Late Quaternary Tectonic Movements on the Nishi-tsugaru Coast, with Reference to Seismic Crustal Deformation

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Introduction

Positive relationship has been reported on late Quaternary tectonic movement and seismic crustal deformation on the Pacific coast of Southwest Japan and southern Kanto (Sugimura *et al.* 1954, 1955, Yonekura 1968, 1975, Yoshikawa *et al.* 1964, Yoshikawa 1970). These seismic crustal deformations are related to great earthquakes occurring along the oceanic trench or trough, which are generally explained as interaction between oceanic and continental plates (Yonekura 1975, Yonekura *et al.* 1973, Matsuda *et al.* 1974).

On the other hand, the inner zone of Northeast Japan Arc is characterized as a zone of shallow-sheeted earthquakes of smaller magnitude in which seismic crustal deformations have been frequently recorded in recent and historical time (Imamura 1921, Nakamura *et al.* 1964). Acute vertical crustal deformations have remarkably taken place in this zone, whereas horizontal displacements occurred dominantly in the inner zone of Southwest Japan Arc.

In order to examine a relationship between seismic crustal deformations and late Quaternary tectonic movements in the shallow-sheeted earthquake zone on Japan Sea coast, the writers chose the Nishi-tsugaru coast for a sample area. This coast is furnished with suitable conditions for this type of study, as deformed coastal terraces are widely distributed at several levels and destructive earthquakes accompanied with crustal deformation have attacked in historical time and moreover first-class bench marks are set along the coast.

Divided by Omagoshi faults running in the N-S direction, the Shirakami anticlinal mountains composed of Lower Neogene volcanics and pre-Tertiary granitic rocks stand steeply 700 m$\sim$1,200 m in the eastern part of the study area, whereas hilly land composed of Middle to Upper Neogene sedimentary and volcanic rocks extend widely below 200$\sim$300 m in the western part (Fig. 1). Omagoshi faults running in the N-S direction are a group of geological faults arranged in echelon with westward down-throw and are remarkably reflected on topography as fault scarps between Cape Odose and Iwasaki, although no active faults have been detected geomorphologically along the major geological faults.

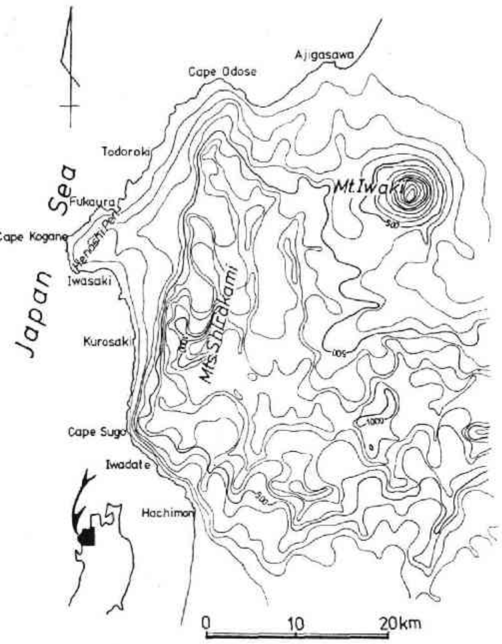

Fig. 1 Summit level map of Nishi-tsugaru, eliminating valleys less than 2 km across

Coastal Terraces and Late Quaternary Tectonic Movements

On the Nishi-tsugaru coast between Ajigasawa and Hachimori at the western foot of the Shirakami mountains, conspicuous coastal terraces are continuously distributed. Terrace surfaces are widely distributed in the northern part of the coast where Upper Neogene sedimentary rocks occupy the area, while they extend narrowly in the southern part, mainly composed of Neogene volcanic rocks. They are classified into six levels: namely H_1, H_2, M_1, M_2, M_3 and Holocene Terrace[1)] in descending order (Fig. 2).

Terrace surfaces are mostly abrasional ones generally overlaid by thin beach deposits, although at some places around the mouths of large rivers, sand and gravel bed more than 10 m thick composes the terrace surfaces. Between Iwasaki and Kurosaki, fluvial surfaces formed by rivers from steep western slopes of the Shirakami mountains are extensively covering coastal terraces. The terrace deposits composing H_1 and H_2 Terraces are weathered and reddish in color. Terrace surfaces are generally flat and smooth, and rarely interrupted by any minor scarps usually observed on terrace surfaces in the zone of co-earthquake

1) Holocene Terrace is not shown in Fig. 2, as it is narrow and scattered and is covered with coastal dunes at places.

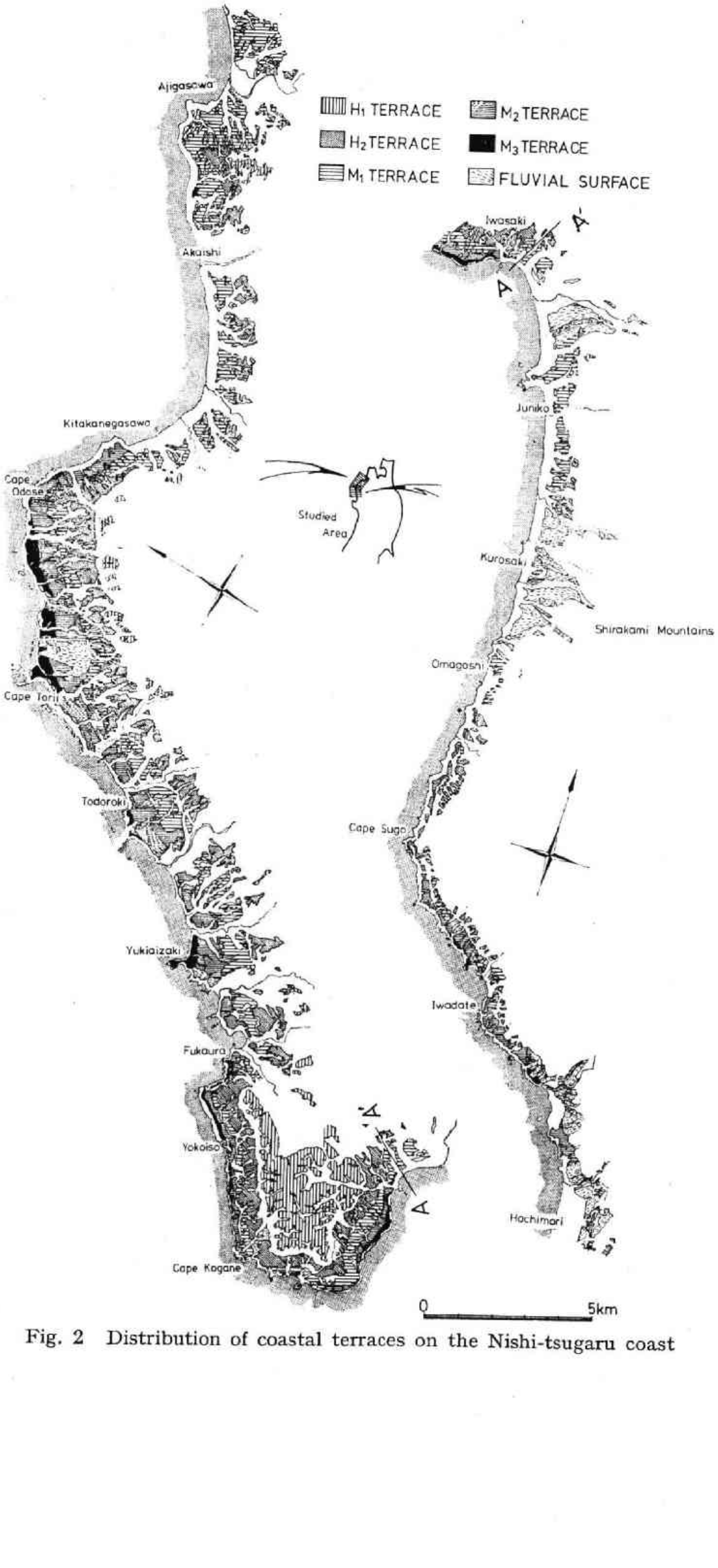

Fig. 2 Distribution of coastal terraces on the Nishi-tsugaru coast

deformation on the Pacific coast of Southwest Japan (Watanabe 1961, Yoshikawa *et al.* 1964). However, terrace surfaces are at places modified by minor faults and cover of coastal dunes (Ota 1960, 1968).

The writers correlated the terraces according to their continuation on the basis of airphoto-interpretation and field observation[2]. M_1 Terrace composed of comparatively thick marine deposits is most universal and continuous throughout the coast.

Considering such geomorphic characteristics of terraces, M_1 Terrace is properly assumed to have been formed at a high stand of sealevel during the last major Interglacial i.e. Riss-Würm Interglacial (Monastirian), starting about 90,000 years B.P. (Fairbridge 1961). If this assumption is accepted, it is further presumed that H_2 Terrace which is also continuously and universally distributed on the northern coast, was formed at a high stand of sealevel during the Interglacial preceeding to Riss-Würm Interglacial that is Mindel-Riss Interglacial (Tyrrhenian) dated about 130,000 years B.P.

These coastal terraces have been deformed by crustal movement throughout late Quaternary. It is interesting to notice that these terraces have been upwarped similarly in mode and their maximum altitudes have been attained between Cape Odose and Todoroki in the northern coast, and between Kurosaki and Cape Sugo in the southern coast (Figs. 3 & 4). There is considerably high positive correlation between altitudes of M_1 and H_2 Terraces (R=0.95) and between those of M_1 and M_2 Terraces (R=0.94). Wave lengths of warping estimated from terrace deformation are 24~30 km in the northern coast and 24~28 km in the southern coast (Table). The higher terraces have experienced the greater deformation and their gradients range 6.7×10^{-3} (H_1) to 1.7×10^{-3} (M_3), although rates of deformation (perennial gradient change) deduced on M_2 and M_1 Terraces coincide well each other (4.2×10^{-6} per 100 years), suggesting continuous uniform rate and mode in crustal movement of this area through late Quaternary. Rate of vertical deformation around Cape Odose is estimated about 1 mm per year from the height (ca 100 m) and age (ca 90,000 year B.P.) of M_1 Terrace. Similar figures are deduced from the height and age of H_2 Terrace, which is also reflected on the correlation coefficient of altitudes of M_1 and H_2 Terraces (Fig. 5). Consequently it can be said that the coast has been under upwarping in nearly uniform rate and

2) Differences between the present writers' classification and correlation of terraces and Ota's (1960, 1968) on the north of the studied area are mainly as follows;
   i) The present writers defined H_1 Terrace above Ota's First Terrace.
   ii) M_1 Terrace in this paper is probably equivalent to Ota's Second Terrace.
   iii) Correlation differs greatly at some places, because the present writers put on importance on continuation for terrace correlation although she considered abrupt elevation changes on faults.

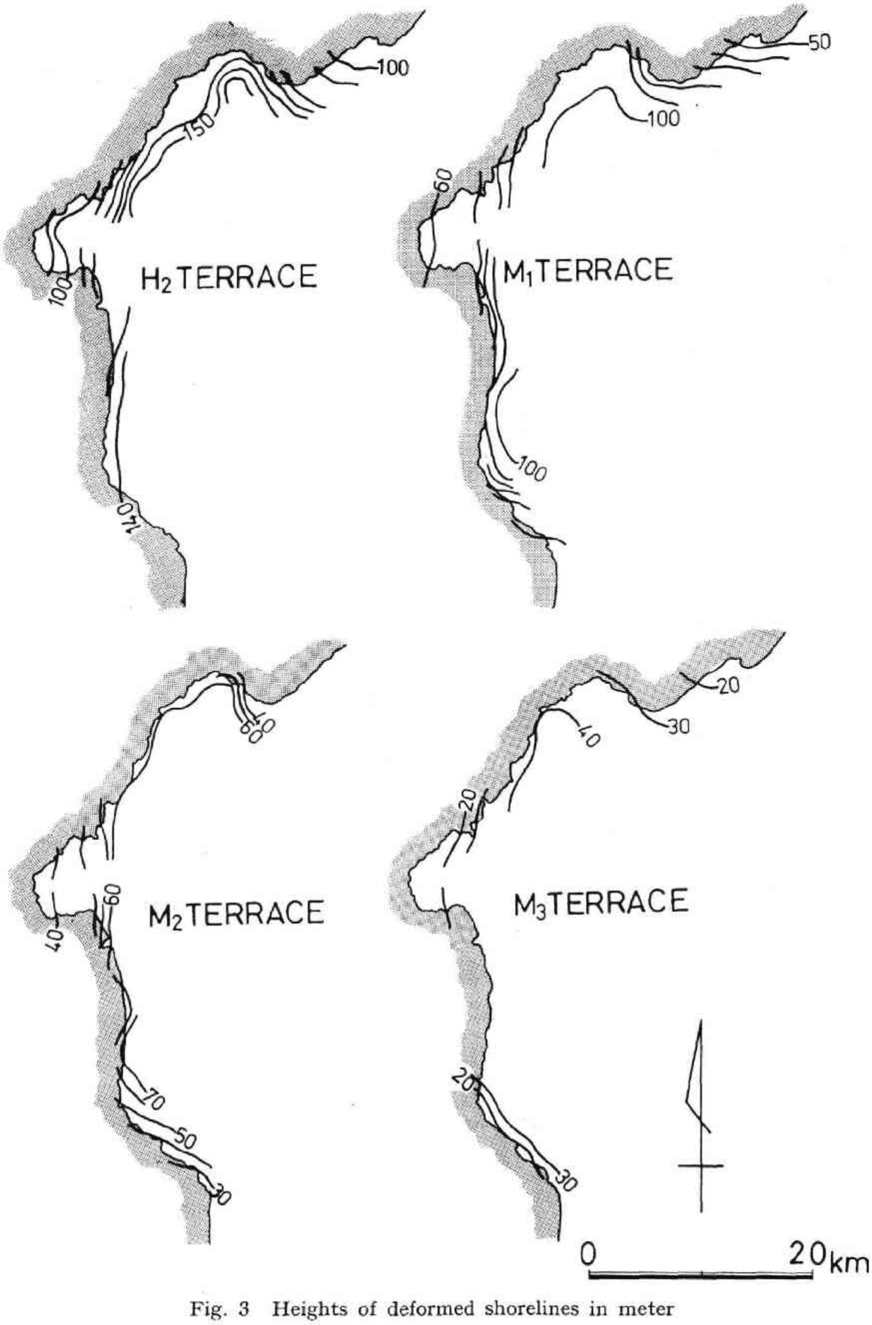

Fig. 3 Heights of deformed shorelines in meter

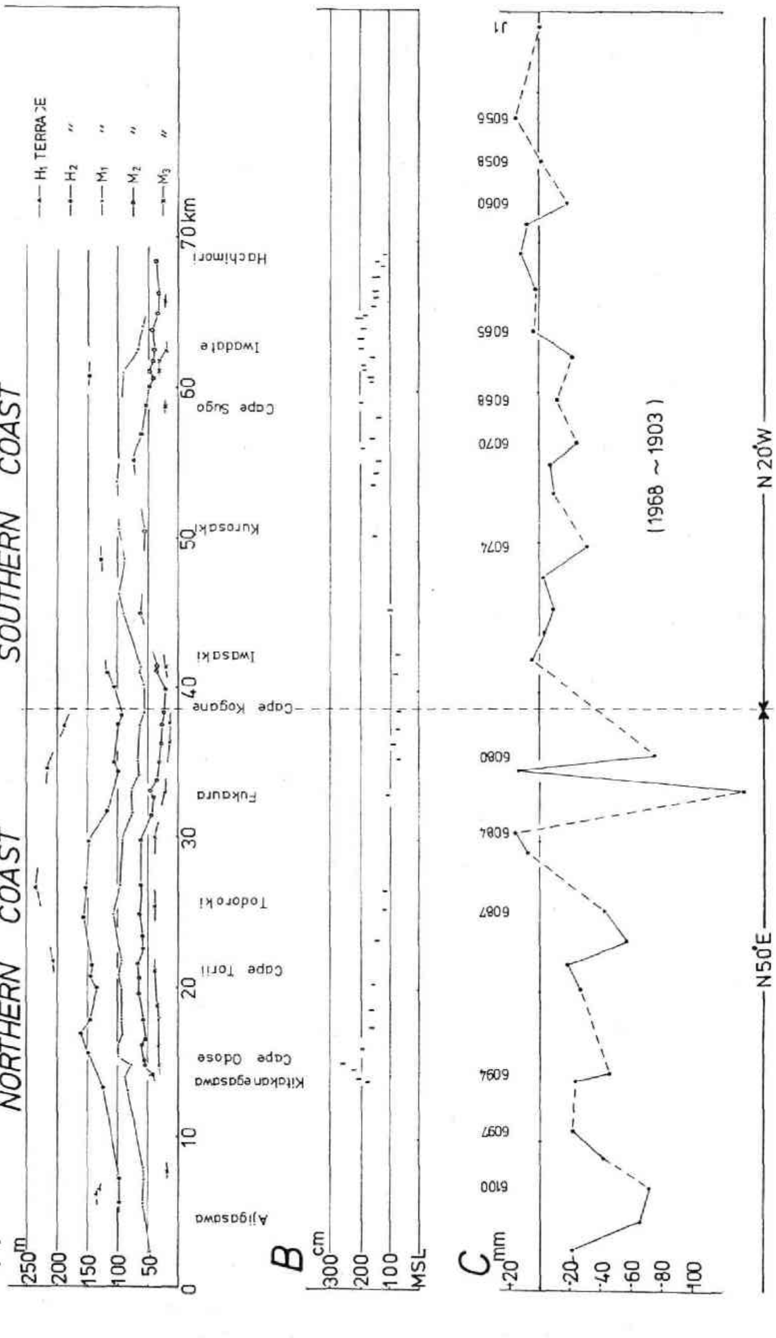

Fig. 4 Distributions of heights of deformed shorelines (A), heights of the lowest emerged benches (B) and relative change of bench marks assuming that J_1 (Noshiro) is fixed (C) on the Nishi-tsugaru coast

Table Wave length, wave height, gradient and rate of gradient change of late Quaternary tectonic movement, co- and inter-earthquake crustal movements

		Wave Length	Wave Height	Gradient	Duration	Rate of Gradient Change per 100yrs.
H_1 Terrace	N.C.	30 km	100 m	6.7×10^{-3}		
H_2 Terrace	N.C.	28 km	75 m	5.4×10^{-3}	13×10^4 yrs.	4.1×10^{-6}
M_1 Terrace	N.C. S.C.	26 km 24 km	50 m 45 m	3.8×10^{-3} 3.8×10^{-3}	9×10^4 yrs. 9×10^4 yrs.	4.3×10^{-6} 4.2×10^{-6}
M_2 Terrace	N.C. S.C.	24 km 24 km	40 m 35 m	3.3×10^{-3} 2.9×10^{-3}		
M_3 Terrace	N.C.	30 km	25 m	1.7×10^{-3}		
Lowest Bench	N.C. S.C.	16 km(L/2) 24 km	180 cm 120 cm	1.1×10^{-4} 1.0×10^{-4}	2×10^3 yrs. 2×10^3 yrs.	5.6×10^{-6} 5.0×10^{-6}
Bench Mark (1968–1903)	N.C. S.C.	16 km(L/2) 28 km	40 mm 30 mm	2.5×10^{-6}* 2.1×10^{-6}*	65 yrs. 65 yrs.	3.8×10^{-6}* 3.3×10^{-6}*

N.C.: Northern coast S.C.: Southern coast * reverse in sense

mode, which have taken place separately on the northern and southern coasts.

Co-earthquake Crustal Movement Accompanied by Earthquakes in Historical Time

It is known from historical records that the Nishi-tsugaru coast have twice suffered destructive earthquakes which were associated with acute crustal deformations (Imamura 1921). At the time of the earthquake in 1704, extensive upheaval of southern coast and huge land slide were recorded at the foot of Mt. Kuzureyama, resulting in the formation of Juniko Lakes. The earthquake in 1793 was accompanied with Tsunami[3] and remarkable uplift of northern coast, which remained prominent rock benches such as "Senjojiki". Such emerged benches can be traced extensively as lowest rock benches along the coast. Estimated magnitudes of these earthquakes are equally 6.9, judging from areal extension of severely damaged region.

The writers levelled the lowest wide rock benches[4] every one kilometer along the coast (Fig. 6), in order to reveal amounts of acute seismic crustal

3) Usami (1975) replaced the epicenter of the earthquake in 1793 into the sea bottom off Cape Odose because of occurrence of 'Tsunami'.

4) The amounts of estimated crustal deformation by the present writers are quite similar to that recorded by Imamura (1936, 1937), except on Henashi Peninsula, where the latter measured the altitude of uncertain abrasional features which are not generally observed along the coast at present.

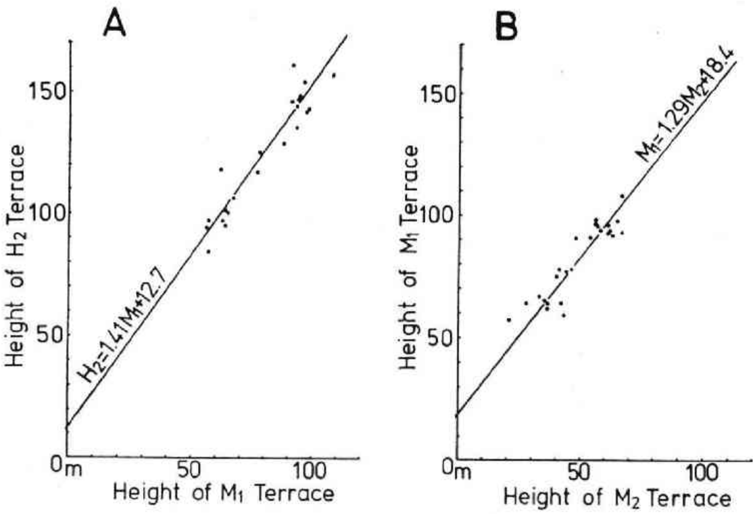

Fig. 5 Relation between heights of raised shorelines
A: M_1 and H_2 Terraces
B: M_1 and M_2 Terraces

deformations in these two destructive earthquakes which realized the similar mode in general to that of late Quaternary tectonic movement. At the time of earthquake in 1704, the southern coast was uplifted most between Cape Sugo and Iwadate and its amount gradually decreased north- and southeastwards. At the time of earthquake in 1793, the northern coast was elevated greatly between Capes Odose and Torii and less east- and southwestwards. The areal extensions of these two acute co-earthquake crustal deformations are also independent each other just like those of late Quaternary tectonic movements on the coast.

Upheaval accompanied at these earthquakes amounted over 2 m at places and it is nearly in maximum order of an earthquake fault based on magnitude-displacement relations (Matsuda 1975). Therefore, it is inferred that earthquake faults at the destructive earthquakes, though invisible on land, must be located quite close to the coast line.

Wave lengths of upwarping in the co-earthquake crustal deformation are 32 km in the northern coast and 24 km in the southern coast (Table), and they are also in concordance with those of late Quaternary tectonics of the area. Wave heights are 1.8 m and 1.2 m respectively in the northern and southern coasts. Hence, gradients calculated are 1.1×10^{-4} and 1.0×10^{-4} respectively.

If the constant uplift of the coast with average rate of 1 mm per year throughout late Quaternary is accepted and if the upheaval is assumed as the

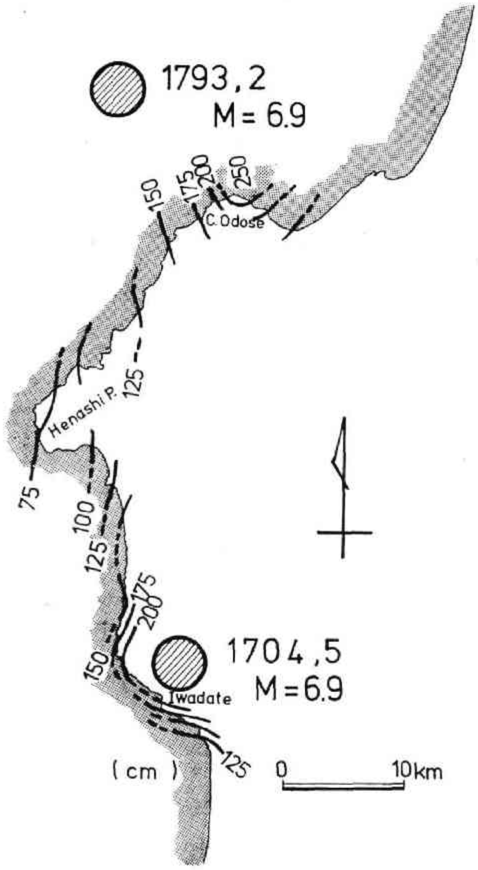

Fig. 6 Estimated vertical displacement accompanied by two destructive earthquakes in historic time (1704 and 1793)

accumulation of co-earthquake crustal movement, expected recurrence interval[5] of such a destructive earthquake is about 2,000 years respectively in the northern and southern coasts, because maximum displacement of co-earthquake crustal deformation is around 2 m, when aseismic fault creep is disregarded.

Rate of gradient change by acute co-earthquake crustal movements is

5) Recurrence interval of destructive earthquakes in this area is calculated about 1,500 years based on magnitude and long-term slip rate relation on a fault (Matsuda 1975). However, the actual amount of co-earthquake displacement in the studied area and length of fault segment seem to be greater than that expected from an earthquake of M=6.9 according to the magnitude and amount of displacement, and magnitude and length of fault segment (Matsuda 1975) judging from wave length and height accompanied by the destructive earthquakes in historical time.

calculated 5.5×10^{-6} per 100 years, in the case of 2,000 years recurrence interval of earthquakes. This rate is slightly more than that of late Quaternary tectonic movement (Table).

Holocene Terrace does not exceed 8 m in altitude along the coast and the altitude is reasonable to accept the above mentioned reccurrence interval of destructive earthquakes on the coast. According to historical records, no great earthquake had taken place on the coast at least over 1,000 years before two destructive earthquakes in 18th century.

Inter-earthquake Crustal Movements Inferred from Geodetic Survey

It is significant to discuss on present crustal movement revealed by geodetic survey in order to deduce mode of chronic inter-earthquake crustal movements of the study area. The first class bench marks have been set along the coast[6] since 1903 and precise levelling has been carried out in 1935, 1956 and 1968. As nearly 200 years have passed since the latest destructive earthquake took place in the coast, crustal movement during recent 65 years may represent only a part of inter-earthquake crustal deformations and the geodetic data are only given as relative altitude changes among each presurveyed bench mark. However it is still useful to detect the recent chronic crustal movements on the view point of gradient change. Mode of the inter-earthquake crustal movements between 1968 and 1903 is, though obscure, nearly reverse to that of the co-earthquake crustal movements both in northern and southern coasts. On the northern and southern coast, the areas more uplifted in the acute co-earthquake crustal deformation tend to be relatively more subsided. The wave lengths of the chronic inter-earthquake crustal movements are roughly estimated 32 km on the northern coast and 28 km on the southern coast, and their wave heights of down-warping are about 40 mm and 30 mm respectively. Gradients of these chronic crustal movements in a reverse sense to that of acute ones are calculated 2.5×10^{-6} and 2.2×10^{-6} on respective coasts. Subsequently, gradients of acute co-earthquake crustal movements have been recovered at the rates of 3.8×10^{-6} and 3.3×10^{-6} per 100 years during 1903~1965. These chronic crustal movements are hardly considered to continue throughout the inter-earthquake period with the duration of about 2,000 years at the above rates in reverse sense because the rate and amount of inter-earthquake movement would much exceed the expected ones which would adjust margins between acute co-earthquake crustal movement and late Quaternary tectonic movements (Fig. 3). Therefore, the recent chronic crustal movement should be regarded as a component of rather rapid post-earthquake crustal movement, which

6) Bench marks numbered 6080 to 6082 have been set along the road across the Henashi Peninsula.

is generally recognized in the outer zone of Southwest Japan (Yoshikawa 1968).

Conclusion

From the above mentioned characteristics of crustal movements of three kinds, it is concluded that late Quaternary tectonic movements on the Nishi-tsugaru coast have continued in a similar mode to the seismic crustal deformations associated with two destructive earthquakes in historical time. The maximum rate of vertical displacement on the coast is estimated about 1 mm per year throughout late Quaternary and the recurrence interval of destructive earthquakes is calculated about 2,000 years.

The gradient of terrace deformations seems to be proportional to the age of each terrace and the rate of gradient changes throughout late Quaternary seems to have been constant.

The rate of gradient change in co-earthquake crustal deformation is slightly greater than that of late Quaternary and it is assumed that they have been adjusted by inter-earthquake crustal deformation which is in a reverse sense to the co-earthquake crustal deformation.

The seismic crustal deformations accompanied by two historic earthquakes range about 24～30 km with two separate areal extensions which coincide with those of late Quaternary tectonic movements. This fact suggests that the Nishi-tsugaru coast has been under two separate seismic crustal movements of a nearly same dimension, occurring sequentially throughout late Quaternary.

Although no evidence of earthquake fault along major geological faults has been found on land, it is proposed that relation between earthquake and geological faults should be further studied in order to clarify role of the seismic crustal deformations on morphogenetic crustal movement of mountains in the area, as it is considered that the distribution of altitudes of coastal terraces are in accordance with Quaternary morphogenic crustal movement of Mountains (Ota 1968).

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