GEOCHEMISTRY AND DOLOMITIZATION OF PLEISTOCENE CORAL REEFS, IN THE GULF OF AQABA REGION, SOUTH SINAI, EGYPT

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ABSTRACT

Pleistocene coral reef terraces are exposed in two levels at the southeastern part of Sinai Peninsula along the Gulf of Aqaba coast. Mineralogically, the reef formations are made up by aragonite, low and high Mg-calcite and protodolomite. Evaporites and iron oxides/hydroxides were also identified.

Petrographic characteristics of the two reef sequences revealed that the reefal carbonates were affected by early, near-surface dolomitization and pervasive dolomitization. In the former case, aragonites and Mg-calcites were replaced respectively by dolomites. Pervasive dolostones were formed by mimetical replacement of aragonitic and high Mg-calcitic allochems. Reefal limestones and dolostones were analyzed for Ca, Mg, Sr, Mn, Fe and Na. Concentrations of these major and trace elements are consistent with progressive diagenesis of the reef terraces under evaporated marine water, brine and freshwater conditions. Oxygen and carbon isotope values range between -9.60 to +3.39 ‰ PDB δO^{18} and -4.35 to +3.17 ‰ PDB δC^{13} respectively suggest dolomitization by marine water modified by evaporation. The depleted isotope values related to freshwater diagenesis.

INTRODUCTION

The coastline of the Gulf of Aqaba along the southern Sinai Peninsula (*Fig. 1*) is fringed by a narrow belt of modern coral reefs. Two well preserved uplifted fossil reef terraces (*Fig. 2*) stretch along the coast in a belt extending up to 30 m above mean sea level (FATHY and HAAS, 1994). These terraces are made up by reefal carbonates of Pleistocene age.

Previous studies on the South Sinai terraces recognized the significance of dolomitization of the reefal carbonates, but did not discuss the process in detail. STRASSER et al. (1992) suggested that pervasive dolomitization took place in a seawater-dominated mixing zone.

Aim of the present paper is to display the major mineralogical and geochemical characteristics of these dolomitized reefal carbonates and discuss the process of dolomitization.

Petrographic characteristics and geochemistry of the studied sequences indicate that the reefal carbonates were affected by early, near-surface dolomitization (*Fig. 3*) and pervasive dolomization (*Fig. 4*). Dolomites in the former case were similar to calcian dolomites of Abu Dhabi sabkhas, because they replaced aragonite and associated with evaporites as postulated by ILLING et al. (1965), BUTLER (1969), MCKENZIE (1981), PATTERSON and KINSMAN

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(1982) and GUNATILAKA et al. (1984), whereas pervasive dolostones were formed by mimetical replacement of aragonitic and high Mg-calcitic allochems. Petrographically similar dolostones are widespread in the Cenozoic. Features of these dolomites were reported from Jamaica (LAND 1973a), Egypt (LAND et al. 1975, CONIGLIO et al. 1988 and QING SUN, 1992), San Salvador (SUPKO, 1977), Bonaire (SIBLEY, 1980) and underneath the Bahamian platform (KALDI and GIDMAN, 1982; DAWANS and SWART, 1988; VAHRENKAMP and SWART, 1994). Dolomites in these Cenozoic sequences were generally assumed to be mixing-zone origin, although the validity of such an interpretation has been questioned (MACHEL and MOUNTJOY 1986 and 1990).

METHODS

For petrographic investigations thin sections stained by Feigl' solution and standard Alizarine Red-S were used. Bulk powdered rock-samples were used for mineralogical analysis.

X-ray analyses were carried out for most of the samples, using X-ray diffractometer Philips PW 1710 goniometer, applying Cu-filtered Cuk a radiation, With setting at 30 mA and 40 kV. The speed of the chart was $2°$ min^{-1}. This method allowed to determine various diagenetic phases and choose samples for geochemical analysis. Fourty-eight analyses for major and trace elements were made by JY-70 ICP-Oes spectrometer. The carbonate fraction of the bulk-rock samples taken from the Pleistocene coral reef terraces and modern reefal sediments was extracted by 1N HCL, following the procedure worked out by ROBINSON (1980). The solutions were analysed for major elements (Ca, Mg) and trace elements (Sr, Na, Fe and Mn). Magnesium and strontium content of 3 unaltered Pleistocene corals (Porites sp) were determined by electron microprobe.

Oxygen and carbon stable isotope analyses were carried out in the Laboratory of Environmental Studies, Debrecen, Hungary. The stable isotope ratios for the carbonates are given in parts per mil (‰) deviations from the PDB isotopic standard.

TECTONIC AND STRATIGRAPHIC SETTING

The southern tip of the Sinai Peninsula is located at the triple junction between the African plate, the Arabian plate and the Sinai subplate (*Fig. 1*). Rifting of the Red Sea system began in the Late Oligocene, reactivating Late Precambrean zones of structural weakness (MAKRIS and RIHM, 1991). The Gulf of Suez began forming by extension and basin subsidence in the Early Miocene. By the Middle Miocene, the extension in the Gulf of Suez slowed down. Geological history of the Gulf of Aqaba initiated in the Late Miocene, when a left-lateral transform zone, came into being along which the Dead Sea and the Gulf of Aqaba were formed as pull-apart basins (LYBERIS 1988). Intense uplift of the graben shoulders and block-fauling started in the Middle to Late Miocene and have been continous until today. The developing rift filled up by Miocene to Early Pliocene sediments (syn-rift). Accumulation of sediments was controlled mainly by rift-faulting. The overlying Quaternary sequences (post-rift) consist of biogenic carbonates and continental, alluvial sediments.

FACIES, DEPOSITIONAL ENVIRONMENTS AND MINERALOGY

As inferred from microfacies study of the Pleistocene coral reef terraces of the Gulf of Aqaba (*Fig. 5*), the deposition of the reef successions (cycles) was generally started by formation of intertidal calcareous sandstones. Terrigenous components of these sandstones originated from the eroded basement rocks. Carbonate grains are of biogenic origin. This mixed sedimentation was followed by the proliferation of calcareous algae (coralline algal grainstone facies) and then accumulation of reef-derived skeletal grains (bioclastic packstones facies) representing back-reef inner shelf zone. Reefs started to grow as fringing reefs, composing of coral/red algal boundstones, with subordinate bryozoans in the outer reef crest zone. The reef slope is indicated by the occurrence of branching corals. The back reef (inner shelf) peloidal packstone facies occuring at the top of the studied sections, indicates the termination of the growth of the buildups and progradation of the backreef zone.

Various carbonate minerals: aragonite, low and high Mg-calcite and dolomite were found in the studied samples taken from the emerged Pleistocene coral reef terraces. Mineralogical composition of the carbonates (*Fig. 6a,b*) seems to be controlled mainly by the grade of their diagenetic alteration. For example in the calcareous sandstone and bioclastic packstone facies (partially dolomitized), sediments contain 8 to 35% aragonite and 12 to 80% calcite. High Mg-calcite containing 8–20 mole% $MgCO_3$ may also occur in a quantity from 26 to 66%. Amount of stoichiometric dolomite is minor (about 3–6%) or it is absent, however, protodolomite may be abundant (4–97%). In the coralline algal grainstone facies (pervasively dolomitized), amount of protodolomite is as high as 80% and amount of calcite is 0–7%. The coral-algal boundstone facies is rich in calcite (max. 86%). In the biomicrosparitic limestone facies of the older reef sequence protodolomite is present, however, only in subordinate quantity (1%) and the sediments are characterized by low Mg-calcite (about 95%). This may indicate fresh water influence during the diagenesis, just like in the pelletal packstone facies, in which quantity of low Mg-calcite may reach 97%.

In most of the Pleistocene reefal facies, contribution of land-derived material is significant (3–30%), showing a gradually increasing trend towards the near-shore facies. Evaporites were also identified (1–25%). They were represented by magnesite (6%), anhydrite (1–4%), celestite (1–2%) and halite (2–24%). The highest amount of evaporite was recorded in the partially dolomitized facies.

The recent reefal sediments of the Gulf of Aqaba coast are an admixture of terrigenous siliciclasts (8–81%) and bioclasts. Their carbonate content is between 30 and 75%, showing a trend of gradual increase, seaward. Aragonite is the most common carbonate mineral, however, high Mg-calcite is also common. Thus, mineralogical composition of the studied modern carbonates are controlled by quality and quantity of the rock-forming bioclasts and amount of the terrigenous material.

GEOCHEMISTRY

Major and trace elements

Results of the geochemical analyses of the recent reefal sediments and the studied Pleistocene reef facies are listed in the Table 1.

Calcium and Magnesium

There is a positive relation between these two major chemical components in the Gulf of Aqaba's modern reefal sediments, which can be explained by their original ratio in the skeletons of marine organisms, because both Ca and Mg are mostly derived either from modern or fossil biogenic sources.

Considerable variation in the magnesium content was detected in the originally aragonitic coral skeletons and bulk-rock samples from the emerged Pleistocene terraces (*Fig. 7*). These values reflect mainly the state of diagenetic alteration. The slightly increased Mg content in the low-Mg calcite rich facies are in consistence with their meteoric diagenesis, because Mg^{2+} ions incorporate more easily into calcite than aragonite. For example, coral-algal bound facies contains 1.53% MgO in average, whereas pelletal packstone facies and biomicrosparitic limestone facies contain 1.21% and 0.70% MgO in average, respectively.

Naturally, there is a positive correlation between percentage of dolomite and Mg content. The completely dolomitized samples contain 15.84% MgO in average and 34.05% CaO, whereas in the partially dolomitized facies of the originally aragonite-rich rock-types, amount of MgO is lower, about 4.64%, whereas amount of CaO is 47.29%, in average. It can be assumed that the higher degree of dolomitization in the coralline algal grainstone facies is related to the enrichment of the encrusting coralline algae, since Mg^{2+} ions, releasing by breakdown of the high-Mg calcite may provide a significant source of magnesium to the dolomitizing fluids.

Sodium

The average value of the sodium content in the Gulf of Aqaba's modern reefal sediments is 3,400 ppm. This value is consistent with the values determined by LAND and HOOP (1973) in the recent carbonate.

Sodium in the emerged Pleistocene limestones ranges from 297 to 6,500 ppm. It shows the following trends: (1) Na values are generally high in the partially dolomitized samples (calcareous sandstone and bioclastic packstone facies) comparing to the completely dolomitized samples (coralline algal grainstone facies). The partially dolomitized samples are Na-rich comparing to the low Mg-calcite-rich facies (biomicrosparitic limestone, coral-algal boundstone and pelletal packstone facies) affected by freshwater diagenesis. (2) In the older terraces the higher Na values are unusual; due to downward infiltration of hypersaline brine from the tidal flat of the younger reefs to the older ones.

On the Na-Ca scatter diagram symbols, representing the measured samples of the distinguished facies, form definite clusters (*Fig. 8*) and suggest general trends. They are as follows: (1) The partially dolomitized facies, in which occurence of evaporites is common shows wide-range of Na values and negative correlation with the calcium content. (2) The completely dolomitized facies is characterized by relatively low Ca and Na content. (3) In the low-Mg calcite-rich facies Na values are lower, in consistence with their meteoric diagenesis.

These relationships indicate that the bulk sodium content in the various facies is related to their diagenetic history. It was certainly influenced by precipitation of NaCl cement, derived from evaporation of marine water. This process may have also related to the formation of the dolomitizing fluids. That is, why in the partially dolomitized samples, Na concentrations are high, whereas the completely dolomitized samples and those which were affected by meteoric diagenesis can be characterized by low Na content.

Strontium

High concentration of strontium in the Gulf of Aqaba's modern reefal sediments is mostly related to the significant amount of coral fragments of high Sr content in these sediments.

Sr content in the emerged coral terraces correlates fairly well with their diagenetic alteration:low Mg-calcite-rich facies are Sr-poor. These low concentrations are consistent with aragonite dissolution by meteoric freshwater. Strontium concentration in the completely dolomitized samples, however, is even significantly lower than that in the low-Mg calcite-rich samples, indicating further removing of strontium in the course of dolomitization. Anomalously high strontium values were recorded in the least altered, only partially dolomitized facies. Strontium content of coral skeletons and recent reefal carbonates is higher, thant that of bulk-rock samples of the emerged coral terraces, as a result of progressive diagenesis of the fossil reefs.

Significant differences in the Sr content of the different facies suggest, that Sr content in Pleistocene coral reef terraces was influenced in addition to their diagenetic history, also by Sr content of the precursor carbonates (memory effect). Original aragonitic grains are still preserved in the partially dolomitized samples, that is why their Sr content is very high, as a rule. Data also show negative correlation between the dolomite content and Sr concentration. Sr^{2+} removed from the sediments, when aragonite and/or high Mg calcite was replaced by dolomite. Low Sr values in the completely dolomitized grainstone facies indicate that in the course of dolomitization alteration of the sediments resulted in decrease in the mean Sr concentration.

The scatter diagram shows positive correlation between the Na^+ and Sr^{2+} contents in the bulk samples (*Fig. 9*).

Iron and manganese

The Fe and Mn contents are relatively low and they show positive correlation with one another in the Gulf of Aqaba's recent reefal sediments.

The concentration values of the emerged Pleistocene coral reefs fall into two groups: (1) the completely dolomitized and partially dolomitized samples are relatively poor in Fe and Mn. This suggests an oxidizing dolomitization environment (surface dolomitizaton) where the pore-waters are Mn-Fe-depleted and Fe and Mn are locked up in oxide/hydroxide compounds.

(2) The low-Mg calcite-rich samples, which were affected by freshwater diagenesis are relatively richer in Fe, than the two dolomitized facies (*Fig. 10*). These higher values may be regarded as indicator of reducing meteoric diagnetic environments. Under phreatic conditions, meteoric waters are relatively rich in Mn and Fe, as a rule.

Oxygen and carbon isotopes

Results of oxygen and carbon isotope analyses of carbonates from the Pleistocene coral reef terraces are given in the Table 1.

The mean $\delta^{18}O$ value of the 8 whole-rock samples, representing the partially dolomitized facies is -1.09‰ (range: -0.36 to -3.40‰ PDB). These values suggest that marine water modified by evaporation, in the peritidal zone was the dolomitizing fluid. This fluid may have been driven through the platform by storm-recharge refluxing and/or evaporative pumping, just like in the hydrological system of the sabkhas. This isotopically heavy water of high $\delta^{18}O$ values may have mixed with the local groundwater. MCKENZIE (1981) reported that $\delta^{18}O$

values sabkha-derived waters from Abu Dhabi range from 2.68 to 5.58‰ SMOW at 20-36°C temperature of the water (temperature of modern sabkha − BUTLER, 1969 and MCKENZIE et al., 1980). The mean $\delta^{13}C$ value is +1.64‰. This value indicates that the supratidal/intertidal dolomites were formed in or just below the zone of bacterial sulphate reduction.

Mean $\delta^{18}O$ value of the 4 whole-rock samples from the completely dolomitized facies is +1.82‰ (range: +0.45 to +3.40‰ $\delta^{18}O$ PDB), heavier than that of the peritidal partially dolomitized samples. This enrichment of ^{18}O is consistent with dolomitization from brines. The mean $\delta^{13}C$ value is +2.92‰, suggesting dolomitization in the zone of methanogenesis.

In the upper part of the uplifted older reef terrace, $\delta^{18}O$ values of the samples affected by freshwater diagenesis are recorded between -5.57 to -9.60‰ PDB and -5.57‰ PDB in one sample from the younger reef. The light oxygen and carbon isotope values indicate influence of meteoric water during the diagenesis (*Fig. 11*).
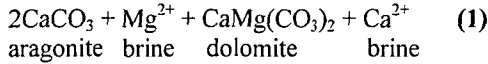
PROCESS OF DOLOMITIZATION − A DISCUSSION

The emerged Pleistocene coral reef terraces in the South Sinai are made up by two major depositional units. Each of them consists of various depositional facies, formed in the marginal reef zones and back-reef inner shelf during the interglacial sea-level highstands. Dolomites occur in both depositional units. Two types of dolomitization could be distinguished. Partial dolomitization, which affected the calcarous sandstone and bioclastic packstone facies, and total dolomitizaton occurs in the coralline algal grainstone facies. In the former case, sediments were dolomitized in the inter/supradital zone. The association of dolomites and evaporites indicates early dolomitization, under subaerial to shallow subsurface conditions. Sabkha-related origin of these dolomites is indicated not only by presence of evaporites, but also by their non-stoichiometric (calcian) composition ($Ca._{62}$ $Mg._{38} CO_3$), geochemical features and isotopic values. High Na^+ content of the studied bulk samples (890 to 6,500 ppm − similar to those values which were detected by LAND and HOOPS (1973) in modern dolomites) indicates that these early diagenetic dolomites were formed in an environment of increased salinity. They contain, generally, more than 2,000 ppm Na^+, (in most ancient dolomites Na^+ concentration is lower than 1,000 ppm). The Sr content seems to depend mainly on aragonite content of the precursor sediments. The strontium concentrations in our samples (ranges from 1150 to over 5,000 ppm) similar to those of recent intertidal sabkha dolomites in Abu Dhabi (FRISIA, 1994). $\delta^{18}O$ values (mean value is -1.30‰) are consistent with dolomitization by marine water modified by evaporation, and mixed with local groundwater.

In the completely dolomitized facies (coralline algal grainstone facies), fabric of the originally Mg-calcite and calcite components preserved and mimetically replaced by dolomites, whereas the originally aragonitic components were leached, resulting in moldic or vuggy porosity. These dolomites are also Ca-rich ($Ca._{59} Mg._{41} CO_3$). The average Sr and Na concentrations (514 ppm and 1,313 ppm, respectively) are lower than those in above-mentioned partially dolomitized rock-types. Na content of our samples seems to be within the range expected for dolomites, precipitated from moderately evaporated sea water, as described by SASS and BEIN (1988), whereas, Sr concentration of the studied samples (ranging between 300 to 730 ppm) reflects the Sr content of the replaced (precursor) minerals. Their high $\delta^{18}O$ values are consistent with dolomitization by hypersaline solution.

Principal controlling factors of geochemical characteristics of the investigated dolomites are the following:

Geochemistry and mineralogy of the precursor carbonates:

Since partial dolomitization took place in supratidal and intertidal environments, dolomites were mostly formed by replacement of aragonite according to equations (1) given by Patterson and Kinsman (1982):
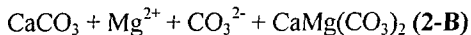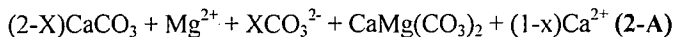
$$2CaCO_3 + Mg^{2+} + CaMg(CO_3)_2 + Ca^{2+} \quad \textbf{(1)}$$
$$\text{aragonite} \quad \text{brine} \quad \text{dolomite} \quad \text{brine}$$

Mg^{2+} ions are supplied by the dolomitizing fluid. During this process, dissolution of aragonite to form dolomite would release Ca^{2+} ions, which combine with sulfate in the porewaters to form gypsum. As a consequence, SO_4 and Ca contents decrease. Due to continous evaporation of seawater, Mg/Ca and Na/Ca ratio rise in parallel with rise of salinity. Consequently, activity of solution decreases and the proportion of less strongly hydrated Mg^{2+} ions increases.

The Sr content of the precipitated dolomite governed by the stoichiometry of the reactions involved assuming that the dolomite, once formed, does'nt reequilibre with respect to Sr (SASS and KATZ, 1982 and MACHEL, 1988). Dolomitization proceeds by the stoichiometric reaction according to equation (1), in which Ca releases to the pore fluid and it is taken up by gypsum precipitation. Hence, $^m Sr/^m Ca$ ratio increases in the solution. If aragonite having higher $^m Sr/^m Ca$ ratio, is affected by dolomitization, Sr-rich dolomite is to be formed, since the $^m Sr/^m Ca$ ratio of aragonite is similar to the $^m Sr/^m Ca$ ratio of dolomitizing fluid. This is also true for the Na, which have a dissociation coefficient smaller than one (K^{Na} in dolomite is $2 \times 10-5$). With increasing $^m Na/^m Ca$ ratio in the solution, sodium content increases in the precipitated dolomites either as NaCl inclusions or substitued cations.

Based on considerations discussed above, it is very probable that in the studied dolomitized rocks Sr and Na concentrations depend upon the original concentrations of these elements in the aragonitic precursor carbonates.

The completely dolomitized grainstone facies composed predominantly of coralline algae-rich carbonates (originally high-Mg calcite). They may have been diagenetically stabilized before dolomitization, without an intervening phase of dissolution and reprecipitation. In this process, nearly all the Mg^{2+} released by breakdown of the high-Mg calcite providing significant contribution of Mg to the dolomitizing solution. The sediments were interacted either with the downward moving warm, highly alkaline, Mg^{2+} rich, hypersaline water, which mixed with normal seawater or meteoric water in the pores. It is important to keep in mind that, meteoric diagenesis decreases the Mg and Sr content and increases the Mn and Fe content of the rocks. After meteoric diagenesis, these sediments should have been interacted with slightly modified seawater.

$$(2-X)CaCO_3 + Mg^{2+} + XCO_3^{2-} + CaMg(CO_3)_2 + (1-x)Ca^{2+} \textbf{ (2-A)}$$

$$CaCO_3 + Mg^{2+} + CO_3^{2-} + CaMg(CO_3)_2 \textbf{ (2-B)}$$

According to MORROW (1982), the parameter (X) depends on the density of the carbonate being dolomitized; $X=0.11$ for aragonite and $X=0.25$ for low Mg calcite.

Dolomitization is taken place by the reaction, according to equations 2-A or 2-B, wherein both Mg^{2+} and CO_3^{2-} ions are supplied by the dolomitizing fluids.

Reactions expressed by equations 2-A or 2-B do not add Ca to the same extent as reaction of the equation (1), therefore, most of the Ca^{2+} ions of the precursor carbonate are going to be incorporated into the dolomites. Hence, $^mSr/^mCa$ ratio of the fluid remains higher, than that of the calcite, which has lower $^mSr/^mCa$ ratio. Depending of the amount of Ca, released during replacement of calcite, the $^mSr/^mCa$ ratio of the fluid decreases due to trace-element partitioning, where K^{Sr} for dolomite less than 1 (assuming that replacement of calcite by dolomite takes place molecule by molecule, or nearly so). Correspondingly, low-Sr dolomite forms. This is also applicable to the Na concentration, in accordance with the dissociation coefficient of Sr and Na, both less than one.

Both manganese and iron content of the partially and completely dolomitized samples are generally low (8-70 ppm and 160-1,600 ppm, respectively) and similarly low in the recent reefal carbonate sediments (3-30 ppm Mn and 90-510 ppm Fe). According to MILLIMAN (1974) in the modern marine carbonate sediments, the Fe content varies from ten to several thousand ppm and the Mn content up to 100 ppm.

Kinetics

Aridity of the Gulf of Aqaba region should have been favourable for evaporation of seawater on the tidal flat with concomitant precipitation of evaporites (mainly gypsum and anhydrite). Thus fluids of high Mg/Ca ratio were formed, which may have served as dolomitizing fluids. In addition, with increasing salinity and consequently, decreasing activity of water, the proportion of less strongly hydrated Mg^{2+} ions should have increased, resulting in an increased rate of dolomitization.

The presence of sulfate anions (SO_4^{2-}) in the water is one of the most important kinetic factors controlling the dolomite precipitation in many hydraulic settings. BAKER and KASTNER (1981) concluded that, in organic-rich sequences and supratidal sabkhas, formation of dolomites were induced by sulfate reduction. SIBLEY et al. (1994) pointed out the role of sulfates to inhibit the dolomitization by slowing the rate of calcite dissolution and forming a $CaSO_4$ layer on the surfaces of the calcites. Anyway, sulfate reduction favours to the dolomitization. An effective mechanism for lowering the sulfate content in the pore-fluid is microbial reduction of sulfates or the precipitation of $CaSO_4$ minerals. Hence the alkalinty increases in the pore-waters. Combination of these two factors i.e sulphate reduction and increased alkalinity may create particularly favourable conditions for the dolomitization.

The most important kinetic factors should have been present during dolomitization of the Pleistocene carbonates in the Gulf of Aqaba region: elevated temperature, alkaline fluids with high Mg/Ca ratio and sulfate reduction.

Dolomitizing fluids and rock properties

Common presence of calcian dolomites in our samples may be a result of high Mg/Ca ratio of the dolomitizing fluids and rapid flow of these fluids through the sediments, due to their high permeability. Possible sources of magnesium are as follows. (1) Mg-calcite constituents of the marine sediments. Mg^{2+} ions can be released by breakdown of the high-Mg calcite (e.g. corallinacean algae, may provide a significant contribution of magnesium to the dolomitizing fluids) (2) evaporated seawater. Evaporation leads to significant increase of the Mg concentration. Therefore, relatively small volume of evaporated water is needed. Growth of dolomite crystals or generation of dolomite by replacement can only proceed

when there is an adequate supply of Mg^{2+} ions. However, equilibrium conditions and stability of the solids depend upon the Mg/Ca ratio of the solution.

Downward reflux of large volume of dense and warm, highly alkaline Mg^{2+}-rich hypersaline seawater through the carbonate sediments requires high porosity and permeability. Mimetically replaced dolomites occur mainly in sediment types, of high initial permeability, such as the coralline algal grainstone facies. Therefore, it is plausible that high permeability may have allowed greater rate of fluid flow and as a consequence faster and more intense dolomitization. This process produces extremely small crystals, that is why fragments of coralline algae, echinoids and some foraminifera are mimetically replaced by small dolomite crystals. In contrast, the partially dolomitized sediments belong to the bioclastic packstone facies. In this case, the low initial permeability restricted the flow of dolomitizing solution through the sediments, therefore, the rate of dolomitization decreased and consequently, euhedral dolomite crystals tended to produce.

CONCLUSIONS

Mineralogical examination of the two studied Pleistocene reef sequences on the southeastern coast of the Sinai Peninsula, Egypt has revealed that carbonates are represented by aragonites, low and high Mg-calcites and protodolomites. The vicinity of the continental background area strongly influenced the petrographic composition of the reef terraces and this setting can explain the high percentage of the terrigenous minerals (quartz and feldspar) forming 5–30% (weight percent) of the bulk samples.

Two distinctive types of dolomitization have been identified in the reef terraces: partial and total dolomitization. In the former case, the dolomites replaced aragonites and Mg-calcites. In the intertidal/supratidal depositional facies occurrence of calcian dolomites together with evaporites indicates early dolomitization. Oxygen isotope values in these dolomites suggest dolomitizing fluids of marine origin, but modified by evaporation. Pervasive dolostones were formed by mimetical replacement of aragonitic and high Mg-calcitic allochems. Their high $\delta^{18}O$ vales are consistent with dolomitization by hypersaline fluids.

Modem reefal sediments and rocks of reef terraces were analyzed for Ca, Mg, Sr, Mn, Fe and Na. Concentrations of these major and trace elements are consistent with progressive diagenesis of the reef terraces under evaporated marine water, brine and freshwater conditions. Magnesium concentration reflects the original composition of the precursor biogenic carbonate sediments, and the grade of dolomitization. Strontium is a precursor-derived element and consistent with the aragonite transformation, whereas Na concentration shows correlation with amount of NaCl cement, derived from evaporating marine water. The Fe and Mn concentraton indicate dolomitization in oxidizing environment and precipitation of freshwater calcites under reducing conditions. In general, partially dolomitized carbonates show elevated Na and Sr concentrations, whereas Mg is relatively depleted. In the pervasive dolostones Na and Sr concentrations are relatively low. The low Mg-calcite-rich rock-types have elevated Fe and Mn values whereas Na and Sr concentrations are low showing influence of freshwater diagenesis.

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TABLE 1

Mineralogical, geochemical and stable isotopic data of the studied reefal facies, recent sediments and unaltered aragonitic coral samples

| Mineralogy %			CaO%	MgO%	Na ppm	Mn ppm	Fe ppm	Sr ppm	δ¹⁸O (PDB)	δ¹³C (PDB
A	C	Pd								
			Calcareous sandstone							
87	6	3	44.6	0.33	6500	15	1050	8300		
19	67	3	45.7	1.29	6100	8	175	3500		
19	–	8	38.8*	2.61	2810	10	640	2590		
			45.0	0.88	4500	14	708	3595		
			43.0	1.46	2210	10	620	3800		
			Bioclastic packstone							
8	79	6	51.7#	2.08	1490	42	250	1140	-3.33	+0.25
21	59	13	48.5#	3.23	4250	40	160	2460	-2.10	+1.34
–	–	97	34.2#	17.50	5610	30	210	450	+1.52	+1.67
35	–	6	50.7*	3.41	3430	60	350	3770	-1.44	+1.78
43	19	23	43.4	7.57	3800	17	570	2120	-0.36	+3.13
–	75	10	50.4	2.09	2440	33	960	1510		
23	34	31	47.9#	4.00	1900	18	480	3290		
62	29	4	47.8	3.78	890	30	1110	2450	-1.08	+1.53
24	–	7	42.2*	4.47	1405	45	1600	1310		
–	90	5	51.2	0.96	1220	50	1260	2580		
35	–	6	52.2	2.03	3340	10	230	3450	-0.48	+2.36
			Coraline algal grainstone							
–	7	36	28.6#	13.90	5920	40	320	340	+2.69	+3.17
–	–	80	28.5#	14.40	3250	40	580	520	+3.39	+2.76
			39.7	11.70	730	70	310	500	+0.45	+2.88
–	8	72	32.6	15.20	297	64	1260	390		
–	3	86	40.9	12.17	530	20	680	670	+1.03	+2.87
–	4	91	31.3	16.90	359	62	1080	640		
–	39	40	35.6	17.13	660	40	250	730		
			36.6	16.99	695	28	630	313		
–		69	32.4	18.85	600	52	1004	460		
–	8	82	35.6	17.88	710	43	500	510		
			32.8	19.21	700	50	1300	580		
			Coral-algal boundstone							
–	86	–	47.4	1.43	414	56	890	640		
			45.1	1.40	862	50	1250	700		
–	93	–	48.3	2.62	724	61	1580	1200	-5.57	-2.17
–	88	–	46.9	1.82	658	55	1240	810		
			47.0	1.45	409	50	910	730		
			44.5	0.92	610	38	811	657		
			42.6	1.12	480	42	980	1100		
			Bioclastic pelletal packstone							
–	97	–	54.9	1.02	297	47	940	480		
–	92	–	50.5	1.42	319	116	1230	690		
–	95	–	50.7	1.12	438	48	,590	350		
			51.9	1.20	312	68	1040	520		
			54.7	1.30	7000	55	1000	390		
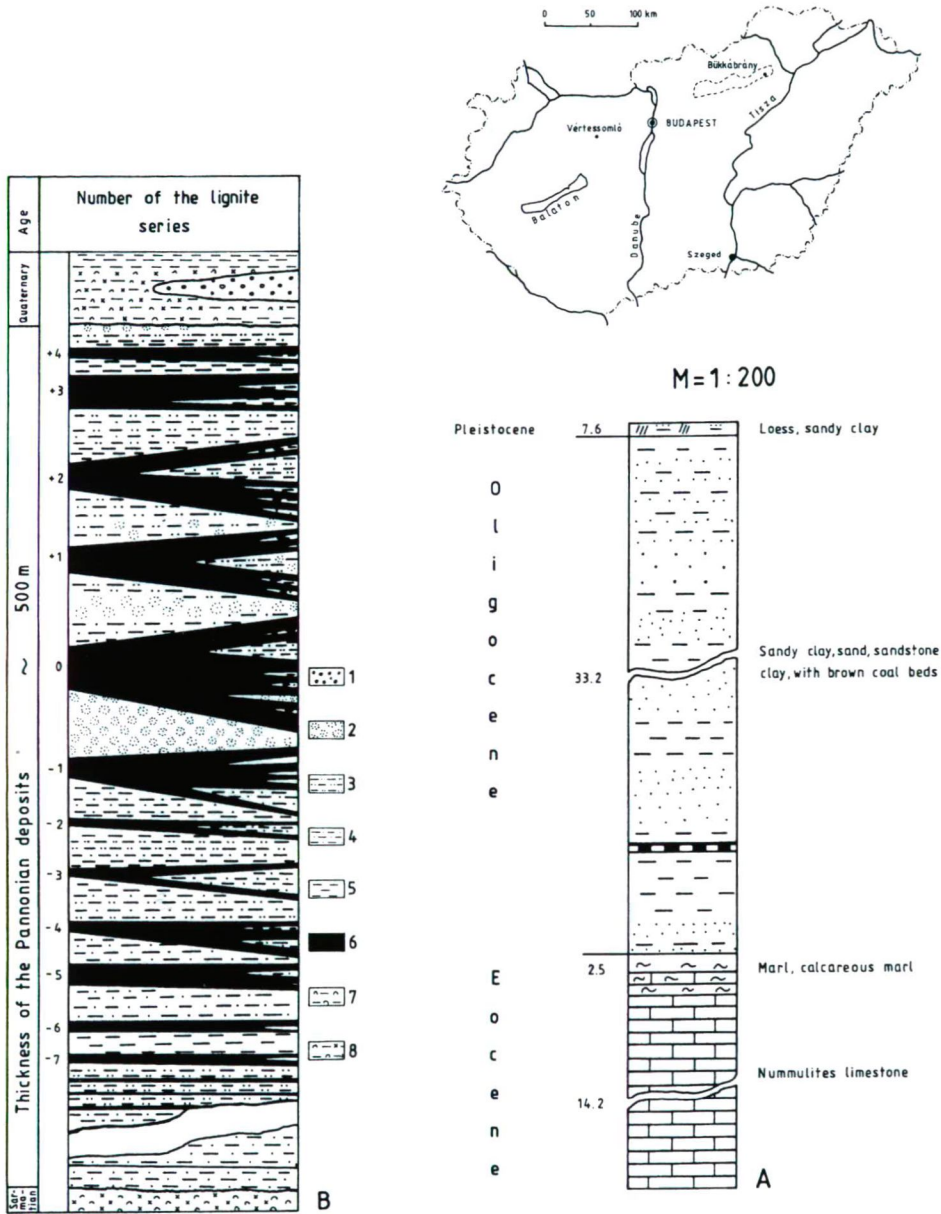
Fig. 1. Location map of the studied area and geological sections to them:
A) detail of the geological section at Vértessomló (after GERBER, 1987);
B) ideal geological section at Bükkábrány (after CSILLING, 1965)
Legend: 1 = Pebble, 2 = Sand, 3 = Clayey sand, 4 = Sandy clay, 5 = Clay,
6 = Lignite, 7 = Rhyolite tuff, 8 = Tuffaceous clay.

TABLE 1 continuation

A	Mineralogy % C	Pd	CaO%	MgO%	Na ppm	Mn ppm	Fe ppm	Sr ppm	$\delta^{18}O$ (PDB)	$\delta^{13}C$ (PDB
			Biomicrosparatic limestone							
–	95	1	51.5#	0.95	2590	80	1930	720	-6.50	-3.21
–	89	1	56.4#	0.36	970	10	130	500	-9.60	-4.35
–	92	–	54.4#	0.54	950	60	460	1110	-5.57	-2.17
			54.1#	0.64	1409	50	840	770		
			54.8#	0.82	1650	22	378	1050		
			Reefal sediments							
82	–	–	17.4*	3.60	3450	7	210	6100		
72	8	–	23.4*	5.48	3783	3	30	9500		
90	4	–	25.3	6.03	2567	23	420	10000		
			20.4	4.76	3800	30	510	10300		
			Unaltered aragonitic coral samples							
			–	0.08	–	–	–	8110		
			–	0.11	–	–	–	7610		
			–	0.03	–	–	–	8700		

older reef samples   A: aragonite   Pd: protodolomite
* contain high Mg calcite   C: calcite
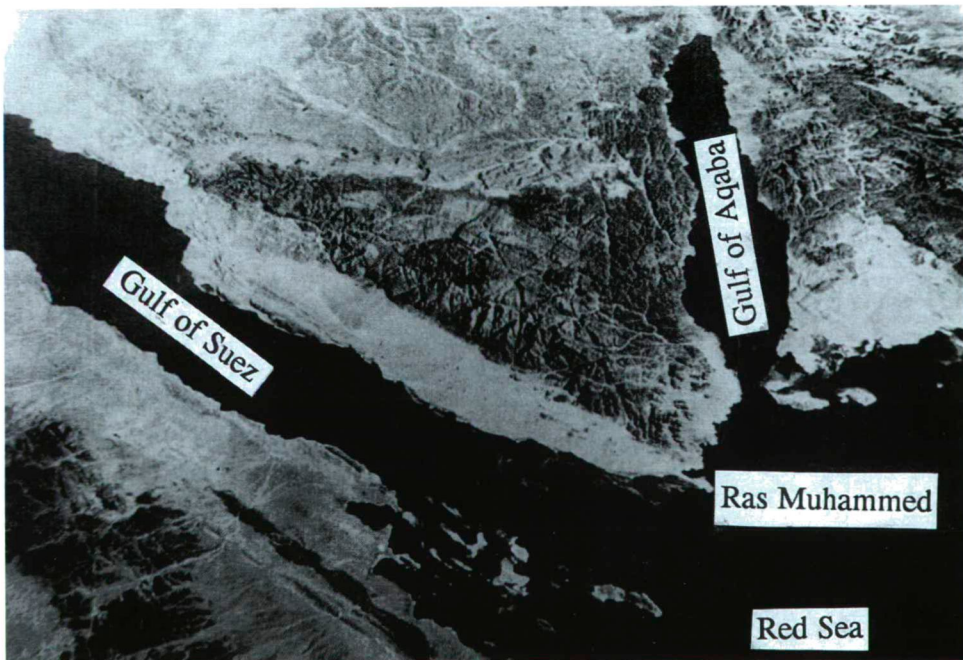
Fig. 1. Sinai Peninsula between Gulf of Aqaba and Gulf of Suez (Landsat image)
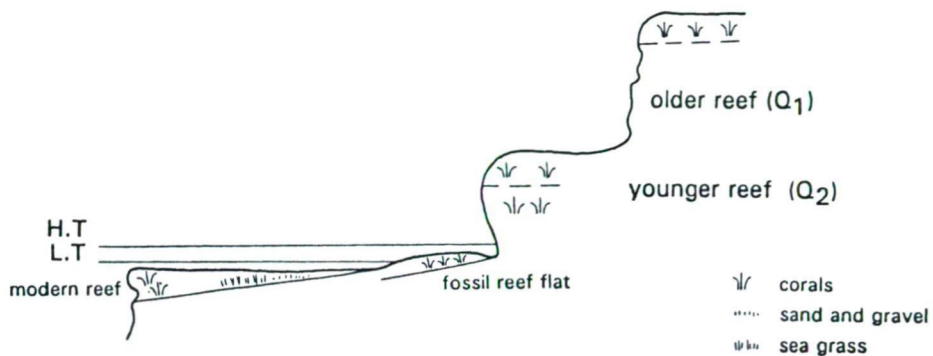
Fig. 2. Sketch of the raised Pleistocene reef terraces, the fossil reef flat and the modern reef between Ras Muhammed and Wadi Kid.
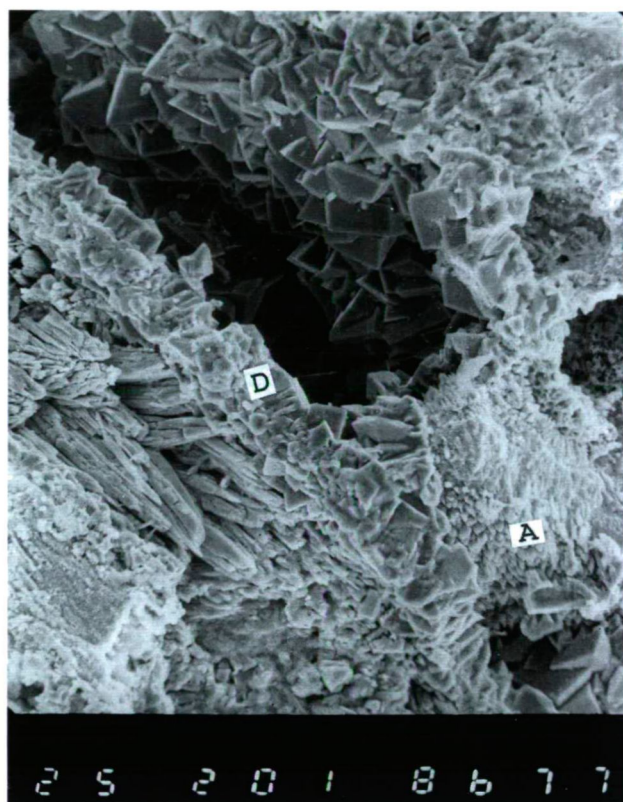

Fig. 3. Dolomite rhombs (D) developed as dolosparite fringing cement around molds and skeletal grains. The marine aragonite cement (A) is made up by fibrous crystals nucleated on grains. Older reef. SEM.200X.
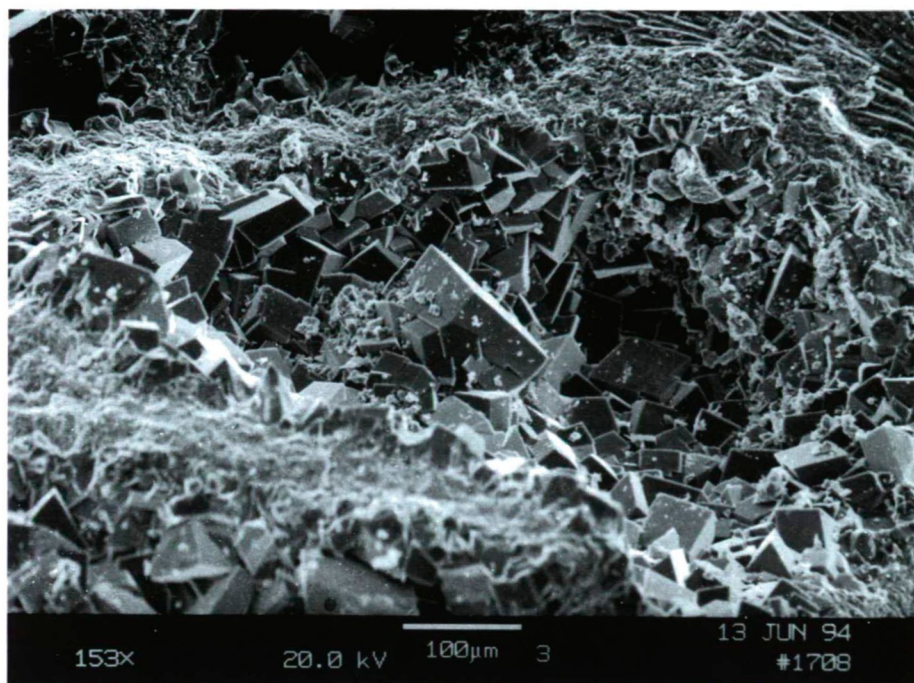
Fig. 4. Small equant rhombic dolomite crystalls fill a moldic pore. Dolomite crystals are, 10–80 μm in size. Older reef. SEM.
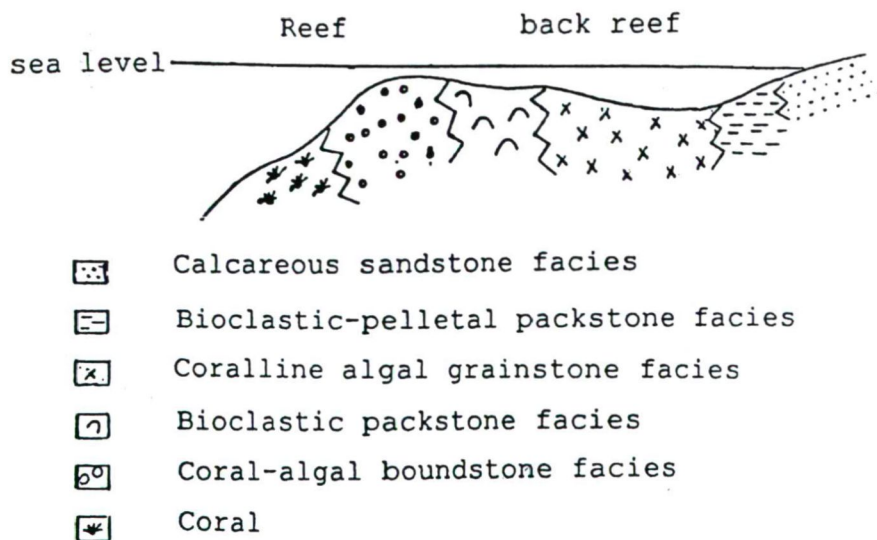

Calcareous sandstone facies

Bioclastic-pelletal packstone facies

Coralline algal grainstone facies

Bioclastic packstone facies

Coral-algal boundstone facies

Coral

Fig. 5. Diagram showing position of various microfacies types of the Pleistocene coral reef terraces.

a

Calcareous sandstone facies

Relative Intensity

Two Theta [deg] / d - spacing

b

Bioclastic packstone facies

Relative Intensity

protodolomite

Two Theta [deg] / d - spacing

c

Coralline algal grainstone facies

Relative Intensity

protodolomite

Two Theta [deg] / d - spacing
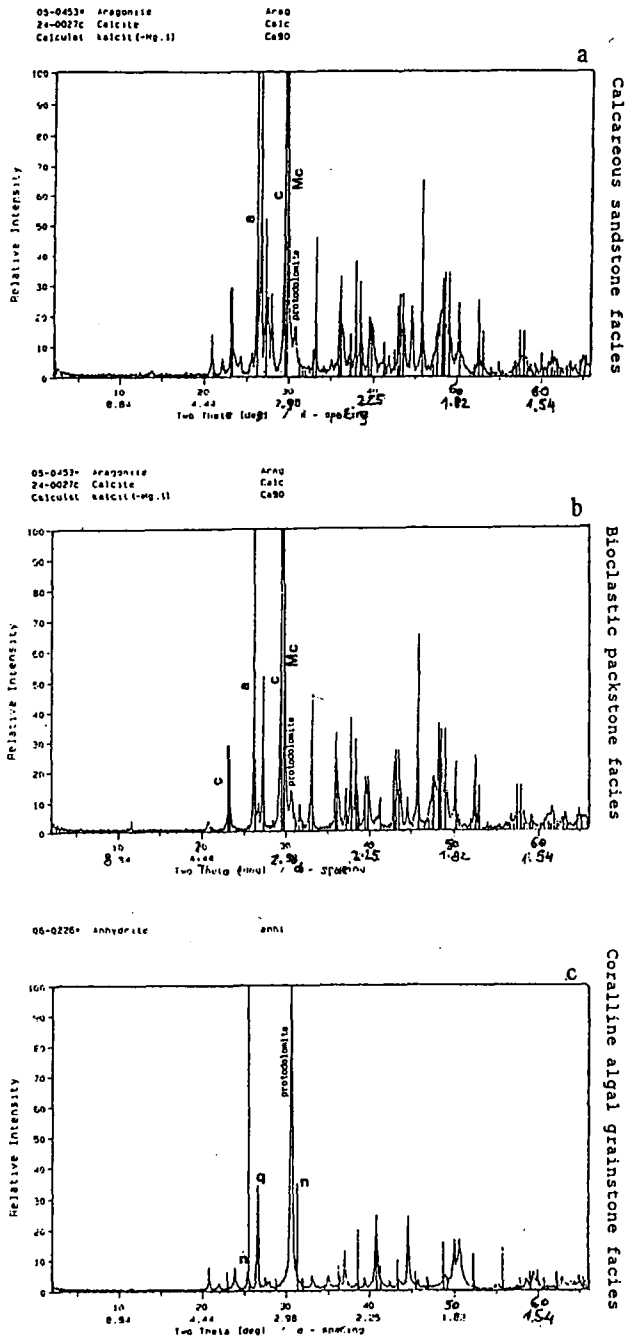
Fig. 6a. X-ray powder diffraction analysis of partially and pervasively dolomitized samples

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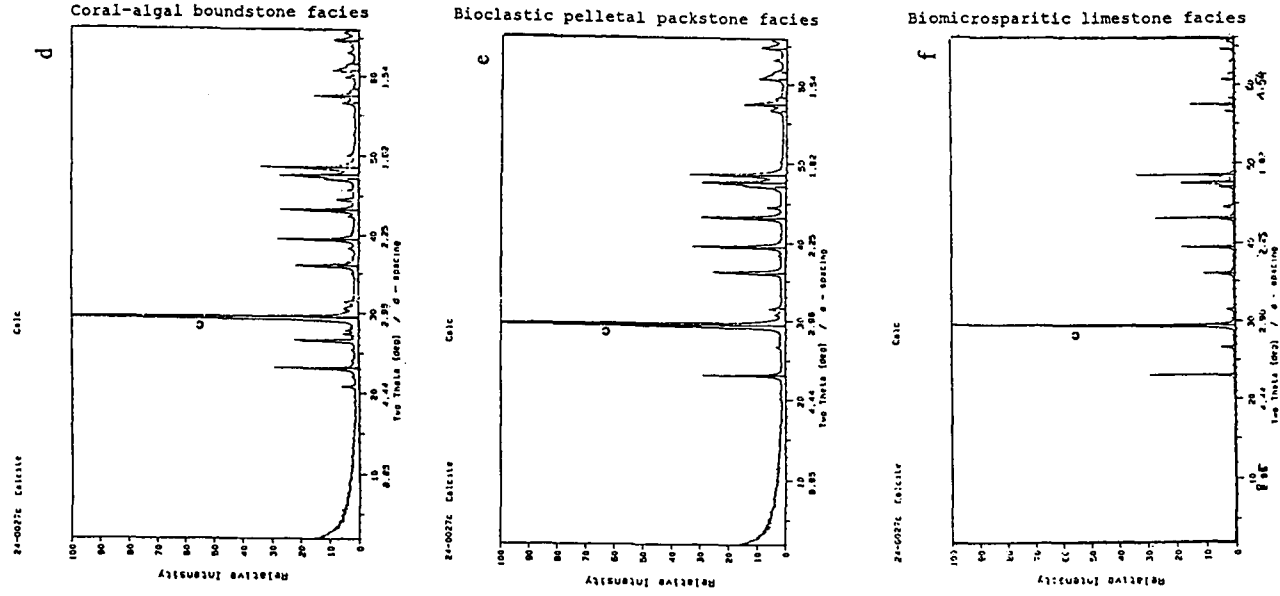
Fig. 6b. X-ray powder diffraction analysis of low Mg calcite-rich samples. a: aragonite, c: calcite, n: anhydrite, q: quartz, Mc: Mg calcite

Fig. 7. Correlation between Sr and Mg concentration.

Legend:
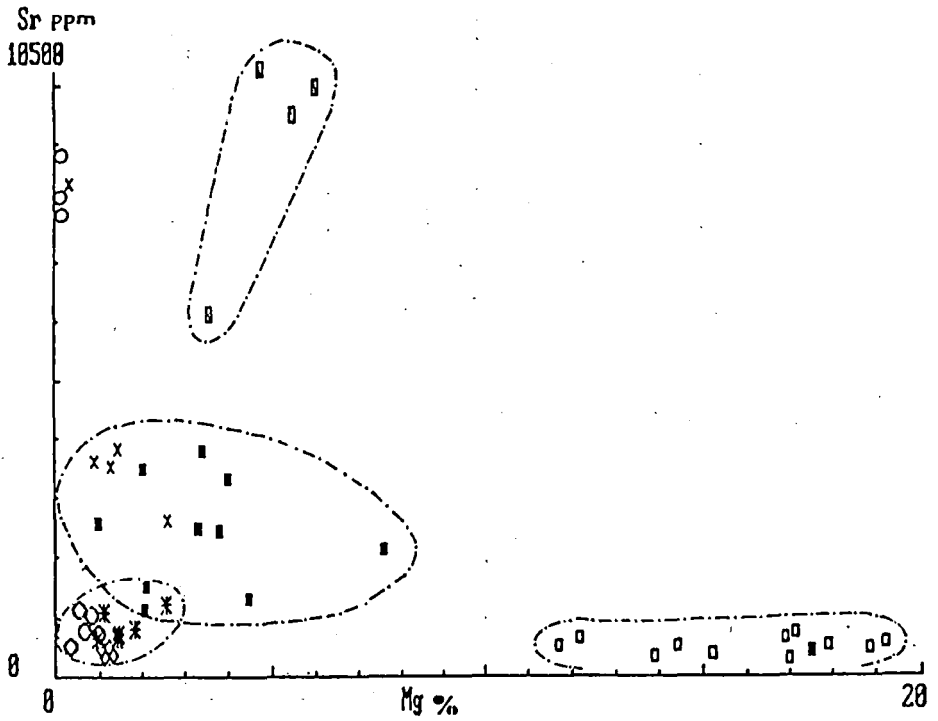
x Calcareous sandstone facies
■ Bioclastic packstone facies
▯ Coralline algal grainstone facies
▥ Coral-algal boundstone facies
Ó Biomicrosparitic limestone facies
◇ Bioclastic pelletal packstone facies
▨ Reefal sediments
O Unaltered aragonitic corals

} Partially dolomitized
— Pervasively dolomitized
} Low-Mg calcite-rich
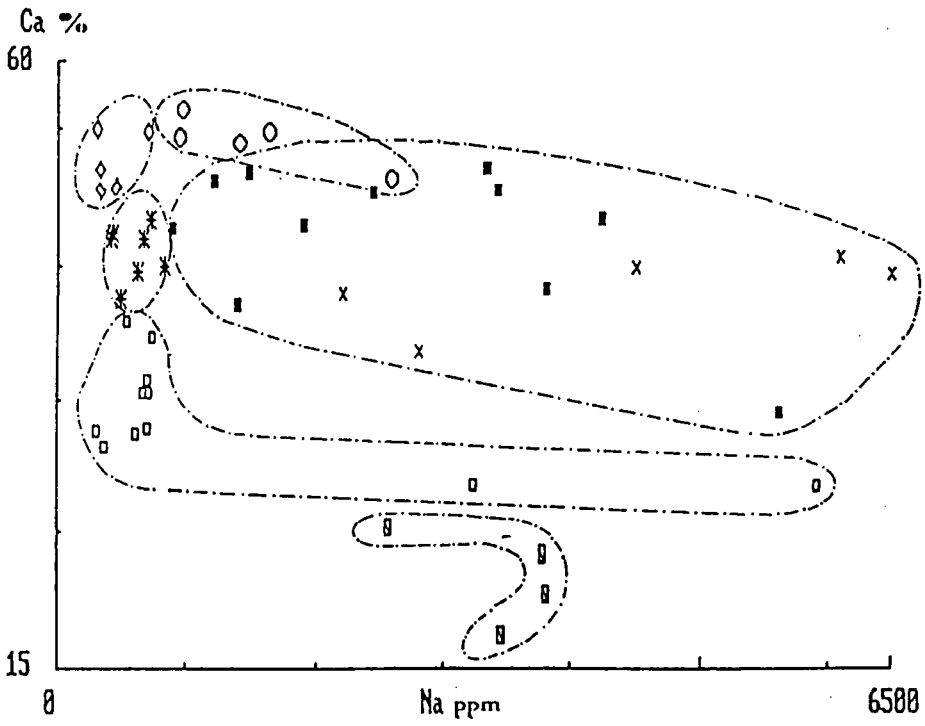
Fig. 8. Correlation between Ca and Na concenration. Legend is same that of *Fig. 7.*
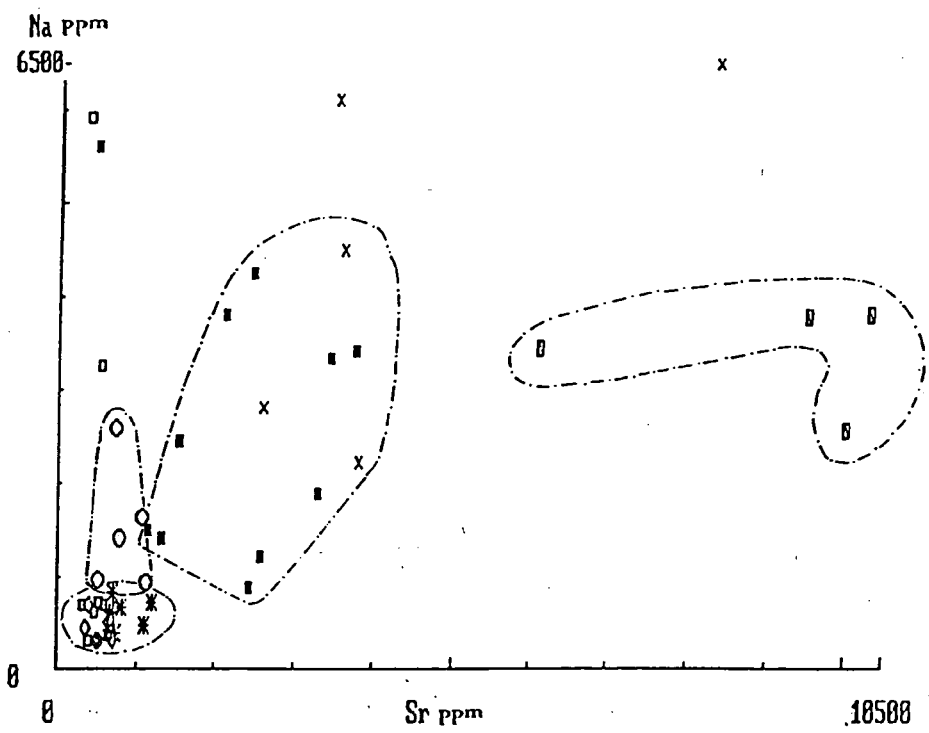
Fig. 9. Correlation between Na and Sr concenration. Legend is same that of *Fig. 7.*
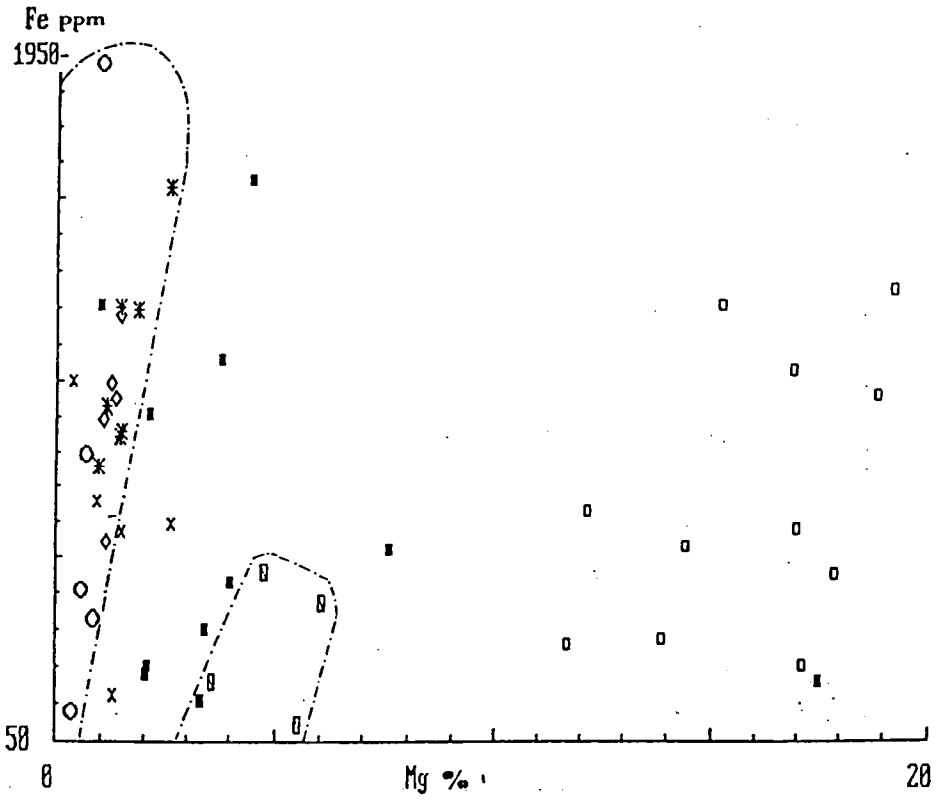
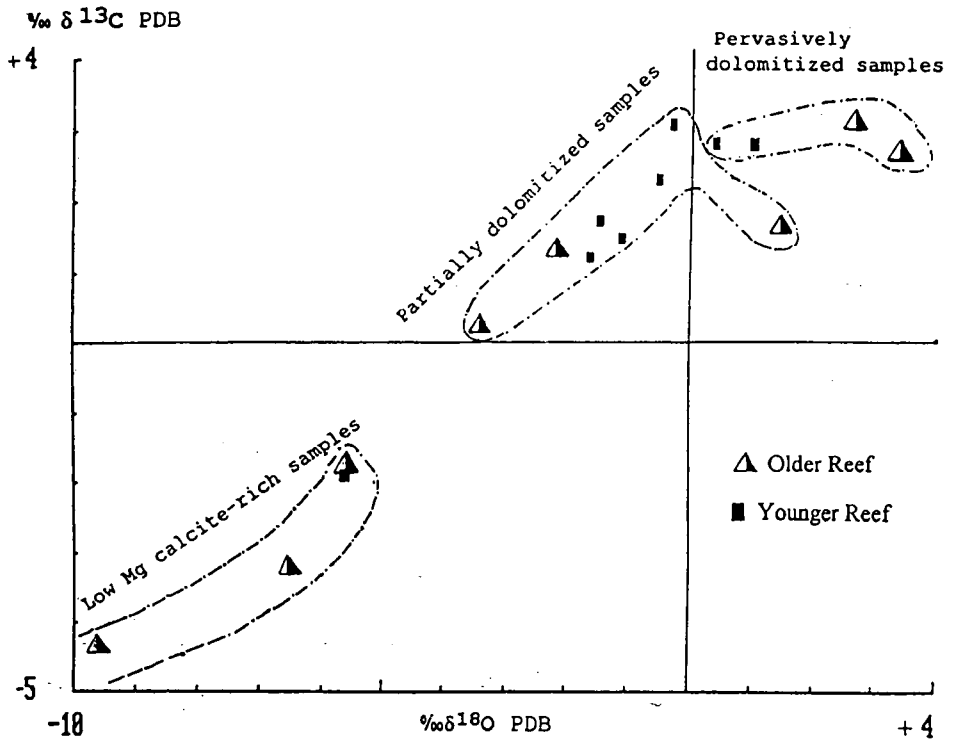*Fig. 10.* Correlation between Fe and Mg concenration. Legend is same that of *Fig. 7.*

Fig. 11. Isotope values of samples in older and younger reef sequence.