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Geomorphology of Motobu Peninsula and Islands off, West Central Coast of Okinawa*

Kasuke NISHIMURA, Takashi NAKATA and Noboru CHIDA

Introduction

Studies on raised coral reefs and coastal terraces are efficient to deduce mode of the eustatic sea-level changes and crustal movements in Pleistocene. The area the writers chose for field investigation, *i.e.* the Motobu peninsula and islands off the west central coast of Okinawa, is furnished with such raised coral reefs and terraces at several levels surrounding the mountain blocks composed of Paleozoic rocks. As the area lies in the northern margin of the coral sea (N26°35′ ~ 45′), coral growth in reef formation must have been sensitively controlled by sea-water temperature in the past, besides other controlling factors, namely, salinity, depth *etc.*. Therefore, the raised coral reefs around the study area have been positively formed during only the climatic optimum at high sea-level of Interglacials, hence providing important keys to elucidate the history of eustatic sea-level changes. The height distributions of these raised coral reefs as well as coastal terraces may indicate the tendency of crustal movements of the area.

The Motobu peninsula protrudes westward from the trunk of Okinawa island in its central part (Fig. 1). The eastern side of the peninsula is truncated by the Nago fault, bounding the northwestern coast of the island in the NE-SW direction (Photo 1). This area belongs to the zone of Paleozoic metamorphic and igneous rocks (Koto (1897), Hatae (1955)) and Konishi's Motobu belt (1965). Steep mountains of Paleozoic rocks mainly composed of limestone and slightly metamorphosed rocks, occupy the central part of the peninsula divided into two blocks by the E-W running depression which is filled with thick gravel and sand. Below 200 m above sea-level raised coral reefs and coastal terraces are surrounding the mountain land. The islands off the peninsula, except Yagachi island, have flat-topped surface and are chiefly composed of reef limestones on the cores of Paleozoic rocks. It is clear and noteworthy that these islands are distributed on the marginal area of an insular shelf extended from the Motobu Peninsula (Fig. 2). Abrupt submarine slope stretches in the E-W direction and continues to the northern coast of the peninsula. To the west of Sesoko island, two submarine mounds appear in a row indicating that these two mounds are possibly submerged coral reefs due

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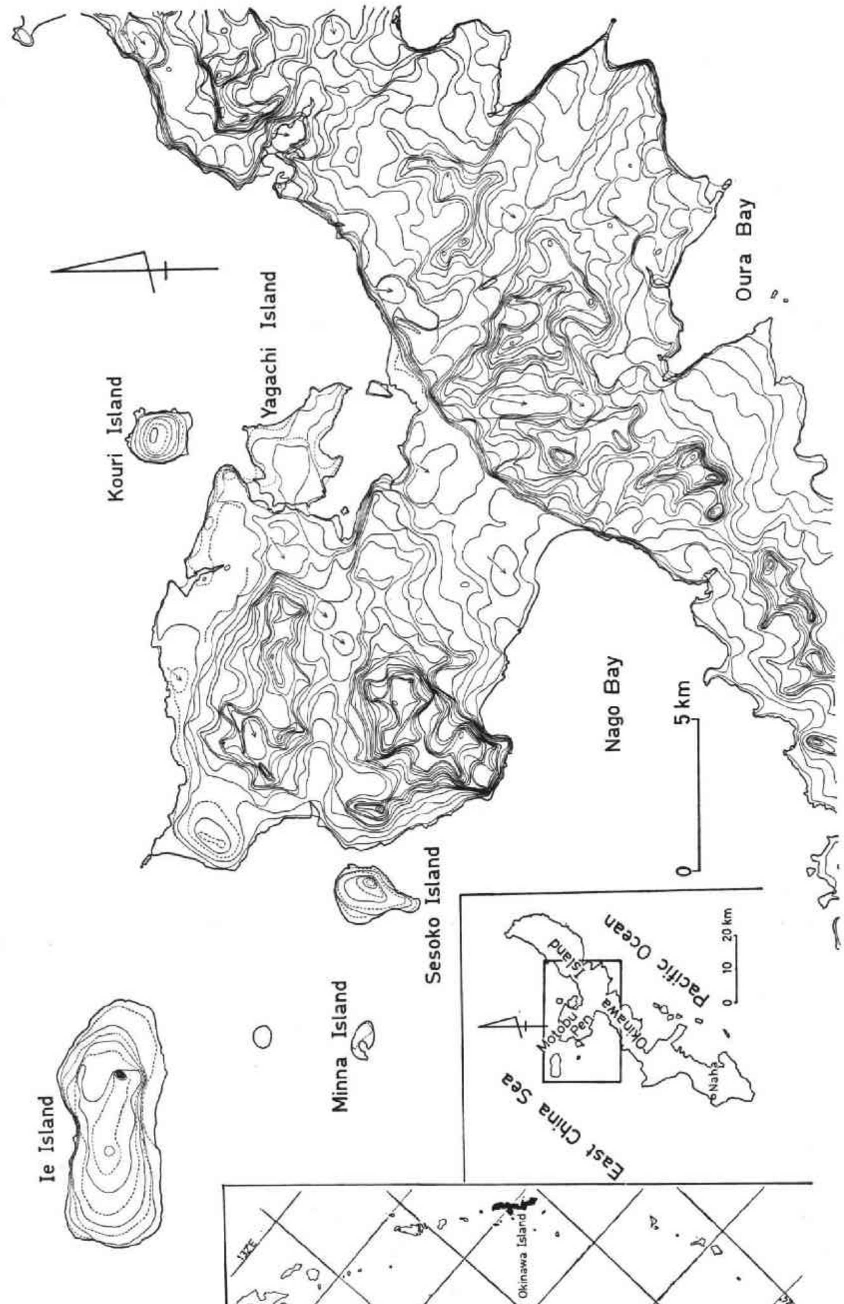

Fig. 1 Restored Map of Northern Central Okinawa eliminating valleys less than 500 m wide (Contour interval: 20 m)

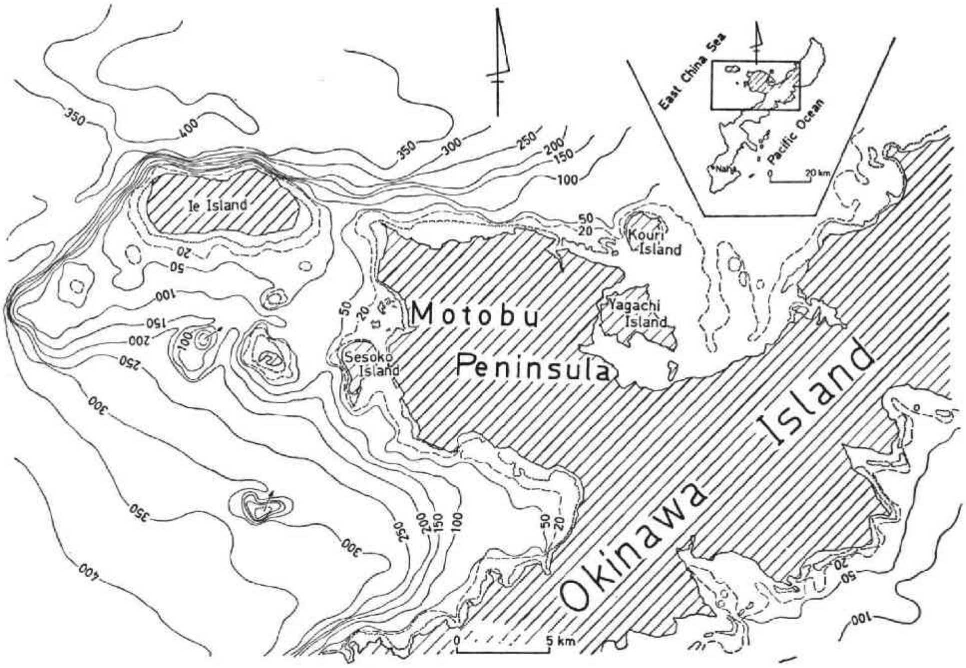

Fig. 2 Submarine topography off the Motobu peninsula (Contour interval: 50 m)

to crustal movement taken place along the southern side of the block. Submarine escarpment to the west of Ie island extending in the NE-SW direction, runs parallel to the Nago fault. The parallelogram block bounded by these tectonic escarpment can be considered a southward tilted block with crest along its northern margin, on which offshore islands and the peninsula are distributed.

First comprehensive work on geology and geomorphology of the Ryukyu islands was done by Hanzawa (1935). He named raised reef limestones overlying his Shimajiri beds Riukiu limestone in general, and gravel and residual soil covering the limestone Kunigami gravel. He also presented a short description on topography of the Ryukyu islands. MacNeil (1960) examined the stratigraphy and paleontology of Cenozoics in Okinawa. He found that the Riukiu limestone of Hanzawa should be subdivided into three limestone beds being grouped as the Ryukyu group. He called them, in ascending order, the Naha, Yontan and Machinato limestones. The former one is of Pliocene and the latter two are of Pleistocene and an erosional unconformity exists between each of them. Kunigami gravel is horizoned as gravel bed contemporaneous intertongued bed with Ryukyu group and residuum of these limestone units (MacNeil 1960). Shoji (1968) carried out stratigraphical and sedimentological studies on "Ryukyu limestone" and reached more or less the same conclusion as MacNeil (1960). Shoji (1968) illustrated the relationship among the three limestones of MacNeil (1960) renamed according to Japanese pronunciation*. Geomorphological works on raised coral reefs of Okinawa are quite few. Hori (1967) studied topography of the Kacchin Peninsula in southwest Okinawa. Wako (1969) made a brief description on the topography around estuaries in the northeastern part of the Motobu Peninsula. Uehara and Yaga** observed the topography of Kouri island and confirmed that the island is an raised coral reef built upon the Paleozoic rocks exposed along the northern coast. Takenaga made studies on geomorphology of coral islands of Japan, extensively and in detail (1965, 1968a, 1968b, 1973 *etc.*). He had carried on the investigation on raised coral reefs of the Motobu Peninsula and the islands off, upto his sudden demise. Parts of his field notes are published in his book (1973). Outside Okinawa, Hirata (1967, 1968, etc.) revealed the distribution of raised coral reefs at several levels in Takara island, Okierabu island *etc.* Nakagawa (1967, 1969a, 1969b) extensively studied raised coral reefs of the islands in the northern Ryukyu islands. He correlated the reef limestones to those of Okinawa (1969b).

Since there are no apparent definite indications for classification of the Pleistocene raised reef limestone, the present writers believe that the classification should be done by careful observation on surface configurations which have been formed as the results from the sea-level oscillation in the past. The present writers consider rather wider distribution of Yomitan and Makiminato limestones in the study area than the previous workers.

Geomorphic classification

Along the northern to western coasts of the Motobu peninsula are coastal terraces distributed at several levels below 210 m. A typical crossprofile of the study area taken from Yonamine coast toward the mountain blocks in the N-S direction (Fig. 4-S), is representing geomorphological profiles around the Motobu peninsula. The highest terrace surface is between 80 m and 210 m below mountain land composed of Paleozoic metamorphic rocks. It is raised marine abrasion surface with veneer of weathered boulder and gravel of Paleozoic rocks, but in places, the surface consists of valley-fill deposits over 30 m thick. This surface is terraced into three steps being separated by escarpments which extend parallel to each other and to the coastal line as well as the transverse fault lines*** in the

* MacNeil's Yontan and Machinato are renamed Yomitan and Makiminato respectively.

** Personal communication (1973).

*** Along these faults, high erosional surfaces in the trunk of Okinawa are dislocated at several places (Flint *et al.* 1959, Hanai 1961).

trunk of Okinawa. Therefore, it is possible, though not certain, to attribute these escarpments to activities along these faults. Dissection of the terrace surface extends considerably, though modified flat surface still remains extensively. The present writers generically name this stepped surface, Surface I.

The highest coral reef limestone is encountered in a shape of mounds resting on reddishly weathered gravel and sand bed at 42 m above sea-level. The limestone has rubbly facies, composed of corals, foraminifera and algae, and is positively correlated to Yomitan limestone (MacNeil 1960, Shoji 1968) from their facies, composition and altitudes of occurrence*. Gravel and sand bed below this reef limestone continues inlandward upto 60 m above sea-level and forms dissected depositional surfaces just below the higher terrace cliff. Since solution of reef limestone on their thinner part has resulted in rough undulation of the surface, original shape of the surface can be restored only as summit level surface. The gravel and sand bed is highly weathered and reddish in color (10R4/8). This bed is considered to have been accumulated during transgression, when optimum coral reef fringed the area. The writers will call the surface composed of these remnants, Surface II.

Similar combination is observed on the structure of the lower surface. Northeast of Yonamine, a low, narrow, elongated hill built up with coral, foraminifera, algae limestone extends in the E-W direction for over 500 m long at the altitudes of 16 m to 27 m. This reef limestone can be clearly distinguished from the Naha limestone with its lithological facies. The reef limestone that exhibit pseudo-bareer reef shape with slightly undulated wide depression behind, is resting on gravel and sand bed intertonguing calcareous part, which is obviously younger and is overlying the sand and gravel bed of the higher surface. The younger sand and gravel bed is less reddish in color (7.5YR4/8). Therefore, it is adequate to consider that reef building took place during a high sea-level of another transgression following to the regression after the formation of Surface II. Considering from topographical appearance and stratigraphical succession, the elongated hill is constructive topography, though it may have been modified by later erosion and solution, rather than differential erosional form due to secondary cementation of older deposits (Flint *et al.* 1953). Depositional surface of sand and gravel and erosional surface cut into the reddish sand and gravel of Surface II, are distributed inlandward which have formed as heterogeneous surface at the high sea-level of the elongated reef limestone hill. The surface formed at this younger transgression

* Wide distribution of the Naha limestone is mapped along the northern coast of the peninsula in geological map prepared by Flint *et al.* (1959) and Shoji (1968). The present writers consider that parts of the limestone belong to the Yomitan and Makiminato ages judging from its lithological facies and geomorphological position.

are summarized as Surface III.

Intermediate levels of erosional surfaces below Surface III are encountered as small patches. They may be products at stands during the dropping of sea-level from the level of Surface III. These small surfaces are treated as Surface III-IV.

Postglacial high sea-level is not clearly recognized in this section. No recent raised coral reefs have been found. Only alluvial lowland along streams and coasts including beach ridge and coastal dune is identified as Recent surface, hence grouped as Surface IV.

The mode of surfaces' occurrence on the offshore islands is quite different from on the coastal zone of the peninsula, since coral reef formation is far much better conditioned around the former than the latter.

Fig. 4-F displays a typical cross section of the southern coast of Ie island. The wide flat surface which is believed to be composed of the Yomitan limestone (Flint *et al.* 1959, MacNeil 1960) occupies the central part of the island ranging 50 m–75 m in alititude (Photo 2). This surface is correlated to Surface II and is considered to have been built during the longest and highest Pleistocene sea-level, which is dated to the Yarmouth (Mindel-Riss) Interglacial (Flint *et al.* 1959). Narrow step of 35 m to 45 m in elevation and less than 200 m in width flanks the main surface. The surface of narrow step has marginal rampart (Photo 3). It positively indicates another stand of high sea-level which is correlated to the high sea-level stand of Surface III on the peninsula. On the seacliff along the northern coast of the island outcrops the Makiminato limestone overlying the Yomitan limestone (Photo 4).

Intermediate obscure steps are encountered further below. They are erosional in origin and are the counterparts of Surface III-IV.

Thus, three high sea-levels in the past are confirmed. Landforms originated during a high stand of Pleistocene sea-level are not always homogeneous. Therefore, it is important to examine the nature of geomorphic surface in the process of identification of high sea-level.

Regional developments of geomorphic surfaces

The distribution of geomorphic surfaces is illustrated in Fig. 3. Special attentions are paid in distinguishing the surfaces according to their origin as well as to their level. Level of the surface is mainly correlated by continuation and height distribution. Among the surfaces on the offshore islands and coastal area, their systematic occurrence is an important key for correlation.

Surface I is distributed from 60 m to 210 m in elevation and is either depositional surface of gravel member of the Naha limestone or contemporaneous ero-

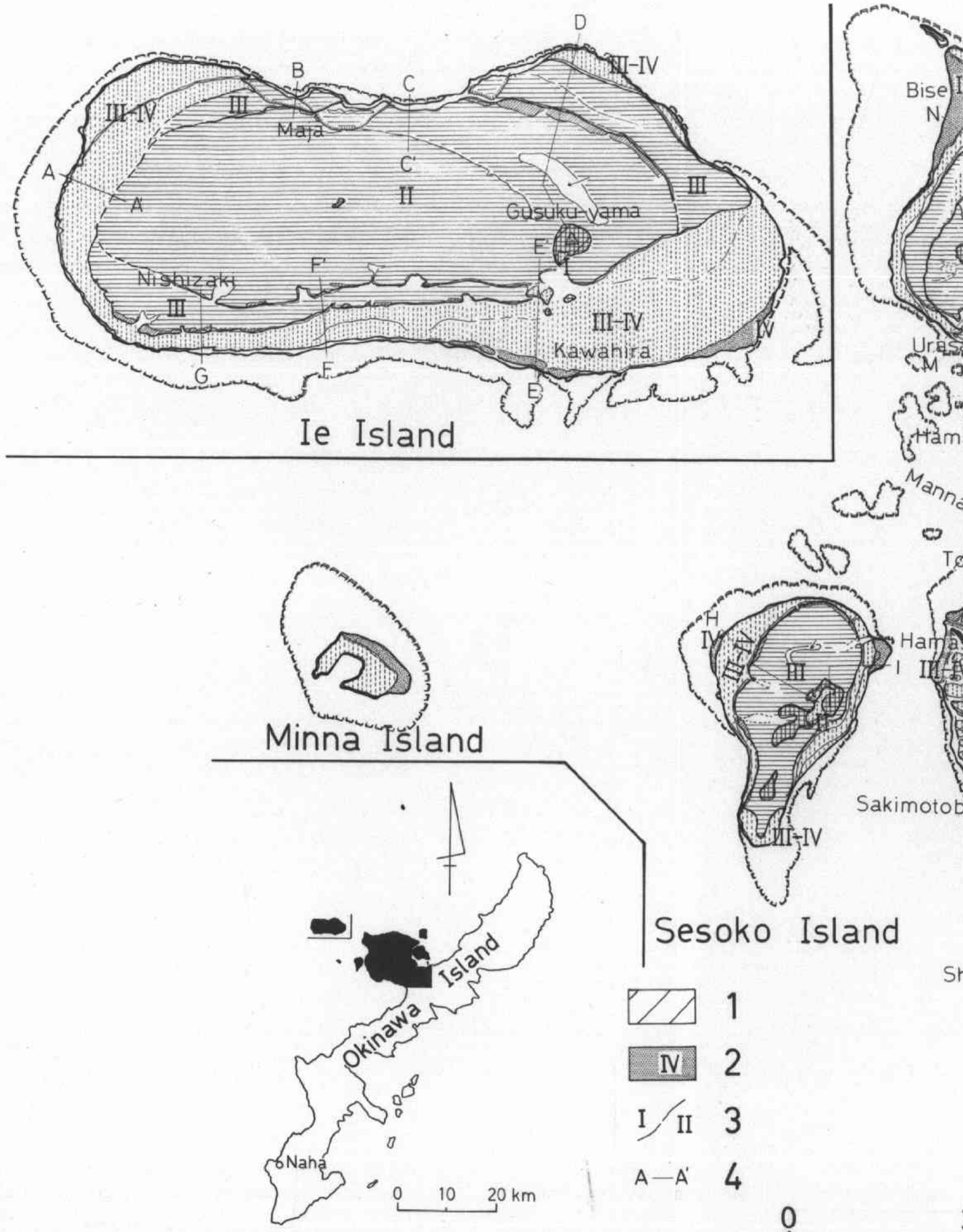

Fig. 3 Surface classification according to level with boundary 1: Mountain land 2: Alluvial lowland 3: Extent of surfaces 4: Location of section

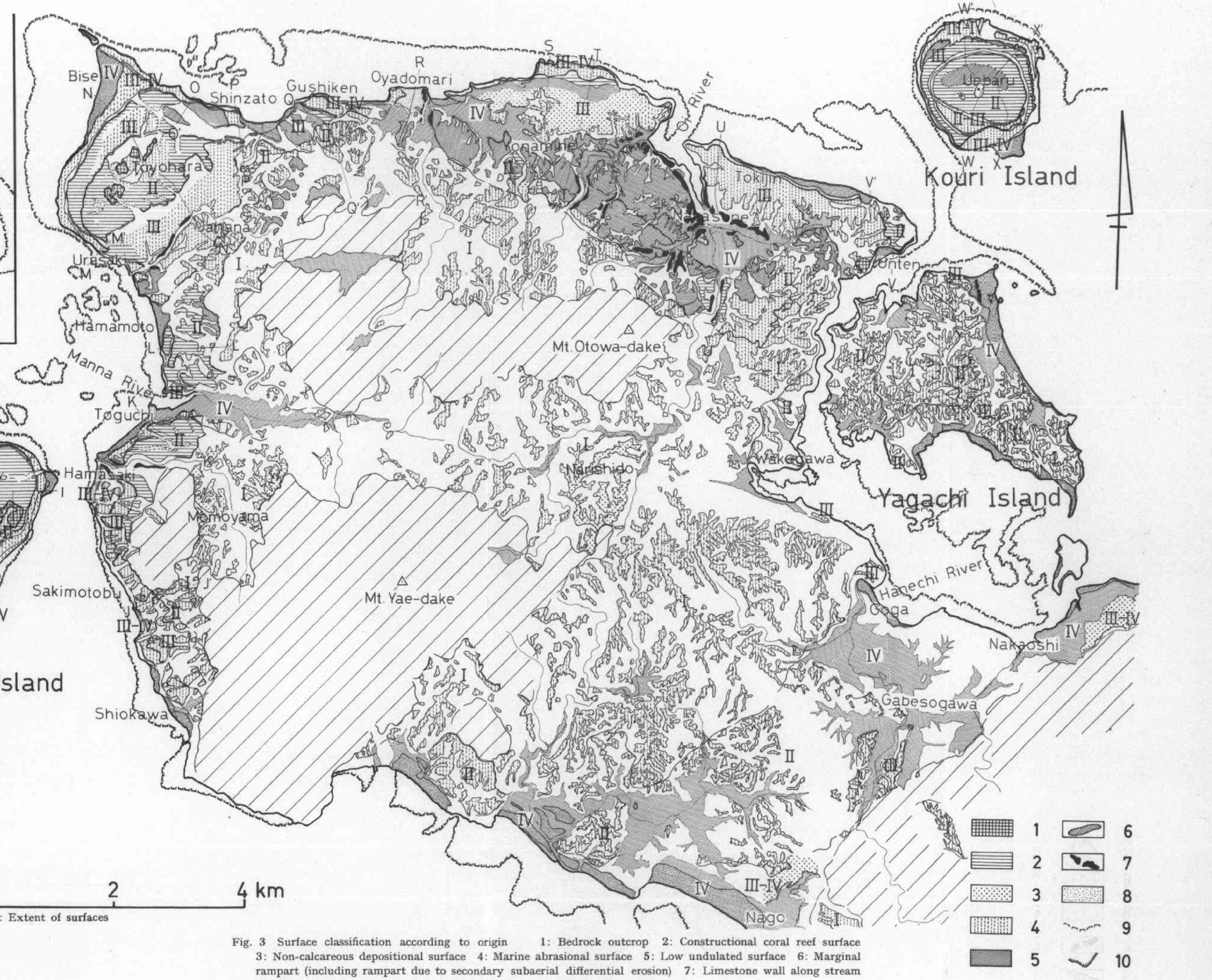

Fig. 3 Surface classification according to origin 1: Bedrock outcrop 2: Constructional coral reef surface 3: Non-calcareous depositional surface 4: Marine abrasional surface 5: Low undulated surface 6: Marginal rampart (including rampart due to secondary subaerial differential erosion) 7: Limestone wall along stream 8: Recent coastal dune and beach ridge 9: Present reef 10: Slip escarpment

Fig. 4 Cross-section of the geomorphic surfaces
Location of section is shown in Fig. 3. 1: Makiminato limestone 2: Yomitan limestone 3: Naha limestone 4: Paleozoic rock 5: Presumed fault 6: Slip

sional surface. In general, surface of thick valley-fills is preserved in the former basin areas surrounded by mountain blocks like the areas around Momoyama (Photo 5) and Narishido. Erosional surface is distributed around the mountain blocks. The surface is preserved better to the east because of escape from later marine abrasion, and its elevation decreases eastward. It is tectonically displaced by several faults running parallel either to the NE-SW directed longitudinal fault of Nago or the NW-SE and E-W directed transverse faults in the trunk of Okinawa. No reef building surfaces are encountered in the area.

Surface II is widely distributed in the offshore island and along the west to north coast of the peninsula. Some groups of surfaces of this class are different in origin mainly due to environmental control. The surface ranges 40 m to 80 m in height, with the exception of extraordinarily high altitude upto 107 m at the top surface of Kouri island (Photo 6). As described before, the surfaces of this class on two islands Ie and Kouri are constructional coral reef of the Yomitan age. The surface on Ie island is extremely well preserved* due to no dissection by subaerial streams (Photo 7). Constitution of the reef limestone is clearly observed along the northern coast around Maja (Fig. 4-C), where coral reef limestone rests on sand and gravel bed embedding a coral bearing calcareous bed (Photo 8), which in turn unconformably lies on the Paleozoic rocks indicating ascending sea-water temperature at the transgression of the Yomitan age. In Kouri island, crescent-shaped rampart with convex side outward, which is presumably algal mound, fringes the northern margin of the surface, and thick Naha limestone underlies the constructional reef limestone of the Yomitan age, covering the core of Paleozoic rocks (Fig. 4-W, X). Similar topography occurs around Toyohara, northwest corner of the Motobu peninsula. The previous workers (Flint *et al.* 1959, MacNeil 1960, Shoji 1968) regarded the coral-rich reef limestone forming the surface to the Naha age. The present writers found the coral-rich reef limestone of the Yomitan age overlying the Naha limestone (Fig. 4-N). Thick Yomitan limestone is quarried to the east of Kamimotobu junior high school and its top surface is erosional one of Surface III by later marine abrasion (Fig. 4-P) (Photo 9). The Paleozoic rock appears at high altitude and coral reef limestone is thinly covering the bed rock around Hamasaki (Fig. 4-L). Along the northern coast, Surface II occurs as raised abrasion platform on bed rock or depositional surface of weathered gravel and sand bed in places. However, possibility of removal of reef limestone by later solution or erosion from the surface still remains. The summit level of highly dissected hills on the east Yagachi island and in the Nago isthmus may be erosional in origin at the Yomitan age.

* The surface measures 2 km in width and 7 km in length.

Surface III consists of various land features of different origin, such as constructional coral reef surface, marine abrasional surface, depositional surface of sand and gravel, or limestone wall along stream. They are distributed between 20 m to 45 m in altitudes, and as narrow strip of terrace fringing Surface II in general.

The most prominent constructional coral reef surface of this class is encountered as the main surface of Sesoko island (Fig. 4-H, I) (Photo 10). The surface ranges 35 m to 45 m in altitude. The constructional coral reef limestone* is about 10 m thick unconformably overlying the Naha limestone. Outward development of coral reef from the Paleozoic mounds** is vividly registered on the surface configuration, *i.e.* marginal rampart with crescent-shaped trough probably originated from shallow lagoon nearly parallel to the rampart of pseudo-barrier reef. Constructional coral reef surface with erosional surface behind fringes around the higher surfaces on Ie and Kouri island (Fig. 4-F, G, W, X). In contrast, along the coast opposite Sesoko island, erosional surface cut into Paleozoic rock is found as the counterpart of the Surface III. The reef building must have been worse conditioned here than at the offshore islands, due to the shadow effect of the island besides other terrestrial disturbances. However, valley-fill deposit is found in an old dissected valley below the erosional surface (Fig. 4-J) (Photo 11), which supports another transgression after that of Surface II with flourish coral reef building. The Surface III between Bise and Toyohara is composed of constructional coral reef surface and erosional surface of Paleozoic rock behind (Fig. 4-N). Erosional surfaces were also cut into the Naha limestone and the Yomitan Limestone (Fig. 4-N, P) in places. A typical erosional surface cut into the Naha limestone is exhibited around Tokijin (Fig. 4-U). Clear geomorphological contrast between the erosional surface and the constructional coral reef surface exists to the north of Yonamine (Fig. 4-S, T). The limestone walls (Flint *et al.* 1953, Wako 1968) are noticeable along the Oi river which do not continue upto the constructional surface (Photo 6). The width of tidal flat in front of the surfaces of this class covered with coral may represent the earlier abrasional retreat of coast. If so, it differs with the difference in origin and composing material of the surfaces in this area. Small erosional terrace surfaces belonging to Surface III are scattered on the eastern part of Yagachi island and in the isthmus of Nago.

Surface III-IV, intermediate surface, appears only as scattered small patches along the coastline. No additional deposits of constructive sense are found thereon. This type is rather widely distributed on Ie island (Fig. 4-A, E).

* It should be correlated to the Makiminato limestone.

** Paleozoic bed rock rises as two isolated mounds on the main surface. Erosional surface of Surface II is cut into the northern mound.

Surface IV, alluvial surface, is not widely in this area. Beach ridge and back marsh combination around Nago, and alluvial lowland around Gabesogawa (Photo 1) and around Nakasone are the major sample.

Conclusion

Variety in geomorphological surfaces formed at higher sea-level stand in the past is clarified in this coral sea area. During the longest and highest sea-level stand in Pleistocene, the Surface II age, the variety is not so prominent, as favourable conditions for coral reef building were prevailing, and constructional reef limestone surface, though it may be modified by later erosion and solution, was formed widely along the coast of the peninsula as well as around the offshore island, except in the area with extremely unfavourable condition, *i.e.* in the narrow belt fringing the foot of the higher surfaces where terrestrial disturbances were severe and in the bay area around Yagachi island and Nago isthmus where mud content, salinity, wave action *etc.* are considered as negative factors.

During the high sea-level stand of Surface III age, the coral reef formation did not seem to be so favourably conditioned as the preceeding one. Its scale depends upon the duration of high sea-level stand as well as other controlling factors. Therefore, to detect definite reason for lesser development of coral reef is rather difficult and it may be adequate to consider the combination of the two mentioned above. In general, constructional coral reef formation was more active at the offshore islands, while non-calcareous terrace formation was prevailing along the peninsula coast.

Fragmental distribution of Surface III-IV may indicate unstable sea-level stand during the descending from Surface III level.

Postglacial transgression filled up estuaries forming wide lowland. Beach ridge and back marsh are also constructed at that last transgression. Recent raised coral reefs of Daly level are not encountered in this area.

Correlation of the Surfaces is important to set up geomorphic history of this area. Flint *et al.* (1959) suggested that the Yomitan limestone was deposited at the highest and longest sea-level stand in Pleistocene which may be correlated to the Yarmouth (Mindel-Riss) Interglacial. MacNeil (1960) and Shoji (1968) recognized erosional unconformity between the Yomitan and the overlying Makiminato limestone. According to the present writers' observation, the constructional coral reef surface of Surface II is correlated to the depositional surface of the Yomitan limestone. It can be deduced by the depositional sequence of surfaces that various types of surfaces belonging to Surface III are contemporary with a depositional phase or another transgression following the regression after the Surface II level. Therefore, the main geomorphic surfaces in the study area, *i.e.* Surface II and Surface III are surely the products during the interglacial high stands of sea-level with high sea-water temperature, which are positively correlated to the Mindel-Riss and Riss-Würm Interglacials.

The highest terrace surface, *i.e.* Surface I, is believed to have been formed at the sea-level when the Naha limestone was deposited in Pliocene.

Alluvial lowland is filled up with deposits showing alternative effects of land and sea on their sedimentary cycle (Wako 1968), following sea-level change of Postglacial transgression.

Thus fluctuation of sea-level mainly due to glacial eustasy played important role in the history of geomorphic development in the area. However, local variation of surface elevation clearly reflects the effects of crustal movement through the history.

Flint *et al.* (1959), MacNeil (1960) and Hanai (1961) suggested that several transverse and longitudinal faults dislocated the surface of the Naha limestone age, *i.e.* the present writers' Surface I, in the mainland of Okinawa as well as the Motobu peninsula. The location of these faults is represented in Fig. 5. Along these faults dip-slip movement is prominent and recent strike-slip is obscure, though large scale horizontal displacement is recorded in older rocks (Flint *et al.* 1959). The Toguchi-Wakugawa fault in the E-W direction between the Yae-dake and Otawa-dake Mountain Blocks brought the relief contrast of about 150 m* after the formation of Surface I. The upthrown block to the south is passed across by two faults in the NE-SW direction and is tilting toward the Nago faults, the most conspicuous geomorphic discontinuity in Okinawa. Though Flint *et al.* (1959) have a negative opinion on younger activities along the Toguchi-Wakugawa fault in its western part, there is a tendency that the lower surfaces *i.e.* Surface II and III attain higher altitudes to the south of the fault around Toguchi, suggesting the possibility of younger movement. Surface I is also dislocated in steps by three parallel running faults in the WNW-ESE direction in the northern coast of the peninsula. Steep submarine slope off the coast is presumed to be of fault origin in the same direction. Transverse faults in the same direction are abundant in the trunk of Okinawa and the faulted blocks usually tilt southward. This tendency of tilting southward together with tilting toward the Nago fault may be reflected in the distribution of raised coral reef on the peninsula and islands off. Owing to the latter tendency appearance of raised coral reef is limited only to the west of the Nago fault in northern Okinawa. The distribution of thick gravel and sand bed is closely controlled by the older block movement before tha Naha

* Since denudation modified more heavily the down-thrown block composed of gravel and sand bed, relief contrast may have been augmented.

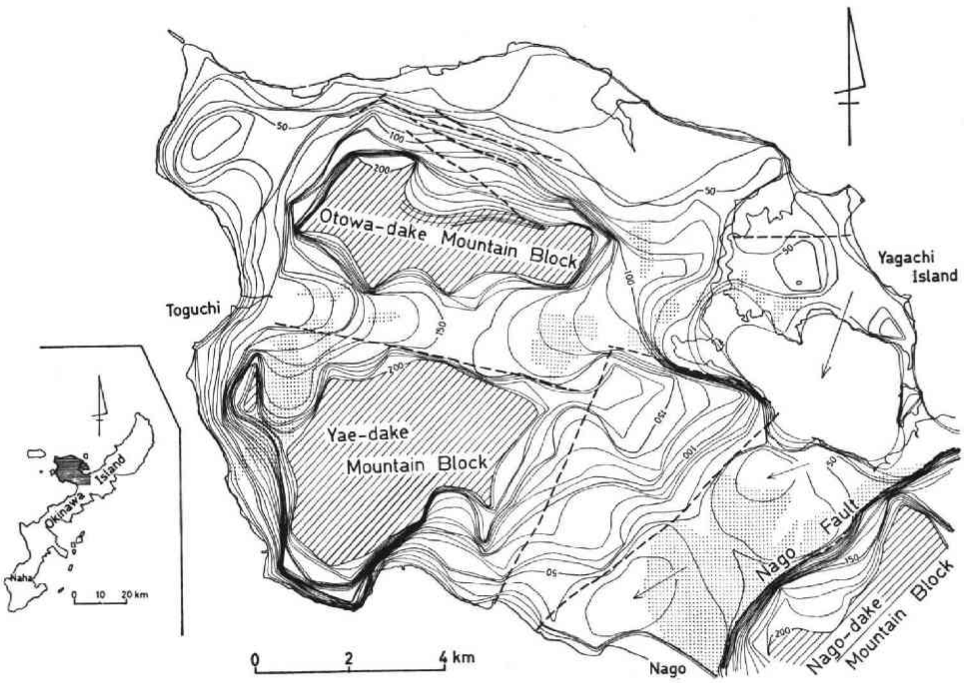

Fig. 5 Distribution of geomorphological faults
Broken lines: Geomorphological fault Oblique lines: Mountain block consisting of Paleozoic bedrock Dots: Gravel member of the Naha limestone (after Flint *et al.* 1959) Contour interval: 10 m

limestone age (Fig. 5).

Recent crustal movements are not clearly known from the deformation of younger surfaces, as they are considerably modified by later subaerial denudation. However, Surface II and III have rather higher altitudes at the northwestern part of the peninsula. Except Kouri island*, Surface II has the highest elevation on the Ie island and generally reduces its elevation toward the east and south**. The height distribution of Surface III has similar tendency. The constructional raised coral reefs are wider at more uplifting area. Therefore, it is considered that the longer stand of high sea-level has been manifested with the superimposition of eustatic sea-level change and uplifting crustal movements at such a area***.

* Altitudes of the surfaces are extremely high and local crustal movement may be responsible for it.

** This tendency is disturbed around Toguchi along the Toguchi-Wakugawa fault as described above.

*** The longer stand of high sea-level was realized at the area where continuous uplifting and transgression near its maximum were combined, and it resulted in the formation of wider constructional surface in coral sea.

The same tendency of crustal movements have taken place during the lower surface formation and geomorphological variety formed at the same sea-level is attributed in part to the crustal movements of the area.

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(* in Japanese ** in Japanese with English abstract)

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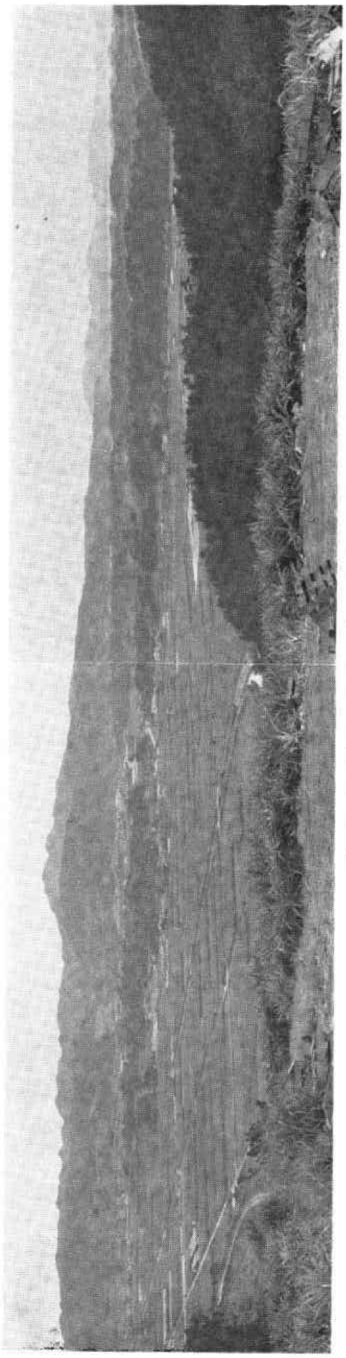

Photo 1 Nago fault viewed from the west

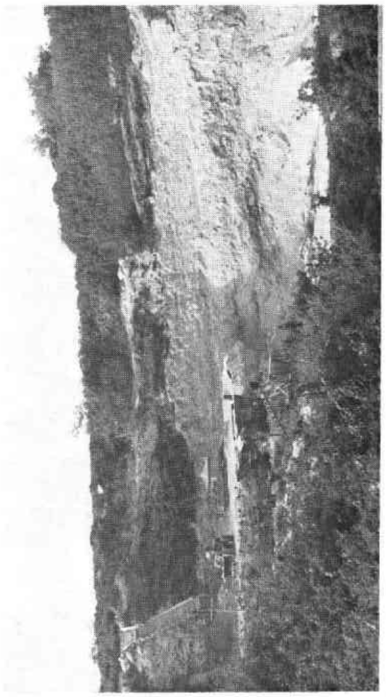

Photo 2 Quarry excavated in the Yomitan limestone in Ie island

Photo 3 Surface sequences in the southern part of Ie island
II: Surface II, III: Surface III, III-IV: Surface III-IV Notice the marginal rampart on Surface III.

Photo 4 Outcrop of the Makiminato limestone overlying the Yomitan limestone on the northeastern coast of Ie island
M.Ls.: Makiminato limestone, Y.Ls.: Yomitan limestone, P.Ls.: Paleozoic limestone

Photo 5 Depositional surface of Surface I around Momoyama seen from the north

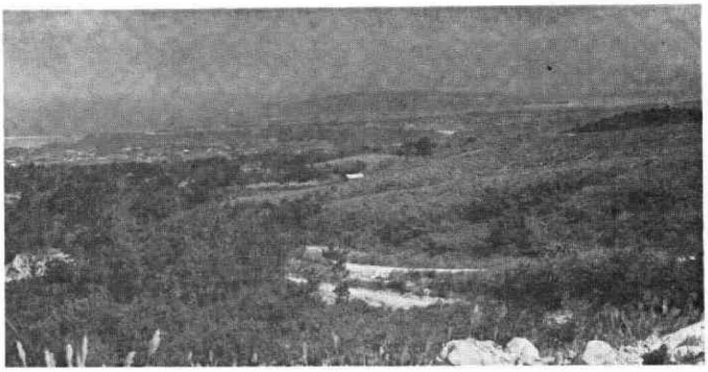

Photo 6 Raised coral reef and terraces in the northeastern coast of the Motobu peninsula and Kouri island

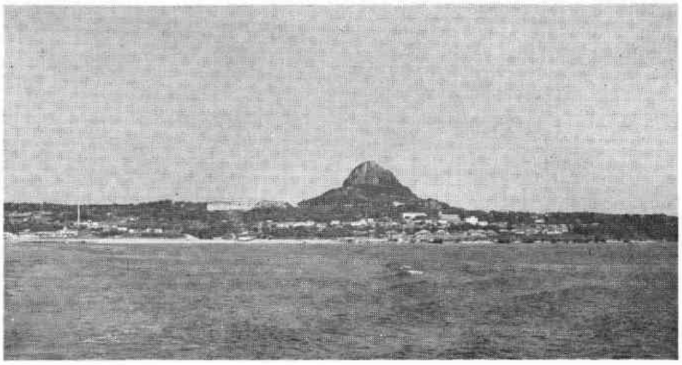

Photo 7 East central part of Ie island viewed from the south

Photo 8 Gravel bed below the Yomitan limestone on the northern coast of Ie island

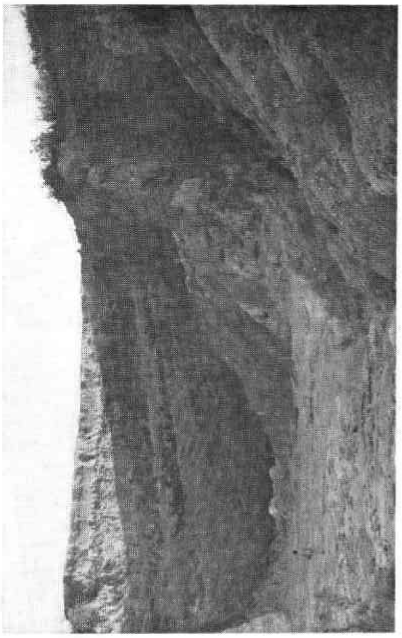

Photo 9 Quarry in the Yomitan limestone near Kamimotobu Junior High School

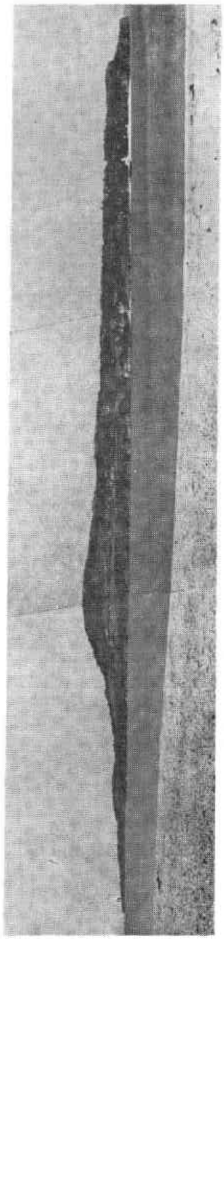

Photo 10 General view of Sesoko island from the east Wide flat topped surface belongs to Surface III.

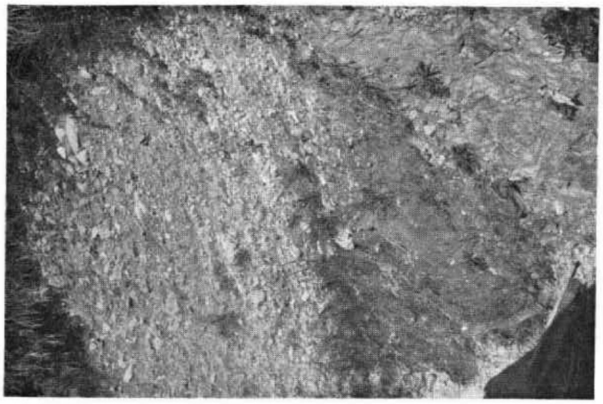

Photo 11 Valley-fill deposits of Surface III at Sakimotobu