



Macrofossils in Raraku Lake (Easter Island) integrated with sedimentary and geochemical records: towards a palaeoecological synthesis for the last 34,000 years

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ABSTRACT

Macrofossil analysis of a composite 19 m long sediment core from Rano Raraku Lake (Easter Island) was related to litho-sedimentary and geochemical features of the sediment. Strong stratigraphical patterns are shown by indirect gradient analyses of the data. The good correspondence between the stratigraphical patterns derived from macrofossil (Correspondence Analysis) and sedimentary and geochemical data (Principal Component Analysis) shows that macrofossil associations provide sound palaeolimnological information in conjunction with sedimentary data. The main taphonomic factors influencing the macrofossil assemblages are run-off from the catchment, the littoral plant belt, and the depositional environment within the basin. Five main stages during the last 34,000 calibrated years BP (cal yr BP) are characterised from the lithological, geochemical, and macrofossil data. From 34 to 14.6 cal kyr BP (last glacial period) the sediments were largely derived from the catchment, indicating a high energy lake environment with much erosion and run-off bringing abundant plant trichomes, lichens, and mosses into the centre of Raraku Lake. During the early Holocene the infilling of the lake basin and warmer conditions favoured the growth of a littoral plant belt that obstructed terrigenous input. Cladoceran remains and Solanaceae seeds are indicative of reduced run-off and higher values of N and organic C indicate increased aquatic and catchment productivity. From 8.7 to 4.5 cal kyr BP a swamp occupied the entire basin. The increase of Cyperaceae seeds reflects this swamp development and, with oribatid mites and coleopteran remains, indicates a peaty environment and more anoxic conditions in Raraku. At around 4.5 cal kyr BP dry conditions prevented peat growth and there is a sedimentary hiatus. About 800 cal yr BP, peat deposition resumed. Finally, in the last few centuries, a small lake formed within the surrounding swamp. Evidence of human activity is recorded in these uppermost sediments.

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1. Introduction

Lakes are natural sediment traps and preserve an archive of the history of the past ecosystems (Smol and Glew, 1992; Battarbee,

2000; Cohen, 2003). Proxy data for the physical, chemical, and biotic composition of the lake and its water can be retrieved from lake sediments and used to provide information about environmental and biotic changes that have occurred over time. Many factors influence the proxy record, such as temperature, precipitation, terrestrial and aquatic biota, human activities, lake-bottom topography, depth, hydrological regime, size and composition of the catchment and other environmental parameters together with their corresponding interactions (Smol and Glew, 1992; Battarbee,

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2000; Birks et al., 2000; Fritz, 2008; Giralte et al., 2008). A lake is integrated with its catchment and geological processes such as weathering, run-off, and deposition can play an important role in influencing the sediment composition (Tschudy, 1969; Birks et al., 2000; Cohen, 2003; Lotter and Birks, 2003). Processes such as bioturbation and diagenesis can modify lacustrine sediments.

Many recent palaeolimnological studies have been directed at reconstructing external environmental variables such as climate, rather than being interested in the lake's history for its own sake (Cohen, 2003; Anderson et al., 2008). However, the lake itself interposes an important filter between our reconstruction of the past external environment and the sedimentary record we use to derive this reconstruction (Cohen, 2003). Understanding the sedimentary evolution of the lake basin is therefore essential in palaeolimnological studies, because it determines the nature of the palaeolimnological record and our ability to infer environmental changes from it.

Macrofossils are one of the most useful biological proxies in palaeoecological studies because they reflect local biota and ecosystems and hence local environmental conditions (Birks and Birks, 2000; Birks, 2007). Macrofossil studies have been developed mainly in Europe and North America in temperate and arctic areas. Plant macrofossils are most frequently used, although other organisms, particularly invertebrates such as coleoptera, chironomids, oribatids, cladocerans, etc. also give useful palaeoecological and palaeoenvironmental information (Birks et al., 2000).

The main within-basin processes that influence the sedimentary patterns of macrofossils are transportation, sorting, redeposition, decomposition, and reworking (Tschudy, 1969; Scheiing and Pfefferkorn, 1984; Birks, 2001; Cohen, 2003). A sound interpretation of fossil evidence cannot be made without considering the influence of these taphonomic processes which act on the chemical and physical attributes of the sediments and the fossils themselves (Tschudy, 1969; Rubensdotter and Rosqvist, 2003). Many studies have shown the importance of taphonomy in the interpretation of a macrofossil record, mainly by the use of modern sediment samples (see review by Dieffenbacher-Krall, 2007).

Palaeoecological research on Rano Raraku and Easter Island has largely involved palynological studies (see studies of Flenley and King, 1984; Flenley et al., 1991; Dumont et al., 1998; Butler et al., 2004; Azizi and Flenley, 2008; Mann et al., 2008; among others). A few studies include macroremains, such as the palaeoecological work of Dumont et al. (1998) and Mann et al. (2008) on Raraku Lake, the study of Peteet et al. (2003) on Rano Aroi, and archaeological work on the island (Orliac and Orliac, 1998; Orliac, 2000; Horrocks and Wozniak, 2008). This paper presents a macrofossil analysis of the glacial to Holocene lake sediments (34,000 calibrated years BP – cal yr BP-) of Rano Raraku and relates the results to previous lithological, sedimentological, and geochemical analyses (Sáez et al., 2009), in order to determine the influence of sedimentological processes on the macrofossil assemblages and the relationship between biological remains and geochemical parameters. The main aim is to improve our knowledge of the palaeolimnology of Rano Raraku and the palaeoenvironment of Easter Island.

2. Study site

Easter Island is a tiny (164 km²) volcanic island situated in the southern Pacific Ocean (27° 07'S, 109° 22'W) (Fig. 1). It is one of the most isolated places on Earth, about 3700 km from the Chilean coast and 2030 km from the nearest inhabited island (Pitcairn). The climate is subtropical, with an average annual temperature of 21 °C and a range of average monthly temperatures between 18 °C in August and 24 °C in January (Mann et al., 2008). The total annual

precipitation is highly variable, ranging between 500 and 2000 mm, with large alternating dry and humid periods (Horrocks and Wozniak, 2008). The island's topography is characterised by volcanic cones and the rolling surfaces of the lava flows between them. The highest point is the summit of the Terevaka volcano (511 m). No permanent surface streams are present due to the high permeability of the volcanic rocks (Herrera and Custodio, 2008). At present, only the craters of Rano Raraku and Rano Kau (occupied by lakes), and Rano Aroi (filled by a swamp) permanently contain freshwater. The floral and faunal diversity have been described as very poor (Skottsberg, 1956; Zizka, 1991). Nowadays the island is mostly (90%) covered by meadows dominated by grasses, with a few tree plantations, shrub areas, and pioneer vegetation (Etienne et al., 1982).

Raraku Lake is a small (0.11 km²) shallow (2–3 m depth) freshwater lake, situated at 75 m altitude inside a volcanic crater more than 300,000 years old (Baker et al., 1974) (Fig. 1). The crater is famous as the quarry of the moais, the gigantic stone sculptures erected by a vanished civilization. The catchment area is about 0.35 km² and it is composed of volcanic tuff rich in glass, feldspar, and ilmenite (González-Ferran et al., 2004). The lake is hydrologically closed and disconnected from the island's main groundwater by impermeable lacustrine sediments, being fed solely by precipitation in the crater (Herrera and Custodio, 2008). The lake water is well mixed, acidic (pH around 6.3), dilute (average specific conductivity is 640 mS cm⁻¹, Geller, 1992) and of a Cl–HCO₃–Na type (Sáez et al., 2009). Today the lake bottom is flat and it is surrounded by a littoral belt formed mainly by a mat of *Scirpus californicus*, which also forms large floating patches. In recent years water has been episodically siphoned out the lake for human consumption and irrigation.

The lithology and main characteristics of the sedimentary infill of Lake Raraku were characterised from eight sediment cores recovered in 2006 (Fig. 2). The nine sedimentary facies described by Sáez et al. (2009) have been generalised here to four major sedimentary facies (Table 1). The lowest facies consists of dark grey–reddish organic-rich muddy silt laminated by water currents, including frequent turbidite episodes. It is interpreted as a being derived largely from the steep catchment slopes by water transport and slope-wash, and is termed the High Gradient Lake facies (HGL). It has the lowest organic content (60% of dry weight) and the largest mineral fraction of the sequence which consists of volcanic minerals (glass, feldspar, and iron oxide), clay minerals, and pyrite aggregates (Sáez et al., 2009). The overlying facies consists of horizontally coloured laminated algal and organic brown banded mud, including rare turbidite episodes, and massive brownish organic mud, all consisting mostly of non-particulate, amorphous organic matter. It is interpreted as being derived from less steep lake-bottom slopes and autochthonous production with little input from the catchment. It is termed the Low Gradient Lake facies (LGL). The sediment above is composed of reddish-brown massive or banded muddy peat, composed mainly of macroremains of sedges (*Scirpus* and *Cyperus* spp.). It is termed the Swamp facies association (SWA). A transitional facies between the LGL and the SWA, composed of organic mud rich in macroremains of sedges, has also been recognised. At the top, a silica-rich silty peat represents shallow water surrounded by floating peat (LFP, Low Gradient Lake with Floating Peat facies).

3. Methods

Core RAR 03 and the lower part of core RAR 07 (Fig. 2) were combined into a complete and continuous stratigraphic section 19 m long. Fifty-six samples for plant macrofossil analysis were

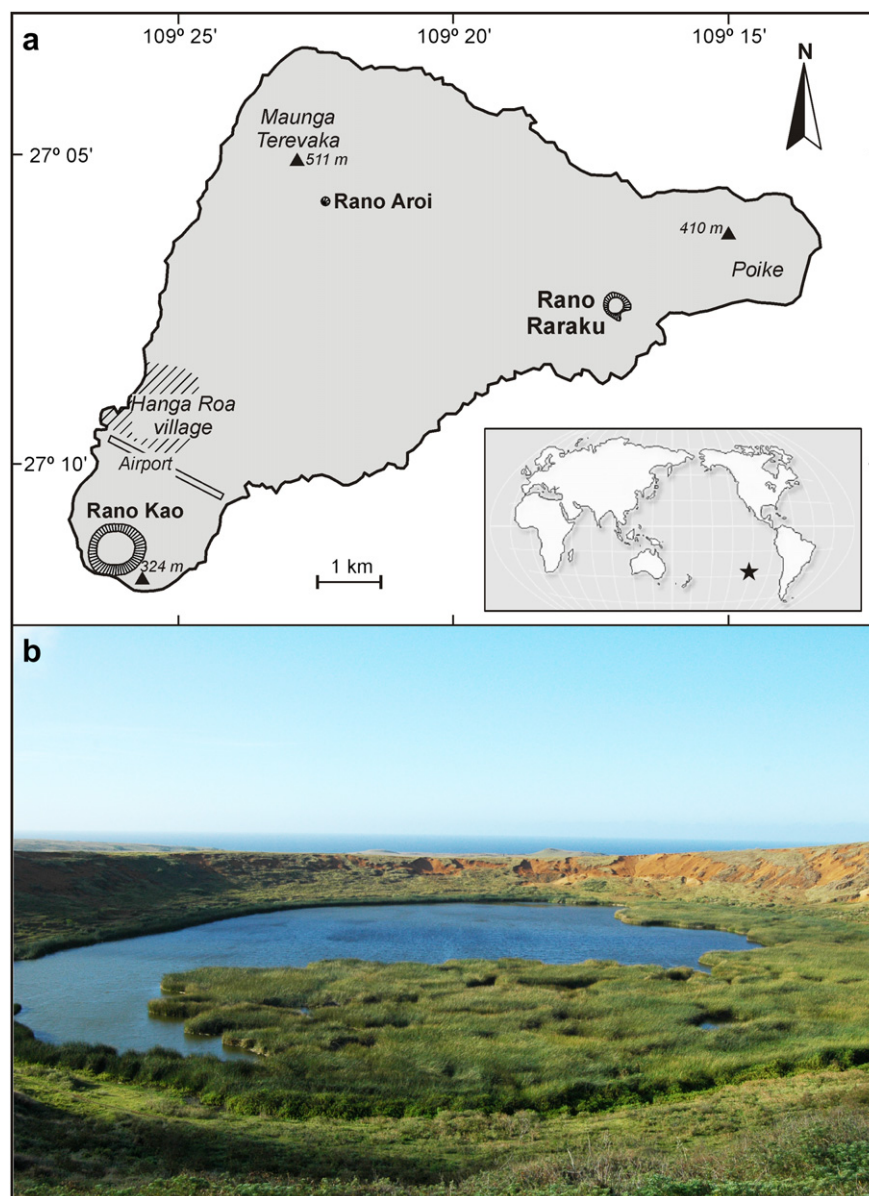


Fig. 1. a) Map of Easter Island showing the location of the three permanent water resources on the island (Rano Raraku and Rano Kao crater lakes and Rano Aroi swamp), and the location of the island in the SE Pacific Ocean. b) Picture of Rano Raraku, a crater lake.

extracted and processed following standard protocols (Birks, 2001). Sample volume, between 20 and 50 cm³, was measured by water displacement. Dispersion of the sediment was facilitated by the addition of a small amount of KOH (10%). The sediment was sieved through 500 µm and 125 µm mesh screens with a gentle spray of tap water. The residue was examined systematically under a stereo-microscope at ×12 magnification. Remains of interest were picked out, identified, and counted. Identification was aided by comparison with reference material and photographs and images from atlases and identification keys (see Birks, 2001).

The chronological framework of Sáez et al. (2009) (Table 2) has been refined with the addition of new radiocarbon dates that date more precisely the duration of the sedimentary hiatus in the upper part of the composite sequence (Fig. 2). In this paper, all radiocarbon dates have been recalibrated using CALIB 6.02 software and the INTCAL09 database (Reimer et al., 2009) for samples younger

than 20,000 ¹⁴C years. Older samples have been calibrated with CalPal (Danzeglocke et al., 2008) (Table 2).

The macrofossil taxa were ordered on the basis of their weighted average (WA) by depth (Janssen and Birks, 1994) using C2 1.4 software (Juggins, 2003) to sort them according to their commonest depth, in increasing order. The macrofossil data were plotted using psimpoll 4.26 (Bennett, 2002) and the diagram was zoned by optimal splitting by information content (Bennett, 1996). The overall temporal trends of the macrofossil data along the sequence were summarised using correspondence analysis (CA) after logarithmic transformation of the concentration data. Rare taxa were downweighted. This analysis assumes a unimodal response model (Jongman et al., 1995), which is the usual case for species–environment relationships (Birks et al., 2010). A principal components analysis (PCA) identified the main stratigraphical variations in the sedimentary and geochemical data previously measured by Sáez et al. (2009) (see Supplementary Material). PCA

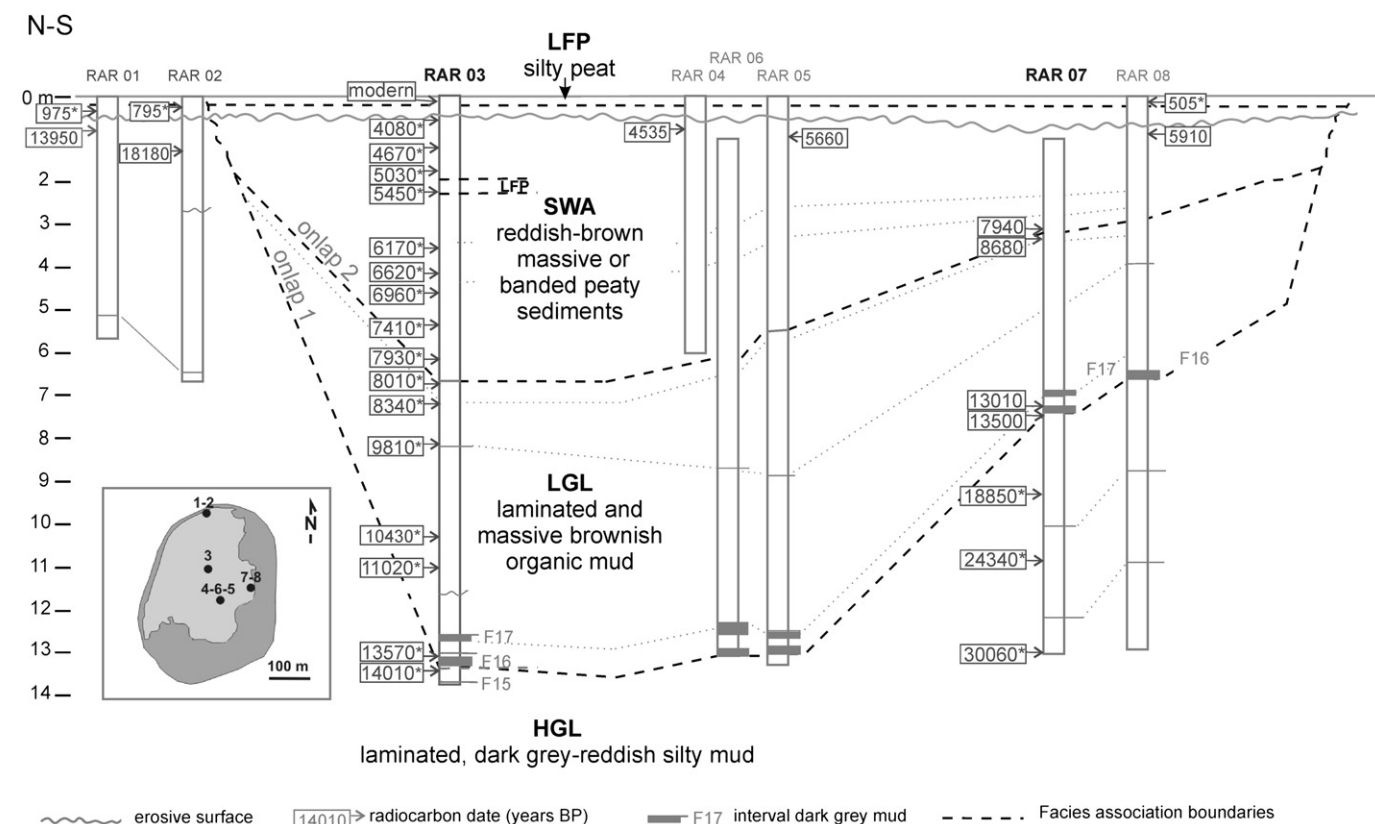


Fig. 2. Schematic N–S correlation panel showing the key sedimentary beds from the eight cores obtained in Raraku Lake in 2006. Core location is shown in the inset map. Facies associations used for the analysis and their description are indicated. HGL = high gradient lake facies association (steep slopes of lake margins), LGL = low gradient lake facies association (gentle slope of lake margins), SWA = swamp facies association, LFP = low gradient lake with floating peat facies association. Figure modified from Sáez et al. (2009). Numbers within boxes are radiocarbon dates. Dates used in this work are marked with an asterisk. See Sáez et al. (2009) for calibrated ages of all radiocarbon dates of Raraku Lake and Table 2 for the dates used in this work.

assumes lineal response, which is usually considered for this kind of data. These parameters include: magnetic susceptibility (ms) measured using a multi-sensor core logger, total nitrogen (TN) and total carbon (TC) measured using an elemental analyser, bulk $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ determined by IRMS in a continuous flux mass spectrometer assembled on line to an elemental analyser, and the total content of Si, Ti, S, Fe, Ca and a value of X-ray incoherence/coherence ratio [inc_coh_ratio] (as a proxy of organic matter) determined by X-ray fluorescence using a core scanner. The nine facies described by Sáez et al. (2009) have been grouped into four facies associations as described above (Section 2) and incorporated into the analysis. Both indirect analyses (PCA and CA) were done with R software package (R Development Core Team, 2008). To identify the major structure in the macrofossil data two-way indicator species analysis (Hill, 1979) was carried out with TWINSpan (version 2.3, M.O. Hill 1979, modified by C.J.F. ter Braak,

H.J.B. Birks, and P. Šmilauer). This method is widely used in community ecology to construct a hierarchical classification by successive dichotomous division of the data. It is a semi-quantitative method as some quantitative aspects of the data are retained by delimiting pseudospecies (see Hill, 1979). Significant groups were determined using TWINDEND (version 0.4, J. M. Line and H.J.B. Birks, unpublished), which evaluates the explanatory power of each TWINSpan division in the hierarchical classification, calculating the mean internal dispersion (or heterogeneity) of the TWINSpan groups at each division level as a percentage of the mean dispersion of the total data. TWINSpan classification is an informative and robust method for detecting structure in noisy and heterogeneous data-sets (Gauch and Whittaker, 1981). The program DISCRIM (version 1.2 a modification of TWINSpan by C.J.F. ter Braak, modified by J.M. Line and H.J.B. Birks) was used to relate the external geochemical and sedimentary data to the

Table 1
Correspondence between facies associations used in this study and the facies and units described by Sáez et al. (2009), their description and palaeoenvironmental interpretation.

Facies association this study	Facies Sáez et al. (2009)	Units Sáez et al. (2009)	Description	Palaeoenvironmental interpretation
HGL	Facies 1, 2	Unit 1, bottom Unit 2	Laminated grey-reddish, muddy silt with frequent turbidite layers	High gradient lake (steep slopes of lake margins)
LGL	Facies 4, 5, 6, 7	Mid and upper Unit 2	Laminated- coloured and banded- massive brown organic mud with rare turbidite layers	Low gradient lake (gentle slope of lake margins)
SWA	Facies 8	Units 3, 4a	Reddish peat	Swamp
LFP	Facies 9	Unit 4b	Silica-rich silty peat with diatoms	Low gradient lake with floating peat

Table 2

^{14}C AMS radiocarbon age measured in pollen extract and *Scirpus* sp. remains of Raraku Lake core samples used in this work. All dates are from Sáez et al. (2009) except those marked by (*) which have been collected from this study. The first three dates (in grey) correspond to samples from cores different than those used for composite section studied here, and have been incorporated by stratigraphic correlation. Calibration using the CALIB 6.02 software and the INTCAL09 calibration curve (Reimer et al., 2009) and, for samples older than 20000 radiocarbon years BP, CalPal (Danzeglocke et al., 2008).

Sample name	Laboratory name	Composite depth (m)	Fraction dated	^{14}C yr BP	±	Dates (cal yr BP)	±
RAR08.01.12–13	Poz-32007	0.125	Pollen extract	505*	30	528	25
RAR02.01.20	Poz-19933	0.25	Pollen extract	795	35	721	49
RAR01.01.37	Poz-19930	0.37	Pollen extract	975	30	866	71
RAR03.01.54	Poz-33774	0.54	Pollen extract	4080*	40	4576	80
RAR03.02.27	Poz-33775	1.28	Pollen extract	4670*	40	5394	82
RAR03.02.85bis	Poz-20571	1.85	Scirpus macrorest	5030	40	5801	96
RAR03.03.30	Poz-19935	2.30	Pollen extract	5450	40	6247	62
RAR03.04.55	Poz-24027	3.55	Scirpus macrorest	6170	40	7059	110
RAR03.05.14	Poz-24030	4.14	Scirpus macrorest	6620	50	7504	70
RAR03.05.65	Poz-18689	4.65	Pollen extract	6960	40	7778	88
RAR03.06.34	Poz-24031	5.34	Scirpus macrorests	7410	50	8261	103
RAR03.07.15	Poz-24032	6.15	Scirpus macrorests	7930	50	8806	178
RAR03.07.83	Poz-18690	6.83	Pollen extract	8010	40	8879	132
RAR03.08.33	Poz-18691	7.33	Pollen extract	8340	50	9361	120
RAR03.09.35	Poz-19936	8.35	Pollen extract	9810	60	11240	116
RAR03.11.10	Poz-18693	10.39	Pollen extract	10430	50	12318	212
RAR03.12.10	Poz-18694	11.25	Pollen extract	11020	50	12896	191
RAR03.14.40	Poz-18696	13.39	Pollen extract	13570	70	16699	234
RAR03.14.60	Poz-18695	13.59	Pollen extract	14010	70	17043	218
RAR07.09.10	Poz-19938	15.27	Pollen extract	18850	130	22566	411
RAR07.10.85	Poz-19939	16.95	Pollen extract	24340	230	29112	483
RAR07.11.140	Poz-18705	18.97	Pollen extract	30060	240	34229	192

TWINSPAN classification of the biological data (Ter Braak, 1986). This method constructs simple discriminant functions and classifies attributes given a hierarchical classification analysis (in our case a TWINSPAN classification) of the external macrofossil data, with the aim of discovering which external variables are most closely associated with and most strongly discriminate between different *a priori* groups of samples based on their macrofossil composition. In the DISCRIM analysis we incorporated some geochemical parameters -total organic carbon (TOC), total inorganic carbon (TIC), C:N ratio, and total sulphur (TS)- that were not taken into account in the PCA to avoid possible overweightings. All quantitative data were transformed into ranges with MILTRANS (version 2.5; C.J.F. ter Braak, J.M. Line, and H.J.B. Birks) prior to being used in DISCRIM. Some geochemical parameters and biological data were plotted as box-whisker plots to highlight visually the differences between the biosedimentological units.

4. Results and interpretation

4.1. Macrofossil analysis

The most common remains in the Raraku core are Cyperaceae fruits, Solanaceae seeds, fern sporangia and scales, moss and lichen remains, oribatid mite fragments, cladoceran ephippia, chironomid capsules, coleopteran fragments, and other unidentified remains (Fig. 3). The remains have been named with a code (IBB-) for further study and included in a general reference collection of biological micro- and macroremains kept at the Botanical Institute of Barcelona. Four macrofossil assemblage zones have been statistically defined (Fig. 4).

Zone MA-1 (18.9–12 m, 34–14.6 cal kyr BP) has a low plant macrofossil content, with very few, small vegetative macroremains of sedges and grasses. The main characteristics of this zone are the abundance of IBB-65 (likely a stellate trichome) and the presence of moss (IBB-89, IBB-92, IBB-96) and lichen (IBB-87) remains. Fern sporangia (IBB-63) and some animal remains are consistently present in low amounts.

Zone MA-2 (12–6 m depth, 14.6–8.7 cal kyr BP) is the most heterogeneous section with the lowest macrofossil quantity and

diversity. The most distinctive remains are cladoceran ephippia (IBB-98), which appear at the top of zone MA-1 and extend up to the end of MA-2, and likely cladocera eggs (IBB-72) with an irregular presence but a concentration in this zone. Solanaceae seed is confined to this zone. Mosses and lichens disappear and trichomes decrease until they disappear at the end of the zone. Fern sporangia and oribatid mites also decline in abundance but increase again near the top of the zone together with coleopteran remains (IBB-58, IBB-61, IBB-64), and Cyperaceae seeds, mainly Cyperaceae-2 (IBB-62, *Scirpus* seed), associated with sedge and grass vegetative remains. Cladocera and ferns show marked maxima near the top of this zone.

Zone MA-3 (6–1.5 m depth, 8.7–5.5 cal kyr BP) contains many large vegetative remnants of sedge and grass. Below 5 m, Cyperaceae-2 fruits (IBB-62, *Scirpus*) are dominant, and fern sporangia and scales are frequent. The latter finally disappear at about 4 m. Towards the top of the zone, Cyperaceae-1 (IBB-60, *Cyperus* cf.) becomes frequent. Other characteristics are the presence of IBB-111, the highest abundance of oribatid mites, chironomids, some insect remains (IBB-51, IBB-52, IBB-57, IBB-58, IBB-61, IBB-64), and the presence of a large variety of other remains in low amounts.

A dominance of large sedge and grass vegetative fragments continues into Zone MA-4 (1.5–0 m depth, 5.5 cal kyr-present). Cyperaceae-2 fruits are abundant, together with reduced amounts of fern sporangia, oribatid mites, chironomids, Cyperaceae-1 fruits, and other insect remains (IBB-51, IBB-52, IBB-57, IBB-58, IBB-61, IBB-64). At the top, a subzone (MA-4b, around 800 cal years BP to present), can be distinguished by the presence of charcoal, *Plumatella* (IBB-228), chironomids (IBB-54), Cladocera ephippia, and the appearance of IBB-188, IBB-194, IBB-199, IBB-218, among others. The two uppermost samples (about 500 cal years BP) are differentiated by peaks of charcoal and traces of macrofossils that have not appeared before (Cyperaceae-3, IBB-166, among others).

Correspondence analysis (CA) based on the abundance of macroremains summarises the stratigraphical or temporal patterns in the macrofossil data (Fig. 5). Five axes are significant according to the broken-stick model, explaining 68.24% of the total variability. In the plane defined by the first two CA axes



Fig. 3. Several macrofossils frequently observed in the Raraku Lake sediments. The scale line is 1 mm. a) IBB-60, Cyperaceae-1 fruit (*Cyperus* cf.); b) IBB-62, Cyperaceae-2 fruit (*Scirpus californicus* cf.); c) IBB-130, Solanaceae-2 seed; d) IBB-83, Solanaceae-1 seed (*Solanum* cf.); e) IBB-65 (trichomes cf.); f) IBB-76, fern sporangium; h, i, j) IBB-89, 92, 96 respectively, moss fragments; k) IBB-87, lichen; l) IBB-228, *Plumatella* statoblast; m) IBB-50, Oribatid mite (Hydrozetidae/Ameronothoroidea cf.); n) IBB-98, Cladocera ephippia; o) IBB-54, Chironomidae capsules; p) IBB-72, Cladoceran egg cf.; q) IBB-109, Diptera larvae; r) IBB-111; s) IBB-57; t) IBB-252; u) IBB-51, Diptera larvae Ephyrididae; v) IBB-52 leg Curculionidae Molytinae–Cossoninae cf.; w) IBB-58 pronotum coleopteran Curculionidae Molytinae – Cossoninae cf.; x) IBB-61 Curculionidae Molytinae – Cossoninae cf.; y) IBB-64 elytron Curculionidae Molytinae – Cossoninae cf.; z) IBB-134; aa) IBB-81, ventral part of thorax (sternum) coleopteran Dystiscidae; ab) IBB-90; ac) IBB-91, abdominal segment insect; ad) IBB-194; ae) IBB-103; af) IBB-199; ag) IBB-218; ah) IBB-166, Cyperaceae-3 (*Cyperus* cf.) IBB-164; ai) IBB-166; aj) IBB-188; ak) IBB-59; al) IBB-168; am) IBB-162; an) IBB-128; ao) IBB-122; ap) IBB-148; aq) IBB-131; ar) IBB-106; as) IBB-94; at) IBB-108.

(39.8% of variance explained) the samples from each macrozone are grouped together (Fig. 5a). Samples from MA-1 are joined in a very homogeneous group in the low right quadrant. Samples from MA-2 are distributed loosely in the upper right of the CA plot reflecting the heterogeneity within this zone. The MA-3 and MA-4 samples are situated in the lower left quadrant, with samples from MA-4 being closer to the negative end of axis 1. When the axis scores are plotted stratigraphically, they summarise the main

changes in the site (Fig. 5b). Axis one shows little difference between zones MA-1 and MA-2, as shown by their position on the first axis of the CA plot (Fig. 5a). In contrast, axis 2 separates samples in MA-2, reflecting its heterogeneous composition and the different macroremains observed in the samples from a shallow lake environment (Fig. 5b). Both axes show a strong change from lake assemblages in MA-2 to peat assemblages rich in Cyperaceae remains in MA-3 (Fig. 5b).



Fig. 3. (continued).

4.2. Litho-geochemical PCA

PCA of the geochemical and lithological data shows a strong stratigraphic/temporal pattern (Fig. 6). The two significant axes, according to the broken-stick model (69.8% of the total variance explained) in the biplot separate four distinct groups (Fig. 6a). Samples below 13 m have high values of magnetic susceptibility, Fe,

Ti, and Si, and are grouped as the High Gradient Lake facies association on the positive side of PCA axis 1 suggesting a high terrigenous input into the lake by run-off. They are clearly separated from the organic-rich lacustrine mud with algal laminations and lacustrine-peat sediments on the negative side with low values of Fe, Ti, and Si. Axis 1 (eigenvalue = 8.79) reflects the gradient of allochthonous/autochthonous input to the sediment. PCA axis 2 could be

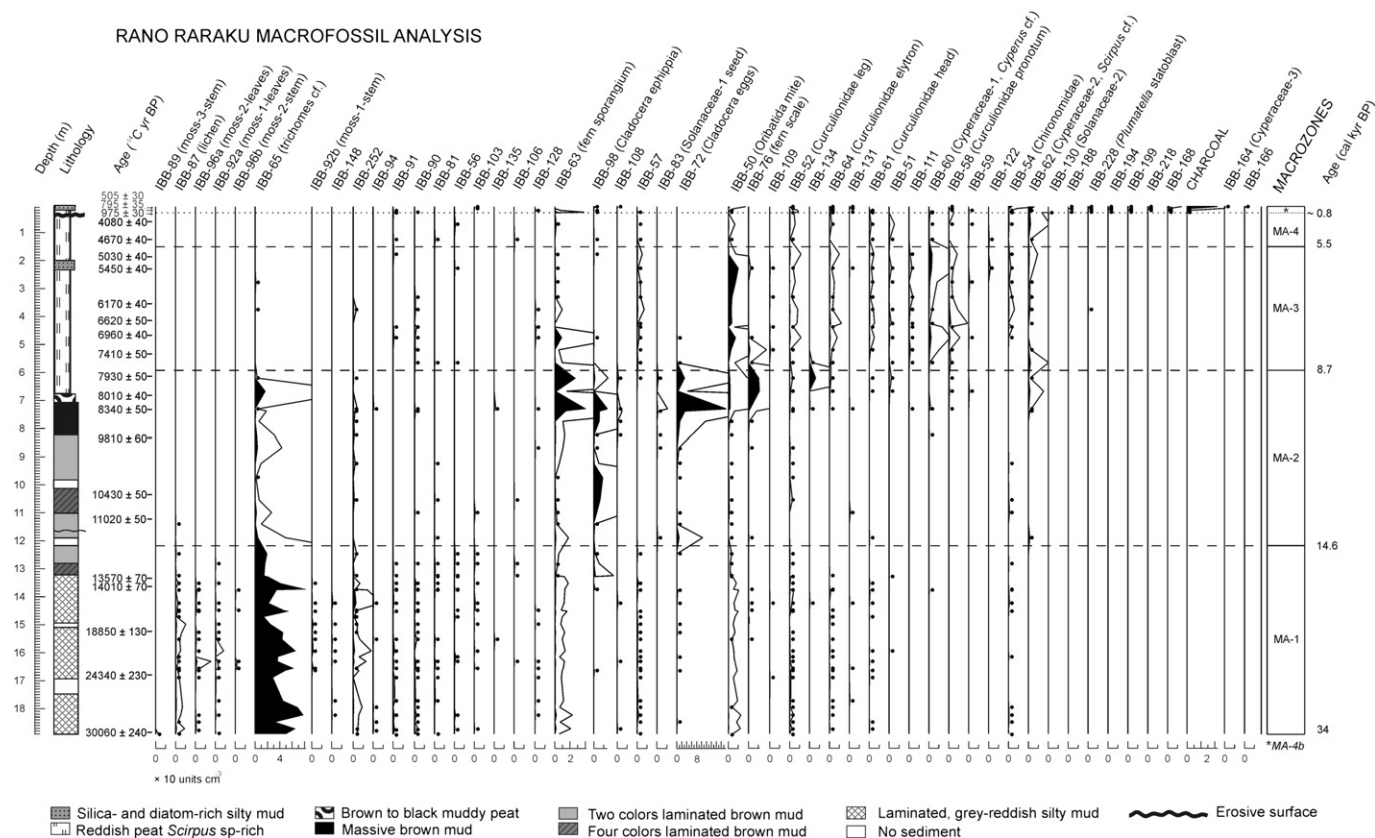


Fig. 4. Stratigraphic diagram of the main macrofossils observed in the Raraku Lake sediments. The four zones based on the macrofossil content are marked with dashed lines. Subzone MA-4b is marked with a dotted line. Lithology and radiocarbon dates are shown at the left side of the diagram. The first three radiocarbon dates from the upper part of the core (marked with →) correspond to other cores, and have been incorporated by stratigraphic correlation. The calibrated age corresponding to the limits of the zones are indicated at the right. See Table 2 for radiocarbon age details.

interpreted as reflecting redox conditions. Samples associated with the Low Gradient Lake facies association are grouped at the positive end of PCA axis 2 and are related to high values of total nitrogen. Samples from peat sediments, mostly associated to the Swamp facies

association, are grouped at the negative end and correlate with the high $\delta^{15}\text{N}$ values that are related to denitrification associated with anoxic conditions. The uppermost samples are localised in the centre, showing transitional conditions between the extreme

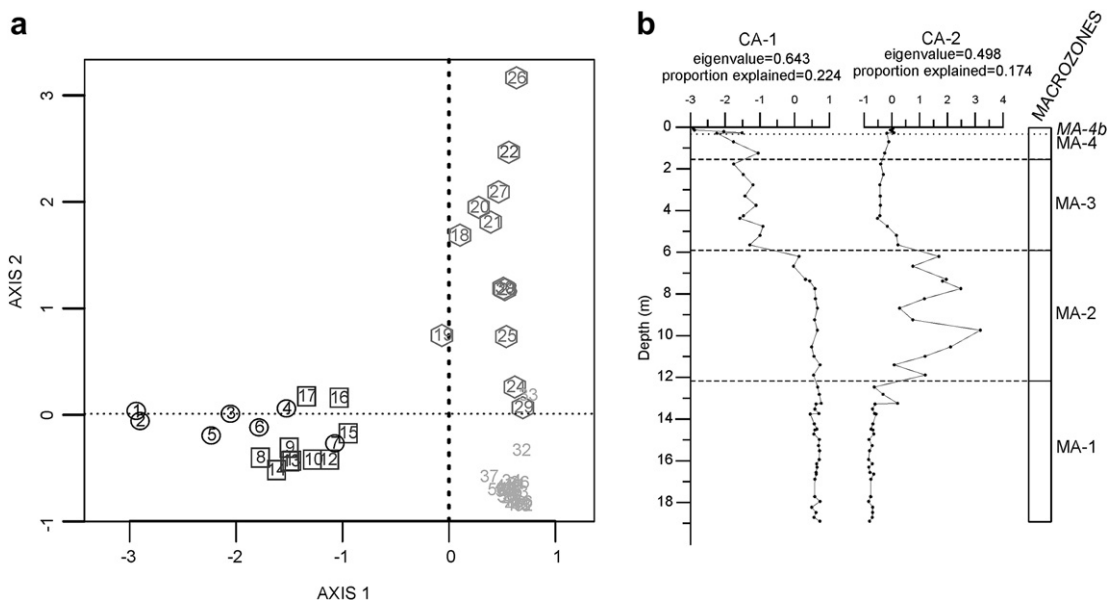


Fig. 5. a) Scatter plot of the samples (numbers) on the two first axes of a correspondence analysis (CA) of the biological data. The four macrozones previously described are indicated by symbols around the sample number: without symbol = MA-1, hexagon = MA-2, square = MA-3, circle = MA-4. b) The scores on the first two significant axes of the correspondence analysis (CA) plotted stratigraphically. Macrozones are indicated at the right.

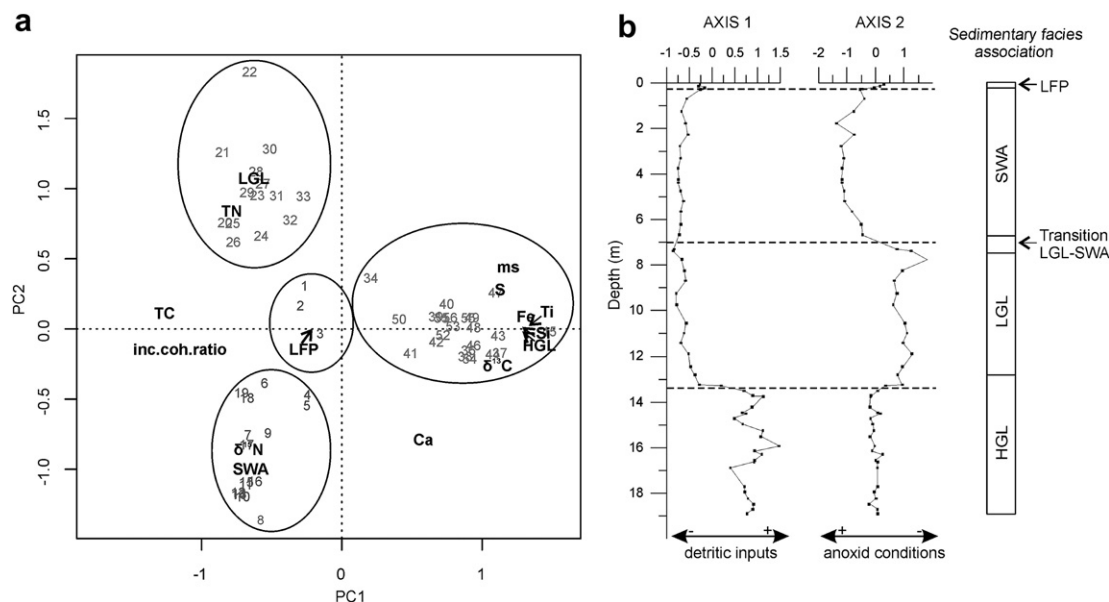


Fig. 6. Results of PCA of the geochemical and sedimentological data. Two significant axes were found according to the broken-stick model: Axis 1 (eigenvalue = 8.790, variability explained = 51.7%), Axis 2 (eigenvalue = 3.082, variability explained = 18.1%). a) Scatter plot on the two PCA axes of geochemical and lithological data of the 56 samples. ms (magnetic susceptibility), Fe (iron), Ti (titanium), Si (silica), $\delta^{13}\text{C}$ (carbon 13 isotope), Ca (calcium), S (sulphur), $\delta^{15}\text{N}$ (nitrogen 15 isotope), TC (total carbon), TN (total nitrogen), inc.coh.ratio (incoherence and coherence ratio), HGL (High Gradient Lake facies association), LGL (Low Gradient Lake facies association), SWA (Swamp facies association), and LFP (Low gradient lake with Flotating Peat facies association). b) The scores on the first two axes of the PCA plotted stratigraphically. The sedimentary facies associations are indicated at the right.

groups. When plotted stratigraphically (Fig. 6b) the major changes at 13.7 m reflect the end of allochthonous input and the major changes at 7 m indicate increased anoxia within the peat sediments.

4.3. TWINSpan and DISCRIM analyses: relationship between macrofossil, geochemical, and sedimentary data

To relate the macrofossil changes to the geochemical changes, TWINSpan and DISCRIM analyses were undertaken. Six significant groups of samples are differentiated by the TWINSpan and TWINDEND analyses (Fig. 7). Two of them are small, with 2 and 4 samples. These 6 samples are amalgamated in Group A and are the uppermost samples in the sequence, being differentiated from all the other samples by the high abundance of Cyperaceae seed-2 (IBB-62). The DISCRIM analysis associates high values of total carbon (TC) and total nitrogen (TN) and low values of $\delta^{15}\text{N}$, $\delta^{13}\text{C}$ and total inorganic carbon with this group. Group B (12 samples) derives from the second division in TWINSpan within the large sample group. It contains samples 7 to 19 (except sample 18) whose indicator taxa are Cyperaceae-2 (IBB-62), IBB-111, Cyperaceae-1 (IBB-60), coleopteran pronota (IBB-58) and high abundance of oribatid mites (IBB-50). DISCRIM relates this group to $\delta^{15}\text{N}$ and the Swamp Facies association SWA, associated with *Scirpus* sp-rich reddish peat. The third TWINSpan division separates the 38 remaining samples into Group C (10 samples) and Group D (28 samples). Group C has IBB-83 and IBB-72 as indicator taxa. The indicator taxa of Group D are IBB-65 and IBB-87 which are related to high values of Fe by DISCRIM.

The sedimentary facies, the *psimpoll* zones, and the TWINSpan groups are compared in Fig. 8. They are closely similar. Group A corresponds to MA-4 although the deepest sample of this zone is not included in the group. Group B corresponds to MA-3 plus one sample from MA-2 and one from MA-4, suggesting the existence of transitions between the macrozones. Unlike other zonations, the TWINSpan analysis is not stratigraphically constrained and allows samples above or below the zone boundaries to be partitioned into

different groups and to highlight patterns of similarities between samples that are not necessarily stratigraphically adjacent (see Grimm et al., 2011). Group C consists primarily of samples from MA-2 plus the lowest sample from MA-3 suggesting that the transition here is fast. Group D comprises samples from MA-1 plus three samples from MA-2, suggesting a gradual transition between these two zones.

4.4. Palaeoecological history of Raraku Lake during the last 34,000 years

The macrofossil sequence is closely correlated with the geochemical parameters and the sediment lithology, thus providing useful information for reconstructing the evolution and palaeoecology of the lake. The changes in the macrofossil assemblages in the Raraku sediments are likely to be a result of the interplay between: (1) lake ontology and catchment processes, (2) climatic changes, and (3) human activities in the last millennium. Five major environmental lake stages can be identified in the Raraku record over the 34,000 calibrated years BP (cal yr BP).

4.4.1. Stage 1 (>34 to 14.6 cal kyr BP)

Macrofossil assemblages during zone MA-1 are dominated by terrestrial material. The absence of aquatic organisms suggests a low lake primary productivity. The C/N ratio is around or higher than 20, which is typical of terrestrial plants, in contrast to C/N ratios of 4–10 for aquatic organic matter (Meyers, 1994; Kaushal and Binford, 1999; O'Reilly et al., 2005). The steep walls of the crater formed steeply sloping lake margins at the initial stage of the lake evolution, resulting in a high gradient lake (HGL) which allowed terrestrial material to reach the centre of the lake. Maybe high turbidity prevented colonisation by aquatic organisms, thereby explaining their absence in the record. Previous sedimentological and pollen studies also indicate that there were high terrigenous inputs from run-off, low evaporation rates, high water balance, and the coldest conditions in the last 34,000 cal years BP

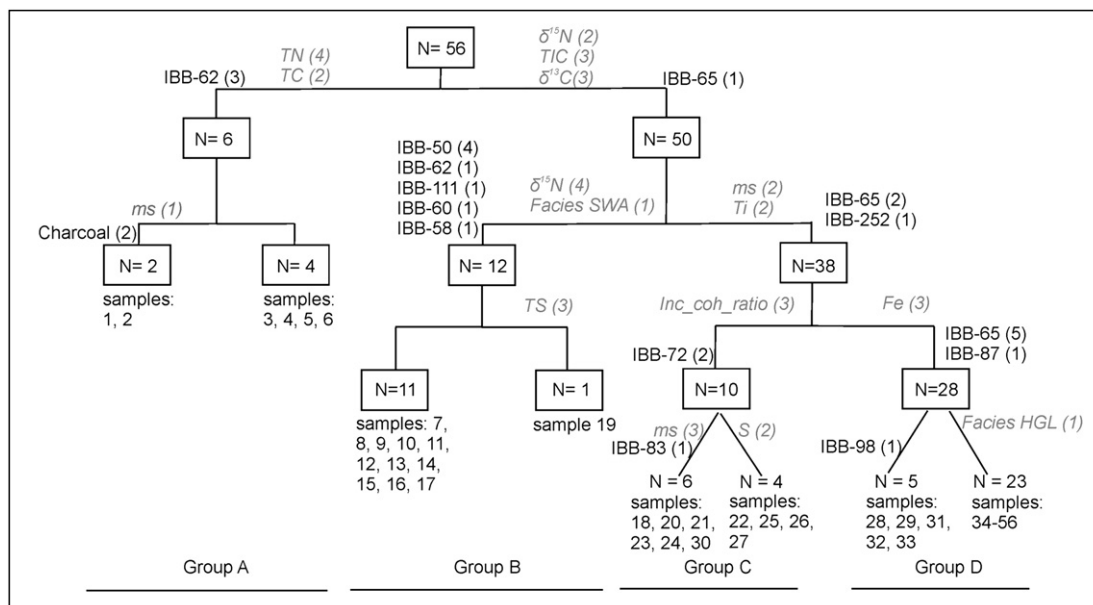


Fig. 7. Results of TWINSpan and DISCRIM analysis arranged in a hierarchical dichotomous tree. The number of samples in each division is indicated by N. The significant divisions and groups according to TWINDEND are indicated with a box. Main indicator macroremains for each division are shown. The pseudospecies' indicator value is marked in brackets after the name of the taxon. Values equal to one indicate that the presence of the taxa is sufficient to distinguish groups. A higher value indicates that higher abundance of the taxa is necessary to define the group. The lithological and geochemical parameters that best discriminate between the branches according to DISCRIM analysis are marked in italics. ms (magnetic susceptibility), Fe (iron), S (sulphur), $\delta^{13}\text{C}$ (carbon 13 isotope), $\delta^{15}\text{N}$ (nitrogen 15 isotope), TC (total carbon), TN (total nitrogen), TIC (total inorganic carbon), inc.coh.ratio (incoherence and coherence ratio), TS (total sulphur), Ti (titanium), IBB-62 (Cyperaceae-2, *Scirpus* cf.), IBB-65 (trichomes cf.), IBB-50 (Oribatid mite), IBB-60 (Cyperaceae-1, *Cyperus* cf.), IBB-58 (Curculionidae fragment), IBB-252 (unknown), IBB-72 (Cladocera eggs cf.), IBB-83 (Solanaceae-1, *Solanum* cf.), IBB-87 (lichen remains), IBB-98 (Cladocera ephippia). The samples in each division are placed in Groups A–D.

(Azizi and Flenley, 2008; Sáez et al., 2009). This stage corresponds to the last glacial period.

4.4.2. Stage 2 (from 14.6 to 8.7 cal kyr BP)

Gradual sedimentary infilling resulted in more gently sloping lake margins leading to the formation of a low gradient (LGL) lake with the development of a narrow littoral vegetation fringe in shallow water. The littoral plant communities became thicker and denser over time as shown by the records of Cyperaceae seeds and they prevented coarse terrigenous inputs characteristic of zone MA-1 from reaching the lake centre. The decrease in terrestrial input could also be related to increases in the vegetation cover in the catchment and stabilisation of the landscape in the warmer Holocene climate. The associated increases of Cladocera remains,

total carbon, organic matter (measured by the incoherence/coherence ratio), and total nitrogen indicate the development of a more productive lake system or quieter waters. However, the C/N ratios still suggest a mainly terrestrial origin for the high organic matter of the sediment, possibly derived from inwash of humus colloids as soils developed in the catchment and marginal lake sediments were eroded. Solanaceae-1 could be an important component of the vegetation colonising the lake margins during this stage. The trend to a more productive lake with age is one of first signs of lake ontogeny under a warming climate (Kling, 2000). Warmer environmental conditions during the deglaciation also resulted in an increased evaporation over precipitation (E/P ratio) leading to a drop in lake-level which resulted in high detrital deposition from the erosion of exposed littoral sediments (occasional turbidite-like currents) during this stage (Sáez et al., 2009).

4.4.3. Stage 3 (from 8.7 to 5.5 cal kyr BP)

Large vegetative fragments of sedges and grasses form the sediment during MA-3, suggesting a hydrosere succession into a swamp. Trends from high gradient lacustrine stages to low gradient, lacustrine-marsh peats are common in small, closed lakes in many climatic contexts when sedimentary processes result in the complete infilling of a lake basin (Sáez and Cabrera, 2002; Cohen, 2003). The invertebrate faunal remains are probably linked to the development of the swamp vegetation (Fig. 4) such as oribatid mites, a phytophagous group of beetles, the Curculionidae (Molytinae – Cossoninae cf.), and many animal fragments. The transition from lacustrine (MA-2) to swampy (MA-3) conditions coincides with a high abundance of fern remains (sporangia, scales, leaf fragments), IBB-65, Solanaceae-1 seeds, IBB-72, Cyperaceae-1 (cf. *Cyperus*), and Cyperaceae-2 (*Scirpus* sp.) seeds. At least two explanations are possible for this peak of macroremains: an increase in the input of allochthonous material from the basin, or enhanced littoral vegetation development (mainly ferns and *Scirpus*) likely as a result of an

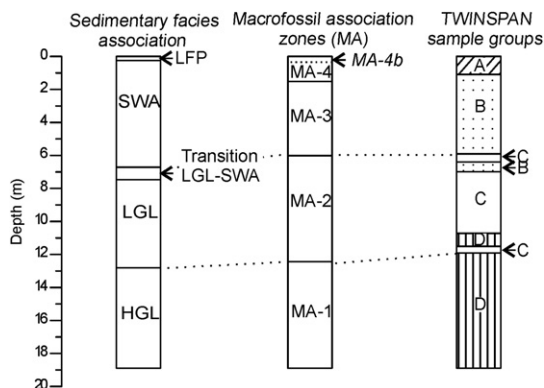


Fig. 8. Correspondence of the facies association, macrofossil zones and TWINSpan groups. HGL = high gradient lake facies association (steep slopes of lake margins), LGL = low gradient lake facies association (gentle slope of lake margins), SWA = swamp facies association, LFP = low gradient lake with floating peat facies association.

increase in total nitrogen. Organic matter accumulation from swampy conditions and vegetation colonising the lake consumed high amounts of oxygen and nitrogen during their decay, and could have led to more anoxic conditions. High values of $\delta^{15}\text{N}$ measured during the stage 3 support this hypothesis.

4.4.4. Stage 4 (from 5.5 ~ 0.8 cal kyr BP)

Although the sediment continues to be dominated by large fragments of sedges, suggesting the prolonged existence of a swamp, *Scirpus* sp. became dominant over *Cyperus* sp. in zone MA-4 at about 5.5 cal kyr BP, accompanied by a decrease in oribatid mites and weevil remains and the disappearance of IBB-111. This stage was interrupted by a sedimentary hiatus between 4.5 and 0.8 cal kyr BP. Widespread arid conditions during the mid-Holocene are documented in the Pacific area and are proposed as the cause of this sedimentary gap (Sáez et al., 2009), which has already been detected in other studies (Mann et al., 2008).

4.4.5. Stage 5 (~0.8 cal kyr BP to present)

Around 0.8 cal kyr BP the record of swampy conditions resumed with a similar biotic composition as the previous stage, with the addition of some new biological remains and charcoal particles in zone MA-4b that are coincident with high values of nitrogen in the sediment (TN) (Fig. 7). The onset of a more humid period which created lacustrine conditions in Raraku is identified by a change in the sediment around 0.5 cal kyr BP that suggests a lake-level increase at the top of the sequence (low gradient lake with floating peat). This also corresponds to the addition of some new biological remains and peaks of charcoal particles in two upper-most samples of zone MA-4b (Figs. 4 and 7).

These changes could be associated, in part, with human presence around the lake. Moreover, the presence of charcoal fragments indicative of a higher fire incidence is commonly associated with human activities. Microcharcoal particles have previously been reported from Raraku cores at this level (Flenley et al., 1991; Mann et al., 2008) and interpreted to be a result of island deforestation. Some authors have proposed this deforestation as a cause of the collapse of the Rapa Nui civilisation (e.g. Flenley, 1993; Flenley and Bahn, 2003), but others attribute the forest decline and the cultural collapse to climatic changes (Dumont et al., 1998; Hunter-Anderson, 1998; Orliac and Orliac, 1998; Nunn, 2000; Orliac, 2000). Nevertheless, the existence of palm forests covering the island is still not convincingly demonstrated and other scenarios are possible in the light of the evidence currently available. Rull et al. (2010) have proposed a mosaic vegetation pattern with forests restricted to sites with a high freshwater table (gallery forest). Unfortunately, the chronological framework of this part of the Raraku core has not been reliably established since the radiocarbon dates are not consistent, and we cannot say anything new about the dates of this assumed human disturbance.

5. Discussion

The stratigraphical variation in the macrofossil sequence (Figs. 4 and 5) corresponds well to the sedimentary facies and geochemical changes (Fig. 6) in the Raraku sequence (Fig. 8). This agreement suggests that the sedimentation patterns were influential in the taphonomic processes that determined the presence of the biological remains in the sediment.

5.1. Main sources of macrofossils and controlling factors in sediment composition

It has been shown that macrofossil assemblages in lakes are usually deposited close to their source and thus reflect local

communities (e.g. Birks, 1973; Zhao et al., 2006; Dieffenbacher-Krall, 2007). The main sources of macrofossils in lake sediments are the lake itself, the marginal vegetation, and the terrestrial catchment (Smol and Glew, 1992; Birks et al., 2000; Birks and Birks, 2006). In Rano Raraku's sediments, the composition of the lake and swamp vegetation and the intensity of run-off from the surrounding slopes are the main factors controlling the composition of the macrofossil assemblages. Groups A and B (Fig. 7) originated in swamp environments and shallow water that laid down peaty sediments, characterised by the dominance of sedge remains. In swamp environments plant remains are deposited on the spot where they grew forming an autochthonous macrofossil assemblage (Greenwood, 1991). The overall increase in animal remains in the peat probably derives from animals that were living in the swamp vegetation. On the other hand, assemblages in Group D (Fig. 7) seem to be strongly influenced by high amounts of run-off inputs which allowed terrestrial material from the catchment such as lichens, mosses, plant trichomes, etc. to be washed into the deep water of the lake centre. The absence of Cyperaceae seeds and other remains of typical littoral biota suggest a weak development of vegetation along the shore that would not hinder the input of terrestrial material. The same factors influenced macrofossil composition in Group C but catchment run-off decreased and coarse terrestrial material including macrofossils became rare or disappeared. The occurrence of Cyperaceae seeds suggests the development of a wider and denser littoral fringe of macrophytes, which would also have limited terrigenous transport to the lake centre. The macrofossil assemblage in Group C is related to the aquatic ecosystem, with the presence of remains of aquatic organisms such as Cladocera (ephippia and eggs) derived from the littoral communities.

5.2. Palaeoecological indicator power of macrofossil remains

Because few of the macroremains in the Raraku sequence could be identified to species, the relationships of the taxa to other environmental proxies needs to be established in order to make palaeoecological inferences from them. The TWINSPLAN analysis resulted in the definition of four groups of samples (A–D; Fig. 7). In Fig. 9b we plot the occurrences of individual taxa within each group, to identify group in which they are most frequent. We have also plotted the values of geochemical parameters in each sample group (Fig. 9a). Using this information combined with their ecological affinities if known and their relationships to sedimentary data and the macrofossil zones (Fig. 8), they can be related to environmental conditions as in the discussion above.

Macrofossils can provide ecological and environmental information for the time when they were deposited. In Group D the high values of terrestrial remains, such as plant trichomes, lichens, and mosses, in association with high values of the erosion proxies magnetic susceptibility, Ti, and Fe (Fig. 9), are indicative of a sparsely vegetated catchment and a high gradient lake environment with high erosion and run-off inputs in the lake. In contrast, cladoceran remains and Solanaceae seeds, characteristic of samples from Group C (zone MA-2) are associated with high values of N and C (mainly organic carbon) and very low values of Ti, Fe, TIC, and $\delta^{13}\text{C}$ (Fig. 9) that indicate fewer run-off events and quieter waters and the development of a shallow-water littoral zone. The presence of some Cyperaceae (cf. *Cyperus*) seeds indicates the development of sedge-swamp growing in shallow water, whereas high quantities of Cyperaceae seeds together with oribatid mites and coleoptera remains characterise peaty environmental conditions. These developed in Stage 3 (MA-3) where high values of $\delta^{15}\text{N}$ in the sediment represent more anoxic conditions (Ogawa et al., 2001). Other taxa, such as oribatid mites, coleopteran remains,

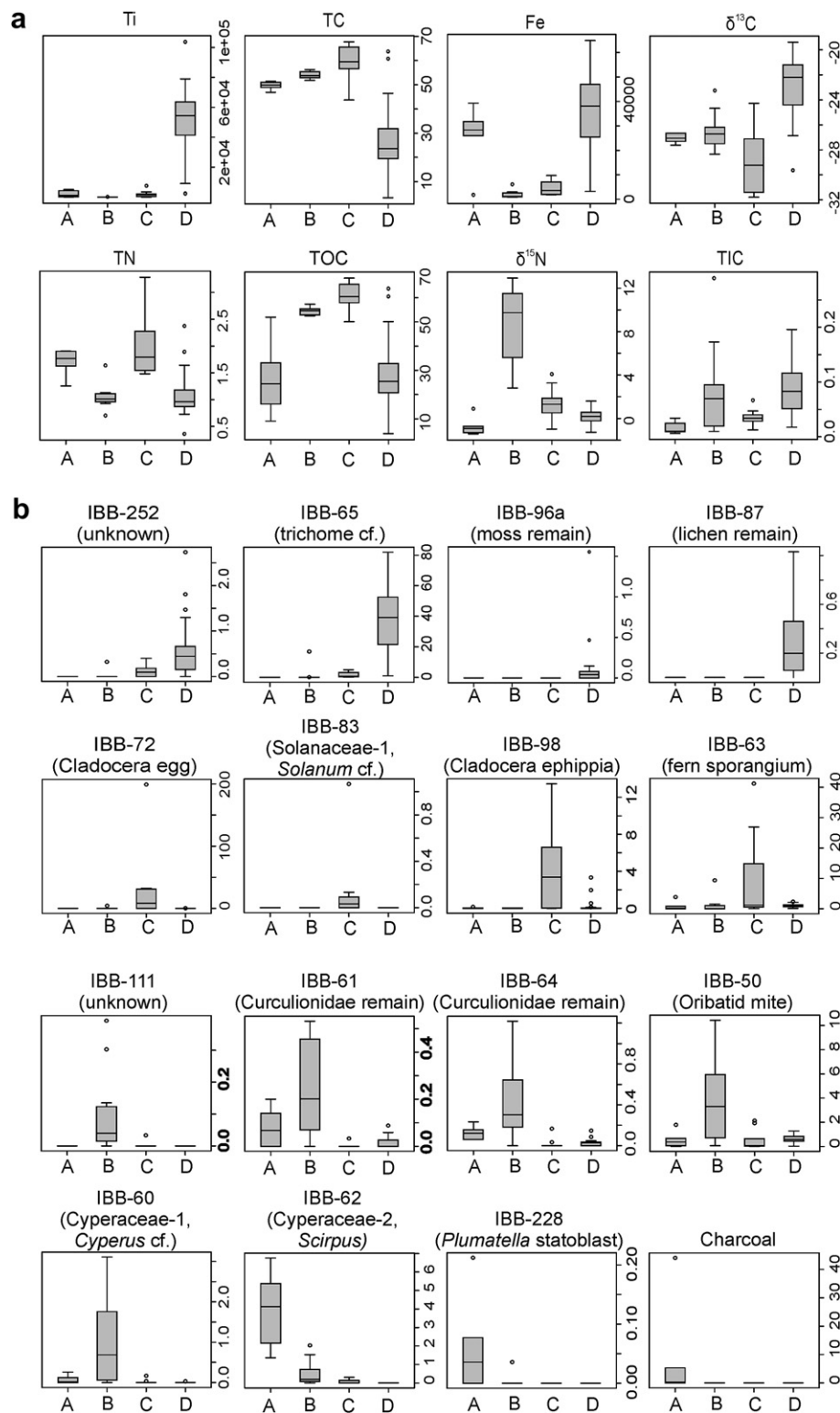


Fig. 9. Box-plots of the most significant (a) geochemical parameters and (b) macrofossils identified for the four groups determined by TWINSpan. Box shows median, and upper and lower quartiles of the respective distribution. Whiskers represent the maximum and minimum range excluding any extreme outliers (shown as dots). Number of samples in each group: group A ($n = 6$), group B ($n = 12$), group C ($n = 10$), and group D ($n = 28$). Ti (titanium), TC (total carbon), Fe (iron), $\delta^{13}\text{C}$ (carbon 13 isotope), TN (total nitrogen), TOC (total organic carbon), $\delta^{15}\text{N}$ (nitrogen 15 isotope), TIC (total inorganic carbon).

the unidentified IBB-111, and Cyperaceae-1 seeds characteristic of Group B (Fig. 7) indicate incipient peat formation and shallow water. The assemblage changes in Group A (MA-4) and high values of Cyperaceae seed-2 and *Plumatella* statoblasts reflect the local formation of shallow open water. Charcoal is derived from the catchment or beyond by water or air transport. Additional studies and more precise identifications, together with information from microfossil analysis, are needed to test the indicator value of past environmental conditions by the macrofossils at Rano Raraku.

6. Conclusions and final remarks

The macrofossil assemblages in the Rano Raraku sequence are greatly influenced by run-off intensity, the vegetation around and in the lake, and the water depth. Terrestrial remains, characterised by plant trichomes, lichens, and mosses, were transported to the lake by run-off from the catchment during the last glacial period. The development of catchment and littoral vegetation in the Holocene influenced the composition of the sediment. The early Holocene swamp fringe acted as a filter that reduced terrestrial inflow and provided locally produced organic material. The continued hydrosere development resulted in peat-forming fen vegetation that supported aquatic plants and animals such as oribatids, coleoptera, etc. Together with sedimentary characteristics and geochemical information, the macrofossils can be used to indicate particular palaeoenvironmental conditions.

The fragmented and unidentified macrofossil record in Raraku Lake hampers a precise reconstruction of the environment and the ontogeny of the lake and its catchment. More information on the taxonomy and autoecology of Easter Island's biota is essential to improve our palaeoecological reconstructions. The study of microfossil is in progress and is expected to complement these interpretations. Nevertheless, the combination of macrofossil, sedimentary, and geochemical data have characterised five palaeoenvironmental stages during the last 34,000 cal years, and have provided an outline of the biotic and environmental changes in and around the lake through time. From 34 to 14.6 cal kyr BP (last glacial period) the lake had low productivity and high terrigenous inputs. During the warmer conditions of the early Holocene, lower energy and a lower lake-level promoted the growth of a littoral plant belt that prevented the transport of terrestrial material into offshore zones. From 8.7 to 4.5 cal kyr BP (early- to mid-Holocene) a swamp dominated mainly by Cyperaceae, first *Cyperus* sp. and later *Scirpus* sp. occupied the entire basin and the sediment became more anoxic. At around 4.5 cal kyr BP (mid-Holocene) peat accumulation and dry conditions prevented further peat growth until about 800 cal yr BP when humidity allowed peat growth to resume. In recent centuries humidity increased further and a small shallow lake developed within the swamp (Fig. 1). Charcoal in the lake sediments records human activity.

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Appendix. Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.quascirev.2011.12.013.

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