CHAPTER NINETY SIX

FORMATION OF TOMBOLO AT THE WEST COAST OF IWO-JIMA

By

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Abstract

This paper intends to clarify why and how such a huge tombolo having a surface area of 1,700,000 m^2 has been formed at the west coast of Iwo-jima for relatively short period of 33 years after 1945.

Analyses are performed on various data obtained through literature survey and field measurements to determine the growth rate of tombolo and variation rate of shore and sea floor surrounding the island. Model tests are also made on the formation of tombolo.

The followings are the conclusions derived through the analyses:

(1). Source of the sediments is the one produced at the northern part of island where sea floor has been lifting at a rate exceeding 30 cm per year.

(2). Waves with dominant direction of N to NE which appear in fall and winter erode the northern coast and currents induced by these waves carry these sediments southward along both coasts of the island.

(3). Waves with dominant direction of S to SE which appear in summer and their induced currents carry the sediments northward along both coasts of the island.

1. Introduction

Iwo-jima is a small volcanic island located in the Pacific ocean at a location which is approximately 1250 km southward from Tokyo(24°45'N to 24°49'N in latitude and 141°17'E to 141°21'E in longitude). This island is situated at the southern tip of Izu-Ogasawara volcanic arc.

Figure 1 shows the present topography of Iwo-jima. Surface area and length of shoreline of the island are 23.2 km^2 and 24.3 km, respectively. Geologically, the island consists of the following three parts:

(1). Motoyama area which is a broad dome or a truncated strato-volcano situating at the northern half of the island.

(2). Suribachi-yama which is a pyroclastic cone locating at the southern tip of the island.

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(3). Chidoriga-hara area which is a gentle slope locating between Motoyama area and Suribachi-yama, formed by the fill of loose volcanic ashes and fine cinders[1,5].

This island is relatively flat except for Suribachi-yama and most surface is covered by considerably thick vegetation. There are no revers in this island, and a few cliffs eroded seriously by waves are found at northern coast. Judging from these features, it seems unnatural to anticipate that sediments are either produced in the island or transported from elsewhere in the vicinity of the island. Nevertheless, Iwo-jima is surrounded by relatively wide sandy beach except for northern part of the island. Further, the shoreline keeps advancing toward seaward year by year.

One of the remarkable characteristics of Iwo-jima is the continuous upheaval of island. This fact can be substantiated by the existance of numerous treads of marine terraces which are found all over the island. Especially for the past few decades, this island has kept lifting at the rate exceeding 30 cm per year at the northern part although upheaval rate at the southern part is smaller considerably[6,10]. This remarkable upheaval seems to have caused the continuous advancement of shoreline toward seaward.

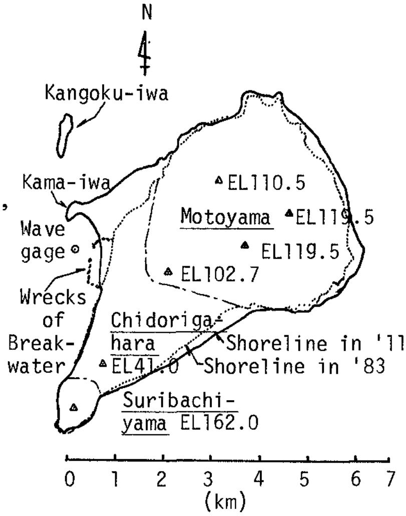


Fig.1. Topography of Iwo-jima.

Advancement of the shoreline has been quite remarkable especially at the west coast of Iwo-jima. Nautical chart published by US Navy in 1945 indicates that a group of rocks named kamaiwa was situated approximately 1 km off the west coast of Iwo-jima and the isthmus between kamaiwa and west coast used to be a navigable channel whose maximum depth was 36 m at that time. This channel got narrower and narrower since 1945, and in June 1968 when the island was returned to Japan, Kamaiwa has finally touched with the tip of west coast to form a huge tombolo there.

This paper intends to clarify the following questions as quantitatively as possible by analyzing maps, charts and aerial photos of Iwo-jima which are available at the present stage and by performing both field surveys and model tests:

(1). Where and how were the abundant sediments produced in this island ?
(2). Why and how was the tombolo formed at the present location ?
(3). Is the present topography of the island stable in future ?

2. Collection of Basic Data

2-1. Collection of data through literature survey

(1). Topographic data of Iwo-jima

To check the variation of both surface and bottom topographies, maps and charts published and photos taken so far of Iwo-jima were all collected. Table 1 summarizes these collected materials.

Table 1. Source of data used for the analysis of topographic features of Iwo-jima.

No	Source of data	Office of publication	Year	Scale
1	Topographic map	Land Survey Dept., Japanese Imperial Army(Iwo To, No.12)	1911	1/50000
2	Chart	Hydrographic Dept., Japanese Imperial Navy (Iwo To, No.220-3003)	1934	1/30000
3	Chart	Hydrographic Office, US Navy (IO JIMA,DMA97BHA97562)	1945	1/20000
4	Map & Chart	US Army (IWO-JIMA,ST632Ⅱ NW)	1952	1/25000
5	Topographic map	Geographical Survey Inst., Japan (Iwo To, NG-54-17-12-3)	1968	1/25000
6	Topographic map	National Research Center for Disaster Prevention,Japan (Volcanic Phenomena of Iwo-jima)	1972	1/10000
7	Chart	Hydrographic Dept., Japan Maritime Safety Agency (Chart of the surrounding Sea of Iwo jima)	1981	1/50000
8	Topographic map	Geographic Survey Inst., Japan (Iwo To, NG-54-17-12-1·3·4)	1982	1/50000
9	Aerial photo	Japan Maritime Self-Defense Force	1983	

Each of these materials was enlarged into the pictures with scale of 1/10000. Positions of the shoreline in each picture was determined at every increment of 5 mm or 5 m in real scale by tracing the shoreline with a device or an A-D convertor which converts the position of tracer into degital figures and punches them on data cards automatically. Depth data was determined in the following way, based on the enlarged pictures of the charts published by US Navy in 1945 and of the one published by the Hydrographic Department of Japan Maritime Safety Agency(JMSA) in 1981;
(a). Provide a common area of 1.4 m in the direction from west to east, be 1 m in the direction from north to south on both enlarged pictures so that the island could by contained in the common area.
(b). Divide the common area into 3500 square subsections each of which has the area of 2 cm by 2 cm.
(c). Determine the depth at each corner of the subsections based on the depth data available in their vicinity.

(2). Meterological data in Iwo-jima

Since 1968, a contigent troop of Japan Maritime Self Defense Force (JMSDF) has stationed in Iwo-jima and has been taking meteorogical data every 3 hour. The data recorded during the period from 1968 to 1977 will be used for the analysis of meteorological features in Iwo-jima.

(3). Upheaval data in Iwo-jima

Kaizuka et al[7] have pointed out in their paper that Iwo-jima is a top portion of a strato-volcano rising roughly 1500 m to 2000 m above the seabed on which foot of volcano is expanding about 40 km in diameter.

Ouyagi and Kumagai[9] made ^{14}C dating test of carbonized wood pieces and corals sampled at various elevation of Iwo-jima and derived the following conclusions:

(a). Geological history of the island might be in the order of 3000 years at most.

(b). Average upheaval rate in the past would be 19 cm per year in Motoyama area and 3 cm per year in Suribachi-yama.

Tsuji et al[10] compared the elevations of several points shown in the topographic map published by US Army in 1952 with the ones of the corresponding points which they got through their levelling performed in 1968. As a result, they found that outer edge of Motoyama area has upheaved roughly 9 m although Suribachi-yama has upheaved less than 2 m for the past 16 years after 1952.

Kosaka et al[8] collected old maps and charts of Iwo-jima published after 1911. They also performed levelling at Iwo-jima four times in the period from 1968 to 1978. By analyzing these data, they found that mean upheaval rate in Motoyama area reached roughly 30 cm per year after 1952 although it was 11 cm per year before 1952.

2-2. Collection of data through field surveys

(1). Wave data at Iwo-jima

Wave data has never been measured in Iwo-jima until lately.

On July 7, 1981, the authors installed a supersonic type wave meter about 450 m off the shoreline of west coast where the depth was roughly 12 m. Figure 2 shows the bottom topography in the vicinity of installation point. Bottom slope around there was roughly 1/40.

A mound made of 5 m steel pile with a diameter of 20 cm was driven 3.5 m in depth into the seabed. The sensor was mounted on the top of the mound and was connected to a pen-oscillograph in an observatory which was built on the shore, through a marine cable whose diameter is 39 mm. This wave meter can record only the fluctuation of water surface at the measuring point. Thus, information of the wave direction can not be obtained from the record. Due to the limitation of recording paper, the recorder was set so that wave data could be recorded for 10 minutes every two hour.

Unfortunately, cable was cut and washed away on August 19, 1981 when

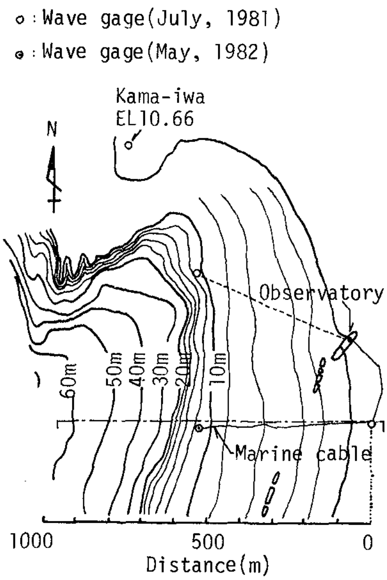


Fig.2. Installation point of wave meter

typhoon #15 hit the island. The record taken just before the incident indicated that the maximum height of the swells was roughly 10 m.

The same wave meter was installed again on May 10, 1982 at the location which is about 500 m south from the former position where the depth is also roughly 12 m(see fig.2). This meter survived for 19 months after the installation alghough it was also washed away on November 7, 1983 while typhoon #17 was hitting the island. For these 19 months, the recorder had kept recording wave data for 10 minutes every 2 hour. These data was processed by the A-D convertor mentioned previously at a sampling interval of 0.5 second and was punched on data cards automatically.

(2). Upheaval data on the backshore of Iwo-jima

Previous works have revealed that upheaval in Iwo-jima is dominant in Motoyama area and that it becomes greater and greater as it goes from the central portion to the shore of the island where the engineers are most interested in. Thus, it was planned to get more reliable upheaval data along the whole backshore of the island. Levelling have been performed three time for 19 months after August 1982, by using 50 measuring stations placed at almost equi-interval on the whole backshore of the island.

(3). Physical properties of sands along the shoreline of Iwo-jima

In order to see if the physical properties of sands around the shoreline will vary both seasonally and regionally, sands were sampled on June 1983 and on February 1984 at 50 locations along the shoreline where the lines each of which contain one of the 50 stations intersect perpendicularly to the shoreline. Both sieve analysis and specific gravity test were performed on all of these sands to determine their physical properties.

3. Analysis of Collected Data

(1). Meteorological features in Iwo-jima

JMSDF made an intensive statistical analysis on the meteorological data recorded in Iwo-jima for the past 10 years after 1968[2]. Through these analyses together with the author's analysis, the following features were revealed on the meteorological characteristics in Iwo-jima:

(i). Temperature in Iwo-jima

(a). Mean monthly temperature is approximately 27°C through summer and fall although it is about 19°C in winter. From spring to summer, temperature rises from 19°C to 27°C almost linearly.
(b). Daily variation of temperature is less than 5°C through the year.

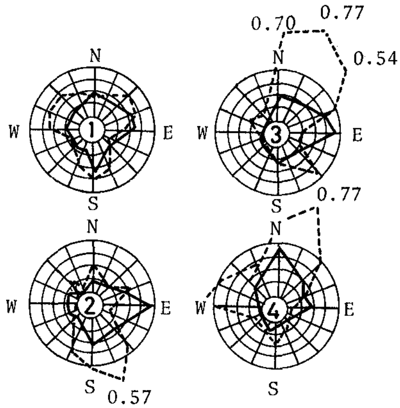
(ii). Rainfall in Iwo-jima

(a). Monthly rainfall exceeds 100 mm during the period from May to December although it is less than 70 mm in the rest of the months.
(b). Rainy days count approximately 145 days per year and yearly rainfall is roughly 1300 mm.

(iii). Winds in Iwo-jima

Figures 3 shows seasonal wind roses in Iwo-jima. In these roses, rigid lines indicate mean frequency of occurrence in each direction

which was determined from whole data of winds, and do the dotted lines the one determined through the data of winds whose velocities are greater than 10 m/s. From these wind roses, the following features were found on the wind characteristics in Iwo-jima:
(a). East winds are dominant in spring, summer and fall although north winds are dominant in winter. After east winds, south winds are dominant in spring and summer.
(b). West winds are quite few through the year.
(c). Only 3.5 % of total winds are the high winds whose velocities exceed 10 m/s.
(d). Dominant direction of high winds ranges from SE to SSE during summer although it ranges from NNW to NE in fall and winter. High winds also blow from the direction ranging from W to N in winter.



No	Season	N
1	Spring	6531
2	Summer	6448
3	Fall	6725
4	Winter	6479

Fig.3. Seasonal wind roses in Iwo-jima.

(iv). Typhoons in Iwo-jima

Figure 4 shows the yearly cumulative number of typhoons generated at the north Pacific after 1945 [3]. In this figure, rigid lines indicates cumulative number of whole typhoons generated at the north Pacific and do the dotted and chain lines the ones which hit Iwo-jima, respectively.

From this figure, the following facts were found on the typhoons in Iwo-jima:
(a). 20 to 40 typhoons are genrated each year at the north Pacific.
(b). At least one fifth of them hit Iwo-jima every year.
(c). Typhoons with central pressure less than 960 mb possibly hit Iwo-jima at least once a year.

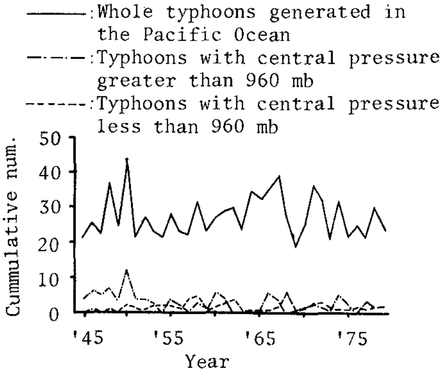


Fig. 4. Typhoon statiscics in the north Pacific and Iwo-jima.

(2). Wave characteristics in Iwo-jima

Each of the 10 minutes records of wave data recorded for 19 months after May, 1982 was processed at a sampling interval of 0.5 second by an A-D convertor to yield 1200 data from it. These processed data were analyzed by means of the zero up crossing method to determine the heights and periods of waves.

Figure 5 shows an example of the analytical results. Huge peak appeared around the righthand edge are the swells which hit Iwo-jima when typhoon #10 with central pressure of 940 mb passed about 350 km off the west coast of Iwo-jima on July 31, 1982.

The maximum height and its significant period of the swells determined from the record taken at 8 AM of July 31 were 9.2 m and 19.0 seconds, respectively.

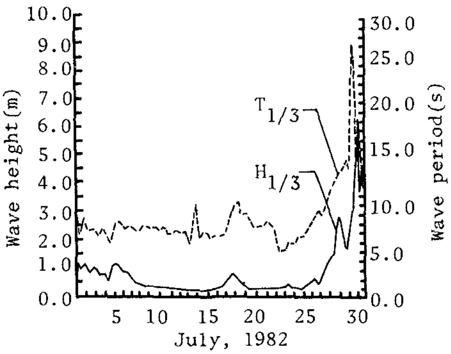


Fig. 5. Variation of significant height and period of waves in July, 1982.

Table 2 summarizes seasonal distribution rate of significant waves whose height and period are in the given ranges of magnitude.

Table 2. Seasonal distribution rate of significant height and period of waves in Iwo-jima.

	$H_{1/3}$(m)				$T_{1/3}$(s)			
	0-1	1-2	2-3	<3	6	6-8	8-10	<10
Spring	62	36	1	1	29	51	16	4
Summer	70	20	4	6	21	42	21	16
Fall	73	14	7	6	8	43	27	22
Winter	59	35	6	0	31	49	16	4

From this table, it can be seen that dominant waves in Iwo-jima are those whose significant heights are less than 1 m and whose significant periods are less than 8 seconds except for the waves appearing in summer and winter.

Table 3. Values of H_{max} and $T_{1/3}$ of the waves recorded while typhoons were hitting Iwo-jima.

No	Date	Time	H_{max}	$T_{1/3}$	Pres.	Location	V_{max}	θ
#4	May 23,'82	0200	8.4 m	18.5 s	980 mb	NNW 150 km	27.5m/s	ENE
#5	Jun 26,'82	1000	5.4 m	11.1 s	975 mb	NW 250 km	32.5m/s	N
#10	Jul 31,'82	0800	9.2 m	19.0 s	940 mb	WNW 350 km	50.0m/s	NNW
#13	Aug 24,'82	2100	Lack of data		940 mb	W 850 km	45.0m/s	NNW
#15	Aug 30,'82	0900	Lack of data		945 mb	W 300 km	45.0m/s	NW
#18	Sep 11,'82	1000	5.3 m	12.0 s	965 mb	WNW 600 km	35.0m/s	NW
#19	Sep 19,'82	0000	5.2 m	8.3 s	940 mb	WSW1400 km	45.0m/s	WNW
#21	Oct 7,'82	1600	9.8 m	11.5 s	920 mb	WSW 600 km	50.0m/s	NNW
#5	Aug 13,'83	0600	9.8 m	13.3 s	915 mb	WSW1040 km	55.5m/s	NNE
#13	Oct 11,'83	1000	1.8 m	8.1 s	980 mb	NNW1050 km	25.3m/s	ENE
#17	Nov 2,'83	0200	Lack of data		985 mb	NNE1030 km	30.0m/s	NNW

Table 3 summarizes the values of the maximum height and the corresponding significant period of waves recorded for 19 months after May, 1982 at the west coast of Iwo-jima while typhoons were hitting the id-land. In this table, location means the direction of and distance to the typhoon measured from the location of wave meter, does V_{max} the maximum velocity of the wind at the center of typhoon, and does θ the advancing direction of thetyphoon.

From this table, it can be noticed that swells whose maximum height is roughly 10 m and whose significant period is greater that 12 seconds will approach to the west coast of Iwo-jima when typhoons whose central pressure is less than 940 mb pass within a circle with semi-diameter of 400 km in which Iwo-jima is situated at its center.

Correlation analysis was performed among the characteristic values of the highest waves of each class. Table 4 summarizes correlation coefficients found among these characteristic values.

Table 4. Correlation coefficients among the characteristic values of waves.

	H_{max}	$H_{1/10}$	$H_{1/3}$	H_{mn}	T_{max}	$T_{1/10}$	$T_{1/3}$	T_{mn}	T_{max}^2	$T_{1/10}^2$	$T_{1/3}^2$	T_{mn}^2
H_{max}	1.00	0.98	0.97	0.95	0.44	0.52	0.54	0.56	0.31	0.48	0.54	0.61
$H_{1/10}$	0.98	1.00	1.00	0.98	0.47	0.55	0.58	0.59	0.33	0.51	0.58	0.64
$H_{1/3}$	0.97	1.00	1.00	0.99	0.46	0.55	0.57	0.59	0.32	0.51	0.58	0.64
H_{mn}	0.95	0.98	0.99	1.00	0.43	0.51	0.53	0.55	0.48	0.49	0.54	0.61

This table indicates that there exists quite high correlation among the wave heights of each class and among the wave periods of each class, respectively although correlation between height and period is quite low.

Table 5 summarizes results of the regression analysis performed among the wave height of the highest waves of each class. In this table, a_I means the regression coefficient determined through the data in Iwo-jima and does R the correlation coefficient, and does a_R the regression coefficient predicted through Rayleigh distribution.

These results clearly indicate that distribution of wave height agree quite satisfactorily with Rayleigh distribution.

Table 5. Results of the regression analysis performed among heights of the maximum waves of each class.

	a_I	R	a_R
$H_{max}/H_{1/10}$	1.21	0.98	---
$H_{max}/H_{1/3}$	1.51	0.97	---
H_{max}/H_{mn}	2.31	0.95	---
$H_{1/10}/H_{1/3}$	1.25	0.97	1.27
$H_{1/10}/H_{mn}$	1.94	0.98	2.03
$H_{1/3}/H_{mn}$	1.55	0.99	1.60

As mentioned previously, no information was obtained from the records of waves on their directions. However, visually observed data is available on the direction of seas and swells.

Figure 6 shows the seasonal distribution of seas and swells in each direction which were determined on the basis of visually observed data by ships at the area in north Pacific in which Iwo-jima is included [4]. In these figures, rigid lines indicate the distribution rate of seas and swells determined through the whole data observed in the period from 1973 to 1979. Comparision of figure 6 with figure 3 clearly indicates that distribution pattern of seas and swells are quite similar to those of the wind roses which were made based on the wind data measured at Iwo-jima.

(3). Physical properties of sands sampled along the shoreline of Iwo-jima

To see whether the physical properties of sands near the shoreline vary regionally and seasonally, sieve analysis and specific gravity test were performed on the sands sampled in June 1983 and in February 1984, respectively at 50 locations along the whole shoreline of Iwo-jima.

Figure 7 shows the distribution of median diameter(D_{50}) and specific gravity (G_s) of sands sampled along the shoreline of four coasts(see figure 9). In this figure, abscissa indicates the distance measured southward along the shoreline on each coast from its northern end.

From these figures, the following features were found on the physical properties of sands along the shoreline of Iwo-jima:

(a). Sands sampled in both N-E and N-W coasts have fairly constant values of D_{50} ranging from 0.3 mm to 0.7 mm through the year.

(b). Sands in both S-E and S-W coasts have larger values of D_{50} through the year in comparision to those in N-E and N-W coasts. Especially, sands sampled at S-W coast in June 1983 have the value of D_{50} which is greater than 5.0 mm.

(c). Sands sampled in June 1983 at each coast have the values of D_{50} which tend to become greater slightly along the shoreline as it goes southward.

(d). Specific gravity of sands is fairly constant through the year ranging from 2.3 to 2.8 except for that of the sands sampled at N-E coast. However, sands sampled in June 1983 at N-E coast have the values of G_s which are greater than 3.0.

(e). Distinct tendency is not found in both reagional and seasonal variation of the value of G_s.

Judging from these findings together with wind

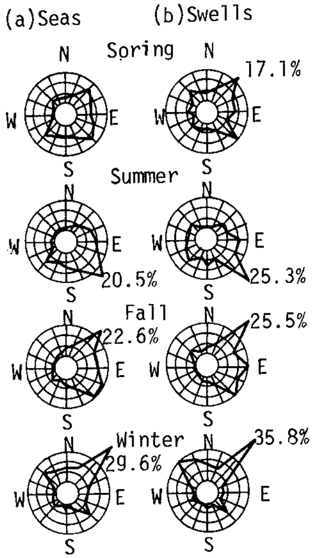


Fig.6. Distribution of seas and swells in north Pacific near Iwo-jima.

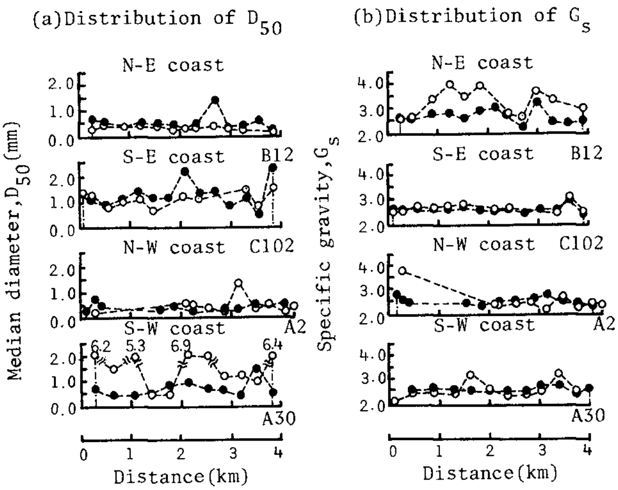


Fig. 7. Variation of median diameter and specific gravity of sands sampled along the shoreline of Iwo-jima.

and wave characteristics in Iwo-jima, it can be anticipated that littoral currents may flow southward in winter but northward in summer along both coasts of the island.

(4). Upheaval phenomena in Iwo-jima

Figure 8(a) shows the iso-upheaval lines in Iwo-jima which were presented by Tsuji et al in 1969. These lines were determined by comparing the elevations of several points shown in the map published by US Army in 1952 with the ones of the corresponding points which were obtained by Tsuji et al through their levelling performed in 1968.

Figure 8(b) on the other hand, shows the mean upheaval rate and cumulative upheaved height of Iwo-jima which were presented by Kosaka et al in 1979. They determined these values by comparing the elevations of several points in Motoyama area shown in older maps and charts published after 1911, and by analyzing their own data of the levelling which they performed four times in the period from 1968 to 1978.

These findings indicate the following facts on the upheaval phenomena in Iwo-jima:

(a). Upheaval rate is not constant over the island but varies remarkably from place to place.

(b). Upheaval rate in Motoyama area is roughly 30 cm per year recently and cumulative upheaved height has reached roughly 12 m since 1945.

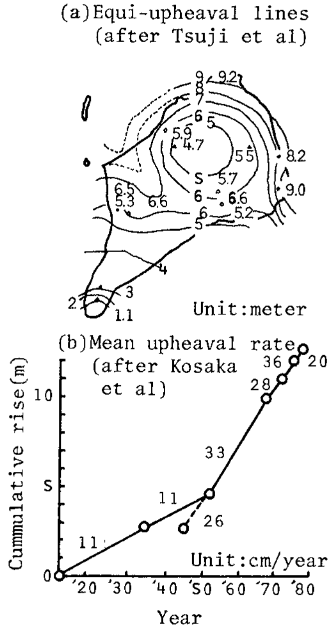


Fig.8. Upheaval phenomena in Iwo-jima.

The authors have also performed levellings on the backshore of Iwo-jima in August 1982, June 1983 and February 1984, respectively by using 50 measuring stations which have been placed along the whole backshore of the island. A bench mark was placed at the foot of Suribachi-yama where upheaval might be smallest in this island.

Figure 9 shows the relative values of upheaval height in each station which were determined on the basis of the elevation of each station measured in August 1982. From this figure, the following facts were revealed:

(a). Stations in N-E coasts had sunk at the rate of roughly 25 cm to 30 cm per year for the first 10 months although they began to upheave at the rate of 30 cm per year after June 1983.

(b). Northern stations in N-W coast began to upheave at a remarkable rate of roughly 1.5 m per year after June 1983 although southern stations near Kamaiwa area sank at the rate of 15 cm per year in the same period.

(c). Stations placed in S-E coast kept upheaving at the rate of roughly 35 cm to 40 cm per year after August 1982.

These findings indicate that Iwo-jima keeps upheaving at present in an order of 30 cm to 40 cm per year as a whole although upheaving does not occur at a constant rate over the island but fluctuates from place not occur at a constant rate over the island but fluctuates from place to place and from time to time.

(5). Variation of the shore in Iwo-jima

Figure 10 shows the shorelines of Iwo-jima in 1911, 1952 and 1983, respectively. It can be clearly seen from this figure that shoreline of the island has kept advancing seaward since 1911. Further, it can be noticed that advancement of shoreline is quite remarkable at the west coast of Iwo-jima.

To see the variation of shore more quantitatively, length of the shoreline and shore area were calculated by using the processed data of the shorelines in each year which was stated previously.

Figure 11 shows the variation of both length of the shoreline and shore area which were the relative values determined by comparing those values with the their corresponding values in 1911.

From this figure, the follwing facts were revealed:

(a). Shoreline in the west coast was elongated continuously until 1972 at mean rate of 60 m per year although it began to be shorten at mean rate of 120m per year after 1972. Shoreline in the east coast, on the other hand has been repeating elongation and shortening since 1911 until present.

(b). Shoreline in the northern tip of the island kept advancing seaward until 1968 at mean rate of 6 m per year although it began to retreat landward at mean rate of 16 m per year after 1968.

(c). Shore area in the west coast kept increasing at mean rate of 3200 m^2 per year until 1972 although it began to decrease at mean rate of 39000 m^2 per year after 1972.

(d). Shore area in the east coast kept decreasing at mean rate of 35000 m^2 per year until 1934 although it has kept increasing at mean rate of 46000 m^2 per year after 1934.

(e). Shore area in northern tip of the island kept increasing until 1968 at mean rate of 5200 m^2 per year although it began to decrease at mean

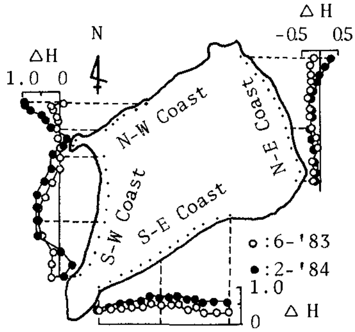


Fig. 9. Upheaval phenomena on the backshore of Iwo-jima.

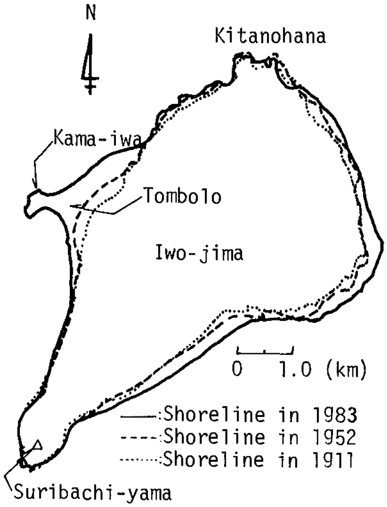


Fig. 9. Upheaval phenomena in the backshore of Iwo-jima.

rate of 18000 m^2 per year after 1968.

(f). Shore area in the whole coast has kept increasing after 1911 until 1968. Increasing was drastic especially after 1952 until 1968. In this period, mean rate of increasing reached 141000 m^2 per year. After 1968 however, shore area in this island has kept almost constant value until present.

Similarly, volmetric variation occurred on the sea floor was also calculated by using depth data in 1945 and 1981, respectively. Here, calculation was made within the zone surrounding the shoreline in 1945 with width of 1 km extended seaward.

Figure 12 shows the result of calculation. In this figure, abscissa indicates the distance measured from the northern edge of the considering area, and do the ordinate either eroded or the deposited volume of the sediments over the subsectional area of 1 km by 200 m in the considering zone.

From this figure, the following facts were revealed:

(a). On the sea floor off the west coast, sediments have been deposited on its most part although sea floor down the southern edge of tombolo has been eroded seriously over the range extending roughly 1.4 km along the shoreline.

(b). On the sea floor off the east coast, sediments have also been deposited on its most part although sea floor has been eroded seriously at the northern part of Suribachi-yama over the range of couple hundred meters along the shoreline.

(c). Total amount of sediments deposited on the sea floor off the west coast is roughly 57.6×10^6 m^3 although the one deposited on the sea floor off the east coast is roughly

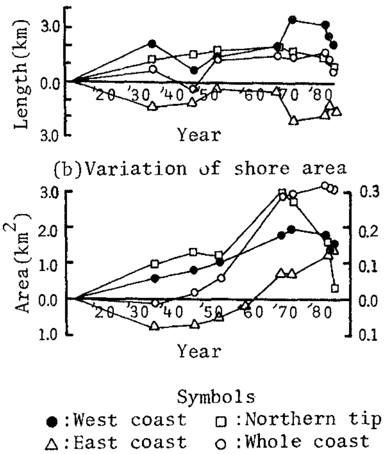


Fig. 11. Variation of shoreline length and shore area in Iwo-jima.

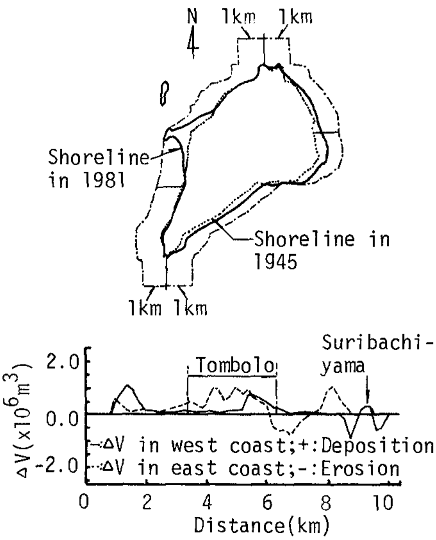


Fig. 12. Volmetric variation of sediments occurred on the sea floor of Iwo-jima.

36.1x10^6 m^3. Further, variation pattern appeared on the sea floor are quite similar in both east and west coasts.

These findings together with the results of the analyses done so far possibly indicate that these huge amount of sediments might be the one produced due to the continuous eroding action of dominant waves excerted on the upheaved sea floor, and that these eroded sediments might have been transported by the wave induced currents to form the present bottom configuration in this island.

To examine the suitability of this assumption, similar analysis was made by assuming that the following four types of upheaval have occurred in Iwo-jima for the past 36 years:

Type 1:Island has upheaved 12 m uniformly.
Type 2:Island has upheaved 10 m uniformly.
Type 3:Island has upheaved with an inclination as shown below:
Upheaved 12 m in the northern edge and 2 m in southern edge of the island.
Type 4:Island has upheaved with an inclination as shown below:
Upheaved 10 m in northern edge and 1 m in southern edge of the island.

Table 6 summarized analytical results.

Table 6. Balance of sediments on the sea floor of Iwo-jima.

	West coast			East coast		
	V_e	V_d	R(%)	V_e	V_d	R(%)
Case 1	39.177	12.416	31.7	29.025	4.470	15.4
Case 2	31.087	14.802	47.6	22.423	7.386	32.9
Case 3	23.254	18.635	80.1	20.104	13.639	67.8
Case 4	15.098	22,547	141.7	14.352	20.127	140.2

Unit of V_e and V_d :x10^6 m^3

In this table, V_e indicates imaginary volume of sediments which was produced by eroding the imaginary sea floor upheaved by adding one of four types of upheaval shown above on the sea floor in 1945 unitl it gets to the sea floor in 1981. Similarly, V_d means the imaginary volume of sediments which was deposited on the imaginary sea floor until it gets to the sea floor in 1981. Further, R is the ratio of V_d to V_e. From this table, the following facts were revealed:

(a). Source of the sediments which contributed to form the present shoreline and sea floor is the one produced by the erosion of upheaved sea floor.

(b). Upheaval assumed in Type 3 might be the most reasonable one which might have occurred in Iwo-jima for the past 36 years after 1945.

4. Formation of Tombolo at the west coast of Iwo-jima

(1). Growth and variation of tombolo at the west coast of Iwo-jima

As stated previously, the channel exsisted between kamaiwa and west coast had got narrower and narrower since 1945 due to the continuous advancement of west coast and was finally closed in 1968 to form there a huge tombolo.

Figure 13 shows the decreasing rate of the channel width and growth rate of shore area at the west coast before the channel was closed and growth rate of tombolo's width at its neck or the narrowest section of tombolo and of the shore area after the channel was closed.

Through this figure, folloing facts were revealed:

(a). After 1945, west coast began to advance seaward drastically at mean rate of roughly 50 m per year until 1968 when kamaiwa was touched by the tip of the west coast. During this period, shore area at the west coast kept increasing at mean rate of 42000 m^2 per year.

(b). After the channel was closed, both tombolo's width at its neck and the area of tombolo kept increasing at mean rate of roughly 20 m and 8200 m^2 per year, respectively until 1978.

(c). After 1978, tombolo has been in almost equilibrium state having the width of 200 m and area of $1.7x10^6$ m^2 although these values have been fluctuating around the respective values stated above.

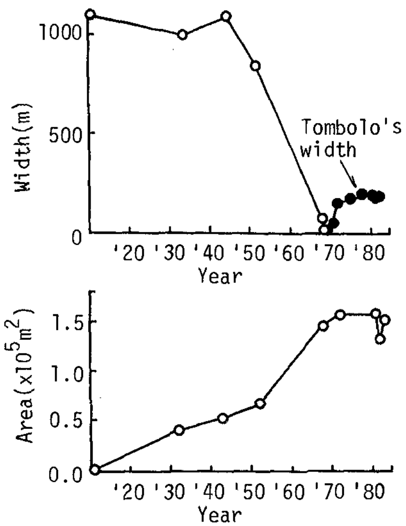


Fig. 13. Growth of the shore at the west coast of Iwo-jima.

(2). Experimental verification of the formation of tombolo

Through the results of analyses done so far, the authors derived the following inferences on the formation of tombolo at the west coast of Iwo-jima:

(a). Dominant waves in Iwo-jima which have the direction ranging from N to NE have produced huge amount of sediments by their continuous eroding action on the sea floor of mainly northern part of the island which had been lifted by the inclined upheaval.

(b). Currents induced by these dominant waves have transported sediments southward along both coasts of the island although the currents induced by huge swells which hit Iwo-jima in summer and early fall have transported sediments northward along both coasts of the island.

(c). Sea floor off the west coast has had the topography which helped form tombolo there.

To verify these inferences, it was decided to perform model tests as follows:

Figure 14 shows the experimental zone and observation area chosen off the west coast of Iwo-jima. Based on the depth data in 1945, model of this zone was built with horizontal scale of 1/1000 and vertical scale of 1/500, by using mortar. This model was placed in a wave tank of 12.5 m long by 4.5 m wide by 1.2 m deep and crushed coals with median diameter of 0.27 mm and specific gravity of 1.72 were lain on its surface in 2 cm thick.

In the observation area of 3.0 m long by 1.75 m wide, a base line was placed for the measurement of various terms. On this base line, 25 measuring stations were provided at every 10 cm interval. Further, a model of breakwater built by US Navy in 1945 was also placed at the corresponding location.

Capacitance type wave gage was installed off the northern end of observation area to measure incident waves. Video camera was also hung down from the ceiling to get continuous records of wave refraction and direction of shore currents.

Because of the difficulty in handling model floor, it was decided to perform experiments only for the limited case when stormy waves are loaded from a direction ranging from N to NE on the shore of the island which is upheaved uniformly at a constant rate per year.

Further, it was decided to perform experiments in accordance with the following procedures:

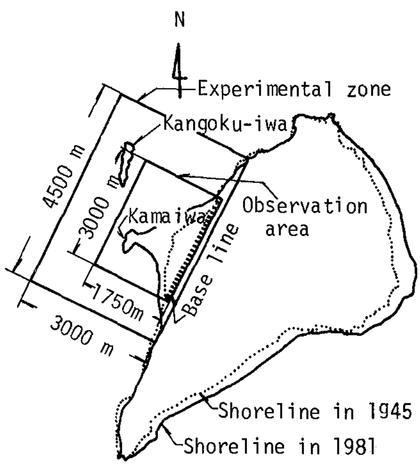


Fig. 14. Experimental zone and observation area chosen for model test.

(a). Crushed coals are supplied at a certain rate manually off the northern end of observation area whenever supplied coals are washed away.
(b). Effect of upheaval is given by lowering water level up to 2 cm in total at a constant rate.
(c). Special dye is injected manually off the northern end of observation area.

Since it is impossible to hold similarity law in such a model test as this, only the wave conditions were determined by referring to Froude law of similarity. The rests of conditions were all determined through the primary runs which were done by changing conditions by trial and error method so that shoreline on the model shore may agree most satisfactorily with the one shown on the chart in 1981.

Here, agreement was evaluated by the values of the standard deviation of shoreline on the model shore from the corresponding one shown on the chart in1981. Standard deviation, ΔS was calculated by using the data measured at every 30 minute along each line which was extended seaward from each station on the base line so that it might be perpendicular to the base line.

Seven different conditions were tried in primary runs. As a result, it was found that shoreline at the northern shore of tombolo could be reproduced quite satisfactorily on the model shore if the test was kept performed for 9 hours successively under the conditions shown in table 7.

Table 7. Test conditions determined through primary runs.

Incident waves			Upheaval rate	Supply rate of crushed coals
Height	Period	Direc		
2.2 cm	0.5 sec	NNE	0.25cm/hr	6000 cm^3/hr

Test was done again under the conditions shown in table 7. Due to the limit of space, variation of shoreline will be described here mainly. Variation of shoreline was measured every 30 minute. Figure 15 shows the shorelines measured at every 90 minute. Tip of the west coast began to advance rapidly when it passed roughly 270 minutes after starting the experiment, and finally reached Kamaiwa one hour later. The tip of west coast advanced along the northern slope of a saddle shaped mound which had originally existed along the sea-bed connecting Kamaiwa and west coast. Exsistence of this saddle resulted in blocking littoral currents there and diverting the course of it into northern tip of Kamaiwa.

As it can be seen from figure 15, shoreline at the northern shore of tombolo has shown quite good agreement with the one in 1981. However, shoreline at the southern shore of tombolo has advanced seaward considerably in comparision to the one in 1981. Further, a sand spit has been formed at the southern lee of Kamaiwa. These might have been formed because waves with the direction of only NNE had been loaded on the model shore.

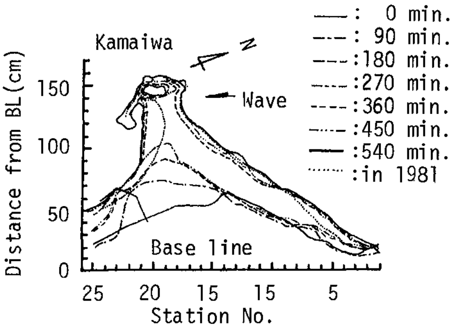


Fig. 15. Variation of shoreline with the lapse of time.

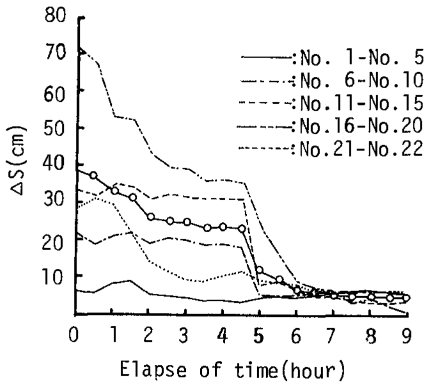


Fig. 16. Variation of ΔS with the lapse of time.

Figure 16 shows the variation of ΔS in the nortern shore of tombolo with the lapse of time. In this figure, line with circles mean the values of ΔS determined on the basis of whole data measured in the observation area, and do the rests of lines, the values of ΔS which were determined on the basis of data measured in each of the 5 subsectional areas which were provided by dividing the observation area at an interval of 500 m to ,see regional variation in the values of ΔS.

From this figure, it can be seen that values of ΔS become small suddenly at every subsectional area if 5 hours have passed after starting the run, and that model shore reaches almost equilibrium state if it has passed 9 hours after starting the run. The values of ΔS in each subsectional area are less than 6 cm at the equilibrium state.

This test also indicates that one hour in the run under the conditions corresponds to 4 years in the field. If this time scale is true, upheaval rate and supply rate of crushed coals in table 7 become 31 cm and 7.5×10^5 m^3 per year, respectively, which are quite resonable values. Further, it should be noted that the test clearly reproduced on the model floor that it took 23 years for the west coast to reach Kamaiwa and that it took 33 years for the west coast to get to an equilibrium state since 1945. These facts clearly indicates that the author's inferences on the formation of tombolo were verified to be mostly true.

5. Conclusion

Growing process of tombolo formed at the west coast of Iwo-jima were investigated by analyzing various data obtained through both literature & field surveys. Inferences for the formation of tombolo derived through the analyses were examined by performing model test, which verified that these inferences were mostly true.

Acknowledgement

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