Buried Terraces in the Lower Sagami Plain, Central Japan : Indicators of Sea Levels and Landforms during the Marine Isotope Stages 4 to 2 (Part I)

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CONTENTS

Abstract

This study aims to reconstruct the paleoenvironments during the Marine oxygen Isotope Stages (MISs) 4 to 2, particularly focusing on sea-level changes and landforms of coastal areas. The isotopic records derived from deep-sea sediments and polar ice cores provide precise environmental changes of the peroid, but direct records of land-based evidence, including deposits and landforms, are poor. For the purpose, the author uses geomorphological information from buried terraces in the lower Sagami Plain, central Japan. Buried terraces in coastal plains are, so to speak, fossil landforms preserved under the earth's surface. These terraces indicate sea-level changes during the glacial period in the area where the tectonic component is known, since they were formed under the influence of sea levels lower than that of present.

The lower Sagami Plain is the most suitable area to identify buried terraces formed during the Last Glacial Cycle in Japan. The reason is as follows : Sea-level changes must have directly affected the erosional and depositional process of the river because there is no distinct continental shelf around the present mouth of the Sagami River. This caused the formation of a flight of terraces. The area is also favourable for correlating these terraces with regional stratigraphy by using tephra layers derived from Fuji and Hakone volcanoes.

The author examined the buried terraces in the lower Sagami Plain by using many borehole logs. The buried terraces are correlated with subaerial ones in the upper reaches by using morphological continuity and tephra sequence covering the terraces.

A chronological framework for the Sagami region is shown on the basis of

tephrostratigraphy and radiometric age of marker tephras in south Kanto. The lower Sagami Plain has a flight of well-developed subaerial fluvial terraces. They are Sagamihara terraces (S1-5), Nakatsuhara terrace (N), Tanahara terraces (T-1 and T-2) and Minahara terraces (M) respectively. These terraces and their constituting deposits are chronologically determined by tephrostratigraphy, pollen stratigraphy, and regional stratigraphy. The author correlates subaerial S1-3 terraces with the MISs 5c-5a (100-80 ka), N and T-1 terraces with the MIS 3 (60-25 ka), and T-2 and M terraces with the MIS 2 (17-14 ka).

The author recognized buried S3-5, N, T-1 and M terraces in the lower Sagami Plain by interpreting borehole logs and correlating buried terraces with subaerial ones. The correlation of these buried terraces with those in the Paleo Tokyo River basin suggests that Tachikawa-1 terrace, the most extensive one, be correlated with the N terrace (the MIS 3) in the lower Sagami Plain.

On the basis of geomorphological features of buried terraces in the lower Sagami Plain, the author reconstructs relative sea-level changes by subtracting tectonic components from the observed heights of buried terraces near the present Sagami River mouth. The tectonic component of the average uplift rate was estimated as 0.07 m/ky, by an extrapolation of the height of the tilting MIS 5e deposits, from Koza upland to the present river mouth. The calculated (and observed) sea levels at the culmination of each stage are as follows : -40 to -31 m (-34 to -25 m) in the MIS 5a, -109 to -95 m (-104 to -90 m) in the MIS 4, -90 to -79 m (-86 to -75 m) in the MIS 3, and -111 to -101 m (-110 to -100 m) in the MIS 2. The relatively low sea level remained throughout the MIS 3. This result proposes low sea levels in the MISs 4 and 3, and generally agrees with sea-level curves shown by the isotopic records.

This study shows the landform development of the lower Sagami Plain during the MISs 5a to 1 from the above mentioned results. A broad fan-deltaic plain was formed at the culmination of the MIS 5a. A deep and narrow valley incised the plain during the MIS 4 because of the drop in sea level. During the MIS 3, this deep valley was filled, and a relatively wide plain of compound fans developed. A deep and narrow valley was formed again in the MIS 2. The Sagami Bay has intruded into the lower Sagami Plain only in the MISs 5e and 1.

The buried terraces in the lower Sagami Plain provide much information on changes of sea levels and landforms during the Last Glacial Cycle, especially for the MISs 4 to 2. This study suggests the low sea level during the MIS 4 was nealy the same as that of the MIS 2, and was stagnant during the MIS 3. The results contribute to the reconstruction of paleoenvironments : the global paleoenvironment, such as the estimation of ice volume, and regional ones, such as the blockage of the Japan Sea during the Last Glacial Cycle.

1. Introduction

This study aims to reconstruct the paleoenvironments during the marine oxygen isotope stages 4 to 2, particularly focusing on sea-level changes and landforms of coastal areas. Questions on which this study is focused, viewpoints for the solution, and the purpose of this study will be stated in this chapter.

1.1 Questions on the Paleoenvironments during the Last Glacial Cycle

Various kinds of evidence have accumulated over the past few decades to reveal the paleoenvironments of the Last Glacial Cycle, which consists of the Last Interglacial, the Last Glacial and the Holocene (present interglacial). Among them, oxygen isotope studies of fossil foraminifera in deep-sea sediments and those of polar ice cores have succeeded in reconstructing global changes during this period. Consequently, the Last Glacial Cycle is referred to as the Marine oxygen Isotope Stages (abbreviated as MIS) 5 to 1 (Holocene).

The MIS 5 has three culminations of interglacial to interstadial levels : substages 5e, 5c and 5a in chronological order. It is widely accepted that the substage (MIS) 5e corresponds to the Last Interglacial period. Therefore the Last Glacial period is equivalent to the interval from the MISs 5d to 2. The isotopic records precisely show these changes.

On the other hand, paleoenvironmental records derived from terrestrial deposits and landforms of the Last Glacial Cycle are fragmentary. In general, although much is known about interglacials of the MISs 5e and 1, the MIS 2 (the Last Glacial Maximum) is moderately known, and little is known about the MISs 4 and 3. They will be reviewed in chapter two.

Because of the shortage of landside evidence, the following questions on sea levels (and ice volumes), coastal landforms and other terrestrial environment have not been solved for the periods of the MISs 4 to 2.

1) Questions on sea levels during the MISs 4 to 2

The evidence of paleo sea levels has been obtained mainly from studies on coral terraces. They provide ages and levels of relatively high sea-level periods by the Uranium-series dating method. The ages and sea levels of the MIS 5e, 5c and 5a have been discussed by this dating of coral terraces. Sea levels of these periods can be estimated on the basis of the present altitude of the coral reef and the average uplift rate in the area.

On the other hand, it is hard to obtain evidence of lower sea-level stands corresponding to the MISs 4 to 2. This is because they are submerged, or buried under the younger deposits in the coastal areas. As the MIS 2 has generally been correlated with the lowest sea-level stage of the Last Glacial Maximum sea levels during the MISs 4 and 3 are situated within the range between those of the MISs 5e and 2. Since the estimation of sea levels from oxygen isotope records contains some indirect interpretations, we need other independent data suggesting the former sea leves. Here the author presents the following questions.

-How high (deep) was the lowest sea level in the culmination of the MIS 2?

-How high (deep) was the sea level of the culmination of the MIS 4? Was it higher than that of the MIS 2?

-How high (deep) was the sea level of the culmination of the MIS 3? When did it culminate? How long did it last?

-What kind of direct evidence can we obtain to determine the sea levels during the MISs 4 to 2?

2) Questions on terrestrial environments during the MISs 4 to 2

Terrestrial records are discontinuous and fragmentary in general, compared with detailed records from deep-sea sediments and ice cores. For instance, evidence on glacial advance in the Last Glacial period has been obtained, but it is mostly of the maximum glacial extent corresponding to the MIS 2. Since the former evidence was eliminated by the following glacial advance, little is known on glacial fluctuations during the MISs 4 to 3.

Pollen analysis can provide information on the climate for the period. Pollen sequence in Europe has shown some stades and interstades in the Last Glacial period. However the correlation of such periods with isotopic records is difficult because the samples are discontinuous or poor-dated.

Changes in landforms of coastal plains and lowlands along rivers have been associated with sea-level change. Therefore it is accepted that river regimes have changed during the glacial-interglacial cycle and resulted in the formation of fluvial terraces. However, the identification of former landforms in coastal plains is difficult, especially for the periods of MISs 4 to 2. This is because remnants of the river plain in the lower reaches have been buried under the Recent deposits.

Questions on terrestrial data for the periods of the MISs 4 to 2 arise as follows.

-How can we correlate terrestrial data with isotopic data?

-Can we recognize sea-level changes in the Last Glacial Cycle in terms of landforms in coastal and fiuvial plains?

3) Questions on age determination

The radiocarbon (^{14}C) dating method is available for organic materials for the late Last Glacial period. On the other hand, the U-series dating method can cover the whole Last Glacial Cycle. However it is available only for carbonates, such as coral and speleothem.

One possible solution for the problem is tephrochronology, which is useful for the correlation of deposits and landforms between distant areas. Tephras commonly occur and give ages to marine sediments, peat bogs and terrace deposits in Japan and other volcanic regions. The questions regarding the age are as follows.

-When did each stage start, and how long did it last?

-Can we get reliable ages for the MISs 4 to 2 by tephrochronology?

1.2 Viewpoints for the Solution

In order to answer the above questions, the author considers terrace landforms in the south Kanto region, central Japan. The reason for the consider ation is that marine and fluvial terraces corresponding to the Last Glacial Cycle are broadly developed in this area (Fig 1.1). Abundant tephras from Mt. Fuji, Hakone and other volcanoes covering these terraces provide good markers for chronology. Accordingly, south Kanto is one of the most intensely investigated areas on landforms and deposits of the Late Quaternary in Japan (*e.g.*, Machida, 1975 ; Kaizuka, 1987 ; and Yamazaki, 1992). A standard stratigraphy of the Late Quaternary in Japan has been established in this area. Consequently, this area is suitable for giving answer to the above questions.

The author intends to recognize buried geomorphic surfaces and deposits corresponding to the MISs 4 to 2 mainly in the lower Sagami Plain of south Kanto, and to get information on relative sea-lavel changes. Buried terraces in coastal plains are, so to speak, "fossil landforms" corresponding to the low sea-level periods. The correlation of subaerial terraces with underground ones seems to be possible in this area.

1.3 The Purpose of This Study

The purpose of this study is to answer the following questions based on the study of buried terraces in south Kanto :

-How did the sea level (or ice volume) change during the MISs 4 to 2?

-How long did the MISs 4, 3 and 2 last?

-How did the coastal landforms change during the MISs 4 to 2?

To answer the above questions, the author carries out the following procedures :

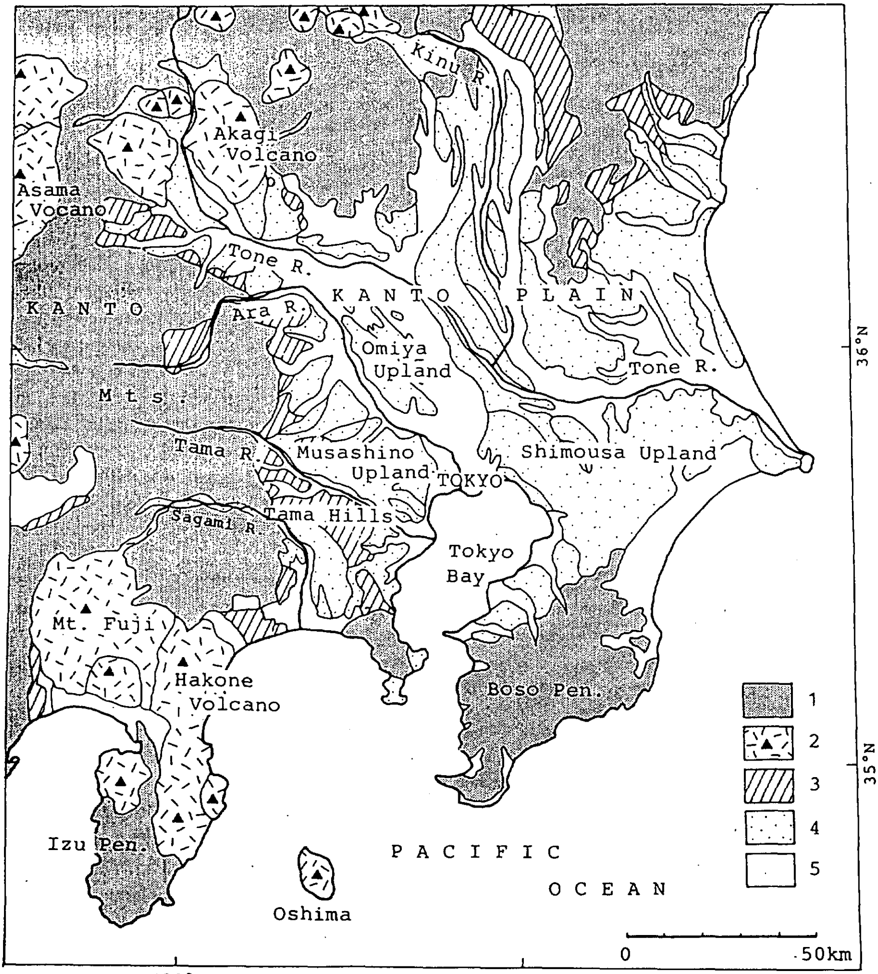

Fig. 1.1 Map showing the landforms in south Kanto (Kubo, 1990, revised after Kaizuka, 1987)

1 : mountain, 2 : volcano, 3 : hill, 4 : upland, 5 : lowland

-clarifies the distribution of buried terraces,
-correlates each buried terrace with a subaerial terrace, and
-improves the chronology of subaerial and buried terraces.

The goal of this study is to reconstruct the following changes :
-relative sea-level changes during the MISs 4 to 2, and
-changes of landforms during the period in coastal areas.

2. Previous Studies on Paleoenvironments during the Marine Isotope Stages 4 to 2

Various techniques have been used to reconstruct the paleoenvironments of the Late Quaternary. A great deal of information on temperature, sea level, glacial ice extent, flora and fauna, atmospheric chemistry and so on, has been obtained from deep-sea sediments, polar ice, terrestrial sediments and landforms. To describe the paleoenvironments for the period of the MISs 4 to 2, the author reviewed studies on marine isotope stages and paleornvironments during the MISs 4 to 2 taken from several sources.

2.1 Deep-Sea Records

1) Oxygen isotope stratigraphy

The oxygen isotope ratio ($\delta^{18}O$) in foraminifera tests from deep-sea sediments has been useful in the study of the Earth's past climates and in paleoceanography. Emiliani (1955) first obtained the record derived from planktonic foraminifera from the Atlantic, Caribbean and Pacific cores. He interpreted the $\delta^{18}O$ curve as the paleo-temperature changes and gave the stage numbers for the curve : odd numbers for warm periods, and even numbers for cold periods. The present warm stage is designated as No. 1, and stage 5 in deep-sea cores tentatively corresponds to Riss/Würm or the Sangamonian Interglacial period.

The mean $\delta^{18}O$ of the whole ocean varies with the quantity of isotopically light ice stored on the continents, so that the record from foraminifera in a particular core mainly represents the global ice volume.

The isotopic record in planktonic foraminifera may be affected by differences in surface salinity, as well as by changing seasonal growth and depth habitat. Shackleton and Opdyke (1973) used oxygen isotope ratios from benthic formanifera rather thatn from planktonic foraminifera, as benthic ones provide a better record of global ice volume. On the basis of the Pacific core V28-238, Shackleton and Opdyke (1973) established 22 stages, of which stage 19 penetrated the Brunhes/ Matuyama magnetic boundary.

The ratio of ^{18}O in sea water is a function of the fraction of water stored as ice in glaciers. Detailed measurements of $^{18}O/^{16}O$ in deep sea cores have provided a continuous record of climatic change over the past 10^6 years. The approach, however, has been limited by the inability to independently assign an absolute chronology to this record. The time scale of the oxygen isotope record is interpolated from ages of B/M boundary and several radiometric dates of coral terraces.

Recently, "orbital tuning" is often applied to the time scale for oxygen isotope chronostratigraphy (*e.g.* Imbrie *et al.,* 1984 ; Martinson *et al.,* 1987). This is based on the assumption that orbital parameters of the Earth are pacemakers of global climatic changes. It is said to be a modern version of the Milankovitch's Theory.

During the Last Glacial Cycle, three conspicuous peaks within the marine isotope stage 5 occured ; MIS 5e (or 5.5), MIS 5c (5.3) and MIS(5.1) (*e.g.,* Imbrie *et al.,* 1984). Martinson *et al.* (1987) showed more detailed subdivisions, such as the MISs 5.53, 5.51 , 5.33 and 5.31, as well as within the MISs 4, 3 and 2.

2) Sea-level estimation for the Last Glacial Cycle

Shackleton and Opdyke (1973) illustrated a glacio-eustatic sea-level curve derived from oxygen isotopic measurements of Pacific core V28-238 for the period of the Last Glacial Cycle. A good agreement was seen in high sea-level periods of 120, 100, 80 and 50 ka (kilo years ago) with coral terraces in Barbados (Broecker *et al.,* 1968) and Papua New Guinea (Veeh and Chappel, 1970). On the basis of the rough correlation of oxygen isotope ratio and sea-level change (0.1‰ to 10 m), they pointed out a 120-m maximum sea-level drop in the MIS 2 (17 ka), and 80-m sea-level drop in the MIS 4.

However, Chappell and Shackleton (1986) pointed out a discrepancy between the sea level estimated by raised coral terraces and the marine oxygen isotope record particularly for the MIS 3. They attributed it to the fact that the temperature of the abyssal ocean cooled down at the end of the

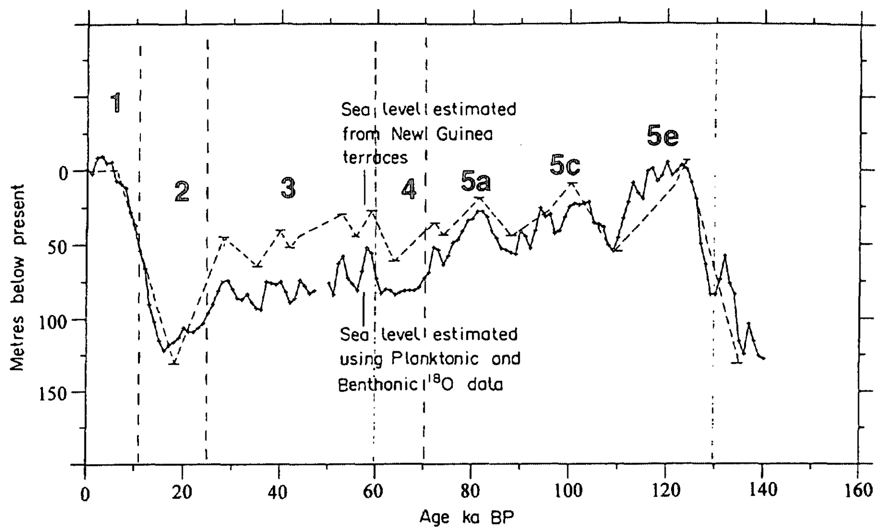

Fig. 2.1 Sea-level history by Shackleton (1987)

MIS 5e, and the temperature remained low until 11 ka.

Shackleton (1987) emphasized that the simple interpretation of the benthic oxygen isotope record as an ideal ice volume or sea-level record is no longer tenable. The oxygen isotope record from benthic foraminifera during the MISs 5a and 5c shows 0.7‰ more positive than that of the MIS 5e. It implies a 70-m sea-level difference, while dated coral terraces show only around a 20-m lower sea level. Shackleton (1987) showed a "more accurate" sea-level record, subtracting the isotopic difference between planktonic and benthic data from the original benthic data. As a result he demonstrated the sea levels of the MIS 4 (70-60 ka), 3(60-20 ka) and 2 (18 ka), as -80 m, -90 to -50 m, and -125 m, respectively (Fig. 2.1).

2.2 Ice-Core Records

Polar ice cores allow the reconstruction of the most highly-resolved climate records for the Last Glacial Cycle. The $\delta^{18}O$ of ice represents the air temperature around the ice sheet (*e.g.* Dansgaard *et al.*, 1969).

The Vostok core from Central Antarctica was the first to yield an environmental record spanning the entire Last Glacial Cycle. The oxygen isotope record by Lorius *et al.* (1985) and a continuous deuterium profile by Jouzel *et al.* (1987) derived from Vostok ice core showed general agreement compared with marine oxygen isotope records. Vostok's time scale was established using an ice-flow model that is independent of other paleo-indicators.

The oxygen isotope records of Greenland ice cores show a series of rapid changes for the MIS 3 (about 55-25 ka). Broecker and Denton (1989) described these phenomena as Dansgaard-Oeshger events. These events have a duration on the order of a millennium and rise-and-fall times on the order of one century. Broecker and Denton pointed out that they are akin to the

Younger Dryas event.

Dansgaard *et al.* (1993) showed a 3,028.8-m-long continuous oxygen isotope record from GRIP ice core at the summint of Greenland. The most striking feature of it is a contrast between the stable Holocene record and the unstable records of the Last Glacial and the Last Interglacial. They recognized 24 interstadials from the GRIP core, between 11.5 ka (Younger Dryas Event) and 110 ka (the MIS 5d). As the MISs 5a and 5c were correlated with Interstadial numbers 21-22 and 23-24 respectively, the MIS 4 seems to be between Interstadials 20 and 21. Consequently, the MIS 3 seems to contain 20 interstadials. The time scale for this period was given according to the ice-flow model.

The isotopic studies provide high-resolution climatic data for the MISs 4 and 3. It is, however, hard to correlate these data with radiometrically dated terrestrial evidence (shown in 2.4) because the isotopic data is indirect and their time scale is hypothetical.

2.3 Coral Reef Records

Marine terraces are good indicators of past high sea levels. Amongst raised coral reef is, so to speak, a fossil tidal gauge, indicating the paleo tide level. Coral terraces in the tectonically uplifted coast provide several periods of high sea-level stands. They can be dated by U-series methods. Therefore, it is possible to correlate the ages of marine terraces with peaks in isotope records.

It is broadly understood that an "interglacial" is used for a period as warm as the present (*e.g.*, Reeh, 1991), which means that the sea level of an interglacial must be the same or higher than that of Holocene. Therefore, the estimation of paleo sea level is necessary in establishing the chronology for the Last Glacial Cycle along with the dating of deposits.

Records of marine terraces suggest that only the MIS 5e is the interglacial period, whose sea level was higher than that of present, within the MIS 5. The ages of high sea-level stands during the MISs 5c and 5a derived from coral terraces also agree well, while sea-level data during the MISs 4 to 2 varies.

1) Sea-level records during the MIS 5

Broecker *et al.* (1968) showed distinct high sea-level stands of 122 ka, 103 ka and 82 ka ($^{230}Th/^{234}U$) in Barbados, and speculated paleo sea levels for each period as + 6 m (assumed), -13 m and -13 m, respectively. Mosolella *et al.* (1969) showed high sea levels in Barbados as 125 ka, 105 ka and 82 ka.

Bloom *et al.* (1974) showed major reef-building episodes at 118-142 ka, 107 ka and 85 ka in Huon Peninsula, Papua New Guinea. They estimated paleo sea levels at + 6 m (assumed), -15 m and -13 m respectively, subtracting the height based on the ground uplift rate.

Konishi *et al.* (1974) correlated coral terraces in Ryukyu Islands with those of Barbados and Papua New Guinea. The 125 ka, 100 ka and 80 ka coral reefs extensively occur in Kikai Island.

Fairbanks and Matthews (1978) have correlated coral terraces in Barbados dated 125 ka, 105 ka and 82 ka, with the MISs 5e, 5c and 5a, and estimated sea levels respectively, at + 5 m, -43 m and -45 m. The latter two values are lower than those by Broecker *et al.* (1968) in Barbados. Fairbanks and Mattews (1978) calibrated the above sea levels by the estimation of 0.011‰ $\delta^{18}O$ of corals to 1 m.

There has been an apparent agreement about the ages of a number of coral terraces corresponding tothe MISs 5e, 5c and 5a. However, there is some disagreement about estimated paleo sea levels of the MISs 5c and 5a (Table 2.1).

Table 2.1 Comparison of estimated sea-levels in previous works

researcher	MIS 5e	5c	5a	4	3	2	material
Broecker *et al.*, 1968	+6*	-13	-13				Barbados corals
Shackleton & Opdyke, 1973				-80		-120	Pacific ^{18}O
Bloom *et al.*, 1974	+6*	-15	-13		-28 to -41		New Guinea corals
Konishi *et al.*, 1974	+6*	-10**	-15**		-20 to -40**		Kikai corals
Fairbanks & Matthews, 1978	+5	-43	-45				Barbados corals
Aharon & Chappell, 1986		-12	-19		-28 to -44		New Guinea corals/shells
Shackleton, 1987	+5	-20	-25	-80	-50 to-90	-125	Pacific ^{18}O
Bard *et al.*, 1990b				<-70	<-80		Barbados corals
Chappell *et al.*, 1994					-38 to-91		New Guinea corals

* assumed value
** shown in Figure

2) Sea levels during the MISs 4 to 2

There are records of coral terraces providing well-defined high sea-level stands diring the MIS 5. On the other hand, sea-level data for the MISs 3 and 4 are insufficient. Some dated coral reefs showed relative high sea levels in these periods. They were correlated with the interstades in the MIS 3 (Table 2.1).

Veeh and Chappell (1970) reported a "transgreesion" at coral terraces in Papua New Guinea between 50 ka and 35 ka (by ^{14}C and ^{230}Th), that was not identified in Barbados because of a lower uplift rate. The samples were obtained from reef complexes II, III and IV, with their height between 10 and 100 m a.s.1. (above sea level).

James *et al.* (1971) reported a high sea-level stand at 60 ka in Barbados, that was derived from 0 to 4.5 m a.s.1. They correlated the deposits with St. Pierre Interstadial in North America (referred in section 2. 4).

Bloom *et al.* (1974) showed reefs at 61 ka, 41 ka and 28 ka, with calculated paleo sea leves at -28 m, -38 m and -41 m in Huon Peninsula. Konishi *et al.* (1974) also showed two succeeding relative high sea-level periods in Kikai Island, dated 65-55 ka and 45-35 ka. They estimated the sea levels of these periods at between -20 and -40 m.

Aharon and Chappell (1986) showed some short-lived high sea level stands in the MIS 3 at Huon Peninsula, Papua New Guinea. They were at 60 ka, 45 to 40 ka and 31 ka, with sea levels at -28 m, -32 m to -44 m, and -42 m. They generally agree with the results of Bloom *et al.* (1974).

A database for Late Pleistocene high sea-level stands (Smart and Richards, 1992) demonstrated relatively high sea-stands of 61.5 ($\pm$6.0) ka, 50.0 ($\pm$1.0) ka, 40.5 ($\pm$5.0) ka and 33.0 ($\pm$2.5) ka (numbers in parenthesis are standard deviations), after the sharp peaks of the MISs 5e, 5c and 5a. These post-MIS-5a peaks correspond to Events 3.31, 3.3, 3.13 and 3.1 of Martinson *et al.* (1987). However, these peaks in age frequency distribution are relatively small, and they were reported only from highly uplifted areas such as the Huon Peninsula.

3) Difficulties of the low sea-level period

Reconstruction of sea levels throughout the MISs 4 to 2 has been limited to only rapidly uplifted areas because sea levels throughout the MISs 4 and 3 were lower than the present sea level. Only extremely high uplift rates can preserve terraces of these periods. In order to estimate the paleo sea level, one must show the uplift rate.

The evaluation of uplift rate, however, is another problem. Interpolation from the difference in terrace heights between 130 ka and 6 ka provides an average uplift rate in the area because paleo sea levels at 130 ka and 6 ka are known. Bloom *et al.* (1974) estimated paleo sea levels using the assumption of uniform uplift rate, as the "best assumption". If the uplift rate is not uniform, the estimation of paleo sea levels between 130 ka and 6 ka is unreliable. This makes it difficult to know sea levels of the MISs 4 and 3.

Recently Bard *et al.* (1990b) obtained U-Th ages of submerged terraces in Barbados and showed that the sea level was below -70 m during the MIS 4 (70 ka), and below -80 m for the end of the MIS 3 (30 ka).

Chappell *et al.* (1994) revised the sea levels between 70 and 30 ka, by using new U-series dating in Huon Peninsula. Their new results, -38 m to -91 m, are systematically lower than the previous results, but overlapped the isotopic results of Shackleton (1987).

A question arises concerning the interstades of the MIS 3 on the basis of recent coral data. Further dating and measurements of depths of submerged terraces in the tectonically stable areas may help solve the problems.

2.4 Terrestrial Records

Various kinds of terrestrial deposits and landforms have revealed the stades/interstades during the Last Glacial period. These kinds of evidence, such as aeolian, glacial and fluvial deposits, pollen assemblages, and speleothem growth, have been correlated with oxygen isotope stages.

1) European records

Western Europe is a classical field for stades and interstades during the Last Glacial period.

Interstades named Amersfoort, Broerup, Odderade, Moershoofd, Hengelo and Denekamp are known during the early to middle Last Glacial (Weichselian) period, derived from pollen assemblages in the Netherlands. Radiocarbon ages were measured for Amersfoort as 67,500 + 1,800/-1,400 yBP, and Broerup as 62,000-64,000 yBP, and for Odderade as 61,000 + 900/-800 yBP, using the thermal diffusion isotopic enrichment method. The Moershoofd, Hengelo and Denekamp interstadials were radiocarbon dated 55,000-45,000 yBP, 40,000-37,500 yBP and 32,000-29,000 yBP (Grootes, 1978 ; Nilsson, 1983).

Recently Dawson (1992) correlated Broerup and Odderade Interstadials with the MISs 5c and 5a, where classic Eemian corresponds to the MIS 5e. However, he did not correlate the Amersfoort with the isotope stages. The above radiocarbon ages correspond to the MIS 5 seem to be too young, thus limiting the reliability of the method. On the other hand, the latter three interstades seem to correspond to the MIS 3.

Woillard (1978), Guiot *et al.* (1989) and Pons *et al.* (1992) presented a 140,000-year climate reconstruction from two pollen records, La Grande Pile and Les Echets in eastern France. After the Last Interglacial (Eemian), two warm periods, named St-Germain 1 and St-Germain 2, were recognized and correlated with the MISs 5c and 5a. Lower Pleniglacial (the MIS 4) was given its age as 74-60 ka. Pollen records suggest the climate parametes of the Middle Glacial period (the MIS 3) are either fluctuating (Les Echets) or poorly marked (La Grande Pile). Since their time scale, exceeding 30 ka, was based on the marine isotopic chronology, it is still difficult to recognize short events, such as Dansgaard-Oeshger events (Broecker and Denton, 1989), using pollen records.

U-series dating is available for speleothem and vein calcite. According to the growth frquency curve of speleothem in Great Britain (Gordon *et al.*, 1989), 57 ka, 50 ka, 45 ka, 36 ka and 29 ka were correlated with the warmer periods with increased growth of vegetation for the MIS 3. However, they did not show the significance of peak magnitudes of the above periods.

2) North American records

St. Pierre, Port Talbot and Plum Point interstades have been recognized in the Great Lakes region during the Wisconsin (the Last Glacial) period (*e.g.*, Dreimanis and Raukas, 1975). Stuiver *et al.* (1978) measured the radiocarbon ages of these interstadial deposits by the thermal diffusion method, which extended the range of C-14 dating. An age of 74,000 yBP for St. Pierre interstadial deposits in the Pacific Northwest in the United States, corresponded to the European Amersfoort interstade.

Early Wisconsin glaciation around 75 ka to 65 ka has been considered to be the MIS 4. Accordingly, St. Pierre seems to correspond to the MIS 5a.

Winograd *et al.* (1992) showed a 500,000-year continuous climate record from Devils Hole vein calcite, Great Basin, USA. It reflects isotopic variations in atmospheric precipitation. Though the data lack younger records, they compared the record with the records of SPECMAP and Vostok ice core, and concluded that climate centered at 65 ka (the MIS 4) was just as cold as the Last Glacial Maximum (the MIS 2).

The left two interstades, Port Talbot (1 and 2), and Plum Point correspond to the MIS 3. They appear to have culminated between 48 ka and 40 ka, and Plum Point occurred between 30 ka and 25 ka (*e.g.*, Dreimanis and Raukas, 1975).

The MIS 3 in North America was generally regarded as a time of climatic amelioration, or an interstadial complex. Consequently, the retreat and/or decay of Laurentide and Cordilleran ice sheet are a considerable subject (*e.g.*, Dawson, 1992).

The use of terrrestrial records in determining synchronous events such as sea-level changes is difficult. Global correlation for the MISs 4, 3 and 2 is an example of this problem. Continuous terrestrial records with radiometric datings will improve the knowledge of paleoenvironments for these periods.

2.5 Paleoenvironmental Records in Japan

Much has been studied on the paleoenvironment during the Last Glacial Cycle in Japan. This section focuses on the evidence derived from marine terraces, glacial deposits and plant fossil assemblages.

1) Marine terraces

Ota and Machida (1987) summarized Quaternary sea-level studies in Japan. Sea-level changes in the late Pleistocene is well established in the Ryukyu Islands and south Kanto. In conclusion, they recognized four high sea-level periods during the Last Glacial Cycle : centered at 130 ka, 100 ka, 80 ka and 60 ka respectively.

Kikai (lat. 28° N) and Hateruma (24° N) islands in Ryukyu provided high sea-level ages of 125-120 ka, 100 ka and 80 ka, supported by U-series dating of corals. Terraces of 60 ka and 40 ka occur only in Kikai island, due to the relatively large uplift.

Tephrochronological approaches enabled geomorphologists to reconstruct detailed sea-level history in south Kanto. Four marine terraces, named Shimosueyoshi (S), Hikihashi (H), Obaradai (or Musashino 1) and Misaki (or Musashino 2) terraces have been identified in south Kanto.

The Shimosueyoshi Terrace, the most extensively occurring marine terrace in South Kanto, is widely accepted as the 130 ka terrace. Evidence of this age was given by fission-track dating of pumice beds, named Hk (Hakone)-KlP-6 and Hk-KlP-8 (derived from Hakone Volcano) that covering marine formation. Machida (1975) correlated the Hikihashi terrace with the 100 ka-terrace, from the fission-track age of Hk-KmP-1 pumice bed (98 ka) ; Obaradai Terrace, 80 ka, from On-Pm1 Pumice bed (80 ka) ; and Misaki Terrace, 60 ka.

This sequence of four major terraces (130 ka, 100 ka, 80 ka and 60 ka) has been widely accepted in Japan, and correlated with marine terrace sequences, from the north (Hokkaido) to the south (Ryukyu), using tephrochronology. However, Ota and Machida (1987) pointed out a discrepancy concerning the timing of the low sea level at around 70 ka (the MIS 4). If the ages of the Obaradai and Misaki terraces are 80 ka and 60 ka respectively, no evidence shows a lowering of sea level between this time interval.

Recently, Machida and Arai (1992) reexamined the age of Aso-4, an im-

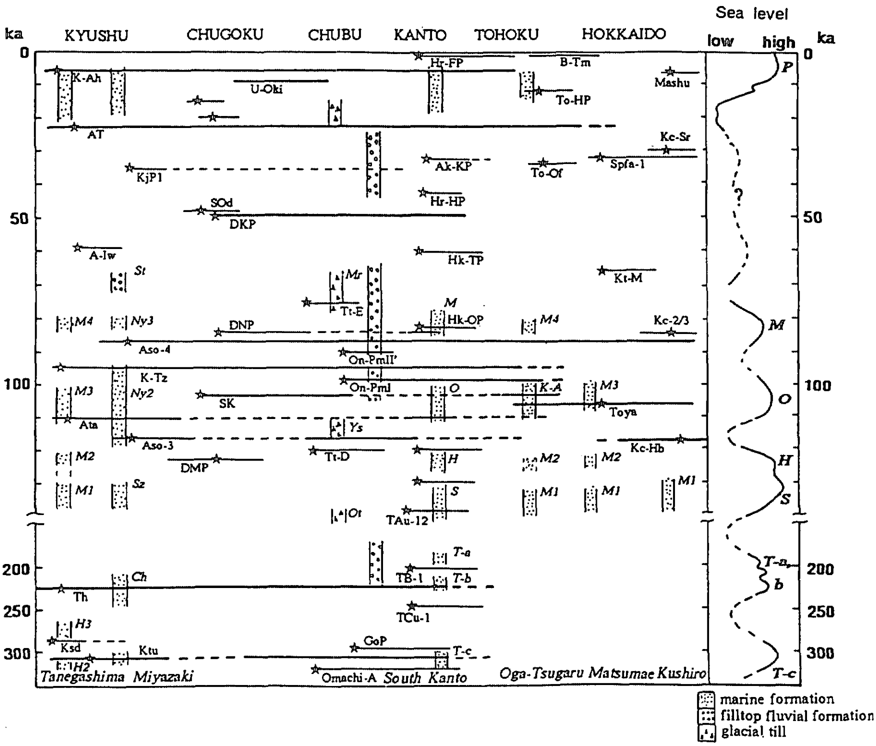

Fig. 2.2 Time-space diagram of marker tephra layers with the representative marine, fluvial and glacial sequence for the last 300 ka. (Machida and Arai, 1992)

portant widespread tephra, and suggested the age of it (formerly estimated 70 ka) should be 80-90 ka. The revised age came from TL, ESR and K-Ar dates, and the stratigraphical position of the tephra in the oxygen isotope fluctuations determined in deep-sea cores around Japan. Other widespread tephras in Japan have also been determined in the marine isotope stratigraphy.

They suggested the following revisions : a), Shimosueyoshi and Hikihashi terraces correspond to the MIS 5e (130-125 ka), b) Obaradai Terrace corresponds to the MIS 5c (105 ka), and c) Misaki Terrace to the MIS 5a (80 ka) (Fig. 2.2).

This will be an alternative standard not only in south Kanto, but also for all marine terrace sequencing in Japan. This idea solved the discrepancy of timing for the MIS 4 low sea level, but the chronology during the MISs 4 and 3 still remains doubtful. According to the revised chronology, the duration of middle-to-late Last Glacial period (the MISs 4 to 2) must be longer.

Moreover, some confusion exist. For instance, relative high sea-level stand presumably correlated with the MIS 3 has been reported from marine terraces "M4" in Tanegashima and SW Hokkaido (Ota and Omura, 1991). Ota and Machida (1987) described these terraces and correlated them with the Misaki terrace in south Kanto. Recent interpretation by Machida and Arai (1992) suggests it to be the MIS 5a. Therefore, marine terraces that had been correlated with the MISs 5c, 5a and 3 should be reexamined.

Regarding marine terraces of the MIS 3, two levels of terraces occur in Kikai Island, Ryukyu. They are c. 60 ka terrace and c. 40 ka terrace (Konishi *et al.*, 1974). These well-preserved marine terraces of the MIS 3 in Kikai Island are exceptions of marine terrace sequences in Japan. Active faulting and rapid differential uplift may have separated the coral reef terraces of 125 ka, 60 ka and 40 ka. Each terrace occurs in different altitudes.

For this reason the estimation of paleo sea levels derived from this island contains many problems. On the other hand, there are no well-defined marine terraces of the MIS 3 in south Kanto, even in the most extensive uplifted area, such as Oiso Hills and Boso Peninsula. The marine terraces of the MIS 3 may exist submerged or buried.

To summarize, late Pleistocene marine terraces in Japan, those of the MISs 5e and 5c are ordinarily seen ; the MIS 5a terraces are seen in highly uplifted areas ; the MIS3 terraces are extremely rare. Therefore, it is unrealistic to reconstruct paleo sea levels from marine terraces except for the period of the MIS 5.

2) Glacial deposits

Ono (1991) showed two stades of glacial advance during the Last Glacial period from the correlation between the Japan Alps (central Japan) and Hidaka Range (Hokkaido). The older glacial advances of Yoko-o Glacial in Mt. Yari-Hotaka (Ito, 1982) and Murodo Glacial in Tateyama (Machida and Arai, 1979), central Japan, and Poroshiri Stade in Hidaka (Ono and Hirakawa, 1975) are dated at the age of 70-50 ka, Younger glacial advances of Karasawa Glacial (Ito, 1982), Tateyama Glacial (Machida and Arai, 1979) and Tottabetsu stades (Ono and Hirakawa, 1975) at 20 ka. These significant glacial advances were respectively correlated with the MISs 4 and 2 by Ono (1991). By this chronology, the age of the MIS 4 corresponds to 70-50 ka, based on the ages of marker tephras ; Aso-4 (70 ka) and DKP (50 ka).

The estimation of this cold stage disagreed with the transgressive period of marine Misaki Terrace, which was previously dated as 60 ka. This discrepancy was solved by revising the age of the Misaki Terrace which dates back 80 ka (the MIS 5a).

Ono (1991) also discussed the oldest glacial stades in central Japan, Chogatake Glacial, and Otanihara and Yoshiwara stages. There are two possible chronological positions for these stades, the MIS 5d (Sakaguchi, 1988) and the Penultimate glacial (the MIS 6). Information on cold periods during the Last Glacial Cycle should be improved.

3) Plant fossil assemblages

The study on paleoclimates during the Last Glacial Cycle have been strongly linked with tephrochronology in Japan.

Tsuji (1980) and Tsuji and Minaki (1982) demonstrated a detailed paleoclimatic environment during the Shimosueyoshi stage (the MIS 5e) from Kissawa Formation in Oiso Hills, where plant fossils and pollen assemblages are abundant and associated with tephras from Hakone Volcano. They subdivided the Kissawa Formation (c. 150-120 ka) into two plant fossil assemblage zones (Kissawa-I and II), bordered by Hk-KlP-2 tephra. The earlier Kissawa-I was characterized by warm temperate taxa, while late Kissawa-II lacks them. They confirmed that the Shimosueyoshi transgression (the MIS 5e) culminated around the age of Hk-KlP-1 tephra, older than the Hk-KlP-2.

Tsuji *et al.* (1984) found an important change in climate of the early Last Glacial period, from analyzing plant fossils and pollen assemblages in south Kanto. They demonstrated the change from relatively warm climate during the Misaki transgression (the MIS 5a), chracterized by a cool temperate deciduous forest indicated by *Quercus* subgen. and *Lepidobalanus,* to a cold climate characterized by subarctic coniferous forest indicated by *Picea, Larix-Pseudotsuga* and *Alnus.* This cold stage can correspond to the Murodo Glacial in Mt. Tateyama, Japan Alps, or the middle stage of the Last Glacial period (the MIS 4). Marker tephras of On-Pm1, F-YP, Hk-AP and Hk-TP were used for the stratigraphic determination of these stages.

Sakaguchi and Katoh (1993) have compared the records of pollen analysis from terrace deposits in Hokkaido with marine oxygen isotope records. The pollen assemblage around the Aso-4 tephra (they settled the transition of the MISs 5a/4 at Aso-4 horizon ; based on the assumption of Aso-4 age as 70 ka) showed a "glacial type" climate, while those around Mpfa-1 (age : > 46,000-^{14}C yBP), Spfa-7 and Spfa-4 tephras (the beginning of the MIS 3) showed a "glacial maximum type". There is still a matter for debate on age determination for these periods.

2.6 Problems of Paleoenvironments of the MISs 4 to 2

Although the correlations of terraces and deposits with the MISs 5 and 2 are generally accepted, there is no total agreement on the identification and paleoenvironment especially for the MISs 4 and 3. This problem may result from the fact that no continuous record of paleoenvironmental change covering the whole span of the Last Glacial Cycle has been obtained in Japan.

The high quality records showing paleo sea levels were obtained from the emerged coral reefs. These records can reconstruct paleo sea levels of the MISs 5e, 5c and 5a. Coral terraces have provided control points for chronology of oxygen isotope results by U-series dating.

Glacial remains also support the first-hand records for the chronology of cold stages, but they are isolated and not continuous. They have problems in correlating with each other.

Carbon-14 dating is not available for the overall MISs 4 and 3. Thermal diffusion and AMS dating methods have been used to achieve measurements of older samples by ^{14}C. However, no calibration for these ages has been carried out.

U-series dating is available for the entire Last Glacial Cycle. Thermal Ionization Mass Spectrometry (TIMS) U-series dating is a hopeful method for precise dating. However, the application is limited for calcareous samples such as corals, speleothems and vein calcite, which are relatively rare in Japan.

Tephrochronology is effective for correlating and dating various deposits in Japan. As effectively dated marker tephras during the MISs 4 and 3 in south Kanto are lacking, unfortunately, there remains more to be debated.

Problems unsolved are summarized as below.

-Sea-level records or data for proxy environments during the MISs 4 and 3 are scarce and contain some uncertainties.

-High-resolution isotope records need time controls.

-We need first-hand land-based evidence to calibrate the isotope record.

South Kanto has an ability to provide land-based data on sea levels, climate and vegetation history on the basis of tephrochronology.

(to be continued)