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Relics: penguin population programs

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What has been responsible for the increase in Chinstrap penguin populations during the past 40 years in maritime Antarctica? One view ascribes it to an increase in availability of their prey brought on by the decrease in baleen whale stocks. The contrary opinion, attributes it to environmental warming. This causes a gradual decrease in the frequency of cold years with extensive winter sea ice cover. A number of penguin monitoring programs are in progress and are expected to provide some answers to these questions. Unfortunately, it is not easy to distinguish natural variability from anthropogenic change since penguins are easily accessible predators of krill and the feeding range of the penguins has almost overlapped with the krill fishery in time and space in the last four decades. Therefore it is important to reconstruct the change of ancient penguin abundance and distribution in the absence of human activity. Many efforts have focused on surveying the abandoned penguin rookeries, but this method has not been able to give a continuous historical record of penguin populations. In several recent studies, ancient penguin excreta was scooped from the penguin relics in the sediments of the

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lake on penguin rookery, Ardley Island, maritime Antarctica. In these studies, penguin droppings or guano soil deposited in the lake and changes in sediment geochemistry have been used to calculate penguin population changes based upon the geochemical composition of the sediment core. The results suggest that climate change has a significant impact on penguin populations.

Introduction

Populations of many krill-eating Southern Ocean predators, especially penguins, have undergone significant changes during the last 40 year[1]. The 4 to 5°C midwinter warming of the western Antarctic Peninsula (WAP) climate observed over the last 50 years is presumed to have taken a toll on Adelie penguin[2].

It is known that Antarctic krill (*Euphausiasuperba*) is a key species for seabirds, marine mammals and human fisheries in the Antarctic and sub-Antarctic. From a survey, the commercial krill fishery harvest in the South Shetland Island was estimated at 1.0×10^8 kg krill, approximately 12% of total consumption of all land-based predators (Chinstrap penguins, 7.8×10^8kg; Adelie penguins, 3.1×10^7 kg; Gentoo penguins, 1.0×10^7kg; Antarctic fur seals, 3.6×10^6 kg)[3]. Since the commercial krill harvest overlaps the peak demand of penguin and fur seal for krill, the commercial krill fishery can have an effect on the survival of the predators, especially penguins. There are also many reports on effects of tourism and research on the decline of Adelie penguin populations in Antarctica[4,5].

In some locations, such as Togresen Island, however, the Adelie penguin population decreased by 19% between 1975 and 1982 while the penguin population decreased by 43% during the same period on Litchfield Island. In both areas human activities including tourism and research, continue to increase[6]. There may also be effects imposed by other environmental factors.

This raises a serious question about how environmental change has influenced the Antarctic marine ecosystem and how we can distinguish natural factors from anthropogenic effects on the penguin population in Antarctica.

A modern penguin census in maritime Antarctica was carried out to answer the following questions: (1) does the feeding range of the penguins overlap with the krill fishery in terms of time and space? (2) What are the penguins' normal levels of breeding success and food consumption? (3) What is the natural variation in diet and breeding success from year to year? (4) What factors are responsible for these natural variations? (5) How much krill can be fished without affecting the animals and birds that depend on it?[7]

Unfortunately, almost all the long-term penguin monitoring programs have been carried out for just a short time and too many factors are included. It is difficult to identify the dominant factors for penguin change. For example, there are two opposite explanations for the increase in Chinstrap penguin populations during the last 40 years. One focuses on the factor of human activity and says that the increase in Chinstrap penguin populations results from an increase in prey availability brought on by the decrease in baleen whale stock[8]. The other suggests that the gradual decrease in the frequency of cold years with extensive winter sea ice cover resulting from environmental warming is responsible[1].

Therefore, knowledge of historical penguin changes without human activities would be very helpful for understanding the factors that affect the penguin population change. Recent studies on lake sediments located in the penguin rookery are a good start in providing such knowledge[9].

Penguin relics in the lake sediment

Abandoned penguin rookeries have been important for palaeoenvironmental research in Antarctica. Relics of penguin in the colony, marked by the preservation of nest stones, ornithogenic soils (formed from bird guano), food and chick, can provide information on the past penguin population change and the migration of penguins. Penguin colonies have been found to be as old as 13,000 years before present (yr BP) in the Ross Sea region, as calculated from the guano soil radiocarbon dating[10] on the Windmill Islands, Budd Coast, East Antarctica, the radiocarbon dating of an Adelie penguin skull in the rookery yields 3,290 yr BP (ref. 11). Several abandoned colonies of penguin near Palmer station, Anvers Island, Antarctic Peninsula were excavated. Radiocarbon analyses dated the oldest site near Palmer station to 644 yr BP (ref.12). There were abundant fish bones and otoliths and squid beaks in the sediments of the colony.

The penguin relics have changed significantly during the different penguin occupation intervals. Giving the diagenetic processes that affect the preservation of penguin relics, these relics can be used to estimate the penguin dietary shifts in response to changing environmental conditions. Squid and fish were identified from bones, beaks and otoliths recovered from measured volume of matrix excavated from abandoned colonies of Adelie penguin in Palmer Station area. Based on these findings, it seems that Adelie penguins may have changed their diet following warming and cooling cycles[12].

Preliminary results from studying relics of the penguin colony in some locations in maritime Antarctica have been used to elucidate the palaeoecological response to climate change[13]. However, there are a number of problems with using this method to reconstruct the historical penguin population change. In the first place, this method cannot provide a continuous record of penguin population change. Secondly, in order to find relics such as bones, this method demands a large amount of sampling. Furthermore, it was speculated that erosion may have destroyed most of older rookeries, formed more than 1,000 yr BP, especially in the Antarctic Peninsula where climatic cycles, causing glacial advances, could scour the terrain[12].

We found that penguin remnants preserved in the colony can be deposited into the lake located on the rookeries (see Figure 1). The lake that was present in the ice-free area in maritime Antarctica, formed following climate warming-up and ice regression. The sediment profile of the lake will record the course of the glacial advance

Fig. 1. *Krill is the main food of penguins, constituting 81.79%, 86.87% and 100% of diets for Adelie penguin, Gentoo penguin and Chinstrap penguin respectively. In the breeding period, it is estimated that penguins on the Ardley Island discharge about 139 tons of droppings based on a hypothesis that every day a penguin excretes 84.5 g droppings (dry weight). Since the penguin colony is located on the lake catchments, droppings were transferred by ice or snowmelt water and at least some of them deposited in the lake. The relics in the lake sediments record the ancient penguin waste products (Taken by Liguang Sun, in Antarctica austral summer,1999/02)*

and retreat as well as environmental changes since the Holocene. Investigating the sedimentological data recorded by sediment cores, such as visual descriptions, sedimentary structures, magnetic susceptibility, sand contents, water content, pollen, foraminiferal ooze, siliceous mud, terrigenous mud, sometimes plant remnants, can provide us with data on palaeoenvironmental changes[14]. The change in the population of historical fur seals, one of the important marine mammals in Antarctica, has been inferred from the hairs in the sediment profile and was found to be negatively correlated with whale harvesting[15]. Thus, relics in the lake sediment can be an ideal method for reconstructing the historical penguin change.

By looking at a lake sediment core dating back to approximately 3,000 radiocarbon years, the sediment amended by penguin dropping has been identified by the chemical composition of this core[9]. The lake sediment core was collected from the Ardley Island (62°13°S, 58°54°W) situated about 500m east of the coast of Fildes Peninsula, Maxwell Bay, King George Island. This island is about 0.5km east of the Chinese station Great Wall and about 1km southeast of the Russian station Bellingshausen and the Chilean station Teniente Marsh. It is defined as a site of special scientific interest by SCAR. The site has the largest concentration of Gentoos penguins (*Pygoscelis papua*) within the South Shetland Islands (see Figure 2). The average number of breeding pairs is estimated at about 4,000. In addition, there are also about 1,200 pairs of breeding Adelie penguin (*Pygoscelis adeliae*) and a small number of Chinstrap penguins (*P. antarctica*). Large inter-season fluctuations in numbers and the breeding success of each species of penguin are observed from the results of a modern census since 1979. It is presumed that these population fluctuations are a direct response to disturbance by large numbers of visitors, vehicles and low-flying aircraft. The effects of these impacts will continue to be monitored as an integral part of the long-term ornithological research being undertaken at this site[16]. In addition to monitoring the modern penguin changes in this island, ancient penguin waste products is also expected to have accumulated.

Chemical characteristics of sediments amended by penguin dropping

The elements in the lake sediments on the Ardley Island show some particularities. The characteristic ratio of strontium over barium (Sr/Ba) is different from that in the other lakes without surrounding penguin rookeries (see Figure 3). The average value of this ratio in the lake sediments on Ardley Island is much higher than 3.3 (ref.

Fig. 2. *The area was covered by snow in December 1998, a breeding period. Modern census indicates that penguin numbers decline on this rookery. The fluctuation of modern penguin populations has been contributed to disturbance by humans. An opposite opinion considers that more snow due to a warmer atmosphere holding much moisture may make it harder for penguins to breed. The status might be likened to a 'canary in the coal mine'[2]. (Taken by Liguang Sun)*

17). But this ratio is typically less than 3.3 for lake sediments. Values higher than 3.3 suggest that the sediments are deposited in the marine environment. The concentrations of sulphur (S), phosphorus (P), calcium (Ca), copper (Cu), zinc (Zn), selenium (Se), strontium (Sr), barium (Ba) and fluorine (F) are at a high level and show a similar fluctuation against depth in the sediments by penguin droppings[9] (see Figure 4) and are clustered into a group using R-mode factors according to the coefficient (see Figure 5). These elements also have a high concentration in the penguin droppings[18]. In other organic matter or plant, enrichment of S, P and Se can also be expected[19]. Biogenic barium profile in the sediment samples from the Weddell sea, Antarctica, was found to be influenced by palaeoproductivity[20]. So far these nine elements have not been reported together in high concentration in any organic material except penguin droppings.

Developed on abandoned penguin rookeries, ornithogenic soils (guano soils) are rich in P, Ca, F, Cu, Zn, Mg, K and lack Si, Al, Fe, Mn (refs 21–28) It is estimated that penguins alone can carry

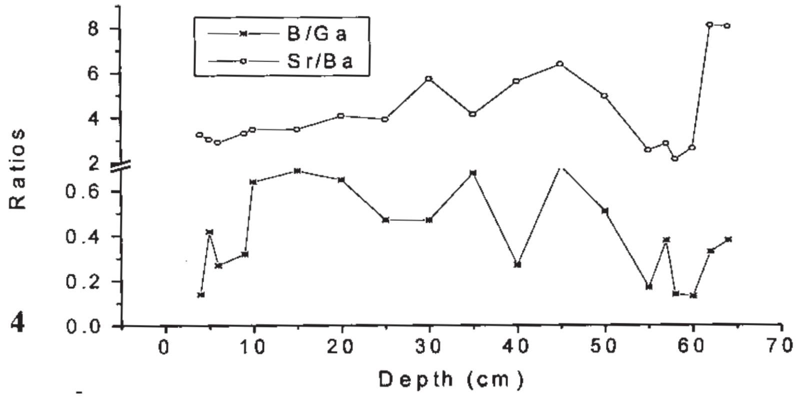

Fig. 3. *The ratios of Sr/Ba in the sediments of Ardley Island are higher than 3.3, with a mean value of 4.92 and a standard value of 1.53. Maximum ratio is 8.8. This characteristic indicates that sediments deposit in oceanic environment not in the freshwater lake. This is in contrast to the implication of the ratios of B/Ga, which is less than 1.0, with a mean value 0.43 and standard value 0.26 and suggests that the sedimentation environment should not be oceanic. The contradiction can be explained by the fact that penguin droppings is attributed to oceanic source and the sediments in the lake were affected by this material (redrawn from ref. 17, Sun, 2000)*

1.5×10^4~ 2.0×10^4 tons of P annually to the land via discharging droppings[21]. Phosphatization was observed in the subsurface zone as the result of a reaction between guano leachates and weathered volcanic rocks. More than 10 secondary phosphates including struvites ($Mg(NH_4)P0_4.6H_2O$), fluorapatites ($Ca_5(PO_4)_3F$) and brushites ($CaHPO_4.2H_2O$) can be found in this type of soil. Krill (*Euphausia superba*), eaten by penguins, is rich in fluorine. Fluorine concentration in penguins' excreta increased to approximately 0.43% (ref.29) compared with the fluorine concentration level in krill. The concentration of fluorine grew up to 2.2% during mineralization of organic matter in guano[29]. Fluorine mainly occurred in apatite in a surface layer of guano. Sometimes fluorine was also bound with amorphous aluminium phosphate (up to 2.0%), formed as a result of incongruently dissolving of minyulite in pure water[29]. Fe and Mn may migrate and be lost due to guano dissolving during occupation.

The assemblage of elements including Sr, F, S, P, Se, Ba, Ca, Cu and Zn is an important geochemical characteristic of the lake sediments impacted by penguin droppings or guano soil. Without

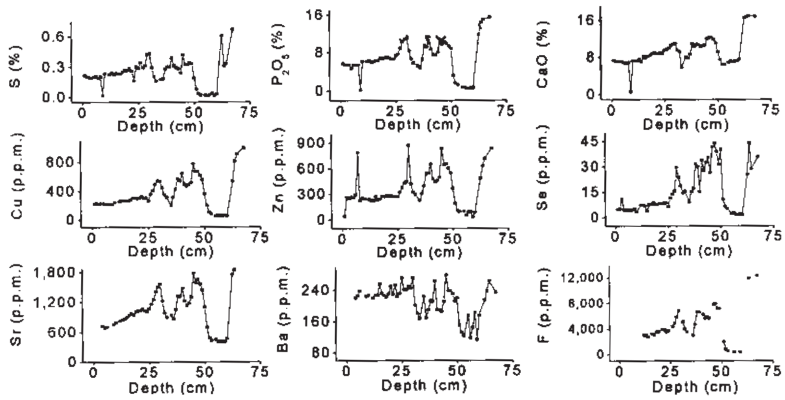

Fig. 4. *Exceptional enrichment of sulphur (S), phosphorus (as P_2O_5), calcium (as CaO), copper (Cu), zinc (Zn), selenium (Se), strontium (Sr), barium (Ba) and fluorine (F) and similar fluctuation against depth indicate that the lake sediments on the Ardley Island have been impacted by penguin droppings (redrawn from ref. 9, Sun, 2000). This typical chemical element distribution can be regarded as an ideal index of penguin excreta depositing on the lake.*

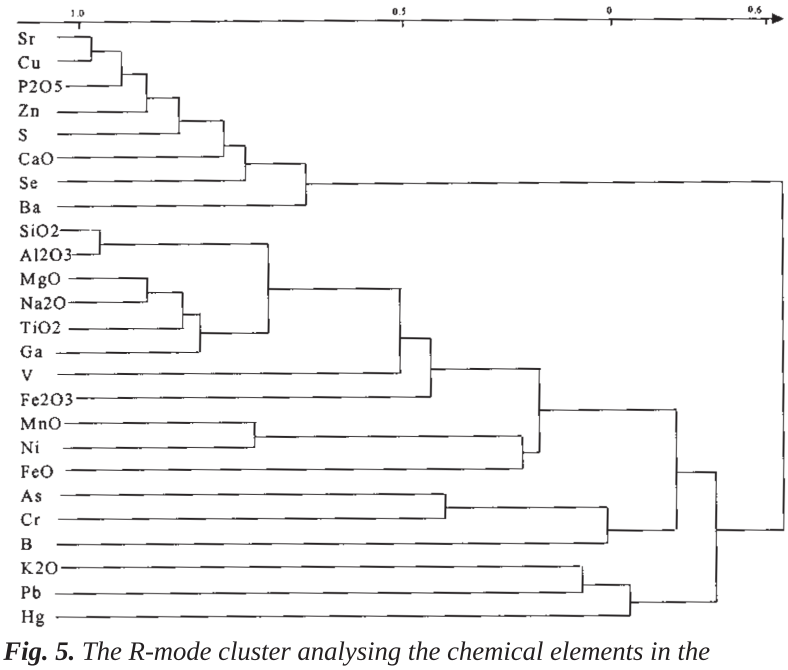

Fig. 5. *The R-mode cluster analysing the chemical elements in the sediment sequence of lake on the Ardley Island, Antarctica yields at least three groups. It is obvious that Sr, Cu, P (as P_2O_5), Zn, S, Ca (as CaO), Se and Ba consist of one group (redrawn from ref. 18, Sun, 2000)*

remnants of penguin droppings, these nine elements cannot accumulate together since their chemical activities are so different. Ornithogenic soils or penguin droppings could be deposited into the lake by ice or snowmelt water or directly discharged into the lake.

In addition, the reason for ascribing the fluctuation of elements in the lake sediments to the penguin droppings or guano soil is further supported by the fact that these elements were significantly correlated with the variations of total organic carbon and carbon stable isotope ($\Delta^{13}C_{PDB}$), which can suggest the source of organic matter. The values of $\Delta^{13}C_{PDB}$ of the organic carbon in the lake sediments amended by penguin droppings will be higher than that of the terrestrial vegetation. Primary results of $\Delta^{13}C$ value of a krill, penguin remains Adelie guano soil are in turn –28‰, –22‰ and –22 to ~25‰ (refs 27, 30).

Reconstruction of the historical penguin population change

With the belief that chemical characteristics of the lake sediments are mainly influenced by penguin-droppings or guano soil, Q-mode factor analysis, a method for decomposing multiple factor[31] was used to determine the change of penguin droppings in the sediments, which suggests the dynamics of penguin populations.

Combined with the radiocarbon dating in the sediment, we can reconstruct the historical penguin population change with time. Apparent ages (radiocarbon dating known shows that most of carbon of marine source has been found to be older yielding ages) of the sediments impacted by penguin droppings (marine source) might be older than the actual ages[27].

The penguin population change on the Ardley Island indicates that penguin rookeries existed on this island at least 3,000 years ago and a slump in penguin populations appeared during 1,800–2,300 yr BP (see Figure 6).

This method is not capable of identifying the sub-species of penguin according to the chemical characteristics of penguin relics nor provide information about ancient population changes of different subspecies. New methods needs to be developed to address this issue.

Factors affecting the historical penguin population change

What then are the major factors affecting penguin population and its distribution in the absence of human activity?

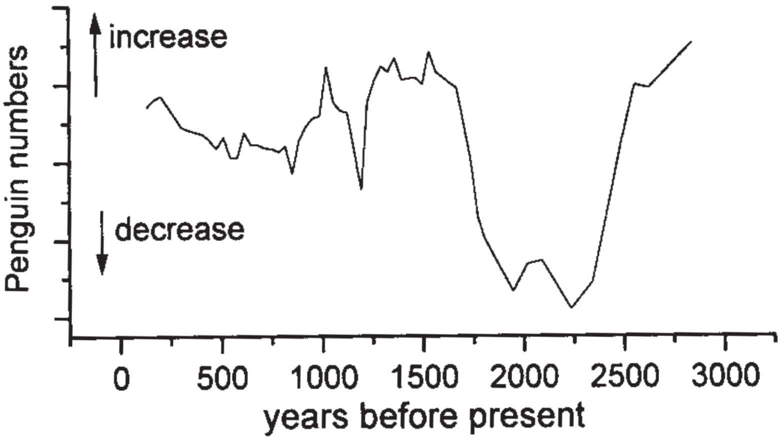

Fig. 6. *Change in penguin population during the past 3,000 years on the Ardley Island recorded by the lake sediments suggests that during a cold period somewhere between 1,800 and 2,300 yr BP penguin numbers slumped. Climate change seems to be an important factor affecting penguin survival (redrawn from ref. 9, Sun, 2000)*

The penguin population on the Ardley Island began to decline approximately 3,000 yr BP[9], corresponding to the glacial advances in King George island[32]. The low level of penguin population somewhere between 1,800 and 2,300 yr BP is in accord with the low temperature and precipitation[33,34]. Although the former census of the abandoned rookeries cannot give a continuous record of change in penguin numbers, the preliminary result suggests that following the glacier retreat in southern Victoria Land after the last maximum glacial penguins firstly arrived in this region at approximately 11,000–13,000 yr BP. Between 3,000 and 4,000 yr BP, a period of favourable environmental conditions, the greatest distributions of penguin rookeries occurred, followed by a sudden decrease shortly after 3,000 yr BP, as inferred from radiocarbon dating on the abandoned penguin rookeries[10]. From 3,000 years ago, the climate became cooler as can be seen from the ice-core and sediments record in Antarctica. From these results and observations, climate change is probably responsible for the penguin population change.

It is argued that different species of penguin may respond to climate change differently as inferred from modern census (see Figure 7)[1]. Further studies on the climate effect on the abundance and survival of ancient different special penguins are expected to be carried out in the near future to obtain more detailed knowledge.

Conclusion and prospect

Remnants of ancient penguin droppings in the lake sediments on penguin colonies can be identified by their chemical characteristics and provide information about the historical penguin population changes. Results from the studies on penguin droppings suggest that the penguin population change is affected mostly by climate. In the near future, reconstruction of past penguin population changes, especially in the Holocene around maritime Antarctica obtained from geochemical characteristics of the lake sediments in penguin colonies, is expected. This will provide more detailed data about both penguin population and climate changes.

Based on the presumption that Chinstrap penguin and Adelie penguin are 'bio-indicators' of climate change, the history of the last 10,000 years – years of glacial retreat and advance in maritime Antarctica – can be inferred from the historical penguin population change. Optimistically we may also be able to get some historical information about ancient krill in the Southern Ocean. To our knowledge, very few, if any studies have been done on historical krill change.

Together with the ^{137}Cs or ^{210}Pb dating of the sediment sequence, the geochemical analysis on the penguin droppings in the lake sediments is able to infer 50-year or 200-year records of penguin. This

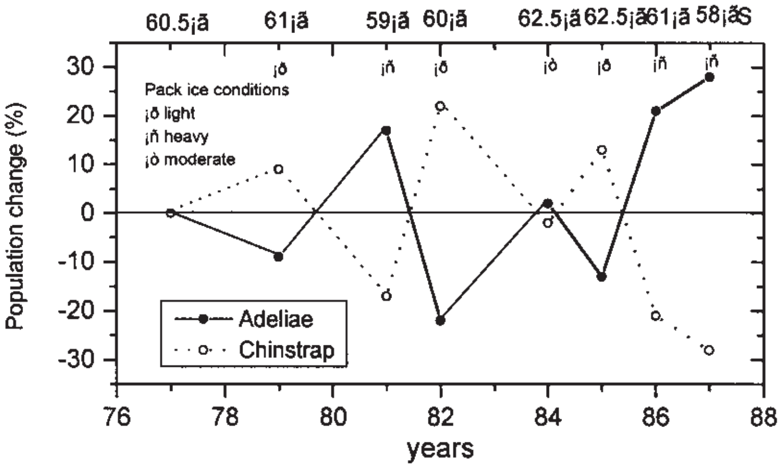

Fig. 7. Contrast between Chinstrap penguin and Adelie penguin reacting to the climate change. Warming-up increases the Chinstrap penguin populations, whilst decreasing the number of Adelie penguins(redrawn from ref. 1, Fraser, 1992)

will provide an opportunity to compare the results from the lake sediments with the modern monitoring results. Furthermore, we can establish a quantitative function to estimate the exact historical penguin population.

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