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EVOLUTION OF THE ANTARCTIC ICE SHEET SINCE LATE PLEISTOCENE

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Abstract Available data show that the of fossil plants testified that the Antarctica was a rather warm or even hot and humid region covered with forest from Devonian to Cretaceous periods. Furthermore, even Antarctic coasts stilll kept in a warm and humid condition until early Tertiary of 37 Ma ago. It therefore can be considered that the Antarctica was not situated at its present position, but in tropic or temperate zone before the Tertiary.

Antarctic ice sheet has begun to appear in the Pligocene of 26Ma ago. It was very much earlier than the glaciations in everywhere of the world. For the reasons a most important event was the separating of Antarctic Peninsula from South America in 35 Ma ago. Drake Passage therefore occurred and Antarctic circulation appeared, and then Antarctic continent became an isolated cold land.

Glacial changes have happened on the Antarctic ice sheet from late Tertiary to Quaternary periods. However, it has been confirmed that the Antarctic ice sheet has a great extension during the latest Pleistocene glaciation of 25000–10000a B. P. About 18000a ago, the Antarctic ice sheet was 450–1000 m thicker and much larger than that at present. By that time the ice sheet grounded on the conticental shelves. Sea level might be 100–150 m or more lower than present sea level. Sea ice covered areas in winter and in summer were 10 and 2 times respectively than that today.

It was much warmer in middle Holocene (7500–5000 a B. P.) than today in Antarctic region. By that time, a large amount of ice was melt away, which, on one hand, caused a rapid rising of sea level, transgression immediately occurred; on the other hand, as continental load decreased due to the melting of ice sheet, the isostatic uplifting consequently followed and the marine terraces formed along Antarctic coasts in middle Holocene, Now the glacio-isostatic uplift is still going on. For a total uplift of 10–25 m since 6000 a B. P. the mean rate of 1.5-4mm/a is estimated in different places of Antarctic coasts.

Antarctic ice sheet (including ice shelves) has been retreating recently, Meanwhile, the inland snow accumulation has been increasing in the past decades of years, both of them are corresponding to the rising of annual mean temperature since 1910 A. D.

Key words Antarctica, Paleography, Evolution of ice sheet.

Question on the evolution of Antarctic Ice Sheet Since late Pleisticene linked with global changes is very important to mankind. In past 30 years many works concentrated on environmental changes of Antarctica were carried out. (Pewe, 1960; Meguro, 1963; Nichols, 1968; Denton *et al.*, 1971; Hendy *et al.*, 1969; Ward and Webb, 1979; Carrara, 1979; Hughes *et al.*, 1981; Yoshida, 1983; Zhang *et al.*, 1984) For such big question available data and evidences are still not strong enough against the biggest ice sheet of the world. After a year round of geomorphological and Quaternary investigaitions in the Vestfold Hills, Elizabeth Land, East Antarctica, carried out by the author in 1981, two events of transgression in late-Pleistocene and in mid-Holocene and three times of glacial advance and recession in late-Holocene were discovered. From which and some available data, a few correlated questions on evolution of Antarctic ice sheet, such as glacial advance and recession, climatic and sea level changes and glacialisostatic rebound, etc., since late-Pleistocene are discussed in this paper.

1. The Last Antarctic Ice Sheet in Last Ice Age of Late Pleistocene

It has been considered that the Antarctic Ice Sheet was in a great expension period during the last ice age of late-Pleistocene (Pewe, 1960; Denton *et al.*, 1971, 1975; Hughes *et al.*, 1981).

The ice thickness at about 18000 YBP was 450-1000m thicker than that at present, and antarctic continental shelves were almost all covered by grounded continental ice. For instance, Ross and Weddell Sea were covered by grounded glacial ice of more than 1000 m thick (Hughes, 1981). Present ice surface of Burd Glacier is about 1200 m lower, than that of lost glaciation (Hughes, 1979). Former glacier ice was at least 450 m thicker than that at present on Orville Coast, Antarctic Peninsula (Carrara, 1979). In east Antarctic inland and coasts, some 1000 m in difference of ice thickness between last ice age and present day were estimated. Ckark and Lingle, 1979; Voronov, 1964). In ice free area of the Vestfold Hills ice was probably as thick as sereral hundreds of meters during last glaciation, and continental ice could be grounded onto the continental shelf some 160 km far away from present coast line to the north (Zhang, 1985).

Areas of sea ice surrounding Antarctica in summer and in winter seasons were estimated to be 25 million km^2 and 40 million km^2 in area in 18000 YBP respectivily, about 10 and 2 times against 2.5 million km^2 and 20 million km^2 of antarctic sea ice at present (Cooke and Heys, 1982).

However a warmer period (interstadial) within last glaciation in Antarctic region was discovered from a natural exposure of marine deposits some 20 m above sea level in the Marine Plain in Vestfold Hills. In which many fossils of mairne lives including bivalves, diatoms and feraminiferas were found (Zhang, 1985). A ^{14}C date of fossil shells from upper layer of the exposure is 31000 ± 476 YBP (Jin, 1985) and the age of lower layer of the exposure is estimated to be 40000 to 50000 years BP according to the paleo-magnetic measurements (Zhu, 1985). Assemblages of fossils (diatoms, foraminiferas and bivalves) are similar to living ones in coastal shallow cold sea water around east Antarctica, but mixed with a few species of diatoms and foraminiferas which lived in warm warters (Li, 1985; Li and He, 1985; Lan, 1985). It shows that these marine sediments were interstadial deposits of last glaciation in late-Pleistocene, and they are about same to the late-Quaternary sediments occured on the coast from Cape Royds to Cape Barne at Ross Island (Ward and Webb, 1979). ^{14}C dates of those marine sediments are 36000 ± 2300 YBP (Hendy *et al.*, 1969) and 49000 ± YBP (Stuiver and Denton, 1977) from different layers.

It shows that an ingression was happaned to antarctic coasts in the duration from 50000 to 25000 YBP when climate was warming up. consideration in general the sea level in that stage was little lower than that at preaent. But the marine sediments of interatadial period are appeared on the height from 20 to 60 m asl along antarctic coasts. Raising of la Pleistocene marine sediments is probably caused by glacial-isostatic rebound after last glaciation becaurce the East Antarctica has been a long stable shield and very weak at Neotectonic movement.

Expansion and thickening of Antarctic Ice Sheet in the last ice age (around 18000 YBP) must generate the sae level droping down significantly (Robin, 1983). According to a few data collected from off and on shore Vestfold Hills, the author suggests that the sea level during last glaciation maximum (18000 YBP) was at least 150 m lower than that today (Zhang, 1985). The estimation is taken account as follows: Coastal sea off Vestfold Hills is about 400 m deep, assumed glacial ice covered onto continental shelf was 300 m thick at 18000 YBP, of which about 250 m thickness of ice was under sea water, thus sea level droping of 150 m was necesary for grounding of glacial ice.

2. Changes of Antarctic Ice Sheet during Holocene Age

2.1 Holocene optimum

Large quantities of data documanted in the world show that there has a climatic optimum appeared in mid-Holocene age followed with a world wide ingression and high temperatures (Hughes *et al.*, 1981; Mayowski *et al.*, 1981; Anderson, 1981; Shi and Wang, 1981; Grove, 1979). After a long study of climatic changes in China since 5000 YBP, Professor Zhu Kezhen got an excelent result. Which shows that about 5000 years ago mean annual temperature in China was 2°C higher than at present, and the average dayly temperature in January wa 5°C higher than today (Zhu, 1973). East China coasts and many places in the world were suffered a large scale of ingression in that stage (Wang and Wang, 1980).

A similar event in Antarctic region has been infered by a few evidences (Cameron and Goldthwait, 1961; Nichols, 1968; Meguro *et al.*, 1963). Now some additional evidences from the Vestfold Hills may confirm the existence of that event occured along antarctic coasts in mid-Holocene age. Mid-Holocene marine deposits are well developed around saline laeks in valleys (fromer armes of sea) and on the coasts in vestfold Hills. They consist of four steps of terraces or raised beaches. The highest one is 15 m asl with a^{14}C date of 7616±104 YBP; the lowest of 2–3 m high is 3325±103 YBP of^{14}C date, and the remain two in the between, 4 m and 6 m high, are aged from 5000 to 6600 YBP (Jin, 1985). It means that a comparatively large ingression was hapened to this ice free area from about 7500 YBP to 3300 YBP.

It was comparatively warm in mid-Holocene in antarctic coastal aresa infered by depositional features and assemblages of marine fossil lives. Diposists of terraces of Lake Watts, 7500-6000 YBP in ages, derrived from terrain are mainly consisted of coarse sands, pebbles and boulders with large angle (15°-20°) of tilted layer. It shows that terrain currents of melt warter due to high temperatures was strong enough to carry these coarse debris into laks or arms of sea in that stage. As a comparison, melt warter at present is small without any power to carry so much coarse debris. Within the second terrace deposits (6100±108 YBP) of Lake Watts, there are lot of calcic fossils of worm tubes (Hydroides sp. and Sperobis sp.) (more than 60% of content) (Zhang, 1985) and also very rich in marine lives fossils, including six species of bivalves (Lan, 1985), 67 species of Ostracodas (belong to 44 genera) (Gou and Li, 1985) and 57 species of diatoms (belong to 20 genera) (Li, 1985). Most of them are similar to the living ones existing in Antarctic coastal sea, but there also existed a few species of diatoms and foraminiferas which usually live in warm waters of sub-antarctic sea (Li, 1985; Li and He, 1985). Beside, a few pieces of fragments of coral were also found out from the diposits (Li and He, 1985). Therefore it might be considered that the coastal sea of east Antarctica was much warmer in mid-Holocene than that at present to fit many marine lives lived in and generated successfully. But it is still difficult to estimate the temperatures of mid-Holocene at moment.

Ingression of mid-Holocene is not only happened to the Vestfold Hills but also appeared in other coastal araeas of east Antarctica and antarctic Peninsula and sub-Antarctic islands as mentioned above. On Windmill Is. off shore of Wilkes Land, for instance, marine deposits of 6040 YBP in age is placed at 23 m asl (Cameron and Goldthwait, 1961). So the Holocene optimum (about from 7500 to 5000 YBP) is considered to existing in Antarctic region.

Those mid-Holocene raised marine beaches certainly are the marks of ancient shore lines, but they do not indicate that sea level in mid-Holocene age was 15 or 23 m higher than at present. Available data show that the amplitude of up and down of Antarctic Sea was limited in 0.7 m in past 5000 years (Clark and Lingle, 1979). Therefore rising of marine beaches are depended on uplifting of the land, but east Antarctic shield has been long stable in the history, uplifting of the land is probably no matter with Neotectonic movement.

The author considers that a possible generation for the uplifting of the land is glacialisostatic rebound. As mentioned before, about 1000 m thick of ice (occupied about 2.5% to 4% of crustal thickness of east Antarctica and of west Antarctica respectively) (Bentley, 1982) were reduced from the Antarctic Ice Sheet after last glaciation maximum (18000 YBP). It may give an important effect to the crustal rebound after so much of unloading, which has been testified on the Scandinavian Peninsula (Meinetz, 1973). Two combined deffects followed with melting of large amount of antarctic ice from early to middle Holocene; Rising of sea level coupled with ingression and isostatic rebound coupled with uplifting of the lands. The latter effect may delay for a distance after melt away of the ice. In the Vestfold Hills, isostatic uplifting probably begun at 7500 YBP and it was comparatively fast with about 3 mm/y in the first stage (from 7500 to 3200 YBP). Some four steps of raised beaches (terraces) were formed in this stage. Uplifting has been much slow (about 1 mm/y) since then, but still going on at present which is evidenced by the forming of fresh beaches and lagoons in the area. Some 2-2.5 mm/y of average rate of isostatic uplifting in Vestfold Hills was estimated since 6000 YBP (Zhang, 1985).

3. Neoglaciation

The Neoglaciation or New ice age suggested by Matthes (Matthes, 1935, 1939) has been accepted by glacio-meteorologists (Denton and Porter, 1970; Flint, 1971; Karlen, 1973). They believe that droping significantly down of temperatures begun from about 3000 YBP and since then the climatic fluctuations occured widely in the world (Grove, 1979; Zhu, 1973). Prof. Zhu confirmed that in past 3000 years, there existed three times of droping down of temperatures apparently occured by 3000 YBP and 2000 YBP and from seventeenth century to mid-nineteenth century respectively (Zhu, 1973). Mean annual temperature during the first stage was 1-2°C lower than at present, snow line was 100-300 m lower than that today and mountain valley glaciers advanced for about 2 km in western China (Shi and Wang, 1981). The second droping of temperatures also generated mountain glaciers to advance temporally. Third temperature droping by 1700 A.D. coincided with "little ice age" in western China where mountain glaciers readvanced significantly (Shi and Wang, 1981; Zhu, 1973).

Similar effects also appeared in north Eaurop and south Asia. For instance, three times of glacial advances were discovered in 3000–2500 YBP, 2000–1600 YBP and from 1500 A.D. to 1916 A.D. respectively in Sweden and Norway (Karlen, 1973, 1976; Griffey, 1976). During these stages tree lines were 100–175 m lower than that today. Even in New Guinea there also existed three times of glacial advances appeared by 2900 YBP, 2500YBP and from

16th to 19th century (Hope and Peterson, 1975).

Neoglaciation also apparently effected onto Antarctic Ice Sheet. Comparing with mid-Holocene, marine lives in deopsits of low terrace (^{14}C date of 3325 ± 103 YBP) around Mud Lake in southern part of Vestfold Hills were very poor both in numbers and in species. In which only one species of bivalve and 8 species of foraminiferas (belong 4 genera) were found (Lan, 1985; Li and He, 1985). It infers that temperatures droped significantly in that stage and the new ice age might come into east Antarctic coastal areas (Zhang, 1985).

Some direct evidences have been found out from north side of Sorsdal Glacier on southern bourder of the Vestfold Hills where three ranks of new lateral moraines spread parallely away from existing glacier in distance of 800 m, 400 m and 100–200 m. The nearest one to the glacier is a well continued and ice cored moraine which is connected with fresh shear moraine spread at the front of ice sheet to the east of Vestfold Hills. Similar features of shear moraines are also occured at front of ice sheet near Cacey Station on Wilkes Land (Zhang, 1985) and at front of Colins Ice Cap on King George Island. Three stages of glacial advances could be distiguished from these three ranks of moraines since about 3000 YBP. But it is not confirmed whether these glacial advances correspond to world wide climatic fluctuations as mentioned above, because of no dates taken from the moraines.

However these features of recent glacial advance and retreat may indicate that significant climatic changes were apparently occured since about 3000 YBP in antarctic region. In recent times the Antarctic Ice Sheet has been retreating at the edges due to rising up the temperatures. In past tens of years a rising of 0.3°C of mean annual temperature at Dome C was discovered (Bolgan *et al.*, 1979). Such tendency may be still going on in future.

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