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Article

Records of Holocene Environmental Changes in Terrestrial Sedimentary Deposits on King George Island, Antarctica; A Critical Review

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Abstract: In this study we discuss some problems that emerged from paleolimnological and paleontological investigations of terrestrial Holocene ecosystems on King George Island (South Shetland Islands) conducted by an Argentine-Polish research group. Biological and geochemical markers commonly used in standard analytical procedures are considered insufficient in tracing overlapping records of past environmental changes preserved in peat banks, lake sediments and ornithogenic remnants. Records that might be explained by predictable natural events (related to glacio-isostatic uplift of land), roughly predictable events (ecological succession), or unpredictable events (volcanic eruptions or accidental destruction of aquatic moss) may overlap or interfinger one with another providing that signals of regional and/or global climatic changes, are hardly identifiable. A more sophisticated and more selective methods are recommended to do discrimination between records of local and regional/global processes in studies on Holocene climatic history of the South Shetland Islands.

Key words : Antarctica, Holocene, paleolimnology, tephra, pedology

1. Introduction

A global scenario of geological events that occurred during the transition from the Late Pleistocene to Holocene is well recognized. A sudden melting of ice shelf in the polar regions just before 10 ka BP caused global rise of sea level and initiated glacio-isostatic uplift of land that continues till the present time. It is also known that deglaciation of land occurred between 8 and 5 ka BP (data summarized by Berkman *et al.* 1998, and Ingólfsson *et al.* 1998). However, development of terrestrial ecosystems during following minor fluctuations of Holocene climate on ice-free patches of land in the maritime Antarctic is still the question under discussion. Since the South Shetland Islands are located close to the boundary between maritime and continental climatic modes, one may expect a sensitive response of the area to any climatic changes. Some indicators of a mid-Holocene glacial advance 5.3-4.5 ka BP, circum-Antarctic climate warming 4-3 ka, as well as pronounced climatic fluctuations in the historical times were already suggested for the Antarctic Peninsula region (Björck *et al.* 1991a; 1991c; Björck *et al.* 1993; Mäusbacher *et al.* 1989; Ingólfsson *et al.* 1998; Emslie *et al.* 1998; Emslie 2001; Angeles Barcena *et al.* 1998). Thus, the question arises: are there any factors that might constrain paleoclimatic interpretations of a terrestial sedimentary record in that region? As a background for discussion we present data and hypotheses that emerged from paleolimnological

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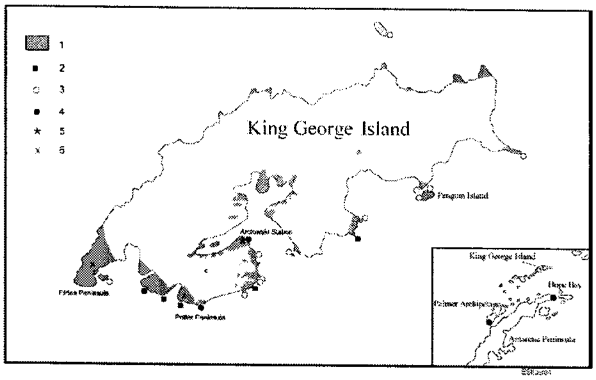

Fig. 1. Localization of sites investigated by Argentine-Polish team in the maritime Antarctic 1-area free of ice, 2-abandoned penguin rookeries, 3-active penguin rookeries, 4-partially abandoned penguin rookeries, 5-peat bank near, 6-lakes.

and paleontological investigations of terrestrial ecosystems in the South Shetland Islands.

The materials presented here were collected mainly on King George Island (Fig. 1) during the 4th (1979/80), 9th (1984/86) and 27th (2002/03) Expeditions of the Polish Academy of Sciences to Antarctica, as well as during Argentina – Polish Field Party in winter 1985 (Myrcha and Tatur 1986). Partial results of the expeditions have been already presented in several papers (Tatur and del Valle 1986, Tatur and Myrcha 1988, Tatur 1989, Tatur and Keck 1990, Tatur *et al.* 1991, Martinez-Macchiavello *et al.* 1996, Tatur *et al.* 1997, 1999a, 1999b, Tatur 2002).

2. Results and discussion of selected examples

Peat banks in the vicinity of Arctowski Station

There are only few thin peat banks on King George Island and most of them are located near Arctowski Station (Birkenmajer *et al.* 1985; Tatur and del Valle 1986; Tatur 1989; Fabiszewski and Wojtuñ 1993). They occur either in the narrow valleys affected by fluvial and gravity flows or in the form of eroded relic patches of originally wider surfaces that covered elevated beaches. Uncorrected and non-calibrated C-14 ages of peat bank bases range from 3.8 to 5.0 ka BP. All the banks were carefully investigated by Tatur *et al.* (1999b) and again during the 2002/2003 Expedition for the presence of tephra horizons but no any tephra was found.

The palynological record in peat banks on King George Island is extremely poor, although it has allowed to suggest the existence of a mid-Holocene climatic optimum (Birkenmajer *et al.* 1985; Fabiszewski and Wojtuñ 1993). The composition of mosses is poorly diversified and marks mainly local succession processes. The occurrence of clastic intercalations suggests hiatus intervals in peat formation (Tatur and del Valle 1986). Thus, indicators of past climate changes commonly used in the other parts of world are almost useless here. Since no tephra horizons were found in the preserved peat banks, so the peat banks most probably were formed after a mid-Holocene tephra fallout dated in lakes between 3.8 (corrected C^{14} age of aquatic moss detritus) and 5.0 ka BP (apparent C^{14} age of aquatic moss detritus) (Tatur *et al.* 1999b), being coeval to upper gyttja in the Hotel Lake (see below). Thus, archives of paleoenvironmental changes preserved in peat banks on King George Island are shorter than in the lake sediments, and probably also less informative (lack of tephra horizons) than 5.5 ka BP dated peat bank on Elephant Island (Björck *et al.* 1991c).

Long Lake

The Long Lake is located on Fildes Peninsula, King George Island, in the abandoned melt-water channel, behind raised beach 12 m above sea level. A sediment core 2.3 m of length was taken from the 4 m water depth. The core profile (Fig. 2) represents local Holocene prograding sequence of marine - estuarine - lacustrine sediments and encompasses an upward-fiming sediment cycle formed at the mouth of a meltwater stream during regional isostatic

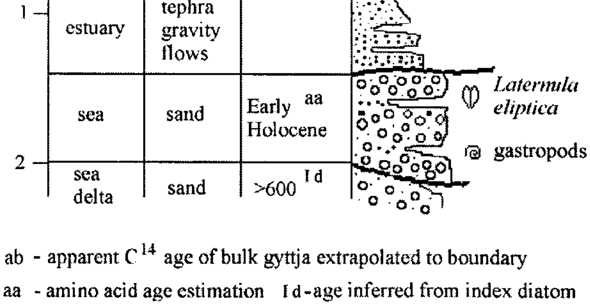

Fig. 2. Lithostratigrafic units in the core of bottom sediments from Long Lake (prepared on the basis of data published by Martinez-Macchiavello *et al.* 1996).

uplift that followed early Holocene deglaciation and marine inundation events (Martinez-Macchiavello *et al.* 1996). The base of the sequence consists of lower Holocene sublittoral sand (including marine diatoms and abundant molluscs), overlying (deltaic?) clastic sediments of presumably one of the pre-Holocene interglacial periods (index diatom *Actinocyclus ingens* suggests an age >0.62 Ma). The lower Holocene marine sand is truncated by middle Holocene gravity flows carrying volcanic ash. A sedimentary structures and presence of brackish diatoms suggest that they were deposited in a high-energy estuarine environment. The estuary gradually changed into a freshwater lake as it was separated from the sea by the subsequent formation of the beach. Accumulation of moss gyttja containing a freshwater diatom assemblage marks the final late Holocene stage of this coastal sedimentary sequence.

Diatom assemblages were used to reconstruct the sequence of geological and environmental changes that proceeded commonly in lakes dispersed along shore line. They have been usually formed during the last 6 ka behind marine beaches raised up to 16 m by glacio-isostatic processes. Paleoenvironmental record observed in the sediment core of Long Lake is therefore directly related to global climate change at the Late Pleistocene (multiple glacial interglacial cycles, early Holocene inundation followed global melting of the sea ice), although it documents mainly biota evolution from the marine to lacustrine environment.

The youngest unit, clay gyttja with moss detritus, has been accumulated in Long lake since 2.9 ka BP (Martinez-Macchavello *et al.* 1996). Would it be possible to use record preserved in continuous sedimentation of this gyttja for reconstruction of climate fluctuation, despite the absence of pollen? Late Holocene clay gyttja with moss detritus described from Long Lake might be considered a typical sediment for many similar lakes occurring in the maritime Antarctic. The moss detritus forms thin horizons (< 3 cm thick) in the clay matrix. Six such horizons (more distinctive than in other lakes) were recognized in the sediment core of Long Lake. The moss detritus must have focus proliferation of epiphytic diatoms attached to them. The question arises whether such horizons with specific diatom composition are of important staratigraphic value and might therefore record past environmental (climatic?) events?

The bottom of the lake is covered today by patchy carpet of mosses. It was observed that bottom mosses might be completely destroyed during dry and windy winter. Dust generated by eolian process during dry winter covers sometimes ice surface of the lake and prevents penetration of light to bottom mosses in the lake. Therefore, after the ice melts, dead moss floats on the lake surface and sinks to form horizons, which are observed in the sediment cores. Patchy distribution of moss on the bottom and accidental events of its destruction suggest that moss detritus horizons might have been formed in gyttja core by accidental events, costing doubts on usage of moss bearing gyttja sediment as a valuable diatomic archive of past climatic changes in such case.

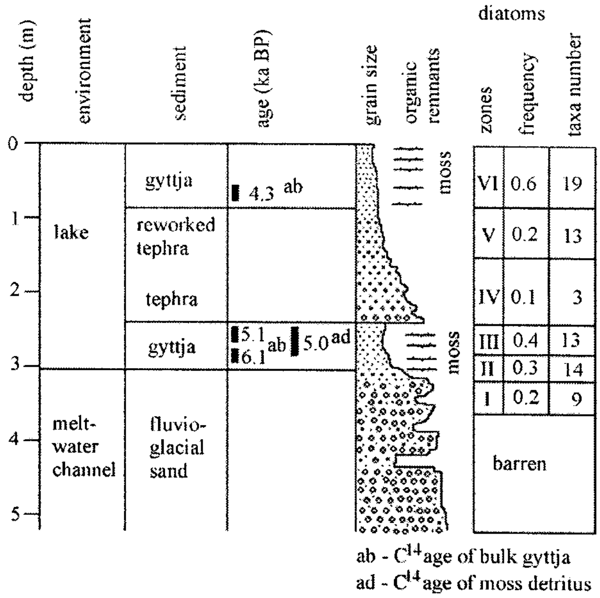

Fig. 3. Lithostratigraphic units in the core of bottom sediments from Hotel Lake (prepared on the basis of data published by Tatur *et al.* 1999b).

Hotel lake

The Hotel Lake is located at an altitude 40-45 m, on the edge of an extensive, flat erosional surface in an abandoned subglacial channel cut by meltwater stream. Barren fluvio-glacial clastics form the base of Holocene sediment deposited in the lake (Fig. 3). Diatoms appeared at the top of clastic sediment, which is dated to about 7-6 thousand C-14 (apparent) years BP, thus marking time of deglaciation of the Hotel Lake. The clastic sediment passes upwards gradually into gyttja rich in moss detritus. The gyttja consists of the upper and lower parts that are separated by a tephra horizon overlain by reworked tephra that was washed down from the catchment area to the lake by gravity flows about 4-5 ka BP (apparent age). The thickness of tephra and reworked tephra layer reaches 1.5 meter (Fig. 3). Several thinner (< 5 cm) tephra horizons were also recognized. All these tephra horizons (probably except for a thin one at 286 cm) were derived from Deception Island volcano

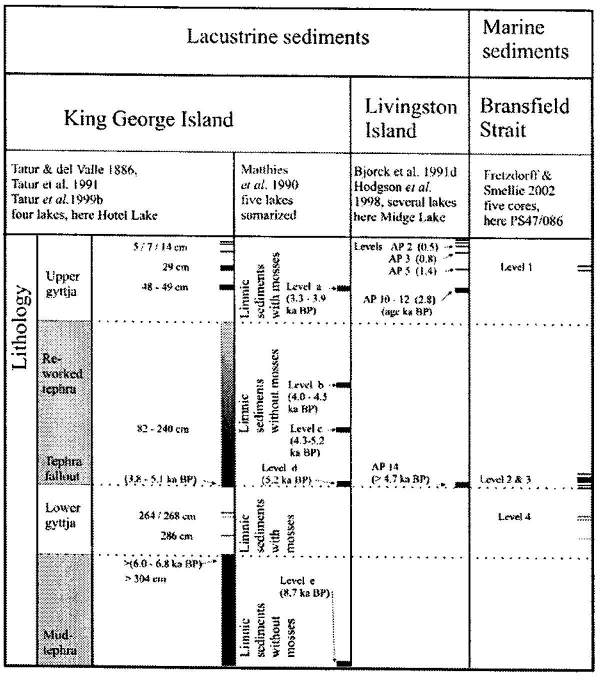

Fig. 4. Attempt of correlations among proposed tephrochronological models for Holocene in the South Shetland Islands.

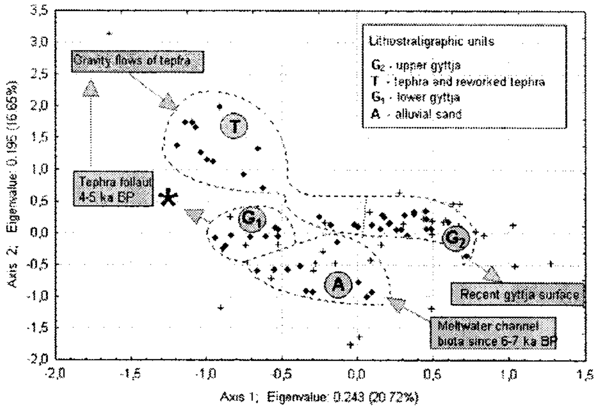

Fig. 5. Gradual changes of sedimentation and diatoms in Hotel Lake, Fildes Peninsula, King George Island during the 6-7 ka (CA analysis prepared on the basis of data presented by Tatur *et al.* 1999a). Description: Fields cover sediment samples in four lithostratigraphic units (A, G_1, T, G_2), containing similar diatom assemblages: (+) 32 diatom species, (◆) 53 sediment samples from the core.

(Tatur *et al.* 1999b).

Tephra horizons of the same origin were found in lacustrine sediments at other localities on King George Island (Fildes Peninsula and Potter Peninsula), on Livingston and Elephant islands, on the Antarctic Peninsula and in the Bransfield Strait (Tatur del Valle 1986; Matthies *et al.* 1987; Matthies *et al.* 1990; Björck 1991d; Tatur *et al.* 1991; Tatur *et al.* 1999b; Fretzdorff and Smelie 2002). All mentioned authors agree that uniform model of Holocene tephrochronology would be an excellent tool for regional paleo-environmental studies in the region where organic deposits suitable for C-14 age determination are only scarcely known. However, different modes of core description (discussed in detail by Tatur *et al.* 1999b), and largely misleading C-14 age determinations of lacustrine sediments (discussed by Björck *et al.* 1991b; 1991d; and Ingólfsson *et al.* 1998) impeded the construction of the chronologic scheme. So far, as a option the tephrochronology for the youngest volcanic eruptions was proposed by Björck *et al.* 1991d, and its broader application was confirmed by Hodgson *et al.* (1998) and Tatur *et al.* (1999b). Moreover, Tatur *et al.* (1999b) suggested that compilation might be applicable to a time period since the beginning of Holocene deglaciation (since 6-7 ka BP). This model of tephrochronology accounted for new data of Fretzdorff and Smelie (2002) is presented in the Fig. 4. Age correlation of mid-Holocene volcanic eruption records between Hotel Lake and Bransfield Strait PS47/086 site has been done with the assumption that the rate of sedimentation in the sampling site PS47/086 was approximately 130 cm kyr^{-1} as it was documented in the vicinity by Angeles Barcena *et al.* (1998) in sediment core "Gebra-1". It seems to be obvious, that proposed model of tephrochronology in the South Shetland Islands should be verified using rare earths elements and stable isotope analyses of the lake and marine pyroclastics.

Changes of diatom assemblages in the sediment core of Hotel Lake (Tatur *et al.* 1999a) strongly suggest that tephra fallout should be considered an important factor disturbing lake biota (Fig. 5). Lake biodiversity (here expressed as the number of diatom species) and trophy (frequency of diatoms and trophy index diatoms) had increased since lake formation (6-7 ka BP), but was highly reduced due to a sudden tephra fallout (4-5 ka BP). The recovery of biodiversity and trophy took place in the lake coeval with the change of clastics to gyttja sediments. However, the diatom species composition of new upper gyttja assemblage is different from that of lower gyttja. Several new species substituted the former dominants at the same ecological functions (Tatur *et al.* 1999a).

This example indicates that succession resulted from stress after tephra fallout might be considered a driving factor that commonly changed biota of lakes on King George Island. However, period of mid-Holocene tephra sedimentation in Hotel Lake correlates exactly with cessation of a mid-Holocene deglaciation, wetter climate or even glacial advance inferred from other lakes in the area (Mäusbacher *et al.* (1989); Schmidt *et al.* (1990); Ingólfsson *et al.* (1992) and Hjort *et al.* (1997). This climatic event seems to be of regional importance and has been confirmed by many scientists working in the vicinity of the Antarctic Peninsula (see Ingólfsson *et al.* 1998 for references). This means that paleoenvironmental signals from tephra fallout and climate change overlap each other in lake sediments.

Abandoned penguin rookeries

Traces of past penguin breeding activity have been found in a small "Green Valley" (45 m a.s.l) between hills over the recent functioning rookery at Orange Cliff, near Arctowski Station (Tatur and del Valle 1986; Tatur *et al.* 1997). Abundant bones of *Pygoscelis adeliae* (Tatur and Myrcha 1988) have been recognized in the phosphatic clay occurring at the depth of 1.5 m under the fluvial deposits intercalated with moss dated at the base to 4.9 ka BP (Birkenmajer *et al.* 1985). TL dating of sand from ornithogenic horizon suggests that this deposit might be even of Eemian age (Tatur *et al.* 1997), but C-14 AMS dating of collagen (?) from penguin bones yield the calibrated age of 4.2 ka BP (Tatur unpubl.). However, the bones appeared to be severely diagenetically modified. Ca^{2+} has been totally removed, and bone-apatite has been replaced by leucophosphite (hydrated, basic Al-Fe phosphate bearing K and NH_4 ions). Pseudomorphs of leucophosphite imprint exactly the bone morphology providing that they look like the modern bones (Tatur and Keck 1990).

Traces of abandoned penguin rookeries are dispersed along shorelines in Antarctica. Particular populations of penguins are used to nest at the same sites every season, and only extraordinary events might break that habit. The main reasons for the latter situation are as follows: restricted access to the nesting sites due to morphological changes in the coastal zone during isostatic rebound of land (Tatur and del Valle 1986; Tatur *et al.* 1997), and restricted access to the nesting sites on the beginning of breeding season due to unsuitable sea ice cover near shoreline as a result of climate cooling (Baroni and Orombell 1994; Emslie *et al.* 1998, Emslie 1995; 2001). On the basis of dated penguin remains, Holocene climatic scenario for the Antarctic continent (Baroni and Orombell 1994) and for the maritime Antarctic (Emslie *et al.* 1998; Emslie 2001) have been proposed.

C-14 age determinations of penguin bones need correction for old oceanic water effect. Old deep oceanic water reaches the ocean surface around Antarctica due to upwelling. The proposed correction values range from 600 to 1300 years, and differ from site to site, and from species to species. This creates some serious problems when relatively young bones are dated. Young bones are widespread in the maritime Antarctic mainly at the surfaces of abandoned nesting sites. The older bones were washed downslope and usually occur in buried horizons (Tatur *et al.* 1997; del Valle *et al.* 2002). They were included into raised beach sediments (Barsch and Mäusbacher 1986) or were exposed on the surface due to polygonal ground formation (Emslie 2001). It might be supposed that replacement of apatite in bones by composite Al-Fe phosphates is a common process in wet climate of the maritime Antarctic (Tatur 1989; 2002). Does the pseudomorph after bone apatite keep original ornithogenic collagen or might be it just undefined dissolved organic carbon (DOC) washed into the porous bone from the surrounding? The question is open at least in a case described by us.

Climatic scenario for the maritime Antarctic inferred from ages of ornithogenic remnants collected in abandoned rookeries imply colonization of coastal areas in the maritime Antarctic by penguins about 6 ka BP with deglaciation of land (Barsch and Mäusbacher 1986, del Valle *et al.* 2002, Tatur 2002). Then between 5 and 4 ka BP there was an interruption in colonization resulted from climate cooling, and continuous colonization since 4 ka till now (Emslie 2001). C-14 datings of bones collected near Arctowski Station at Potter Peninsula (del Valle *et al.* 2002) and also in a raised beach at Fildes Peninsula (Barsch and Mäusbacher 1986) fit exactly after correction (700 years) to the proposed period of climate cooling 5-4 ka B.P.. These datings together with those of Emslie (2001) suggest that penguins started to colonise shores in the maritime Antarctic as soon as they could, and that this process is lasting probably continuously till now. However, we do not have yet any concrete evidence proving important changes of past penguin population following climatic fluctuations in the maritime Antarctic. Some promising data were obtained from micropale-ontological investigations on the diet of ancient penguins, the remnants of which were preserved in abandoned nesting sites Emslie *et al.* 1998.

3. Conclusions

Data inferred from terrestrial sedimentary deposits on King George Island support global and regional scenario of geological and ecological events around the Late Pleistocene / Holocene boundary. The rates of shelf and coast deglaciation and glacioisostatic rebound of land, as well as colonisation of terrestrial oasis by mosses and appearance of penguin population are coherent with data from surrounding areas. However, detailed chronology of paleoenvironmental changes following after the deglaciation of land between 8 and 5 ka BP remains uncertain. Important part of natural terrestrial archives of the past history (peat banks, guano, and subfossil bones) has been largely eroded and is often missing. The only certain continuous record of environmental changes since deglaciation is preserved in the bottom sediments of lakes located on Fildes Peninsula. However, chronology of this record is still unprecise, due to limited reliability of C-14 datings. Moreover, regional tephra isochrons for the Holocene, which are an important tool for solving chronological problems, are still not sufficiently documented, despite of many papers dealing with the subject. At present, only tephrochronology for historical time by Björck *et al.* (1991d), Hodgson *et al.* (1998) and Tatur *et al.* (1999b) seems to be realiable.

For the interpretation of paleoenvironmental changes, much more attention should be paid to clarify what records might be explained by natural predictable (e.g., uplift of land), roughly predictable (e.g., ecological succession) or unpredictable (e.g., volcanic eruptions, accidental destruction of aquatic moss) events and what might be explained by regional or global climatic changes.

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