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Eco-environmental Change Records of Antarctic Ice-free Areas in the Sediments Influenced by Marine Animals

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Abstract: The accumulative profiles of seabird and sea animal excrement together with the depositional sequences influenced by the excrement have been utilized to reconstruct the historical populations of Antarctic penguins and seals, also to study the eco-geology in the ice-free areas of Antarctica and Arctic. The historical populations of Antarctic penguins show dramatic fluctuations, the period of sharp decrease coincides well with Neoglaciation, and extremely cold or warm climate conditions are unfavorable for the survival of Antarctic penguin. The historical change of seal population seems to be related to climatic variations, sea-ice coverage and its forage behavior. The fluctuations of Hg (mercury) in the seal hairs and the sediments influenced by seal excrement were found to be closely associated with ancient gold and silver mining activities and the ancient civilization over the past several thousand years.

Key words: Antarctica; sediments influenced by animal excrements; penguin; seal; eco-environmental variation; human civilization

Introduction

Considering the earth as a whole, the plan of Past Global Changes (PAGES) is to fully research the interactions among atmosphere, biosphere, hydrosphere, pedosphere and lithosphere, and to accurately evaluate the influence of human activities on natural systems. The information about these interactions is preserved in the proxy recorders such as tree ring, coral, stalagmite, loess, ice core, lake and ocean sediments etc., and substantial researches have been performed using these materials at different spatial/temporal scales [1]. For example, ice core is a key proxy recorder for understanding the climatic change in polar and global areas.

The polar eco-environmental history plays an important and indispensable role in global changes studies. The active history of sea animals such as penguins and seals in the polar ice-free areas is closely related with the advance or retreat of ice sheet, climatic change, sea level rise or fall, and marine productivity. These relationships provide abundant scientific information for evaluating and predicting the influence of climatic change on Antarctic ecological system and for understanding of the ecological response to global changes.

According to the monitoring results in recent years, the penguin populations in Antarctica has shown striking fluctuations. Some scientists argued that dramatic climatic changes are responsible for these population occurrences and penguins can be used as an ideal bio-indicator [2] for environmental changes. In contrast, other scholars proposed that these changes are mainly caused by anthropogenic factors [3]. Unfortunately, it is difficult to distinguish natural factors from anthropogenic ones, since penguins mainly feed on krill, and their feeding range almost overlapped with the krill fishery in time and space for the last four decades. For Antarctic seals, the available data for the last two centuries showed that the population changes are linked to human interferences, e.g. the activities of sealing and whaling industries [4], and the natural influences remain unclear. Therefore, it is important to reconstruct historical

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population changes of penguins and seals in the absence of human activity.

1 Purpose of studying sea animal excrement sediment sequence

Eco-geologists have been trying to study the landing history of penguins in Antarctica. The main method is to dig abandoned ancient penguin rookeries and to perform radiocarbon dating on the relict bones in nests. By this means, Baroni *et al*. [5] have found that the penguin colonies were as old as 13000 a BP in the Ross Sea region. Goodwin [6] pointed out that the time of penguin breeding on the Windmill Islands of East Antarctica was earlier than 3290 a BP. Emslie *et al*. [7] presumed that the penguins appeared on Torgersen Island at 281 a BP. These studies answered the question when and where the penguins colonized. For reconstructing historical penguin population change, however, this method has many problems. First, it cannot provide a continuous record of penguin population change. Second, in order to find relics such as bones, it demands a large amount of sampling. And last, erosion may have destroyed most of older rookeries, formed more than 1000 a BP, especially in the Antarctic Peninsula where glacial advances could scour the terrain.

In order to explore the ecological history of Antarctic ice-free areas, it is necessary to find a sediment stratum with time sequence information, wide distribution and high resolution, which is closely related to biological activities. As seen in the numerous recent studies [8−15], the accumulative profiles of biotic excrement and the depositional sequences influenced by these excrements (containing biological reliques, relics and ichnites) are good archives to study the eco-geology in the ice-free regions of Antarctica and Arctic under the condition of polar eco-environment. Additionally, the lake sediments in the palaeo-notch can be used as a new proxy material to reconstruct palaeoecological and palaeoenvironmental records due to their special geographical site adjacent to coast and the characteristic of lake deposition [16].

In brief, the eco-geological studies of Antarctic ice-free areas are based upon multi-disciplinary approaches including field observation, Quaternary geology, elemental and isotopic geochemistry, sedimentology, glaciology, tectonics, biogeochemistry, organic geochemistry, palaeoclimatology, ecology, zoology, botany, microbiology and modern measurement technologies; then using the records of bio-geochemistry on a microcosmic level; and combining with the field investigations on landform and physiognomy such as changes of sea level and tectonic evolution. Palaeoecological, palaeoclimatic and palaeo-environmental changes are explored on a macroscopic scale by the means mentioned above. The eco-geological study in the Antarctic ice-free areas is becoming a new research direction in the frontier of two frontier subjects of earth system and global change sciences.

2 Triple property of excrement sediment sequence

The eco-geological studies in the Antarctic ice-free areas focus on the interacting processes between Antarctic biosphere and other natural spheres, especially the interfacial cycles of materials. For this purpose, a single special discipline responsible for single earth sphere is not sufficient, and an effective integration between different disciplines becomes indispensable. We have to investigate not only the environmental and geological backgrounds of individual subsystems such as atmosphere, soils, water, biology, landform and physiognomy, but also the inter-linking between them from a holistic point of view.

Some seemingly contrary phenomenon could become consistent under the uniform natural background, and the reasonable conclusions can only be drawn in the interfacial researches of sphere interactions. For example, during field investigations in the Antarctic Great Wall Station, we collected a 67.5 cm long sediment core from a freshwater lake Y2 on the Ardley Island. In this sediment core, the P_2O_5 content was very high up to 5%−15%, the Sr concentration was also at high levels and up to 600−1800 μg/g, and the levels of nine inorganic elements, such as Sr, F, S, Se, P etc., were significantly positively correlated [8]. The values of Sr/Ba were greater than 1, indicating a typical marine sedimentary environment, but the B/Ga ratios were lower than 3.3, suggesting a typical freshwater lacustrine sediment environment [9, 12]. These results seemed to be contradictory and confusing at first, but they ended as a beautiful picture of logitic consistence after further and in-depth researches under a larger frame of interacting natural systems.

The Y2 sediment section is a typical example for the interfacial-cycles. In the polar food chain, the main diet of penguins is krill, and the krill mainly feeds on algae. The krill and algae are enriched with some inorganic elements such as Sr, F, P, Se etc. Through biogeochemical cycling processes, these marine elements were transported into the freshwater lacustrine sediments by penguins via droppings. The material migration mediated by the seabirds occurred spatially from marine to land and from marine biology to

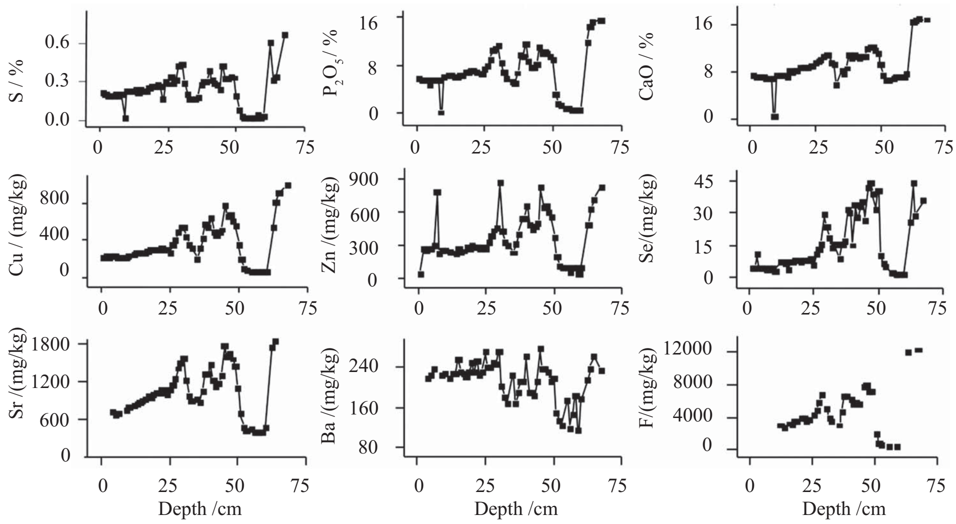

Fig. 1 Changes in the concentrations of nine bio-elements versus depth in the Y2 lake sediments [12]

freshwater lacustrine sediments. This leads to the lake sediments characteristic of triple properties including marine, lacustrine and biological depositions. The nine elements including S, P, Ca, Cu, Zn, Se, Sr, Ba and F have significant correlation with each other, their assemblage is characterized by the sediments influenced by penguin droppings, and the variations in their levels thus are associated with historical population changes [11−12].

The above new approach was also successfully used to reconstruct historical seal population. Because of the different trophic levels in the food chain of the Southern Ocean, however, the characteristic assemblage of chemical elements in the seal excrement sediments is different from that of the sediments influenced by penguin droppings. According to geochemical studies on the elements of seal excrement sediments [10,15], the elements including Se, F, S, P_2O_5 and Zn, which are closely related to the seal hair abundance, total nitrogen (TN), total organic carbon (TOC) and loss on ignition (LOI), are identified as the characteristic bio-elemental assemblage for the seal excrement sediments.

During these researches, we became aware that the weathered soils uninfluenced by penguin excrements also contain trace contents of the above nine typical elements and these background concentration fluctuations could affect the reconstructed historical penguin and seal populations (Fig. 1). Therefore, it is necessary to seek better elemental and isotopic proxies with both good biological implications and very low contents and small fluctuations in the weathered soils. For this purpose, we applied stable isotopic geochemistry to study palaeoecological processes of penguins and seals, and obtained better results [14, 17]. For example, the ratios of $^{87}Sr/^{86}Sr$ in the acid-soluble fractions and $\delta^{15}N$ values in the animal excrement sediments were found to be more sensitive for measuring historical penguin and seal population changes (Fig. 2 and Fig. 3). Recently, we found that the change patterns of organic geochemical proxies in the volatility compositions of the excrement sediments are very consistent with those of elemental and isotopic, and this further validates the use of excrement sediments for studying the palaeoecological processes of seabird and sea animals in the Antarctic ice-free areas.

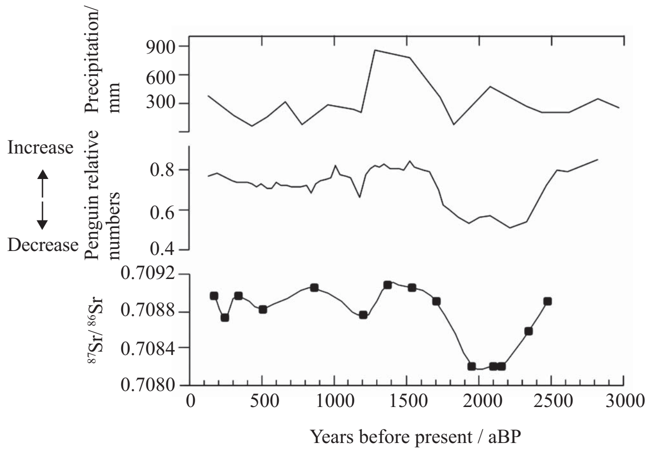

Fig. 2 Changes of historical penguin populations (middle curve) on the Antarctic Ardley Island [11], precipitation (upper curve) [18] and $^{87}Sr/^{86}Sr$ ratio in the acid-soluble fraction of Y2 lake sediments (bottom curve) [14]

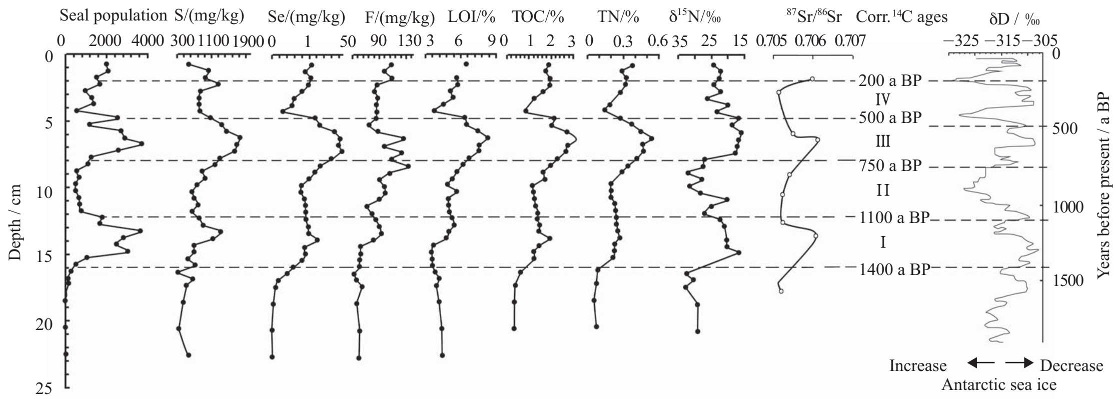

Fig. 3 Change in seal population over the past 1500 years [10] (Zones I and III correspond to the peaks in the seal population, Zones II and IV correspond to extremely low seal abundance, respectively. $^{87}Sr/^{86}Sr$ ratios are determined in the acid-soluble fractions of the seal excrement sediments. Taylor Dome data are obtained from World Palaeoclimate Data Center (ftp://ftp.ngdc.noaa.gov/paleo/icecore/antarctica/ taylor/ deld_td.txt). δD record of the Taylor Dome ice core (five-point moving average) are interpreted as a proxy for atmospheric temperature in coastal Antarctica and the extension of the Antarctic sea ice. The ^{14}C ages in the figure are reservoir-corrected radiocarbon years)

3 Eco-environmental information in the excrement sediments from the Antarctic ice-free areas

Based on the characteristic assemblage of elemental and isotopic geochemistry, substantial amount of the eco-environmental information in the ice-free areas of Antarctic have been deciphered, and in this section we discuss two interesting results.

3.1 *Historical changes of penguin and seal populations since the Holocene and their influencing factors*

According to the elemental geochemical study on the lake sediments influenced by penguin droppings on the Ardley Island in the maritime Antarctic, we found that the concentrations of elements such as sulfur, phosphorus (represented by P_2O_5), copper, zinc, selenium, strontium, barium and fluorine are high and show similar fluctuation patterns versus depth. The assemblage of Sr, F, S, P, Se, Ba, Ca, Cu or Zn is an important geochemical marker of the lake sediments impacted by penguin droppings or guano soil, and these elements were thus identified as typical elements for penguin guanos. With the belief that chemical characteristics of the lake sediments are mainly influenced by penguin droppings or guano soils, Q-mode factor analysis was used to determine the change of the penguin droppings in the sediments and thus the historical penguin populations. This revealed that 99.8% of the variance in the data could be explained by two factors (54.7% for factor 1 and 45.1% for factor 2). The first factor reflects the changes in the input of penguin droppings to the sediments. Combined with the ^{14}C, ^{210}Pb and ^{137}Cs dating in the sediments, we reconstructed the historical penguin population changes during the past 3000 years. The results showed that the penguin population began to decline at around 3000 a BP, and reached to lowest at 1800−2300 a BP, namely, the Neoglacial period. After that, the population increased and peaked somewhere at 1400−1800 a BP, which was corresponding to a warmer period. It was unfavorable for penguin survival under extremely high or low temperature. Therefore, we suggested that the size of penguin populations seemed to relate to climate, and the climate change may still affect the survival and abundance of modern penguin populations [11−12].

Concurrently, we studied the sediments with seal hairs and excrement. The results showed that elements including S, Se, F, Zn, Hg and P_2O_5 were potential bio-elements and their concentrations could be used as inorganic geochemical indicators for tracking seal palaeoecological processes in the Antarctic region. Based on the findings, the historical seal populations at King George Island, Antarctica, for the past 1500 years were estimated from the seal hair abundance, bio-element concentrations, total organic carbon (TOC), total nitrogen (TN), $\delta^{15}N$ and $^{87}Sr/^{86}Sr$ in the acid-soluble fractions in one terrestrial sediment sequence influenced by seal excrement. The results indicated that prior to human interference the seal populations showed

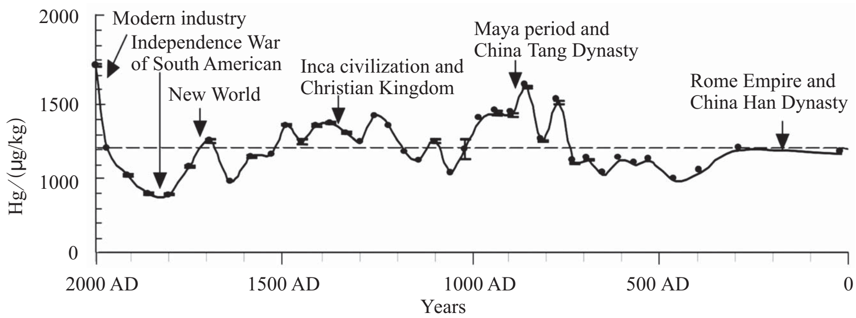

Fig. 4 A 2000-year record of mercury concentration in seal hairs in response to ancient civilizations [21]

dramatic fluctuations with two peaks during 750−500 a BP and 1400−1100a BP and two troughs during 1100−750 a BP and 500−200 a BP (Fig. 3). A tentative comparison of the seal populations and historical climates in the Antarctic Peninsula region suggested that the seal populations is linked to climate-related factors such as sea ice coverage and atmospheric temperature.

In the recent decades, it has been noticed that the superimposing influence of materials and energy consumed by human activities may become more substantial than natural ones, and this trend may produce profound, long-term and unfavorable influences on the human living environment. The monitoring data over the past decades revealed large fluctuations in the penguin and seal populations, and many people attribute these variations to the human activities in the Antarctic and/or climatic warming in recent years [19−20]. Our research results on the historical penguin and seal population records over the past several thousands years, however, showed that there existed notable fluctuations in the Antarctic penguin and seal populations before human landing on the Antarctic continent and Southern Ocean. These findings have attracted strong attention of international society and scientific community [10−11]. There are substantial implications to distinguish accurately the anthropogenic influence from the natural one on the Antarctic ecosystem for evaluating the present and future human activities.

3.2 *Historical record of human civilization in the sediment sequences influenced by animal excrement*

The processing and smelting activities of bronze vessels began from ancient Egypt civilization and Chinese Dawenkou culture. It is estimated that since the time of ancient Rome, about 0−300 AD, human has released hundreds of thousands of tons of mercury (Hg) into the atmosphere — much enough to increase natural Hg concentrations in seawater, atmosphere and earth surface. The pollutants such as Pb and Hg are usually dispersed in the open system of atmosphere and water cycles, and they could be enriched by biomagnifications along the food chains of marine biology, transported and deposited in the biological excrement sediments to provide a good archive of human civilization history.

We observed remarkable fluctuation of Hg concentration in seal hairs over the past 2000 years in a lake-sediment core on King George Island, West Antarctica. It is found that these variations were closely correlated with ancient activities of gold and silver mining by using Hg-amalgamation process around the world (Fig. 4) [21]. The record of lead isotopes could even be used to identify the source of Pb. This indicates that the influence of human civilization on the Antarctic did not start at the beginning of human landing on this continent. And this method may offer new clues for seeking lost civilizations and studying the development of society and the cost of environmental health.

4 Conclusions

(1) Under the condition of polar eco-environment, the accumulative profiles of seabird and sea animal excrement and the depositional sequences influenced by the excrement are good archives to study the eco-geology in the ice-free areas of Antarctica and Arctic.

(2) The historical populations of Antarctic penguins and seals experienced notable fluctuations due to the climate changes over the past several thousands of years prior to humankind landing on the Antarctic continent and the Southern Ocean.

(3) The historical information of human civilizations over the past several thousands of years is well preserved in the Antarctic seal hairs and the sediments influenced by their excrement, and this offers a novel approach for archeological researches of human civilizations.

Acknowledgements

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References

[1] Stokstad E. Myriad ways to reconstruct past climate [J]. Science, 2001, 292: 658−659

[2] Croxall J P, Trathan P N, Murphy E J. Environmental change and Antarctic seabird populations [J]. Science, 2002, 279: 1510−1514

[3] Woehler E J, Penney R L, Creet S M, *et al*. Impacts of human visitors on breeding success and long-term population trends in Adelie penguins at Casey, Antarctica [J]. Polar Biology, 1994, 14: 269−274

[4] Hodgson D A, Johnston N M. Inferring seal populations from lake sediments [J]. Nature, 1997, 387: 30−31

[5] Baroni C, Orombelli G. Abandoned penguin rookeries as Holocene paleoclimatic indicators in Antarctica [J]. Geology, 1994, 22: 23−26

[6] Goodwin I D. Holocene deglaciation, sea-level change, and the emergence of the Windmill Islands, Budd Coast, Antarctica [J]. Quaternary Research, 1993, 40: 70−80

[7] Emslie S D, Fraser W R, Smith R C, *et al*. Abandoned penguin colonies and environmental change in the Palmer Station areas, Anvers Island, Antarctic Peninsula [J]. Antarctic Science, 1998, 3: 257−268

[8] Sun Liguang, Xie Zhouqing, Zhao Junlin. The sediments of lake on the Ardley Island, Antarctica: identification of penguin-dropping soil [J]. Chinese Journal of Polar Science, 2001, 12 (1): 1−8 (in Chinese)

[9] Sun Liguang, Xie Zhouqing, Zhao Junlin. The characteristics of Sr/Ba and B/Ga in lake sediments on the Ardley Islan, maritime Antarctica [J]. Marine Geology & Quaternary Geology [J]. 2000, 20 (4): 44−46 (in Chinese)

[10] Sun Liguang, Liu Xiaodong, Yin Xuebin, *et al*. A 1500-year record of Antarctic seal populations in response to climate change [J]. Polar Biology, 2004, 27: 495−501

[11] Sun Liguang, Xie Zhouqing, Zhao Junlin. A 3000-year record of penguin populations [J]. Nature, 2000, 407: 858

[12] Sun Liguang, Xie Zhouqing. Relics: penguin population programs [J]. Science Progress, 2001, 84 (1): 31−44

[13] Sun Liguang, Zhu Renbin, Yin Xuebin, *et al*. A geochemical method for reconstruction of the occupation history of penguin colony in the maritime Antarctic [J]. Polar Biology, 2004, 27: 670−678

[14] Sun Liguang, Zhu Renbin, Liu Xiaodong, *et al*. HCl-soluble $^{87}Sr/^{86}Sr$ ratio in the sediments impacted by penguin or seal excreta as a proxy for the size of historical population in the maritime Antarctic [J]. Marine Ecology-Progress Series, 2005, 303: 43−50

[15] Liu Xiaodong, Sun Liguang, Yin Xuebin, *et al*. A preliminary study of elemental geochemistry and its potential application in Antarctic seal palaeoecology [J]. Geochemical Journal, 2005, 39 (1): 47−59

[16] Sun Liguang, Liu Xiaodong, Yin Xuebin, *et al*. Sediments in palaeo-notches: potential proxy records for palaeoclimatic changes in Antarctica [J]. Palaeogeography Palaeoclimatology Palaeoecology, 2005, 218: 175−193

[17] Liu Xiaodong, Sun Liguang, Yin Xuebin, *et al*. Palaeoecological implications of the nitrogen isotope signatures in the sediments amended by Antarctic seal excrements [J]. Progress in Natural Science, 2004, 14 (9): 71−77

[18] Zhao Junlin. The Characteristics of the Modern Environmental Geochemistry and Natural Environmental Evolution in the Region of Antarctic Great Wall Station [M]. Beijing: Science Press, 1991: 1−68 (in Chinese)

[19] Fraser W R, Trivelpiece W Z, Ainley D G, *et al.* Increased in Antarctic penguin populations: reduced competition with whales or a loss of sea ice due to environmental warming? [J]. Polar Biology, 1992, 11: 525−531

[20] Kaiser J. Is warming trend harming penguins? [J]. Science, 1997, 276: 1790

[21] Sun Liguang, Yin Xuebin, Liu Xiaodong, *et al*. A 2000-year record of mercury and ancient civilizations in seal hairs from King George Island, West Antarctica [J]. Science of the Total Environment, 2006, 368: 236−247