*论文题目：南极阿德雷岛地区湖泊沉积与企鹅生态环境演变*

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# 摘 要

企鹅在联系南极陆地、淡水、潮间带和海洋生态系统上起到了关键的作用：它们在陆地繁殖和栖息；在潮间带捕食帽贝；在海洋中捕食鱼和磷虾；企鹅栖息地往往发育含有较高含量无机营养盐的鸟粪土，它们是初级生产力所必需的。这使得营养盐合理地重新分配于各系统间，疏通了各系统间的物质流动。企鹅数量的波动势必对南极的生态系统平衡造成影响,因此，对于企鹅数量变化的研究成了南极研究的热门课题之一。根据近年来的监测结果，生态环境学家指出企鹅数量的增多或减少可能与目前剧烈变化的气候环境和人类活动有密切关系。由于现代企鹅数量变化可能同时受到错综复杂的自然因素和人为因素的耦合作用，要确切了解影响企鹅种群分布和数量变化的关键因素及其影响程度就必须在监测现代企鹅数量变化的同时探讨历史时期企鹅数量的变化。本文采用生物地球化学方法在南极湖泊集水区研究了历史时期企鹅数量的演变及其影响因素等相关内容。

1．企鹅粪土层的识别和历史时期企鹅数量变化的恢复

南极阿德雷岛(62°13′S,58°54′W)地处南极半岛乔治王岛,邻近中国南极长城站。阿德雷岛为国际南极科学考察委员会确定的特别科学兴趣区，面积大约为 2km2，最高海拔只有 70m,主要由第三纪安山岩、玄武岩和凝灰岩组成，分布有上升的海岸阶地和小湖泊以及积水洼地。目前，阿德雷岛是南设得兰群岛地区最大的金图企鹅聚居地，大约有 4000 对该种企鹅；另外，还有大约 1200 对阿德利企鹅和少量的南极企鹅。从 1979 年以来智利和德国科学家发现该岛企鹅数量和每种企鹅的繁殖成功率出现相当大的波动。这种变化被认为是由于大量的参观人员、机动车辆和低空飞行的飞机所干扰的结果。

企鹅的食物主要为磷虾、鱼类及甲壳类、软体动物，其中磷虾是企鹅的主要食物来源。大磷虾在阿德雷利企鹅和南极企鹅食物中所占比例分别为 81.79%、86.87%和 100%。每只企鹅每天排泄物大约有 84.5g（干重），在繁殖期，该企鹅聚居地将产生 139 吨的企鹅粪。这些粪土经冰雪融水迁移而沉积在企鹅聚居地的湖泊中。

在中国第十五次南极考察期间（1998/1999），我们用直径为 12cm 且经过清洁处理的 PVC 塑料管在该岛 Y2 湖等四个湖泊采集了泥芯样品。其中，Y2 湖芯样品海拔高度大约 12m,为 67.5cm 长的原状沉积物，散发出浓烈的臭味。样品取得后冷藏保存，带回实验室进行岩性鉴定描述，并进行样品分割。Y2 湖上部 64cm,按 1cm 间隔分割样品，底部 64～67.5cm 为一个样品，共 65 个样品。

样品在室内进行 14C 定年，底部年龄为 2795±60 年。样品同时进行元素、稳定同位素、有

机挥发性组份、有机碳、粒度和石英微形貌等测试分析。

采用相似系数对其中的 25 种元素结果进行 R 聚类统计分析。这些元素被分为三大类：第一类包括 Sr、Cu、P(或 $P_2O_5$)、Zn、S、Ca(或 CaO) 、Se 、Ba；第二大类包括 $SiO_2$、$Al_2O_3$、MgO、$Na_2O$、$TiO_2$、Ga、V、$Fe_2O_3$、MnO、Ni、FeO、As、Cr、B；第三大类包括 Pb、Hg、$K_2O$。

Y2 湖沉积物 Sr/Ba 比值为 4.92±1.53，均大于 3.3，最大的达到 8.8。这表明沉积相应为海相沉积，但是，它们的 B/Ga 比值却为 0.43±0.26，均小于 1，表现出淡水湖泊相。这一现象归因于 Y2 湖受到企鹅粪土的沉积改造。13C 同位素数据也证明了该观点。进一步与对照区（非企鹅聚居区）长城站西湖沉积物、原岩和植物相比，Y2 湖沉积物第一类元素和 F 的平均浓度明显偏高，其 S/P、Ca/P、Cu/P 和 Zn/P 等比值接近现代企鹅粪，另外，P 元素的富集是鸟粪土的明显特征，因此，第一类元素和元素 F 是企鹅粪土沉积的标型元素组合。

采用 Q 类因子分析提取出了标型元素的特征变化曲线。该变化曲线反映了企鹅粪在沉积物中的含量变化。利用企鹅粪的含量变化作为企鹅数量变化的替代性指标，结合放射性定年，恢复了大约 3000 年来企鹅数量的演变。该企鹅数量变化曲线和文献报道的古降雨量和古温度以及本文采用湖泊沉积物 Rockeval 参数 S2/S1 比值以及沉积物中有机挥发性组分的排放量作为古温度的替代指标进行对比。结果表明：大约距今 3000 年，企鹅数量开始减少，距今 1800-2300 年的新冰期，企鹅数量锐减，而距今 1400-1800 年的温暖期，企鹅数量逐渐达到最多，温度过高或过冷均不利于企鹅生存。从历史角度看，企鹅数量的变化似乎与气候有关且气侯的变化可能还影响到现代企鹅的生存和数量。

2．现代企鹅对南极气候变化的响应

在南极阿德雷岛相邻的巴登半岛 40 米高地金图企鹅聚居地采集了两个沉积剖面，并分析了其中的企鹅粪土标型元素，发现该聚居地是最近 40 多年来才出现的。对该地区湖泊沉积物中的放射性核素进行测量表明这一时期也是该地区气候变暖的时期。气候变暖导致冰川融化，其所携带的放射性核素使得湖泊沉积物中的蓄积量增大，远高于直接来自大气沉降。该企鹅聚居地的出现可能反映了现代气候对金图企鹅生活习性的影响。

3．企鹅对人类活动和自然环境的响应

工业革命前企鹅粪中 Pb 浓度较低且几乎没有变化，但是，在过去 200 年特别是过去 50 年里呈现明显上升趋势。这表明由于人类活动造成的全球环境污染已经影响到南极生态圈。重金属元素 Pb 通过在南极食物链中不断积累并传递给企鹅。

企鹅粪土中富集元素 F，在企鹅骨骼中也发现 F 元素的富集，但经过 X 光鉴别并未发现企鹅患有氟骨病。企鹅体中高浓度的氟可能是在长期进化过程中适应高氟食料磷虾的结果。该地区受到企鹅粪影响的土壤、植被和水体，其 F 浓度都比较高。

4.根据企鹅数量的变化和气候变化提出了 3000 年来南极阿德雷岛地区企鹅聚居地环境构造演变概念模式，该演变模式包括 4 个主要阶段：

第一阶段（I），距今 2,500 至 3,000 年,Y2 湖为位于高潮海平面之上的无冰区,为企鹅大规模聚居地, 沉积物中企鹅粪多，该时期温度和降水量(或降雪量)较低（或较少），是冰期初期。

第二阶段（II），距今 1,800 至 2,500 年,该时期气候骤冷,温度急降,该时期乔治王岛的冰帽有所扩张，同时在阿德雷岛上也出现小规模冰进，由于“地壳均衡”补偿使得该岛边缘古一级阶地处于高潮海平面之下,Y2 湖周围的企鹅聚居地消失,该时期 Y2 湖沉积表现为泻湖相沉积，与 Y2 湖相邻的 Fildes 半岛燕鸥湖边海拔 14 米的上升海滩的三级阶地 14C 年龄为 2180±95yr.BP 也说明该时期古一级阶地处于高潮海平面之下。冰进使得位于现在四级阶地以上的地貌受到不同程度的侵蚀，因此，阿德雷岛 Y3 和 Y4 湖沉积物年龄都小于 1,800 年，G 湖底部沉积物 2,120 年说明该岛冰进可能没有到达 G 湖位置。

第三阶段（III），距今 1,000 至 1,800 年,该时期气候较温暖,温度上升,降水量逐渐增多,冰川融化、后退,地壳均衡上升, Y2 湖上升至高于高潮海平面的位置,出现适合企鹅聚居的地区,企鹅开始大规模出现,沉积物中有大量的企鹅粪土沉积。

第四阶段(IV),距今 1,000 年以来,总体上 Y2 湖周围保持一定规模的企鹅聚居,期间随气候变化,企鹅聚居地有一定的变化。

# Lake sediment and change of ecological environment of penguin on Ardley Island in Antarctica

## Abstract

Penguins play a key role in linking the ecological system of land, freshwater, tideland and ocean. They breed and inhabit in the land, fish shellfish in the tideland, and take fish and krill in the ocean. In the penguin rookeries, guano soil with high inorganic nutrient salt is commonly developed, which is necessary to the primary production. These redistribute the nutrient salt in the ecosystem and make the materials flowing reasonably. Definitely, the fluctuation of penguin number in size will impact on the balance of ecosystem in marine Antarctic. Surveying on the change in penguin population therefore becomes a hot research field. Based on the modern monitoring results, ecological environmental scientists point out that the increase or decrease of penguin numbers may be ascribed to the abrupt climate change and human activity. Accordingly, in order to understand the key factors controlling in the penguin population and distribution, historical penguin populations should be studied in addition to monitoring the fluctuation of modern penguin numbers. Here we develop a biogeochemical approach to studying historical penguin population and the influencing factors in the catchments of lake and related topics.

Identification of penguin-dropping soil and reconstruction of historical penguin population

Ardley Island (62°13'S, 58°56'W) is located in the Antarctic Peninsula region, near the Chinese Great Wall station on King George Island. It was defined as a site of special scientific interest by the Scientific Committee on Antarctic Research (SCAR). The area of this island is about 2 km2 with a maximum 70 m height above sea level. Geologically, it consists mainly of Tertiary andesitic and basaltic lavas and tuffs together with raised beach terraces and small lakes and ponds. The site has the largest concentration of Gentoo penguins(Pygoscelis papua) within the South Shetland Islands. 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). Chilean and Germany scientists have observed large fluctuations in numbers and the breeding success of each species of penguin 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.

Krill, fish, shellfish and mollusk make up of the diets of penguin, of which krill occupies of 81.79%, 86.78% 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 139×103 kg of droppings based on a hypothesis that every day a penguin excretes 84.5 g droppings (dry weight). Droppings are transferred by ice or snowmelt water and at last some of

them are deposited in the lake located on the penguin rookeries.

During the fifteenth China Antarctic Research Expedition (1998/1999), we used a 12cm-diameter PVC pipe, which was cleaned firstly, to collected lake cores of 4 lakes on this island. A 67.5-cm core (Y2) is 12 m height above the sea level, giving off strong pungent odor. The sample was cold storage until lab analysis. In laboratory, the lithology of Y2 core was described and then divided into subsamples. This core was sectioned at 1.0-cm intervals for the upper 64 cm, with the bottom section being a consolidation of 64-67.5cm. The total number of subsamples was 65.

We collected, stored and processed samples using clean techniques, and then dating the samples. The core spanned 2795±60 radiocarbon years. Geochemical elements, isotope 13C, organic volatile compounds, organic carbon, grain size and quartz microtextures were analyzed at the same time.

The results of 25 elements were classified using R-mode cluster analysis method according to their similar coefficients. These elements were separated into three groups. The first group includes Sr, Cu, P (or $P_2O_5$), Zn, S, Ca (or CaO), Se, Ba and the second group includes $SiO_2$, $Al_2O_3$, MgO, NaO, $TiO_2$, Ga, V, $Fe_2O_3$, MnO, Ni, FeO, As, Cr, B and the elements in the last group are Pb, Hg, $K_2O$.

The ratios of Sr/Ba in the sediments of Y2 lake core 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 sedimentation environment should not be oceanic. The contraction can be explained by the fact that penguin droppings are attributed to oceanic source and the sediments in the lake were affected by this material. The results of stable isotope 13C were also agreeable with this explanation. Comparative research on the concentration of elements in Y2 lake sediments, Xihu lake sediments at the Chinese Great Wall Station with absent of penguin, mother rock and plants, the first group of elements and F shows enrichment in Y2 lake sediments, of which the ratios of S/P, Ca/P, Cu/P and Zn/P are similar to the ones in modern penguin dropping. It is also well known that guano soil is characterized by the enrichment of P. This leads to a conclusion that the assemblage of elements including Sr, Cu, P (or $P_2O_5$), Zn, S, Ca (or CaO), Se, Ba and F, so called “bio-elements”, is an important geochemical characteristic of the lake sediments impacted by penguin dropping deposition.

Q-mode factor analysis, a method for decomposing multiple factors, was applied to determine the concentration of these elements in the sediments. We have used changes in the deposition of “bio-elements” from penguin droppings as an indirect measure of population change. Thus, a 3,000-year record of penguin populations was established. Change in penguin population was compared with reported palaeoprecipitation and palaeotemperature as well as the temperature inferred from the ratios of S2/S1 calculated from Rockeval parameters and the total amount of organic volatile compounds in Y2 lake sediments. The results show that the penguin population began to decline at approximate 3,000 yr before present(BP) and was lowest at 1,800～2,300 yr

BP, a period of low temperature. After that , the population increased, peaking between 1,400～1,800 yr BP. Higher and/or lower temperature is not favor for the penguin survival. Historically, the size of penguin populations seems to be related climate and climate change might still affect the survival and abundance of modern penguin populations.

## Modern penguin in response to climate change

We collected samples from two deposition profiles on the Gentoo penguin rookeries with 40m-height above the sea level in the Barton Peninsula, closed to Ardley Island. The "bio-elements" were analyzed and indicated that these penguin colonies were established only approximate 40 years ago. This period was experienced with climate warming up inferred from change in the inventories of 210Pb and 137Cs in the lake sediment. The supply of radionuclides via a great amount of ice-melt water resulting from increase temperature made the inventories observed in the lake sediments higher than the one directly coming from the deposition of atmosphere. This suggests that change in climate might impact on the behavior of modern Gentoo penguin.

## Penguin in response to human activity and natural environmental change

Lead concentration in penguin dropping has been found significantly increased somewhere 200 years ago, especially 50 years ago, comparing with the low and stable lead level before the industrial revolution. This clearly indicates that global environmental pollution via human activity has influenced on the Antarctic ecological system. Heavy metal (Pb) may access the food web and bioaccumulate and be passed along the chain to penguin.

Penguin dropping soil enriched fluorine, whilst deadly fluorine concentration was also detected in penguin bone. However, radiographs of Adelie penguin bones show no symptoms of fluorosis. This could be the result of the long-term evolution to adapt to the main food krill, which is enrichment of fluorine. Soil, vegetables and water impacted by penguin droppings in Antarctica have also been found with the high level of fluorine.

## A conceptual model

A conceptual model of change in environment and structure of penguin rookeries on Ardley Island in Antarctica during the past 3000 years is forward based upon the fluctuation of historical populations and climate change. It consists four stages below:

1. Between 3,000 yr BP and 2,500 yr BP. Y2 lake located on the ice-free area above the high tide sea level. Large numbers of penguin occupied in this region, resulting in high level of penguin dropping in the lake sediment. This period is initial stage of neo-glacial age and the temperature and precipitation began decrease.

2. Between 2,500 yr BP and 1,800 yr BP. This was a neo-glacial age with a cold snap. The ice-cap on the King George Island and Ardley Island advanced. Iso-static adjustment lowered the

palaeo-first terrace at the edge of Ardley Island under the high tide sea level. This made the rookeries around Y2 lake disappear and Y2 lake changed into a lagoon. The fact of Y2 lake under the sea level was coincident with the radiocarbon age (2180±95 yr BP) of the modern third raised beach terrace with 14m-height above the sea level near Yin'Ou lake in the Fildes Peninsula. Ice-advanced eroded the landform higher than the fourth terrace and made the radiocarbon ages of Y3 and Y4 lake sediments younger than 1,800 yr BP. However, ice-advanced might not reach at the location of G lake, as the age of the bottom sediment of this lake was 2120 yr BP.

3. Between 1,800 yr BP and 1,000 yr BP. Climate was warming up. The temperature and precipitation increased, resulting in ice melted and retreated. Role of iso-static adjustment raised Y2 lake above the high tide sea level. Consequently, penguin colonies established and the size of penguin number increased. Thus, a larger amount of penguin dropping deposed in Y2 lake.

From 1,000 yr BP to today. Penguin rookeries changed in response to climate change, however, this fluctuation was slight.