covering a total length of 210 cm. The first tube was hammered down to a depth for 123 cm after which, the gauge was used to core around the tube to release and retrieve the tube from the surrounding deposits. The second PVC tube was introduced in the same hole. The second tube spans from 123 to 210 cm.

The PVC tubes were packed and transported by ship from Iles Kerguelen to France and Belgium. The cores were split in half and the archive core is stored at the Geography Department of Ghent University (Belgium). The work core was brought to Lund University, Sweden to be analyzed. There is slight distortion of the sediments found at the bottom core, which may have resulted from the coring procedure.

2.2 Laboratory procedure

2.2.1 Core examination and sub-sampling

Before sub-sampling the cores were photographed in increments of 20 cm length. A total of 154 samples, of 1cm^3 each, were retrieved from the cores. Subsequently, 119 samples were used for LOI, pollen analysis, and radiocarbon dating. In order to obtain data from every section or lithological unit, samples were taken in accordance with visual changes in the lithology.

2.2.2 Core description

A thorough description was made of both cores, from bottom to top (210 cm-0 cm). The descriptions were based on lithological changes composed mainly of grain size, color of sediment, and presence of organic matter. The boundaries between each unit were categorized based on two distinctions; erosional and gradual.

The units containing peat were categorized based on the degree of decomposition, and based on the Von Post Scale of Humification; H1-undecomposed peat, H2-almost undecomposed, H3-very weakly decomposed, H4-weakly decomposed, H5 -moderately decomposed, H6-well decomposed, H7-strongly decomposed, H8-very strongly decomposed, H9-almost completely decomposed, H10-completely decomposed peat. The presence of visible plant remains was also noted.

2.2.3 Magnetic susceptibility

Magnetic susceptibility (MS) measurements is an non-destructive method providing a crude estimate of the amount of minerogenic matter present in the deposits within the sequence. The MS was measured before sub-sampling at a 5 mm resolution, using a Bartington Instruments Ltd MS2E1 sensor and a TAMISCAN-TS1 automatic conveyer at Lund University, Sweden (Sandgren and Snowball, 2002). This analysis was performed in the fall of 2012 by Nathalie Van der Putten.

2.2.4 Loss on Ignition

Loss on Ignition (LOI) analysis was performed in order to estimate the weight percent of organic matter present in each unit of the sediment sequence. LOI analysis consisted on weighing the fresh samples along with a pre-weighed crucible. These were then placed in an air circulation oven at 105°C for at least 12 hours to dry. Thereafter, the samples were taken out of the oven, placed in the desiccator to cool, and weighed once again to obtain the dry weight of the sample ($DW_{105°}$). Subsequently the crucibles with samples were placed in a muffle oven, which burned for 4 hours at 550°C. The samples were then placed back in the desiccator to cool, and a final weight was recorded ($DW_{550°}$). The same steps were repeated with all 75 samples.

The following equation after Heiri et al.(2001) was used to calculate the amount of organic matter in the samples.

$$LOI_{550°} = \left(\frac{DW_{105°} - DW_{550°}}{DW_{105°}}\right) \times 100$$

2.2.5 Radiocarbon dating

Four samples were submitted for radiocarbon dating: at 10.5 cm near the top of the sequence, at 206.5 cm to obtain a basal date for the sequence, at 151.5 cm which is the onset of peat formation and an intermediate one at 114.5 cm. The samples were soaked overnight in 5% NaOH solution and subsequently sieved for picking of plant macrofossils. A mix of monocot epidermis was picked due to the limited availability of other terrestrial recognizable plant remains. These were pretreated through the acid alkali acid (AAA) method and processed at the single stage Accelerator Mass Spectrometer (AMS) at the Lund University Radiocarbon Laboratory and at LMC14 (CEA Saclay, France, SacA-samples). The resulting ages were then calibrated with the OxCal 4.2 (Bronk Ramsey, 2009) program, using the Southern Hemisphere13 (ShCal 13) calibration curve.

2.2.6 Age-depth modeling

The age depth model is based on four ^{14}C dates. In the age-depth model the median was used together with the 2σ errors (figure.8). Variable k value was applied as changes in sedimentation rate are unknown, and two lithological boundaries were introduced in the model where clear and sharp changes in the lithology occured. The depth interval was interpolated by the model at every 0.5 cm. The age-depth model was constructed using OxCal 4.2 (Bronk Ramsey, 2009) program.

The accumulation rates were calculated taking in account the age depth model and the thicknesses of each unit; the results are given in mm/yr.

2.2.7 Pollen preparation

Sampling for pollen analysis was done at about every 2.5cm on average, and a total of 75 samples were retrieved. However, the analysis was only performed on 40 samples due to time limitations. The selection of the samples was not based on resolution, but rather selected on the basis of lithostratigraphical changes. There was a need to cover the entire sequence, and so the best way to do it was to gather samples from every stratigraphic unit. However, organic units were always prioritized.

Standard pollen extraction techniques (Faegri et al., 1989) based on gravity separation were applied to all 40 samples. In this case, a heavy liquid, tungsten based (Sodium polytungstate) was used, rather than the typical hydrofluoric acid (HF) for pollen preparation. This was done in order to preserve mineral or 'dust' particles in the samples, which would have been dissolved with HF acid.

The pollen preparation was performed in the following manner: Samples were placed in glass tubes, then a sodium hydroxide solution was added to the tubes in order to get rid of humic acids; about 30-35 mL. Thereafter, samples were placed in a centrifuge for 3 minutes at 3500 revolutions per minute. The solution was then decanted, leaving sample material at the bottom of the tube. *Lycopodium* tablets were then added at this time. The *Lycopodium* tablets were obtained from Lund University (batch # 710961), this were added in order to estimate pollen concentrations (Stockmarr, 1971).

During the acetolyzation process 25 mL of 100% acetic acid was added to the tubes containing sample material. Acetic acid was added in order to remove H_2O. Then, acetic anhydride and sulfuric acid were added; the instant reaction between the acetic acid and the sulfuric acid is what causes the acetolysis; the acetolysis is performed on pollen samples in order to remove non-sporopollenin substances (Hesse and Waha, 1989). Finally, the heavy liquid was added to the tubes and subsequently shaken. Lastly, the pollen and fine minerogenic particles concentrate in a thin layer at the top of the tubes. This thin layer was then extracted with a pipette, and placed in tubes. Glycerin and sample material were then added on to slides, and which were sealed by a cover glass. The pollen preparation took place at the Department of Geology and Soil Science, Gent University, Gent, Belgium and under the supervision of Professor Emeritus Cyriel Verbruggen.

2.2.8 Pollen analysis

The 40 pollen slides were analyzed under a light microscope (Olympus BX41) at 400 times magnification. Pollen grains, spores, and algae were counted, and the amount of minerogenic particles was estimated during this process. The latter was scaled from 0-5; 0 having no minerogenic particles and 5 having the most. The pollen grains were identified to species or family level, with the help of reference material provided by Nathalie Van der Putten collected on various expeditions to the sub-Antarctic, and prepared by Cyriel Verbruggen in Belgium. Francoise Hennion (ECOBIO, Universite de Rennes 1, France) provided plant material from the species *Lyallia kerguelensis* and *Pringlea antiscorbutica*, collected on the Kerguelen archipelago. Where possible exotic pollen grains were identified to family or genus level, otherwise they are represented as morphological types. Pictures and descriptions from previous studies were also used during the identification process (Barrow, 1976; Bellair, 1967; Markgraf and D'Antoni,1978; Leopold et al.,2012). Pollen analysis was performed at the Department of Geology, Lund University, Sweden.

Absolute pollen counts of both the native taxa and exotic pollen grains were used to calculate percentages and concentrations. The pollen sum is defiend as the sum of all native phanerogam taxa. Exotic pollen grains were not included in the pollen sum, butthe percentage of exotic grains was calculated in relation to the pollen sum (Σ pollen + Σ exotic pollen).

Pollen concentrations were calculated using the following equation:

$$\frac{\textit{Lycopodium}\text{ added}}{\textit{Lycopodium}\text{ counted}} \times \frac{\text{fossil pollen grains counted}}{\text{volume (cm}^3)} = \text{fossil pollen concentration} \left(\frac{\text{grains}}{\text{cm}^3}\right)$$

The results were inserted in to a spreadsheet, and both percentage and concentration diagrams were generated using the software Tilia (Grimm, 2007).

2.2.9 Other organisms in the pollen slides

The use of a heavy liquid during the pollen slide preparation, allowed besides the preservation of the fine minerogenic particles also the preservation of diatoms. An estimate of the amount of diatoms was made using a scale ranging from 1-5, going from 1, very low presence to 5, very high.

3 Results

3.1 Core description

The stratigraphy of the 210 cm sequence was simplified into 12 units from 42 units described in detail in Appendix (1). The lowermost unit (Unit A 210-198 cm) (Fig. 6) is mainly made up of a brown to dark brown clayey-silty gyttja. The upper boundary at Unit A is characterized as sharp. Also, there is plant material found throughout this unit. The following unit, (Unit B 198-176cm) (Fig. 6) comprises of greyish-brownish gravel, with clast supported matrix and a gradual upper boundary. Unit C (176-162cm) (Fig. 6) is made up of silty gyttja sand at the bottom grading into a more sandy gravelly sediment towards the top. The upper boundary of Unit C is erosional.

Next, Unit D (162-153 cm) (Fig. 6) is made up of a brown silty clay gyttja, followed by Unit E (153-148 cm) which is a dark brown-blackish well decomposed peat. The upper boundary at Unit E is characterized as an sharp boundary. Thereafter, the sediment transitions to more clayey material. Unit F (148-123 cm) is mainly made up by a laminated, brown,clay gyttja. The laminations are of different color shadings and organic material is constantly present throughout; the upper boundary is gradational.

Unit G (123-115 cm) (Fig. 6) is predominantly made up by a greyish-brownish, sandy-silty peat. Unit G then transitions smoothly in to (Unit H 115-88 cm) (Fig. 6). This unit is made up by a light brown and well preserved fibrous peat. This fibrous peat gives way to a more decomposed, humidified peat at approximately 102 cm and continues until the erosional upper boundary found at the top of Unit H. Unit I (88-71 cm) (Fig. 6) is a light brown silty gyttja with some clay.

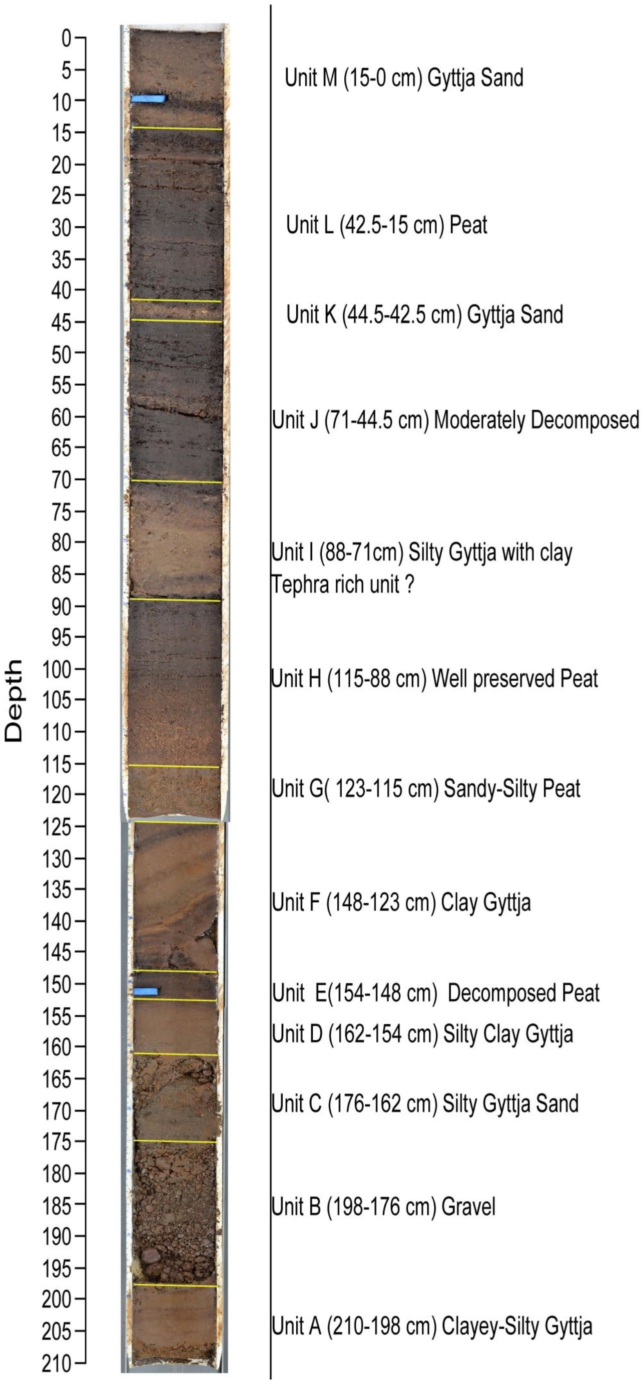


Fig. 6. Sequence retrieved from P12 with corresponding depth (cm) and units (A-M).

Unit J (71-44.5 cm) (Fig. 6) is predominantly made up of dark brown moderately decomposed peat, with thin sandy-gravelly sections intercalated in this unit, such as at 59 cm. Plant material is very abundant in this section. Unit J is overlain by a thin gyttja sand layer. Unit K (44.5-42.5 cm) (Fig. 6) is a light brown unit, containing plant remains, and minerogenic particles as big as 0.5 cm; and with a sharp upper boundary.

Unit L (42.5-15 cm) (Fig. 6) is a unit almost entirely made up of peat. The peat found in this unit ranges from moderately decomposed, to almost entirely undecomposed peat, and displays different shades of brown. There is a thin silty gyttja unit intercalated within the peat at 20 cm. The upper boundary found at unit L, is sharp. Unit M (15-0 cm) (Fig. 6) is mostly composed of a light brown gyttja sand, with intercalated peat at 11-10 cm.

3.2 Magnetic susceptibility (MS)

The part with highest MS values of the record, is found at the bottom at Unit A, and until Unit E (Fig. 7). Here the measurements range form 2000 to about 10000 10^{-6} SI. Hereafter, in Unit F some fluctuations can be seen, but absolute values are generally low in comparison with before, with a maximum of about 500 10^{-6} SI.

The top portion of the sequence, that is from 123-0 cm shows very low MS readings, very little variability is recorded in this section. One clear spike is recorded at unit G (Fig. 7), with readings of up to 1000 10^{-6} SI. Similar values are recorded at Unit I, corresponding with the presence of the silty gyttja. Then, at 60 cm more variability is recorded, and a slightly larger spike at 44 cm. From about 42-15 cm MS values are close to 0, with the exception of a few spikes, corresponding to drops in LOI percentage. Finally, in Unit M larger variability is recorded at about 9 cm, with a spike of about 6000 10^{-6} SI (Fig. 7).

3.3 Loss on ignition (LOI)

The overall pattern obtained from the LOI analysis performed on the sequence clearly shows that organic matter increases from the bottom of the record at 210 cm to the surface level. The LOI results that will be mentioned in this section, will be separated in to units as in the previously mentioned in the core description section.

The LOI values found here and throughout the bottom of the core, at Unit A ranges from about 15-5%, this then plunges to almost 0% at Unit B (Fig. 7). In Unit C the percentage of organic matter increases back to about 5%. However, the percentage of organic matter increases drastically at Unit D-E boundary. Unit D shows a clear gradual increase of LOI values, and at the top of this same unit, continuing to Unit E, the percentage of organic matter surpasses the 40%

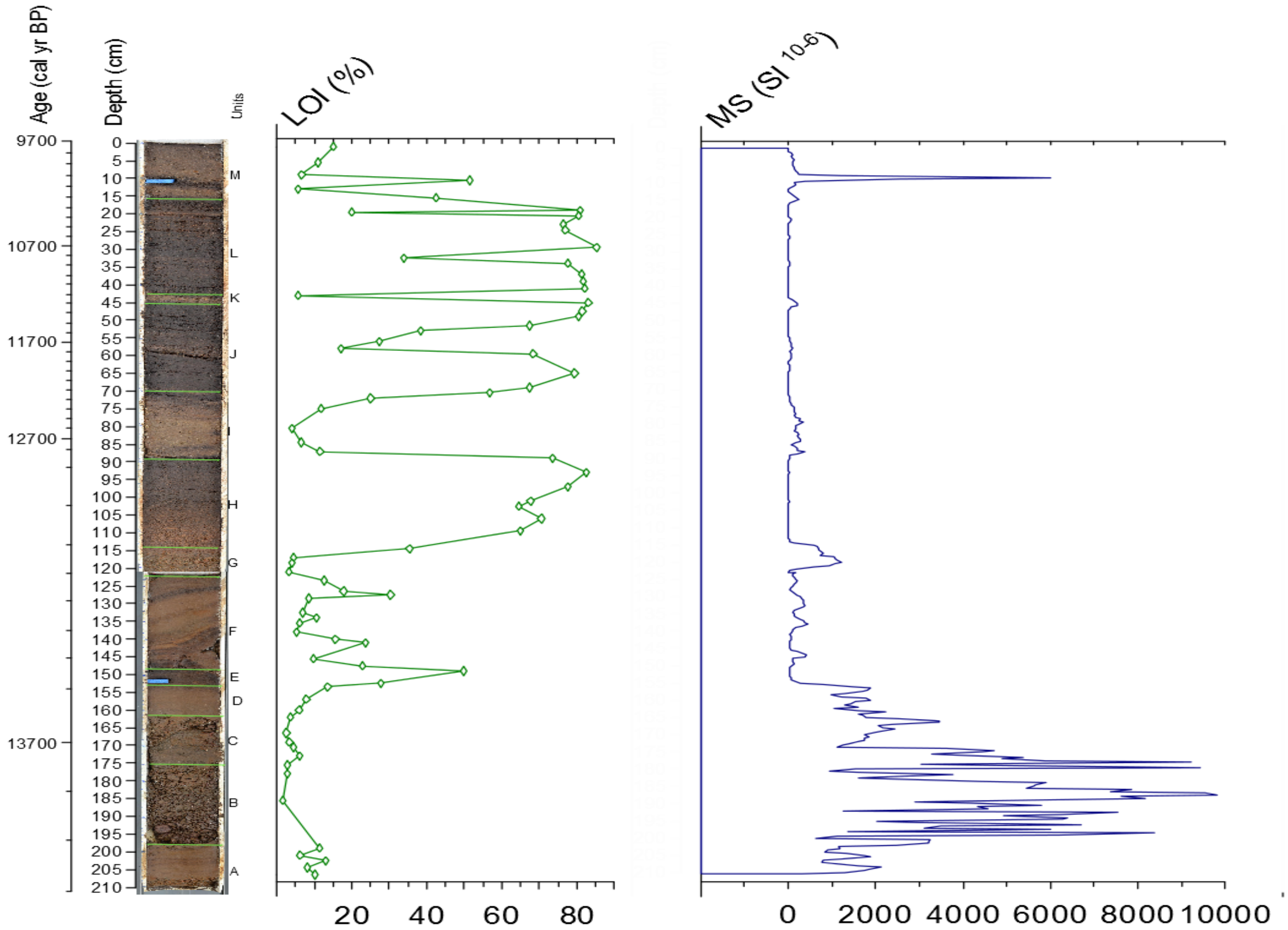


Fig. 7. Picture log with corresponding lithological units (green lines and letter units). Loss on Ignition (%) and Magnetic Susceptibility (SI 10^{-6}) results.

Table. 1. Radiocarbon dates from P12, displaying sample depth, ^{14}C, error, Age (cal yr BP), code and material picked.

Depth (cm) in age model	14C	Error	2 sigma	Code	Material picked
10.5	8925	50	10189-9770	SacA 24105	Monocot epidermis
114.5	11245	60	13213-12891	LuS 11122	Monocot epidermis
151.5	11950	60	13953-13560	SacA 24106	Monocot epidermis
206.5	12050	55	14042-13734	LuS 11123	Monocot epidermis

for the first time in the sequence (Fig. 7).

Hereafter, the percentage of organic matter fluctuates between 5 and 25% throughout Unit F. The LOI values then plunges back to lower values. At about 119 cm (Unit G) the percentage of organic matter is about 5%. However, at 115 cm which corresponds to the top portion of Unit G (Fig. 7), the percentage of organic matter increases to about 60%. In Unit H the percentage of organic matter is consistently high, ranging from about 65% at the bottom of the unit and reaching 80% near the top of the unit. However, at about 90 cm the LOI values starts to decrease, reaching about 10% at 89 cm, the top of Unit H (Fig. 7).

The percentage of organic matter plunges further in Unit I (Fig. 7), reaching about 5% at 80 cm, but increases gradually towards the top of this unit. By about 72 cm the LOI values have reached 30%. The high percentage of LOI persists through the overlaying unit, (Unit J). At 65 cm the LOI values are around 78%. However, this pattern of increasing LOI values suddenly changes at approximately 60 cm, which corresponds with the thin intercalated sandy-gravelly unit found within Unit J (Fig. 7). However, the percentage of LOI then increases once again reaching 80% at 46 cm.

The LOI then decreases dramatically at Unit K (Fig. 7). Measurements of about 5% organic matter are obtained at this unit. Opposite results are obtained at Unit L, where the percentage of organic matter is more or less persistently high, about 80%. However, some fluctuations are observed at approximately 33 cm where organic matter drops to about 40%, and at 20 cm where organic matter reaches about 20%. At the very top of Unit L (Fig. 7), at approximately 16cm the percentage of organic matter is very high once again, until the transition with Unit M is reached. The percentage of organic matter is generally low at Unit M (about 15% for the most part), except 11-10 cm, where the LOI increases to about 55%. (Fig. 7)

3.4 Radiocarbon dating and age-depth model

In total, four radiocarbon dates were obtained from the sequence. All dating information, including calibration results is presented in Table 1.

Figure. 8 shows very high accumulation rates at the bottom of the sequence (201-150 cm), ranging from 1.4-1.3 mm/yr. From 150-115 cm the accumula-

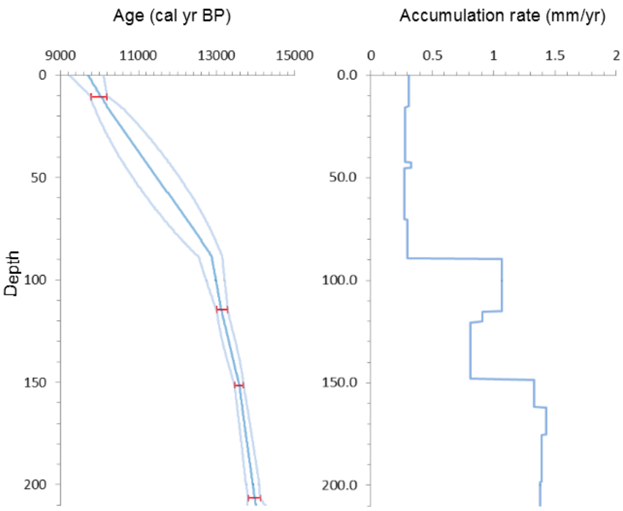


Fig. 8. Graph displaying age (cal yr BP) on the x-axis and depth on the y-axis, as well as error bars (red). The sediment accumulation rate (mm/yr) is plotted vs depth.

tion rates stay below 1 mm/yr. However, the accumulation rate increases again above 1 mm/yr at 113cm until about 89.5cm. Thereafter, the accumulation rate drops considerably at 89 cm where the rate is of about 0.3 mm/yr. From here on, the accumulation rates are more consistent, with rates ranging from 0.3-0.32 mm/yr.

3.5 Pollen analysis

A total of 40 slides were analyzed in which 14760 pollen grains were counted. The total amount of pollen grains found in each slide fluctuated drastically, ranging from 71 to 922. A total of four zones were distinguished by dominance of a native species throughout the zone, and based on pollen, spores, algae, and exotic pollen grains or long distance grains.

Zone 1 (210-140 cm) (Fig. 9) is dominated by Poaceae, which represents about 60-80% of the pollen spectrum. *Azorella selago* is also present in this zone, with relatively high percentages at the bottom of the sequence, and low percentages towards the top of

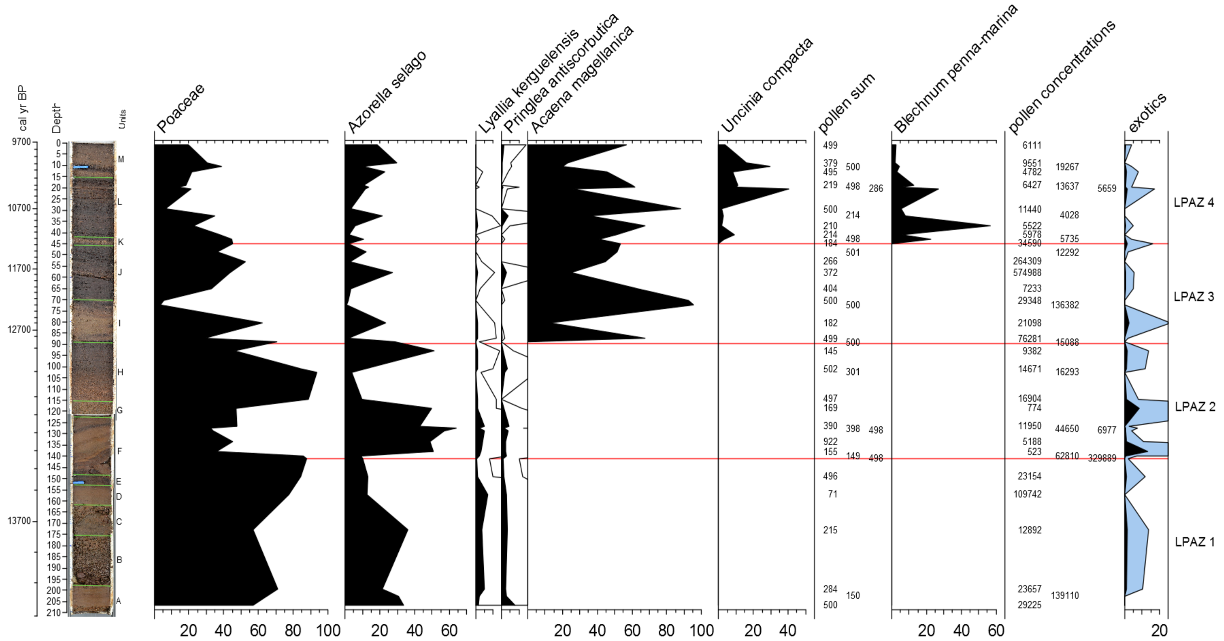


Fig. 9. Pollen diagram with corresponding depth (cm) and units (A-M) displaying local taxa and Long distance (exotics). Pollen data is expressed as percentages, pollen sum as the sum of total native phanerogam taxa, and pollen concentrations in grain/cm^3. Exotics data is expressed as percentages. 10x exaggeration is used for *Lyallia kerguelensis*, *Pringlea antiscorbutica*, and exotics.

Zone 1. *Lyallia kerguelensis* and *Pringlea antiscorbutica* are also present in Zone 1. The records of these two species generally show a similar pattern. However, *Pringlea antiscorbutica* shows a higher percentage at the bottom of the sequence. It is also worth to note that the best preserved grains of both these species are found within this zone. The first appearance of long distance pollen grains is recorded at 199-200 cm, and a total of 10 grains were identified, including the South American *Alnus* (Appendix 2).

Zone 2 (140-88 cm) (Fig. 9) is characterized by higher percentages of *Azorella selago*, becoming more dominant in this zone, with percentages ranging from 40-65%. Poaceae, which has lower percentages than in the previous zone. *Lyallia kergulensis* and *Pringlea antiscorbutica* more or less maintain the same pattern as in Zone 1, with percentages around 5%. *Crassula moschata, Galium antarcticum,* and *Colobanthus kerguelensis* show up for the first time in the sequence, but in very low percentages (Fig. 10). Zone 2 is also characterized by a wide range of long distance grains. Twenty-five different morphological types exotic grains were found in this zone, including cf. *Alnus acuminata*, Podacarpaceae sp. Brassicaceae sp., to name a few (Appendix 2).

Zone 3 (88-44.5 cm) (Fig. 9) is characterized by the sudden expansion the species *Acaena magellanica*, which shows up for the very first time in the sequence, with percentages ranging from 45-80%. Poaceae and *Azorella selago* are much less important in Zone 3 relative to previous zones, with percentages of about 40%, and 25% respectively. *Lyallia kerguelensis* and *Pringlea antiscorbutica* have a less continuous distribution and very low percentages. The abundance of exotic grains is lower, with only 11 different morphological types present in this zone (Appendix 2).

Zone 4 (44.5-0 cm) (Fig. 9) shows similar characteristics to Zone 3, with dominance of *Aceana magellanica*, and lower percentages of both Poaceae and *Azorella selago.* The presence of *Lyallia kerguelensis* and *Pringlea antiscorbutica* continues to be minimal and considerably low. However, two new species appear in this zone. *Uncinia compacta,* and the fern *Blechnum penna-marina* are present for the first time in the sequence. This zone is also characterized by the presence of *Lycopodium* sp. and *Pediastrum* sp. Also, the presence of long distance pollen grains are less common in this zone, with only eight types recorded (Appendix 2) .

4 Discussion

4.1 Paleoenvironmental and paleoclimatic interpretation of the Port Douzieme sequence

4.1.1 Lithostratigraphic data (description, magnetic susceptibility, and loss-on-ignition)

Units A-E (c.14000 cal yr BP – c.13500 cal yr BP)
In Unit A, the LOI values are around 20 % and the MS values are somewhere in the 2000 SI 10^{-6} . However, Unit B displays different sedimentary characteristics than those found in Unit A. Here sediment accumulation rate increased slightly (Fig. 8), while the grain size considerably increased (Appendix 1). The LOI values found at Unit B are low (< 5), and the MS readings are very high ~ 10000 SI 10^{-6} (Fig. 7).

In Unit C we see an increase of the LOI %, and lower MS readings. The LOI in unit C is ~ 5 %, and the MS readings range between 4000-2000 SI 10^{-6} (Fig. 7). However, the accumulation rates increased to about 1.4 mm/yr (Fig. 8). In Unit D the LOI % continuously increases reaching > 40 % at the top of the Unit, while the MS readings continue to decrease (Fig. 7). The very top of Unit D is made up by an organic layer that resembles a highly decomposed peat (Fig. 6).

What the stratigraphic data and the topography of the site indicate is that at the time of deposition of Unit A (c.14000 cal yr BP), P12 was a fairly deep basin in which sediment accumulated under water in a low energy environment. This is based on the characteristics of the sediment (very fine grained) and sedimentary structures (laminations) found within the unit (Appendix 1). The site and the surrounding area is inferred to have been ice free and sparsely vegetated.

Then at the transition to Unit B (c.13900 cal yr BP), P12 and its surrounding areas became a much higher energy environment. This inferred from the presence of gravel, and the high MS values within unit B. The depositional environment at P12 progressively became much calmer during the deposition of Unit C. Here the grain size is much finer and the MS values are much lower than those observed at unit B. When analyzing both Units B and C, a clear normal grading pattern is observed from coarser to-finer sediment, which corroborates that P12 became progressively calmer towards the end of Unit B. It is not known whether the sources of the sediments that make up Units B-C are found in the immediate proximity of the site, or if these were carried downstream from much further inland. During deposition of Unit D, P12 may have been filled in by sediments, becoming a much more terrestrial environment. During Unit E, vegetation in the surrounding areas increased and peat began to form at the site.

Units F-H (c.13500 cal yr BP- c.12900 cal yr BP)

The sediments found within Unit F, are characteristically clayey-silty and laminated. The LOI percentage is generally above 20 % and the MS readings are very low. In Unit G, we find a sandy-silty peat, in which the LOI percentage drops to about 5 % while the MS readings increase to about 1000 SI 10^{-6} (Fig. 7) . Here, the accumulation rate considerably drops to about 0.8 mm/yr (Fig. 8). In contrast, in Unit H the LOI percentage drastically increases up to about 80%, and the MS readings drop close to 0 SI 10^{-6}(Fig. 7).

During deposition of Unit F at c.13500 cal yr BP, P12 was still a terrestrial environment; however, the morphological characteristics of the sediments (very fine grained sediment and laminations) suggest that more hydrologic processes governed the site (Appendix 1). At this time P12 may have been characterized by the presence of small peat ponds like those inferred by Van der Putten et al. (submitted) for the Estacade site (Fig. 10). These peat ponds are shallow bodies of water that form on the surface of peat during

Fig. 10. Photo of shallow peat pond found on the Peninsule Courbet, Iles Kerguelen. (Photo by Nathalie Van der Putten, December 2006).

wetter periods. Sediments must have been transported by wind or increase runoff, and deposited in the peat ponds. At P12, a combination of both wind and fluvial processes brought sediments to the peat ponds.

By about 13200 cal yr BP, peat began to expand at P12, and the peat ponds began to dry. However, precipitation may have persisted. The peat that comprises Unit G contains high quantities of inorganic material (Fig. 7), which suggests that erosive processes during this time were continuously providing areas of low topographic relief with high amounts of minerogenic material. However, it was not until c.13100 cal yr BP, when peat forming processes started to take form and the peat ponds completely dried up.

The bottom part of Unit H consists of a light brown and well preserved peat (Fig. 6). This evidence suggests that during the time in which this peat was formed, the water table was very high, reducing oxygen and slowing down the processes of humification and decomposition. Towards the top of Unit H the peat becomes very dark and humidified (Fig. 6), which could be due to changes in the hydrology of the site, such as the lowering of the water table, as well as changes in the peat forming vegetation. In general, it can be inferred that conditions became increasingly drier by the top of Unit H c.12900 cal BP based on the peat stratigraphy.

Units I-J (c.12900 cal yr BP- c.11300 cal yr BP)

In Unit I the lithostratigraphy drastically changes, which is also reflected by the LOI and MS values. The LOI percentage drops below 5%, and the MS values increase slightly to about 500 SI 10^{-6} (Fig. 7). Also in this unit, the sediment accumulation rate remarkably drops to 0.29 mm/yr (Fig. 8). The stratigraphy suddenly changes at the Unit H-I transition, from peat to a unit with lesser organic material, which consists of volcanic material, including tephra and volcanic glass shards (Fig. 6). Unit I gradually transitions to Unit J.

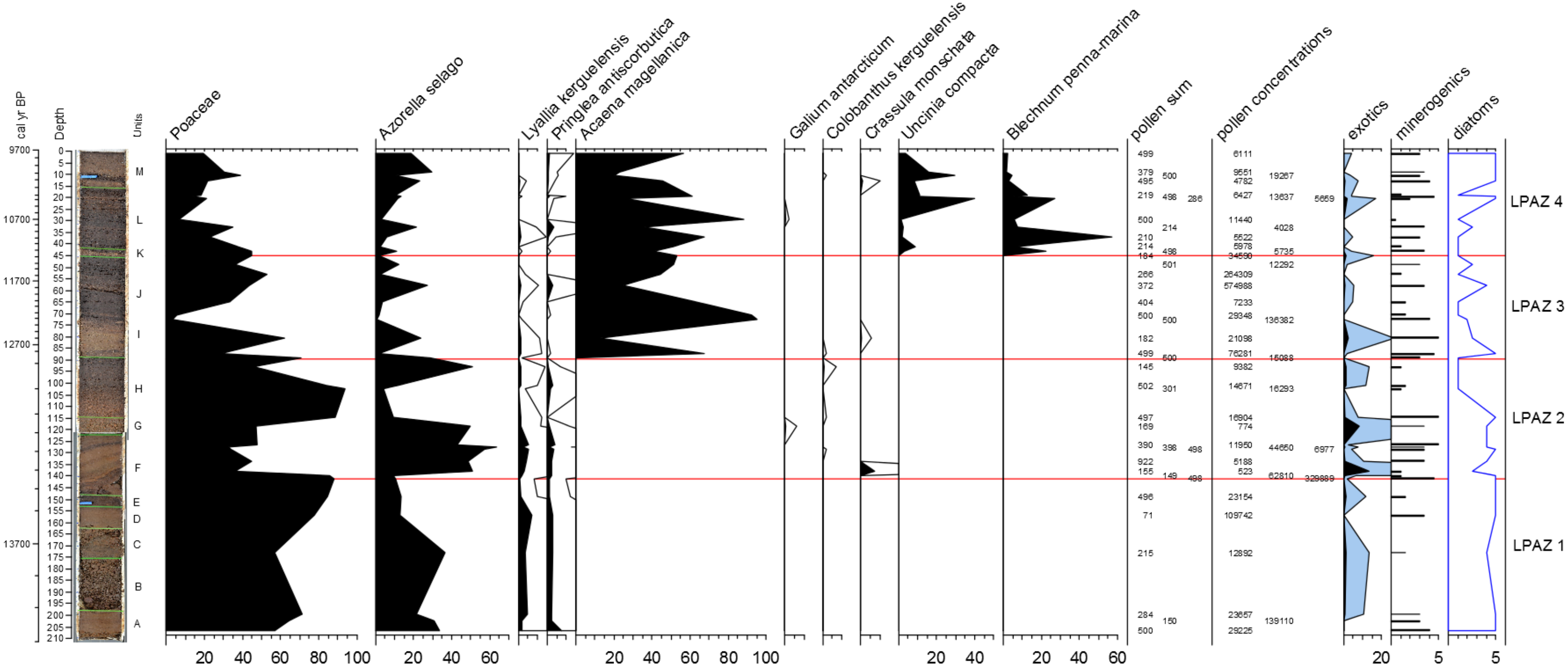


Fig. 11. Pollen diagram with corresponding depth (cm) and units (A-M) displaying native phanerogam taxa and Long distance (exotics) pollen. Pollen data is expressed as percentages, pollen sum as the sum of total native phanerogam taxa (not including *Blechnum penna-marina*), and pollen concentrations in grain/cm^3. Exotics data is expressed as percentages. Minerogenic and diatoms are expressed as 1 (lowest) to 5 (highest). 10x exaggeration was used Lyallia, Pringela, Galium, Colobanthus, Crassula and exotics.

Here the LOI percentage is high once again, reaching almost 80%, and the MS values are very low (Fig. 7).

At approximately 12900 cal yr BP, peat production suddenly ceased and tephra was deposited. However, the source of the tephra and the mode of transport are unknown. Vegetation expanded once again at approximately 12300 cal yr BP, when peat began to form again and it continued until about 11300 cal yr BP. The peats within Unit J are moderately decomposed, which can infer that climate conditions during this time most-likely persisted to be warmer and drier.

Units K-M (c.11300 cal yr BP- c.9600 cal yr BP)
Unit K is made up of a thin gyttja sand layer with a low percentage of LOI (~5%), and a minor peak in the MS values (Fig. 7). Unit K is then followed by Unit L, which is a peat unit, thus containing much higher LOI values (Fig. 7). However, there are several sections in Unit L in which the LOI percentages drop. These drops in the LOI % also correspond with minor peaks in the MS readings. Finally, Unit M contains much more minerogenic material, low LOI percentages and high MS readings, except for a thin peat layer that it is intercalated in this unit at about 10 cm. The MS values suddenly display a peak soon after the thin peat layer (Fig. 7).

At c.11300 cal yr BP, peat deposition was paused and replaced by deposition of dominantly inorganic material. Unit K may have been deposited by increased runoff during storms, or during a short-lived wet period. Peat deposition resumed approximately 100 years later. However, conditions may have been less stable at P12 during deposition of Unit L compared with Unit J. There are at least two instances (c.10800 cal yr BP and c.10300 cal yr BP) in which erosion increased as suggested by the small peaks in the MS values, thin intercalated minerogenic layers in the peat and lower LOI %. Then, at c.10200 cal yr BP, peat deposition ceased and minerogenic material was deposited at the site. Fluvial processes may have governed during this time at P12, with much more material derived from runoff being deposited at the site due to the formation of a small stream (Fig. 12).

Fig. 12. Small stream cutting through peat in the vicinity of P12 (red star). Photo by: Nathalie Van der Putten

4.1.2 Vegetation

LPAZ 1 (c.14000 cal yr BP - c.13400 cal yr BP)
The pollen record found in LPAZ 1 is predominantly characterized by the presence of grasses Poaceae*,* the cushion plants and wind tolerant A*zorella selago, Lyallia kerguelensis,* and the cabbage of the sub-Antarctic, *Pringlea antiscorbutica*. However, *Lyallia kerguelensis* and *Pringlea antiscorbutica* are not as abundant as Poaceae and *Azorella selago* at any level within this zone, with Poaceae being the dominating taxon. As for the presence of long distance taxa, there were only a few grains present within this zone, most of which have unknown sources. The slides corresponding to this pollen zone contain high quantities of minerogenic particles, corresponding with low LOI % and high MS values (Fig. 7).

During LPAZ 1 (Fig. 11), P12 and its surrounding areas possibly had very sparse vegetation, as inferred from the low LOI %, high MS values, and high amount of minerogenic particles within the slides. The vegetation at this time was likely dominated by Poaceae and *Azorella selago.* The taxon Poaceae is found in all type of terrains, while *Azorella selago* is typically found on fellfield environments, which are environments characterised by strong winds and severe weather exposure (Young and Schofield,1973;Van der Putten et al.,2012). *Lyallia kerguelensis* the endemic species of Iles Kerguelen is consistently present in this zone and it is typically found together with *Azorella selago* on exposed surfaces. *Pringlea antiscorbutica* has a rather wide distribution and can occur near the coast but also, in colder conditions and exposed surfaces. However, it always occurs io rather wet surfaces (Bartish et al., 2012).

The specific environments in which these species are typically found today suggest that LPAZ 1 represents rather cold conditions at the P12 site and its periphery. This assumption is corroborated by the available stratigraphic record, LOI %, MS readings, and the high abundance of fine minerogenic particles within the slides. Also, pollen concentrations within this zone are relatively low (Fig. 11). This evidence together indicates that during the time between c.14000 cal yr BP and c.13400 cal yr BP the P12 site and its surrounding areas were most likely barren terrains, with small patches of vegetation.

LPAZ 2 (c.13400 cal yr BP to c.12900 cal yr BP)
The boundary to LPAZ 2 is of importance, as it is here where the pollen assemblage shifts from being Poaceae dominated as found in LPAZ 1 (Fig. 11), to an *Azorella selago* dominated pollen spectrum. *Pringlea antiscorbutica* and *Lyallia kerguelensis* continue to be present in the pollen record, but with lower percentages than those found in Zone 1. Additionally, pollen

grains of the species *Crassula moschata*, a sea-spray tolerant species typically found along the coast, is found here. Remarkably, it is in this zone that the long distance pollen record suddenly expands (Fig. 11). Twenty-six different morphological types are found in LPAZ 2, including Alnus type, and the taxa Brassicaceae, Asteraceae, Podacarpaceae, to name a few (Appendix 2).

The combination of an increase in pollen from the species *Azorella selago* and the rise in the long distance pollen grains in LPAZ 2 (Fig. 11) suggest that conditions may have become increasingly windier. This assumption is made on the modern occurrence of the wind tolerant *Azorella selago*, typically found on exposed surfaces. Moreover, the exotic grains must have been carried by wind from continental masses such as southernmost South America and South Africa. The occurrence of a wide diversity of long distance taxa in this zone, which is observed more than in any other zone, suggests that wind must have been strong and persistent enough to carry pollen grains over long distances. While examining and comparing the LOI (fluctuating percentages), MS (low values), and the stratigraphic record (fine grained sediments with laminations) (Fig. 7), together with pollen data from LPAZ 2 (Fig. 11), it can be inferred that conditions at P12 may have turned increasingly windier and wetter from c.13400 cal yr BP to c.12900 cal yr BP.

LPAZ 3 (c.12900 cal yr BP to c.11300 cal yr BP)

Here, the two taxa that dominated the pollen assemblages in the first two zones (*Poaceae* and *Azorella selago*) are partly replaced by the species *Acaena magellanica* (Fig. 11). This Rosaceae species currently occurs in all environments in the archipelago. However, the species is more common at lower altitudes, and not found in modern fellfields. Optimal environments for *Acaena magellanica* to flourish in are sheltered areas with well-drained soils (Van der Putten et al.,2012).

Acaena magellanica appears in the pollen record just above LPAZ 3 at approximately 89 cm, and dominates throughout the entire zone (Fig. 11). Today, this taxa is typically confined to lower altitudes in the Kerguelen archipelago. In the pollen record, *Acaena magellanica* has been associated with more favorable conditions (Young and Schofield, 1973; Van der Putten et al., submitted). Additionally, The LPAZ 3 pollen record indicates that fellfield vegetation became less prominent after c.12900 cal yr BP, which indicate warmer and less windy conditions at P12. Also, the long distance pollen record for LPAZ 3 is made up of 11 different species, and this is roughly the same amount as in Zone 1, but significantly less than the amount of long distance grains found in LPAZ 2 (Appendix 2). It can be inferred that less windy conditions prevailed during this time.

Humidified peats found at the end of LPAZ 2 also suggests that conditions may have turned increasingly drier and warmer at P12. The LOI percentages corroborate the notion that during this time, conditions at P12 may have become more favorable, as organic matter increases throughout the zone, except for the tephra unit at the beginning of LPAZ 3 (Fig. 11).

LPAZ 4 (11300 cal yr BP to ~ 9600 cal yr BP)

This zone is characterized by the presence of a new species, the Cyperaceae species *Uncinia compacta*, which is known to inhabit drier mires, and is a representative of the lowland flora, requiring the warmest of settings (Van der Putten et al.,2012; Young and Schofield. 1973). LPAZ 4, also displays a the distinct presence of spores (Fig. 11). The spores that make up this zone are *Blechnum penna-marina* and *Lycopoduim* spp (Appendix 2). There is one species of ferns currently growing on Kerguelen. This is the fern species *Blechnum penna-marina,* which covers extensive areas on well drained slopes (Van der Putten. 2008). The presence of spores of this species in the pollen record is generally associated with warmer conditions (Young and Schofield, 1973). *Blechnum penna-marina* is typically found in lower altitudes, shelter environments; a typical constituent of lowland vegetation in the Kerguelen archipelago. The long distance pollen record contains 12 different species, roughly the same amount of long distance grains found at LPAZ 1 and 3 (Appendix 2). In general, we can infer that conditions were warmer at P12 during this time.

The stratigraphic record corresponding with pollen LPAZ 4 is mostly made up by humidified peat, suggesting that the water table was lower. As a result, conditions may have been warmer/drier at the site, allowing the expansion of *Uncinia compacta.* This Cyperaceae species is known to occur in the warmest of settings (Young and Schoifield, 1973; Van der Putten et al., 2012). However, peat production suddenly stops at 15 cm (Fig. 6), giving way to minerogenic material. Additionally, the LOI percentages are continuously very high in comparison with the rest of the sequence, until 15 cm, when the LOI values drop. The MS values, displays much more variability after 15 cm. Vegetation was more or less well established at P12 and the surrounding areas until c.10200 cal yr BP, when erosion increased. Today, small streams are seen cutting through peat around the P12 site (Fig. 12). Here, a similar process is suggested for the deposition of minerogenic material from 15 cm on.

4.2 Climatic and environmental conditions in the Kerguelen Archipelago c.14000 cal yr BP- 9700 cal yr BP

In the peat deposits of the Peninsule Courbet, approximately 50 km north east of P12 (Fig. 3), we find the Estacade site. Here, Van der Putten et al. (submitted) suggested a minimum age for deglaciation at about 16000 cal yr BP, when peat began to form. The pollen record found at the Estacade site indicates that from about 16000 cal yr BP to c.13500 cal yr BP the vegeta-

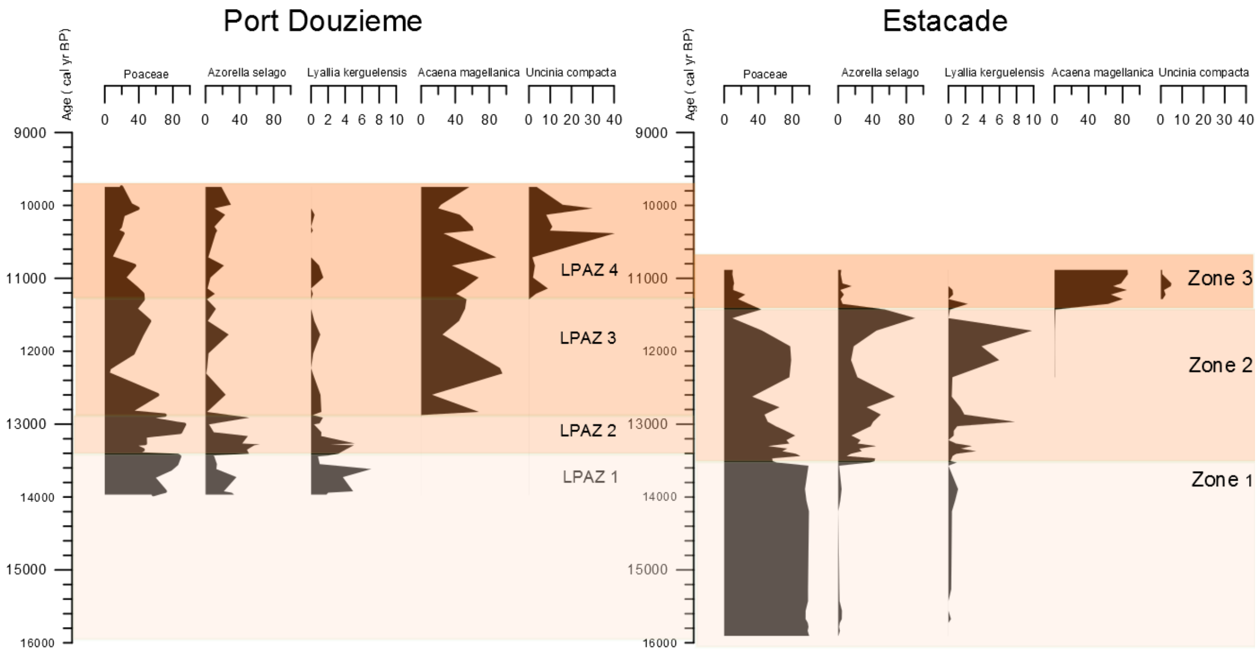


Fig. 13. Regional pollen diagram of Iles Kerguelen. Pollen data is expressed as percentages. Color bands represent similar pollen assemblage from P12 and Estacade (Van der Putten et al., submitted).

tion was dominated by Poaceae. Then from about 13500 cal yr BP the pollen record shifts from Poaceae dominated to *Azorella selago* dominated. Subsequently, at approximately 11500 cal yr BP, a sudden expansion of *Acaena magellanica* takes place, followed by the Cyperaceae species *Unicinia compacta* at about 11400 cal yr BP (Fig. 13).

Alternatively, at P12, the stratigraphic record only extends back until about 14000 cal yr BP. However, the pollen stratigraphy found at P12 shares similar features with the pollen stratigraphy from the Estacade record. Pollen LPAZ 1 from P12, which is dominated by Poaceae, is synchronous with part of the Pollen Zone 1 found at the Estacade record. Also, both records show a significant increase in the presence of *Azorella selago* in Zone 2. However, pollen Zone 2 in the Estacade record shows a more distinct increase of *Azorella selago*, while the P12 pollen record for this zone has generally lower percentages. Additionally, the cushion endemic species of Kerguelen, *Lyallia kerguelensis* is also consistently found in both records throughout Zone 2, but decreasing in importance towards the end of the zone (Fig. 13).

However, the species *Pringlea antiscorbutica* present in LPAZ 1-2 at P12, has not been recorded at Estacade. This species seems to decrease in importance towards the end of LPAZ 2, in a similar way as *Lyallia kerguelensis* (Fig. 11). Wagstaff and Hennion (2007) reported on the high sensitivity of *Lyallia kerguelensis* to dry conditions, and Bartish et al. (2012) suggested optimal terrains for *Pringlea antiscorbutica* to be wet or moist soils, corroborating that conditions may have turned increasingly drier and warmer after 12900 cal yr BP .

Although exotic grains were not counted at the Estacade site, in P12, 46 different types of non-local pollen grains were recorded (Appendix 2). The most important zone in terms of long distance grains is Zone 2 (c.13400 cal yr BP to c.12900 cal yr BP) containing 26 different long distance grains (Appendix 2). However, the main difference between the two records is found in pollen zones 3 and 4. In P12, *Acaena magellanica* suddenly expands at 12900 cal yr BP, which is 1400 yr earlier in comparison to the Estacade record. It is also important to mention that in the Estacade record, *Acaena magellanica* expands simultaneously with the species *Uncinia compacta*, contradictory to P12, where *Uncinia compacta* does not show up in the pollen record until about 1700 years later. However, both records agree by showing a dominance of *Aceane magellanica* after c.11300 cal yr BP, and a subsequently reduced importance of both Poaceae and *Azorella selago.* The strongest similarity between the two records is the sudden appearance of *Uncinia compacta* by c.11200 cal yr BP (Fig. 13).

There are some similarities in the lithostratigraphic records found at both sites. In general, the lithostratigraphic record at the Estacade site is predominantly composed of peat, while at P12, the lowermost 87 cm corresponding to LPAZ 1 are mainly comprised of minerogenic material ranging from gravel to clay with some organic matter. Despite this, both records display similar sediments within pollen Zone 2. The sediments found here are lacustrine type sediments; clayey-silty sediments with laminations. Van der Putten et al. (submitted) interpreted these sediments as peat pond sediments formed under shallow ponds that form on peat surfaces (Fig. 10). They suggested that the input of minerogenic material to the peat ponds was most likely due to wind activity. As mentioned previously, pollen Zone 2 is dominated by the wind tolerant taxa *Azorella selago* and *Lyallia kerguelensis*, typical fellfield plants of the region (Fig. 13). Also, the presence of a wide range of long distance pollen grains in this zone suggests that this may have been a windier period (Appendix 2).

The peat from 115 cm-100 cm corresponding to pollen LPAZ 2 at P12 is a well preserved peat (Fig. 6), suggesting that the water table was likely high during this time, consistent with the Estacade record. In general, based on stratigraphic and pollen records from both P12 and Estacade sites, it can be inferred that from about 13400 cal yr BP to c.12900 cal yr BP the climate of the Kerguelen archipelago became increasingly wetter and windier.

The stratigraphic record corresponding to pollen zones 3 and 4 at P12 are also comparable with the stratigraphic record corresponding to pollen Zone 3 at the Estacade site. These zones are predominantly composed of peats with less well preserved organic matter, suggesting that the water table may have been lower during this time (c.12900 cal yr BP to c.9600 cal yr BP). However, at the onset of pollen LPAZ 3 in P12, the lithostratigraphic record is very different from any part of the lithostratigraphic record found during pollen Zone 3 at the Estacade site. The lowermost 13 cm of pollen LPAZ 3 at P12 is made up of a tephrish layer (Appendix 1). It is not clear whether this tephra rich unit was deposited during a volcanic eruption, or if it consists of older reworked tephra transported by runoff or increased erosion in the catchment. The onset of the tephra layer may be regarded as the result of an eruption, as numerous small glass shards were found in a sample at 88 cm (B. Moine, pers. comm.). As the landscape was covered by ash, subsequent in-wash of volcanic deposits could have occurred. Pollen concentrations of the native phanerogams in this tephra unit are relatively low in comparison with other units. Low concentrations can suggest that unit I was rapidly deposited. What is even more puzzling about this unit is that the deposition of tephra coincides with the sudden appearance of *Acaena magellanica*, about 1400 yr earlier than the appearance of *Acaena magellanica* at the Estacade site (Fig. 13). This evidence suggest that regional conditons may have been favorable enough by c.12900 cal yr, enhancing the expansion of the taxa *Acaena magellanica* at P12 and its periphery, contradicting the Estacade record findings. More radiocarbon dates must be obtained just below and above the tephra rich unit in order to resolve this important question. However, evidence from P12 does corroborate that the fellfield type community seems to be less predominant by the end of the glacial-interglacial transition, giving way to the so called lowland communities composed of *Acaena magellanica* and *Uncinia compacta* and ferns.

Two possible scenarios are put forward to explain the sudden increase of *Acaena magellanica* pollen at the base of the tephra rich unit in P12. According to the first one, tephra was deposited by a volcanic eruption, most likely from Rallier du Baty in the south west of Kerguelen (B. Moine) (Fig. 3). The vegetation dominated by *Azorella selago*, *Lyallia kerguelensis* and Poaceae was subsequently reduced. *Acaena magellanica* was already present before the volcanic event, but when conditions were right and the appropriate ecological space was available, *Acaena magellanica* began to thrive in small communities in a poorly vegetated environment. Given the availability of sediment and the lack of vegetation, the tephra would be easily transported and reworked during periods of torrential rain. Pollen concentrations are relatively low in this unit, which indicates that this unit was rapidly deposited, and thus a volcanic event may be a possible explanation. However, a major flaw with this hypothesis is lack of information related to volcanic activity in the area, particularly for the period between c.12900 cal yr BP and c.12300 ca yr BP, assuming that the chronology implemented in this study is reliable, as it was built with only four radiocarbon dates (Fig. 8).

A second hypothesis to explain the sudden increase of *Acaena magellanica* pollen at the base of the tephra rich unit in P12 is an increase of precipitation or a single event such as a storm, enhancing the hydrological cycle at the archipelago, consequently increasing erosion. It is not hard to imagine volcanic sediments being easily eroded and re-deposited, as exposed tephra dunes are common of the landscape in the archipelago (Van der Putten, pers. comm.). Also conditions must have been favorable enough for *Acaena magellanica* to be present in the area at about 12900 cal yr BP (Fig. 11), with small communities of this lowland species well established by this time at the site or in the periphery of the site. The presence and high abundance of diatoms in some parts of this tephra rich unit suggest that these sediments may have been deposited by fluvial activity rather than by solely volcanic processes. Increased runoff would not only redeposit readily available sediment, but also increase the concentration of pollen grains of a common species within this environment. However, pollen concentrations corresponding to this tephra unit are somewhat low for all of the native phanerogams, contradicting this hypothesis.

Based on the stratigraphic record and pollen data from both P12 and the Estacade sites, we can infer that after deglaciation c.16000 cal yr BP, the vegetation of the Kerguelen archipelago was dominated by grasses and small communities of the wind tolerant species *Azorella selago* and *Lyallia kerguelensis*, and the presence of *Pringlea antiscorbutica* on wet soils. Then, at about 13400 cal yr BP, conditions may have turned progressively wetter and windier, forming shallow water bodies on the surface of peat (Fig. 10). At this time the vegetation was dominated by typical fellfield communities. The wind tolerant species *Azorella selago* dominated the landscape, and small communities of the endemic species *Lyallia kerguelensis* were regularly present.

At about 12900 cal yr BP, conditions on the archipelago became warmer, allowing higher biological productivity and the establishment of the "lowland" species *Acaena magellanica*. However, it was not until c.11300 cal yr BP that conditions became much drier as well as warmer, allowing the full establishment of *Acaena magellanica* and the presence of plant communities in sheltered areas made up by *Uncinia compacta, Blechnum penna-marina,* and *Lycopodium* sp. (Appendix 2).

4.3 Late glacial and early Holocene climatic conditions in the Kerguelen archipelago in a Southern Hemisphere context

Post LGM warming on the Antarctic continent is believed to have begun at about 18350 cal yr BP (e.g. Stenni et al., 2011). In the Kerguelen archipelago, the oldest reported basal radiocarbon date of a peat sequence is c.16000 cal yr BP, which can be regarded as a minimum age for deglaciation, at least in the eastern part of the archipelago (Hodgson et al., 2014; Van der Putten et al., submitted). The sequence from P12 only extends back to c. 14000 cal yr BP (Fig. 8), but the pollen record suggests that a sparsely vegetated environment was already in place by the beginning of the record. Both of the pollen records available from Iles Kerguelen (Estacade and P12) suggest that Poaceae was the dominant species until about 13400 cal yr BP (Fig. 13). Thereafter, in Pollen zone 2 (c.13400 cal yr BP- 12900 cal yr BP), the wind tolerant species *Azorella selago* and *Lyallia kerguelensis* dominate the pollen spectra in both records. In previous studies, increased percentages in the pollen record associated with the upland species *Azorella selago*, have been interpreted as reflecting colder periods (Bellair and Delibrias, 1967; Roche-Bellair, 1976a; Schalke and van Zinderen Bakker, 1971; Young and Schofield, 1973).

However, in the recently studied sequence from the Estacade site, Van der Putten et al. (submitted) inferred windier and wetter conditions from about 13650 to about 12950 cal yr BP, based on the formation of peat ponds and sudden expansions of the wind tolerant species *Azorella selago* and *Lyallia kerguelensis,* in both the pollen and macrofossil record. Subsequently, a decrease in wind intensity was suggested from 12950 cal yr BP, based on the decreased presence of *Azorella selago* in the macrofossil record, while in the pollen record *Azorella selago* was persistently high. This, along with the increasing presence of the algae *Botryococcus*, which thrives in protected environments, as well as a decreased input of minerogenic material, supports the hypothesis of less windy conditions (Van der Putten et al., submitted).

At P12, lacustrine-type-sediments, followed by well-preserved peats, occur within the dating errors synchronously with lacustrine sediments at the Estacade site. In this study, the lacustrine-type-sediments are also interpreted to have been deposited during the formation of peat ponds (Fig. 10). Similarly, both pollen records reflect an increase of the species *Azorella selago* at about 13400 cal yr BP, however, the species seems to have been less important at P12 (Fig. 13). This may reflect differences in preservation or fewer individuals locally at the site.

Additionally, 26 morphologically distinct types of long distance pollen grains were found within Zone 2 at P12, which were not detected in the Estacade record. Various studies have associated the presence of exotic pollen grains on remote islands with atmospheric circulation changes (Scott & van Zinderen Bakker.,1985; Björck et al., 1993; van der Knaap et al., 2012; Strother et al., 2015). Two of the most interesting constituents of the exotic pollen record from P12 are the identified grains of Podocarpaceae and *Alnus*. Podocarpaceae occurs today in both South America and South Africa, typically in high elevation, wet montane forests (Hansen.,1995; Beuning et al., 2011), while *Alnus* is only found in South America. However, questions still remain whether the *Alnus* grains were introduced during pollen preparation or if it was deposited in situ. *Alnus* is commonly found in Europe (Sweden and Belgium), places in which the cores and samples were handled. However, if the presence of *Alnus* was due to contamination, it is rather strange that no other pollen grains from common European trees were detected in the samples. There are also more general questions about the significance of the exotic pollen grains. It is not known whether these grains represent increased wind intensity, changes in vegetation at the source area of the exotics, especially during the last glacial-interglacial transition, or both (e.g. van der Knaap et al., 2012).

The sudden increase of *Azorella selago,* the presence of long distance pollen grains, and the lithostratigraphy in LPAZ 2 (c. 13400 - 12900 cal yr BP) at P12 together with the inferred windy conditions from the Estacade record suggests stronger winds and wetter conditions in the Kerguelen archipelago. Today, the Kerguelen archipelago is situated in the core of the SHW (Van der Putten et al., submitted) making conditions rainy and wet on the archipelago. A study by Moreno et al. (2001) at 41° S in the Chilean Lake District, suggests cooler conditions between c.15200 - c.13500 cal yr BP and an expansion of Podocarpaceae at about 13800 cal yr BP, which is within the dating uncertainties of the *Azorella selago* expansion, as well as the presence of Podocarpaceae in the P12 pollen record at about c.13450 cal yr BP. However, more radiocarbon dates are needed from the P12 sequence to establish a more reliable chronology, and to properly correlate with the findings of e.g. Moreno et al. (2001).

During the ACR, it is hypothesized that the SHW were positioned north of their current location, reducing CO_2 ventilation, and bringing colder conditions to the mid-high latitudes in the SH (e.g. Toggweiler et al., 2006; Anderson and Burckle, 2009).

However, conditions were not cold enough to suppress the expansion of vegetation in the Kerguelen archipelago. The Estacade record suggests a minimum age for deglaciation at c. 16000 yr cal BP when peat began to form (Van der Putten et al., submitted), while at P12 evidence suggests a sparsely vegetated environment by c. 14000 cal yr BP.

Stenni et al. (2001) suggested the occurrence of an Oceanic Cold Reversal (c. 13600 cal yr BP- c. 11600 cal yr BP) recorded in the EPICA Dome C ice record (based on deuterium excess), which draws its majority of moisture from the southern Indian Ocean (Fig. 1). Whether the OCR is a change in sea surface temperature in the source area of Dome C or a shift in the source area is still debated (Stenni et al., 2011). At Iles Kerguelen, Van der Putten et al. (submitted) found evidence for the onset of the OCR as it is at 13650 cal yr BP that most proxies from the Estacade record display a major change suggesting a strengthening of the SHW. This is consistent with the evidence from P12 showing increases in *Azorella selago* and long distance pollen at roughly 13500 cal yr BP (Fig. 11). In the present study, this evidence is attributed to strengthening of SHW. However, it is difficult to say whether the strengthening was solely caused by the onset of the OCR, as the OCR took place within the ACR.

In LPAZ 3 of the P12 record, Aceana magellanica suddenly increases at c.12900 (Fig. 11), coinciding with the end of the ACR and the onset of the Younger Dryas (YD) in the NH (e.g. Rasmussen et al., 2006). Today, this species is typically found in low altitude, sheltered areas in the Kerguelen archipelago. It has been suggested that drier/warmer conditions prevailed at the southern mid-high latitudes at the end of the ACR (e.g. Denton et al., 2010). Rapid cooling during YD resulted in a southerly shift of the ITCZ, pushing the SHW south closer to the Antarctic divergence, and enhancing ventilation of CO_2 to the atmosphere (Anderson et al., 2009; Denton et al., 2010; Lamy et al. 2010, Toggweiler et al., 2006). Interestingly enough, the stratigraphic record at P12 suddenly changes from peat to the mysterious tephra rich unit at c.12900 cal yr BP. The question still remains whether this tephra unit is associated with a volcanic eruption or older reworked sediments, although the first hypothesis is more probable based on the presence of numerous glass shards, at least at the onset of the tephra rich unit (B. Moine, pers. comm.). In the Estacade record, Van der Putten et al. (submitted) suggested slightly drier, less windy conditions after c. 12900 cal yr BP, based on the multi-proxy record of the Estacade sequence. Less windy conditions, possibly due to a more southerly positioning of the SHW, are supported by the decrease in long distance pollen at P12. However, further dating needs to be made at the onset of the *Acaena magellanica* expansion at P12 in order to test whether the increase in pollen of this species is associated with the end of the ACR.

What is very clearly reflected in the terrestrial records of the Kerguelen archipelago is that conditions became increasingly warmer by c. 11400 cal yr BP. By this time, it appears that the lowland species *Acaena magellanica* was established at both Estacade and P12. Finally, the two species that need the most sheltered and probably warmest environment, *Uncinia compacta* and *Blechnum penna-marina* (Young and Schofield, 1973), appear in both pollen records at about 11200-11400 cal yr BP (Fig. 13), coinciding with the early Holocene climatic optimum found in the Antarctic ice records (Masson et al., 2000).

5 Conclusions

A general vegetation pattern could be observed from the Port Douzieme pollen record. Poaceae is the dominating species from the beginning of the record at c.14000 cal yr BP. Then the wind tolerant, cushion plant *Azorella selago* expanded, and became a much more influential species at c. 13600 cal yr BP and until c.12900 cal yr BP, when the lowland species *Acaena magellanica* suddenly expanded, becoming the dominating species until c.9700 cal yr BP. Finally, the species *Uncinia compacta*, and *Blechnum penna marina*, which represent the warmest of settings on the Kerguelen archipelago show up on the pollen record at about 11200 cal yr BP. This vegetation pattern can be correlated with findings from the Estacade pollen record Van der Putten et al. submitted, suggesting that this may have been a regional vegetation history since the onset of peat accumulation about 16000 cal yr BP.

Additionally, the pollen record from P12 revealed higher influence of the SHW, at about 13600 cal yr BP, when a great diversity in long distance pollen grains is recorded, and which were not accounted for by Van der putten et al. (submitted), coinciding with the expansion of the wind tolerant species *Azorella selago,* as well as the presence of lacustrine-type-sediments at both the Estacade site and P12.

Also, the presence of the endemic species *Lyallia kerguelensis* and *Pringlea antiscorbutica* since the beginning of the record at c. 14000 cal yr BP, further strengthens the notion that contemporary native phanerogams were present before the Holocene and mostlikely survived major glaciations in refugia (Van der Putten et al., 2010).

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Appendix 1

Core description Table

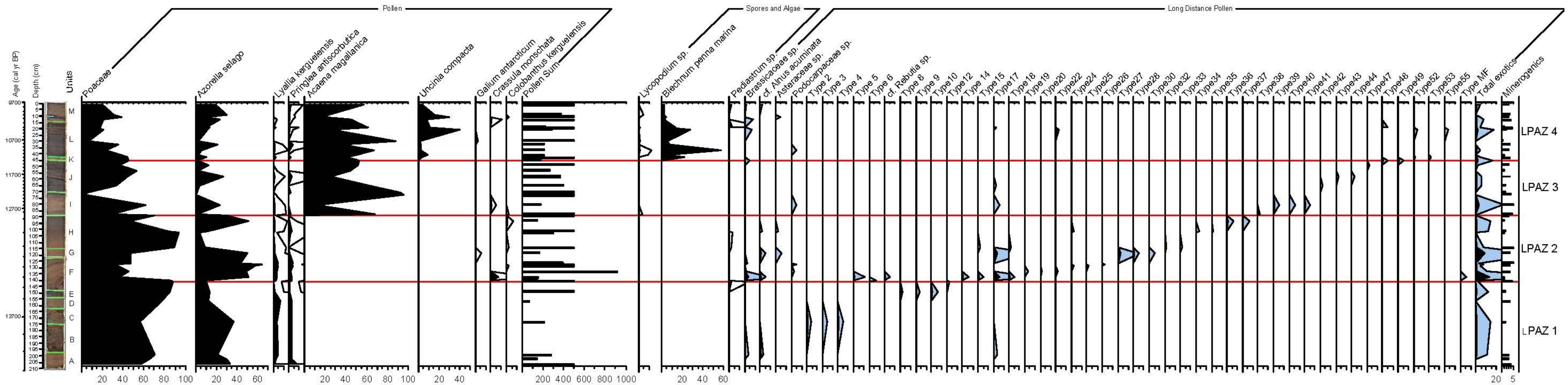
Description	Color	Comments
210-208 cm medium-coarse sand -some silt	Brown	Plant material found. Erosional upper boundary.
208-204 cm clay gyttja	Brown	Less water content than the following section. Plant material present.
204-202 cm clay gyttja	Dark brown	Contains black spots and organic material and high water content.
202-198 cm silty-clay gyttja	Brown	Organic material/plant material present. Erosional upper boundary.
198-176 cm gravelly unit	Greyish-brownish	Some of the clasts have a burgundy tarnish. It fines upwards and it contains a gravel supported matrix. Plant material is present. Upper boundary is gradual. Unsorted.
176-170 cm silty gyttja sand	Brownish-greyish	High water content and plant material present. Gradual upper boundary.
170-167 cm sand	Brownish-greyish	Well sorted sediment, with Plant material. Upper boundary is erosive.
167-161 cm gravely	Brownish-greyish	Contains big oxidized clasts as big as 3-4 cm. Igneous rocks?
161-153 cm silty clay gyttja	Brown	Contains some plant material.
153-148 cm well decomposed peat	Dark brown- Blackish	With very muddy water released when squeezed. Erosional upper boundary; 1cm clasts present at the upper boundary.
148-146 cm clay gyttja	Dark brown	With a high water content and organic material.
146-140.5 cm clay gyttja	Dark brown	With a high water content and plant material.
140.5-139 cm clay gyttja	Light brown	With very sticky clay (high water content?). Plant material present.
139-136 cm silty gyttja	Brownish-greyish	Organic material present; black dots. Upper boundary is gradual.
136-134.5 cm clay gyttja	Greenish- brownish	With different color shades and plant material is present.
134.5-133 cm clay gyttja	**Brown (darker shade)**	**Very sticky and more humidified. Contains more organic material than preceding sections. Upper boundary is gradual.**
133-128 cm clay gyttja	**Brown**	**some organic material is present. Upper boundary is gradual.**
128-127 cm Peat	Black	Upper boundary is gradual
127-123 cm silty gyttja	Brown	plant material present.
123- 118 cm sandy silty peat	Grayish –brownish	With bigger particles than the preceding section and plant material.
118-115 cm silty sand	Light grey	plant fragments.
115-102 cm well preserved sedge peat.	Light brown	Less humidified.
102-88 **cm** moderately decomposed peat	Dark brown	very muddy water and granular peat released when squeezed. Plant fragments are visible. Erosive upper boundary.

88-71 cm silty gyttja with some clay. Tephra rich unit?	**Light brown**	**fining upwards. Plant fragments are present along with black patches (organics?)**
71-70 cm moderately decomposed peat.	Dark brown	
70-69cm slightly decomposed peat.	Light brown	
69-59 cm moderately decomposed peat	Dark brown	very muddy water and granular peat released when squeezed. Sediment is consolidated. Plant fragments are present.
59-57 cm sandy-silty peat	Light brown	lots of minerogenic particles; some particles are as big as 1 cm. Plant fragments present. Gradual upper boundary.
57-52 cm moderately decomposed peat	Light (lighter shade than preceding section) brown	very muddy water and granular peat released when squeezed. Minerogenic particles are present.
52-48 cm slightly decomposed peat	Dark brown	very muddy water released when squeezed. Friable or non-consolidated sediment.
48-44.5 cm almost entirely undecomposed peat	Dark brown	clear or yellowish water released when squeezed. Plant material is present, and the sediment is consolidated.

44.5-42.5 cm gyttja sand	**Light brown**	**particles as big as 0.5 cm. Plant remains are present. Erosive upper boundary.**
42.5- 40 cm moderately decomposed peat	Dark brown	Plant remains and minerogenic particles are present.
40-33 cm moderately decomposed peat	Dark brown	very muddy water and some granular peat released when squeezed. Plant remains are present.
33-32 cm moderately decomposed peat	Light brown	
32-24 cm moderately decomposed peat	Dark brown (darker shade)	very muddy water along with a very small amount of granular peat released when squeezed. Plant fragments present.
24-20.5 cm very slightly decomposed peat	Dark brown	with muddy brown water released when squeezed. Plant remains present.
20.5-19.5 cm silty gyttja	Light brown	Plant remains present.
19.5-15 cm slightly decomposed peat	Dark brown	very muddy water released when squeezed. Plant remains are present.
15-12 cm gyttja sandy silt	Light brown	With consolidated sediment and very small pebbles. Upper boundary is gradual.
12-10 cm almost entirely undecomposed peat	Dark brown	yellowish water released when squeezed. Plant remains are present.
10-0 cm gyttja sand	Brown	with pebbles ranging from 1 mm- 2 cm. The sediment is consolidated and plant remains are present.

Appendix 2

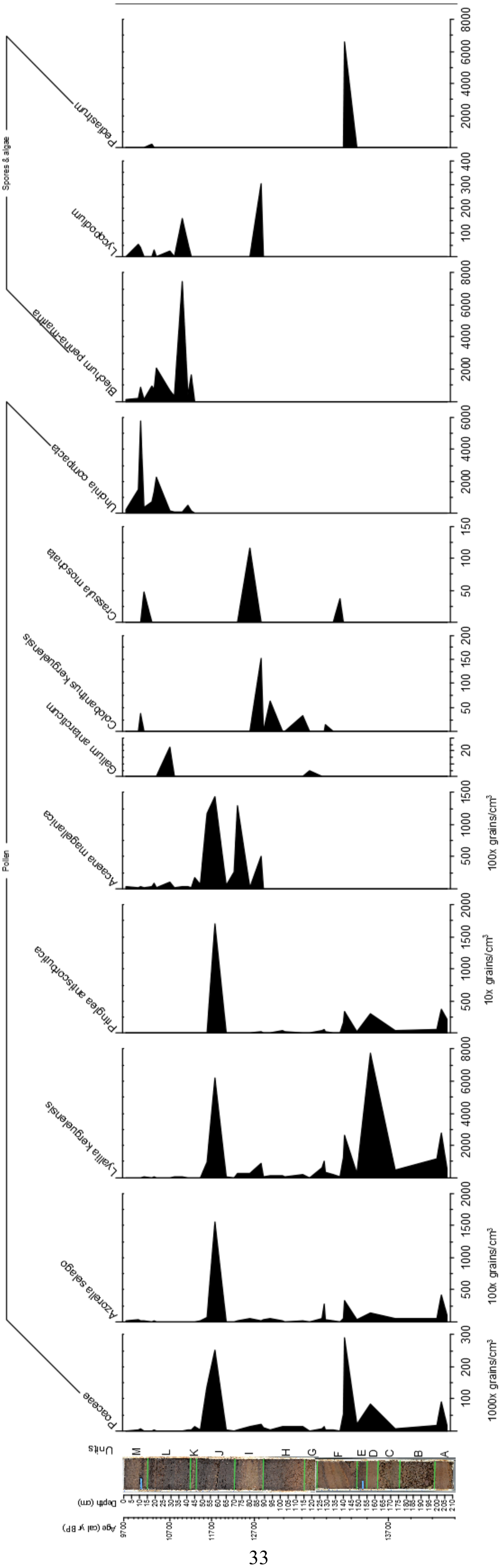
Pollen diagram P12



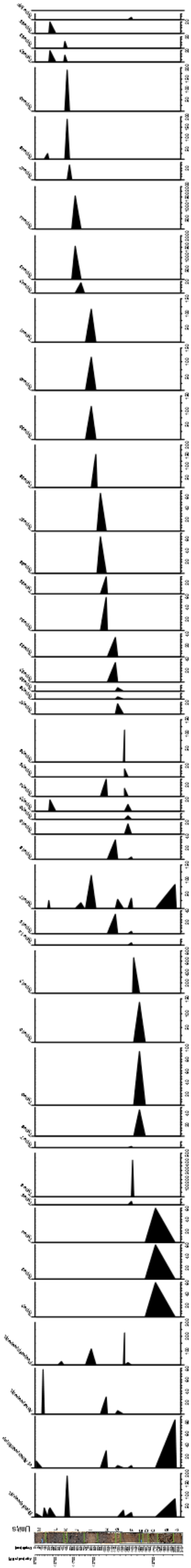
Complete pollen diagram with corresponding depth (cm) and units (A-M) displaying native phanerogam taxa and Long distance (exotics) pollen. Pollen data is expressed as percentages, pollen sum as the sum of total native phanerogam taxa (not including *Blechnum penna-marina*). Exotics data is expressed as percentages. Minerogenic and diatoms are expressed as 1 (lowest) to 5 (highest). 10x exaggeration was used Lyallia, Pringela, Galium, Colobanthus, Crassula and exotics.

Appendix 3

Pollen concentrations (grains/ cm^3)



Appendix 4



Exotic pollen concentrations (grains/ cm^3)

Vegetation types and endemic species

Sea–salt tolerant Vegetation type

Crassula moschata (yellow plant) and *Leptinella plumose* (green plant)

Lowland Vegetation type

Acaena magellanica (red plant) and *Blechnum penna -marina* (fern)

Fellfield Vegetation type

Azorella selago

Photos: Bart Van de Vijver

Mire Vegetation type

Bryophytes, *Juncus scheuchzeriodes* and *Ranunculus biternatus*

Photo: Nathalie Van der Putten

Endemic species of Iles Kerguelen

Lyallia kerguelensis

Photo: Wagstaff and Hennion, 2007

Endemic species of the KPZ

Pringlea antiscorbutica

Photo: Francoise Hennion

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