Late Quaternary Shorelines in the Japanese Islands¹⁾

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The recent progress of late Quaternary shoreline studies in Japan are reviewed. In the first half, outcomes of the estimation of ages and elevations of shorelines during high sea-level stand of the late Pleistocene are exemplified for five localities, Hateruma Island in the Ryukyus, Matsumae Peninsula of Hokkaido, Tanegashima Island to the south of Kyushu, Noto Peninsula in the Japan Sea side of Chubu district, and Muroto Peninsula of southeastern Shikoku. The latter half is a summary, mainly as to the elevation of shorelines of the last interglacial, and gives some informations on younger (isotope stages 5c or 5a) and the penultimate interglacial (isotope stage 7) shorelines in the Japanese Islands. There it is evidenced not only how to confirm the elevation of each shoreline but also how to determine the age of it.

I. Introduction

Most Quaternary shorelines in the tectonically active Japanese Islands are preserved as a series of marine terraces, including coral reef terraces. Rapid uplift and great amounts of precipitation result in extreme dissection of early to middle Pleistocene terraces. However, late Quaternary terraces are usually still well preserved and provide excellent data for the understanding of sea-level changes and tectonic movement. In addition to many papers discussing the late Quaternary shorelines of particular areas, several review papers have been published (e.g., NARUSE, 1981; NARUSE and OTA, 1984; YONEKURA and OTA, 1986; OTA and MACHIDA, 1987). Considerable shoreline data are listed in the "Inventory of Quaternary Shorelines" (YOSHIKAWA, ed., 1987). The "Quaternary Maps of Japan" (JAPAN ASSOC. QUAT. RES., ed., 1987) also summarize the available shoreline data. Published papers on late Quaternary sea-level records were compiled by OTA *et al.* (1987). Based on these papers and materials, this paper intends to review the recent progress of late Quaternary shoreline studies in the Japanese Islands. In particular, various methods for the estimation of terrace age and their problems, and the

implications of terrace distribution and terrace height are discussed.

II. Age estimation of marine terraces

It is a fundamental task to date terrace sequences for the understanding of late Quaternary chronology and terrace deformation. In addition to direct dating of terrace deposits, indirect methods such as tephrochronological correlation, or paleontological analysis have been tried in order to estimate terrace age and the environment of terrace formation. In many places, where useful marker tephra and fossils are not available, the morpho-stratigraphical method is still the only way to estimate terrace age. In the following, four examples (Fig. 1, 1~4) which use different methods for age determination is introduced.

1. Hateruma Island, the Ryukyus — morpho-stratigraphy and uranium-series dating —

It is not necessary to say that radiometric dating of terrace deposits provides the best data for terrace age determination. Coral reef terraces in the Ryukyus are suitable for this kind of study. However, as corals are usually too recrystallized for dating, it is not necessarily easy to determine the age of coral reef terraces.

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Fig. 1 Map showing tectonic setting (after NAKAMURA, 1984) of the Japanese Islands and localities cited in the text

Numerals in circle, from 1 to 4, indicate localities discussed in the section II

Well-dated late Pleistocene coral reef terraces, dated by the uranium-series method, are known only from Kikai Island (KONISHI *et al.*, 1974; OMURA *et al.*, 1985; OMURA, 1988), Hateruma Island (OTA and HORI, 1980; OTA *et al.*, 1982; OMURA, 1984), the Daito Islands (OTA, *et al.*, 1991), and Yonaguni Island (OMURA *et al.*, unpubl.). The ESR method of dating also gives an estimation of terrace age (*e.g.*, Koba *et al.*, 1987). This method is particularly important for the age estimation of middle to early Pleistocene terraces which are beyond the upper limit of the uranium-series method. Here, Hateruma Island is discussed, because in this island the terrace chronology and age estimation by the morpho-stratigraphical method are fully supported by abundant $^{230}\text{Th}/^{234}\text{U}$ ages.

There are six coral reef terraces on Hateruma Island, numbered I to VI, in descending order (Fig. 2-A). Terrace III, which is the widest and most continuous depositional terrace, underlain

by coral limestone more than 10 m thick, is considered to represent the high sea-level of the last interglacial of *ca.* 120 ka (OTA and HORI, 1980). They considered that the highest, terrace I, also depositional in origin, might have been formed at *ca.* 200 ka, and terrace IV and V at *ca.* 100 and 80 ka, respectively, judging by their progressive westward tilting, assuming a uniform rate of tilting (terrace heights are shown in Fig. 2-A). This estimation has been proven by uranium-series dating of coral limestones (OTA *et al.*, 1982). Further dating by OMURA (1984) on about 90 newly obtained samples also provide a very good age control for all the terraces (Fig. 2-A). About 120 ka old corals are found in many localities on terrace III as well as on younger terraces. However, no 120 ka corals exist on terrace I, which is underlain by transgressive corals of *ca.* 190 ka or more, or on terrace II. Similarly, *ca.* 100 ka corals were found on terrace IV and younger terraces, but not on terrace III and higher terraces, and *ca.* 80 ka corals are from terrace V and lower but not from terrace IV and higher (Fig. 2-A and B). Thus, the presence of high sea-levels corresponding to isotope stage 5e, 5c and 5a, as well as stage 7 are confirmed in Hateruma Island.

This study is a good example, showing the agreement of morpho-stratigraphical estimations with radiometric dating. It is important to note that corals older than the terrace itself are found not on the terrace surface but in the lower part, namely on bedrock of the terrace in question. This shows the importance of establishing terrace stratigraphy, based on detailed observation of the relationships between terrace surfaces and underlying coral limestones, even though it is not easy to distinguish an unconformity between coral limestones making the terrace itself and those comprising the bedrock. Because of relatively low uplift rates (maximum average uplift rate is *ca.* 0.3 m/ka), the high sea-level of isotope stage 3 (*ca.* 6 ka) and of younger stages do not appear on land as coral reef terraces in Hateruma. Despite the large number of dated corals, however, the age of terrace II is not certain. Terrace VI may be erosional in origin, affected by modern storm waves and splash.

Fig. 2 Coral reef terraces of Hateruma Island

A : Distribution of terraces, elevations and dated corals (OTA and HORI, 1980 ; OMURA, 1984)

B : Geomorphological and geological profile along A-B line of Fig. 2-A showing occurrences of dated corals

2. Matsumae Peninsula and Tanegashima Island— morpho-stratigraphy and tephro-chronology —

Tephrochronological study is particularly important for the establishment of terrace chronologies in the Japanese Islands which form the volcanic belt and include many sources of volcanic ash. The tephrochronological study of terraces, aided by fission track dating of important tephra was established in the southern Kanto (e.g., MACHIDA, 1975) where high sea-level stages nearly equivalent to those observed for Papua New Guinea (e.g., CHAPPELL, 1974) and the Barbados (MESOLELLA *et al.*, 1969) were identified. Discovery of wide-spread tephra (e.g.,

Toya ash : 110~130 ka, MACHIDA *et al.*, 1987 ; Aso-4 ash : ca. 70 ka, MACHIDA *et al.*, 1985) make it possible to correlate terraces over extensive areas. This method has been successfully applied in many areas (e.g., in northern Honshu : MIYAUCHI, 1988 ; in southeastern Kyushu : NAGAOKA, 1986, 1988).

Fig. 3(above) shows the relationship between marine terraces and ashes in Tanegashima, to the south of Kyushu. The M1 and M2 terraces are covered by the airlaid KTz and Ata ashes, and M3 terrace deposits bear the waterlaid Ata ash and are covered by KTz ash. The M4 terrace was formed after the eruptions of KTz and Aso-4. Such stratigraphic features in Tanegashima

Fig. 3 Representative marine terrace profiles showing relation with wide-spread tephtras (OTA and MACHIDA, 1987)

indicate the possibility that the M1 terrace, the most prominent one, is assignable to the last interglacial maximum (isotope stage 5e), and terraces M2, M3 and M4 are correlated with isotope stages 5c, 5a and 3, respectively.

Fig. 3(below) shows the marine terrace profile with the stratigraphic position of the Toya ashes, at Matsumae, southwestern Hokkaido, where strong uplift is recorded (MIYAUCHI and YAGI, 1984). The M1 terrace should be assigned to the last interglacial maximum and the M2, M3 and M4 terraces possibly correlate with those in Tanegashima, judging by the occurrence of Toya ash.

Tephrochronology is certainly a useful way to do terrace correlations, based on the occurrence of wide-spread tephtras, which are characterized by unique reflective indices of glasses, mineral assemblages and characteristic chemical compositions of minerals in each tephra, but some uncertainties still remain about their absolute age. For example, the fission track age of Toya ash is 130 ± 30 ka (OKUMURA and SANGAWA,

1984), but stratigraphically it is estimated to be *ca.* 90 ka in northern Honshu (MIYAUCHI, 1988). Different ages from 90 to 130 ka for Toya ash are thus estimated by different authors. Similarly, the age of many tephtras is only estimated stratigraphically or by an assumption of uniform rates of deposition. Therefore, further direct dating of important tephtras themselves is absolutely necessary.

3. Noto Peninsula —morpho-stratigraphical and paleontological evidence supported by uranium-series dating and the presence of a wide spread tephra—

The Noto Peninsula protrudes into the Japan Sea from northern central Honshu. At least nine marine terraces, dating back to the middle and early Pleistocene, are well developed on this peninsula. The M1 terrace, up to 110 m in elevation, is the widest and most continuous terrace, containing with incorporating an irregular pattern of former shoreline (Fig. 4-A). Most of the M1 terrace is underlain by thin beach deposits but in some places it is underlain by thick transgressive marine deposits. These suggest that M1 was formed during the major transgression of the last interglacial maximum, at 120 ka (OTA and HIRAKAWA, 1979).

Fig. 4-B shows a topographical and geological section of the northeastern peninsula, where the former shoreline of the M1 terrace is *ca.* 70 m in elevation, and where two lower terraces, M2 and M3 are preserved. An important point about this profile is that the Hiratoko shell bed representing warm fauna, preserved in valley-fill deposits, is found at *ca.* 35 m elevation on the M2 terrace (Fig. 4-B). Therefore, previous work correlated this M2 terrace with the major transgression of the last interglacial, and indicated that the Uji shell bed, at *ca.* 30 m elevation, was younger than the Hiratoko bed. However, OTA and HIRAKAWA (1979) noticed :

- 1) the valley-fill sediments of the Hiratoko and Uji shell beds, which have a uranium-series age of *ca.* 120 ka (OMURA, 1980), laterally thinned out and changed into beach gravels of the M1 terrace ;
- 2) both shell beds are unconformably covered by a veneer of beach gravel which ends at the

Fig. 4 Marine terraces of Noto Peninsula (OTA and HIRAKAWA, 1979)

A : Former shoreline of M1 terrace (last interglacial maximum)

B : Geomorphological and geological profile of terraces (location is shown in Fig. 4-A ; U-series dates, after OMURA 1980 ; SK : Sanbe-Kisuki volcanic ash, TOYOKURA *et al.*, 1989).

geomorphologically estimated shoreline of M2 (Fig. 4-B) ; and

3) there is no discontinuity in terrace surface height between the Hiratoko and Uji beds. Consequently, they proposed that these shell beds were constituents of the M1 terrace, representing isotope stage 5e, and were truncated by the M2 terrace deposits, indicating that M2 can be dated to either *ca.* 100 ka or 80 ka, and the lower M3 terrace to either *ca.* 80 ka or 60 ka.

The occurrence of the recently found Sanbe-Kisuki volcanic ash (SK), estimated to be *ca.* 90 ka, fits well with the above-mentioned age estimation ; namely, SK ash is found within deposits of M2, but on the beach deposits of M1 (TOYOKURA *et al.*, 1989). This example emphasizes the importance of recognizing the beach deposits directly corresponding to the terrace surface itself, even though they are only veneer.

4. Muroto Peninsula, southeastern Shikoku —morpho-stratigraphical evidence combined with age estimations based on the assumption of a constant uplift rate—

A series of well-defined marine terraces is preserved in the Muroto Peninsula. These terraces are classified as H1, H2, M1, and M2 (Pleistocene) and L (Holocene). Their former shorelines show a progressive landward (northwestward) tilting (Fig. 5), away from the Nankai Trough which is a plate boundary (Fig. 1). Deformation of these terraces has been discussed, based on a comparison of coseismic deformation associated with the 1946 Nankai earthquake and the pre- or post-seismic deformation revealed by repeated leveling (YOSHIKAWA *et al.*, 1964). They (1964) correlated the M1 terrace, up to *ca.* 200 m in elevation, with

Fig. 5 Geomorphological and geological profiles of marine terraces of Muroto Peninsula, Shikoku (after YOSHIKAWA *et al.*, 1964)

Dashed lines indicate the correlation among terraces and the northwestward tilting of the area.

the last interglacial maximum, for the following reasons. First, the presence of thick fluvial to marine deposits in the vicinity of major streams on M1 suggests this terrace was formed in association with a sea-level rise. Similarly, H2, underlain by transgressive deposits, has been correlated with the penultimate interglacial. This study is one of the first which discussed the significance of eustatic sea-level change for terrace formation on tectonically uplifting coasts. Secondly, relative sea-level changes, deduced from terrace sequences, fit well with the composite curve of eustatic sea-level changes and tectonic uplift, with a uniform rate of 2 m/ka in the southern part of the peninsula, caused by the resultant uplift of one seismic cycle.

Despite long efforts to find wide-spread tephra and fossils, however, still nothing datable has been found in the Muroto Peninsula, and the morpho-stratigraphical method is the only method of age estimation available. There are many areas similar to the Muroto Peninsula, lacking datable material, as shown in the following section.

5. Problems of age estimation of marine terraces

The marine terraces assigned to isotope stage 5e have been identified for most of the Japanese coast, although some uncertainties still remain about exact correlations. However, age determination of terraces older than the last interglacial maximum is more difficult. Marine terraces equivalent to isotope stage 7, or older

stages, are identified and dated in only a few places, for example, Hateruma Island by uranium-series dating (OTA *et al.*, 1982 ; OMURA, 1984), and the southern Kanto by tephrochronological methods (MACHIDA, 1975 ; MACHIDA *et al.*, 1980).

Certainly a series of sea-levels older than isotope stage 5e are preserved as marine terrace remnants on the Japanese coast, in other than the above-mentioned areas. Their ages have often been estimated, on the basis of an assumed uplift rate during the late Quaternary when the last interglacial terrace has been identified in some way. Younger terraces than 5e also exist on the relatively strongly uplifted zones of the coast (Fig. 7). Although the tephrochronological method is useful for age determination, some of the terrace ages are estimated by the same methods as those for the older terraces. However, both the identification of the last interglacial terrace and assumption of a constant uplift rate are tentative. Sometimes the distinction between 5c and 5a is rather difficult (MIYOSHI, 1983). Three examples mentioned above indicate the reliability of the morpho-stratigraphical method for age estimation, but certainly more positive data is necessary for the establishment of the late Quaternary chronology and tectonic rates.

III. Shorelines during the late Pleistocene in Japan

In addition to the above-mentioned examples from separate areas, we attempt here to sum up the data on elevations of late Pleistocene shorelines in the Japanese Islands (Figs. 6 and 7). The main aim of this section is not only to show the elevation of former shorelines, but also to demonstrate how to confirm the elevation of each shoreline and how to determine the age of it.

1. Methods for the definition of former shorelines

The methods employed to determine a shoreline formed during high sea-level stands in the late Pleistocene can be classified into the following three categories :

1) Topographical features, like shore platforms, sea cliffs, and shoreline angles and the extent of the marine terraces.

2) Sedimentological nature and elevation of terrace deposits, *e.g.*, the upper surface of marine deposits like beach gravel, marine sand or gravel, reefy limestone and so on.

3) Paleontological evidence, such as the upper surface of shell beds and marine sediments, including benthic foraminifera, coralline algae or reef-building corals in growth position.

Many former shorelines have been defined by using two or more methods, *e.g.*, by combining the topographical and sedimentological evidence (the morpho-stratigraphical method) or the topographical and paleontological ones. That is, 1) and 2) listed above are most frequently employed to define former shorelines in the Japanese Islands. The elevations of shorelines formed during the high sea level stand of the last interglacial maximum, are described at a total of 323 localities in YOSHIKAWA *et al.* (1987). Topographical and sedimentological features have been utilized at 315 localities (corresponding to 98 % of the total), whereas paleontological evidence provided the basis for establishing the former shoreline at only eight (*ca.* 2%) localities.

Several types of technique have been utilized so far, in order to estimate the age of terrace deposits, as stated in section II. The uranium-series (*e.g.*, the traditional α -spectrometric $^{230}\text{Th}/^{234}\text{U}$ and $^{231}\text{Pa}/^{235}\text{U}$ or the non-destructive $^{226}\text{Ra}/^{238}\text{U}$) and the electron spin resonance (ESR) methods are considered to be the most reliable for dating late Pleistocene sediments. There are, however, only a few examples (6 localities in Fig. 6, five islands in the Ryukyus and one in the Noto Peninsula, Chubu) in which the uranium-series methods of dating were applied, because of the severe limitation in kinds of samples datable. The mass-spectrometric uranium-series method (*e.g.*, EDWARDS *et al.*, 1987) has not yet been applied to the age determination of any late Pleistocene bed in Japan. Paleomagnetic data were successfully used at a locality in the southeastern part of the Tohoku district. Tephrochronological correlation has been used effectively for the age determination of late Pleistocene beds distributed through Kyushu and the Kanto, Tohoku and Hokkaido districts.

Although radiometric dating and tephrochro-

nological correlations have been developed to a certain degree, the conventional morpho- and / or litho-stratigraphical correlation is still used as the major technique for estimating the age of a former shoreline. Former shorelines at 194 (60 %) localities, among the 323 locals described in YOSHIKAWA *et al.* (1987), were morpho- and litho-stratigraphically assigned to the last interglacial maximum. That is, the depositional surface inferred to have been formed by major transgression (followed by small-scale transgressions at rapidly uplifting coast) preceding the Holocene, is assigned to that stage, in many localities. These stratigraphical methods have offered the best data for discussing the pattern and rate of tectonic deformation in coastal areas of Japan, as stated below.

2. Elevations of shorelines during the last interglacial stage

The elevation of shorelines during the high sea-level stand of the last interglacial maximum are shown in Fig. 6. Symbols used at each locality denote the method for age determination. Although many stratigraphical units of marine deposits correlated to the isotope stage 5e of SHAKLETON and OPDYKE (1973) occur, it is very difficult to estimate the accurate elevation of former shorelines in the Kanto district, because of the obscure relationship between marine and fluvial terraces. For that reason, in some localities only the approximate position is shown by dotted lines in Fig. 6.

The maximum elevation of the isotope stage 5e shoreline is more than 224 m above the present sea-level, at the eastern part of Kikai Island, in the Ryukyus. Some localities have been uplifted greatly and hence the present elevation of the shoreline is more than 100 m above sea-level (Fig. 6). Such localities are limited to two coastal regions on the Pacific side from the south Kanto to Kikai Island, the Ryukyus, and on the Japan Sea side from Chubu to Okushiri Island, located to the southwest of Hokkaido.

Fig. 6 implies that the elevation of shorelines during this stage varies from place to place, and even among adjacent localities. This means that the Japanese Islands have been deformed considerably during the last 120,000 years. The

Fig. 6 Representative elevation (m) of shorelines during the high sea-level stand of the last interglacial maximum, correlated to isotope stage 5e

(compiled from OTA, 1975 ; YOSHIKAWA (ed.), 1987 ; JAPAN ASSOC. QUAT. RES. (ed.), 1987 ; MIYAUCHI, 1988).

Fig. 7 Representative elevation (m) of shorelines during the high sea stand following the last interglacial maximum

(isotope stage 5c or 5a : complied from YOSHIKAWA (ed.), 1987 ; JAPAN ASSOC. QUAT. RES. (ed.), 1987), and four types of deformation occurring since the late Pleistocene (OTA, 1975).

Japanese Islands consist of several island arc systems and are situated in an area that is tectonically the most active in the world, due to the convergence of five plates, the Eurasian, North American, Pacific, Northeast Japan Micro and Philippine Sea Plates (Fig. 1). Hence, discussions of regional differences in deformation of former shorelines must fully consider these conditions. In accordance with this viewpoint, OTA (1975) classified shoreline deformation patterns into four types, shown as A, B, C and D in Fig. 7. Each pattern reflects the different response of tectonic regions to island arc movements (for details, refer to OTA, 1975; OTA and YOSHIKAWA, 1978).

1) Type A is warping with a small wavelength of 20 to 30 km, parallel to the coastline, mainly on the Japan Sea side of Hokkaido and the Tohoku districts. This area is also characterized by rapid uplift, due to the action of a newly discovered plate boundary.

2) Type B is tilting of small blocks, 10 to 30 km long, found on the Japan Sea coast of central Honshu, including the Chubu and Kinki districts.

3) Type C is very gentle undulation with a wave-length longer than 100 km, which predominates on the Pacific coast of Northeast Japan.

4) Type D is notable landward tilting of coastal zones, similar to the deformation pattern associated with historical earthquakes, within an area of 30 to 50 km wide, by which the Pacific coastal region from the south Kanto through the Ryukyus, located on the landward margin of the Philippine Sea Plate, is deformed. The uplift rates in this area reach the maximum for the Japanese coast.

3. Elevation of shorelines during the other stages

Figure 7 gives an outline of information on shorelines younger than the last interglacial maximum, correlated to isotope stages 5c or 5a. For this recent period, trustworthy information on shorelines during the high sea-level stand of the penultimate interglacial (isotope stage 7) or on shorelines during the other warm stage of the middle Pleistocene, is very limited (see II-5), because of poor chronological data and poor preservation of topographical and other evidence

useful for the definition of shorelines.

The elevations of shorelines of isotope stages 5c or 5a, have been reported for two coastal regions, the Japan Sea side from Tohoku to Chubu and the Pacific side from the south Kanto to the Ryukyus, which are comparable to areas where the present elevation of the stage 5e shoreline reaches more than several tens of meters above the present sea-level, because lower uplift rates than *ca.* 0.3 m/ka are unable to bring the relatively lower sea-levels of stage 5c or younger up to present land levels. At some localities, marine terraces of the middle Pleistocene have developed, but it is very difficult to correlate them to the isotope stages, except in the southern Kanto. For that reason, appropriate dating methods must be established.

Various views on the level of the lowest sea stand at the last glacial maximum, have been presented. All of the estimated levels are within the range of -80 m to -140 m. Each is based on the depths of buried valley floors, of the shelf edge and of buried channels on the continental shelves, or on the topography of the straits around the Japanese Islands. The -100 m isobath is shown in Fig. 7 as a reference, but the area surrounded by the contour does not necessarily represent the real extent of land emergent due to the regression of the last glacial maximum.

IV. Concluding remarks

The elevation of former shorelines, shown in Figs. 6 and 7, indicates that most of the coastal areas surrounding the Japanese Islands undoubtedly were uplifted during the late Quaternary. Elevations of shorelines give us the most reliable information for discussing the pattern and amount of vertical deformation. Every area with types A, B, C and D of deformation is considered to have been progressively deformed in a similar pattern during the late Quaternary. We already mentioned that four types of deformation pattern can be identified throughout whole islands. Assuming a constant rate of uplift, the paleo-sea-level height and the age of undated terraces can be estimated within a given area having the same type of deformation. In fact, uplift rates and the paleo-

sea-levels have been proposed from some areas, such as the southern Kanto (MACHIDA, 1975), Kikai Island, the Ryukyus (KONISHI *et al.*, 1974), and Hateruma Island (OTA and MACHIDA, 1987). It is, however, considered questionable, in recent years, whether the uplift rate has been constant during the last 120,000 years. An accelerated uplift rate towards the present has been suggested, by comparing the elevation of the last interglacial terrace and that of the Holocene terrace (OTA and YOSHIKAWA, 1978 ; OTA, 1986), and also by comparing the rates of uplift deduced from the late Pleistocene terraces assigned to isotope stages 5a, 5c and 5e (*e.g.*, OMURA, 1988). This possibility should be further examined, because paleo-sea-level elevation, which still has some discrepancies not only between Japan and elsewhere but also within the Japanese Islands, has been estimated by assuming a constant rate of uplift.

In any case, development of absolutely reliable methods for dating, which can be applied to as many materials as possible, is one of the most urgent problems in the late Quaternary study of Japan. Of course, the precise dating of late Pleistocene volcanic products, whose eruptive ages are not yet known but which have potential to be useful as time-markers, is indispensable to the study of Pleistocene beds in the Japanese Islands.

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