A NOTE ON THE ICE SHEET FLUCTUATIONS AND PROBLEMS OF CENOZOIC STUDIES IN ANTARCTICA

Yoshio YOSHIDA

National Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173

Abstract: This note outlines briefly the present state of research on some aspects of glacial history in Antarctica and attempts to compare chronologically the glacial events in several regions of Antarctica with one another as the basis for future investigations.

Investigations on the ice sheet fluctuations have been carried out in many regions of Antarctica, and important results are being accumulated. In particular, the history of glacial events is considerably well-known in the McMurdo Sound region, and studies in other regions often refer to it for chronological arrangement. It seems still difficult, however, to correlate glacial events precisely among the respective regions, mainly due to the scarcity of reliable age determination data. Tentative correlations can only be made by comparison of "phase" of fluctuations, taking notice of specific events seemingly common to most of the regions. Difficulty arises also from the obscurity in time- and spatial-scale of events. In this connection, more efforts should be made to investigate regional characteristics of the events and their relations to those of a continental scale. On that occasion, the finding of marine microfossils in the Sirius Formation, above all, compels us to reexamine the glacial history which has been more or less compiled in each region.

1. Introduction

The diagnostic evidence of early cooling of the Antarctic continent is thought to appear in the age of early Eocene, middle Eocene or Oligocene (*e.g.* MARGOLIS and KENNETT, 1971) from glacially scoured quartz sand and microfossils such as Foraminifera. Therefore, one of the main subjects of the Antarctic Cenozoic studies is to elucidate the history of long-term fluctuations of the Antarctic ice sheet and their global effects. The global history has been studied through surface geology and geomorphology of ice-free areas, marine geology and geomorphology of the surrounding oceans, and subglacial landform and crust investigations of the continent, though the correlation of the results from the respective fields is not easy.

Rich information has been obtained from the Dry Valleys region in southern Victoria Land and the Transantarctic Mountains to the south. Nevertheless, it seems rather difficult even in these regions to construct the Cenozoic history of the continent faultlessly because of the paucity of clues to the correlation of geological phenomena. Recently new findings of marine microfossils from glacial sediments in these regions gave an impact on the elucidation of the ice sheet history. On the other hand, data on the datings of the geological events are poor in other regions of Antarctica, and the chronological treatment has been made tentatively in some places, taking the results

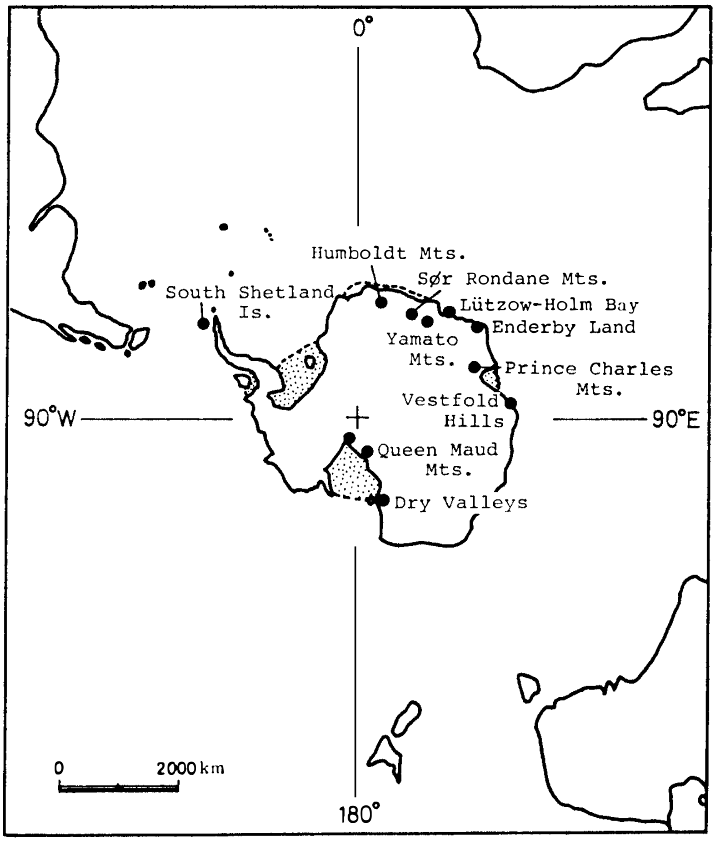

Fig. 1. Location map.

of investigations in the southern Victoria Land into consideration. Accordingly, reappraisal of the Cenozoic history will be required not only in the Transantarctic Mountains region but also in most of ice-free areas. This note is to outline the present state of research concerned and to reexamine the events in the Lützow-Holm Bay region on the provisional chronological table as the basis for future investigations (Fig. 1).

2. Dry Valleys Region

PÉWÉ (1960) identified for the first time the multiple glaciations (glacial advance episodes) named McMurdo, Taylor, Fryxell, and Koettlitz from older to younger in the McMurdo Sound and the Dry Valleys region, and tentatively correlated them with four major glaciations in the northern hemisphere. After that, K/Ar datings of the McMurdo Volcanics have progressed and some marine organic remains on a valley floor were identified as *in situ* fossils. Accordingly, the interrelationship among ice sheet fluctuations, invasions of the ice shelf into dry valleys, mountain glacier fluctuations, and marine transgression has been studied on the basis of radiometric and fossil age determinations (*e.g.* DENTON *et al.*, 1970; CALKIN *et al.*, 1970; WEBB, 1972). Major results are as follows; 1) The trunk valleys of this region had been formed before 4.2 Ma, and subsequent four advances of the ice sheet into valleys did

Table 1. Chronology of glacial events in Dry Valley region and Queen Maud Mountains.

Epoch / Age (Ma)	Denton et al. (1970) Taylor Valley: trunk v.	Denton et al. (1970) Taylor Valley: Ross-v.	Denton et al. (1970) Taylor Valley: Alpine	Calkin et al. (1970) Wright Valley: trunk v.	Calkin et al. (1970) Wright Valley: Ross-v.	Mayewski (1975) Queen Maud Mts.	Denton et al. (1983) Dry Valleys
Holocene							
0.01 Ma	Taylor I Gla.	Ross I	Alpine Gl. I 12.2 Ka	Wright Upper I	6-9.5 Ka; Wright Lower 34.8 Ka or older	Amundsen Gl. 9.5 Ka	
Pleis-tocene				↑ Wright Upper II	Trilogy		
0.1		Ross II	Alpine II 0.4 Ma	~		Shackleton 49 Ka-1.6 Ma	
	Taylor II	Ross III		Wright Upper III ↓	Loop		
		Ross IV 1.2 Ma			Pecten 1.2 Ma		
	Taylor III 1.6 Ma		2.1 Ma			(moist period)	
2							
Pliocene	2.1 Ma Taylor IV 2.7 Ma	3.1 Ma	2.1 Ma Alpine III 3.5 Ma	2.1 Ma Wright Upper IV		Scott 2.1-2.4 Ma	2.0 Ma Alpine Moraine 3.3 Ma
	3.5 Ma						latest overriding episode (basal till: Peleus Till)
5	4.2 Ma Taylor(s) V			Valley-cutting episodes		"Interglacial" 4.2 Ma (fluvial channels potholes)	Pecten Gravel (Middle or early Pliocene)
Miocene						Queen Maud 4.2 Ma (Sirius Formation, Ice sheet erosion)	glacimarine diamicton (Jason Diamicton) (9-15 Ma)
20							↑ ~ Major valley systems (due to mainly local ice cover) ↓
30 Oligocene							
40 Eo.							

not cover the whole areas of the valley floors. 2) Since 1.2 Ma ago, the Ross Ice Shelf invaded several times into valleys from the Ross Sea due to grounding of the ice shelf, induced by the lowering of the sea level during major glaciations of the northern hemisphere. 3) Alpine glaciers have been nourished by water vapor supply from the Ross Sea when the Ross Ice Shelf retreated to such extent as at the present time; therefore, the sense of fluctuations of alpine glaciers is contrary to those of the ice shelf. The behavior of the Ross Ice Shelf since the last glaciation has been studied enthusiastically (STUIVER *et al.*, 1981).

Studies of cores obtained by the Dry Valley Drilling Project (DVDP) in 1973–1975 provided fruitful information on the glacial and interglacial events and marine invasions in the Dry Valleys region (*e.g.* BRADY, 1982) Miocene glaciomarine deposit in the lower Taylor Valley indicates that the major valleys were eroded at least before late Miocene in age. Studies on cores obtained by the McMurdo Sound Sediments and Tectonic Studies (MSSTS) in succession to DVDP are also important for Cenozoic investigations, as will be mentioned later.

On the other hand, the results of echo-soundings inland of the Transantarctic Mountains (DREWRY, 1982) suggested that advance and retreat of the ice sheet into the Dry Valleys did not always reflect increase and decrease of the East Antarctic Ice Sheet. The investigation is being carried out again on the large ice advance after the major valley cutting (DENTON *et al.*, 1983). The latest overriding by the ice more than 500 m thick is thought to have happened in the Pliocene age.

Part of the above-mentioned results are shown chronologically in Table 1.

3. The Queen Maud Mountains Region

Significant results of glacial geology of the East Antarctic Ice Sheet have been obtained also from the vicinity of the Queen Maud Mountains in the Transantarctic Mountains.

In the Reedy Glacier area, a shallow depression was found in the plateau remnants which constitute the higher parts, about 3000 to 3500 m in elevation, of the mountains. It is filled with a 40 m thick till which consists of the basal till derived from a hill nearby and of the clay-rich matrix containing fragments of various kinds of rocks derived from the plateau surface (MERCER, 1968). This till was thought to have been deposited by wet-based ice which might have covered the plateau extensively. On the other hand, stranded lateral moraines occur at three different levels above the surface of the Reedy Glacier which is an outlet glacier draining the Polar Plateau ice. These levels indicate former variations in thickness of glacier ice which were thought to have been caused by the migration of grounding line of the Ross Ice Shelf. The ice-marginal lake sediments and solifluction flow deposits in the Reedy Glacier valley were interpreted as "interglacial" features.

In the Beardmore Glacier area, the largest outlet glacier in the Transantarctic Mountains, the thick till which occurs at higher parts of the mountains about 2000 to 2300 m above sea level was named Sirius Formation by MERCER (1972). Some peaks are capped by this till. The till includes lenses of sorted drift and is thought to be a lodgement till deposited beneath the wet-based ice flowing off the Transantarctic

Mountains. At the margins of the Beardmore and the adjacent glacial valleys younger lateral moraines occur at three different levels above glacier surface. These moraines were thought to have been formed by the increase in ice levels due to grounding of the Ross Ice Shelf, as was the case in the Reedy Glacier area.

MAYEWSKI (1975) investigated the Queen Maud Mountains region from the Beardmore Glacier in the north to the Scott Glacier in the south. He distinguished glacial events from older to younger as follows: 1) Queen Maud Glaciation characterized by the largest expansion of the East Antarctic Ice Sheet which overrode the Transantarctic Mountains, based on the reexamination of the Sirius Formation; 2) "Interglacial" characterized by fluvial features cutting into the Sirius Formation and by the marine invasion of the Wright Valley in the southern Victoria Land; 3) Scott Glaciation, Shackleton Glaciation, and Amundsen Glaciation represented by three lateral moraines in glacial valleys which are thought to indicate the expansions of the ice sheet during the respective periods. He apparently interpreted the fluctuations of ice levels shown by the lateral moraines as a result of mainly the increase and decrease in volume of the East Antarctic Ice Sheet. He estimated the volume of the ice sheet at each Glaciation by the ice surface reconstruction, and calculated the sea-level lowering capability of these Antarctic Glaciations.

No data on age determination was available in this region, though he attempted the correlations between the events in this region and those in the southern Victoria Land. Part of results are also shown in Table 1.

STUIVER *et al.* (1981) criticized Mayewski's interpretation, and stated that the increase in elevation of the surface of glaciers after Scott Glaciation was not caused by the increased volume of the East Antarctic Ice Sheet but by the increased thickness of the West Antarctic Ice Sheet caused by the grounding of the Ross Ice Shelf. This conclusion seems to be acceptable to the present author, judging from the data presented by the above authors up to the present. However, much more data would be necessary for final conclusion, because the eustatic fall of sea level, hence a seaward advance of the grounding line of the ice sheet, may not always expand the whole Antarctic Ice Sheet.

On the other hand, the views on the fluctuations of the Antarctic Ice Sheet are subject to reconsideration by the fact that marine microfossils were found recently in the Sirius Formation, as will be mentioned later.

4. East Antarctic Shield

There are few data relating to dates of glacial events in the East Antarctic Shield regions, except information on very young events. BARDIN (1972) distinguished three moraines at levels of 200, 80 and 50 m above the ice sheet surface and designated them Insel III, II and I Glaciations at Alexander-Humboldtfiella in western Queen Maud Land, correlating them tentatively with McMurdo, Taylor and Koettlitz Glaciations, respectively. He (1982) also distinguished glacial events in the Prince Charles Mountains as follows: 1) Gray moraine, 2) Intermediate conglomerate (interglacial?) 3) Brown moraine, 4) Mt. Collins morain 1, 2, and 3. He proposed their ages to be Miocene–Pliocene, early Pliocene, late Pliocene, and Pleistocene, respectively, mainly on the basis of degree of weathering.

VAN AUTENBOER (1964) discussed fluctuations of the ice sheet in the Sør Rondane Mountains region. He distinguished ice sheet retreat after maximum inundation of the ice, subsequent subaerial weathering of bedrock, readvance of the ice sheet, and then shrinkage of the ice sheet which continued up to the present. Part of summit areas of the mountains would have escaped the ice sheet cover even during the maximum expansion of the ice. It seems difficult, however, to date the events.

The Yamato Mountains, 300 km west of the Sør Rondane Mountains, had been covered completely by the ice sheet at least at its maximum expansion. During the lowering of the ice sheet surface, one stagnant stage of the lowering seems to exist. Moraine fields which cover the ice surface near the mountains and low bedrock surface might have been formed during the recent stagnation of the ice sheet surface. These three events were provisionally named Yamato, Fukushima, and Meteorite Glacial Stages (YOSHIDA, 1983a).

Moraines in this mountains can be divided into several groups by the degree of development, that is, thickness, with or without ice core, surface features, location, etc. Moraines without ice core cover the higher slopes of the northern part of the mountains. Moraines on the higher slopes in the middle part have a little thick (10 to 30 cm) layer of finer materials underlain by ice core. Moraines on the ice core are very thin on the lower slopes in the middle part and on the higher to lower slopes in the southern part. This differentiation of moraines according to locations suggests that the ice sheet shrinkage progressed earlier in the northern part than in the southern part in this mountains. It is difficult, however, to correlate distinctly the groups of moraines with the glacial stages in this region at the present stage. It can be only suggested that Meteorite Glacial Stage may be correlated with Insel I in western Queen Maud Land.

In the Yamato Mountains, striae with direction different from that of present ice flow are found in some places. This fact indicates the ice drainage pattern during the period of vast ice cover over the mountains, and also may suggest that the mountains were subjected to glacial scouring by the wet-based ice sheet. Pothole-like topography is found on the glaciated bedrock surface having striae and grooves in the Minami-Yamato Nunataks. If such topography is a sort of tafoni, it indicates that weathering took place during the ice retreat period between two ice advances as the case in the Sør Rondane Mountains. If holes are true potholes, they suggest either pothole formation during "Interglacial" as the case in the Transantarctic Mountains (MAYEWSKI, 1975) or glacial scouring of the wet-based ice sheet in this area. No decisive evidence has been obtained up to the present. The last case seems probable, because of the pothole configuration and the occurrence of potholes in close association with striated bedrock.

If it is true that the summits of the Yamato Mountains about 500 m above the present ice level suffered glacial scouring of the ice sheet, the former ice sheet, at least at its maximum expansion, was thicker by about 1000 m than the present ice sheet, assuming that the uplift of the mountains has not taken place since that time. Because a considerable ice thickness would have been necessary for glacial scouring by a wet-based ice sheet in Antarctica, 500 m of ice is thought to be the minimum thickness to account for the observed subglacial features which were formed by the ice overriding the Transantarctic Mountains (DENTON *et al.*, 1983). This inference contradicts the general view that the former East Antarctic ice sheet would be thicker by at most 500 m in inland than the present ice sheet. The problems including crustal movement are to be solved in future.

In the coastal region around Lützow-Holm Bay, marine sediments occur in the glaciated ice-free areas below about 30 m in height. Fossils of marine organisms are found in many places and their radiocarbon dates fall between 2 and 10 Ka B.P. and from 20 to over 30 Ka B.P.

Sediments with fossils of 2–10 Ka are correlative to the Taylor Formation in the McMurdo Sound region and to other similar sediments distributed extensively in the coastal Antarctic regions. Fluvioglacial deposits, concurrently deposited with marine sediments of 2–10 Ka in age, indicate the period of sufficient meltwater supply. Local cirque glaciation would have worked on some places during the last retreat of the ice sheet to the present position, though the age of cirque glacier formation is not known.

The problem is how to explain the distribution of sediments including older fossils on the Lützow-Holm Bay coast. It is usually difficult to discriminate older sediments from younger ones. Older sediments were deposited obviously after the retreat of the ice sheet margin and have no traces of later ice covering by readvance of the ice sheet. A mode of occurrence at some places show *in situ* formation of fossils. Therefore, the ice sheet would have retreated from presently ice-free areas before at least 30 Ka ago. Degree of weathering of bedrock seems also to indicate that the last ice retreat took place before 30 Ka ago. Most of glacial deposits formed by the last ice advance are thin ground moraines which are sparcely distributed, while rather thick lodgement till which is tentatively named Osen Glacial Bed is found in the Skarvsnes area (YOSHIDA, 1983b).

Preliminary investigation (YOSHIDA and MORIWAKI, 1983) in Mt. Riiser-Larsen, Enderby Land, indicates that the area was covered completely by the former ice sheet at its maximum expansion. The area, however, might not be buried by the ice sheet during the Last Glacial Age of the northern hemisphere, because most of bedrock surfaces are severely weathered. Ground moraine ("designated old ice sheet drift") over 20 m thick occupies the foot of the mountain. This moraine may be correlative to "Brown" or "Gray Moraine" in the Prince Charles Mountains. After the retreat of the ice sheet, cirque glaciation was active on the upper parts of the mountain, and formed remarkable terminal moraines.

In the Vestfold Hills region, ADAMSON and PICKARD (1983) pointed out the glacial and marine transgression events as follows: 1) Marine sedimentation with fossils of a minimum radiocarbon age of 24 Ka indicated by Marine Plain 20 m high which has survived erosion by Vestfold Glaciation; 2) 10–20 Ka Vestfold Glaciation by the ice sheet; 3) Marine sedimentation after 8.3 Ka; 4) 3–5 Ka Chelnock Glaciation by the outlet glacier. This seems a clear-cut conclusion, compared with the case in the Lützow-Holm Bay region. The difference between the two regions may be partly due to the difference in bedrock topography.

All the above events in East Antarctica are tentatively arranged chronologically in Table 2.

Table 2. Tentative correlation of glacial events in East Antarctica.

Age (Ma)	Bardin (1972) Alexander-Humboldtfj.	Bardin (1982) Prince Charles Mts.	van Autenboer (1964) Sør Rondane Mts.	Yamato Mts.	Enderby Land-Lützow-Holm Bay.	Adamson and Pickard (1983) Vestfold Hills
Holocene				slight deglaciation Meteorite Gl. Stage	Raised beaches Old glaciofluvial deposits 10 Ka	Marine & non-marine sediments (after 8.3 Ka) / Chelnock Gl. 5-3 Ka
0.01 Ma	Insel I (Koetllitz Gl.) = Amundsen Gl. (50m above present ice level)	Mt. Collins moraine 1, 2, & 3 (Pleistocene)	↑ Glacial	deglaciation (lowering of ice sheet surface)	Cirque glaciation (Mt. Riiser-Larsen, Langhovde) ↑ 30 Ka-20 Ka	Vestfold Gl. 10-25 Ka Marine plain (residual, 20m above sea-level 24 Ka
0.1 Pleistocen			Interglacial ~	↑ ~ Fukushima Gl. St. ↓ deglaciation	~ Osen Glacial Bed ↓ glacial erosion	
2	Insel II (Taylor) =Scott) (80m)	Brown moraine (late Pliocene)	Glacial ↓	↑ ~ Yamato Gl. St. ↓	↑ ~ Mt. Riiser-Larsen Old ice sheet drift ↓	
Pliocene		Intermediate conglomerate (early Pliocene)			↑ ~ Glacial erosion ↓	
5	Insel III (McMurdo =Queen Maud (200m)	Gray moraine (Miocene- Pliocene)				
Miocene						
20						
30 Oligocene						
40 Eo.						

5. Antarctic Peninsula

JOHN (1972) showed the chronology of the glacial and interglacial events on King George Island as follows: 1) Maximum glaciation in Saalian Glacial or older Glacial; 2) Subsequent ice retreat and fluvial erosion by meltwater; 3) Formation of the 275 m high elevated beach; 4) Local glaciation by expansion of island ice cap in Weichselian Glacial; 5) Ice retreat after 10 Ka and formation of the 54 m high elevated beach; 6) Readvance of outlet glaciers in 0.8–0.5 Ka; 7) Glacial retreat in 0.5 Ka and formation of the 6 m high elevated beach. Data on radiometric dates are restricted within the last 10 Ka. It is noteworthy that the elevation of the postglacial beach is high compared with that in other regions of Antarctica (Table 3).

On the other hand, BIRKENMAJER (1982) distinguished Pliocene Glaciations on the basis of fossils and volcanics studies. They are 1) Polonez Glaciation in early Pliocene, 2) subsequent Wesele Interglacial, and 3) Legru Glaciation in late Pliocene–Pleistocene (Table 3). Polonez Glaciation is thought to be the only continental

Table 3. Chronology of glacial events in King George Island, Antarctic Peninsula.

	King George Island (South Shetland Is.) John (1972)		
Holocene	Glacier retreat	raised beaches below 6m above sea-level	0.5 Ka
	Readvance of outlet gls.	morainic ridge	0.8-0.5 Ka
	Deglaciation	raised beaches below 54m above sea-level	post 10 Ka
0.01			
Pleisto-cene	Local glaciation	expansion of island ice caps	Weichselian
0.1	Non-glacial interval	residual beaches up to 275m above sea-level	Eemian
	Deglaciation	cutting of meltwater channel	
	Maximum glaciation(s)	glacial erosion	Saalian or earlier
	Birkenmajer (1982)		
2	Legru Glaciation (Scott Gl.)		
Pliocene	Wesel Interglacial (Scallop Hill Formation, Pecten Glavel)		(primitive fluvial pattern, dissection)
5	Polonez Glaciation (Queen Maud Gl.)		(largest late-Cenozoic glaciation) (continental)
Miocene			

glaciation which crossed the Bransfield Strait, inferred from the reconstruction of ice-mainstreams and maximum extension of ice-cap. The age determination was not firmly established before 1982. Thereafter, datings of volcanics are being progressed and results will be available soon (BIRKENMAJER, personal communication).

Glaciogeological studies of the other part of West Antarctica have been carried out in several places. Former glacial flow was inferred from glacial topography in mountains on the Lassiter Coast (WAITT, 1983). Old ice sheet glaciation was revealed in the Jones Mountains by glacial till which contained detritus derived from the Ellsworth Mountains and was covered with basalt flows with K/Ar dates of 7–10 Ma (RUTFORD *et al.*, 1972). The Ellsworth Mountains show also marks of the former glaciation of the ice sheet on the bedrock 300 to 500 m above the present ice level (CRADDOCK *et al.*, 1964). CRADDOCK *et al.* pointed out the freshness of the bedrock which suggests the recent ice retreat.

These results are not included in the chronological table in this paper, because of difficulties in correlation at the present stage.

6. Problem of Sirius Formation and MSSTS

The discovery of marine microfossils from the Sirius Formation would be the most exciting result for glacial history of Antarctica in the last decade. According to WEBB *et al.* (1983), and HARWOOD (1983), fossils are composed of marine diatoms, foraminiferas and radioralians and of reworked ones. They can be divided into four age groups, *i.e.* late-Eocene ~ early-Oligocene, late-Oligocene ~ early-Miocene, middle-Miocene ~ early-Pliocene and middle- ~ late-Pliocene (Fig. 2). Their stratigraphic positions in the formation are not always distinguishable. They appear to occur mixed with one another. WEBB *et al.* concluded that 1) late-Pliocene diatoms indicate that the sediments were deposited within 3 Ma, therefore the present East Antarctic Ice Sheet reoriginated within 3 Ma, 2) the sediments might have been carried by the ice sheet from the Wilkes and Pensacola Basins adjacent to the Transantarctic Mountains, and 3) marine fossils which are divided into four age groups suggest the presence of channels of sea in the Wilkes and Pensacola Basins at the respective periods, and these basins were land areas or ice-filled during the intervening period.

On the other hand, there is at least one contradictory fact to this conclusion. Glacial bads at Table Mountain, southern Victoria Land, are considered to be part of the Sirius Formation in the broad sense of MAYEWSKI (BARRETT and POWELL, 1982). And yet they were deposited before the cutting of major trunk valleys which antedates 4.2 Ma and is probably older than late Miocene but younger than 25 Ma (BARREETT and POWELL, 1982). Therefore, they cannot be considered to be part of the Sirius Formation at the type locality. The Sirius Formation and its equivalents may be subdivided into several groups. (cf. Note added in the last lines of this paper.)

On the other hand, cores from MSSTS drilling show cycles of hiatus by glaciation and sedimentation by marine transgression as indicated in Fig. 2 (WEBB, 1982, from BARRETT, 1982). The results of studies of both Sirius Formation and MSSTS core show considerably good correlation and at the same time some gaps. We expect fruitful information will be obtained by further studies together with ongoing CIROS

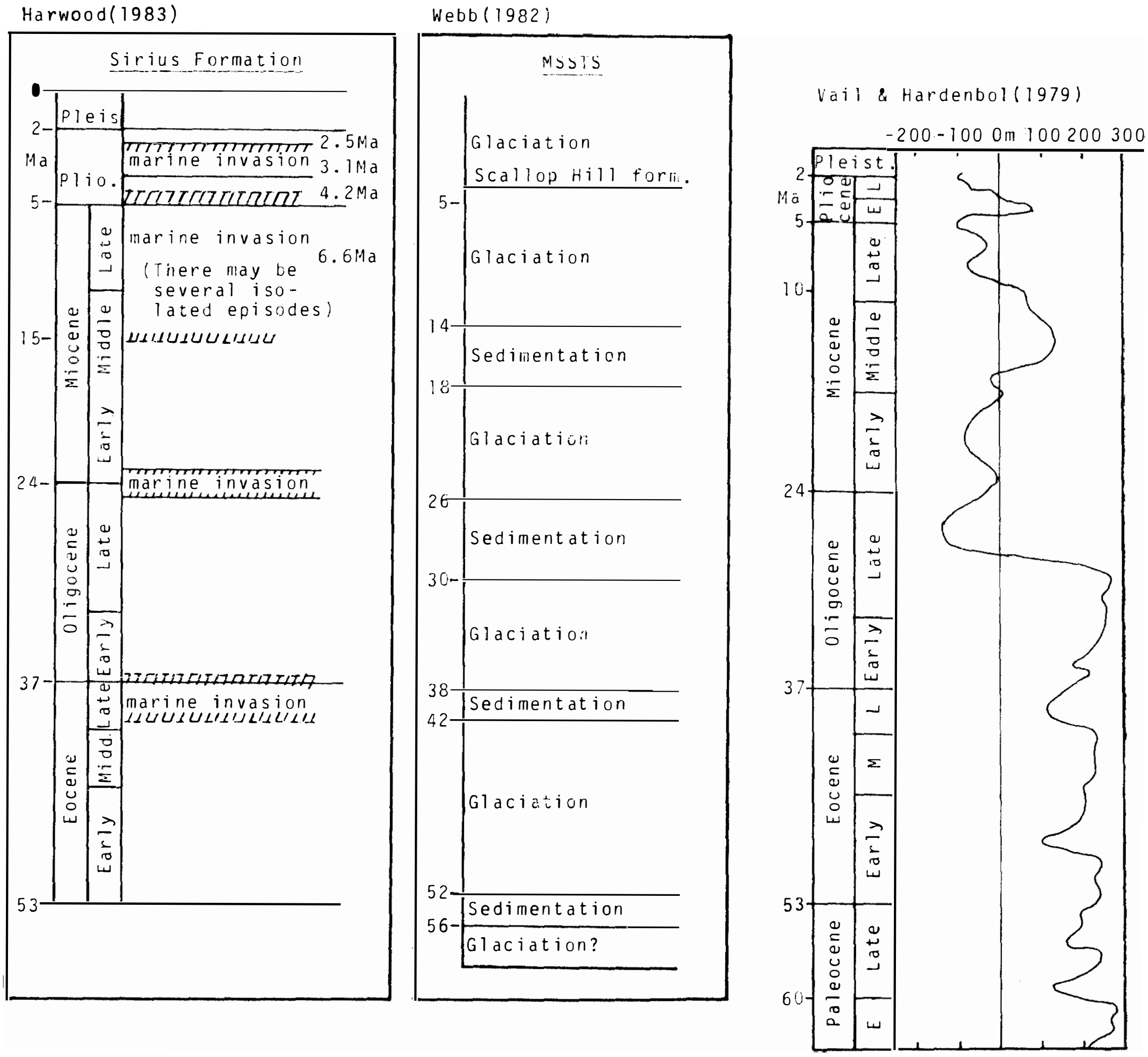

Fig. 2. Glaciation and marine invasion events revealed in Transantarctic Mountains and Ross Sea, and Tertiary eustatic change of sea level.

(Cenozoic Investigation in the western Ross Sea) drilling project.

Tertiary eustatic change of sea level is noteworthy with respect to the formation and disintegration of the East Antarctic Ice Sheet. Tertiary eustatic change of sea level naturally would have affected also the Japanese Islands (AMANO, 1985). Eustatic change is caused by both glacial fluctuation and change of submarine topography. AMANO suggested (1985) that early to middle Miocene Transgression was caused by the eustatic rise of sea level due to a rise of the Pacific Ocean floor by plate movement. Therefore, if so, it may be natural that Tertiary sea level curve proposed by VAIL and HARDENBOL (1979) cannot be explained well by the fluctuation of the Antarctic Ice Sheet. However, the amplitudes of eustatic movement shown by the curve are not always large compared with the magnitudes of glacial eustasy which are expected from the drastic change of the East Antarctic Ice Sheet proposed by WEBB *et al.* (1983). Therefore, the relationship between Tertiary eustatic change of sea level and the fluctuation of the Antarctic Ice Sheet should be examined, including the cause and effect relation.

7. Concluding Remarks

The following remarks are made from the brief survey of knowledge on the Antarctic glacial history in particular for the basis of future investigations, though no definite conclusion has been reached as yet.

Investigations on the ice sheet fluctuations have been carried out in many regions of Antarctica, and important results are being accumulated. It seems still difficult, however, to correlate these events precisely among the respective regions, mainly due to the scarcity of reliable age determination data. Tentative correlations can only be made by comparison of "phase" of fluctuations, taking notice of specific events seemingly common to most of regions. Difficulty arises also from the obscurity in time- and spatial-scale of events. In this connection, more efforts should be made to investigate regional characteristics of the events and their relations to those of a continental scale. On that occasion, the finding of marine microfossils in the Sirius Formation, above all, compels us to reexamine the glacial history which has been more or less compiled in each region, because this means that at least large-scale deglaciation has occurred within 3 Ma and it might have affected greatly the glacial events in the respective regions.

Acknowledgments

The author wishes to express his hearty gratitude to Dr. T. YOSHIKAWA, emeritus professor of The University of Tokyo, for his critical reading of the manuscript and advice. He is also indebted to the colleagues who participated in the discussion on the occasion of the Symposium.

References

ADAMSON, D. and PICKARD, J. (1983): Late Quaternary ice movement across the Vestfold Hills, East Antarctica. Antarctic Earth Science, ed. by R. L. OLIVER *et al.* Canberra, Aust. Acad. Sci., 465–469.

AMANO, K. (1985): Dai-kôzui jidai; Nishi-Kurosawa Kaishin to kaisuijun hendô (The great flood age; Nishi-Kurosawa Transgression and eustatic movement of sea level). Kagaku (Science), **55**, 42–46.

BARDIN, V. I. (1972): Moraines of Antarctica. Antarctic Geology and Geophysics, ed. by R. J. ADIE. Oslo, Universitesforlaget, 663–667.

BARDIN, V. I. (1982): Composition of East Antractic moraines and some problems of Cenozoic history. Antarctic Geoscience, ed. by C. CRADDOCK. Madison, Univ. Wisconsin Press, 1069–1076.

BARRETT, P. J. (1982): Proposal for Cenozoic Investigations in the Western Ross Sea (CIROS). Wellington, Victoria Univ. Wellington, 17 p.

BARRETT, P. J. and POWELL, R. D. (1982): Middle Cenozoic glacial beds at Table Mountain, southern Victoria Land. Antarctic Geoscience, ed. by C. CRADDOCK. Madison, Univ. Wisconsin Press, 1059–1067.

BIRKENMAJER, K. (1982): Extent and course of the Pliocene glaciations in West Antarctica. Bull. Acad. Pol. Sci., Ser. Sci. Terre, **30**, 9–20.

BRADY, H. T. (1982): Late Cenozoic history of Taylor and Wright Valleys and McMurdo Sound inferred from diatoms in Dry Valley Drilling cores. Antarctic Geoscience, ed. by C. CRADDOCK. Madison, Univ. Wisconsin Press, 1123–1131.

CALKIN, P. E., BEHLING, R. E. and BULL, C. (1970): Glacial history of Wright Valley, southern Victoria Land, Antarctica. Antarct. J. U. S., **5**, 22–27.

CRADDOCK, C., ANDERSON, J. J. and WEBERS, G. E. (1964): Geologic outline of the Ellsworth Mountains. Antarctic Geology, ed. by R. J. ADIE. Amsterdam, North-Holland, 155–170.

DENTON, G. H., ARMSTRONG, R. L. and STUIVER, M. (1970): Late Cenozoic glaciation in Antarctica; The record in the McMurdo Sound region. Antarct. J. U. S., **5**, 15–21.

DENTON, G. H., KELLOGG, D. E. and KELLOGG, T. B. (1983): Ice sheet overriding of the Transantarctic Mountains. Antarct. J. U. S., **18** (5), 93–95.

DREWRY, D. J. (1982): Ice flow, bedrock, and geothermal studies from radio-echo sounding inland of McMurdo Sound, Antarctica. Antarctic Geoscience, ed. by C. CRADDOCK. Madison, Univ. Wisconsin Press, 977–983.

HARWOOD, D. M. (1983): Diatoms from the Sirius Formation, Transantarctic Mountains. Antarct. J. U. S., **18** (5), 98–100.

JOHN, B. S. (1972): Evidence from the South Shetland Islands towards a glacial history of West Antarctica. Polar Geomorphology, ed. by R. J. PRICE and D. E. SUGDEN. London, Inst. British Geographers, 75–92 (Spec. Publ. No. 4).

MARGOLIS, S. V. and KENNETT, J. P. (1971): Cenozoic paleoglacial history of Antarctica recorded in Subantarctic deep-sea cores. Am. J. Sci., **271**, 1–36.

MAYEWSKI, P. A. (1975): Glacial geology and late Cenozoic history of the Transantarctic Mountains, Antarctica. Inst. Polar Studies, Rep. No. **56**, 168 p.

MERCER, J. H. (1968): Glacial geology of the Reedy Glacier area, Antarctica. Geol. Soc. Am. Bull., **79**, 471–486.

MERCER, J. H. (1972): Some observations on the glacial geology of the Beardmore Glacier area. Antarctic Geology and Geophysics, ed. by R. J. ADIE. Oslo, Universitetsforlaget, 427–433.

PÉWÉ, T. L. (1960): Multiple glaciation in the McMurdo Sound region Antarctica; A progress report. J. Geol., **68**, 498–514.

RUTFORD, R. H., CRADDOCK, C., WHITE, C. and ARMSTRONG, R. L. (1972): Tertiary glaciation in the Jones Mountains. Antarctic Geology and Geophysics, ed. by R. J. ADIE. Amsterdam, North-Holland, 239–243.

STUIVER, M., DENTON, G. H., HUGHES, T. J. and FASTOOK, J. L. (1981): History of the marine ice sheet in West Antarctica during the Last Glaciation; A working hypothesis. The Last Great Ice Sheets, ed. by G. H. DENTON and T. J. HUGHES. New York, J. Wiley, 319–436.

VAIL, P. and HARDENBOL, J. (1979): Sea-level changes during the Tertiary. Oceanus, **22**, 71–79.

VAN AUTENBOER, T. (1964): The geomorphylogy and glacial geology of the Sør-Rondane, Dronning Maud Land. Antarctic Geology, ed. by R. J. ADIE. Amsterdam, North-Holland, 81–103.

WAITT, R. B., Jr. (1983): Thicker west antarctic ice sheet and peninsula icecap in late-Wisconsin time—Sparse evidence from northern Lassiter Coast. Antarct. J. U. S., **18** (5), 91–93.

WEBB, P. N. (1972): Wright Fjord, Pliocene marine invasion of an Antarctic dry valley. Antarct. J. U. S., **7**, 227–234.

WEBB, P. N., HARWOOD, D. M., MCKELVEY, B. C., MERCER, J. H. and STOTT, L. D. (1983): Late Neogene and older Cenozoic microfossils in high elevation deposits of the Transantarctic mountains; Evidence for marine sedimentation and ice volume variation on the east antarctic craton. Antarct. J. U. S., **18** (5), 96–97.

YOSHIDA, Y. (1983a): Physiography of the Prince Olav and the Prince Harald Coasts, East Antarctica. Mem. Natl Inst. Polar Res., Ser. C (Earth Sci.), **13**, 83 p.

YOSHIDA, Y. (1983b): Geomorphic nature of some unconsolidated deposits in the Langhovde and Skarvsnes areas, Sôya Coast, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **28**, 231–239.

YOSHIDA, Y. and MORIWAKI, K. (1983): Landform of Mt. Riiser-Larsen, Amundsen Bay, Enderby Land; Results of a preliminary survey. Mem. Natl Inst. Polar Res., Spec. Issue, **28**, 240–246.

(Received May 2 1985; Revised manuscript received July 1, 1985)

Note added after submission of the manuscript: MCKELVEY *et al.* (Antarct. J. U. S., **19**(5), 42, 1984) suggested recently that the Pliocene Sirius Formation at Mount Feather was deposited [from plateau-derived ice onto a landscape which was sculptured in Miocene or older time and buried largely beneath locally derived ice at the time of the Sirius Formation deposition.