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# Origin of Unconformities and Depositional Processes of the Pleistocene Carbonate Rocks in the Humid Subtropical Conditions, the Ryukyu Group on Southern Okinawa Island, Southern Japan

By

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*with 21 Text-figures and 55 plates*

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ABSTRACT: Unconformable boundaries of carbonate rocks were studied with the petrographic aspects in the Ryukyu Group mainly in southern Okinawa Island, southern Japan. There had been many studies about features of unconformable boundaries exposed in arid to sub-humid climate, because the active evaporation forms characteristic secondary calcite known as calcretes. However, exposure features under the humid conditions have been little studied like those found in the Ryukyu Group. In this study, the author reports some examples of the unconformities in the humid and subtropical Ryukyu Group, which is expected to have been affected by cyclic sea-level change and exposure events during the Pleistocene gracial-intergracial periods. Recognition of the unconformable horizons is important for understanding of the depositional processes and history.

To clear the diagnostic features of unconformities, recent exposure surfaces were studied first. In inland places, unconsolidated reddish brown soil of several tens cm covers the rock surfaces. The bedrocks are often pedogenically brecciated. We can observe characteristic features of karstic topography in southern Okinawa Island, which are ramparts developed at fault scarps, and karstic planation surfaces developed at foot of the ramparts. These plane surfaces are probably responsible for the high permeability of the young limestone which has many initial and secondary voids. This feature leads to diffuse way of flowing groundwater, causing relatively uniform dissolution on the ground. The plane nature of the karstic surfaces is highly suggestive for the fact that unconformable boundaries in the Ryukyu Group could be flat. It is in contrast to the Palaeozoic limestones of the Motobu Peninsular, having low stratal permeability, which leads to represent complicated karstic surfaces like cockpit karst.

On the contrary, in coastal areas, bedrocks lack the mantling of soil layers, and have jagged surfaces related to formation of phytokarst. In intertidal to subtidal zones, endolithic organisms like sipunculids actively bore into the bedrocks, changing it to be micritic, poorly sorted materials. In supratidal zone, plants can live utilising fractures and pores. The fractures are usually filled with coastal sand, which help the plants survive. The plants alter the sands and the bedrocks into brown pedogenetic materials, which are usually consolidated in coastal areas.

Important features of the past exposure surface in the Pleistocene Ryukyu Group are, rhizolith, neptunian dykes, pedogenic breccias, and phytokarstic structures. Unconsolidated soils are also important, which often survived at only depressions and fissures. Cutting of the underlying limestone structres are also well observed just below the unconformities.

The Ryukyu Group in the southern Okinawa Island can be divided into three, that are, the "Reddish Limestone" (equivalent to the "Chinen Sandstone"), the Naha Formation, and the Minatogawa Formation. It seems that different stratigraphic horizons have different features of the unconformities. It seems that preservation of the pedogenetic features is mainly related to the time-dependent factors in period of subaerial exposure. Sedimentation environments may also affect to the preservation of the diagnostic features like unconsolidated palaeosols.

In this study, it is cleared that the Naha Formation can be divided into lower and upper parts in the western part of the southern Okinawa Island, where many quarries exist. A couple of sedimentary sequences are recognised in each of the lower and upper Naha Formation, but there is overall shallowing upward trend in each, which in many

case ends by shallow types of coral limestones. The same trend was also reported from Motobu Peninsular, Ie and Toku-no-shima Islands. The distribution of coral limestone of the uppermost Naha Formation is limited just around Yoza to Maehira areas. However, the distribution of the centre of the coral limestone of the lower Naha Formation is at Kyan, though it has wide distribution compared to that of the upper Naha Formation. From this viewpoint, some crustal movement might have been related to form unconformities between the lower and upper Naha Formation.

Contents



## I. Introduction

Sequence stratigraphy is a noticeable theory which provides us a valuable breakthrough to understand depositional histories of sediments (Vail et al., 1977; Vail et al., 1984; Van Wagoner et al., 1990; Wilson, 1992; Emery and Myers, 1996). In this theory, sea-level changes, having cyclicity of various orders of time, are the most important factors that form cyclic sedimentation. A sequence, a basic unit of the theory, is a set of a succession of sedimentary facies. The sequence is formed under transforming environments, followed by a set of relative sea-level changes, and sediment fills are normally composed of piles of the sequences. Unconformities are important boundaries, which mean a depositional gap by a subaerial exposure, caused by significant eustatic sea-level fall or tectonic uplift. Accordingly, unconformities and correlative conformities are used to divide sequences, and the boundaries are named as sequence boundaries. Thus, to place the unconformity boundaries in sediments is essential for understanding of the sequences and depositional history. If we can recognise the unconformities in outcrops in fields, it can provide very important information.

Features of unconformities developed in carbonate rocks are different from those of siliciclastic rocks. Carbonate system is mainly biogenic, and this cause topographic complicity of reef structures, and lithologic boundaries including unconformities. Besides, limestone tends to be massive, and it is difficult to find unconformable plane if they lack visible characteristic features like paleosols. In carbonate systems, however, vadose and meteoric-phreatic diagenesis of the past may provide available clues to find ancient subaerial exposure surfaces. For example, we can see many karstic features of characteristic topography, cave, cements, and sediments under subaerial surfaces of carbonate rocks. However, there are also problems that the limestone we can now observe in field has also undergone recent vadose and meteoric-phreatic diagenesis, and this confuses the recognition of the subaerial exposure surfaces of the past. In sub-arid to sub-humid conditions, calcrete commonly develops especially on carbonate rocks, and can be distinct criteria to recognise unconformity. Calcretes represent characteristic features of accumulation of secondary calcium carbonate, and they have been attracted attention of many researchers (Wright and Tucker, 1991). However, their appearance is usually limited by the moisture conditions of sub-arid to sub-humid climates, although there are some exceptions (ex. Goudie, 1983). In humid climate, calcrete tends not to develop, and recognisable features of the past unconformities in fields are little studied.

Ryukyu Islands are located in 123-130°E longitude and 24-29°N latitude (Fig. 1). Annual temperature is around 19-24°C. It has much rain throughout the year, and 2128 mm in Naha City is typical annual rainfall. These conditions

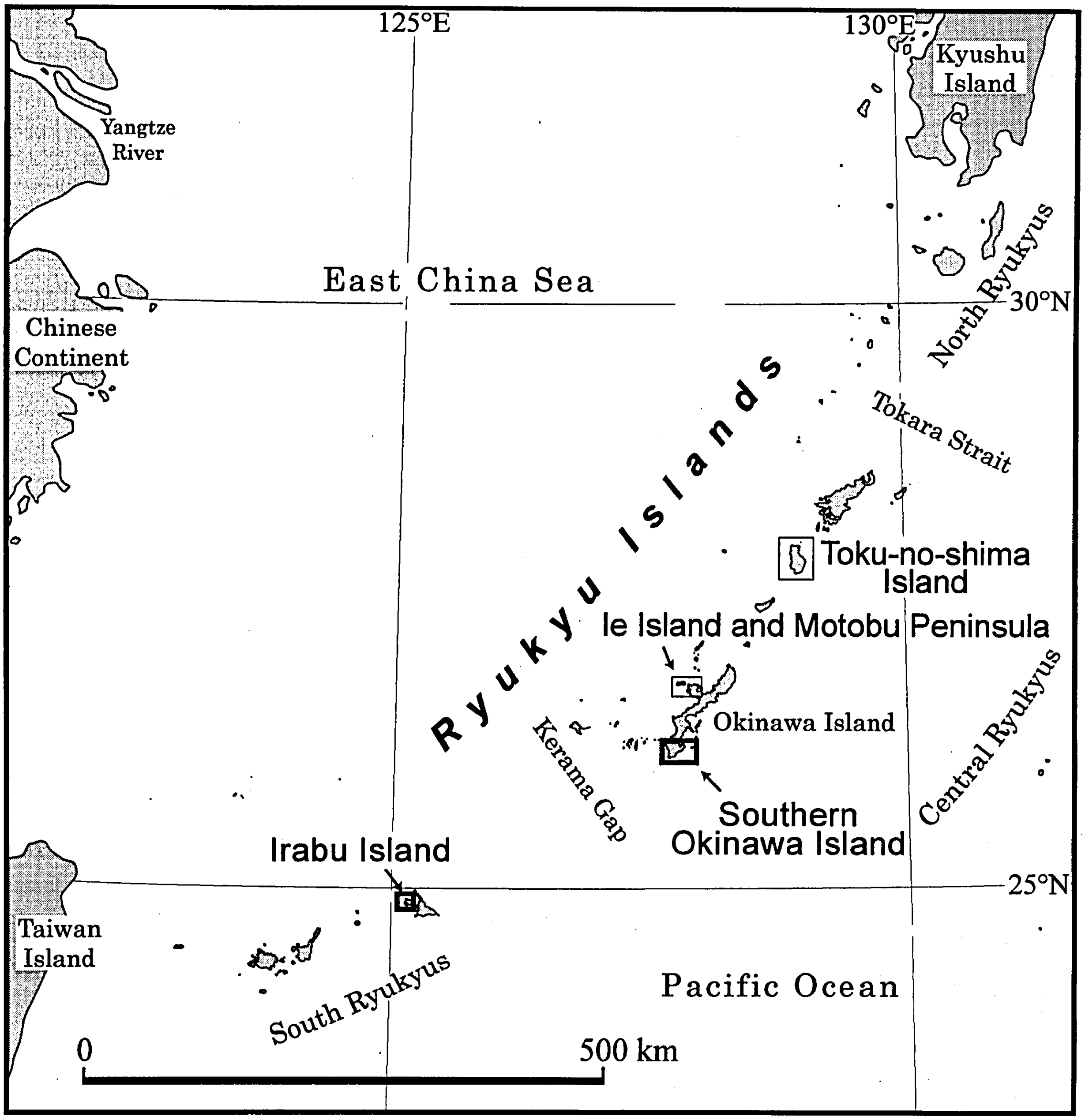


Fig. 1. Location map of the Ryukyu Islands and studied areas.

indicate the subtropical-humid climates. There are the Quaternary carbonate sediments in southern and most of the central Ryukyus, and they provide one of the best places to study humid sub-tropical carbonate systems. In this study, subaerial surfaces of limestone formed in the past and present are investigated, the features are described, and criteria for recognising of the unconformities in humid sub-tropical carbonate systems is attempted to be cleared. With recognition for the unconformities, the stratigraphy and depositional processes are discussed for the Ryukyu Group mainly in southern Okinawa Island.

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## II. Previous Studies of Unconformities in the Quaternary Ryukyu Group

The Ryukyu Group is the Pleistocene deposits in the Ryukyu Islands, and consists mainly of limestone, which partly contain siliciclastic sediments. Depositional age of the Ryukyu Group is estimated to be late early to middle late Pleistocene (Chapter XI). The Ryukyu Group has depositional period of about 1 Ma. Besides, the Quaternary is a period of frequent eustatic sea-level changes due to repeated glaciation and deglaciation. Oxygen isotopic data of deep-sea core samples and terraces of the Quaternary reefs indicates sea-level fluctuating several 10 meters with a 100 – 40 thousand years periodicity (Chappell and Shackleton, 1986). The Group was deposited in a relatively shallow sea from island shelf to beach, and it was clearly influenced by the repeated sea-level changes. This means that the Group must have been experienced several terrestrial exposures which result in many unconformities.

Unconformities in the Ryukyu Group have been recognised mainly at formation boundaries. For example in southern Okinawa Island, an unconformity between the Naha and the Minatogawa Formations in the Ryukyu Group has been well known (Nakamori, 1986). They have different cementation and fossil preservation, which result different lithological outlooks. They also have different terrace altitudes, which indicate the existence of considerable crustal movements between deposition of these formations. These facts suggest that there was a long non-depositional period between these formations. A direct evidence for terrestrial exposure was also known as a paleosol layer between these formations (Ujiie, 1986). Besides, two paleosol layers are also known within the Minatogawa Formation, as indicated by Kawana et al. (1992). Kaneko (1994) reported a distinct unconformity near the basement of the Naha Formation of Nakamori (1986). He distinguished the terrigenous component rich limestone below the unconformity as the "Reddish Limestone", and considered it to be contemporaneously heterotopic facies of the "Chinen Sandstone", and treated it as a separated formation.

Matsuda (1995) reports some unconformity in Irabu Island. There is an distinct unconformity between the Lower and the Middle Members of the Ryukyu Group. The lithology clearly changes across the unconformity. The uppermost Lower Member is rudstone or floatstone of mainly hermatypic coral and encrusting algae, while the basal Middle Member is grainstone or packstone mainly of foraminifera and algae. Paleosol is found at the unconformity and solution vugs in the uppermost Lower Member. Samples below the unconformity show a clear negative shift on carbon stable isotopes, which may result from near-surface diagenesis on subaerial exposure. In the Middle Member, negative shifts are also observed in several horizons, especially in carbon isotope. Isotopic behaviour on subaerial exposure including these shifts have been studied by many researchers (ex. Allan and Matthews, 1982; Goldstein, 1991; Dickson and Saller, 1995).

In the southern Okinawa Island, the Naha Formation is the thickest unit in the Ryukyu Group, and has cycles of different sedimentary facies. The formation is probably correlated to the Middle Member of the Ryukyu Group in Irabu Island, and it must record several unconformities. However, the unconformities have not been detected yet, other than Ooshiro (1977), who found the outcrop of a clino-unconformity in the detrital limestone in the Naha Formation in the southern Okinawa Island.

The circumstance that unconformities have not been detected may result from difficulty in recognition of unconformity in limestone sections on outcrops. On the other hand, this may also result from poor knowledge on structures formed and remained under the subaerial exposure surfaces in a humid condition such as the Ryukyu Islands. Therefore, we need to understand subaerial diagenetic features under a humid condition in order to recognise unconformable boundary more easily in outcrops.

## III. Geological Study of the Southern Okinawa Island

### A. Previous Studies in Southern Okinawa Island

Fig. 2 shows stratigraphic outline of the representative studies about the southern Okinawa Island.

Geology of the Ryukyu Islands has been investigated from late 19th century (Koto, 1898; Hanzawa, 1935; MacNeil, 1960; Nakamura and Furukawa, 1980). The first geologic map and a brief account of the geology of Okinawa Island was published by Kada (1885), and he used the names Shimajiri and Naha in at least an informal stratigraphic sense. Kuroiwa (1894a, b) reported that northern two third of Okinawa Island is composed of Proterozoic rocks which are now assigned to Carboniferous to Paleogene, while southern one third part of Okinawa Island is composed of porous limestone, lying on young mudstone and sandstone. Yoshiwara (1901) published a brief description of the geology of Okinawa Island. Hanzawa (1925) proposed the Shimajiri group for all of the beds exposed below the porous limestone. The porous raised reef limestone is named as the Ryukyu (Riukiu) limestone by Yabe and Hanzawa

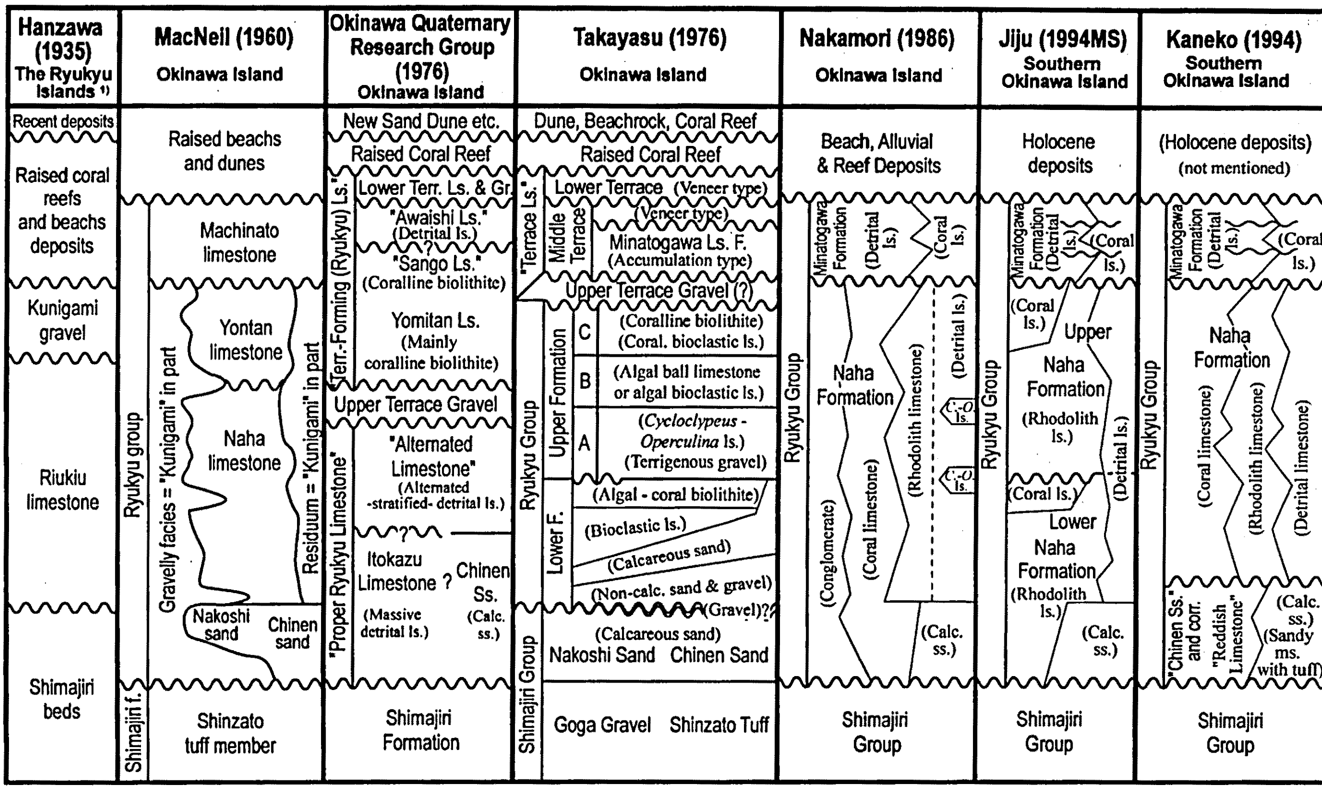



Fig. 2. Comparison of representative stratigraphic studies of the Ryukyu Group.Each of the columnars is partly modified from the original. (F.,f.=Formation; ss.=sandstone; ls.=limestone; terr.=terrace; calc.=calcareous; C.=*Cycloclypeus*; O.=*Operculina*)
[1)]In Iriomote Island, he described Sonai congromerate lying unconformably below the Riukiu limestone.

(1930). Hanzawa (1935) indicated the marked unconformity between the Riukiu limestone and all the older formations representing a prolonged and extensive period of subaerial denudation. He also mapped the Kunigami gravel, which consists of lateritic soils and gravels, and he considers that they rests on the Riukiu limestone.

Stratigraphy within the Ryukyu (Riukiu) limestone is mainly studied after World War II. MacNeil (1960) used a name the Ryukyu group to describe the Yabe and Hanzawa's Riukiu limestone, because the limestone was divided into disconformable units as reported by Flint et al. (1959). According to MacNeil (1960), the Chinen sand came to lowermost of the Ryukyu group in the southeastern part of Okinawa Island, while the Nakoshi sand takes the same role in the northwestern part. Naha limestone overlies the sands, and is disconformably overlain by the Yontan limestone. He found that the gravelly facies called "Kunigami" is not only above the limestones but also situated below and within them. The Machinato limestone rests unconformably on these limestones and the Shimajiri group. Because MacNeil (1960) did not show the geological map, distributions of these rock units are not clear. Shoji (1968) re-examined geology of Okinawa Island, and renamed the formation names as the Yomitan and Makiminato Limestones, instead of Yontan and Machinato in MacNeil (1960). According to Shoji's geological map, the Yomitan Limestone and the Kunigami Gravel are not exposed in southern Okinawa Island. Shoji (1968) indicated that each of the distributional plane of his Naha, Yomitan and Makiminato Limestones could be correlated with each terrace plane in Tokunoshima and Okinawa Islands, and concluded that they have been formed in relation to the intermittent falls of sea-level. Terrace planes of the Ryukyu Limestone was recognised on other islands of Ryukyus, and used to have been categorised into two terrace-forming beds, which were further correlated to Kudo and Shimosueyoshi planes in Kanto district (Nakagawa, 1967, 1969a, b).

Besides, Ibaraki (1975,1979) did not recognise disconformities between the Shimajiri Group and the Chinen Sand, and concluded that the Chinen Sand is a member of the Shimajiri Group rather than the Ryukyu Group. This conclusion was also supported by the fact that there are no significant change in community of the planktonic foraminifera (Ibaraki and Tsuchi, 1975) and the calcareous nannofossils (Nishida, 1980).

Okinawa Quaternary Research Group (1976) indicated that much of the Ryukyu Limestone is developed without relation with terrace planes, and that there is also clear dislocation by faults. Uruma Crustal Movement was proposed for the dislocation, which was later described in detail in Takayasu (1978). Simultaneously, they indicated that there are also limestones of generally very thin ones, which form terraces. Therefor they divide the Ryukyu Group of Okinawa Island into "Proper Ryukyu Limestone" (Itokazu Limestone Formation, "Alternated Limestone" Formation), and "Terrace-forming (Ryukyu) Limestone" (Yomitan Limestone, "Sango Limestone", and "Awaishi Limestone" Formation). However, their classification is principally not so different from MacNeil (1960), though they used the names Itokazu Limestone Formation and "Alternated Limestone" Formation instead of Naha limestone, and "Awaishi Limestone" Formation instead of Machinato limestone. They also mentioned that the Chinen Sandstone conformably changes into the "Alternated Limestone" Formation.

Takayasu (1976) renamed the Machinato Limestone as the Minatogawa Formation, as he changed the type locality for convenience. He include "Coral Limestone", and "Awaishi Limestone" Formation of Okinawa Quaternary Research Group (1976) to the Minatogawa Limestone Formation. He reexamined the stratigraphy of the "Ryukyu Limestone" and divide it into the Ryukyu Group and "Terrace Limestone", in the same manners of Okinawa Quaternary Research Group (1976). Takayasu (1976) reconstruct the stratigraphy of the Ryukyu Group, and divide it into the Lower and the Upper Formations, and the Upper Formation is subdivided into three members of the A (*Operculina* and *Cycloclypeus* limestone), B (algal ball limestone) and C (coralline biolithite) by their lithologic characteristics ascendingly. He included the Yomitan Limestone and the Itokazu Limestone in the Upper Formation. The Chinen Sand was included to the Shimajiri Group. Takayasu (1978) had a same concept, but he called "Terrace Limestone" as the accessory limestones, by contrast to the main limestones as the Ryukyu Group.

On the contrary, from late 1970's, the Ryukyu Group has been considered to be a deposit of reef complex composed of different lithologic biologic facies, and had been developed reflecting Quaternary sea-level changes (Iryu, et al., 1992). Consequently, accurate depositional environments of the Ryukyu Group became to be taken in account by correlating with modern environments using organic component of such as corals, algae, and foraminifera. Nakamori (1986) argued from this viewpoint, and pointed out that these limestones and gravels indicate contemporaneous heterotopic facies, and each limestone and gravel appears repeatedly in different horizons in several sections. Therefore, he united the Kunchan Gravel, the Naha Formation, and the Yontan Limestone, and called them the Naha Formation collectively. He also included brown coloured calcareous sandstone corresponding the "Chinen Sandstone" into the Naha Formation, as he indicated the existence of the unconformity on the Shimajiri Group. Furthermore, he included again the Minatogawa Formation into the Ryukyu Group. On the other hand, Jiju (1994MS) recognised an unconformity within the Naha Formation, and similar lithological changes to that of Takayasu (1976), which have two cycles. Therefore, Jiju (1994MS) divided the Naha Formation into upper and lower. However, there remains as problems that the Naha Formation can really be divided into just two, because it is considered to be deposited through several cycles of eustatic sea-level changes. Besides, more clear criteria were needed to recognise subaerial surfaces of the past. Kaneko (1994) recognised the "Reddish Limestone" bounded by

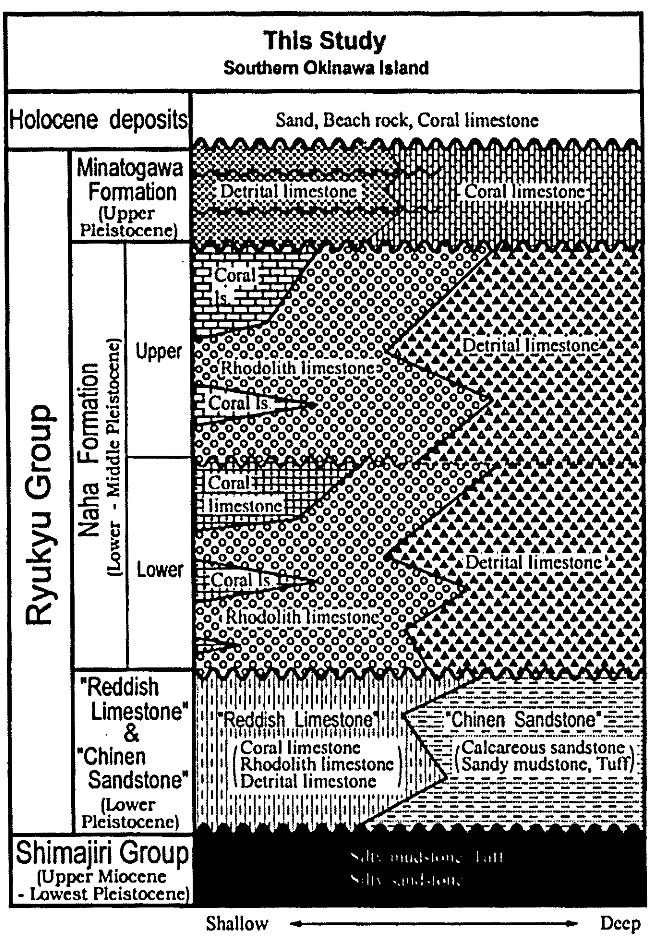



Fig. 3. A schematic columnar section of this study of the geology of the southern Okinawa Island. Wavy lines indicate large unconformities. ls.=limestone.

a clear erosional plane in the bottom part of the Naha Formation in southern Okinawa Island. He considered that the "Reddish Limestone" is contemporaneous heterotopic facies of the "Chinen Sandstone" and divided from the Naha Formation. In this study, characteristics of unconformable boundaries and stratigraphy of the southern Okinawa Island are minutely studied, and it is confirmed that stratigraphy of Jiju (1994MS) and Kaneko (1994) is principally available. Thus, stratigraphy of this study follows to Jiju (1994MS) and Kaneko (1994) (Fig. 3; Chapter IX).

**B. Geological Outline of the Southern Okinawa Island**

In the northern and northern central Okinawa Island, basement of the Ryukyu Group is mainly composed of the Pre-Tertiary sedimentary rocks. In the southern central and southern Okinawa Island, the Shimajiri Group ranging from late Miocene to earliest Pleistocene is widely distributed, and forms a basement of the Ryukyu Group. The Shimajiri Group has more than 2,000 m in total thickness, and in southern Okinawa Island, it is mainly composed of bluish grey silty mudstone intercalating silty sandstone and tuff layers (Natori and Kageyama, 1987).

The Shimajiri Group is slightly tilt about less than 5° toward southeast in southern Okinawa Islands (Ujiie, 1994). Relationship to the overlain Ryukyu Group is clino-unconformity. There are many faults in the Shimajiri Group in the southern Okinawa Island extending to NW-SE direction, which is perpendicular to the NE-SW extension of the Ryukyu Island Arc. These faults do not cut the Ryukyu Group, and can be differentiated from the faults that cut both the Shimajiri and the Ryukyu Group. Ujiie (1994) concluded that the faults were formed by the upward warping of the Ryukyu Island Arc region associated with subsidence of the Okinawa Trough region at a period during the sedimentation gap of the Shimajiri and the Ryukyu Groups.

Sediments of the Shimajiri Group are poorly consolidated and thought to be easily eroded. Consequently, unconformable boundary to the Ryukyu Group shows a complicated geometry in southern Okinawa Islands. Especially in the Minatogawa area, the Shimajiri Group was incised and the deep valley was later filled with the Ryukyu Group. In this valley, the Ryukyu Group is the thickest in the Okinawa Island, and total thickness reaches about 150 m (Furukawa, 1983). The Naha Formation in this area is mainly composed of stratified detrital limestone. The unconformable boundary of the groups tend to elevated eastward at Oyakebaru, where the elevation reaches to about 150 m.

Because porous limestone of the Ryukyu Group overlies argillaceous silty mudstone of the Shimajiri Group, meteoric water tends to flow just above the boundary. The poorly consolidated mudstone may be easily eroded, that results in collapse and gravity slip of the unstable limestone. It is typically seen around Fusato in Tamagusuku Village, where elevation of the limestone do not match with geological mapping (Kuroiwa, 1894b). The collapse and slip is also common feature along the sea cliff especially in eastern part of the Okinawa Islands where the boundary is above the sea-level.

The Ryukyu Group has also many faults in the southern Okinawa Island. The faults form scarps of the limestone. Extending of these normal faults tends to directs NNW-SSE and ENE-WSW. As a result, these faults divide area of the Ryukyu Group into many blocks, and each block tends to tilt toward southwest, forming cuesta topography (Figs. 4, and 5). To reconstruct the sedimentological profile of the Ryukyu Group in the southern Okinawa, it is necessary to consider these crustal movements.

Limestone of the Ryukyu Group in the southern Okinawa Island is lithologically divided to rhodolith, coral, and detrital limestones.

**1. Rhodolith Limestone**

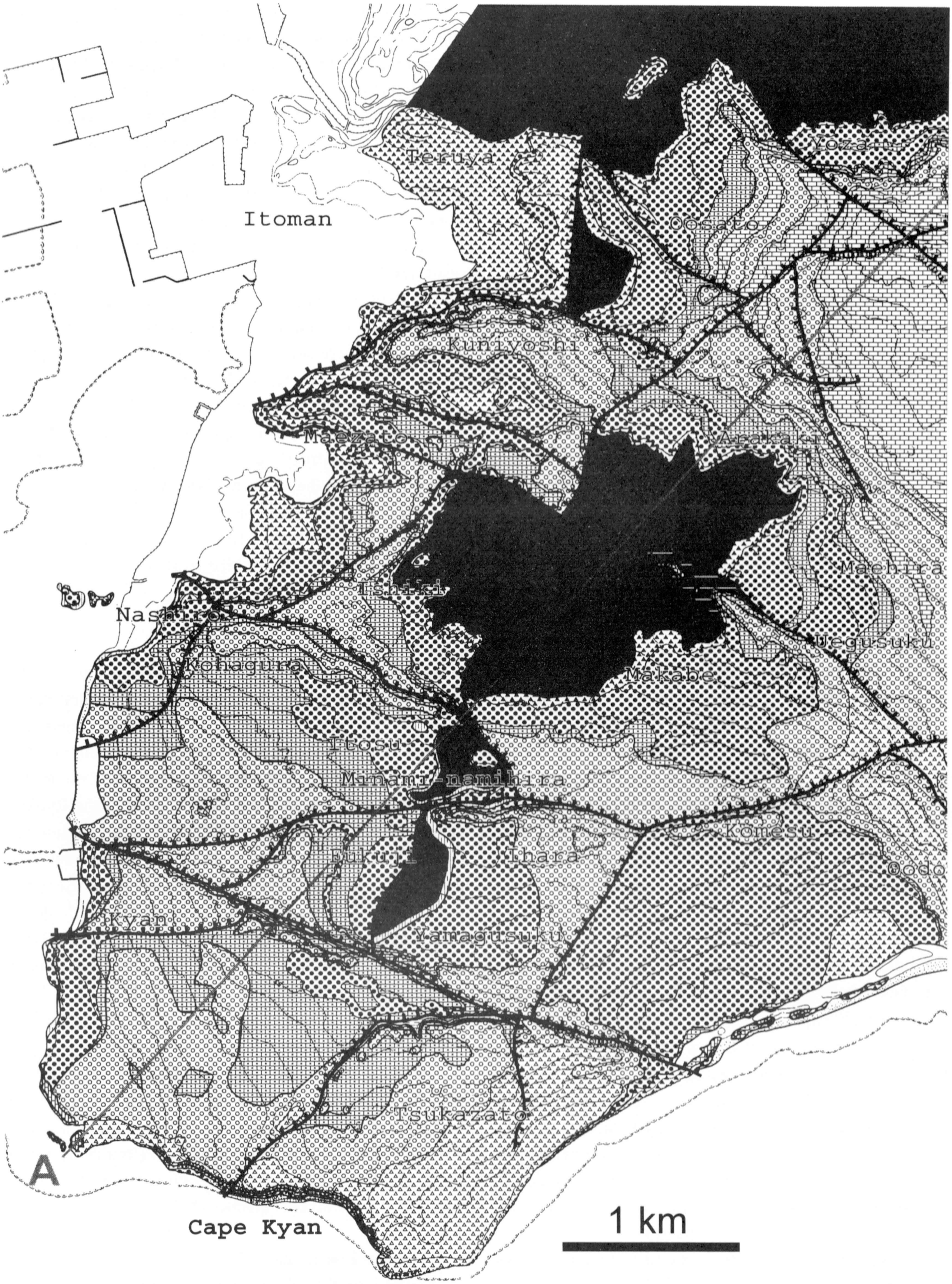
Rhodolith limestone (Pl. 1) contains many rhodoliths, which are spherical or ellipsoidal in shape, several cm in diameter, and are made of crustose coralline algae and foraminifera, encrusting nuclei materials. Minoura (1979) examined the relationship of the percentage of rhodoliths in the total rock volume and its frequency in the Ryukyu Group, and he found clear boundary of the percentage of Rhodoliths at a 20% frequency. This is the point that distinguishes rhodolith limestone from other lithologies (Iryu et al, 1992). Sedimentological environments of rhodolith limestone are inferred to deep fore-reef or continental shelf at the depth from 50m to 150m (Iryu et al., 1992; Tsuji, 1993; Iryu et al., 1995).

**2. Coral Limestone**

The definition of the coral limestone (Pl. 2) is that it contains autochthonous coral skeletons (Iryu et al., 1992). Sedimentological environments of coral limestone are inferred to the place shallower than 50 m (Iryu et al., 1992). More detailed sedimentological environments are further inferred by the coral communities (Nakamori, 1986).

**3. Detrital Limestone**

Detrital limestone do not contains large fossils such as


Teruya
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Makabe
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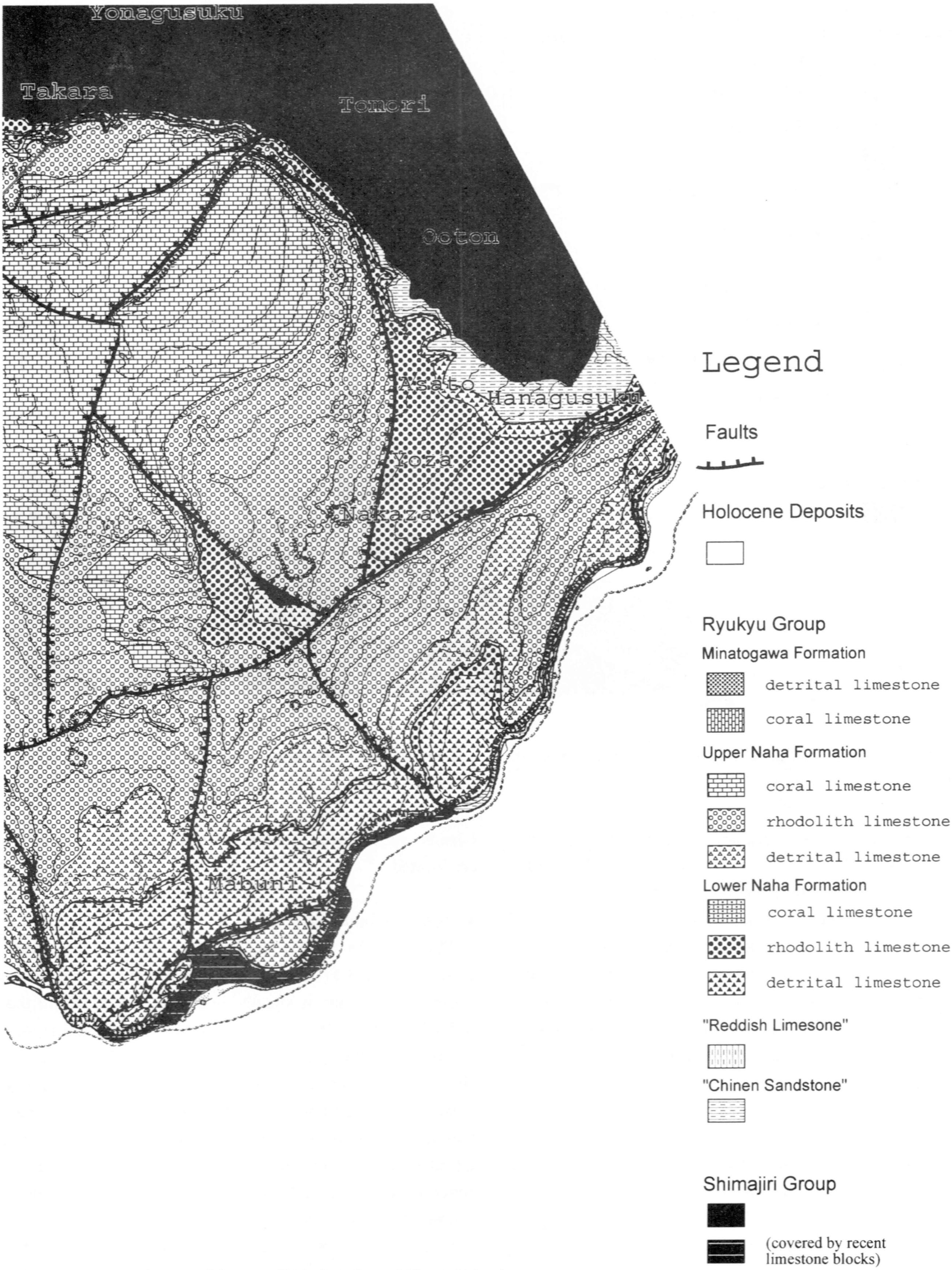



Fig. 4. Geological maps of the west side of southern Okinawa Island.

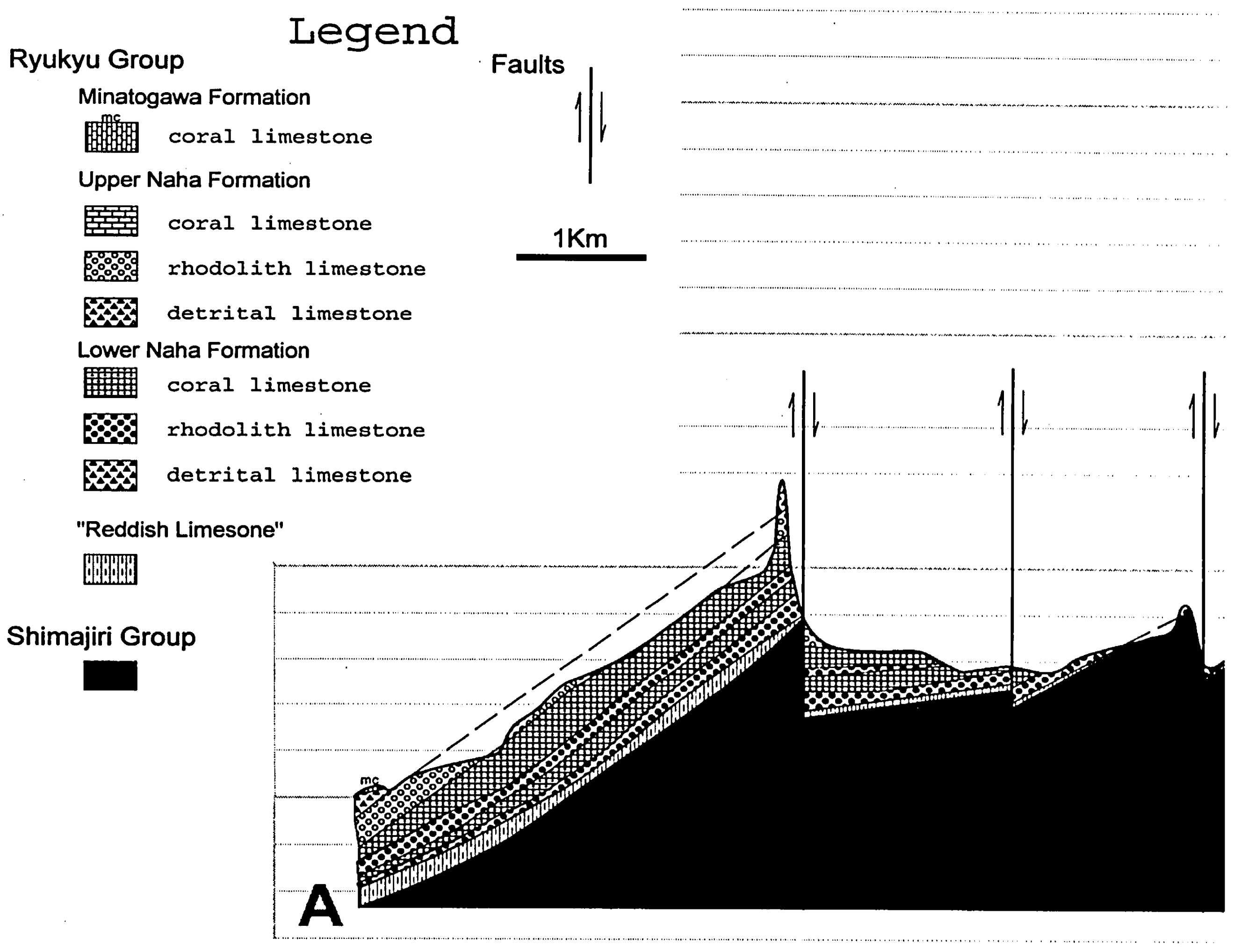



Fig. 5. A cross section of the southern Okinawa Island. The locality is shown in Fig. 4. Note that the horizontal and vertical scales are different.

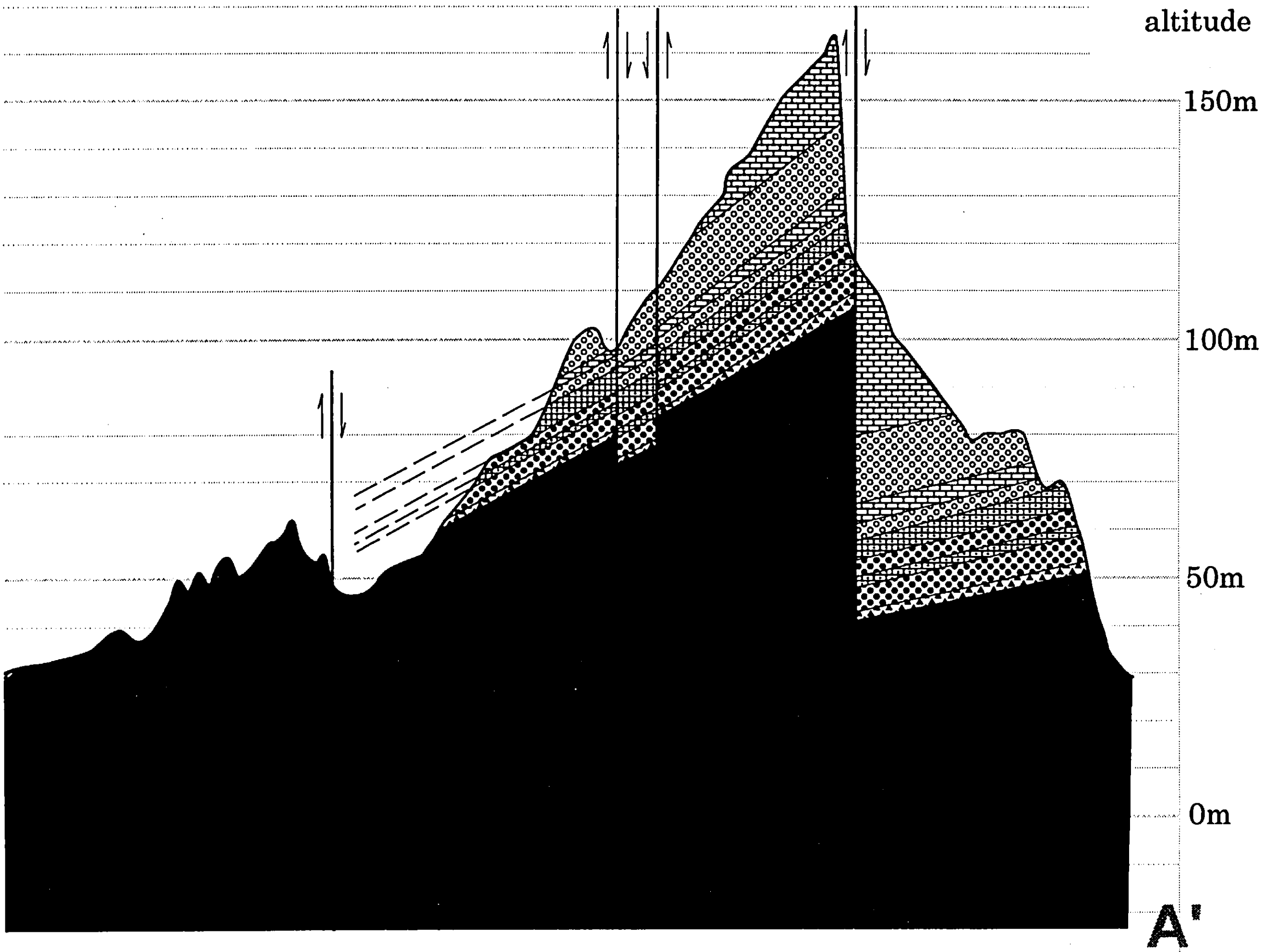
rhodolith or coral. They often laterally and vertically change into rhodolith limestone and coral limestone. The poorly sorted type is estimated to deposit in a reef slope and an insular shelf. A deeper insular shelf (150-200 m in depth) is the best estimate, if bryozoans are abundant (Iryu et al., 1995). On the other hand, the well-sorted type is estimated to be product of very shallow place like moat, beach, sandbar, and dune. Typical well-sorted type is well known as "Awaishi" in the Minatogawa Formation, which is used as building stone.

## IV. Stratigraphy of the Ryukyu Group in the southern Okinawa Island

The Ryukyu Group can be divided into following stratigraphic units (Fig. 3). Geological map, cross and columnar sections of the west side of the southern Okinawa Islands are indicated in Figs. 4-12, where a lot of quarries are located.

### A. "Chinen Sandstone"

The "Chinen Sandstone" is composed of calcareous sandstone and siltstone. It covers Shimajiri Group unconformably, and is situated below the lowermost of the Naha Formation. We can observe trace fossils and rip-up clasts at the boundary. The boundary is also seems as clino-unconformity (Pl. 3). The "Chinen Sandstone" laterally changes the thickness, and is distributed in limited areas, that is, Chinen-misaki, Kirabaru, Aragusuku, Gushikami, Uesato, etc. Lower part of the "Chinen Sandstone" is generally coloured dark olive grey, which change to more yellowish in colour when it is suffered by weathering. It is silty and similar to siltstone of Shimajiri Group. Differences between them are that the "Chinen Sandstone" is coarser and contains many fossils like bryozoan and foraminifera.




Upper part of the "Chinen Sandstone" is generally bright yellowish brown in colour. It is coarser and contains more fossils than the lower part. Total thickness of the whole "Chinen Sandstone" is less than 20 m in the southern Okinawa Island. Kaneko (1994) considered the "Chinen Sandstone" as contemporaneous heterotopic facies of the "Reddish Limestone".

**B. "Reddish Limestone"**

Kaneko (1994) divides the "Reddish Limestone" from the lower part of the Naha Formation. The limestone is commonly argillaceous and is bright reddish brown in colour. It tends to have more vadose silt in voids and fractures, compared to the Naha and the Minatogawa Formations. It has usually rounded pebbles of silty mudstone of Shimajiri Group. The "Reddish Limestone" includes rhodolith, detrital, and coral limestones.

Depositional age of the "Reddish Limestone" is estimated as 1.3 Ma by Sr isotopic method (Kaneko and Ito, 1995). It is probably comparable to the Lower Member of the Ryukyu Limestone of the Irabu Island (Sagawa, 1998MS) from the age (1.36-0.89 Ma from nannofossils in the Irabu island; Honda et al., 1993) and the argillaceous reddish outlooks.

The "Reddish Limestone" is situated under the Naha Formation. Distribution is limited and it does not appear in the north of Makabe. The northern borderline is around Nashiro, Minami-Namihira, Ihara and Uegusuku. It also tends not to appear with "Chinen Sandstone" with exception at an outcrop of Uesato.

It also shows karstic features at the upper part. Especially, bright reddish brown pedogenetic materials and neptunian dikes filling tiny caves are prominent. These features are also characteristics of the "Reddish Limestone". Details are shown in Section VII-A.

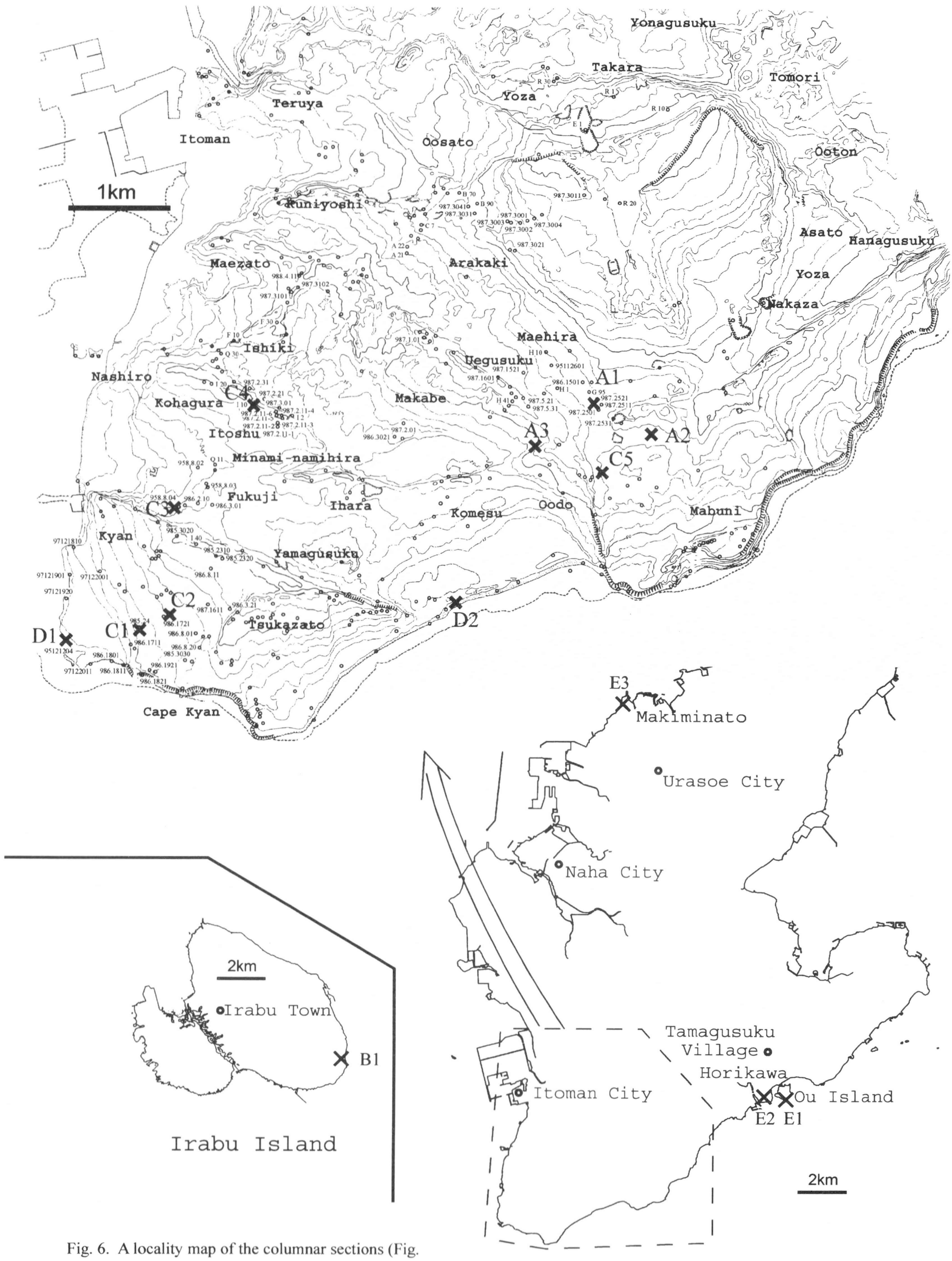



Fig. 6. A locality map of the columnar sections (Fig. 7-12) and studied outcrops.

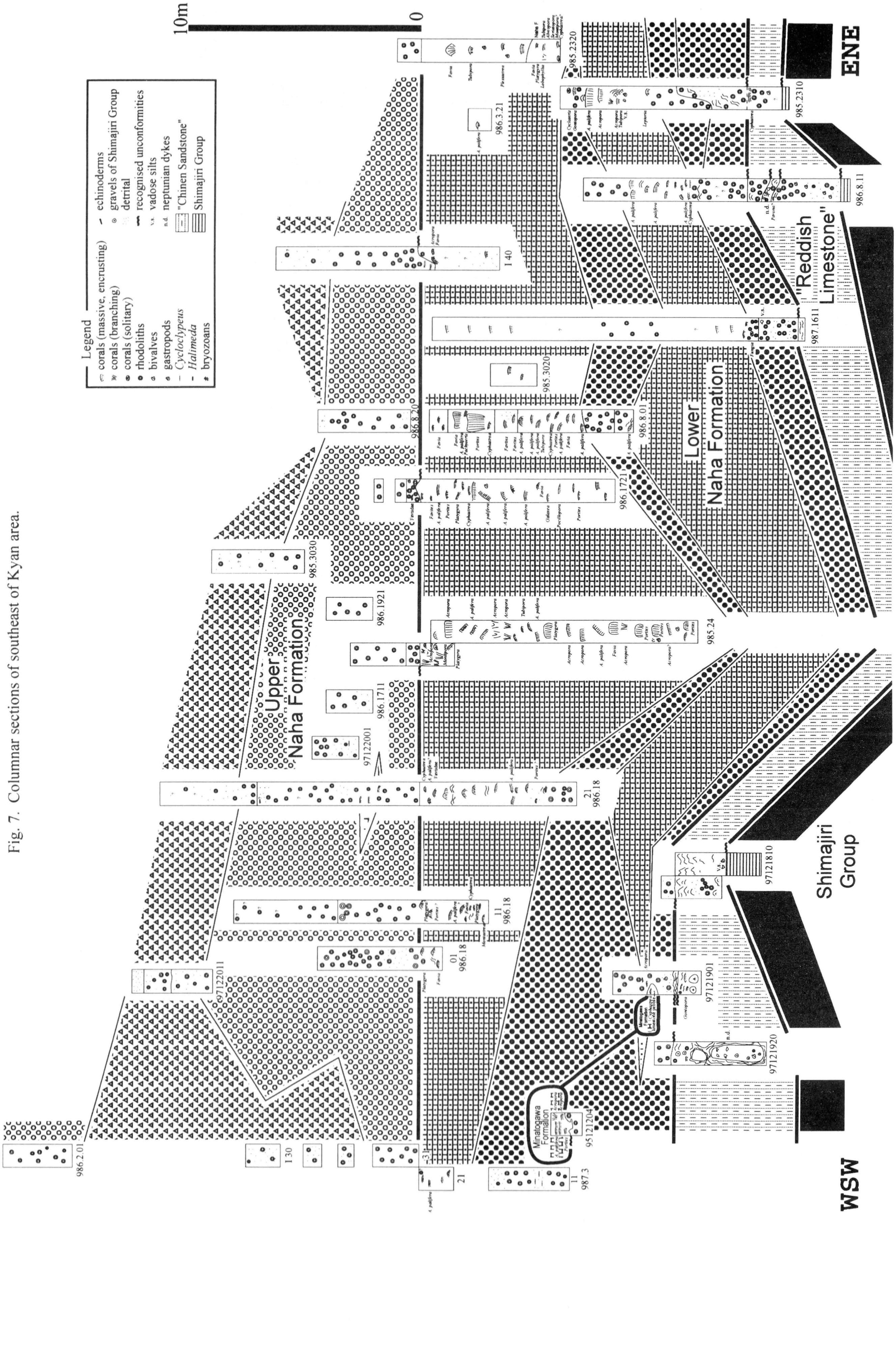



Fig. 7. Columnar sections of southeast of Kyan area.

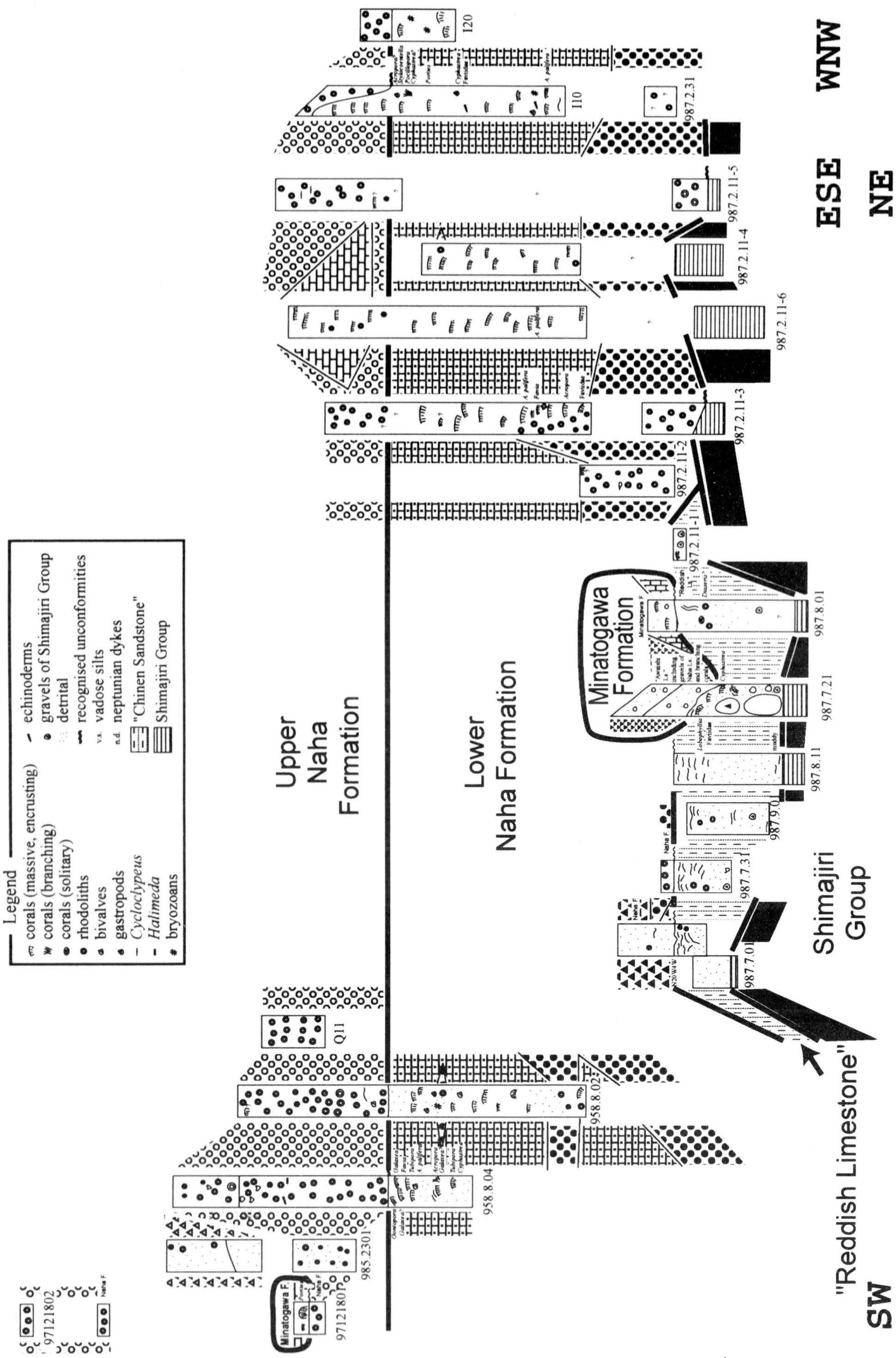



Fig. 9. Columnar sections of Itosu area.

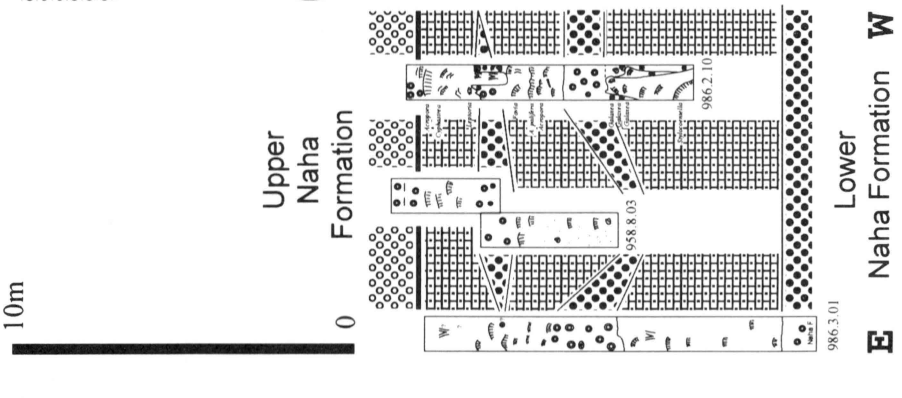



Fig. 8. Columnar sections of Fukuji area.

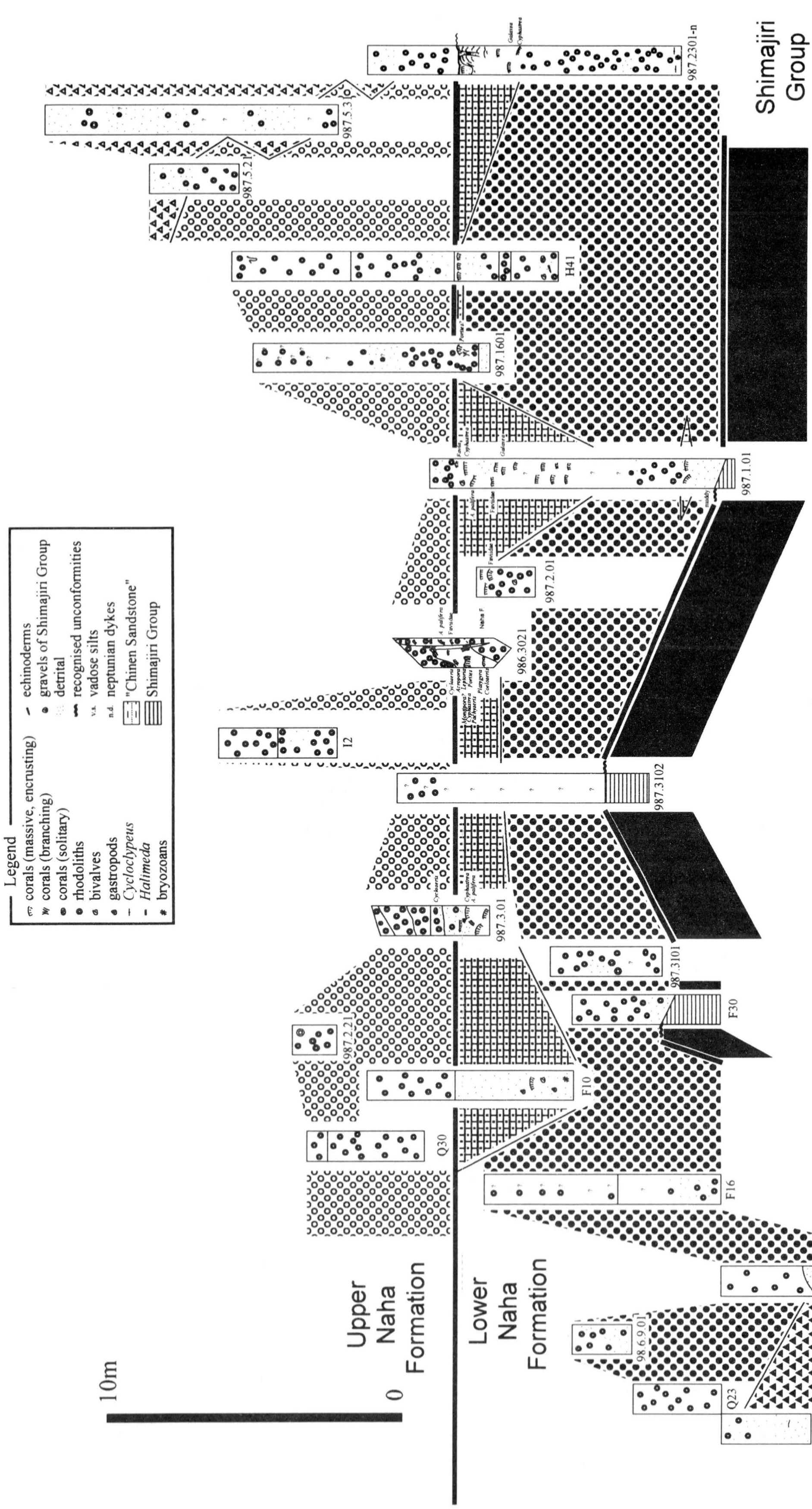
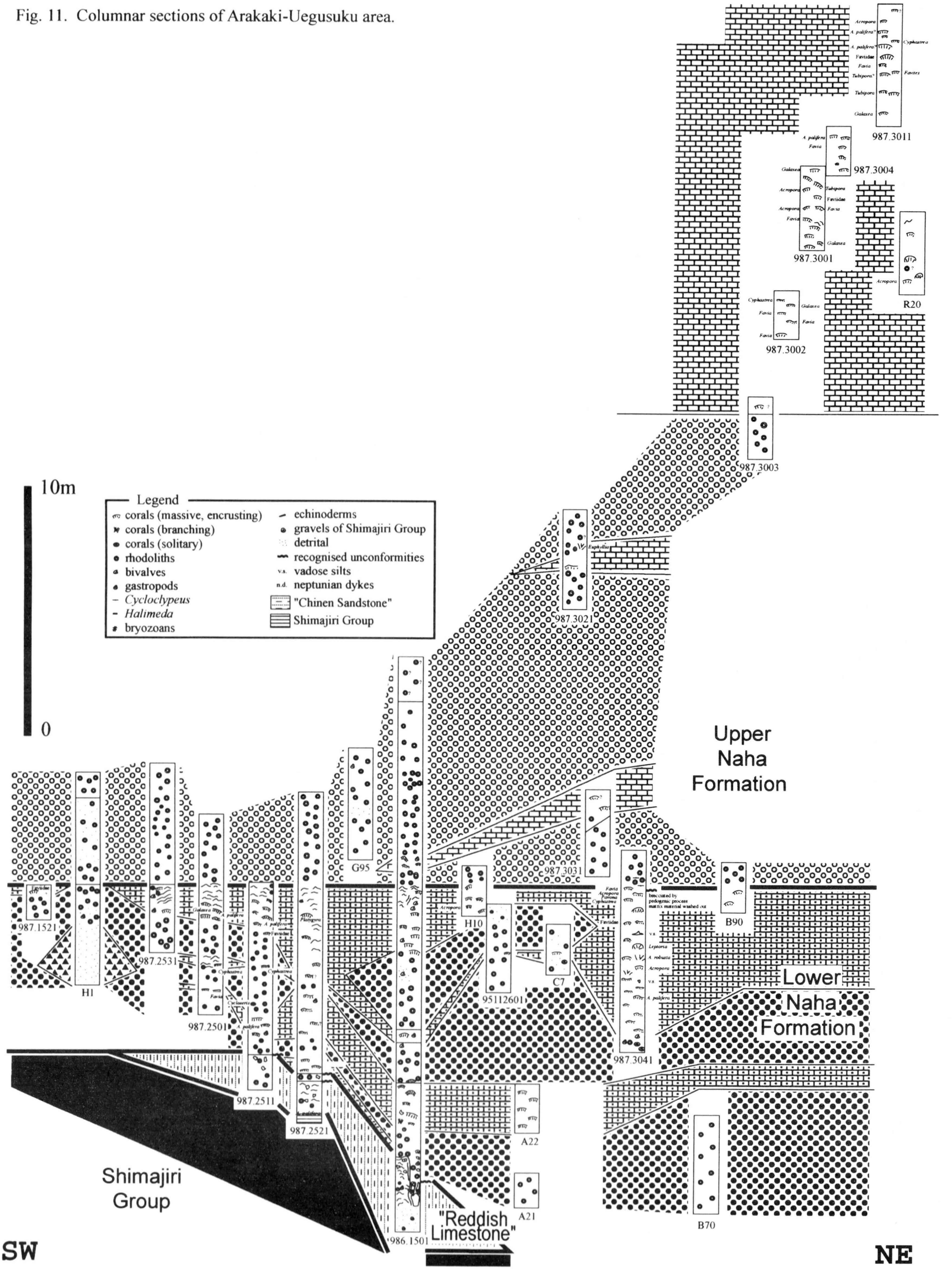



Fig. 10. Columnar sections of Ishiki-Makabe area.

Fig. 11. Columnar sections of Arakaki-Uegusuku area.



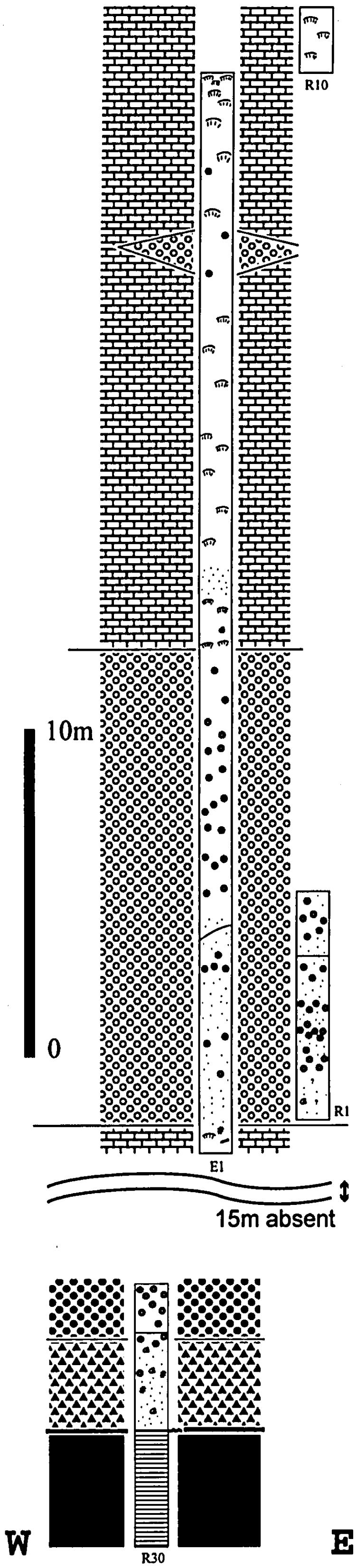



Fig. 12. Columnar sections of Yoza-Takara area. Legend is the same to Figs.7-11.

**C. Naha Formation**

The Naha Formation is thickest and most prevailed in the Ryukyu Group in the southern Okinawa Island. It is composed of white to light grey limestone of various types including detrital, rhodolith and coral limestones.

In the southern Okinawa Island, it is characteristic that deeper facies such as rhodolith and detrital limestones are dominant, compared to other localities of Okinawa Island like Yomitan and Ie-jima. Coral limestone mainly distributes around Kyan, Komesu, Takara, and Kirabaru. Rhodolith limestone is often intercalated within coral limestone, but not around Yamashiro, Mabuni, and Nakaza, where rhodolith limestone composes thick sections. Rhodolith limestone tends to distribute around the coral limestone. Detrital limestone deposits rather far from the coral limestone, Detrital limestone mainly distributes as thick succession around Arasaki, south of Mabuni, and Horikawa. They often have dips of several degrees toward opposite direction to coral limestone.

The Naha Formation can be divided into the lower and upper part by unconformable and correlative boundaries. Details are shown in Chapter IX.

Depositional ages of the Naha Formation are not well known because they are usually sustained by too serious diagenesis for conducting ESR and U-series datings. Jiju (1994MS) and Jiju (1994) conducted Sr isotopic dating for the 18 samples of the upper Naha Formation, and obtained the mean value $-19 \times 10^{-6}$ which differ from the recent seawater value. This value corresponds 0.7 Ma to fit the reference curve of Farrell et al. (1995).

**D. Minatogawa Formation**

The Minatogawa Formation is mainly distributed around Minatogawa area, and it forms terrace around the Yuhi River. The topographic heights of the terrace is generally 15m but it tend to increase toward inland, and eventually attains the heights of 60 m. The Minatogawa Formation is also found at Cape Kyan, and seashore of Oodo, and the formation overlies the sea cliff of the Naha Formation.

Mean value of the Sr isotope of four samples of the Minatogawa Formation has almost same value as Recent (Jiju, 1994MS; Jiju 1994), which corresponds the age younger than 0.3 Ma (Farrell et al., 1995). Nakamori (1986) correlated the formation to the Takanasaki Formation, in which the radiometric age of 0.13 Ma is obtained (Konishi, 1980; Omura, 1983, 1984).

They are poorly consolidated compared to the Naha formation. The Minatogawa Formation is divided into two lithofacies, that are coral and detrital limestones.

The coral limestone contains autochthonous coral skeletons, such as *Porites*, *Diproastrea*, and *Acropora*. The upper surface of the coral limestone exhibits the projections of about 3 m height from the base, and frequently covered by coralline algae. This topography resembles spur-and-groove structure and this limestone are inferred to be formed in reef flat.

The detrital limestone generally overlies the coral limestone. These are generally called "Awaishi" which means the stones made of millet grains. The grains are composed of the clasts such as foraminifera and calcareous algae, and they are well sorted. Cross lamination is frequently developed. Herringbone lamination is also found between the paleo-topographic height of coral limestone. This limestone is inferred to be formed in the very shallow sea like moat, beach, and sandbar. At least two paleosol layers are intercalated in the limestone (Section VII-E).

## V. General Criterial Features Seen in Unconformity of Carbonate Systems

There are different diagenetic environments in carbonate systems, and we can normally distinguish five zones. Vadose zone is situated above a water table. Meteoric phreatic zone is situated under a water table, where the sediments are always submerged under freshwater. Marine phreatic zone is situated under sea-level, and therefor the sediments are saturated with seawater. In mixing zone, pore water is of mixture of freshwater and seawater. Burial environment is another important diagenetic environment that is situated in deep underground, but it is not seen in young carbonate systems like the Ryukyu Group.

Subaerial exposures mean that at least a part of the sediment is under the vadose and meteoric-phreatic environments. Accordingly, it is important to notice diagenetic features under these environments for recognising unconformities in carbonate sections.

We can observe various diagenetic features in vadose and meteoric-phreatic zones, which differ due to mainly climatic conditions. Features related to calcretes are mainly observed in semi-arid to semi-humid climates, while karstic features are well developed in more humid climates.

### A. Calcrete Features

Calcrete is a near surface, terrestrial, accumulation of predominantly calcium carbonate, which occurs in a variety of forms from powdery to nodular to highly indurated. It results from the cementation and displacive and replacive introduction of calcium carbonate into soil profiles, bedrock and sediments, in areas where vadose and shallow phreatic groundwater becomes saturated with respect to calcium carbonate (Goudie, 1973; Watts, 1980; Wright and Tucker, 1991).

Calcretes are not restricted to soil profiles (pedogenic calcretes) but also can occur, for example, below the zone of soil formation but within the vadose zone, or at the capillary fringe and below the water-table to form groundwater calcretes. Though we have to pay attention that multiple calcrete horizons can form as groundwater calcretes (penetrative calcretes) related to only one subaerial exposure event (Rossinsky et al., 1992), the most important and widespread calcretes are those which form in soil profiles (Wright and Tucker, 1991).

Pedogenic calcretes are recognised as calcic or petrocalcic (if indurated) horizons in soil profiles in the terminology of soil scientists. It has been estimated that such soils today cover an estimated 20 million km$^2$ or about 13 % of the total land surface (Yaalon, 1988). The source of calcium in pedogenic calcretes is varied (Goudie, 1973, 1983), but main source is wind-borne in origin (Machette, 1985). In coastal areas, source of the calcium of calcrete is principally from seawater, and contributions from bedrock are generally small, according to Sr isotopic analysis of soil carbonate in South Australia and Victoria (Quade et al, 1992). However, calcic horizons could be better developed in regions of calcareous parent materials than in regions of non-calcareous parent materials (Machette, 1985). In these areas, calcrete may form from redistribution of carbonate, especially if it contains metastable carbonate like aragonite. It is likely that such redistribution calcretes form much more rapidly than the dust-dependent type (Wright and Tucker, 1991).

The degree of development of calcrete is related with the time over which soils and paleosols of dry climates formed. In studies of soils of various age in deserts of New Mexico and neighbouring states (Gile et al., 1966, 1980; Machette, 1985), six stages of calcrete development have been noted from less than 7000 years old to over 1 million years old (Retallack, 1990, 1997). Other factors are also influenced to the development of calcrete, as calcic horizons form more slowly under more sparse vegetation, on less calcareous parent materials and in extremely arid and subhumid to humid climates. However, it is possible to estimate time for formation of calcretes to an order of magnitude (Retallack, 1997).

Calcic horizons are generally formed in dry climates (about 100-1000mm mean annual precipitation). The depth to the top of the calcic horizon is generally related to the mean annual rainfall, with the calcic horizon closer to the surface in drier climates (Retallack, 1994, 1997). However, to interpret palaeoclimate from the relation, climatic changes and the degree to which a paleosol may have been eroded before burial and compacted after burial need to be considered (Retallack, 1997).

Calcretes can be micromorphologically classified into two end member types; alpha calcretes, and beta calcretes (Wright and Tucker, 1991). Beta calcretes exhibit microfabrics dominated by biogenic features such as rhizocretions, needle-fibre calcites, microbial tubes, alveolar septal fabric, and Microcodium. Beta calcretes appear to be best developed in semi-arid to subhumid areas with extensive vegetation cover, the biofabric of the pedogenic carbonate seeming to reflect this relatively high degree of biological activity. By contrast, Alpha calcretes consist of dense, continuous masses of micritic to microsparitic groundmasses, typically with such features as nodules, complex cracks and crystallaria, circum-granular cracks, rhombic calcite crystals, and floating sediment grains. Alpha calcretes generally occur in areas with an arid climate and less biological activities. Evaporation/evapo-transpir ation and degassing may be the main mechanism in alpha calcretes, although recrystallization has to be taken account.

The author could not recognise calcrete features in the humid Ryukyu Islands, except for needle-fibre calcite in voids of some recent exposure surfaces (Jiju, 1995).

### B. Karstic Features

Karst is a diagenetic facies, an overprint in subaerially exposed carbonate bodies, produced and controlled by dissolution and migration of calcium carbonate in meteoric waters, occurring in a wide variety of climatic and tectonic settings, and generating a recognisable landscape (Esteban and Klappa, 1983). Choquette and James (1987) used the term karst in the broad sense to include all of the diagenetic features – macroscopic and microscopic, surface and subterranean – that are produced during the chemical dissolution and associated modification of a carbonate sequence.

Many factors control the karst formation, and we can divide the factors into intrinsic and extrinsic ones (Choquette and James, 1987). Important intrinsic factors include mineralogy that effects solubility and formations of pores, stratal permeability, and fractures, which are all effected to how groundwater flows. On the other hand, the most crucial extrinsic factor is climate, although vegetation, the relationship between initial subaerial relief and diagenetic base level, and the time duration of exposure are all important.

In the Ryukyu Group, we have to pay attention when we recognise unconformities by karstic features. The Quaternary is ice-house period, and development and diminution of ice sheet cause large amplitude and short cycle of sea-level changes. In this circumstances, thick meteoric freshwater lens is developed due to large scale of sea-level rise, resulting thick meteoric diagenesis (Kano et al., 1995). Moreover, the Ryukyu Islands are areas of active crustal movement area of near of the Ryukyu Trench and the Okinawa Trough. The Pleistocene Ryukyu Group has been already extensively emerged, causing broad meteoric diagenesis. In these situations, many kinds of karstification features including cave systems, speleothems and vadose silt may extend deeply from exposure surfaces, which may overprint. In many cases, it is impossible to differentiate multiple karstic stages by investigating such features in limestone sections. Therefor, the author stressed to notice to the diagnostic structures formed only just beneath the exposure surfaces.

In this aspect, following structures are important, and useful to identify unconformable events in the past on field investigation.

**Karren** are organised morphological features resulting from the karstic dissolution of soluble rocks. The various recent morphologies are studied and classified by many researchers (e.g. Allen, 1982). Similar forms have been recognised at unconformities of ancient limestones (e.g. Read and Grover, 1977; Wright, 1982). Folk et al. (1973) used the term phytokarst for a landform produced by rock solution in which boring plant filaments are the main agents of destruction. It has dark grey to black colour of such surfaces, which was attributed to microorganisms (Jones, 1994). The development of phytokarst can be attributed to the activity of the endolithic and epilithic microorganisms (Jones, 1989), although there are also studies suggesting that microorganisms are not responsible for the weathering (Viles and Spencer, 1983; Spencer 1985a, b). In the Ryukyu Islands, the Ryukyu Limestone exposed in coast commonly exhibits similar features (Section VI-B).

**Neptunian dikes** are deposits of marine sediment infilling voids in older rocks (Smart et al., 1988). Smart et al. (1988) also classified different type of void infill deposits; fissure fills for terrestrial deposits, and cavern fills for brackish or phreatic freshwater deposits. However, origin of the voids is not restricted, and they can respectively be initiated and enlarged in multiple environments. Smart et al. (1988) suggest that neptunian dikes include not only fills of fissures that is directly open to the surface, but also fills of roofed voids, and seems not to restrict their shapes. In this paper, the author emphasises the phenomenon of infilling of marine sediments in definition of neptunian dikes, and does not restrict any origin of the voids, shapes, and sizes.

The voids enlargement could be take place in various environments. If subaerial karst processes operate, we can see irregular enlargement of the void from the initial configuration and they generate a distinctive suite of surface dissolution features including karren, phytokarst, and root moulds (Smart et al., 1988). Submarine enlargement processes are probably least effective. The reasons are that normal marine pore fluids generally supersaturated with respect to carbonate mineral species (Bathurst, 1975), and precipitation of marine cements is the major processes rather than chemical dissolution (Moore, 1989). Though mixing corrosion must be taken in account, karst process plays very important role to form voids of neptunian dykes. If the voids are formed by subaerial exposure events, neptunian dykes are very important for criteria of unconformities. The reason is that they indicate that the sediments had been submerged after the exposure period, and that the structures were accordingly not formed by recent exposure event.

**Breccias** developed on exposure surfaces are also important petrologic features. Many breccias are known as karst breccias related to karst formation (Choquette and James, 1987). We can divide the breccias into two types, that is "cave and sinkhole" type and "mantling" type. Former type, including breccia pipes, cave-roof collapse breccias, and evaporite-solution breccias, is a result of dissolution-collapse of cave systems. "Mantling" type is important, because it could occur just upon the subaerial surfaces. It often shows autochthonous in origin. Wright (1982) reports the intense level of solution piping on paleokarst on the Lower Carboniferous of South Wales, resulting in the rubbly facies. Wright (1982) noticed that some of the smaller solution pipes in the paleokarst resemble root lapies. These features are comparable to Recent Kavornossen karren (Jennings,1971; Gams, 1973), and similar features seen in the karsted Aymamon Limestones of Puerto Rico (Monroe, 1966; Ireland, 1979). Similarly, Wright and Wilson (1987) reported a highly-brecciated erosion surface on the Middle Jurassic limestones in Portugal, which is overlain by the Upper Jurassic red mudstones and conglomerates. Matrix of the red mudstone shows tubular structures representing rhizocretions, and shows pedogenic microstructures. Breccia by root penetration is also described in Pennsylvanian and Lower Permian carbonates in the southwest Andrews area of the United States by Dickson and Saller (1995).

**Rhizoliths** are organosedimentary structures produced by roots, and provide evidence of higher plant colonisation of subaerially exposed sediments and rocks in the post-Silurian rock record (Klappa, 1980). They are found in calcrete and non-calcrete soils and related substrates. Klappa (1980) studied rhizoliths of the Quaternary of Spain and classified them in terms of their textural characteristics. *Root moulds* are tubular voids left after roots have decayed. Preservation of the morphology of root networks indicates that soil materials must have had sufficient rigidity to prevent collapse of root mouldic porosity. If soil materials are completely lithified, roots may bore into the rock or occupy pre-existing tubular voids. *Root casts* are produced by filling of a root mould, either by sediment or cement, or both. *Root tubules* are cement or cemented sediment cylinders around root moulds. The cement usually consists of low magnesian calcite, and the cementation may take place during life or during decay of the root. Needle-fibre calcite, which has distinctive crystal shape produced by specific fungal hyphae around roots (Callot et al., 1985; Verrecchia and Verrecchia, 1994), is also responsible for producing root tubules (Strong et al., 1992). *Rhizocretions* are pedodiagenetic accumulations of mineral matter (low magnesian calcite) around existent (possibly decayed) roots. Accumulation, usually accompanied by cementation, may occur during life or after death of plant roots. *Root petrifactions* are mineral (e.g. calcium carbonate, silica) impregnations, mineral replacements, encrustation and void-filling of organic matter which have preserved anatomical features of roots partly or totally. In calcrete deposits, calcite is the dominant mineral which preserves plant morphology.

Rhizoliths are sometimes confusable with burrows, but following features can be used to discriminate the root traces (Plaziat, 1971; Klappa 1980; Retallack, 1997). Rhizoliths have irregular tubular shape, and have downward (or outward from a centre) bifurcations with decreasing diameters of second, third and fourth order branches. They might also have presence of contained root materials.

These fossil root traces are the best field criteria for identifying fossil soils in sequences of sedimentary rocks (Retallack, 1997). However, we have to pay attention not to confuse fossil rhizoliths and recent root penetration from earth surface, especially when we investigate young sediments as the Ryukyu Group.

## VI. Recent Exposure Surfaces in the Ryukyu Islands

**A. Exposure Surfaces in Inland Terrace**

On the inland terraces of Okinawa Island, dense high-diversity vegetation supports dark red soils tens of centimetres in thickness (Pl. 4). The soils resemble to but is different in composition from terra rossa, which probably reflects a more humid condition than Mediterranean areas (Urushihara, 1990). The soils are mainly wind-borne in origin as indicated by the oxygen isotopic analyses of quartz particles (Naruse et al., 1986; Inoue et al., 1993). They are probably transported from arid areas of China, or from sediments on the exposed continental shelf of East China Sea during the glacial periods.

The soils are normally unconsolidated, and the boundary to the underlying limestone is usually sharp and it cuts skeletal grains of the bedrocks. However, the contact often has a complicated surface. Especially, in the area that pedogenesis has some matured features, underlying limestone has been intensely fractured, forming karst breccia of mantling type (Pls. 4, and 5; Section V-B). The clasts generally have angular in shape, and size is several cm. The clasts sometimes connect to each other in three-dimensional view, indicating that they are autochthonous in origin. Rhizoliths are often seen at the matrices (Pl. 6). This type of karst breccia is widespread on the recent exposure surface of the Ryukyu Limestone, but it tends not to be found by following reasons. The matrix soil materials are not consolidated, and the clasts are easily hidden by scattering the powdery soil. Moreover, when outcrops are made by breaking the rocks to create road cut or mine limestones, the rocks of breccia parts are considered to break from the unconsolidated matrix.

Underlying limestone substrates also show some changes by subaerial exposure. Matrices of the limestone substrates, especially of 3–4 m from the boundary, are often washed out by meteoric water, leaving pores which have been filled later by blocky calcite cement (Jiju, 1995).

Karst landforms of the southern Okinawa Island have quite distinct features. Limestone ramparts are commonly seen at fault scarps. Backward of the rampart is commonly flat, forming limestone planation surfaces (Arakawa and Miura, 1990; Pl. 7). We can only see residual pinnacles of several metres distributed very sparsely on the planation surfaces. These landforms seem to have no relation to the sedimentary facies, and they must have been formed by karstic erosion. Indeed, it seems that limestones of the lower part is much exposed at foot of the ramparts as seen in Tsukazato and other areas (Fig. 4). The ramparts commonly have elevation of ten or twenty metres compared to the planation surfaces of backwards. Accordingly, the limestone must have been eroded at least equivalent metres from the top of the original surfaces.

These landforms are quite different from the landform of the area of Palaeozoic limestone in the northern Okinawa Island, where cockpit karst is developed (Arakawa and Miura, 1990). The landform of the Palaeozoic limestone have many cones and cockpits, and has topographic differences of a hundred metres. The difference of the landform is probably due to erosional time and their lithologies. The Palaeozoic limestone has been suffered by long-term erosion in the northern Okinawa Island, resulting mature karstic features. Moreover, stratal permeability of the Palaeozoic limestone is quite low, and water mainly moves by conduit flow through fractures and cave systems (Choquette and James, 1988). This probably causes selective erosion due to dissolution along the conduit passes, creating many cockpits. By contrast, in the southern Okinawa Island, karstification of the Pleistocene Ryukyu Group is not enough matured to create such undulated topographies. Moreover, stratal permeability of the Pleistocene limestone is quite high, because they preserve many primary intergranular and intragranular porosities, and also secondary porosities of dissolved biological aragonitic skeletons. Water mainly moves by diffuse flow in the limestone itself in this situation (Choquette and James, 1988), and dissolution of the limestone proceeds uniformly, forming karstic planation surfaces (Arakawa and Miura, 1990). The limestone ramparts at fault scarps are probably created by following mechanisms. In southern Okinawa Island, many faults separate the Ryukyu Limestone into many blocks, and each block tilt toward south to southwest (Section III-A; Figs. 4, and 5). In this case, soils tend to move toward to downwards in each block, and the soil cover become thin or almost does not exist at the top of the fault scarp. As a result, the fault scarp can escape from the serious dissolution by acid from soils mainly of $CO_2$ and active cementation occurs at exposed rock, causing case-hardening (MacNeil, 1954; Ireland, 1979). These conditions are considered to form limestone ramparts on the fault scarps. On the other hand, Hoffmeister and Ladd (1945) shows that similar features of limestone ramparts can be easily created by simple experiments. They gave a fall of hydrochloric acid rain of a thousand litters to a rectangular parallelepiped of limestone among three months, which was set to have five degree from horizontal ground. They observed a rimed feature developed at edge by the erosion proceeding at downward of the acid rainfall. Purdy (1974) also shows more detailed experiments, and indicate that short time of the inundation of rainwater is needed to form a ridge of the edge.

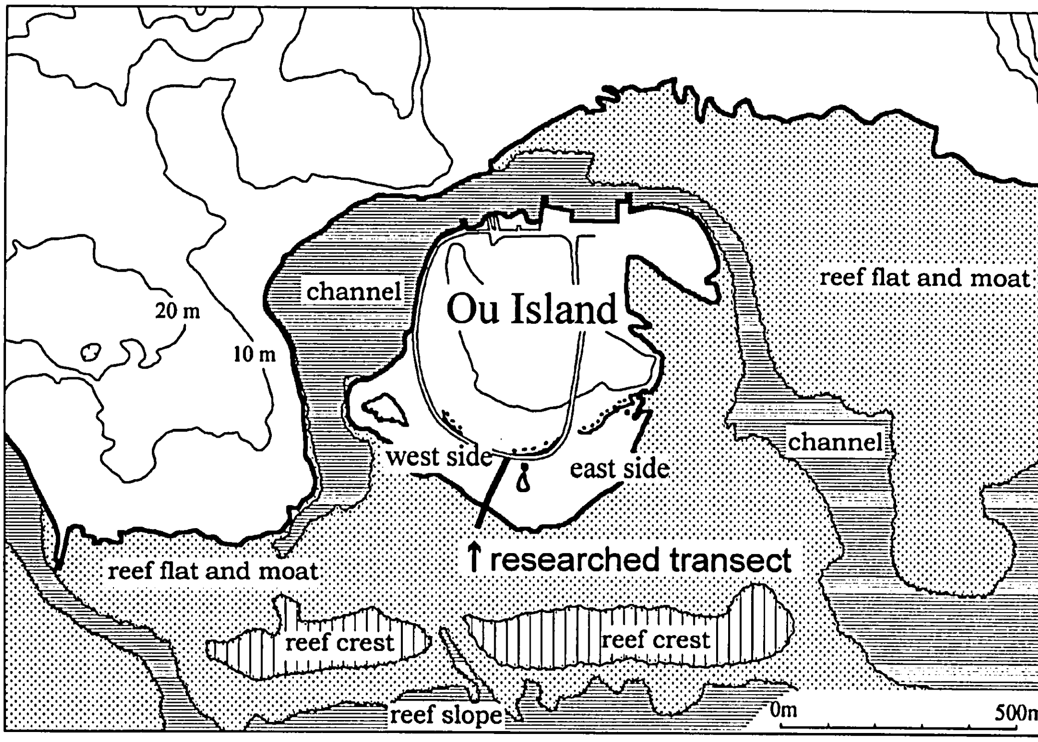
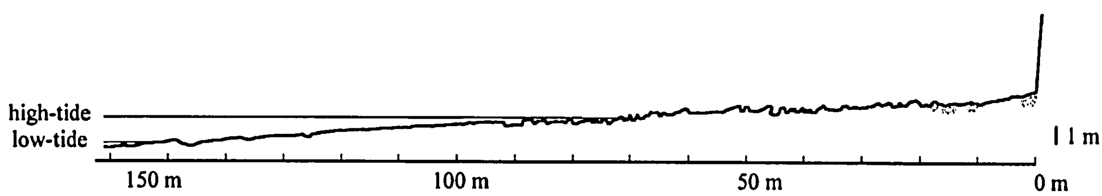



Fig. 13. Locality of the researched transect of recent coastal alternation. The research is conducted at southern coast of Ou Island, Tamagusuku Village in southern Okinawa Island. The south coast is divided into east and west sides. The east side is situated in more severe condition for plants because the side faces to the channel. The study was mainly done at the west side where many coastal plants are seen.




| Environments | Subtidal | Intertidal | | | Supratidal | |
|---|---|---|---|---|---|---|
| **Zones** | *Goniastrea aspera* | Sipunculids | *Isognomon - Planaxis* | | *Limonium* | *Lepturus* |
| **Seawater conditions** | Always wet by seawater | | Dry during a low tide | | Usually away from seawater | |
| **Surficial features** | Relatively smooth surface, although many borings are developed | | Karren | Undurating surface having karren and kamenitzas | | Sand deposition, kamenitzas development |
| **Substrate alteration** | Heavily bored by invertebrates destruction of original textures | | Less bored, relatevely preserve original textures | | Rhizoliths are developed, although borings are not common, sporadical development of consolidated soil | |

Fig. 14. Transect of the recent coast in Ou Island. Localities are shown in Fig. 13. Scales are vertically enlarged at three times. The transect is divided into five zones by the dominant biological components.

The limestone planation surfaces are widely spread not only in the southern Okinawa Island, but also in most of the Ryukyu Limestone exposing areas of the Ryukyu Islands. The flatness of the limestone plane surface is highly suggestive for the flatness characteristics of the unconformable surface in limestone of the Ryukyu Group. In other words, we should not expect a complicated geometry of the unconformable boundary of Pleistocene limestone, and it could be a similar appearance to an ordinary bedding plane.

**B. Exposure Surfaces in Coastal Areas**

In coastal areas, the rock surface is not covered by unconsolidated soils as seen at inland areas. The rock surfaces are directly exposed, and this leads to formation of characteristic exposure surfaces in coastal areas.

To clarify present coastal exposure features, outcrops, fauna, and flora were observed along the transect (Fig. 13) in the rocky cost of Ou Island (E1 in Fig. 6) which includes the shallow subtidal, intertidal, and supratidal environments (Fig. 14). The observation along the transect was mainly made in February 18-23, 1997. The substrate is well-sorted detrital limestone of the Minatogawa Formation, which is foraminiferal and algal grainstone, containing autochthonous coral skeletons in some cases. Pedogenesis on the inland terraces is also observed at some localities of the Ryukyu Group.

The coastal area of Ou Island is divided into east and west side by the central rock bodies (Fig. 13). In the east side, plants are barren and limestone substrates are not altered by pedogenesis. This may results in the fact that east side of the coast is located beside a channel and often influenced by storm waves, that causes a severe condition for the plants. Well development of kamenitzas (Pl. 7) might indicate frequent splash to the east side. Karren are also developed but the surfaces are relatively smoother than that of the west side. In the west side, a supratidal area of the coast is protected by the reef crest and the central rock bodies from waves and winds on storms. As a result, the limestone substrates are sporadically covered and altered by plants in the supratidal environment. By contrast, in intertidal to subtidal areas of both the east and west sides, the limestone substrates are altered by boring organisms.

The transect was placed on the west side in order to clarify the influence of the plants and pedogenesis to the underlying limestone substrates. It includes the very shallow subtidal, intertidal, and supratidal environments. The transect is further subdivided into five zones by dominant fauna and flora; from seaward to landward, they are *Goniastrea aspera*, sipunculids, *Isognomon-Planaxis*, *Limonium* and *Lepturus* zones (Fig. 14).

*Goniastrea aspera* zone

This zone is a very shallow subtidal environment, and the limestone substrates are always under the seawater. Corals such as *Goniastrea aspera* sparsely grow on the substrates. The limestone was only coated by very thin sand connected by algae, and is almost exposed to seawater. In this situation, various organisms live and bore the limestone substrate.

Sipunculids zone

In this zone, the limestone emerges during a low tide, although the limestone substrates are always wet by seawater. The surface of the limestone is relatively smooth (Pl. 8). Corals are not living and non-calcareous algae such as Monostroma nitidum cover the substrates. Sipunculids, together with other invertebrates, commonly bore and they seriously destroy the limestone substrates (Pl. 9).

*Isognomon-Planaxis* zone

In this zone, the limestone substrates are dry during a low tide. The limestone has jagged surfaces, and karren and kamenitzas are prominent from the middle of this zone toward land (Fig. 14; Pl.10). Sipunculids are not able to live in this zone. Instead, bivalves and gastropods live onto the rocky substrates (Pl. 11). The most common bivalves, *Isognomon* acutirostris live in the seaward part of this zone. Gastropods, such as *Planaxis* sulcatus are most common in this zones, but occurrence of gastropods such as *Nodilittorina* spreads to the *Limonium* and the *Lepturus* zones.

*Limonium* zone

Seawater does not reach even during a high tide in this zone. Karren and kamenitzas are prominent. Plants such as *Limonium*, *Philoxerus*, *Portulaca*, and *Suaeda* are growing, although diversity of the plants is small (Pl. 12). Unconsolidated dark red soils, which are largely distributed on the inland terrace of Okinawa Island, is not developed. In this situation, the plants seems to grow on rock surfaces using the fissures and pores. The substrates usually exhibit sporadic distribution of the pedogenetically altered parts (Pl. 12) coloured bright brown to pale yellow.

*Lepturus* zone

This zone is characterised by accumulation of coastal sand in the depressions of kamenitzas (Pl.13). The flora growing on the sandy substrates is dominated by *Lepturus* and *Zoisia*. The roots of these plants probably stabilise the sandy sediment, and penetrate the sand and also the underlying limestone substrates (Pl. 14). This leads to plants such as *Limonium* also live on the rocky surface of this zone. The sand is often removed and relatively smooth surfaces are left at the site.

Limestone substrates are intensely bored and decomposed by sipunculids and other invertebrates in the *Goniastrea aspera* and sipunculids zones. The bored holes of these invertebrates are often filled with materials of light grey colour. The substrates themselves are also altered to materials of dark greyish yellow in colour, where the superimposed borings decompose the original texture (Pl. 9). Both of the materials have consolidated features and are fine grained, which may be consolidated by or composed of micrite cements. Variable amount of bioclasts and quartz grains occurs in the materials, and give the materials a very poorly sorted feature (Pl. 15). Substrates are also bored by molluscs in the *Isognomon* and *Planaxis* zone, although they usually do not completely decompose the original textures of the limestone substrates.

In the subaerial environment, different type of alteration occurs. In the *Limonium* and *Lepturus* zones, limestone substrates are affected by pedogenic alteration, instead of the alteration by boring invertebrates. The alternation is mostly associated with the rooting of plants. The coastal plants tend to vegetate on sand bodies in fissures, on kamenitzas, and pores. Bottom parts of the sand bodies are commonly humic and black to dark-brown in colour (Pl. 14). This humic sand sometimes develops only around the roots, especially of the plants such as Limonium, which cannot keep a large amount of sand under the roots.

The humic sand and limestone substrates around roots are considered to alter into characteristic bright brown to pale yellow fine-grained sediments. The rigid skeletons, such as foraminifera and corals tend to be preserved. These brown sediments are commonly well lithified, except for very recent ones which often exhibit muddy features by wetting. The sediments generally contain brown ped clots of 1–2 mm in diameter, and also abundant rhizoliths in the matrix (Pl. 16). Thin section shows details on altered textures. The materials show a poorly-sorted micritic texture and contain fine quartz grains (Pl. 17). Friable limestone particles are also observed in the altered material. The rhizoliths are often filled with finer light grey micritic material.

Microborings by fungal or algal endoliths are found in almost all the specimens from the transect. They mainly bore the topmost part about 5 mm from the exposure surface (Jiju, 1995). The borings penetrate not only skeletal grains but also blocky calcite cements, and this case indicates that the limestone was bored after the lithification. Rock surfaces are commonly coloured grey to olive black, and have characteristics of phytokarst together with the jagged surfaces (section V-B).

## VII. Unconformable Boundaries in Limestone in the Ryukyu Islands

### A. Unconformity between the "Reddish Limestone" and Overlying Limestone in the Naha Formation

An unconformable boundary between the "Reddish Limestone" and the overlying Naha Formation is well exposed at quarries in Mabuni, Uegusuku, Kyan, and Oyakebaru areas. Observation of the boundary is mainly made at quarries in Uegusuku-Mabuni area (Fig. 6, A1-3). A detailed sketch of the outcrop of A1 (Pl. 18) is shown at Fig. 15.

The "Reddish Limestone" usually consists of detrital or rhodolith limestones, which does not indicate shallow marine environment, but beneath the unconformable boundaries, it often includes algal crusts and even changes into coral limestone. The unconformable boundary is commonly very sharp, and cuts corals and crustose algae in the underlying limestone (Fig. 15; Pl. 19).

The boundary commonly appears a jagged surface, and there are many irregular voids of several centimetres below the boundary (Fig. 15; Pls. 20, 21, 22, and 24). These textures are very similar with what we can see at landscape of coastal phytokarst of the recent exposure surfaces (Section VI-B). The void is normally filled with marine sediments, forming neptunian dykes. The sediments include foraminifera, sometimes rhodoliths and molluscan shells. The upper parts of the voids are often not completely filled with the sediments, and the spaces were later filled with cements, forming geopetal textures (Figs. 22, and 25).

The boundary normally lacks unconsolidated paleosols. Instead of the unconsolidated palaeosols, the limestone of 20 cm beneath the boundary normally exhibits consolidated brown coloured substrates, probably due to coastal pedogenesis (Pls. 23, and 24). It has also tiny voids of 1 millimetre probably of root moulds, which are also well observed at recent coastal areas (Pl. 25). In contrast, sediments of the neptunian dikes are commonly white in colour, and usually there is no evidence of pedogenesis (Pl. 21). An exception that there are no unconsolidated palaeosol is only found at Makabe Quarry (Fig. 6, A3; Pl. 26). In the

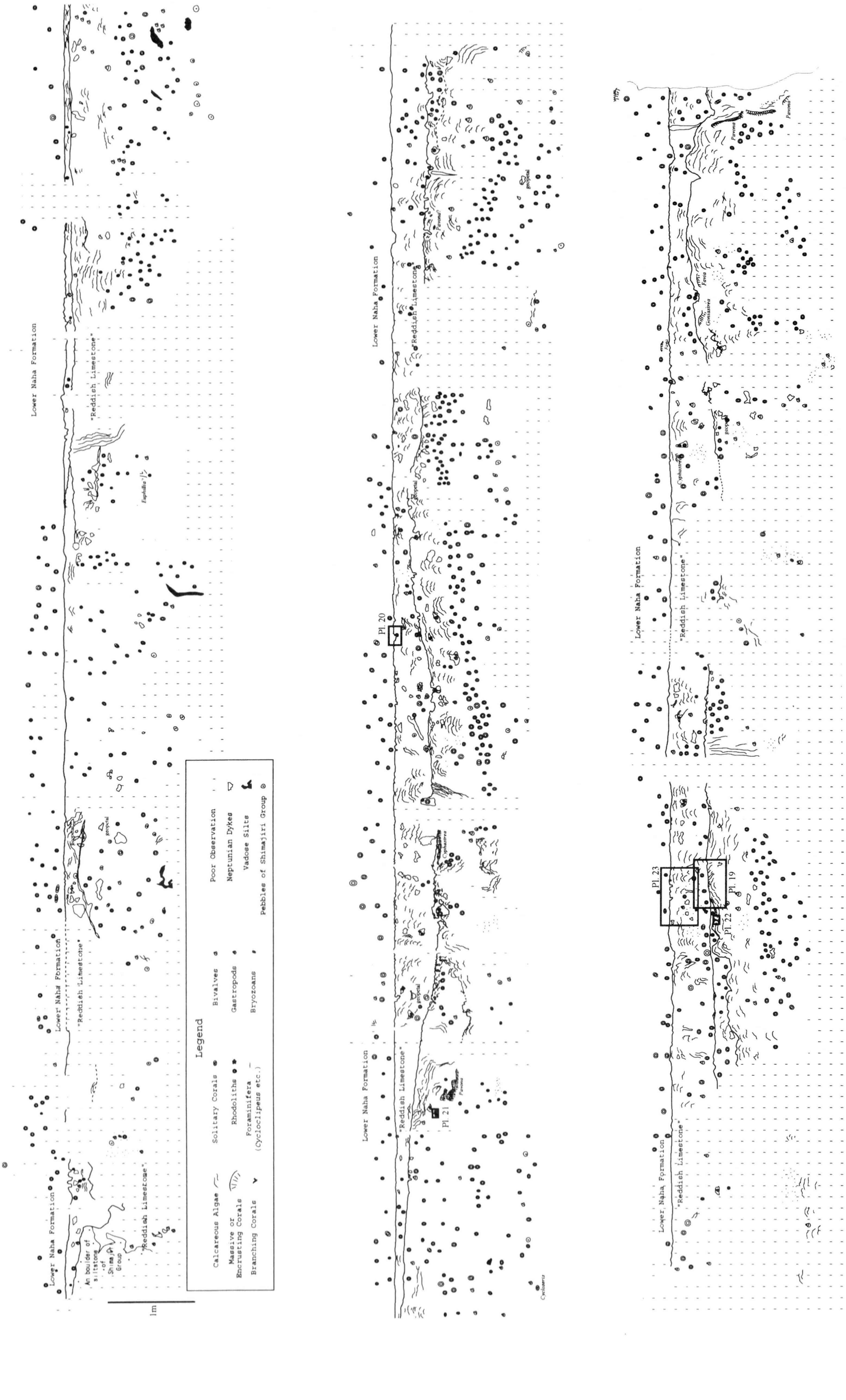



Fig. 15. A sketch of the outcrop showing unconformable boundaries between the "Reddish Limestone" and the lower Naha Formation, which is continued to next pages. This sketch is drawed at an outcrop of Pl. 18 of a quarry A1 in Fig. 6. Tiny neptunian dykes are seen below the boundary, and fill pores of probably coastal erosional origin. There seems to be three erosional surfaces. Each of them cut the structures of underlying limestones. Locations of plates are shown as black squares.

Makabe quarry, palaeosols are seen at depression of the boundary. Development of the soil is good, and fairly easy to recognise it as a palaeosol compared to the palaeosols in the Naha Formation (section IV-B). Root tubules are seen in the palaeosols, though it is necessary to pay attention that they might form after the quarry is made (Pl. 27).

Locally, it seems that this unconformable horizon include similar three unconformable surfaces (Fig. 15). The lowermost surface is normally undulated and has different topographic height of several tens cm. The middle surface is less undulated, and it cuts the lower surface. The uppermost surface is normally very flat, and it cuts the lower two surfaces. Other characteristics of these surfaces are quite similar. Each of the surfaces has jagged surfaces, and it cuts fossil skeletons of the underlying limestone. Each of the underlying limestone commonly has similar brown colour and neptunian dikes. Lithologies are also seems to be same, as algal crusts are common, and often corals are seen. Lithology apparently changes at the uppermost surface. Above the uppermost surface, we can not observe pebbles of the Shimajiri Group, and the colour change into white due to reduction of terrestrial component. Algal crusts and corals is not common, instead, many rhodoliths are seen. Thus, the uppermost surface seems to be a formation boundary.

These boundary surfaces are normally flat in outcrop, having less than a metre-scale undulation (Fig. 15). The flatness is probably due to flatness of original sedimentary topography of rhodolith or detrital limestone often covered by decimetre scale algal crusts. Moreover, erosion can also create flat surfaces as abrasion surface on coastal areas, though karstic planation can also create flat surface at more inland place. The flat unconformable boundaries seem to be somewhat undulated in wider scale than outcrops (Fig. 5).

The "Reddish Limestone" is laterally change into blocks of boulder size (Pl. 28). Suggestive recent features for these boulders are seen in western coastal areas of Kyan (Pl. 29). The seaside of rocks are eroded at coastal areas, lose the balance, and are divided into many rocks. The limestone of the Ryukyu Group would probably slipped down on the muddy Shimajiri Group, and we can see the limestone separated into many blocks there.

### B. A Distinct Unconformity of the Ryukyu Group in Makisan Quarry in Irabu Island

We can observe a distinct unconformity in Makisan quarry in Irabu Island (Fig. 6, B1). This boundary is correspond to the unconformable lithological boundary in lower part of the Middle Member (between C-1 and R-1 units) by Honda et al. (1993), and to the unconformity boundary between the Lower and the Middle Members by Sagawa (1998MS).

In Makisan quarry, thick coral limestone in which terrigenous component is rich are superimposed by pure limestone in which rhodoliths and corals are intermixed. It seems that there are at least three unconformable planes within the intermixed sediment of several metres, though these planes could not entirely be traced at the outcrop (Fig. 16; Pl. 30).

The unconformable planes cut fossil skeletons of corals and algal crusts of underlying limestones (Pl. 31). Beneath each of the plane, the colour appears brown, and there are many neptunian dikes (Pls. 32, and 33), which are quite similar features of the unconformable boundaries of the "Reddish Limestone" and the overlying Naha Formation of the Naha Formation in the southern Okinawa Island..

These planes have undulated features, having more than 3 metres elevation height undulation (Fig. 16), which is in contrast to relatively flat features of the boundary of the southern Okinawa Island. The undulating shapes of the boundary are often followed by colonial configuration of corals and algal crusts, though some of them are steeply cut by the unconformable boundaries (Pl. 31). The underlying coral limestone is considered to have been developed in shallow sea, which is characterised by thick corals like *Acropora*. Therefor, it is plausible that the undulating shapes are mainly ascribed to the complex shapes of thick coral limestone, which is considered to be developed at shallow sea, and has spur and groove structures.

### C. Unconformable Boundaries in the Naha Formation

Unconformable boundaries within the Naha Formation show relatively obscure features, and tend not to be recognisable in outcrops. The author provides examples of distinct unconformities found in Kyan and Mabuni areas, displaying the typical features, which are found between the lower and upper the Naha Formations.

#### 1. The boundary in Kyan Area

There are quarries in Kyan area, in which a distinct unconformity is well observed (Fig. 6, C1-3). The unconformable boundaries exist between relatively thick coral limestone containing *Acropora* and the overlying rhodolith limestone.

In the quarry C1 that is located in south of Kyan (Fig. 6; Pl. 34), we can see branching corals just below the boundary, indicating that they developed at very shallow depth like moat (Fig. 17). Above this coral limestone, rhodolith limestone indicating palaeodepth of 50-150 m,

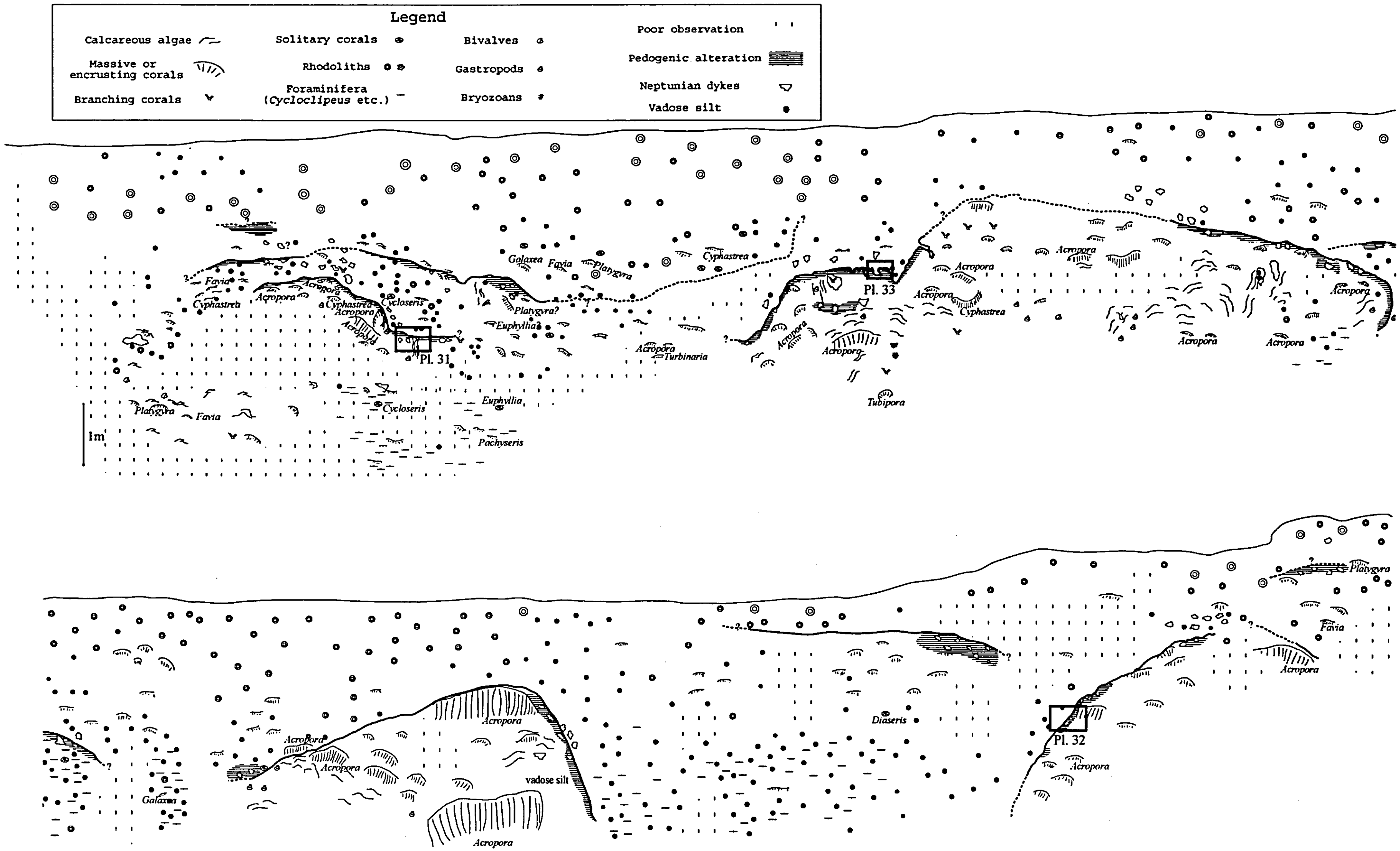



Fig. 16. A sketch of the outcrop showing unconformable boundaries between the Lower and the Middle Members of the Ryukyu Group in Irabu Island. It is continued to next pages. A view of the quarry is shown in Pl. 30. Tiny neptunian dykes are seen below the boundary, and fill pores of probably coastal erosional origin. There seems to be three erosional surfaces. Each of them cut the structures of underlying limestones. These characteristics are similar to what we can see in the Fig. 15. However the boundaries are more undulated than the case of the southern Okinawa Island. Locations of plates are shown as black squares.

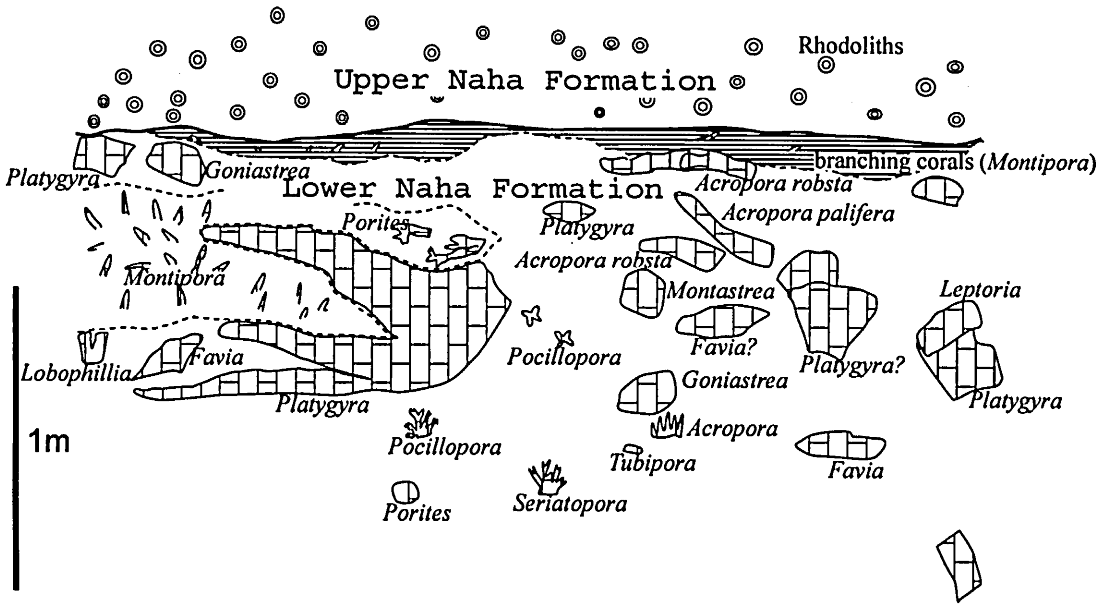



Fig. 17. An unconformable boundary between the lower and the upper Naha Formation in a quary located in southern Kyan (C1 in Fig. 6; Pl. 35). Corals are shown by brick pattern, while rhodolith are shown by double circles. Palaeosols (horizontal line) are seen just below the boundary and fill the spaces among branching corals.

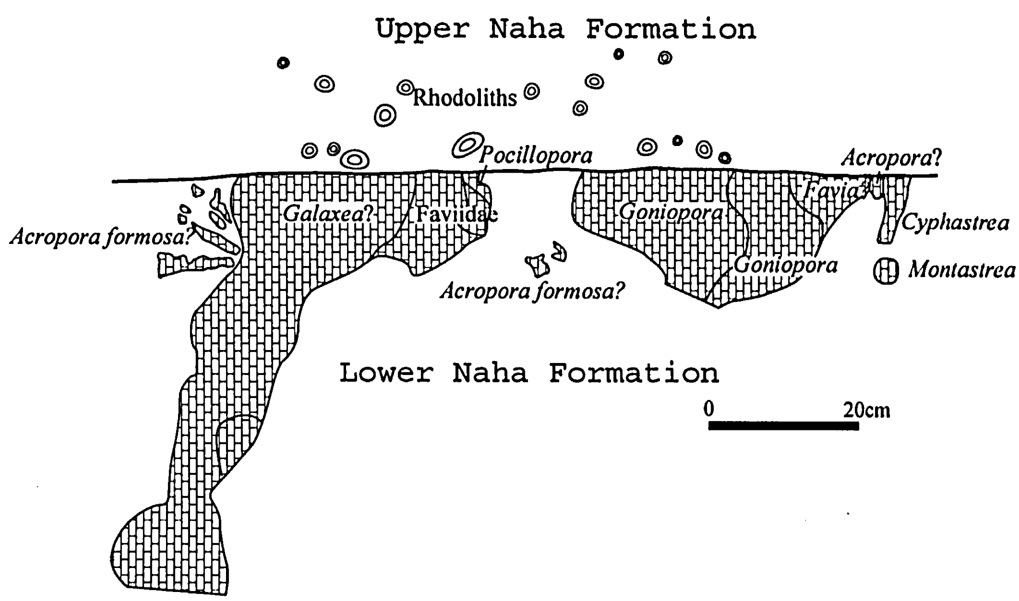



Fig. 18. A sketch of the boundary between the lower and the upper Naha Formation, in a quarry north of Kyan (C3 in Fig. 6; Pl. 37). The coral skeletons of the lower Naha Formation are cut by the bounday.

directly overlies. Unconsolidated palaeosol is seen just below the boundary, especially of their loose parts, and fills voids of porous coral limestone, such as ones between coral branches (Pl. 35). The palaeosol developed within the Naha Formation is normally not conspicuous compared to those developed between the formation boundaries. Therefor, it might be confused with recent soil coming from top of the ground through conduit, unless it is found only just below the boundary. The boundary seems very flat, and is almost concordant with bedding planes dipping several degrees toward west in a quarry of C1 (Pl. 34). The plane is very sharp and the lithological change from coral to rhodolith limestones is abrupt (Fig. 17).

In a quarry of C2, which is located at nearby the C1, a comparable unconformable boundary seems to cut coral limestone structures (Pl. 36). This very sharp boundary

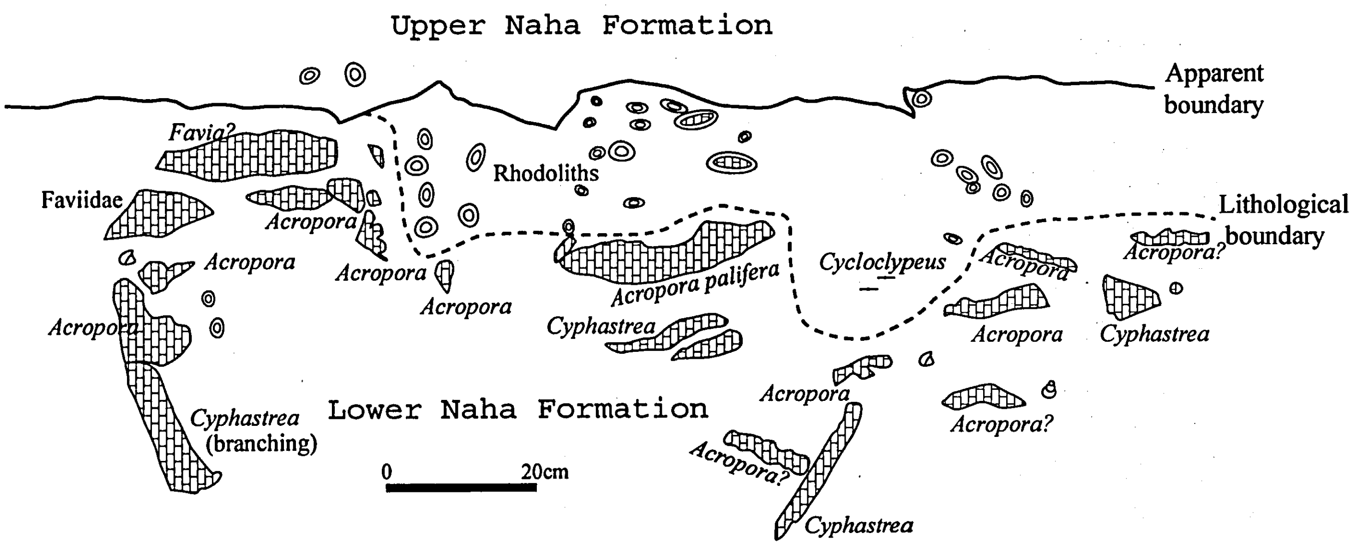



Fig. 19. A sketch of the boundary between the lower and the upper Naha Formation, which is located at the same quarry of the Fig. 18 (Pl. 38). The lithological boundary is not concordant with the apparent boundary seen from a distance.

becomes ambiguous at southern coastal areas. We often cannot place the exact boundary at outcrops where they lack remains of paleosols, and lithologies of above and below the boundary have similar characteristics, such as colours, grain size, cementation and hardness. Additionally, freshness of the outcrops seriously influences the recognition of the unconformities.

There is also an interesting phenomenon that the apparent boundary, which is clearly seen from a distance, does not always indicate the true unconformable boundary. The boundary appears very sharp and flat, when we observe it apart from the outcrops. In a quarry of C3, an unconformable boundary is seen, which is comparable to the boundary of C1. The lithologic change from the coral to rhodolith limestones is abrupt in the quarry. Many coral fossils are cut by the boundary (Fig. 18; Pl. 37), and this indicate that the boundary is formed by erosional event, such as subaerial exposure. These features are very similar to what we can see at a quarry of C1. However, true boundary, which is traced along the surface dividing different lithological components is not always concordant with the apparent boundary seen from a distance, and it partly runs below the flat appearance boundary. Fig. 19 (Pl. 38) is a sketch of the same boundary of the Fig. 18 from the same quarry, where the lithological boundary of coral and rhodolith limestones are not concordant. Similarly, in an outcrop of C4 in Itosu, the lithologic boundary between the lower coral to the upper rhodolith limestones is not partly concordant with a flat apparent boundary. In this outcrop, the apparent boundary is covered by a speleothem of 5 millimetres (Jiju, 1994MS), which may indicate that the apparent boundaries were formed by passing groundwater. These facts may indicate that the appearance boundaries were formed in meteoric diagenesis, and that hydrological behaviour of groundwater was controlled by lithological difference in permeability. If it is true, the true unconformable boundary is somewhat more undulated than the flat appearance boundaries.

**2. The boundary in Mabuni Area**

In Mabuni area, an unconformable boundary exists within rhodolith limestone of the Naha Formation. The boundary seen at a quarry of C5 (Fig. 6) does not show conspicuous features, but unconsolidated palaeosol remains in fissures and voids just below the boundary (Pl. 39). Rhizoliths of root tubules cemented by sparry calcite are seen in the palaeosol (Pl. 40). Neptunian dykes are also found beneath the boundary (Pl. 41).

Limestones of both above and below the boundary shows a similar lithology of rhodolith limestone. However, coral skeletons are only seen around the boundary in a part of several cm sections (Pl. 42). It is difficult to identify whether the corals belong to upper or lower limestones. However, occurrence of the corals indicates shallow environments during a period when the unconformity was formed. It is considered that the sea-level rise and fall was too rapid to remain thick shallow-sea deposits.

**D. Unconformity between the Naha and Minatogawa Formations**

We can see an unconformable boundary between the Naha and Minatogawa Formations at coastal areas of Cape

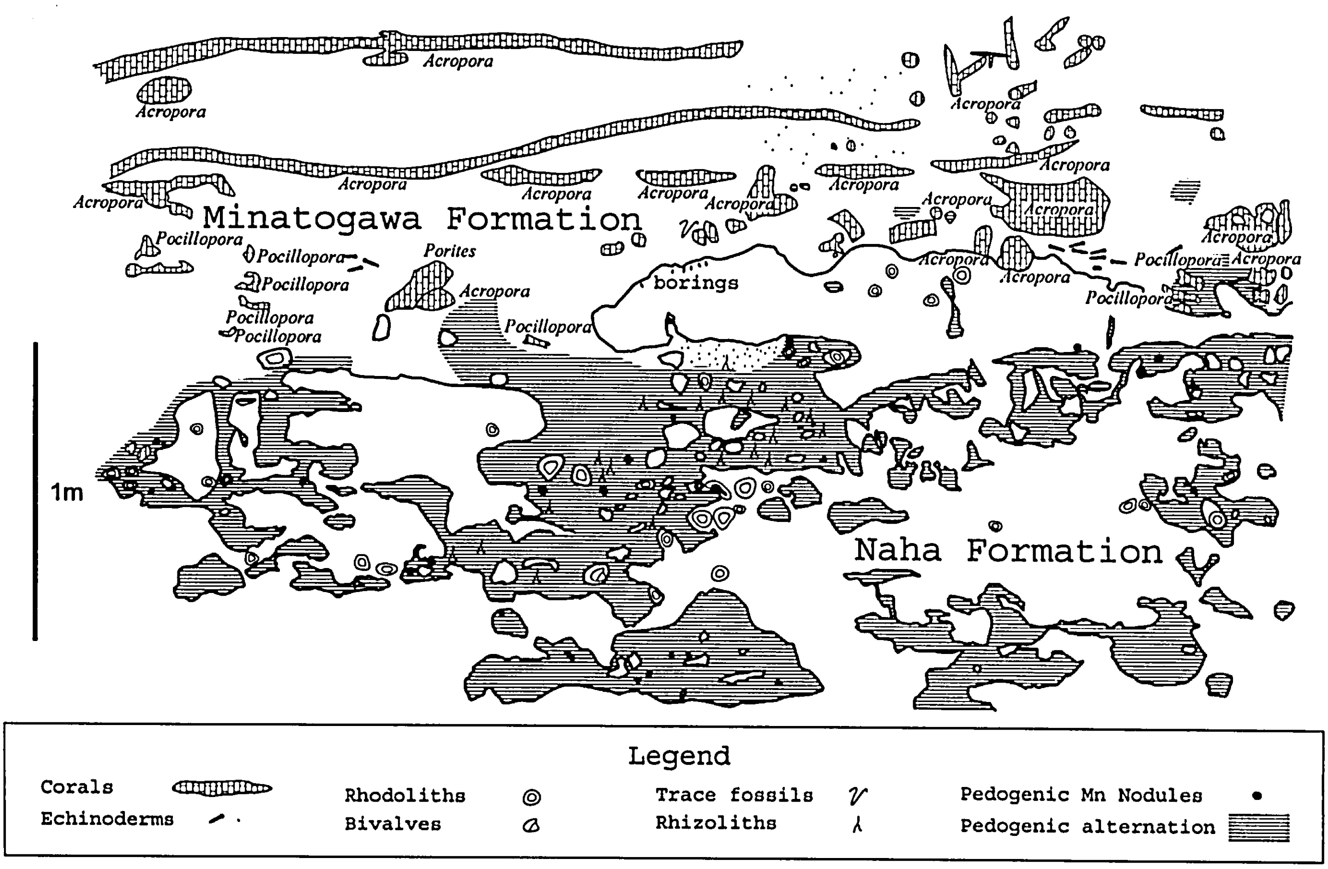



Fig. 20. Unconformable boundaries between the Naha and the Minatogawa Formations in southern Kyan (D1 in Fig. 6; Pl. 43). The Naha Formation was affected by intense pedogenic processes and highly brecciated, and many rhizoliths and pedogenic Mn nodules are observed.

Kyan (D1, Fig. 6) and Komesu (D2, Fig.6).

In the Cape Kyan area, the Naha Formation consists of rhodolith and detrital limestone, while the overlying Minatogawa Formation consists of limestone conglomerate and coral limestone in an ascending order. The conglomerate includes abundant coral skeletons and lithoclasts of the Naha Formation. The thickness of the limestone conglomerate of the Minatogawa Formation varies laterally (normally less than 1 m) and thins out on the outcrop of D1 (Fig. 20, Pl. 43).

The underlying Naha Formation typically shows brecciated texture (Pls. 44, 45 and 46), which resembles to recent pedogenic breccia (Pls. 4, and 5). Matrix of the breccia is commonly consolidated and consists of bright brown to light yellow orange and very fine material. Rhizoliths are also commonly developed in the matrix (Pl. 47). The altered sediment contains many manganese nodules (Pl. 47), that resemble to manganese nodules found in recent soils of the Ryukyu Islands (Ooshiro and Nohara, 1976; Ooshiro, 1977).

The breccia is commonly autochthonous in origin. The clasts of the breccia have sometimes very angular shapes, showing that the breccia is formed by fracturing the underlying limestone (Pl. 44). Some of these clasts show more rounded shapes especially in mature breccia, and look like limestone conglomerates of the overlying Minatogawa Formation. However, the clasts of the breccia show irregular shapes, and lack coral skeletons that are not components of the Naha Formation in this area. In the rhodoliths limestone, the clasts tend to consists of limestone fragment of rhodoliths (Pls. 45 and 46), which commonly show very irregular shapes. It seems that rigid parts of limestone like rhodolith survived from the alternation, and friable or week parts like matrices and fractures were selectively attacked by pedogenetic processes.

As the outcrop is exposed for long time, the younger Minatogawa Formation was also affected by recent pedogenetic alteration. The unconformable boundaries seems ambiguous by the alternation. However, this alternation is not intense enough to create much soil materials and prevailed breccia, seen at the uppermost Naha Formation.

We can see other interesting structures i.e. tiny trace fossils on the surface of the boundary (Pl. 48). The textures are similar to those we can see at recent coastal areas (Section VI-B).

**E. Paleosol within the Minatogawa Formations**

Two paleosol layers occur within detrital limestone of the Minatogawa Formation in the quarry of Horikawa, Tamagusuku Village in the southern Okinawa Island (Fig. 6, E2). They generally show unconsolidated features. They are extremely flat, and develop parallel to bedding planes of the detrital limestone (Pl. 49). The thickness is ten to several tens centimetres.

A paleosol layer is also exposed in southern coast of Ou Island (Fig. 6, E1; Pl. 50). As it exposes on coastal area, the paleosol is consolidated. It resembles to recent pedogenetic products on coastal areas, but we can recognise it as a layer intercalated with detrital limestone. Rhizoliths of various sizes are common in the paleosol (Pls. 51, and 52). Rhizoliths of a few centimetres in diametre are well observed, which are too large compared to recent plants nearby intertidal zone, and presumably of ancient age (Pl. 52).

At Makiminato in Urasoe City (Fig. 6, E3), detrital limestone appears and they show steep cross-lamination which have dips of about 15° (Pl. 53). It seems eolian deposits in this area. A paleosol layer of about 20 centimetres is very flatly intercalated in the limestone (Pl. 54). We can find many rhizoliths in the paleosol (Pl. 55).

The paleosols in the Minatogawa Formation are characteristic in terms of having extremely flat surface at the contact to the underlying limestone. This may be related to original flatness of the detrital limestone, and also to the relatively short exposure time.

## VIII. Characteristic Features of Unconformable Boundaries in the Ryukyu Islands

Unconformities in Okinawa Island are classified into four in terms of stratigraphic relation; that are, 1) unconformities between the "Reddish Limestone" and the Naha Formation, 2) within the Naha Formation, 3) between the Naha and Minatogawa Formation, and 4) within the Minatogawa Formation. They are different in features, which result from the different circumstances of exposures and depositions.

The unconformity between the "Reddish Limestone" and the Naha Formation is characterised by the textures of a phytokarst in recent coastal areas. The surface is relatively flat, but somewhat jagged, and commonly accompanied with neptunian dykes filling small karstic voids (Section VII-A). The pedogenesis probably affected on coastal areas to form consolidated soils (Section VI). It seems that coastal karstification prevails on the unconformable boundaries. Exceptions are only seen in Makabe Quarry that has an unconsolidated paleosol in depressions of the layers, which could be developed in inland areas. In some case, the unconformity includes three unconformable planes within a metre sections, which shows quite similar features. The unconformity in the Ryukyu Group in Makisan quarry in Irabu Island has similar features to that on the "Reddish Limestone" in Okinawa Island. The two unconformities are probably correlatable in both terms of pedogenetic environments and age of formation. Undulated features in Irabu Island is in fact different from relatively flat features in southern Okinawa Island, but it seems that the difference comes from basement topography of underlying limestones (Section VII-B).

The unconformities seen in the Naha Formation show less clear features, compared with all other unconformities. This is mainly because of similarity in lithologies above and below, and lack of sufficient soil development. The small amount of soil is only observed at fractures and voids. The unconsolidated nature of the soils was probably originated from inland pedogenetic environment, where soils are not consolidated. Because the pedogenesis was weaker, compared with one forming unconformity between the Naha and Minatogawa Formations, the exposed substrates was not brecciated. As a result, unconsolidated soils only remained at small fractures and voids after the transgressive seawater eroded the mantling inland soils. The lithological change is abrupt from coral to rhodolith limestones along the sharp boundary. However, the boundaries are ambiguous in cases without paleosols and sharp lithological change. Whether we can find evidences of unconformity also depends on freshness of outcrops. Because of poor development of paleosols or unconsolidated features of the paleosol, the paleosols are easily confused as soils from the ground. However, the soils from the ground surfaces tend not to be completely arranged with the bedding plane.

According to Honda et al. (1993) and Sagawa (1998MS), there are several unconformable boundaries in the Middle Members of the Ryukyu Group, which may be correlated with the Naha Formation. The author also observed some of the outcrops on Irabu Islands, but could not detect clear diagnostic features of unconformities at the outcrops, except for very unclear pigmentation of soils. This may indicate that there are many unconformable boundaries within the

Naha and correlative formations, which is difficult to be identified in outcrops.

The unconformity between the Naha and the Minatogawa Formations has more matured features. The outcrops show pedogenically brecciated textures, including many Mn nodules in the matrices. The matured features may imply long time interval of non-deposition.

The unconformities within the Minatogawa Formation have flat surfaces that probably reflect to the original topography of stratified detrital limestone, and also short time interval of exposure. Unconsolidated paleosols are well preserved, probably because the paleosols were quickly buried under sediments at beach, and were protected from erosion by seawater.

It seems that the unconformities have variation in features due to the age of sediments, although they have developed under the same climate of the humid subtropical Ryukyu Islands. At the same time, the unconformities of the same stratigraphic position share peculiar features. This probably means that the textural variation is related to the pedogenetic modes i.e. exposure intervals, substrate topographies, soil-forming places, and so on (Jiju, 1999).

There still remains some questions that the author could not reach to the answers. Why the coastal erosional surfaces were widely remained especially on boundaries of the "Reddish Limestone" and Naha Formation, which have three erosional surfaces? Were the large amplitude sea-level changes truly happened between each of the three unconformable boundaries, as indicated by the change in environment from subaerial to depth of rhodolith limestone (50-150m)?

## IX. Geology of the Southern Okinawa Island

### A. Evolution of the Ryukyu Group in the southern Okinawa Island

In this study, the Naha Formation in the southern Okinawa Island is separated into the lower and upper parts. Evidences that indicate unconformities described in Section VII-C is mainly observed from the boundary, including neptunian dykes, palaeosols, and cutting structures of underlying limestones. In the columnar sections in Figs. 7-12, wavy lines show the horizons where any kinds of evidences of the unconformities were found. The wavy lines concentrate their distribution near the boundary between the lower and upper parts of the Naha Formation. The fact indicates that this boundary was formed by a serious pedogenetic processes and is regarded as the most prominent unconformity in the Naha Formation. This unconformity mostly accords with the boundary of the Lower and Upper Formations of the Ryukyu Group in Takayasu (1978) and that of the Lower and Upper Naha Formations in Jiju (1994MS).

To consider succession of the Naha Formation, we have to take in account what kind of columnar sections can appear in different localities, because the columnar sections are expected to be quite different by their locations mainly reflecting their original depths. Fig. 21 shows the schematic relation between the sedimentary facies of columnar sections and their original depths, in the circumstance that cyclic sea-level changes reflected to the vertical facies changes. The shallowest places are shown at A in Fig. 21, where much of the section is expected to be composed of the shallow coral limestones and to have many unconformities. In the sections B and C, coral limestone reduces their thickness instead of the rhodolith limestone gaining their thickness. We have to take attention that in these locations, a number of the interfingering coral limestones is largest, and reduces toward both shallow and deep sides. In the section C, coral limestone become thinner, and their biological communities may indicate deeper facies. On the other hand, rhodolith limestone prevails and detrital limestone begins to be intercalated in the section D. The deepest section E consists mainly of detrital limestone intercalated with some rhodolith limestones.

In the lower Naha Formation, most of the area contains some coral limestone layers intercalated with rhodoliths limestones (Fig. 4), and it corresponds to B and C in the Fig. 21. The areas including Komesu correspond to D, and the areas including south Makabe correspond to E, but these areas are relatively narrow. The coral limestone is thickest in the Kyan area (Figs. 5, and 7), which was the centre of the coral limestone. The lower Naha Formation typically begins with deeper facies and ends by widely spreading coral limestones and a related unconformity, although some cycles of deeper and shallower facies are seen. The boundary to the upper Naha Formation is in some case located within the rhodolith and detrital limestones in narrow deeper facies.

On the contrary, in the upper Naha Formation, rhodolith limestone is dominant facies, which correspond to D in the Fig. 21. The facies corresponds to E is only exist around the sea cliff. The facies corresponds to B and C is only seen at the area between Yoza (north) and Maehira, where the coral limestone is thick (Figs. 4, 11, and 12). This fact indicates that centre of the coral reefs of the upper Naha Formation was moved to this area, from Kyan area in the lower Naha

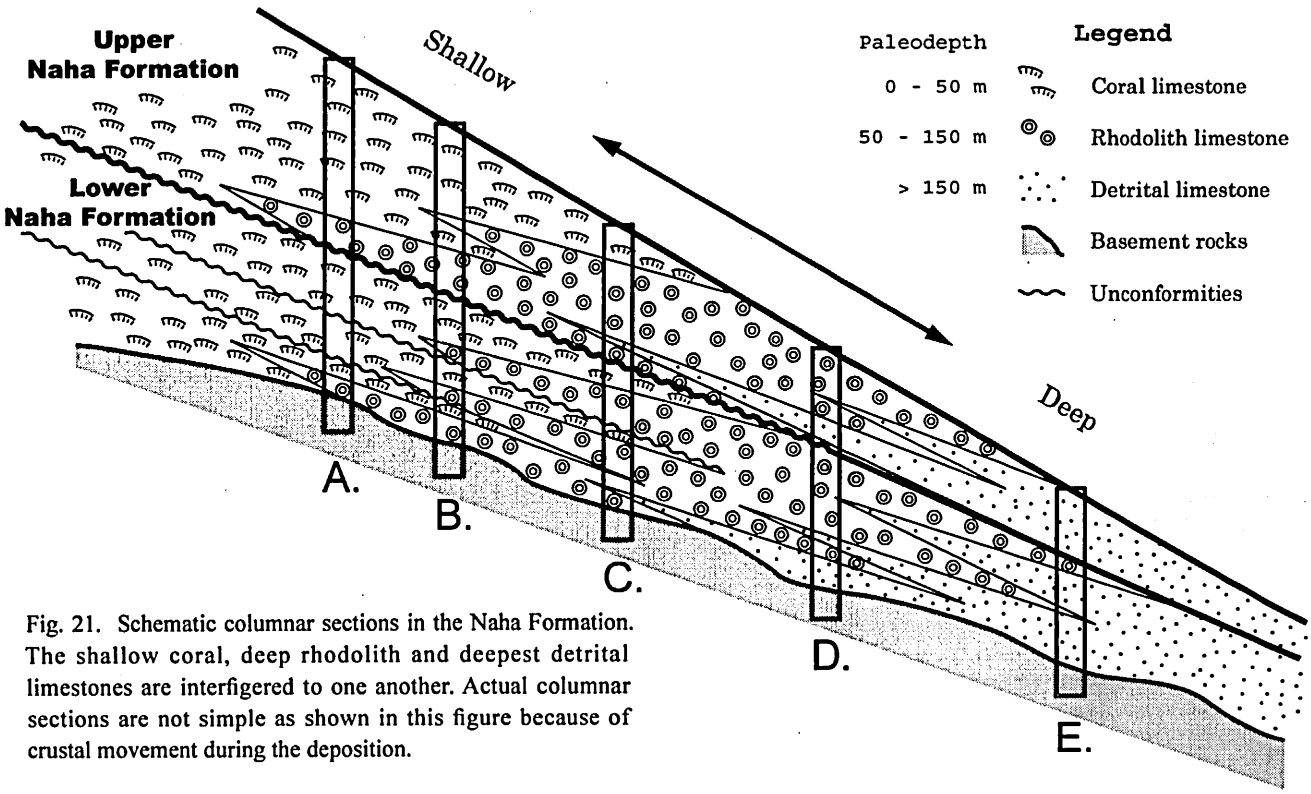



Fig. 21. Schematic columnar sections in the Naha Formation. The shallow coral, deep rhodolith and deepest detrital limestones are interfigered to one another. Actual columnar sections are not simple as shown in this figure because of crustal movement during the deposition.

Formation. On the other hand, the area of deep detrital limestone is situated at south of Tsukazato and Mabuni. The arrangement of the facies is fairly concordant with the recent topographic trends (Fig. 4). The upper Naha Formation also began with deeper facies and ended by shallower coral limestone in the shallow places, although it has some cycles of deeper and shallower facies.

In the same way, the "Reddish Limestone" seems to be thick at Kyan area or more seaward, and diminish the thickness toward Makabe. It does not appear in north of Makabe. In short, centre of the coral reef may move from Kyan area to the Yoza (north)-Takara area during the deposition of the "Reddish Limestone", the lower, and the upper Naha Formations. The upperward development of each sequence of the "Reddish Limestone" and the Naha Formation indicates that it was developed in a transgressive trend.

The Minatogawa Formation appeared just at coastal areas which has low elevations. Thus, this formation is considered to be developed in a regressive trend.

### B. Stratigraphic correlation to other regions of the Ryukyu Group

We can divide the Ryukyu Group of the southern Okinawa Island into the overall transgressive stages of the "Reddish Limestone" and the Naha Formation (Fig. 22). This trend agrees with the data from Irabu Island (Sagawa, 1998MS; Sagawa et al., 1999). In comparison with the Irabu Island, the "Reddish Limestone" and the Naha Formation can be correlated with the Lower and Middle Members of the Ryukyu Group of Irabu Island (Sagawa, 1998MS), respectively, from the ages and lithologies (Fig. 22). The Minatogawa Formation may be correlated to the Upper Member in Irabu Island, though definite correlation is not available at this moment. The boundary of the lower and upper Naha Formation is not correlatable because several unconformities were suggested within the Middle Member of Irabu Island (Fig. 22).

However, this boundary of the lower and upper Naha Formation could be lithologically correlated with unconformable unit boundaries in two geographically-closer regions including the Motobu Peninsular (Jiju and Orita, 1998), and the Ie Island (Fujishiro, 1996MS; Fig. 22). In the Ie, the unit boundary has unconformable irregular plane, and the both units above and below the boundary (units B and A; Fig. 22) have shallowing upward sequences from detrital or rhodolith to coral limestones. In the southern Okinawa Island, evidences of the unconformities are mostly found from the boundary. Both units above and below the boundary (the upper and lower Naha Formation) have similar shallowing upward sequences, although several cycles from the rhodolith to coral limestones indicating

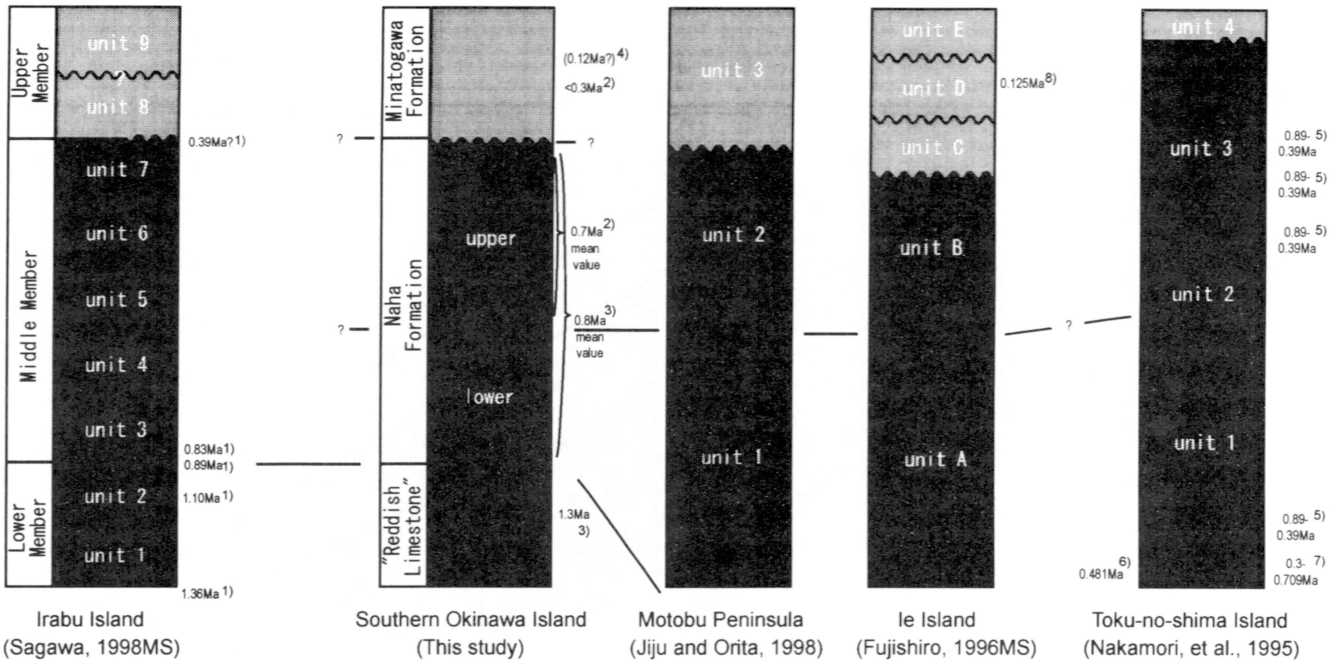



Fig. 22. Correlation of the Ryukyu Group. Coral reefs of transgrasive stage were shown by dark colour, whether those of regressive stage is shown as light colour. Determined ages are also shown, which are 1) nannofossils (Honda, et al. 1993), 2) Sr isotope (Jiju, 1994MS), 3) Sr isotope (using Kaneko and Ito, 1995; recalculated with Farrell et al., 1995), 4) Correlation with Takanasaki Formation in Hateruma Island (Nakamori,1986), 5) nannofossils (Nakamori, et al., 1995), 6) ESR (Nakamori, et al., 1995), 7) U-series age (Omura, 1982), 8) U-series age (Sasaki, private communication).

higher orders of cyclic sea-level changes are more clearly shown in the southern Okinawa Island. The typical columnar section of southern Okinawa Islands (Fig. 11) is quite similar what we can see in Motobu Peninsular (Figs. 5 and 6 in the Jiju and Orita, 1998). A couple of relatively thin coral limestone layers are seen in unit 1, and the uppermost coral limestone is thickest. These facts are shared with the southern Okinawa Island, though unit 1 is slightly thicker than the lower Naha Formation. The upper unit of Motobu Peninsular (unit 2) is also similar in terms of facies and distribution. The unit 2 mainly distributes in areas of high altitude, and its facies distribution indicates bathymetry well following to the recent topography.

There seems to be crust movements between the depositional periods of the "Reddish Limestone" to the age of the Naha Formation. The boundary of the lower and upper Naha Formation could be extended to other regions on Okinawa Islands, but not much to Irabu Island probably indicates difference in tectonic setting between the two islands.

Toku-no-shima Island also has similar stratigraphy in terms of the thickness and having two cycles of shallowing upwards. If the boundary between the two cycles is correlatable to one within the Naha Formation, similarity in tectonics is inferred. However, an ESR-dating (Nakamori et al., 1995) possibly indicates that the sequence (units 1-3) in Toku-no-shima was younger and much more quickly deposited than the Naha Formation. It is hard to consider that this thick limestone of Toku-no-shima Island can really deposit within 0.1 Ma only at about 0.39-0.481Ma ago, because there is no other reports of such high sedimentation rate from the Ryukyus. Probably, the problem is that depositional ages of the two regions (Toku-no-shima and Okinawa Islands) are poorly determined. Sr isotopic method also does not have resolution of 0.1 Ma orders, which is necessary for inter-regional correlation, although the method is still valid to differentiate the ages of the Minatogawa, Naha, and "Reddish Limestone".

## X. Conclusion

- The Pleistocene Ryukyu Group in southern Okinawa Island was mainly researched to clear the features of unconformities developed in humid-subtropical Ryukyu Islands. To elucidate the features, many outcrops of recent exposure surfaces and Pleistocene unconformities were surveyed.
- In recent inland places, unconsolidated soils are developed on the rock surfaces. Breccias of pedogenetic origin are often developed at the surfaces of the bedrocks. Unconsolidated paleosols in fissures and voids, pedogenic

breccias, and neptunian dykes can be diagnostic of unconformable boundaries. Calcrete features are usually poor, and seem not to be important to find unconformities. Karstic features including speleothems, crystal silts, caves, and cave deposits, may also be not important, because, during these features are normally developed in deep subsurface ice-house periods as Pleistocene, when amplitudes of eustatic sea-level changes are large. Karstic surfaces of the Pleistocene limestone tend to be flat, as the groundwater flows by diffuse way, because of their high permeabilities. Although the fault scalps usually form limestone ramparts, the vast development of the flat surfaces seems to reflect to the flatness of the unconformable boundaries in the Pleistocene limestone.

- In recent coastal areas, textures of the bedrocks were altered by boring organisms on the subtidal to intertidal zones, and by coastal plants on the supratidal zones. Jagged surfaces of coastal phytokarst and the brownish consolidated pedogenic material at the supratidal zones are especially useful to find unconformities. If subaerially formed voids are filled with neptunian dykes, they can be best criteria to recognise unconformities, because they indicate that the sediments were certainly submerged during the exposure events.
- The unconformable boundaries between the "Reddish Limestone" and the Naha Formation indicates a coastal environment during the emergence, which formed jagged surface with consolidated brown pedogenic materials, and neptunian dykes which fills the voids.
- The unconformable boundaries within the Naha Formation are not prominent, probably because the exposure period was not long enough to develop an extensive pedogenesis. However, we can often see paleosol in voids and fissures, and neptunian dykes in the underlying limestone. Structures of the underlying limestone are often cut by the unconformities.
- The unconformable boundary between the Naha and the Minatogawa Formations shows mature features like pedogenic breccia. Terrestrial Mn nodules are also seen in the pedogenetic material.
- In the unconformable boundaries within the Minatogawa Formations show very flat features. Unconsolidated soils remains in the unconformable horizons, probably because of rapid sedimentation of detrital limestone of foreshore sand origin.
- Unconformities of different stratigraphic horizons seen in the Ryukyu Group have thus different characteristics. They must be related to reflect the characteristics of the age like emergence time and depositional environments.
- The Naha Formation of the Ryukyu Group in the southern Okinawa Island can be separated into lower and upper parts, and many unconformable evidences are found at the boundary. Centre of the coral reef seems to move northwards away from Kyan in the "Reddish Limestone" to Yoza (north) areas of the upper Naha Formation
- The boundary between the lower and upper Naha Formation could be correlated to unit boundaries seen in Motobu Peninsular, and Ie Island. The boundary in Toku-no-shima Island might be also correlated. On the other hand it could not be easily correlated with the Irabu Island limestone. This probably reflects the difference of the tectonic settings.

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### Explanation of Plates

Pl. 1. Typical coral limestone. Autochthonous corals (C) are included.Yoza in the southen Okinawa Island.

Pl. 2. Typical rhodolith limestone. Ishiki in the southern Okinawa Island.

Pl. 3. A boundary between the underlying Shimajiri Group of bluish grey silty mudstone (SH) and the brownish coarser "Chinen sandstone" (CH). Cape Chinen, southern Okinawa Island.

Pl. 4. Typical matured soil in the Ryukyu Islands. Irabu Island.

Pl. 5. A section from a limestone quarry of the Ryukyu Group, presumably left is upper side originally covered with unconsolidated soil. The brecciated textures are well observed because the matrix soils are somewhat washed out by cutting. Miyako Island.

Pl. 6. Enlarged features of brecciated textures of Pl. 5. Many rhizoliths (R) of 1-2 mm in diametre are well observed in the matrix.

Pl. 7. Landscape of east side of the Ou Island coast. Development of kamenitzas (K) probably indicates frequent splash of seawater.

Pl. 8. Landscape of the sipunculids zone of Ou Island. This zone shows relatively flat surfaces.

Pl. 9. A broken surface of the rock surfaces of the sipunculids zone. Ou Island. The rocks are seriously bored by the organisms.

Pl. 10. Landscape of *Isognomon-Planaxis* zone. Karren become prominent in this zone.

Pl. 11. *Isognomon-Planaxis* zone. Ou Island. In this zone, bivalves and gastropods are well observed.

Pl. 12. Photographs of *Limonium* zone. Ou Island. The substrates are altered sporadically into brown pedogenic materials.

Pl. 13. *Lepturus* zone. In this zone, kamenitzas are developed and plants tend to stabilise sands on the kamenitzas. Ou Island.

Pl. 14. Sand on the kamenitzas is humic sand (S), having dark brown colours. Rock substrates also changed into consolidated brown pedogenic materials (B). Ou Island.

Pl. 15. A photograph of a thin section of a sample of the sipunculids zone of Ou Island. Multiple boring destroyed the original textures. A poorly sorted feature is one of the characteristics of this zone.

Pl. 16. Pedogenic alteration by plants. Brown ped clots of 1mm (P) and rhizoliths (R) are seen in the brown altered material. Ou Island.

Pl. 17. Microscopic textures of the pedogenic alteration. Micritic relatively poorly sorted matrices are characteristic features. Quartz grains scatter in the matrix. Ou Island.

Pl. 18. An outcrop of a quarry of A1 in Fig. 6. This plate shows left part of the sketch of Fig. 15. The boundary of the "Reddish Limestone" and the Naha Formation is shown.

Pl. 19. An unconformable boundary cutting the dome structure of an algal crust. The unconformable surface is second one from the top of the "Reddish Limestone". The location is shown in Fig. 15.

Pl. 20. An unconformable boundary of a first one from the top of the "Reddish Limestone", which corresponds to the formation boundary between the "Reddish Limestone" and the Naha Formation. The boundary cuts the rhodolith grain of the limestone below at the centre of the photo. The location is shown in Fig. 15.

Pl. 21. An irregular void cutting the structure of rhodoliths (R), which was later filled with marine sediments, forming tiny neptunian dykes. The unconformable surface is the middle one. The location is shown in Fig. 15.

Pl. 22. A geopetal structure (G) just below the lowermost boundary. The location is shown in Fig. 15.

Pl. 23. An outcrop of the formation boundary between the "Reddish Limestone" and the overlying Naha Formation. Location is shown in Fig. 15. The rock colour changes into brown beneath the boundary. There are many solution voids and borings along the unconformable surface.

Pl. 24. An unconformable boundary of the second one from the top of the "Reddish Limestone". It has brown pedogenic material of 5 cm thick. Many irregular voids filled with marine sediments, forming neptunian dykes. The shape of the jagged surface is similar to recent phytokarst in coastal areas. A quarry of A2 in Fig. 6.

Pl. 25. A slab just below the unconformable boundary of Pl. 24. Left is upper side. Complicated erosional voids are filled with white marine sediments (W). The top of the voids were later filled with cements (C), forming geopetal structures. The substrates had been altered to brown pedogenic materials, having many tiny tubular voids of rhizoliths (R), as seen in recent coastal areas.

Pl. 26. An outcrop of the boundary between the "Reddish Limestone"(RL) and the Naha Formation (NF) of a quarry of A3 in Fig. 6. The boundary is located at one-third from the bottom of the photograph. Unconsolidated dark brown palaeosols (P) are only remained at depressions of the underlying "Reddish Limestone". A hammer (H) for scale at bottom part of the right side.

Pl. 27. A clod of the palaeosol of Pl. 26. Tiny root tubules (R) fringed with white cement are seen.

Pl. 28. A boundary between the "Reddish Limestone" and the overlying Naha Formation (NF), an outcrop of A5 in Fig. 6. The "Reddish Limestone"(RL) are brecciated.

Pl. 29. Recent correlatives of the brecciated "Reddish Limestone". The coastal limestone is often separated into many blocks, probably due to erosion of seaward and losing of the potential balance.

Pl. 30. A view of the Makisan Quarry in Irabu Island. Location of the sketch of Fig. 16 is shown as a black square.

Pl. 31. An algal crust skeleton (A) is cut by the unconformable boundary (horizontal black dots). The location is shown in Fig. 16.

Pl. 32. An unconformable surface, whose location is shown in Fig. 16. Colour of the surface is pedogenically altered to brown. Complicated voids are filled with marine sediments, forming neptunian dykes.

Pl. 33. An unconformable surface, whose location is shown in Fig. 16. Complicated shape of voids are similar to that of phytokarst. Tiny tubular voids of 1 mm in diametre are seen (R), which are presumably rhizoliths.

Pl. 34. A view of the quarry of C1 in Fig. 6. Paleosols (P) are observed only loose part of the limestone just below the boundary which separates the Naha Formation into lower (LN) and upper (UN) part. The boundary tilts toward west at several degrees at this outcrop, which is almost concordant with the bedding planes.

Pl. 35. The unconformable boundary between the lower and upper Naha Formations of Pl. 34. Location of the sketch of Fig. 17 is shown by black square.

Pl. 36. The unconformable boundary within the Naha Formation, which is same to the Pl. 35 from a quarry of C2 (Fig. 6). The arrows show the direction of the coral colonies, which is cut by the unconformable boundary between the lower (LN) and upper (UN) Naha Formations.

Pl. 37. The unconformable boundary between the lower and upper Naha Formations. The sketch is shown in Fig. 18. Corals are steeply cut by the sharp boundary. A quarry of C3 in Fig. 6.

Pl. 38. The unconformable boundary between the lower and upper Naha Formations in the same quarry of the Pl. 37. The sketch is shown in Fig. 19.

Pl. 39. The unconformable boundary between the lower (LN) and upper (UN) Naha Formations. The paleosol (P) is only seen at fissures below the boundary. A quarry of C5 in Fig. 6.

Pl. 40. Cemented rhizoliths (root tubules) (R) are seen in the dark brown palaeosol of the left side of the Pl. 39.

Pl. 41. Neptunian dykes (N) which fill the irregular voids are seen right side of the photos. They are found at just below the boundary of the unconformity between the lower and upper Naha Formation. A quarry of C5 in Fig. 6.

Pl. 42. The lower and upper Naha Formations in a quarry of C5 are both composed of rhodolith limestone (RL), whereas corals (C) are only seen at the unconformable boundary.

Pl. 43. An outcrop of the boundary of the Naha and Minatogawa Formations at the south coast of Kyan (D1 in Fig. 6). The sketch is shown in Fig. 20.

Pl. 44. Pedogenic breccias near the outcrop of the D1 in Fig. 6. The shapes of the clasts are angular, and it seems the breccia was developed by fracturing.

Pl. 45. Pedogenic breccias at the coast of Komesu (D2 in Fig. 6).

Pl. 46. The clasts of the pedogenic breccia are rounded. However, it is different from conglomerate of the Minatogawa Formation, in terms of irregular shapes of the clasts, and lacking of coral skeletons. An outcrop near D1 in Fig. 6.

Pl. 47. Matrices of the pedogenic breccia. Pedogenic Mn nodules (M) and many tiny voids of rhizoliths are seen. An outcrop of D1 in Fig. 6.

Pl. 48. The limestone of the Naha Formation (NF) is seriously bored just below the unconformity to the overlying Minatogawa Formation (MF). An outcrop of D1 in Fig. 6.

Pl. 49. The plane palaeosol (P) developed within the Minatogawa Formation. A quarry of E2 in Fig. 6.

Pl. 50. A palaeosol layer (brown part) seen in the southern coastal area of Ou-Island (E2 in Fig. 6). Above this, well sorted detrital limestone overlies in outcrops nearby.

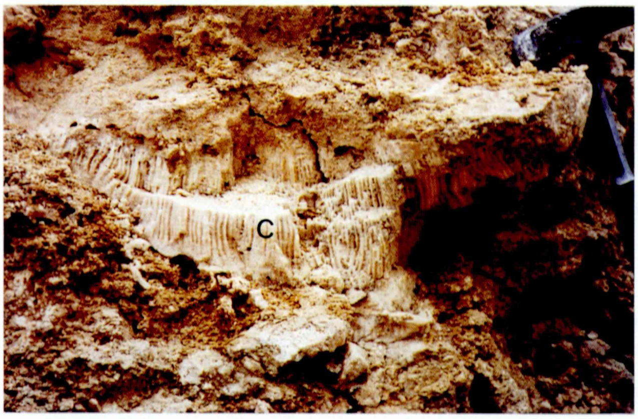
Pl. 51. Many tiny rhizoliths (R) developed in a palaeosol layer observed in an outcrop of Pl. 49.

Pl. 52. Rhizoliths having a couple of centimetres in diametre. An outcrops of Ou-Island (E1 in Fig. 6).

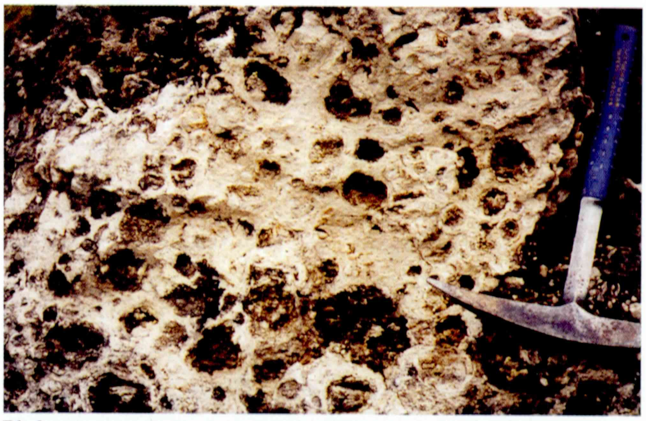
Pl. 53. Detrital limestone of the Minatogawa Formation in Makiminato region (E3 in Fig. 6). It has steep cross bedding.

Pl. 54. A paleosol layer is intercalated within the Minatogawa Formation in Makiminato region (E3 in Fig. 6).

Pl. 55. Rhizoliths seen in the paleosol within the Minatogawa Formation in Makiminato region (E3 in Fig. 6).



Pl. 1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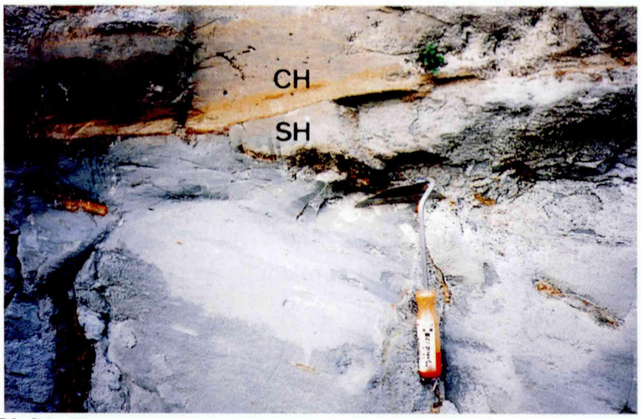
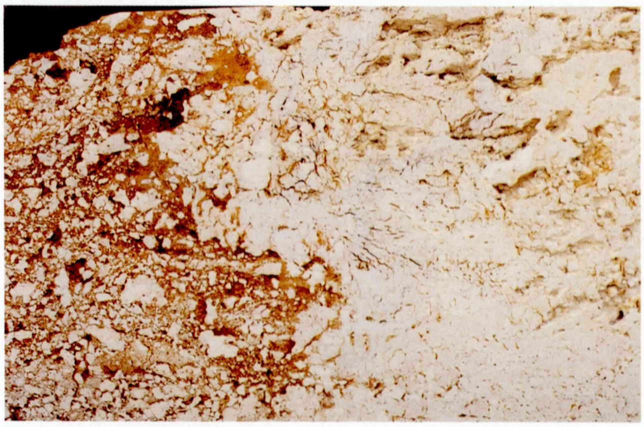


Pl. 3


Pl. 4


Pl. 5 10cm

Pl. 6 1cm

Pl. 7


Pl. 8

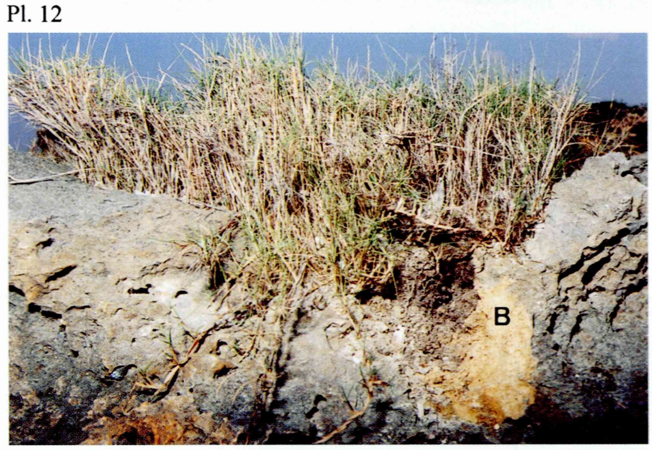

Pl. 9


Pl. 10

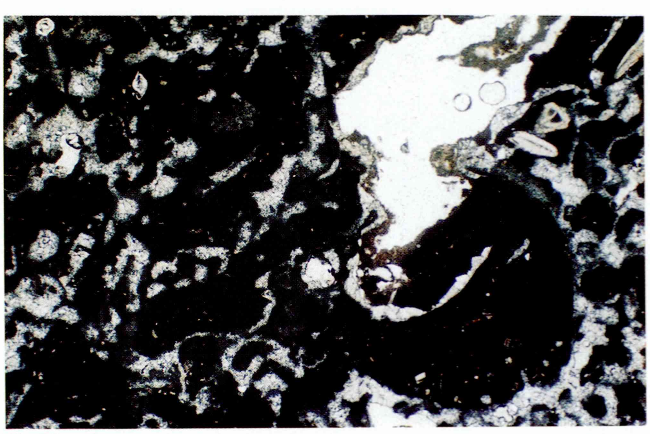

Pl. 11 1cm

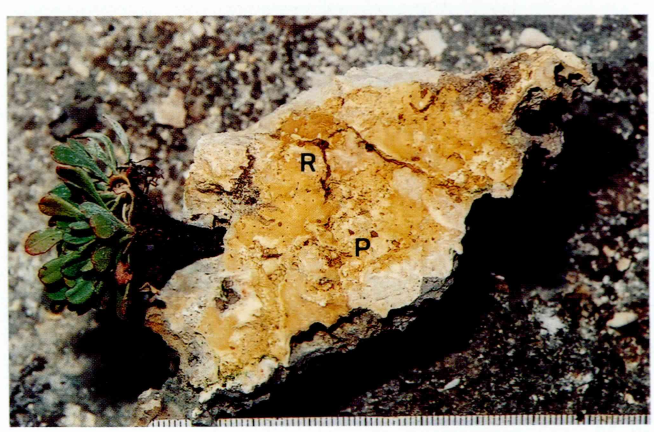

Pl. 12


Pl. 13

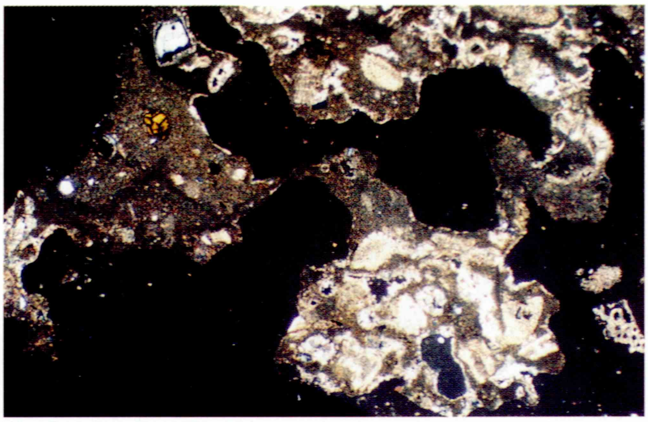


Pl. 14 10cm


Pl. 15 1mm



Pl. 16

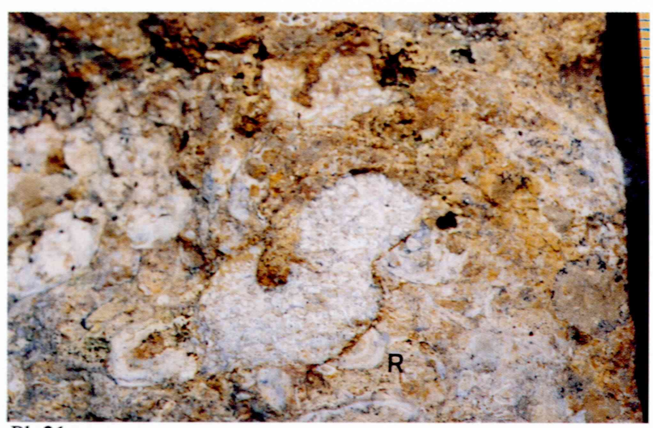


Pl. 17 1mm

Pl. 19

Pl. 18 1m

Pl. 20

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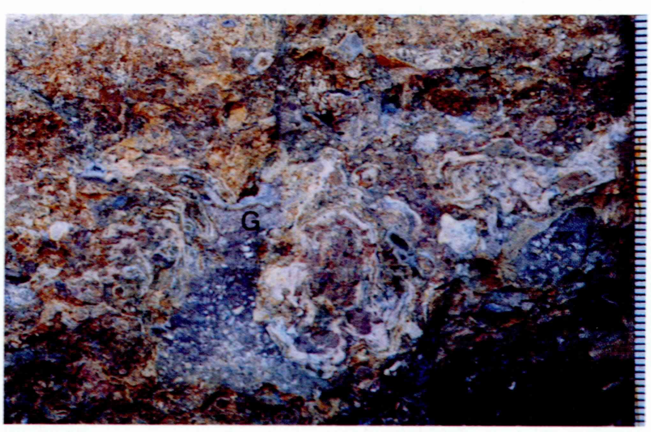
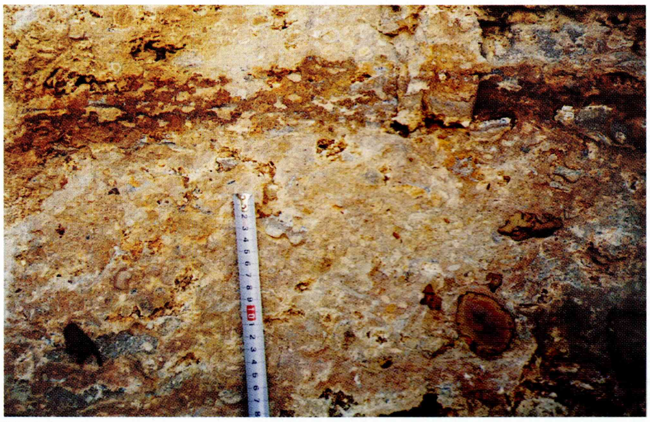



Pl. 22

Pl. 23



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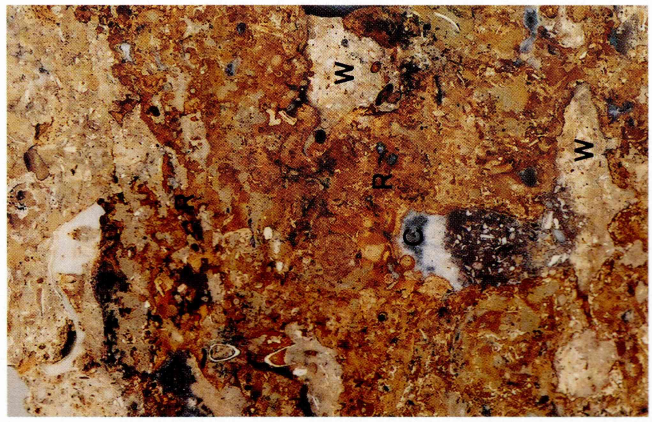
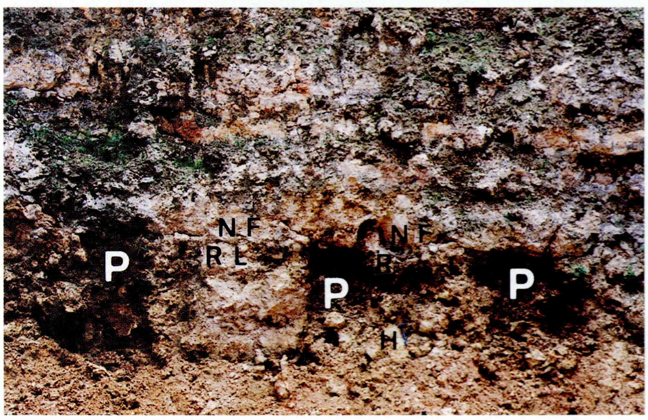
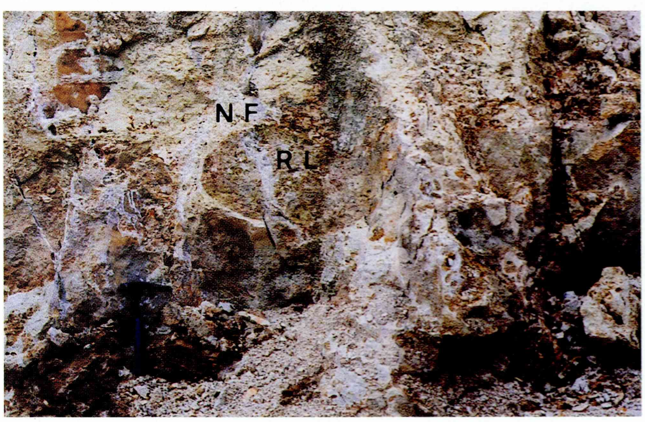



Pl. 25 1cm




Pl. 26 1m

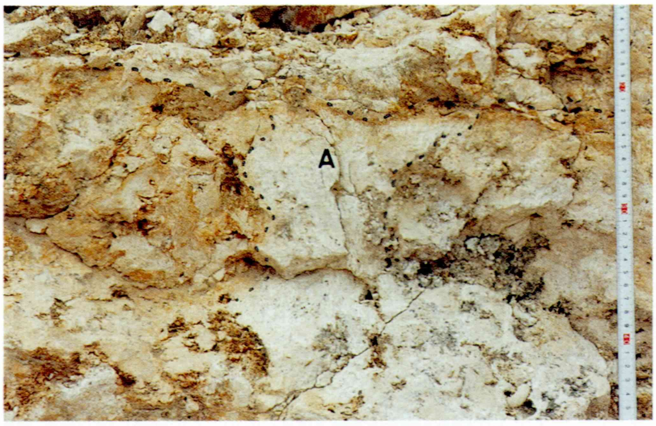

Pl. 27




Pl. 28

Pl. 29

Pl. 30

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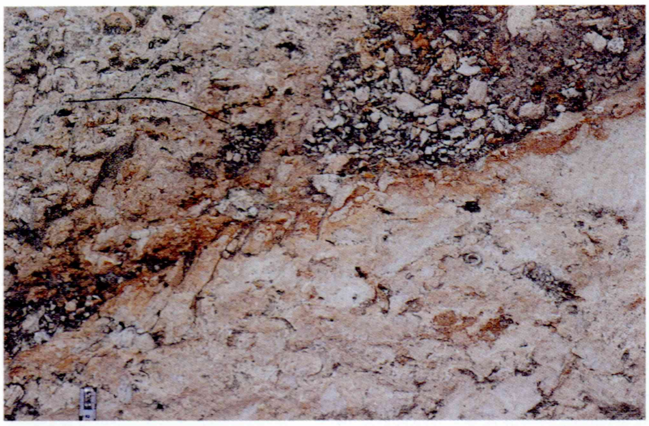
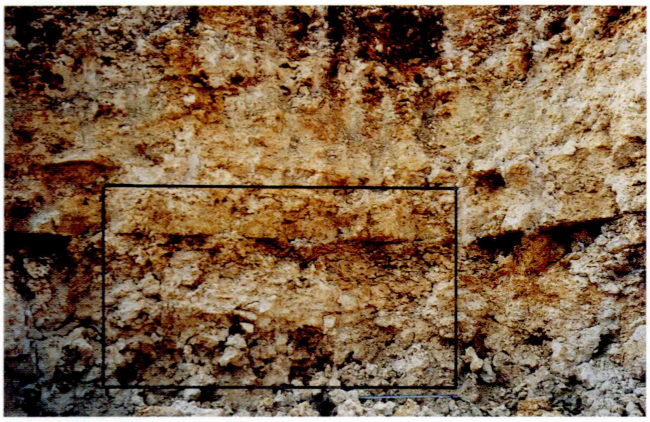


Pl. 32

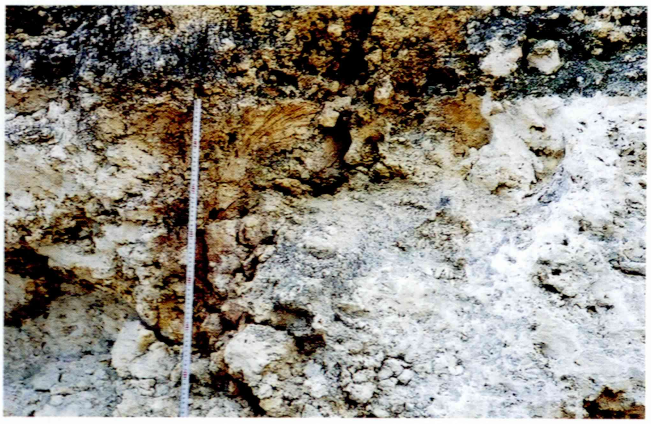

Pl. 33 1cm



Pl. 35 1m


Pl. 34


Pl. 36



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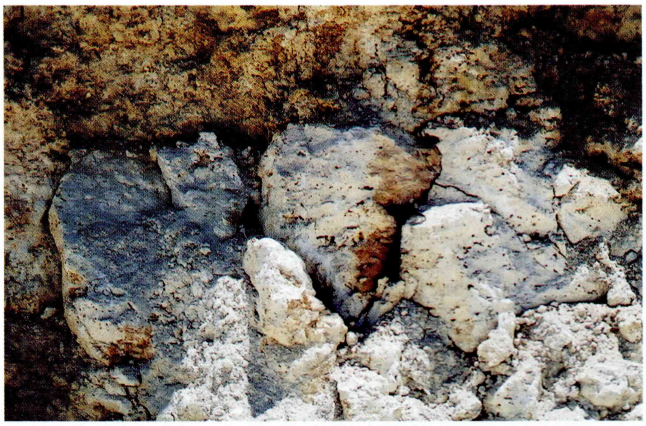
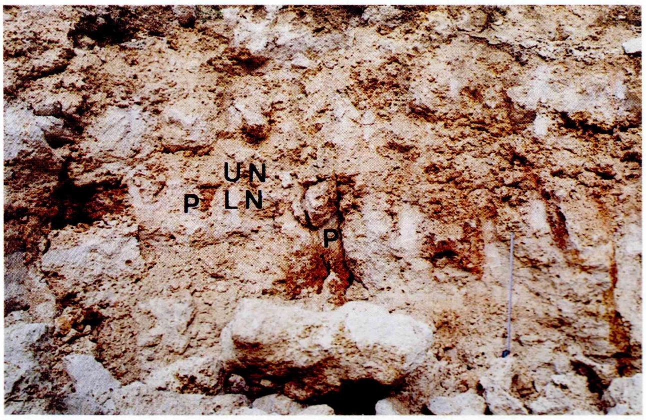
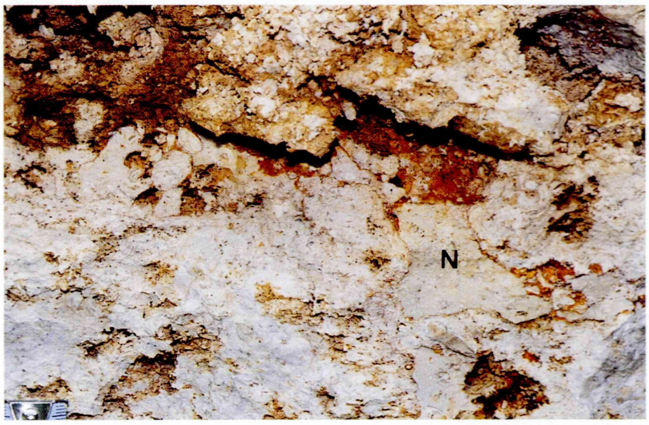


Pl. 38 10cm

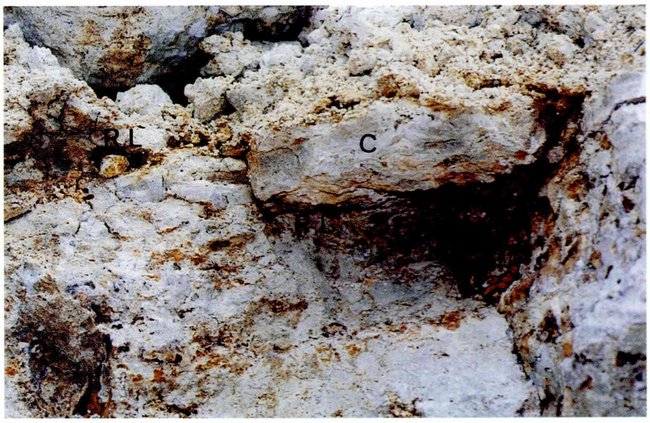



Pl. 39 1m

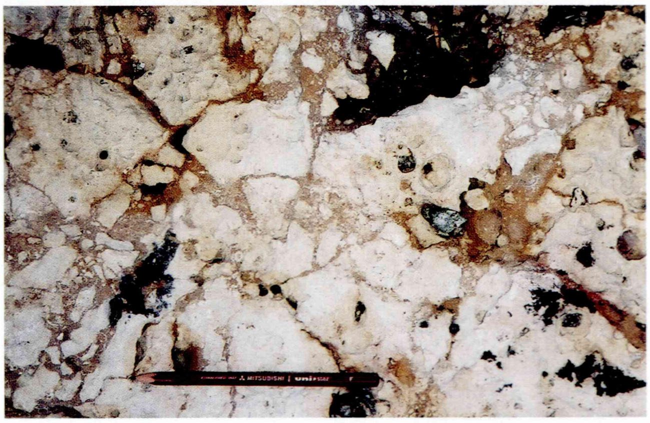

Pl. 40




Pl. 41

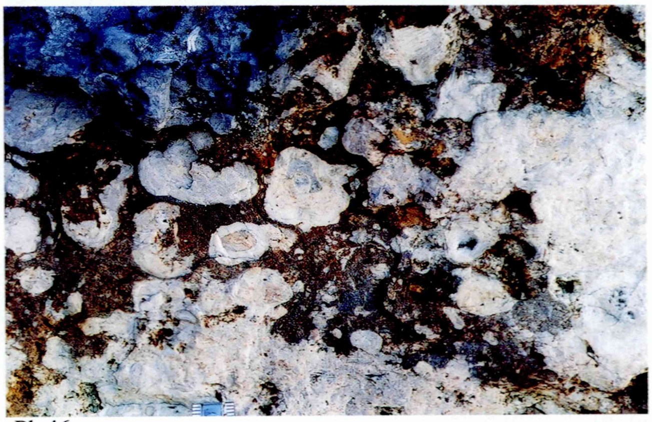



Pl. 42 10cm



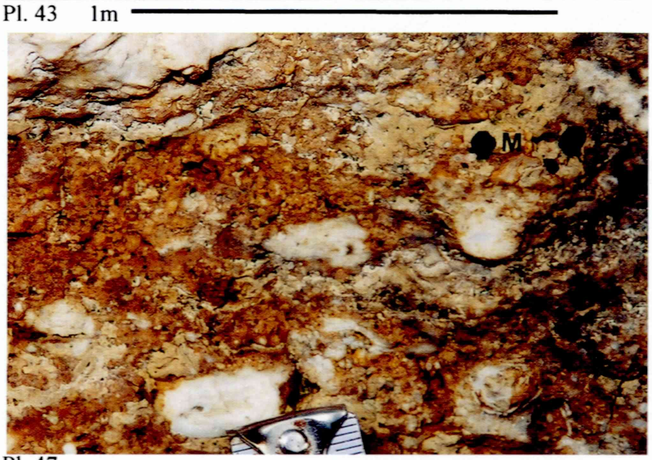
Pl. 44

Pl. 45 10cm



Pl. 46

Pl. 43 1m

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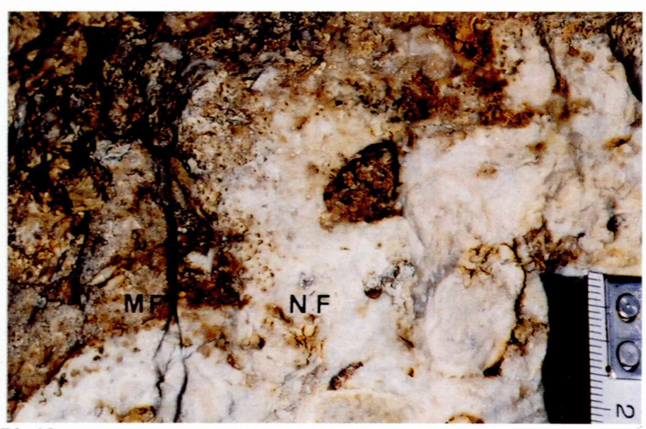
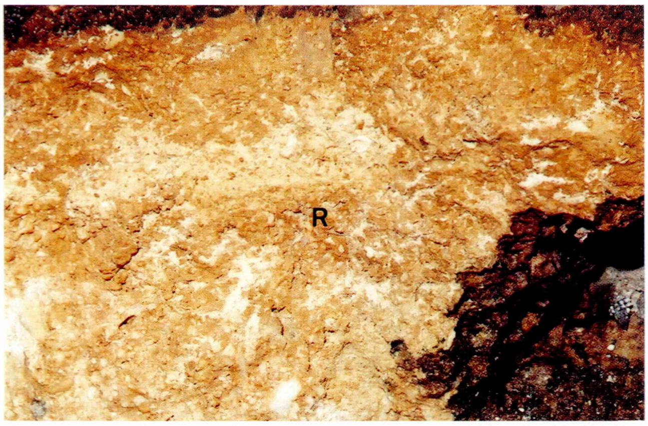


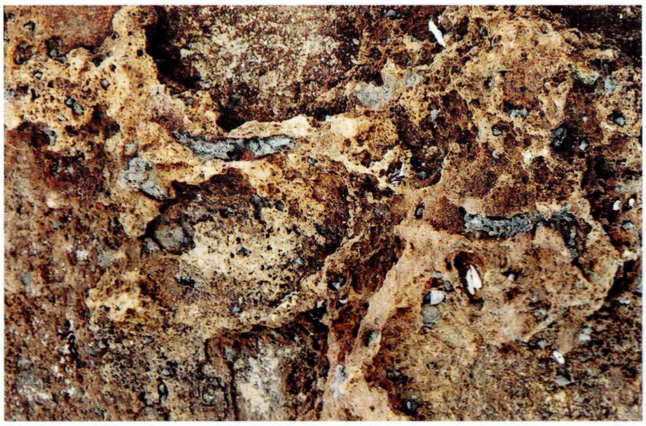

Pl. 48


Pl. 49

Pl. 50

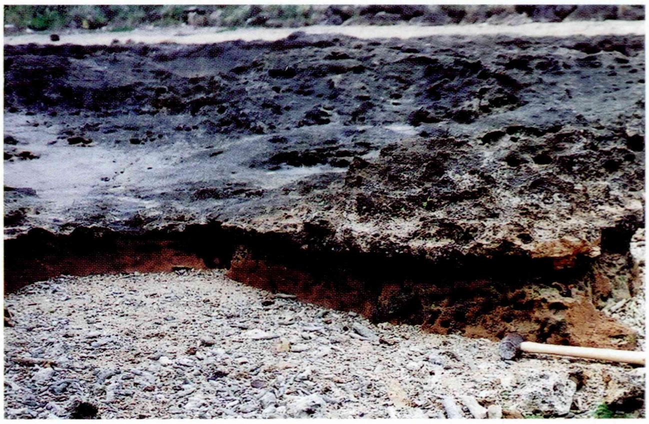



Pl. 51 1cm



Pl. 52 10cm

Pl. 53



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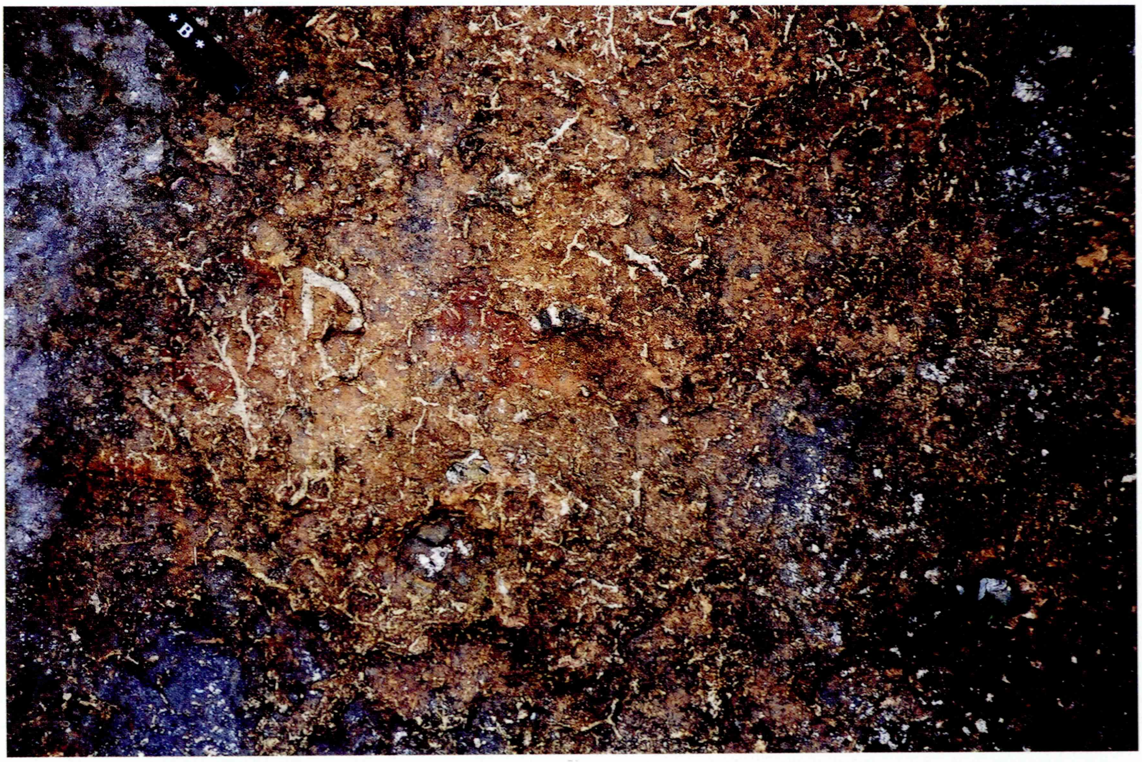

Pl. 55