# Carbonate Rocks of the Tosabae Bank off the Kii Strait, Southwest Japan

By

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## Abstract

Carbonate rocks consisting of calcite, magnesian calcite and dolomite in various proportions, were dredged from the Tosabae bank off the Kii strait. The petrology of these sediments was investigated by optical, X-ray diffraction, differential thermometric and electron microprobe techniques in order to study the lithification of the carbonate sediments in the Tosabae bank.

Magnesian calcite is considered to be a post-depositional precipitate, which occurred at water-sediment interface during cessation of sedimentation.

Dolomite is non-ideal, i.e., protodolomite, which is restricted to the superficial zone of the carbonate sediments. Dolomite may be formed by replacement of the pre-existing carbonate minerals in very shallow water or hypersaline lagoon environment. If pre-existing carbonate is magnesian calcite, formation of dolomite seems to occur more easily.

From these occurrences, the change in the environment of the Tosabae bank is summarized with the related mineralogy of carbonates as follows:

1) Accumulation of hemipelagic sediments on the Tosabae bank during middle or late Pliocene time (calcite)
2) Cessation of accumulation
   (precipitation of magnesian calcite at the surface layer of the sediments)
3) Regression and development of very shallow-water condition and/or hypersaline lagoon environment
   (formation of dolomite at the surface layer of the top sediments of the bank)
4) Subsidence of more than 180 m under sea-level.

## I. Introduction

Carbonate rocks were collected from the Tosabae bank off the Kii strait, Southwest Japan, in the course of dredging undertaken as a part of the research of the submarine geology of the Kii strait and around the Tosabae bank (Shiki et al., 1971; Kagami et al., 1971; Okuda, 1973).

These carbonate rocks may be the same as those Niino (1935) reported as "white calcareous shale" and "marly rock". All of them were hemipelagic sediments in their origin, which were mainly composed of tests of planktonic foraminifers, microcrystalline carbonate ooze and volcanic ash. Judging from the foraminifers, most of them are considered to have accumulated during middle or late Pliocene time

and are roughly correlated to the Nobori formation of Shikoku (Konda, 1972; Shiki et al., 1971). However, they show a heterogeneous assemblage ranging from slightly indurated muds to lithified rock fragments, which contain always low-Mg calcite, high-Mg calcite (magnesian calcite) and dolomite in various proportions (Table 2). They have been affected by processes of diagenesis, such as, submarine cementation and dolomitization.

The concept of submarine lithification of carbonate sediments has gained an increasing attention in recent years (Gevirtz & Friedman, 1966; Milliman, 1966; Fischer & Garrison, 1967; Milliman & Müller, 1973). Dolomitization under marine conditions has been studied by many workers and reviewed by Fairbridge (1957), Arrhenius (1963) and Konishi (1970). Marlowe (1971) and Froget (1972) investigated the lithified carbonate and phosphate rocks on the sea floor, and proposed the sequence of events which established different rock types in Carribean Sea and in Mediterranean Sea respectively.
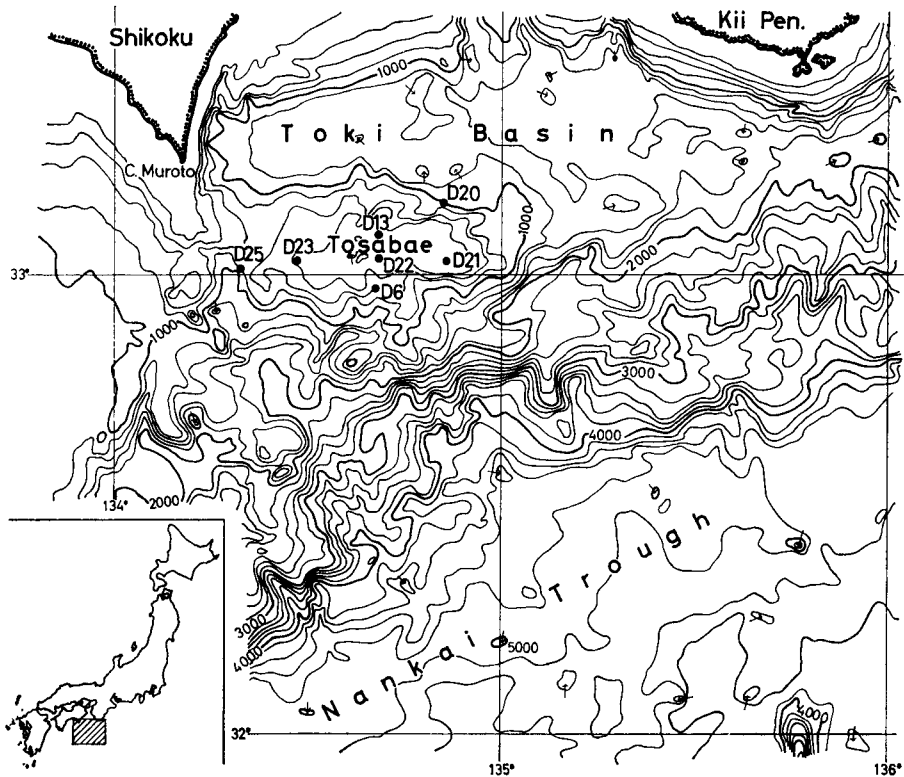


Fig. 1. Bathymetry and dredge locations in the vicinity of the Tosabae bank. Contour lines at 100 meter intervals.

    The purpose of this study is to document the occurrence and distribution of the carbonate rocks on the Tosabae bank and to estimate the environmental change with time in the Tosabae bank.

    The Tosabae bank is located between the Nankai trough and the Toki basin, and extends westward to the ridge running southward from Cape Muroto (Fig. 1). The smallest depth over the bank is 154 m, and its upper surface is characterized topographically by a complex local relief.   The bank is considered to have the basement of Paleogene and/or Miocene sedimentary rocks and some of igneous intrusions, covered with marine sediments from Pliocene to Holocene age (KAGAMI et al., 1971; OKUDA, 1973).


## II.  Analytical Procedure

    The lithified carbonate samples from around the Tosabae bank were collected by dredging during the cruises of KT–70–3 and KT–71–9 of R/V Tansei-maru (157 t).   Locations and depths of these dredges are given in Table 1.

Table 1.   Dredge locations in the vicinity of the Tosabae bank
            : The cruises of KT–70–3 and KT–71–9

| Dredge No. | | Depth (m) | Latitude (°N) | Longitude (°E) | Topographic situation |
|---|---|---|---|---|---|
| D 6 | on | 530 | 32°57.4' | 134°40.3' | the south slope of the bank |
|     | off | 560 | 32°58.4' | 134°41.2' | |
| D13 | on | 250 | 33°05.0' | 134°41.1' | the northern part of the bank |
|     | off | 300 | 33°05.1' | 134°41.6' | |
| D20 | on | 790 | 33°10.0' | 134°50.6' | the northeast slope of the bank |
|     | off | 750 | 33°09.5' | 134°52.5' | |
| D21 | on | 462 | 33°01.5' | 134°51.4' | the eastern part of the bank |
|     | off | 464 | 33°01.9' | 134°52.0' | |
| D22 | on | 222 | 33°01.8' | 134°40.5' | the central part of the bank |
|     | off | 180 | 33°02.3' | 134°41.5' | |
| D23 | on | 388 | 33°01.8' | 134°28.0' | the western part of the bank |
|     | off | 398 | 33°01.8' | 134°28.2' | |
| D25 | on | 665 | 33°00.7' | 134°19.2' | the west slope of the bank |
|     | off | 590 | 33°01.0' | 134°19.5' | |

    Carbonates were identified on powdered samples using a X-ray diffractometer with Cu-K$\alpha$ radiation.   The mole percent of $MgCO_3$ of magnesian calcite was

determined by the method of Goldsmith and Graf (1958b) using difference in the dimension of the (211) lattice plane.

Differential thermal analyses were carried out on the powdered samples with a Rigaku Denki differential thermal analyser after washed by distilled water.

Electron microprobe analyses were done by Mr. T. Ikeno and Mr. Y. Nagasawa using a instrument of JXA–50A in the Application Department, Electron Optics Division of JEOL LTD.

### III.  Occurrence and Lithology of Carbonate Rocks

Four types of carbonate rocks are recognized from lithological characteristics and carbonate assemblage, as listed in Table 2.   Of these, carbonate rocks of St. D6, St. D20 and St. D22 have been studied especially, because they are regarded to be representative in their occurrence and lithology.

Table 2.   Carbonate minerals in the rocks of the Tosabae bank

| Carbonate mineral | Dredge number | | Induration |
|---|---|---|---|
| low-Mg calcite | D13 | (–250∼–280 m) | indurated |
|  | D22 | (–180∼–222 m) | slightly indurated |
| high-Mg calcite | D20 | (–750∼–790 m) | semi-indurated |
| low–Mg calcite | D21 | (–462∼–464 m) | semi-indurated |
| dolomite | D13 | (–250∼–280 m) | semi-indurated |
| low-Mg calcite | D22 | (–180∼–222 m) | semi-indurated |
| high-Mg calcite | | | |
| dolomite | D 6 | (–550∼–590 m) | indurated |
|  | D23 | (–388∼–398 m) | indurated |
|  | D25 | (–590∼–665 m) | indurated |

**D6** (Plate 6–1)

The samples of St. D6 are fragments of well-lithified dolostones.   They are heavily bored by organisms and their surfaces are brownish in color due to iron oxide.   Their dolostones are tuffaceous and composed of volcanic glass, quartz, feldspar, tests of planktonic foraminifers, microcrystalline dolomite and clay minerals. Foraminiferal tests are rather less abundant than those in other carbonate rocks. A part of them are dissolved to form pore spaces which are sometimes filled with ferrugenous materials, and the internal structure of foraminiferal test seems to disappear under the electron microscope.   Aggregates of dolomite rhomb 2 or 3 microns in diameter are also seen in these rocks.   Electron microprobe analysis demonstrates clearly that magnesium is concentrated in both foraminiferal tests and microcrystalline carbonate cements, which are considered to be composed of dolomite (Fig. 2–1). This fact is in good agreement with the result of X-ray diffraction analysis which

indicates that these rocks consist solely of dolomite as a carbonate mineral.

KONDA (1972) gave a description of the foraminifers in these rocks. They are *Globorotaria acostaensis acostaensis, Globigerina decoraperta* and *Globoquadrina dehiscens dehiscens,* and he estimated the age as middle or late Pliocene.

Carbonate rocks dredged from St. D23 and St. D25 also contain dolomite, and are very similar in characteristics to those of St. D6.

**D20** (Plate 6–6)

The carbonate rocks of St. D20 are slightly indurated calcareous sandstones or siltstones which are pebble to cobble in size, and subround or round in roundness. Dozens of rocks were dredged, some of which are penetrated by organic borings. Almost no ferrugenous coating is seen on their surfaces. They are composed of volcanic glass, quartz, feldspar, foraminiferal tests scarcely broken and corroded, microcrystalline carbonate and clay minerals.

Electron microprobe analysis showed that magnesium is concentrated in microcrystalline carbonate and not in foraminiferal tests (Fig. 2–2). Low-Mg calcite and high-Mg calcite (magnesian calcite) are detected by X-ray diffraction analysis. Therefore, the carbonate mineral of the foraminiferal test is low-Mg calcite, and most of the microcrystalline carbonate is magnesian calcite. Electron microscopic measurement indicate that the grains of microcrystalline carbonate are about 6 microns in diameter which is similar to the size of coccolith plate, but they are poorly-defined crystals in shape, and do not look like as biogenic debris. NISHIDA pointed out that none of coccolith plates were detected in these rocks (S. NISHIDA, personal communication, 1973).

KONDA (1972) interpreted that the age of these rocks was the same as in St. D6 from foraminifers.

**D22** (Plate 6–2, 3, 4, 5 and 7)

A large amount of carbonate rocks were dredged from St. D22. They are divided into the following three types lithologically.

**Type I** (Plate 6–4 and 5): Well-lithified carbonate blocks

These blocks are commonly cobble in size and tabular in shape. Their surface is ragged, heavily penetrated by boring organisms and coated by ferrugenous materials. Sessile organisms, sponge, anthozoa, etc., are attached to the surface. One of the blocks has a fracture surface which seems to have been made by the drag of dredge. From these observations, the blocks of Type I are regarded to be a hard layer which was exposed on the sea floor (BATHURST, 1971, p. 395).

They are composed of tuffaceous materials, clay minerals, foraminiferal tests and microcrystalline carbonates. The amount of foraminiferal tests is rather less than that of the other two types of St. D22.

**Type II** (Plate 6–3 and 7): Indurated carbonate rocks

These are commonly subangular pebbles in size and bored by organisms. The

surfaces are partially stained brown by ferrugenous materials.    Several sessile organ-
isms are seen on them.    These rocks contain the same components as those of Type I,
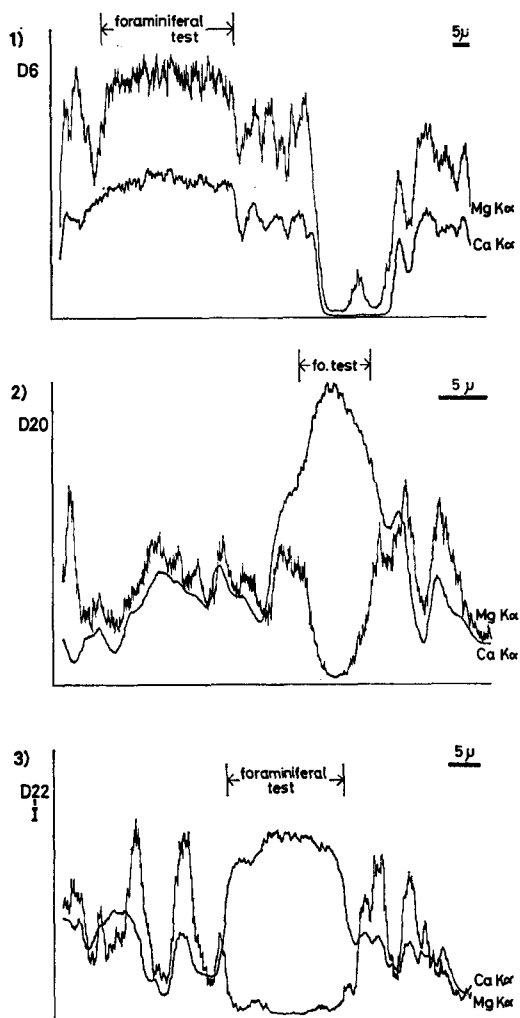


Fig. 2.    Electron microprobe analysis of the carbonate sediments.  Scanning lines are
illustrated in Plate 6–8, Plate 7–1 and 5.   Condition of analysis:

|   | Accelerating Voltage | Absorbed Electron Current | Ca Kα | | Mg Kα | |
|---|---|---|---|---|---|---|
|   |   |   | Crystal | Full Scale | Crystal | Full Scale |
| 1) | 20 KV | 0.01 $\mu$A | PET | $5 \times 10^3$ cps | RAP | $1 \times 10^3$ cps |
| 2) | 20 | 0.02 | PET | $1 \times 10^4$ | RAP | $5 \times 10^2$ |
| 3) | 20 | 0.01 | PET | $1 \times 10^4$ | RAP | $1 \times 10^3$ |

but the foraminiferal tests are more enriched in the rocks of Type II.

By X-ray diffraction analyses, rocks of both types I and II contain dolomite, low-Mg calcite and magnesian calcite in descending order in amount. Electron microprobe analysis shows that magnesium is scarcely enriched in foraminiferal tests as in the samples of St. D20, but is concentrated in carbonate cements (Fig. 2–3). It is supposed that most of the carbonate cements are composed of dolomite, and partly of magnesian calcite. Dolomite crystals are not seen clearly as rhomb under the electron microscope.

**Type III** (Plate 6–2): Slightly indurated rocks

These are composed of subangular pebbles and cobbles which are bored weakly by organisms. Ferrugenous material is not seen on the surface. They are commonly tuffaceous; particularly one of the cobbles contains a significant amount of volcanic ash (Plate 6–2). They contain various amounts of foraminiferal tests ranging in rock-species from foraminiferal sandstone to merely tuffaceous mudstone. The content of microcrystalline carbonate in the rocks of Type III is far smaller than that of the other types of rocks, so the total amount of carbonate materials (Ca. 30 wt%) is smaller than in the others. X-ray diffraction analysis indicates that low-Mg calcite is the only carbonate mineral of this type. These characteristics suggest that these rocks are scarcely or not at all affected by submarine cementation or dolomitization. The age of the rocks of Type III was estimated to be mdidle or late Pliocene (KONDA, 1972), which was supported by K. MATSUOKA (Osaka City University, personal communication) in his paleontological study of dinofragellata.

A dredge was dragged on the sea floor for several hundred or thousand meters long in one sampling operation, so the samples collected by it may not necessarily belong to the deposits of one place. Also these three types of rocks may not have been dredged from only one place. Nevertheless, it may be allowed to suppose that
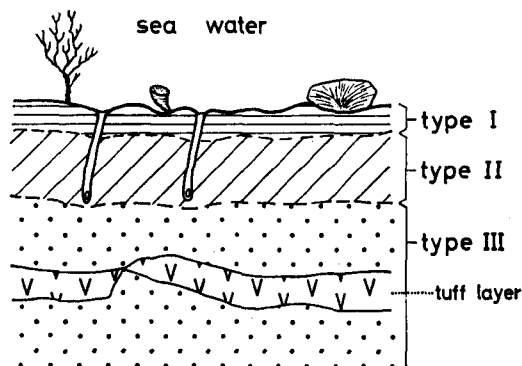


Fig. 3. Hypothetical profile of the bottom sediment at
St. D22.

the three types of rocks were located at the surface of the bank successively deeper from Type I to Type III. It is because the characteristics of the rocks, which suggest the situation of the rocks on the sea floor, gradually changed from one type to another. That is, ferrugenous coating, organic boring, adhesion of sessile organisms, induration and carbonate contents gradually decrease from Type I to Type III. Supposed mutual situation of the three types are illustrated in Fig. 3.

## IV.  Carbonate Minerals and Their Origin

### (1)  Magnesian calcite

Mineralogy:  Magnesian calcite is the main constituent of the rocks from St. D20 and its small amount is contained in the dolomitic rocks in other stations. The magnesian calcite is mainly derived from microcrystalline carbonate cement.

By X-ray diffraction analysis, the dimension of (211) lattice plane of the magnesian calcite was determined to be about 3.005 Å. The observation indicates that the $MgCO_3$ content was about 9 mole percent. This value seems to be in agreement with the $MgCO_3$ content of calcite (about 10 mole percent) equilibrated with sea water (Winland, 1959).

It is generally considered that magnesian calcite consists of randomly substituted magnesium carbonate in a disordered lattice of calcite. The disordered mode of substitution is shown by the differential thermogram (Fig. 4). That is, the differential thermogram of magnesian calcite contains only one endothermic peak at about 910°C. This peak occurs at a relatively lower temperature than that for low-Mg calcite (960–990°C). Moreover, the differential thermogram of magnesian calcite is quite different from that of dolomite which is composed of two large endothermic peaks (approximately at 740 and 940°C).

Origin:  Normal pelagic sediments contain biogenic debris. Tests of planktonic foraminifers, coccolith plates and pteropod shells are most dominant components. Pteropod shells are composed of aragonite, and the others mainly of low-Mg calcite (Milliman & Müller, 1973). Therefore, magnesian calcite is unlikely an original constituent in marine sediments except in the skeletal debris of shallow-water organisms.

Recently, bottom sediments cemented with magnesian calcite have been reported from many locations of oceans (Fischer & Garrison, 1967). As to the samples of eastern Mediterranean and Barbados, Fischer and Garrison reported that most of the magnesian calcite are micrite and probably sparry fillings of tests. And they suggested that the lithification process might involve precipitation of magnesian calcite and/or a partial replacement of the original skeletal carbonates by magnesian calcite. Milliman (1966) assumed that a slow rate of accumulation of sediment is very important for the formation of magnesian calcite cement in this type of sedi-

ment. Recently MILLIMAN and MÜLLER (1973) have suggested that the precipitation probably occurred at water-sediment interface under elevated salinity and temperature conditions.

The carbonate rocks of St. D20 seem to have been in contact with sea water on the sea floor for a long time, and cemented by the precipitates of magnesian calcite. OKUDA (1973) suggested that the major topography of the Toki basin had been almost established at the time of early Pliocene, so it is incredible that the basin was separated from the Pacific Ocean at one time since middle Pliocene, and a highly saline condition may never have occurred around the bottom of St. D20, the northern slope of the Tosabae bank, even if taking into account the tectonic movement and oscilation of the sea level.

KITANO and KANAMORI (1966) synthesized magnesian calcite in the presence of organic acids at room temperature and pressure. Furthermore, KITANO (personal communication, 1970) synthesized the precipitates of magnesian calcite from sea water by adding excess $CO_2$. Hence it seems that high salinity may not be a necessary condition for the precipitation of magnesian calcite around the Tosabae bank, but some sort of materials such as excess $CO_2$ or some organic materials seems to have played a critical role for its formation.

Curiously, no coccolith plate is detected in the carbonate rocks of St. D20 as mentioned previously. The reason remains to be solved.

(2) **Dolomite**

Mineralogy: Dolomite is the main constituent of the lithified carbonate rocks of the Tosabae bank. X-ray diffraction pattern of the dolomite is different from that of ideal dolomite (Table 3) in three characteristics wihch GOLDSMITH and GRAF (1958a) pointed out about protodolomite: (1) An expanded unit cell, (2) Reflections with strong $c$ axis component are more diffuse than those with strong $a$ axis component, (3) The principal order reflections of dolomite seem to be somewhat weakened, as compared with the reflections common to both calcite and dolomite. Ideal dolomite is an ordered carbonate wherein cation layers are composed alternately of calcium and magnesium, whereas protodolomite is non-ideal and possesses an excess of the large calcium over the small magnesium.

The differential thermogram of dolomite gives two large endothermic peaks. It is generally accepted that the first and second endothermic peaks are caused by the release of $CO_2$ from the Mg and Ca lattice positions, respectively. The differential thermogram of protodolomite also gives two large peaks, but the first endothermic peak at about 745°C is stronger and broader than the second peak (Fig. 4). The dolomite of the Tosabae bank may not be ferroan-dolomite, of which the first endothermic peak occurs at a rather high temperature (805°C; KANESHIMA & FUJINUKI, 1973).

Dolomite crystals are generally grained very finely (less than 6 microns in diame-

Table 3.  X-ray diffraction data of protodolomite from the Tosabae bank

| hkl | ASTM 11–78 | | D6 | | D22–I | |
|---|---|---|---|---|---|---|
| | dÅ | $I/I_1$ | dÅ | $I/I_1$ | dÅ | $I/I_1$ |
| 101 | 4.03 | 3 | 4.03 | 4 | 4.04 | 4 |
| 012 | 3.69 | 5 | 3.70 | 7 | 3.70 | 7 |
| 104 | 2.886 | 100 | 2.891 | 100 | 2.895 | 100 |
| 006 | 2.670 | 10 | 2.674 | 4 | 2.677 | 4 |
| 015 | 2.540 | 8 | 2.545 | 4 | 2.545 | 5 |
| 110 | 2.405 | 10 | 2.407 | 14 | 2.409 | 12 |
| 113 | 2.192 | 30 | 2.195 | 31 | 2.196 | 35 |
| 021 | 2.066 | 5 | 2.066 | 4 | 2.066 | 2 |
| 202 | 2.015 | 15 | 2.017 | 19 | 2.017 | 15 |
| 024 | 1.848 | 5 | 1.849 | 4 | 1.849 | 4 |
| 018 | 1.804 | 20 | 1.808 | 12 | 1.809 | 10 |
| 116<br>009 | 1.786}<br>1.781} 30 | | 1.789 | 16 | 1.790 | 14 |
| 211 | 1.567 | 8 | 1.568 | 4 | 1.567 | 3 |
| 122 | 1.545 | 10 | 1.546 | 7 | 1.546 | 7 |
| 10.10 | 1.496 | 1 | — | | — | |
| 214 | 1.465 | 5 | 1.466 | 5 | 1.467 | 5 |
| 028 | 1.445 | 4 | 1.446 | 2 | 1.447 | 1 |
| 119 | 1.431 | 10 | 1.433 | 2 | 1.433 | 2 |
| 125 | 1.413 | 4 | 1.414 | 2 | 1.414 | 1 |
| 030 | 1.389 | 15 | 1.390 | 7 | 1.391 | 4 |
| 00.12 | 1.335 | 8 | 1.337 | 1 | 1.342 | 2 |

ter), and are anhedral or subhedral.   Most of the dolomite are microcrystalline and some of them originate in pore-filling sparry cement and replacement of foraminiferal tests.

Origin:   Dolomitization under marine conditions has been discussed by a number of workers and reviewed by FAIRBRIDGE (1957), FRIEDMAN and SANDERS (1967) and KONISHI (1970).   According to them, most of the dolostones are the results of the action or reaction in hypersaline brines.   Hypersalinity may result from the evaporation of sea water, either in sea-marginal porous sediments or water itself.   In the former case, a concentration mechanism may be "capillary concentration" (FRIEDMAN & SANDERS, 1967), "evaporative pumping" (Hsü & SIEGENTHALER, 1969) or "seepage reflux" (ADAM & RHODE, 1960).   ATWOOD and BUBB (1970) suggested that dolomitization occurred in a tidal flat environment of Sugarloaf Key.   KONISHI (1970) assumed that dolomitization in the temperate region may occur without hypersaline brine as in the case of Sugarloaf Key.   In any case, dolomitization may occur in a very shallow sea water environment, such as hypersaline lagoon, supratidal or intertidal zones.   Recently, deep-sea dolomite has been reported, most of which are discrete crystals (several tens of microns in diameter) in unconsolidated deep-sea muds.

Their ultimate origin is not recognized yet, but some of them must have been formed under the influence of igneous activity, judging from intimate association between dolomite and basic rock or volcanic debris (THOMPSON et al., 1968; DAVIES & SUPKO, 1973).
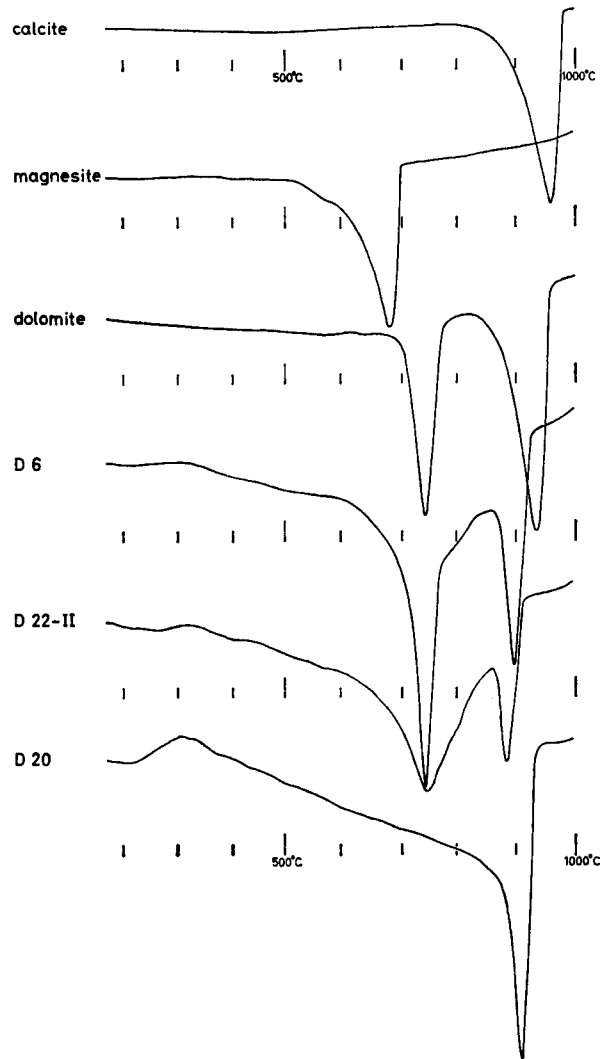
Fig. 4. Differential thermometric analysis of the carbonate rocks.

Lithologically, the dolostones of the Tosabae bank rather resemble the sediments of Sugarloaf Key, that is, most of the dolomite are grained very finely and are concentrated at or near the hard surface of the sediments. In the present sediments
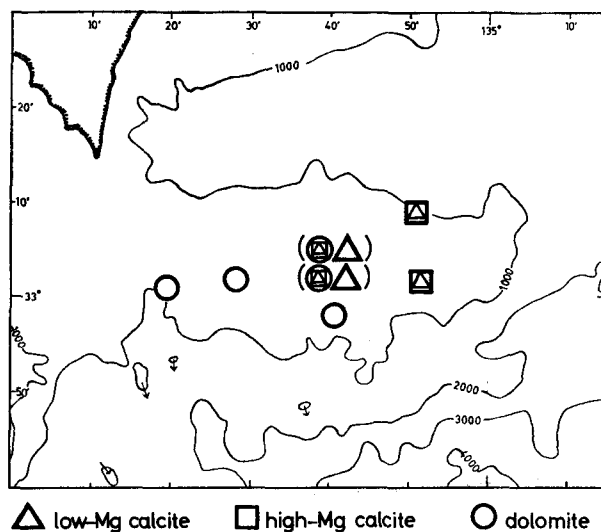
Fig. 5.   Distribution of carbonate minerals in the carbonate rocks of
          the Tosabae bank.

an igneous activity may not give a significant influence on the dolomite formation, because of the following reasons.   The carbonate sediments of the bank are more or less tuffaceous, but all the tuffaceous sediments are not always dolomitized, and most tuffaceous parts in Type III of St. D22 show no evidence of dolomitization. The igneous activity of the basement rocks might have influenced dolomitization, but most frameworks of the bank are made of the sedimentary rocks of Paleogene and/or Miocene in age (KAGAMI et al., 1971).   Furthermore, igneous intrusive rocks are greatly limited in distribution, probably making a part of basement, and igneous intrusion does not seem to be related to dolomitization.

As mentioned previously, the dolostones of St. D22 are limited to surface hard layer, and foraminiferal tests are not dolomitized.   If the surface layer of the carbonate sediments of St. D22 were cemented by the precipitates of magnesian calcite as in the case of St. D20, transformation of magnesian calcite to dolomite would have occurred more easily because magnesian calcite is mineralogically metastable.   Nevertheless, no evidence of dolomitization has been given by a experiment at room temperature and pressure.   Precise mechanism of dolomitization has not been clarified yet, and remains to be solved.

In some dolostones taken from the bank, foraminiferal tests were dolomitized, and some of the tests were resolved to make pore spaces partly filled with iron oxide (samples of St. D6, St. D25 etc.).   In the case, a selective resolution of the tests (low-Mg calcite) may have followed after dolomitization of the sediments except the tests, and a secondary dolomite growth may have occurred partly in those pore spaces.

## V.  Distribution of Carbonate Rocks

During the cruises of KT–70–3 and KT–71–9, eighteen dredgings were operated around the bank.   Except for the recent muds, gravels and sediments were collected from eleven locations.   Carbonate rocks were collected from seven locations.   Although the number of sampling locations are too small to clarify the precise distribution of carbonate rocks, it may be assumed that they are distributed extensively over the bank.

The carbonate rocks with magnesian calcite were dredged from four locations on the flat top and the northeastern slope of the bank.   Of these four locations, St. D20 is fairly deep (750–790 m).   As mentioned previously an upheaval of the bank to cause a condition of very shallow water around that location has never occurred since middle Pliocene.   Therefore, most of the magnesian calcite were supposed to be precipitated at the submarine surfaces of sediments under some favorable condition.

Dolomite-bearing carbonate rocks were dredged from the flat top and the western and southern slopes of the bank.   Dolostones of St. D22 are considered to be autochthonous, and that location should be at least once situated under the condition suitable for dolomitization.   That is, a regression of about 180 m in depth might bring a very shallow-water environment to this location.   In connection with this, Shiki et al. (1971) remarked that blue muds of late Pleistocene which were dredged with carbonate rocks from St. D22 together, contain nannofossils restricted to near-shore environment.   And they suggested that the Tosabae bank was once in a very shallow-water environment or was partly emerged above sea level.   The age of dolomite formation might correspond to that time.

Carbonate rocks were dredged from St. D13 (on the flat top of the bank) together with the sedimentary rocks corresponding to the Miocene Tanabe group and the Paleogene Muro group (Shiki et al., 1971).   These carbonate rocks contain not only dolostones but also limestones which are composed of microspar and ghosts of foraminiferal tests.   The origin of the limestones and their relation to the dolostones are unknown, but possibly the limestones would have been formed by recrystallization under fresh-water environment, i.e., subaerial condition, as discussed by Friedman (1964).

Dolostones seem to be widely distributed around the bank, but all of these except those of St. D22 are angular or subangular gravels, allochthonous gravels in the strict sense.   The upper surface of the bank has a ragged relief, so these gravels of dolostones may have been transported a short distance from the adjacent hills by gravity force or oceanic current.   Furthermore, because of the ragged relief of the bank, there may have developed sporadically in intertidal or supratidal environments and/or hypersaline lagoons which were suitable for dolomite formation.

## VI. Summary and Conclusion

Carbonate rocks consisting of low-Mg calcite, magnesian calcite and dolomite in various proportions were dredged from the Tosabae bank and its environs.

Magnesian calcite contains 9 or 10 mole percent of $MgCO_3$ and is a post-depositional precipitate which occurred at water-sediment interface during cessation of sedimentation. Carbonate rocks containing magnesian calcite are distributed in the northern slope and the flat top of the bank.

Dolomite is non-ideal, i.e., protodolomite. Dolomite bearing carbonate rocks are widely distributed around the bank. Dolomite was formed at the surface layer of the sediment under the conditions of very shallow water or hypersaline brine sporadically developed on the surface of the bank. If pre-existing carbonate is magnesian calcite, formation of dolomite seems to occur easily.

On the basis of the foregoing evidences and arguments, the following sequence of events and related mineralogical changes of carbonate are recognized:

(1) Hemipelagic sediments were deposited on the bank during middle and/or late Pliocene time. Hemipelagic sediments consist of pelagic component (foraminiferal tests, coccolith plates etc.) and volcanic ash. Most of the carbonate minerals were low-Mg calcite.

(2) At the surface layer of the sediment, magnesian calcite was precipitated under some suitable condition. The age of precipitation is unknown, but this process may be going on at the present time.

(3) In very shallow water or hypersaline lagoon environments, dolomite was formed at the surface layer of the sediments through replacement of pre-existing carbonates, most of which were assumed to have been fine-grained crystals of magnesian calcite. The occurrence of dolostones of St. D22 suggests that the amount of regression was at least 180 m, and such a regression may have occurred at the late Pleistocene age. Nevertheless, OKUDA (1973) recognized twice of regressions after the early Pliocene analysing the results of electro-sonic profiling survey. Therefore, the precise age of dolomitization remains to be revealed.

(4) At the present time, the surface of the Tosabae bank is continuously dashed by the Kuroshio current, so recent submarine deposits are greatly restricted in their distribution on the bank, and gravels may have been moved in a short distance.

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## Explanation of Plates

### Plate 6

1)  Carbonate rock dredged from St. D6.   × 1/3
2)  Carbonate rock dredged from St. D22, (Type III).   × 1/3
3)  Carbonate rocks dredged from St. D22, (Type II).   × 1/3
4) &5)  Carbonate rocks dredged from St. D22, (Type I).   × 1/3
6)  Carbonate rock dredged from St. D20.   × 1/3
7)  Carbonate rock dredged from St. D22, (Type II), thin section.   × 40
8)  Backscattered electron image, composition, of carbonate rock dredged from St. D22, (Type I).   × 1200

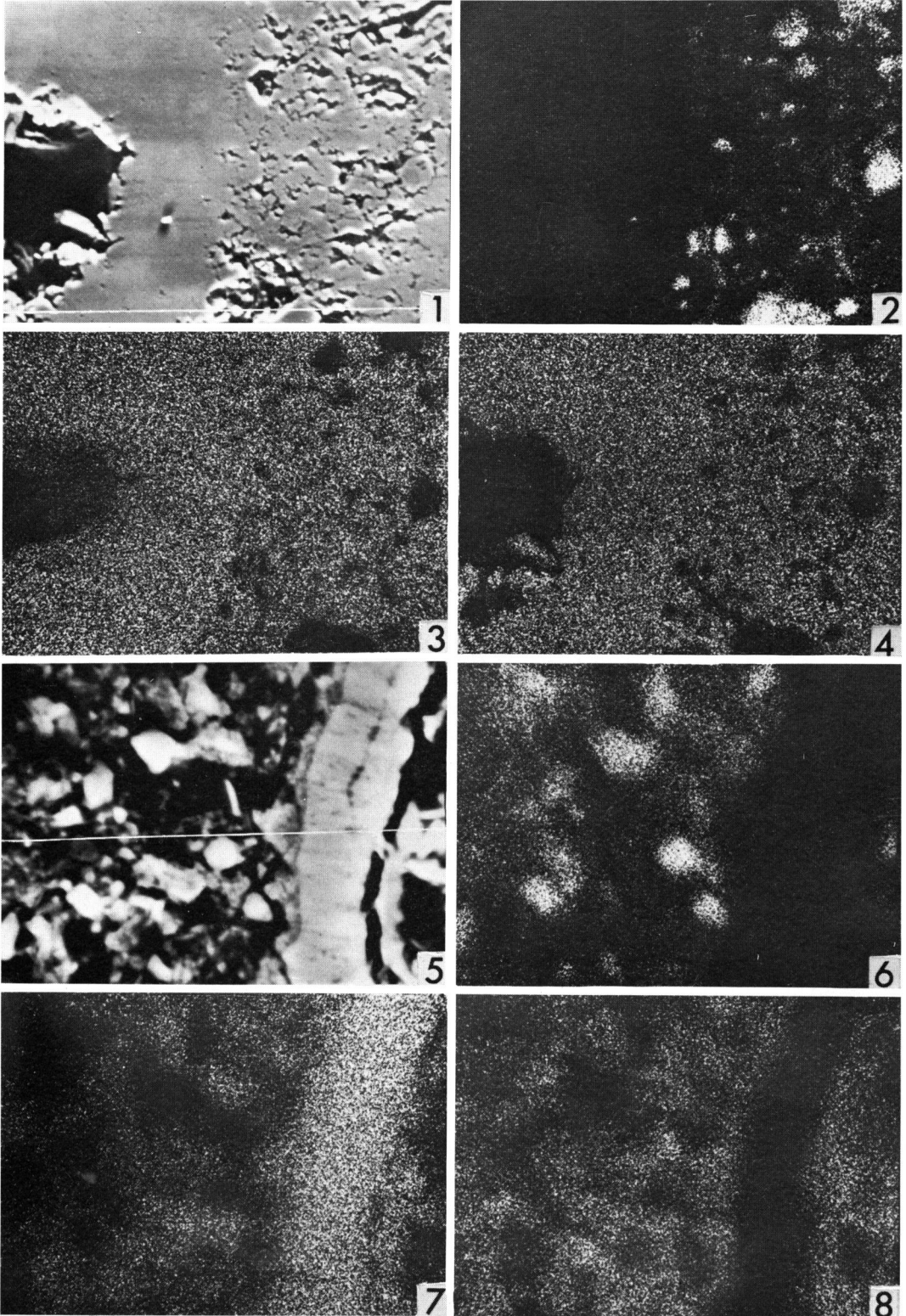### Plate 7

1)  Backscattered electron image, composition, of carbonate rock dredged from St. D6.   × 600
2)  SiKα X-ray image of (1).
3)  CaKα X-ray image of (1).
4)  MgKα X-ray image of (1).
5)  Backscattered electron image, composition, of carbonate rock dredged from St. D20.   × 1800
6)  SiKα X-ray image of (5).
7)  CaKα X-ray image of (5).
8)  MgKα X-ray image of (5).

Horizontal lines in Plate 6–8, Plate 7–1 and 5 show the scanning lines of electron microprobe, of which analytical results are illustrated in Fig. 2.
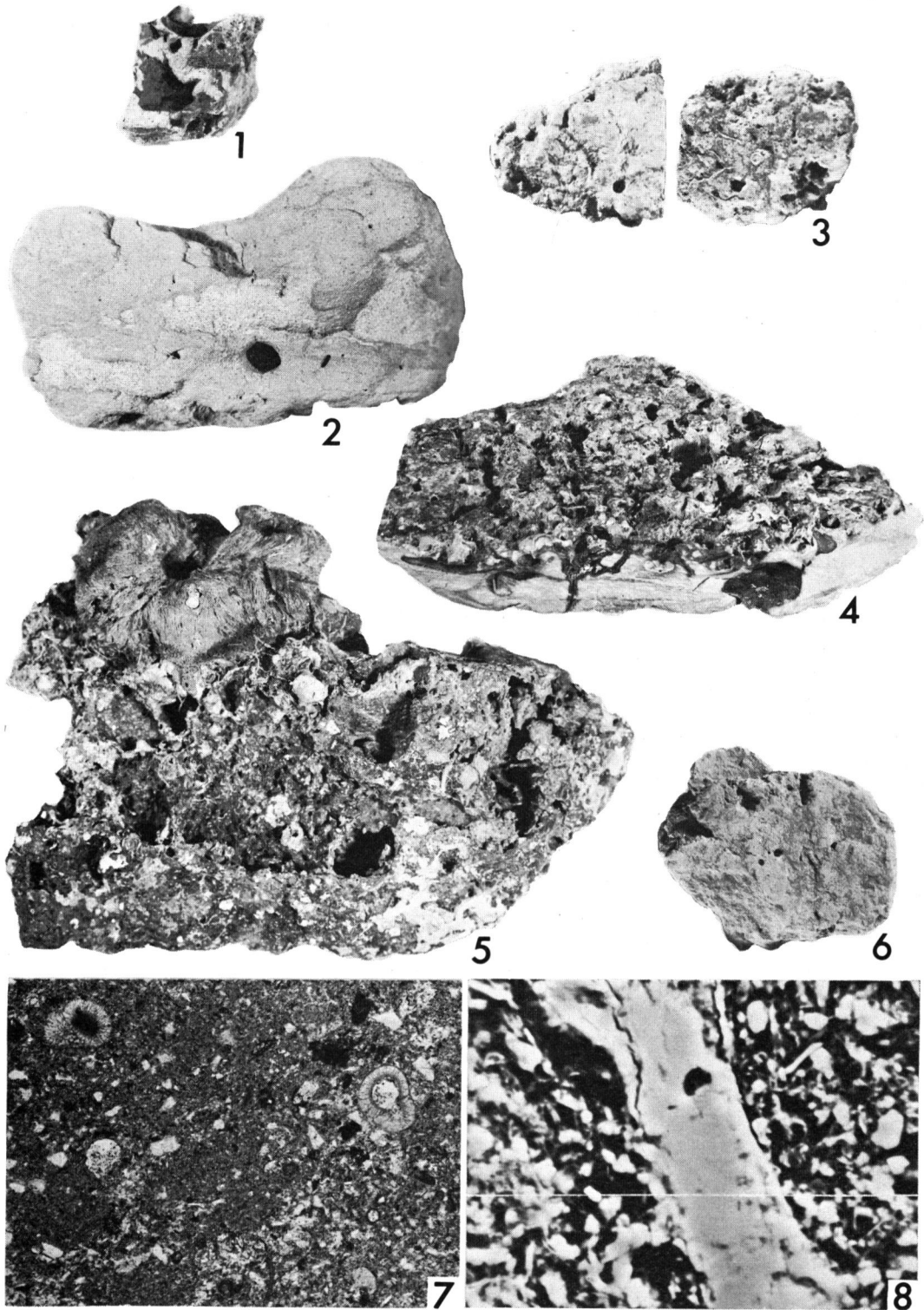
MUSASHINO:   Carbonate Rocks of the Tosabae Bank

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