Environmental processes in Rano Aroi (Easter Island) peat geochemistry forced by climate variability during the last 70 kyr

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A B S T R A C T

We analyze the geochemistry of Rano Aroi mire record (Easter Island) using bulk peat composition (C, N, S) and stable isotopes (δ13C, δ15N, δ34S) and major, minor and trace elemental compositions obtained by ICP-AES (Al, Ti, Zr, Sc, V, Y, Fe, Mn, Th, Ba, Ca, Mg and Sr). Peat geochemistry and the pollen record are used to reconstruct the environmental changes during the last 70 kyr BP. Principal component analysis on ICP-AES data revealed that three main components account for the chemical signatures of the peat. The first component, characterized by lithogenic elements (combined signal of V, Al, Sc, Y, Cr, Cd, Ti, Zr and Cu), evidences long-term changes in the basal mineral material into the mire. This component, in combination with stable isotopes and pollen data suggests a link between soil erosion and vegetation cover changes in the Rano Aroi watershed. The second component is identified by the signal of Fe, Mn, Th, Ba, Zr and Ti, and is indicative of strong runoff events during enhanced precipitation periods. The third component (tied mainly to Ca, Sr and Mg) reflects a strong peat oxidation event that occurred during an arid period with more frequent droughts, sometime between 39 and 31 kyr BP. Correlation coefficients and a multiple regression model (PCR analysis) between peat organic chemistry and the principal components of ICP-AES data were calculated. Isotope chemistry of the peat organic matter further contributes to define Rano Aroi environmental history: δ13C data corroborates a vegetation shift documented by the palynological record from C4 to C3, between 55 and 45 cal kyr BP; the δ15N record identifies periods of changes in mire productivity and denitrification processes, while the δ34S peat signature indicates a marine origin of S and significant diagenetic cycling. The geochemical and environmental evolution of Rano Aroi mire is coherent with the regional climatic variability and suggests that climate was the main forcing in mire evolution during the last 70 kyr BP. The coupling of geochemical and biological proxies improves our ability to decipher depositional processes in tropical and subtropical peatlands and to use these sequences for paleoenvironmental and paleoclimate reconstructions.

1. Introduction

Peatlands are paleoenvironmental archives capable of registering atmospheric, hydrological and ecological changes in the past (Jackson and Charman, 2010). Researchers have traditionally studied peat accumulation and decay dynamics (Clymo, 1984), and attempted to understand the contribution of these organic soils to the global carbon cycle (Gorham, 1991), as well as to reconstruct paleoecological changes using macrofossils, pollen (Barber et al., 2003; Birks and Birks, 2006) and charcoal remains (Whitlock and Larsen, 2001). In more recent times, inorganic geochemical proxies from peat sequences have increasingly been used to obtain high-resolution climatic and environmental reconstructions. For example, wind regime variability has been inferred from changes in the chemical concentrations of dust particles trapped in the peat (Kyllander et al., 2005; Martínez Cortizas et al., 2002, 2007, 2007b; Shotyk, 1996; Shotyk et al. 2001;), and changes in vegetation cover and wet to dry transitions from geochemical compositions of mires (Muller et al., 2008; Kylander et al., 2013).

A complementary biogeochemical approach to mire studies focuses on the characterization of the peat organic matter, through the determination of isotopic signatures (δD, δ13C, δ15N, δ18O, δ34S) or its molecular...
composition (Buurman et al., 2006; Hong et al., 2001; Kaal et al., 2007; Loisel et al., 2010; Schellekens et al., 2011; Tillman et al., 2010). The δ13C has been applied on bulk peat or isolated compounds as a tool to explore the origin of the carbon (C3, C4 plants or aquatic origin) because photosynthesis fractionation is commonly preserved (Meyers, 2003). Moreover, δ13C together with δ15N can track hydrologic changes such as wet to dry transitions or changes in the precipitation–evaporation balance (Hong et al., 2001). Stable isotopes can also be valuable indicators of organic matter origin and decay (δ13C, δ15N) (Talbot and Johannessen, 1992; Aucour et al., 1999), and redox changes (δ13N, δ34S) (Talbot and Johannessen, 1992; Nővák et al., 1999; Jedrysek and Skrzypek, 2005).

The majority of mire studies focus mainly on climate or environmental reconstructions using peat cores from ombrotrophic boreal and temperate mires of the Northern Hemisphere (Clymo et al., 1984; Skoty, 1996; Chambers and Charman, 2004; Gorham and Janssens, 2005; Jackson and Charman, 2010). While receiving increasing attention during the last decades, peatlands in the Southern Hemisphere remain substantially less explored. Few studies have attempted to reconstruct environmental changes on tropical and subtropical mires (Weiss et al., 2002; Kylander et al., 2007; Muller et al., 2008; Page et al., 2010; Dommair et al., 2011). This study presents organic and inorganic biogeochemical data, including pollen analysis from the oldest Southern Hemisphere peat deposit studied to date (Easter Island), to track the environmental changes of the last ~70 kyr BP. While numerous studies have revealed the environmental changes on Easter Island using lacustrine sediments (Azizi and Flenley, 2008; Cañellas-Boltà et al., 2012; Cañellas-Boltà et al., 2013; Flenley and King, 1984; Flenley et al., 1991; Horrocks et al., 2012a, Horrocks et al., 2012b; Mann et al., 2008; Sáez et al., 2009), fewer works have been carried out on the Easter Island peat sequences. The Rano Aroi peat record has been analyzed using pollen (Flenley et al., 1991, Pette et al., 2003) and XRF core scanner and stable isotope data (Margalet et al., 2013). Margalet et al. (2013) combined facies and macrofossil descriptions, bulk peat total carbon (TC), and total nitrogen (TN) and δ13C data with XRF core scanner data (Ca, Fe and Ti elements) data to reconstruct environmental history of the site at a millennial time scale. However, to fully reveal the complex interactions and processes controlling the geochemical signatures at Rano Aroi such as soil dust, flood events, droughts and redox changes, more comprehensive geochemical analyses are needed. Therefore, in this paper, we analyzed bulk peat samples to obtain absolute concentrations of sixteen elements (Al, Fe, Ti, Ca, Mg, Sr, Y, Zr, Ba, Sc, V, Cr, Mn, Cu, Cd, Th). This geochemical dataset is complemented with TC, TN, TS content and the isotopic composition (δ13C, δ15N, δ34S) of the peat and pollen data. Only a few previous studies are based on such a broad dataset including chemical and biological data from the same peat record (Muller, 2006). This comprehensive approach combining inorganic and organic geochemistry reinforced by pollen analysis allows us to establish links between vegetation changes, mineral inputs and biogeochemical processes within peat as a response to autogenic and external forcing. The results improve our understanding of tropical and subtropical peat dynamics and the environmental and climatic history of Easter Island since MIS 4 (~70 cal kyr BP).

2. Study site

Easter Island (27° 07’S, 109° 22’W), known as Rapa Nui in the local language, is a small volcanic island situated on the edge of South Pacific Convergence Zone (SPCZ), Intertropical Convergence Zone (ITCZ) and South Pacific Anticyclone (SPA), the three main features that determine the South Pacific climatic configuration (Fig. 1). The climate is subtropical, with monthly average temperatures between 18 (August) and 24 °C (February) and an extremely variable annual precipitation ranging from 500 to 1800 mm.

There are three permanent water bodies on the island, two lakes (Rano Raraku and Rano Kao) and a mire (Rano Aroi) formed in a volcanic crater. The smooth slopes of the inner part of the volcanic cone constitute the catchment (15.82 ha). The crater itself is near the highest summit of the island, Mauna Terevaka (511 m a.s.l.), composed by highly porific olivinic tholeiite, hawaiite, and basaltic lava flows (Baker 1974, González-Ferran et al., 2004) and covered by andosols. The surface vegetation of the mire is characterized by Scorpius californicus, Polygonum acuminatum, Asplenium polydon var. squamulosum, Vittaria elongata and Cyclosorus interruptus, while the surrounding area is covered by grasslands and a small eucalyptus forest planted during the 1960s (Rull et al., 2010a). Rano Aroi is a minerotrophic fen, fed by rainfall and groundwater; hydrogeological and isotopic studies confirm that the system represents a perched spring connected to the main island aquifer (Herrera and Custodio, 2008; Margalet et al., 2013).

3. Methodology

In March 2006, a 14 m deep peat core (ARO 06 01) was collected in eleven sections from the central part of the mire with a UWITEC® corer, a modular percussion piston coring system. The first two meters of the sequence was not kept to avoid potential anthropic remobilization as described in the central part of the mire previously (Flenley and King, 1984; Flenley et al., 1991). The core sections were sealed, packed, transported to the laboratory and stored at 4 °C until sampling. Core sections were split longitudinally, imaged and the peat facies were described.

3.1. Geochemical analyses

3.1.1. On the core sections

The core was sampled every 5 cm for total carbon, nitrogen and sulfur (TC, TN, TS) and stable isotope (δ13C, δ15N, δ34S) analyses. The 218 samples were dried at 60 °C over 48 h, frozen with liquid nitrogen.
After sonication and evaporation at 50 °C an additional cycle of H2O2 was followed by a 2 day closed vessel digestion at 90 °C with HNO3. Half a day samples were then sonicated and evaporated at 50 °C. This ing solution was then transferred to Savillex vessels and evaporated on stage ramp to 200 °C where samples were held for 20 min. The remaining solution was then transferred to Savillex vessels and evaporated on a hotplate at 50 °C. Thereafter H2O2 was added and allowed to react for half a day. Samples were then sonicated and evaporated at 50 °C. This was followed by a 2 day closed vessel digestion at 90 °C with HNO3. After sonication and evaporation at 50 °C an additional cycle of H2O2 was made. Samples were once again evaporated and then taken up in 1% HNO3 for analysis. The samples were analyzed for elemental concentrations using a Varian Vista AX ICP-AES at the Department of Geological Sciences, Stockholm University, Sweden.

A suite of twenty elements was acquired including Al, Ba, Ca, Cd, Cr, Cu, K, Fe, Li, Mg, Mn, Na, Sc, Sr, Ti, Th, V, Y, Zn and Zr. To date, there is no certified reference material for peat that offers a wide range of elemental data. There is however a peat reference material NIMT/UEF/FM/001 that was tested and analyzed by Yafa et al. (2004). The analytical performance was thus assessed using this material as well as NIST SRM-2711a Montana Soil and NIST SRM-2586 Trace Elements in Soil. Five procedural replicates were made of each reference material. For NIMT/UEF/FM/001, our peat reference material, most elemental recoveries were high, ranging from 99% to 119%. Cadmium however had even higher recoveries (128%) while low recoveries were recorded for Ti (63%). For the other two reference materials, both soils, recoveries were much lower. For NIST SRM-2586 recoveries range from 70 to 91% for Al, Ba, Ca, Mg, Sc, Sr and Y and 53–66% for Cd, C, Fe, Mn, V and Zn. Again Ti had exceptionally low recoveries (44%) while Th had concentrations double the recommended values. For NIST SRM 2711a recoveries ranged between 64 and 84% with the exception of Ti (42%) and Th again had concentrations double the recommended values. Replicates of the reference materials were generally within 20% or better of each other. Procedural blanks were below 3% of the average sample concentrations for the majority of the elements. Slightly higher blanks were found for Al and Mn (<5%), Ba and Cr (<12%) and Zr (<32%).

While the original intention was to make a total digestion of the peat samples, the reference materials suggest that this may not be the case. Although the recoveries for the peat reference material are high, the recoveries for the reference soils are much lower. Nonetheless, in a paleoenvironmental context the relative changes of the elements can still reveal past changes. For this reason all elements, even those with lower (Ti, for example) or higher recoveries (Th, for example) or potentially high blanks (Zr, for example) were included in our interpretation. Some elements were removed from the dataset because of low concentrations in the peat samples (Li and K), contamination during sampling (Zn) or because the concentrations were close to the analytical detection limits (Na). In the case of Th and Zr particularly, both elements present high communalities in the PCA, suggesting that their signals are not just analytical noise, and their behavior has a coherent paleoenvironmental significance.

### 3.1.2. Rock and soil analyses

Determination of the elemental composition of rocks and surface soil samples from Rano Aroi and Rano Raraku craters and other parts of the island was performed on 16 samples. All soil samples (5 samples, see Supporting information) were obtained from the surroundings of Rano Raraku crater, while rock samples (11 samples, see Supporting information) were collected around the Rano Aroi, Rano Raraku craters and other parts of the island. All samples were ground in a ring mill and dried at 60 °C for 24 h. Each 0.1 g of sample was then digested using a mixture of 2.5 ml HNO3 + 5 ml HF + 2.5 ml HClO4 in Teflon tubes at 135 °C for 12 h. Finally, 1 ml of HNO3 and 5 ml of purified water were added to dilute the sample for analysis. The analyses were carried out with a high-resolution ICP-MS (HR-ICP-MS), Element XR Thermo Scientific located at the LabGEOTOP service of the Institute of Earth Sciences Jaume Almera-CSIC (Barcelona). Twenty-three elements were measured. Results are provided in the Supporting information (Table 1).

### 3.2. Pollen analysis

A subset of 25 samples (3–4 g of wet peat) equally distributed along the record was extracted from Rano Aroi peat record and processed for pollen analysis using standard laboratory procedures by Rull et al. (2010b), which includes sieving, digestions with KOH, HCl and HF, and acetolysis. As an exotic marker, one spore table of Lycopodium (Batch No. 177745, Lund University, Sweden) per gram was added to each sample before processing. The slides were mounted in silicone oil (not permanents) to be counted under optical microscope using >40 and ×60 objectives mounted on a ZEISS® microscope with ×10 ocular (ZEISS® Axioplan, ZEISS® Axiostar plus, ZEISS® Axio Scope A1 and ZEISS® Axio Lab. A1).

Pollen counting was carried out until at least a total of 200 pollen grains, excluding spores and aquatic and semi-aquatic plants except for samples with very low pollen concentration. Fern spores are presented as a sum of all spore types. The pollen results are presented in percentages excluding spores and aquatic plants. Spores and aquatic plants are represented as a percentage respect the pollen sum. The pollen zonation was performed using psmioll 4.26 (Bennett, 2002) by optimal splitting (Bennett, 1996). The counting of pollen grains and spores was carried out by comparisons with reference books and atlases for pollen as Hesse et al. (2009); Heusser (1971); Hoeve and Hendrikske 1998; Tryon and Lugardon (1991); Reille (1992); and the online pollen and spore atlas APSA (2007).

Many questions about former flora ecology and distribution of Easter Island remain unsolved, despite that several works have tried to reconstruct vegetation changes from pollen analyses on lake sediments (Azizi and Flenley, 2008; Butler et al., 2004; Dumont et al., 1998; Cânealas-Bolta et al., 2013; Flenley and King, 1984; Flenley et al., 1991; Gossen, 2007) or from macrofossil remains on lacustrine records or archeological sites (Cânealas-Bolta et al., 2012; Dumont et al., 1998; Mann et al., 2008; Orliac and Orliac, 1998; Orliac, 2000; Peteet et al., 2003). As an important number of flora species are now extinct from the island and the native Easter Island flora has been intensely perturbed (Dubois et al., 2013; Rull et al., 2010a), it is not possible to reconstruct paleoenvironments from pollen analyses using local modern analogs. For this reason, a comparison with other islands (Juan Fernández, Hawaii, Rapa Iti) is useful in order to reconstruct vegetation changes observed in the pollen analysis (see Section 4.4 for more information).
3.3. Age-depth model

An age model was built from 19 radiocarbon AMS dates measured from pollen concentrates in the Poznan Radiocarbon Laboratory (Poland) (see Margalef et al., 2013 for full details). Pollen enrichment process followed a classical treatment (Faegri & Iversen, 1989; Moore et al., 1991) modified by Rull et al. (2010b). The AMS ages were calibrated using CALIB 6.02 software, and the INTCAL 98 curve (Reimer et al., 2004) and CalPal (Danzeogleck, 2008) for samples older than 20,000 radiocarbon yr BP. The age model was built by simple linear interpolation between the radiocarbon dates as described in Margalef et al. (2013).

3.4. Statistical analysis

Principal component analysis (PCA) was applied in order to reduce the large ICP-AES dataset to a smaller number of variables. These principal components (PC) could then be interpreted in terms of geochemical and environmental processes. SPSS version 20.0 statistical software was used to perform the PCA including varimax rotation over the previously extracted information Table 1) as documented by previous petrographic studies (Baker et al., 1974). The other major components are found in the following concentrations: Al2O3: 16–22%, MnO: 0.3–0.5% and CaO: 3.3–9%. Minor and trace elements showed the following ranges: Sc: 24–39 μg g⁻¹, V: 170–500 μg g⁻¹, Co: 40–163 μg g⁻¹, Cr: 1–60 μg g⁻¹, Ni: 2.2–29.5 μg g⁻¹, Cu: 16–112 μg g⁻¹, Zn: 110–185 μg g⁻¹, Sr: 76–280 μg g⁻¹, Y: 40–85 μg g⁻¹, Zr: 276–497 μg g⁻¹, Ba: 107–202 μg g⁻¹, Th: 2.4–5.2 μg g⁻¹ (Table 1 of Supporting information). The rock samples around Rano Aroi are particularly enriched in Ti, Al, Sc, V, Cr, Ni, and Cu and depleted in Y, Zr, and Ba, when compared to samples from other areas of the island. On the other hand, the Easter Island andosols sampled for this study were especially enriched in Al, Cr, Y, Zr and depleted in Mg, Ca, Sc, V, Co, Ni, Cu, Zn, and Sr compared to rock samples.

4.2. Mineral grain found on peat cores geochemistry

Most of the mineral grains observed under electronic microscope showed evidence of transport or advanced weathering. At 8.3 m and 10.55 m depth small grains (30–500 μm) were rutile, ilmenite and quartz, while the bigger grains (≥500 μm) were composed of inosilicates (pyroxenes), plagioclases and quartz. The sample from 4.8 m depth showed smaller grains (10–20 μm) composed of iron, magnesium and aluminum oxides, quartz and organic compounds bound to Ca, Br and Mg. Some of these organic compounds were large up to 200 μm.

4.3. Rock and soil analyses

The elemental composition of selected rock and soil samples from the Rano Aroi watershed and other areas of the island was analyzed to investigate the origin of the inorganic fraction arriving to the mire. The ICP-MS analyses show that basalt, hawaiite and tholeite rocks are especially rich in Fe₂O₃ (16–22%) and TiO₂ (2.5–4.4%) (see Supporting information Table 1) as documented by previous petrographic studies (Baker et al., 1974). The other major components are found in the following concentrations: Al₂O₃: 16–22%, MnO: 0.3–0.5% and CaO: 3.3–9%. Minor and trace elements showed the following ranges: Sc: 24–39 μg g⁻¹, V: 170–500 μg g⁻¹, Co: 40–163 μg g⁻¹, Cr: 1–60 μg g⁻¹, Ni: 2.2–29.5 μg g⁻¹, Cu: 16–112 μg g⁻¹, Zn: 110–185 μg g⁻¹, Sr: 76–280 μg g⁻¹, Y: 40–85 μg g⁻¹, Zr: 276–497 μg g⁻¹, Ba: 107–202 μg g⁻¹, Th: 2.4–5.2 μg g⁻¹ (Table 1 of Supporting information). The rock samples around Rano Aroi are particularly enriched in Ti, Al, Sc, V, Cr, Ni, and Cu and depleted in Y, Zr, and Ba, when compared to samples from other areas of the island. On the other hand, the Easter Island andosols sampled for this study were especially enriched in Al, Cr, Y, Zr and depleted in Mg, Ca, Sc, V, Co, Ni, Cu, Zn, and Sr compared to rock samples.

4.4. Peat ICP-AES data and PCA

A PCA was performed using the suite of selected elements from the bulk peat analysis. Three components explaining 85% of the matrix variance were identified. The absolute concentration variations for elements representative of these PCs are shown in Fig. 2. The results of
the PCA are presented in terms of the factor loading of each element in the extracted PCs by showing the fractionation of the communalities (i.e., the proportion of the variation of each variable explained by each PC) (Fig. 3) and by the depth records of the PCs’ factor scores (Fig. 4).

The first component (PC1, 40.8% of the variance) is tied mainly to V, Al, Sc, Cr, Cd and Y (with positive loadings between 0.71 and 0.93, Al shown in Fig. 2) and to a lesser extent to Ti, Zr, Cu and Mn (Ti and Zr shown in Fig. 2, communalities shown in Fig. 3). The second component (PC2, 23.1% of the variance) is characterized by large positive loadings (between 0.69 and 0.93) of Th, Fe, Mn and Ba (Fe shown in Fig. 2) with significant contributions from Ti, Zr and Sr (Ti and Zr shown in Fig. 2, communalities shown in Fig. 3). And the third component (PC3, 21.3% of the variance) is characterized by large positive loadings (between 0.87 and 0.94) of Mg, Ca and Sr and moderate ones of Cu and Ba (Ca shown in Fig. 2, communalities shown in Fig. 3).

PC1 shows high scores in the older section of the peat record (>55.5 kyr BP; 9 m). A clear shift from higher to lower values is observed between 55.5 and 41.5 cal kyr BP (9.13–5.16 m), followed by a rapid increase until 31 cal kyr BP (3.76 m) and stabilization thereafter (Fig. 4). PC2 variability shows a peaky pattern. From the bottom of the core to 6.1 m PC2 scores present peaks at 10.6 m, 10.01 m, 8.7 m and 7.73 m. From 6.1 m to 4.8 m values become high and quite stable, then start to decline gradually until 2.96 m (Fig. 4). Two prominent peaks occur in this last interval (4.8–2.96 m): at 4.05 m and at 3.45 m.

**Fig. 2.** Geochemical proxies analyzed over bulk peat in ARD 06 01 core versus depth. These are as follows: TC, TN, TS (in percentages), C/N ratios, and $\delta^{13}$C, $\delta^{15}$N, $\delta^{34}$S (%). are indicative of the origin of organic matter and early diagenetic processes. Elemental (Al, Ti, Zr, Fe, Ca) concentrations (in ppm) of the Rano Aroi peat deposits. Representative elemental profiles are shown for each of the factors. (Sc and Zr for PC1, Fe and Zr for PC2, Sr for PC3).

**Fig. 3.** Communalities of the elements. Light gray represents the element loadings related to the first component (PC1), dark gray show the element loadings related to the second component (PC2), black color depicts the element loadings related to the third component (PC3).

**Fig. 4.** Variations of scores of PC1, PC2 and PC3 against depth in Rano Aroi peat sequence. PCA has been performed over ICP-AES dataset (Al, Ba, Ca, Cd, Cr, Cu, Fe, Mn, Sc, Sr, Ti, V, Y and Zr).
being the maximum of the entire record. At the upper part of the sequence, from 2.96 m to 2.40 m PC2 shows a progressive increase. The PC3 scores do not show a clear trend at the bottom of the sequence. From 10.49 m to 8.15 m there is a clear declining trend, and a marked see-saw pattern until 5.79 m. Scores rapidly increase from 5.79 m to 5.41 m, defining a broad peak up to 4.25 m. From 4.25 m to 3.16 m PC3 scores decline irregularly, but a clear peak stands out in this interval at 3.86 m. The uppermost part of the sequence presents an increasing trend. (Fig. 4).

4.5. Pollen record

In this work, only the most abundant taxa: Poaceae, Arecaceae, Asteraceae, Coprosma and Cyperaceae pollen types together with fern spores sum have been used. The following taxons are included as “others”: Triumfetta, Acalypha, Trema (Ulmaceae), Pinus, Macaranga, Sapinus, Plantago plus indeterminate and unknown pollen types.

Asteraceae (arbustive types) are present in Hawaii, Rapa and Juan Fernandez Island although nowadays these are not found on Easter Island (Brown, 1935; Flenley et al., 1991; Zizka, 1991). In Hawaii these small trees form scarce-forested landscapes in between true forest and bare lava flows (Flenley, 1991). Native and endemic Poaceae are mainly present in meadows and open landscapes. Some biogeographical and ecological constraints of the known species are given in Table 3 of the Supporting information. Based on the endocarp of fossil seeds, an endemic species of Arecaceae tree has been proposed: Paschalococos disperta (Dransfield et al., 1984). This endemic species is extremely similar to Jubaea chilensis (Dransfield et al., 1984, Flenley et al., 1991) and is presented as an emblematic case of extinction. Coprosma is a genus of flowering plants (small trees) present on many Pacific sites (New Zealand, Hawaii, Borneo, Rapa, Juan Fernandez). It is nowadays completely extinct from Easter Island but found in ancient lake and peat sediments (Flenley, 1991; Horrocks et al., 2013). Cyperaceae is another abundant pollen type predominantly representing taxa found in moist and waterlogged parts of grassland meadows or peatlands (Supporting information, Table 3). Finally, fern spores also constitute an important part of Rano Aroi pollen record, in contrast to the low dominance of fern spores observed in Rano Raraku lake sediment cores (Cañellas-Boltà et al., 2013; Flenley et al., 1991).

Two significant zones were obtained (Fig. 5) over the complete pollen dataset:

Zone I (13.9–7.48 m depth, 71–48.3 kyr BP) is characterized by the dominance of Poaceae (70–90%) with an important contribution of Arecaceae, Coprosma pollen and fern spores.

Zone II (7.48–2.35 m depth, 48.3–8.5 kyr BP) is defined by an increase of Asteraceae at the expense of Poaceae and Arecaceae pollen. The appearance of a higher amount of Cyperaceae, probably from the mire itself, is remarkable. The elevated number of fern spores indicates that these might have been growing in the vicinity of the mire. Cyperaceae as other aquatic and semi-aquatic plants can be useful to determine local conditions because they grow specifically in moist and flooded areas. Because of the strong local signal they are not included in the sum to perform percentages.

This Zone has been divided in three subzones in the following manner:

1. Zone IIa (7.48–5.8 m depth, 48.3–43 kyr BP): this subzone is characterized by very high percentages of Asteraceae pollen (up to 70.5% at 6.15 m depth) while Poaceae pollen percentage...
remains lower than in Zone I. Fern spores start to be more abundant, together with Cyperaceae that depict increasing percentages from bottom to top of the zone.

–Zone Iib (5.8–3.4 m depth, 43–20.6 kyr BP). The subzone consists of a pollen assemblage with a lower percentage of Asterolteres and a higher contribution of Araceaeae, Cyperaceae and fern spores. This subzone also contains a hiatus at 4.25 m (see Section 4.1).

–Zone Iic (3.4–2.35 m depth, 20.6–8.5 kyr BP) is characterized by a considerable reduction in Asterolteres and the dominance of Cyperaceae and ferns.

### 4.6. Correlation between inorganic and organic peat chemistry

In the PCA described above we did not include the variables that characterize the chemical nature of the organic matter, because our main objective was to determine the chemical nature of the minerogenic fraction in the peat. The next step is to correlate the first three PC with the chemical composition of the peat organic matter (TC, TN, TS, and the isotopic composition) to look for covariance and to investigate the underlying processes controlling the changes in peat organic and inorganic matter, and how external and internal (i.e. post-depositional) processes have affected both the inorganic and the organic chemistry. The largest correlation values (Table 1) were found inorganic and organic matter, and how external and internal (i.e. post-depositional) processes have affected both the inorganic and the organic chemistry. The correlation coefficients derived from the PCR analysis.

The PCA performed on the Rano Aroi inorganic elemental dataset identified three main components that enable an identification of specific variables for each component (i.e., chemical elements in this case) whose behavior is similar and, thereby, likely controlled by the same process (Reimann et al., 2008).

### 5. Discussion

#### 5.1. Factors controlling peat elemental composition

The PCA performed on the Rano Aroi inorganic elemental dataset identified three main components that enable an identification of specific variables for each component (i.e., chemical elements in this case) whose behavior is similar and, thereby, likely controlled by the same process (Reimann et al., 2008).

#### 5.1.1. Long-term mineral fluxes of very fine particles

PC1 is characterized by large positive loadings (>0.7) of typically lithogenic elements (V, Al, Sc, Y, Ti, Zr) and some metals (Cr, Cd, Cu). These elements are associated with very fine particulate material and this component can confidently be related to the deposition of soil dust transported by wind together with contributions from hydric erosion. Given the isolation of Easter Island, this signal would be mainly dominated by fluxes from the volcanic rocks and soils of the island itself. Elements on this first component (like Al, Ti, Zr, Cr, Cu and other metals) are enriched in volcanic soils with increasing degree of pedogenesis (Martínez Cortizas et al., 2007, 2007b). Almost the same association of chemical elements (V, Al, Ti, Sc, Cu) was found by Muller et al. (2008) in the study of the composition of the Lynch’s Crater, a mire in NE Australia with remarkable similarities with Rano Aroi (both mires are charcoals). The weathering of volcanic materials leads to the distribution of this association of elements in (1) secondary minerals or organo-metallic compounds, which are poorly crystalline or in (2) primary minerals, which are very resistant to weathering. Most of these mineral phases are characterized by very fine (probably < 50 μm) particles, which are easily mobilized by eolian or hydric erosion. This is consistent with what is found after SEM observations on the Rano Aroi record because particle size (except for Facies C) was dominated by fine silt and clay fractions (<30 μm).

Therefore, PC1 would track the long-term background fluxes of inorganic particulate material coupled to soil pedogenesis and erosion (and factors affecting both). Fine airborne dust particles are enriched in many elements compared to coarser ones (Schuetz, 1989), and these chemical processes lead to potential physical and chemical fractionation during dust transport, which seems to be more intense at short distances from the source area and attenuates during long-range transport, as the grain size of the dust decreases and homogenizes. The elemental composition reflected by PC1 is consistent with these chemical enrichment processes associated to dust input variability.

#### 5.1.2. Strong runoff events and coarser detrital input

The second component, PC2, is characterized by large positive loadings of Fe, Mn and Ba and moderate positive loadings of Ti and Zr. These
elements are associated to coarser particles entering the mire. Non-systematic Scanning Electron Microscopy (SEM) observations of the peat layers corresponding to high PC2 scores showed an abundance of sand (50–600 μm) and coarse silt (20–50 μm) particles.

Iron and Mn are elements which can show a strong redox behavior, tending to be depleted under anoxic conditions due to the mobility of their reduced forms and accumulated under oxidizing conditions in peatlands (Chesworth et al., 2006; Steinmann and Shotyk, 1997). Furthermore, PC2 variability (and the elemental profiles, Fig. 2) does not show a long-term trend as documented for redox sensitive elements (i.e. Fe or Mn) in the Lynch’s Crater record (Muller et al., 2008). However, the Rano Aroi record has rather a peaky pattern resembling an “event signal”. Despite its potential mobility, Fe has been found to be immobile in certain peatlands (Muller et al., 2008; Weiss et al., 2002) and previously formed Fe oxides/hydroxides were found to be stable in lake sediments even under anoxic conditions (Gälman et al., 2009). Additionally, in most soils developed on volcanic rocks such as those in the Rano Aroi catchment, Fe is largely hosted by primary minerals and the Fe that is released during weathering accumulates as non-crystalline or poor crystalline Fe forms (i.e. ferrhydrite, Fe-organic matter associations) and secondary Fe phases (oxides and hydroxides) (García-Rodeja et al., 2007). Barium, Ti, Th and Zr have only one oxidation state and are not sensitive to redox changes, and major hosting minerals of Ba (barite, witherite), Ti (ilmenite, rutile) and Zr (zircon, baddeleyite) are highly resistant to weathering. Thus, in Rano Aroi PC2 is not likely to reflect diagenetic changes associated to changes in redox conditions. Instead, while PC1 reflects the long-term particulate terrigenous input into Rano Aroi, PC2 most likely represents strong, highly erosive runoff events capable of transporting solid particles by suspension or eventually traction to the center of the mire. Peaks in PC2 scores coincide with the presence of Facies C, organic mud, which has been interpreted as being representative of wet events and higher water table levels in the mire (Margalef et al., 2013).

5.1.3. Post-depositional enrichments

PC3 is characterized by large positive loadings of Ca, Sr, and Mg. These elements are transported to the mire included in very fine soil particles (as primary minerals such as plagioclase), but because they are also highly mobile as ions, they are transported to the mire as dissolved species, too. Due to their chemical mobility, groundwater can also greatly contribute to their distribution, sometimes by diffusion from the underlying sediments as a result of the chemical dissolution of Ca-bearing minerals (Shotyk et al., 2002). And, as essential nutrients, they are also subjected to intense biocycling.

The most prominent feature of the PC3 record is the maximum values (Figs. 4, 6, 7) attained between ca. 42–39 kyr BP (4.25 m and 5.41 m depth) coinciding with Facies D (highly decomposed peat, Margalef et al., 2013). Age model, geochemistry and the sharp discontinuity described at the uppermost limit of Facies D suggest that there was a loss (i.e. erosion) of previously accumulated peat layers. This would also mean that the geochemical features exhibited below this sedimentary hiatus (between 5.41 m and 4.25 m depth) were acquired thousand years later than accumulation, as diagenetic changes caused by peat aerial exposure. Given this circumstance the most likely explanation for enrichment on Facies D was an intensive use of these elements as bio nutrients by the plant community because a more intensive input of Ca, Mg and Sr as a solute form would require a wetter climate. The lowering of the mire water table, due to drought phases, is known to accelerate peat decomposition (Ise et al., 2008) and produce an enrichment of certain elements in the peat (Biester et al., 2012;...
Fig. 7. Rano Aroi accumulation rates (A) and PC1, PC2 and PC3 scores obtained from the previous PCA analysis plotted against age together with a selection of environmental and climatic Southern Pacific records. Dotted line on Rano Aroi PC scores indicate the part of the record with chronological uncertainty (see text). From top to bottom: (B) PC1 scores suggest the transit from a period with elevate mineral input into the mire and C₄ plant type dominance to an scenario of C₃ dominance and lower mineral fluxes. (C) High values of PC2 scores might be interpreted as the occurrence of strong runoff events due to enhanced precipitation episodes. On the other hand, (D) high PC3 scores suggest the mobilization of Sr, Ca, Mg due to peat exposure and oxidation. (E) Global sea level as indicator of the Easter Island water table oscillations (Grant et al., 2012). (F) The reflectance record from Cariaco basin as indicative of changes in the latitudinal position of the ITCZ (Peterson et al., 2000). The southward migration of ITCZ has been related to higher precipitation rates over Southern tropical Pacific and intensification of SPCZ, bringing humid conditions to Easter Island. (G) Aridity index obtained by Stuut and Lamy (2004) using Chilean offshore coastal sediments to reconstruct the latitudinal position of Southern Westerlies (SW). A northern position of these prevailing winds contributes to transport the SPCZ cyclones to Easter Island. (H) Southern Pacific Sea Surface Temperatures at 41° latitude for the last 70 kyr BP (Kaiser et al., 2005).
Martínez Cortizas et al., 2007b). The increase of Ca – among other elements – at surface levels when peat stagnates has been explained by Damman et al. (1992) as an effect of the detritus cycle. At Lynch’s Crater, Ca, Sr and Mg were also enriched in the more decomposed peats (Muller et al. 2008). Another example of similar chemical enrichments comes from a Canadian mire composed of a 153-cm-thick layer of ombrotrophic, moderately decomposed peat overlying highly humified, minerotrophic peat: Ca was enriched 10 fold; Mg 2-3 fold; Fe (3 fold) in the highly decomposed peat (Zoltai and Johnson, 1985). In Rano Aroi the maximum concentrations for Ca, Mg and Sr in the c. 42-31 kyr BP (6-4 m depth) peat are around 5 fold, 3 fold and 2.5 fold higher than average concentrations in the peat deposited ca. 55-42 kyr BP (8-6 m).

5.2. Linking the organic and inorganic peat chemistry

5.2.1. PC1 and organic chemistry

The long-term variability of PC1 is similar to the long-term evolution of the δ13C record from 55.5 to 43.9 kyr BP (9-6 m, Fig. 6) where both curves have a declining trend. The δ13C trend shows a shift from values typical of C4 plant types to lighter ones (characteristic of C3 type) and suggests a change in the peat forming plant community (Margalef et al., 2013). This synchronicity between δ13C and PC1 reveals an intimate relation between soil evolution and vegetation cover (see Section 5.3).

The TN content decreases in the upper part of the sequence (Fig. 6) suggesting a link with soil evolution (PC1) and vegetation cover (δ13C). δ15N (Fig. 2) can provide information on organic matter origin, nitrogen fixation (δ15N = 0 to +3‰) or plant productivity, but also syndepositional processes such as denitrification (δ15N ≥ +8‰) (Handley et al., 1999; Meyers and Ishiwatari, 1993; Talbot and Johannessen, 1992). At Rano Aroi the average δ15N is around +2.7‰, which is an isotopic signature typical of nitrogen fixation. The general δ15N trend correlates directly with PC1 variation, as denoted by the high PCR regression coefficient (R = 0.56). Two hypotheses can be proposed to explain this relationship: (1) larger inputs of fine or very fine mineral particles to the mire may have triggered conditions of enhanced productivity and consequently, higher δ15N values; or (2) the vegetation change can entail a differential fractionation of the peat forming plant remains (Talbot, 2001). However, two prominent peaks of δ15N at 66.8 kyr BP and 62.4 kyr BP (12.36 m and 11.07 m, Fig. 1 from Supporting information) are not accounted for by the PCR model and thus, they are apparently not related to the influx of mineral matter or long term shifts (Supporting information, Fig. 1). These very high δ15N values (δ15N ≥ 7.5‰) may have been reached by the preferential loss of light nitrogen through denitrification or ammonization (Talbot et al., 2001) indicating anoxic phases. Therefore, our results suggest that different processes could change the isotopic signature over different time scales: long-term variability related to a shift in the vegetation and short-term variability related to small-scale events such as a change in the potential redox.

Total S (decreasing) and δ34S_CDT (increasing) trends from 55.5 to 43.9 kyr BP (9-6 m) also show a differential S assimilation and fractionation through time (Fig. 2). The changes in S cycling, especially δ34S_CDT, seem partially related to PC1 and the shift in δ13C (Table 1). Sulfur is incorporated by plants and bacteria, especially in the form of organosulfur compounds, which seem to be the dominant S fraction in peat (Novák et al., 1994, 1999; Wieden and Lang, 1988). The chemical composition of the Rano Aroi basin lithology indicates that inorganic S-content is low or negligible and this is not considered a source of S to the mire (Baker et al., 1974, Margalef et al., 2013). Because no volcanic eruption has been recorded nor have ash layers have been described in Rano Aroi and Rano Raraku in late Quaternary sediments (Flenley 1991, Sáez et al. 2009) the most likely dominant S source is marine sulfate. Variations in TS and δ34S_CDT can be therefore explained as changes in the loss after early diagenesis (bacterial sulfate reduction and fixation) that discriminates against the heavier isotope 34S (see Supporting information for additional information about sulfur interpretation).

5.2.2. PC2 and organic chemistry

PCR analyses show that organic matter composition does not significantly correlate with PC2; however, several cause-effect relationships can be drawn from the stable isotopes, TC, and TN records. δ13C second order changes (i.e. peaks) show lower values coinciding with Facies C and PC2 peaks from the bottommost part of the record until 6 m depth (Fig. 6). This relationship between organic matter and Facies C can be explained by differential fractionation due to moisture changes or a higher proportion of C3 plants during wet events (Margalef et al., 2013). Abrupt increases of TN also match PC2 peaks (Fig. 6). High TN values together with low C/N ratios can be attributed to a higher contribution of lacustrine algal material (low C/N), in contrast to high C/N values that indicate higher proportions of terrestrial or aquatic plants (versus algae) organic matter (Meyers, 1994).

5.2.3. PC3 and organic chemistry

The organic chemistry does not correlate with PC3. Nevertheless, the drought event may have partially determined the δ13C signature like the lighter ratios on the highly decomposed part of the record show. The same can be stated for the C/N ratios that are slightly higher between 5 m and 4.23 m depth (Fig. 2). Total S displays a relative enrichment between 5 m and 4.23 m depth while the underlying level, from 6.5 m to 5.5 m depth, becomes depleted in S. This pattern could respond to biodecomposition through the formation of organic S compounds that are more stable under oxidizing conditions at the expense of the S released from the layers that remained under reducing conditions near the watertable interphase (coherently when δ34SCDT reaches the maximum values).

5.3. Rano Aroi environmental reconstruction: climate, basin and peatland interactions

The Rano Aroi dataset and our multi-proxy approach allow us to reconstruct paleoenvironmental changes considering the intermediate interplay between climate forcing, basin and catchment evolution (soil and vegetation changes) and peat processes.

MIS 4 (73.5–59.4 kyr BP) is a period characterized by low southern Pacific SST temperatures (Kaiser et al., 2005, Pena et al., 2008, Fig. 7H). The Antarctic Circumpolar Current (ACC) was enhanced and the Southern Westerlies moved equatorward resulting in sea ice export away from Antarctica (Kaiser et al., 2005). Sea level was globally low, between 90 and 100 m below the present day (Grant et al., 2012, Fig. 7E), which has been proposed as an important factor for Easter Island’s hydrology and groundwater levels as well as that of other small islands (Margalef et al., 2013). A lower sea level would probably also cause lower groundwater levels. This time period sees a complete dominance of C4 plant types (mostly Poaceae) on the Rano Aroi basin and Terevaka area (Fig. 6) and the presence of Araucarias and Coprosma taxa on the island. Some studies have proposed the development of palm tree forests preferentially in the lower areas of the island (Flenley et al., 1991), although other authors suggest that the palynological results obtained so far are also coherent with a mosaic vegetation pattern with forested areas around permanent mires, lakes and the coastline as gallery forests (Rull et al., 2010a).

The prevalence of C4 plants suggests drier conditions that would lead to a low degree of pedogenesis in the catchment soils; a scenario that is coherent with the low global temperatures (Grant et al., 2012; Kaiser et al., 2005; Fig. 7H and E). Additionally, herbaceous plant dominance may have facilitated higher soil erodibility, either eolian and/or hydrological. The result was a higher dust flux of typical lignocarabolic elements and metals into the mire, as summarized by PC1.

Globally warmer conditions heralded the arrival of MIS 3 (59.4–27.8 kyr BP). SST of mid latitudes of Pacific Ocean increased around
5 °C between 62.7 and 61.5 kyr BP (Fig. 7H). This change was coupled to a rapid sea level rise, and between 62.9 and 61.2 kyr BP sea level shifted from ~96 m a.s.l. to ~75 m a.s.l. (Grant et al., 2012). In the South Pacific, atmospheric patterns underwent important reorganizations. A record from the Cariaco Basin (Peterson et al., 2000, Fig. 7F) indicates that between 61.2 and 59.9 kyr BP the Intertropical Convergence Zone (ITCZ) was situated in a stable southern position leading to very dry conditions in Northern Hemisphere tropics. The southern latitudinal migration of ITCZ therefore leads to the opposite hydrologic trend for the low latitudes in the Southern Hemisphere (Leduc et al., 2009; Wang et al., 2007). The early MIS 3 has been characterized in the Rano Aroi record as a humid period, as expressed by the abrupt events of higher sediment delivery (see Section 5.1.2, and Figs. 6 and 7). It is significant that the first important wet event on Easter Island, starting in Rano Aroi at 61.6 kyr BP is apparently synchronous with important global changes in (1) sea level rise, (2) the position of the ITCZ and (3) SST.

The new warmer and wetter conditions of Early MIS 3 (61.6 to ~40 kyr cal BP) were linked to an intensification of the degree of pedogenesis, which led to a decrease in the flux of lithogenic elements to the mire. In parallel to the decline in PC1 values (Fig. 7B), the bulk peat stable isotope data values (δ13C and δ15N) started a gradual decline at 55 cal kyr BP (Fig. 6). The isotopic change indicates a shift in the vegetation community forming the peat, which becomes dominated by C3 plant types. As stated in previous sections, pollen data suggests that a complete dominance of Poaceae (presumably C4 species) was replaced by a combination of Asteraceae, Coprosma, Poaceae and ferns between 51 and 48 kyr BP (Fig. 5). The vegetation change around the mire and the presence of scarce forest, trees and shrubs may have prevented soil erosion and reduced the fluxes of mineral matter to the mire (PC1). Finally, the expansion of Cyperaceae (presumably C3 species, such as Scirpus californicus) probably constituted an important physical barrier during the C3 dominance period, slowing the runoff input, except during stronger events (PC2).

The late MIS 3 (40–27.8 cal kyr BP) has been characterized as a drier phase on Easter Island (Margalef et al., 2013). Sea level dropped relatively rapidly between 31.4 and 29.4 cal kyr BP, but a South Pacific thermal response to global cooling was not recorded until the onset of MIS 2 (Kaiser et al., 2005, Fig. 7H). The Cariaco Basin record shows that between 35 and 31 cal kyr BP, the ITCZ was in a northern position preventing the arrival of strong storms to southern latitudes (Peterson et al., 2000, Fig. 7F). Moreover, several records from South America document intense dry between ca. 41 and ca. 31 kyr BP (Lamy et al., 1998; Stuut and Lamey, 2004) explained by the southern migration of the Southern Westerlies under the precension forcing (Fig. 7G). The combination of these regional climate patterns likely led to a long dry period in the Central Pacific and on Easter Island. The drought started after 39 cal kyr BP, the age of the sharp unconformity in the Rano Aroi sequence that separates highly degraded (below) and fresh peat (above). A lowering of the Rano Aroi water table accelerated peat decomposition producing an increase in the elements representative of PC3 (Ca, Sr, and Mg) as a diagenetic imprint (Fig. 7D). The time interval above the discontinuity depicts net accumulation rates of 0.05 mm/y (Fig. 7A) and represents the reactivation of peat formation after a long-term pause (probably including erosion) where old carbon could be incorporated in younger roots and plant remains. Because of this carbon recycling, the chronology right after the reactivation has to be carefully considered and the exact date of the reactivation and the amount of peat eroded cannot be properly determined.

Although sea level reached a minimum ca. 23 cal kyr BP (Grant et al., 2012; Lambeck and Chappell, 2001; Fig. 7E) and could have negatively affected the groundwater input and the hydrological balance at Rano Aroi, peat formation was active during the LGM. These can be explained by permanent cold conditions preventing strong evaporation (Sáez et al., 2009) and a northernmost position of Southern Westerlies whose influence reached subtropical latitudes during glacial times (Lamy et al., 1998, Fig. 7G).

Rano Aroi peat accumulation reactivated completely by ca. 17.5 kyr BP (the onset of Termination 1). Sea level started a prominent rise and the Intertropical Convergence Zone shifted to its furthermost south position between 21 and 16 kyr BP (Fig. 7F). During MIS 2 (27.8–14.7 cal kyr BP), PC3 values remained low, showing no evidence of a drought period. Conversely, high PC2 events are found during the late glacial at 20.9–19.5 cal kyr BP and 16.4 cal kyr BP, likely representing enhanced precipitation coinciding with HS 2 and 1 (Fig. 7C). Maximum peat accumulation rates (14 cal kyr BP, Fig. 7A) coincide with the highest rates of sea level rise during deglaciation (Dickinson, 2001; Hanebuth et al., 2000; Lambeck and Chappell, 2001). Sea level rise together with warmer SST might have played an important role in the development of enhanced convection storms.

According to several Southern Hemisphere records the Early Holocene was characterized by a warming (Pena et al., 2008) and SST were maximal at approximately 12 cal kyr BP and generally decreased thereafter until modern SST were reached (Kaiser et al., 2005; Kaiser et al., 2008). In ARO 06 01 record, only the early Holocene (11.7–8.5 kyr cal BP) peat remains because the surface levels were rejected to avoid anthropic remobilization. The most important features characterizing this period are high PC2 values around 10.2 cal kyr BP indicating strong runoff events, while PC1 points to catchment soil conditions similar to those recorded ca. 48 cal kyr BP indicating relatively low fluxes of inorganic material under a permanent C3 plant dominance (as shown by δ13C, Figs. 6 and 7).

6. Conclusions

The organic matter composition (TC, TN, δ13C, δ15N, δ34S), inorganic geochemistry and pollen data from Rano Aroi mire provide a coherent reconstruction of the paleoenvironmental history of Easter Island.

Principal component analysis of peat geochemistry reveals that three main environmental processes have controlled the inorganic elemental composition of the peat accumulated. (1) The first process, depicted by PC1, reflects changes in the basin background erosion and transport of the mineral matter as very fine particles into the mire and it is linked to soil evolution and vegetation shift. In Rano Aroi, δ13C can be used to infer an important vegetation change from C4 to C3 plant dominance that occurred from 55 to 50 kyr BP. The correlation of the δ13C and PC1 records reveals that vegetation shifts and the evolution of the soils of the mire basin were intimately related to the rate of allochthonous material transported into the peatland. These environmental changes also affected the δ15N signal that integrates variability in mire productivity and redox conditions. δ34S signatures indicate that the S source is primarily marine. The δ34S ratio and TS concentration suggest that S may have been differentially mobilized depending on vegetation assemblages by sulfate reduction bacteria. (2) The second process is the occurrence of high precipitation events (identified by the PC2 signal) related to strong runoff and delivery of large amounts of terrigenous particles coarser than those mobilized by PC1 process. These events occurred at approximately 60 kyr BP, 52 cal kyr BP and 42 cal kyr BP. (3) Finally, the third process, illustrated by PC3, mainly reflects peat oxidation caused by a long-term drought after ca. 39 cal kyr BP.

The environmental evolution of Rano Aroi mire, largely driven by hydrological changes, is coherent with the regional climatic variability described for the last 70 kyr BP. During MIS 4 the Rano Aroi basin was occupied by open grasslands and C4 Poaceae dominated the mire owing to the generally cold and relatively dry climate conditions. MIS 3 was marked by the onset of wet events, which occurred at ca. 60 kyr BP, 52 cal kyr BP and 42 cal kyr BP.

During the first half of MIS 3 and probably driven by the wetter and warmer conditions, Asteraceae and other small trees became gradually more abundant, forming scantily wooded areas around Terevaka, while C3 peat forming plants colonized the Aroi mire. In contrast, the second
half of MIS 3 was drier. A long-term drought led to a water table drop and enhanced peat mineralization at some time between the 39 and 31 cal kyr BP. During the MIS 2 and LGM the water table recovered and peat accumulation resumed under C3 plant dominance.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.palaeo.2014.09.025. These data include Google map of the most important areas described in this article.

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