

Variations in Mesozoic–Cenozoic skeletal carbonate mineralogy

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Abstract

Literature-based estimates of Mesozoic–Cenozoic shoalwater carbonate composition indicate important changes in frequency distribution of carbonate biota that translate into changes of bulk skeletal mineralogy of the original sediments. This mineralogy was strongly dominated by metastable carbonates during the Triassic (mainly aragonite) and during the Cenozoic (aragonite and magnesian calcite). In between these periods lies an interval of reduced metastable carbonate and consequently high calcite content. This biogenic aragonite–calcite cycle parallels the one observed in (presumably inorganically precipitated) ooids and marine cements.

Introduction

Secular variations in the relative abundance of aragonitic (and magnesian-calcitic) versus calcitic non-skeletal carbonate platform components (oolites and cement) have been described by Sandberg (1983, 1985). Opydyke & Wilkinson (1990) find coeval variations in the latitudinal distribution of such components. For the Mesozoic–Cenozoic period, these studies show maxima for aragonite with a narrow latitudinal distribution in the Triassic and Late Cenozoic and a more broadly distributed ‘calcitic period’ in the Late Mesozoic and Early Cenozoic. These variations have been attributed to the so-called global ‘icehouse–greenhouse cycles’, reflecting periods of different atmospheric CO₂ content, oceanic Ca/Mg ratio and global sealevel, which in turn were thought to be coupled to changes in seafloor spreading rates and mantle convection (Fischer 1981, 1984).

The main purpose of our investigation was to check whether the skeletal mineralogy of Mesozoic–Cenozoic shoalwater carbonate sediments reflects similar trends. Earlier works on a larger time-scale, using primarily species diversity as a quantitative measure, indicated a major change in bio-mineralization during the Phanerozoic. Wilkinson (1979) and Lowen-

stam (1981) postulated a trend from calcite-dominated production in the Paleozoic to aragonite-dominated production in younger Phanerozoic times. Füchtbauer (1988) noticed increased mineralogic diversity in the same interval. We have attempted to quantify changes in biotic carbonate mineralogy directly from published data on the relative abundance of biotic carbonate platform components and their skeletal mineralogy.

Methods

The quantitative estimates of original sediment mineralogy were obtained by the following steps:

- 1) Definition of the original carbonate mineralogy of the major skeletal carbonate producers (Fig. 1A, Table 1).
- 2) Determination of the skeletal composition of carbonate formations from published case studies (Fig. 2, Table 2).
- 3) Data gathered in steps 1 and 2 were then used to calculate the original bulk skeletal carbonate mineralogy (i.e. mineralogy of the sediment prior to diagenesis). Finally, this mineralogy was set out against the geologic time-scale (Fig. 3).

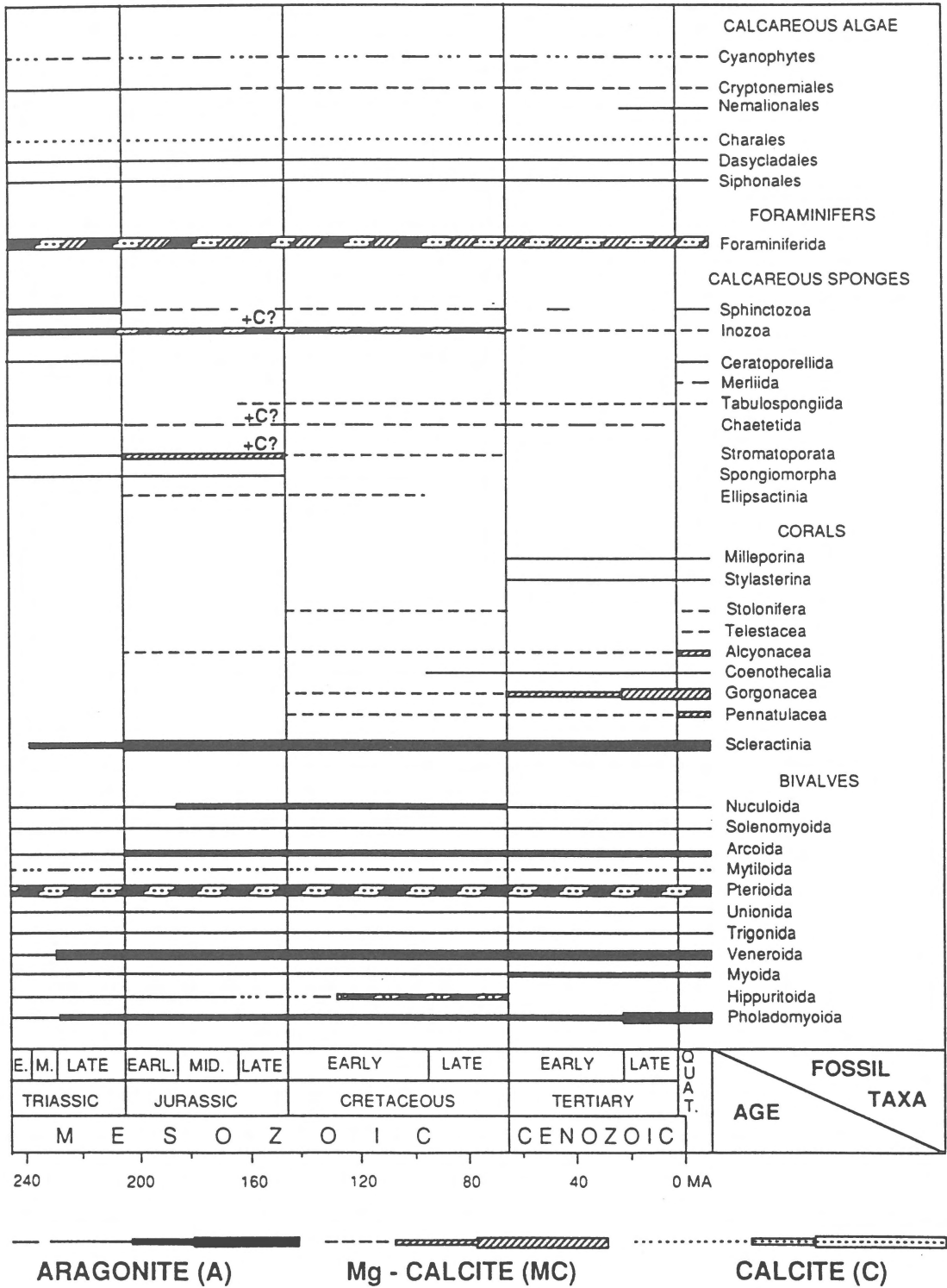


Fig. 1A. Skeletal mineralogy, stratigraphic range and relative importance of major Mesozoic-Cenozoic skeletal carbonate producers (subdivided by order, cf. Table 1). Thickness of line represents relative number of families within order. Geologic timescale from Berggren & Van Couvering (1985) for the Cenozoic, Kent & Gradstein (1985) for the Jurassic-Cretaceous and Odin & Letolle (1982) for the Triassic.

For taxonomic subdivision of the carbonate biota we followed the 'Treatise on Invertebrate Paleontology' (Moore 1953–1974), with some revisions for the Foraminifera as proposed by Loeblich & Tappan (1987) and for the 'calcareous sponges' as proposed in the review edited by Broadhead (1983) and in Rigby (1987). The subdivision of calcareous algae is based upon Wray (1977).

Skeletal carbonate mineralogy is expressed in three categories: aragonite (A); magnesian calcite (MC; calcite with > 4 mol% $MgCO_3$), and calcite (C; calcite with a $MgCO_3$ content < 4 mol%).

Bulk skeletal and mineralogic composition were assigned to three environments for each geologic period: 'Platform Interior' (PI), 'Platform Margin' (PM) and 'Platform Slope' (PS). The Platform Margin environment includes barrier reefs, fringing reefs or shelf-margin shoals. Platform Interior comprises all facies landward of the 'platform margin' (backreef, lagoon with patchreefs and lagoon-floor sediment, beach, etc.). Platform Slope represents facies seaward of the 'platform margin'.

Three categories of data quality are recognized. In Category A, the data are derived from percentage tables or figures representing percentages (e.g. pie diagrams, 'Mae West' diagrams). In Category B, relative frequencies are denominated in extensive graphic sections. The number of graphic representations of each fossil group in one or more sections of a characteristic formation was counted and converted into percentages. In Category C, relative frequencies of different fossil groups are related to a qualitative scale with terms such as 'very rare', 'rare', 'present', 'frequent', 'abundant'. If no further information could be obtained from the text, fossil groups denoted by these terms were given relative frequencies of 1, 5, 14, 35 and 45% in each sample, respectively.

Some data sets were given a lower quality rank when some or part of the main biota groups (commonly the non-framebuilding foraminifers and mollusks) were not quantified in the main literature source and their relative frequency had to be calculated from additional literature data.

Skeletal carbonate mineralogy

Corals, algae, foraminifers and mollusks are the main skeletal carbonate producers in modern carbonate platform environments (Milliman 1974). Data from Gabri el & Montaggioni (1982) and Dullo (1986) suggest that

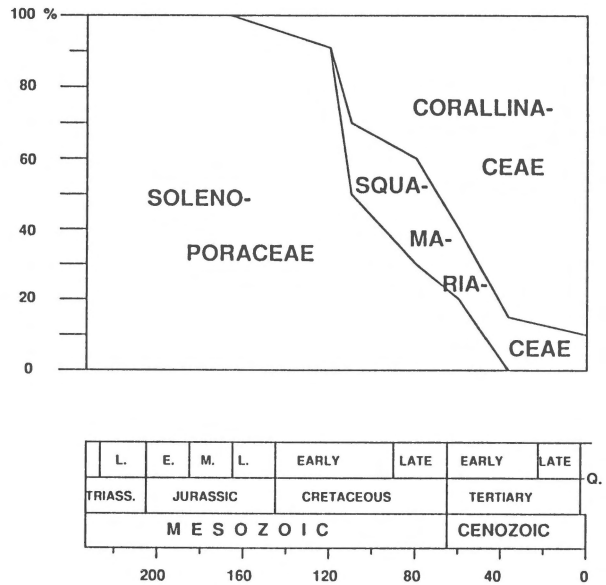
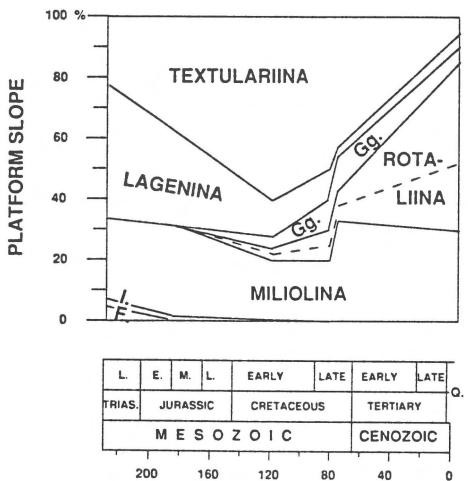
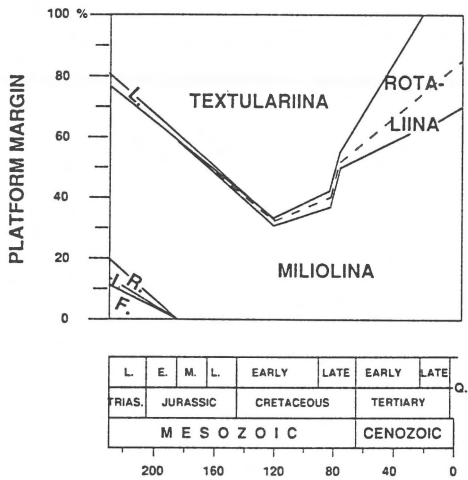
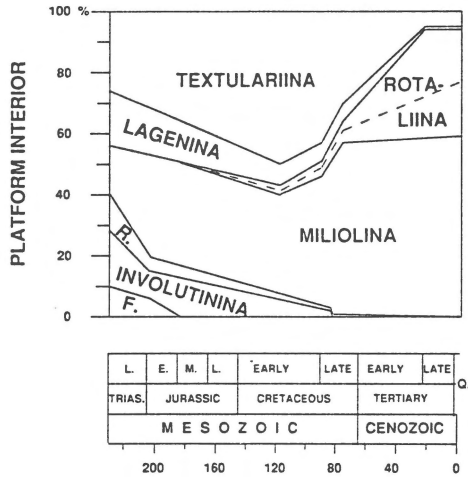


Fig. 1B. Estimated importance of main red algal families in the Mesozoic–Cenozoic. Based on data from Wray 1977, Poignant 1978, 1979, Can erot 1979, Fl ugel 1979, Gollestaneh 1979, Peybernes 1979, R acz 1979, Senowbari-Daryan & Sch afer 1979, H ofling 1985 and Dullo et al. 1990. Note: change from 100% aragonitic taxa (Solenoporaceae) to nearly 100% magnesian calcite taxa (Corallinaceae).

these organisms produce 90 to 95% of the skeletal material of modern warm-water carbonate platform environments, the remainder being supplied by echinoids, bryozoans, ostracods, serpulids and sponges. Calcareous sponges (including stromatoporoids and chaetetids) have been much more important producers in the Mesozoic (Fl ugel 1982a, Stanley 1988, Scott 1988).

Elaborate data on skeletal carbonate mineralogy of Recent organisms were published by Clarke & Wheeler (1922), Vinogradov (1953), Chave (1954, 1962), Lowenstam (1954a, b, 1964), Keith & Weber (1964), Dodd (1967) and Milliman (1974). B oggild (1930), Majevske (1969), Bathurst (1971), Scholle (1978), Wilkinson (1979) and F uchtbauer (1988) have also dealt with carbonate mineralogy of different fossil groups. These overviews form the basis of the compilation in Fig. 1A and Table 1. Below follow explanatory comments on this compilation including additional references on specific details.



←

Fig. 1C. Relative frequency of different foraminiferal suborders in Meso-Cenozoic platform environments. Calculated from data in Hohenegger 1974, Hohenegger & Piller 1975, Schäfer & Senowbari-Daryan 1981 (Triassic); Saint-Marc 1982, Tronchetti 1982, Höfling 1985 (Cretaceous); Sen Gupta & Schafer 1973, Brasier 1975, Martin & Liddell 1988, Culver 1990 (Recent). Additional information from Bilotte 1978, 1985, Bilotte et al. 1978, Decrouez 1978, Frost 1981, Caus 1988, Masse 1989, Dullo et al. 1990. Dashed line marks separation between calcite (above) and Mg-calcite and aragonite (below). Note the relative importance of Robertinina (R), Involutinina (I) and ?Fusulinina (F) (aragonite) in the Triassic and of Miliolina and Rotaliina (mainly magnesian calcite) in the Recent. Gg = Globigerina. The high frequency of Textulariina in the Jurassic-Cretaceous suggests a 'calcite maximum' for foraminifers in this time-interval, but its relative importance cannot be simply deduced from this figure due to the agglutinated shell-structure and the presence of non-carbonate cement.

Calcareous algae

Red (Rhodophyta) and green (Chlorophyta) algae are the major Mesozoic-Cenozoic skeletal carbonate producers (Johnson 1961, Milliman 1974, Wray 1977: fig. 162). Besides, blue-green algae (Cyanophyta) were important in the (earlier) Mesozoic (Wray 1977, Flügel 1982, Dullo et al. 1990), whereas coccoliths (Chrysophyta) are of importance in younger platform slopes (Wray 1977: fig. 144). Skeletal mineralogy is highly variable (Fig. 1A), but remains relatively stable on the family level (Wray 1977; Table 1).

Cyanophyta

Cenozoic blue-green algae (or Cyanobacteria) are commonly restricted to the most internal parts of the carbonate platform (Wray 1977). Riding et al. (1991a, b) point to the importance of cyanophytes in Late Miocene reefs of SE Spain, but the existence of open marine conditions during their deposition is still a matter of discussion (Esteban 1980, Van de Poel 1991).

Data on the mineralogy of calcified filaments of Cyanobacteria and of stromatolites and thrombolites produced or promoted by these organisms suggest that carbonate mineralogy varies in relation to salinity and other environmental factors (cf. Wray 1977). Pure calcite, calcite with variable magnesian contents and aragonite have all been reported as minerals of recent cyanobacterial crusts with calcite as the most common in brackish to fresh waters (Johnson 1961, Dalrymple 1965, Monty 1965, Friedman et al. 1973, Aharon et al. 1977, Botz & Von der Borch 1984, Thompson et al. 1990, Buczynski & Chafetz 1991, Reid & Browne 1991). In a number of modern and fossil examples,

cyanobacterial crusts consist of a mixture of sedimentary particles, peloids, cement and coating of filamentous algae (Reid & Browne 1991, Riding et al. 1991a).

Cyanobacteria were omitted from our counts of bulk skeletal mineralogy because of their mineralogic 'instability' and since their products cannot be reliably separated from inorganic precipitates and clastic components.

Rhodophyta

The main Meso-Cenozoic red algal carbonate producers are the Solenoporaceae, Gymnocodiaceae, Corallinaceae and Squamariaceae, all belonging to the order Cryptonemiales (Wray 1977, James et al. 1988, Dullo et al. 1990).

Taxa from the most prominent 'modern' red algal family, the **Corallinaceae**, commonly have a high magnesium content (Vinogradov 1953, Chave 1954, Moberley 1968, Milliman 1974). Richter & Füchtbauer (1978) present evidence for magnesian calcite in Oligocene, Eocene and Upper Cretaceous corallinaceans.

For the extinct **Solenoporaceae**, Wendt (1977) has reported an aragonitic skeletal mineralogy in the Permian. The equally extinct **Gymnocodiaceae** are generally considered to be closely related to the modern family **Chaetangiaceae** (order Nemalionales), that produces aragonite (Clarke & Wheeler 1922, Dawson 1961, Milliman 1974, Wray 1977).

Recent **Squamariaceae** are generally reported to produce aragonite (Dawson 1961, Ginsburg & James 1976, Flajs 1977, Wray 1977, Buchbinder & Halley 1985, James et al. 1988, Dullo et al. 1990). The studies of Neumann (1965) and Halley (1984), respectively, suggest that magnesian calcite may occur in Recent and Eocene *Peysonnella*.

The changing ratio between aragonite and magnesian calcite produced by red algae during the Meso-Cenozoic (Fig. 1B) has been taken into account when unspecified red algae appear in the counts.

Chlorophyta

The dominant modern green algae belong to the family Codiaceae (order Siphonales) and the order Dasycladales (Milliman 1974, Wray 1977). Dasycladales were most important in the Mesozoic–Early Tertiary (Wray 1977: fig. 162, Deloffre & Génot 1979). At least in southwestern Europe, taxa belonging to the calcitic order Charales are especially frequent in internal parts

of Late Mesozoic–Early Cenozoic carbonate platforms (Canérot 1979, Tronchetti 1982, Caus 1988).

Modern **Codiaceae** and **Dasycladales** produce aragonite needles and skeletal fragments (Clarke & Wheeler 1922, Chave et al. 1962, Keith & Weber 1964, Neumann 1965, Bathurst 1971, Milliman 1974, Flajs 1977, Wray 1977, Génot 1985, etc.). This mineral was also found in Eocene Dasycladales (Flajs 1977, Génot 1985). Masse (1989) reports some 'calcitic or partially calcitic' taxa besides a majority of aragonitic dasyclads in the Early Cretaceous. These taxa, of which the Mg-content is not specified, show a sudden increase in frequency within the Aptian.

Because of the relatively rare occurrence of (Mg-)calcite in green algae, we consider them as an aragonitic group for the studied time-interval.

Foraminifers

The suborders Miliolina and Rotaliina are the dominant modern carbonate-producing foraminifers, whereas Textulariina, Lagenina, Involutinina and Robertinina are important in the Mesozoic (Fig. 1C). The skeletal mineralogy within the order Foraminiferida is highly variable, but it remains relatively stable on the suborder and superfamily level, except for strong variations in Mg-content in the Rotaliina (Blackmon & Todd 1959, Bathurst 1971, Milliman 1974, Tappan & Loeblich 1988; Fig. 1A, Table 1).

Textulariina have especial importance in the Cretaceous (Tappan & Loeblich 1988; Fig. 1C). In some recent genera, the cement of the agglutinated shells consists of calcite crystals (references in Tappan & Loeblich 1988). Bathurst (1971: 41–43) suggests a calcite cement for Carboniferous forms. The role of Textulariina as biomineralizers is reduced by the fact that agglutinated material makes out an important part of their shells (e.g. plates in Bathurst 1971, Toksvad & Hansen 1983, Füchtbauer 1988), whereas the cement is not consistently calcareous (Bathurst 1971, Füchtbauer 1988).

Fusulinina are commonly thought to have become extinct at the Permian–Triassic boundary (e.g. Tappan & Loeblich 1988), but a few genera are consistently reported from the Triassic (Füchtbauer 1988: fig. 6–46; Fig. 1C). Their shells may consist of very finely agglutinated material (Boersma 1978, in Tappan & Loeblich 1988) and some contain coarser agglutinated particles (Tappan & Loeblich 1988). Bathurst (1971) and Tappan & Loeblich (1988) remark that their shell microstructure resembles calcite in the cement of

Table 1. Mineralogy for major skeletal carbonate producing fossil groups, subdivided on the suborder to family level; A = aragonite, MC = magnesian calcite, C = calcite

Fossil group	A	MC	C	Strat. range
CALCAREOUS ALGAE				
Cyanophyta	X	X	X	Precam.-Rec.
Rhodophyta				
Cryptonemiales				
Solenoporaceae	X			Cam.-Eoc.
Gymnocodiaceae	?			Perm.; Jur.-Eoc.
Corallinaceae		X	(X)	L.Jur.-Rec.
Squamariaceae	X	(X)		E. Cret.-Rec.
Nemalionales				
Chaetangiaceae	X			?Mioc.-Rec.
Chlorophyta				
Charales				
Porocharaceae			?	Cam.-Rec.
Characeae			X	Trias.-Rec.
Dasycladales				
Dasycladaceae	X	(X)		?Cam.-Rec.
Siphonales				
Codiaceae	X			?Cam.-Rec.
Chrysophyta				
Coccolithophoridae			X	M.Jur.-Rec.
FORAMINIFERS				
Foraminiferida				
Textulariina				
Ammodiscaceae			?	Cam.-Rec.
Lituolacea	?		X	E.Carb.-Rec.
Fusulinina				
Endothyraceae	?		?	E.Sil.-Trias.
Miliolina				
Miliolacea		X	(X)	E.Carb.-Rec.
Lagenina				
Nodosariaceae			X	M.Carb.-Rec.
Involutinina				
Involutinacea	X			Perm.-Cenoman.
Planispirillinacea	X			Rec.
Robertinina				
Duostominacea	X			Trias.-Hett.
Ceratobuliminacea	X			E.Jur.-Rec.
Robertinacea	X			Paleoc.-Rec.
Spirillinina				
Spirillinacea		X		E.Jur.-Rec.
Globigerinina				
Globigerinacea			X	M.Jur.-Rec.

Table 1. Continued.

Fossil group	A	MC	C	Strat. range
Rotaliina				
Buliminacea		(X)	X	M.Jur.-Rec.
Discorbacea		X	X	L.Jur.-Rec.
Orbitoidacea		X	X	E.Cret.-Rec.
Cassidulinacea			X	E.Cret.-Rec.
Rotaliacea		X	X	L.Cret.-Rec.
Carterina				
Carterinacea			X	Rec.
CALCAREOUS SPONGES				
Calcarea				
Lebetida			X	Cam.-Rec.
Solenida			X	E.Jur.-Rec.
Inozoa				
Chalarina				
Sestrostomellidae	X			Trias.-Cret.
Stellispongiidae	X	X		Trias.-Cret.
Pharetrospongiidae	X			Cret.
Lelapiidae	X	X		Perm.-?Eoc;Rec.
Discocoeliidae	X	X		Trias.-Cret.
Lithonina				
Minchinellidae			X	Cret.-Rec.
other			?	L.Jur.
Other				
<i>Petrobiona</i>			X	Rec.
Murrayonidae			X	Rec.
Sphinctozoa				
Sebargasiidae	X			L.Carb.-Cret.
Cystothalamidae	X			L.Carb.-Perm.
Celyphiidae	X			L.Carb.-Trias.
Cryptocoeliidae	X			Perm.-Cret.
Cassianothalaminiidae			X	Trias.-?Jur.
Barroisiidae			X	Trias.-Cret.
other				
<i>Vaceletia</i>	X			Eoc.-Rec.
Sclerospongea				
Chaetetida	X	X	X	M.Ord.-L.Mioc.
Tabulospongiida				
Acanthochaetetidae			X	L.Jur.-Rec.
Ceratoporellida	X			Trias.; Rec.
Merliida	X	X		Rec.
other				
<i>Blastochaetetes</i>			?	L.Jur.-Cret.
<i>Tatouinella</i>			?	L.Jur.
<i>Calcifibrosporgia</i>	X			Rec.
<i>Astrosclera</i>	X			Rec.

Table 1. Continued.

Fossil group	A	MC	C	Strat. range
Stromatoporata				
Stromatoporoidea				
Disjectoporidae	X			Perm.-Trias.
Actinostromariidae	?	X		Jur.-Cret.
Milleporidiidae		X		Jur.-Cret.
Parastromatoporidae			?	Jur.-Cret.
Stromatoporidae			?	?Ord.-Cret.
Spongiomorpha	X			Perm.-Jur.
other				
Ellipsactiniidae		?		L.Jur.-E.Cret.
CORALS				
Hydrozoa				
Milleporina				
Milleporidae	X			Paleoc.-Rec.
Stylasterina				
Stylasteridae	X			Paleoc.-Rec.
Anthozoa				
Octocorallia				
Stolonifera		X		Cret.-Rec.
Telestacea		X		Rec.
Alcyonacea		X		E.Jur.-Rec.
Coenothecalia	X			Cret.-Rec.
Gorgonacea				
Scleraxonia		X		Cret.-Rec.
Holaxonia	(X)	X		Cret.-Rec.
Pennatulacea				
Sessiliflorae		X		?Sil.; Rec.
Zoantharia				
Scleractinia				
Astrocoeniina	X			M.Trias.-Rec.
Fungiina				
Agariciidae	X			M.Trias.-Rec.
Poritidae	X			E.Jur.-Rec.
Faviina	X			M.Trias.-Rec.
Caryophylliina	X			E.Jur.-Rec.
Dendrophylliina	X			Rec.
MOLLUSKS				
Gastropoda				
Prosobranchia				
Archaeogastropoda				
Bellerophontina	X		X	E.Cam.-E.Trias.
Macluritina	X			L.Cam.-?Cret.
Pleuromariina	X			Cam.-Rec.
Patellina	X	X	X	M.Trias.-Rec.
Trochina	X			E.Ord.-Rec.
Neritopsina	X			M.Dev.-Rec.
Murchisoniina	X			E.Ord.-Rec.
Caenogastropoda	X			Ord.-Rec.

Table 1. Continued.

Fossil group	A	MC	C	Strat. range
Opisthobranchia				
Pleurocoela	X			E.Carb.-Rec.
Pteropoda	X			?Eoc.-Rec.
Pulmonata				
	X			E.Carb.-Rec.
Bivalvia				
Nuculoida	X			Paleoz.-Rec.
Solemyoida	X			Paleoz.-Rec.
Arcoida	X			Paleoz.-Rec.
Mytiloida	X		X	Paleoz.-Rec.
Pteroida	X		X	Paleoz.-Rec.
Unionoida	X			Paleoz.-Rec.
Trigonioida	X			Paleoz.-Rec.
Veneroida				
Chamacea	X		(X)	L.Cret.-Rec.
other	X		(X)	M.Ord.-Rec.
Myoida				
Myina	X			Perm.-Rec.
Pholadina	X			Jur.-Rec.
Hippuritoida				
Megalodontacea	X			M.Sil.-E.Cret.
Hippuritacea				
Diceratidae	X		X	L.Jur.-E.Cret.
Requieniidae	X		X	L.Jur.-Maastr.
Monopleuridae	X		X	E.Cret.-Maastr.
Caprotinidae	X		(X)	E.Cret.-Turon.
Caprinidae	X		(X)	E.Cret.-Maastr.
Hippuritidae	X		X	Turon.-Maastr.
Radiolitidae	X		X	Barrem.-Maastr.
Pholadomyoida	X			M.Ord.-Rec.

recent agglutinants. Füchtbauer (1988: 285) illustrates a Permian fusulinid that may have had an aragonitic shell.

The frequency of *Miliolina* remained relatively constant (Fig. 1C). Recent taxa (both the smaller forms of the family Miliolidae as well as the generally larger taxa of the families Soritidae and Alveolinidae) have intermediate to high magnesium values (Brady 1884, Clark & Wheeler 1922, Chave 1954, Blackmon & Todd 1959, Bock 1967, in Milliman 1974, Ponder & Glendinning 1974). Towe & Hemleben (1976) found magnesian calcite for an Eocene alveolinid. Richter & Füchtbauer (1978) present evidence for Late Triassic, Early Jurassic and Late Cretaceous magnesian calcite miliolinids.

Involutinina are important in Triassic carbonate platforms (Hohenegger 1974, Hohenegger & Piller 1975, Schäfer & Senowbari-Daryan 1981; Fig. 1C). The genus *Trocholina* still is common in the Early Cretaceous. It becomes less frequent within the Aptian (Masse 1989) and disappears towards the top of the Cenomanian (Bilotte 1978, 1985, Tappan & Loeblich 1988). The recent aragonitic *Planispirillina* is considered a relative. Aragonitic mineralogy has been likewise established for Triassic Involutinina and explains their common recrystallization (Piller 1977, Tappan & Loeblich 1988, Hohenegger & Piller 1975). The shell of Cretaceous *Trocholina* is only initially aragonitic (Masse 1989).

The Duostominacea, the earliest representatives of **Robertinina** (Tappan & Loeblich 1988), reach considerable importance in Late Triassic platform facies (Hohenegger 1974, Hohenegger & Piller 1975, Schäfer & Senowbari-Daryan 1981). Aragonitic mineralogy has been established for early Jurassic members of this superfamily (Oberhauserellidae: Fuchs 1969, 1977, in Tappan & Loeblich 1988). Recent Robertinina are also aragonitic, but are insignificant carbonate producers (Fig. 1C).

Rotaliina start to become important in the Late Cretaceous, when also the first common larger forms appear (Tappan & Loeblich 1988, Dullo et al. 1990; Fig. 1C, Table 1). Recent larger Rotaliina generally have a magnesian calcite test, but some important large-sized forms have low magnesium values or are calcitic (*Amphistegina*, *Cymbaloporetta*, *Rotalia*) (Blackmon & Todd 1959, Milliman 1974; Table 1). Smaller Rotaliina generally have calcitic shells (Table 1). They are most characteristic for the slope environment or internal parts of the platform, but some epiphytic genera (*Discorbis*, *Asterigerina*) are important in the reef tract (Fig. 1C).

Calcareous sponges (s.l.)

Modern forms with a basal calcareous skeleton generally are dispersed cave-dwellers, but they locally form bioherms in the deeper fore-reef or on the upper slope (Finks 1983, Hartman 1983, Vacelet 1988). Calcarea (calcareous sponges in the more restricted sense), chaetetids ('tabulozoa') and Stromatoporata ('hydrozoa') are the three groups of calcareous sponges that are important carbonate producers in the (earlier) Mesozoic (Flügel 1982a, Stanley 1988, Scott 1988; Figs 1A, 2). The latter two groups are considered closely related to recent 'sclerosponges' by most modern

authors (Hartman 1983, West & Clark 1983, Vacelet 1988, Wood 1990).

Calcarea

The main skeletal carbonate producers are the Inozoa (or Pharetronida) and the Sphinctozoa (or Thalamida) (De Laubenfels 1955, Flügel 1981, 1982a, b, Finks 1983, Rigby 1987).

Living **Inozoa** have a magnesian calcite skeleton and spicules (Vacelet 1964, Veizer & Wendt 1976, Finks 1983, Gautret & Cuif 1989). The skeleton of Triassic forms consists of aragonite with occasional spicules of magnesian calcite or calcite (Wendt 1974, 1979, Dieci et al. 1974, Veizer & Wendt 1976, Finks 1983). Jurassic and Cretaceous forms have substantial numbers of 'calcitic' spicules in the skeleton (Wendt 1979, Finks 1983). The Mg-content of this 'calcite' is not specified. Veizer & Wendt (1976) describe Jurassic–Cretaceous sponges that have a characteristic geochemistry and mineralogy which is different from that of both Triassic and Recent forms and which may be calcite (Gautret & Cuif 1989).

Sphinctozoa decrease in importance after the Triassic (Flügel 1982, Finks 1983; Fig. 1A) and are represented by only one living genus, *Vaceletia* (Cuif et al. 1979, Finks 1983, Vacelet 1988). The latter has a skeleton of aragonite needles (Cuif et al. 1973, Finks 1983, Gautret & Cuif 1989). Late Paleozoic–Triassic forms commonly also have an aragonite skeleton (Cuif 1973, Cuif et al. 1979, Wendt 1979, Finks 1983). One family of Triassic sphinctozoans exhibits a magnesian calcite mineralogy (Reitner 1987, Cuif et al. 1990; Table 1). In the Jurassic and Cretaceous the family Barroisiidae is important; it has spicules and a skeleton of (?magnesian) calcite (Cuif et al. 1979, Finks 1983, Reitner 1987).

In our counts, Calcarea from the Triassic are taken to be 100% aragonitic, since the one described magnesian calcite family only locally takes up 15% of the sponge fauna and is further rare or absent (Reitner 1987). For the Jurassic–Cretaceous interval we assume a conservative aragonite/magnesian calcite ratio of 1/1.

Sclerospongea

The genus *Ceratoporella*, the most common modern sclerosponge, has an aragonitic basal skeleton both in the Recent (Hartman 1983, Gautret & Cuif 1989) and in the Triassic (Cuif 1974, Dieci et al. 1977). The recent *Astrosclera* and *Calcifibrosporgia* are also aragonitic,

Table 2. Location and references for case studies used to determine biota distribution for different Meso-Cenozoic time-intervals (Fig. 2)

Age	Platform Interior	Platform Margin	Platform Slope
Upper Triassic	Dachstein Lst, W. Austria (Zankl 1969); Dachstein Lst, C. Austria (Dullo 1980)	Dachstein Lst, W. Austria (Zankl 1969, Wurm in Flügel 1981); Dachstein Lst, C. Austria (Dullo 1980); Dachstein Lst, E. Austria (Flügel 1981)	Dachstein Lst, W. Austria (Wurm 1982, pers. comm. J. Reymer 1990)
Upper Jurassic	Plassenkalke, Austria (Fenninger & Holzer 1970); Nova Scotia Shelf (Eliuk 1978)	Nova Scotia Shelf (Eliuk 1978); Slovenia (Turnšek et al. 1981)	Nova Scotia Shelf (Eliuk 1978)
Aptian	Cow Creek Mb, Pearsall Fm, S. Texas (Loucks & Bebout 1985)		
Albian	Glen Rose Fm, S. Texas (Bay 1985); Glen Rose Fm, C. Texas (Perkins 1985)	Glen Rose Fm, E. Texas (Adams 1985); Eguino, NW Spain (Scott et al. 1990)	Glen Rose Fm, E. Texas (Adams 1985)
Santonian	Gosau Series, Bavaria, (Herm 1977, Höfling 1985); Martigues, near Marseille (Marie 1959, Tronchetti 1981)	Collades Mb, Tremp Basin, S. Pyrenees (Scott et al. 1990); Corbières, S. France (Bilotte 1985)	Ugod Lst, NW Hungary (Brezsnyanski 1984)
Paleocene Oligocene	N. Yugoslavia (Babić & Zupanić 1981)	Ras al Hamra, Oman (Rácz 1979) Aquitaine (Boulanger et al. 1970); Vicenza, N. Italy (Frost 1981)	Ras al Hamra, Oman (Rácz 1979)
Recent	Bahama Platform (Illing 1954, Harris 1977); Hogsty Atoll, S. Bahamas (Milleman 1967); Florida Keys (Ginsburg 1956); Yucatan Shelf (Hoskin 1963, 1966); Belize Shelf (Wallace & Schaeferman 1977); C. and S. Caribbean atolls (Milliman 1974); Madagascar, Rodriguez & Mauritius (Masse 1983; Thomassin & Masse 1985); Reunion (Gabrié & Montaggioni 1982); Grand Barrier Reef (Maxwell et al. 1964, Maiklen 1970); Bikini atolls, SW Pacific (Emery et al. 1954); Guam (Emery 1962; Siegrist et al. 1984); Johnston Island, C. Pacific (Emery 1956); Funafuti, Raroia, Ifaluk, Midway, Kure, Pearl & Hermes atolls, C. Pacific (Milliman 1974)	Bahama Platform (Storr 1964); Hogsty Atoll, S. Bahamas (Milliman 1967); Florida Keys (Ginsburg 1956); Yucatan Shelf (Hoskin 1963, 1966); C. and S. Caribbean atolls (Milliman 1974); Madagascar, Rodriguez & Mauritius (Masse 1983, Thomassin & Masse 1985); Reunion (Gabrié & Montaggioni 1982); Gulf of Aqaba (Dullo 1986); Grand Barrier Reef (Maxwell et al. 1964, Maiklen 1970); New Caledonia (Thomassin & Masse 1985); Guam (Emery 1962, Siegrist et al. 1984); Ifaluk, Midway & Kure atolls, C. Pacific (Milliman 1974)	Florida Keys (Ginsburg 1956); Jamaica (Moore et al. 1976); Madagascar, Rodriguez & Mauritius (Masse 1983; Thomassin & Masse 1985); Reunion (Gabrié & Montaggioni 1982); Guam (Emery 1962)

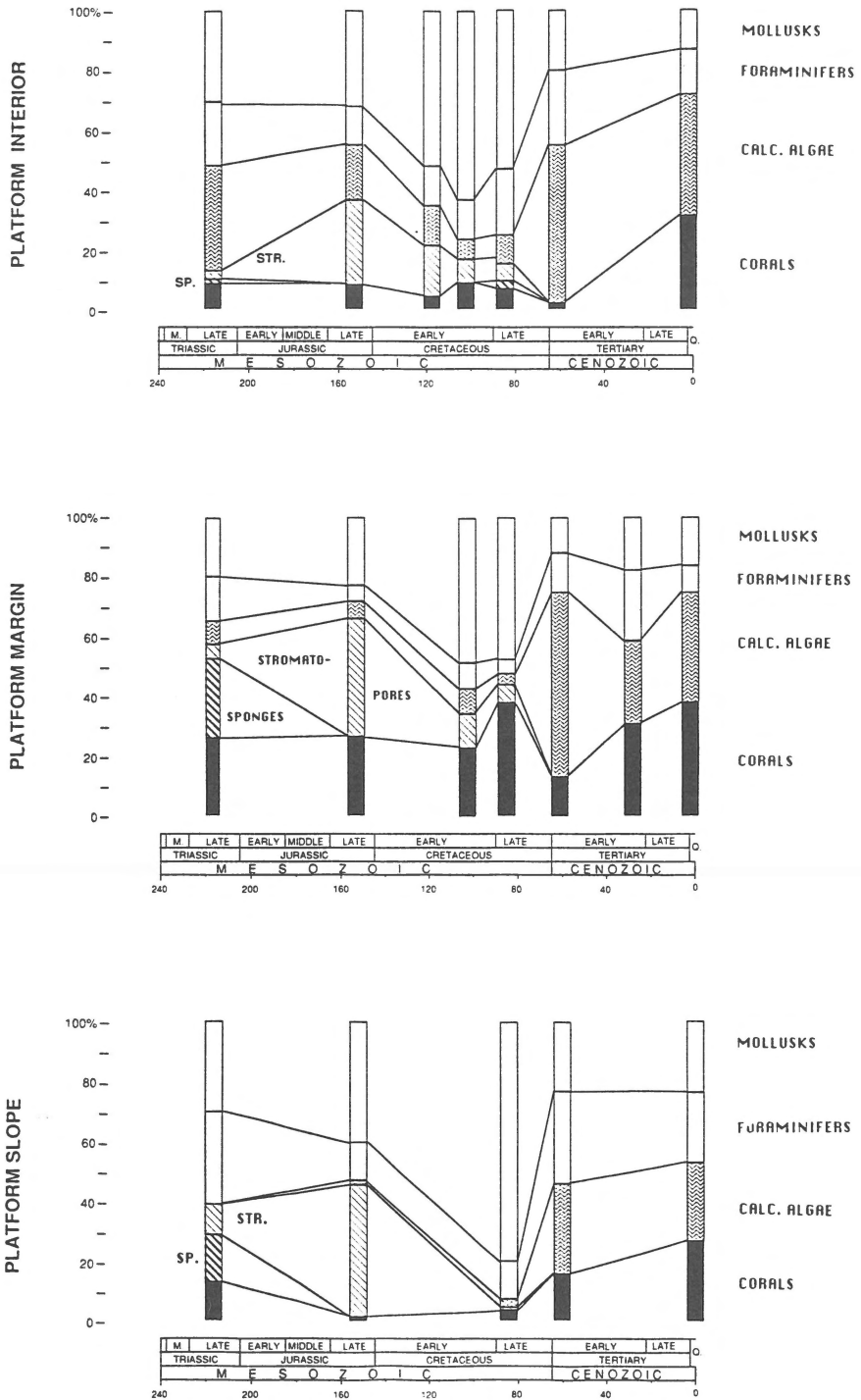


Fig. 2. Frequency distribution of major skeletal carbonate producers through the Mesozoic–Cenozoic for three different carbonate platform subenvironments. Percentages derived from case studies listed in Table 2. Note: successive dominance of different skeletal carbonate builders.

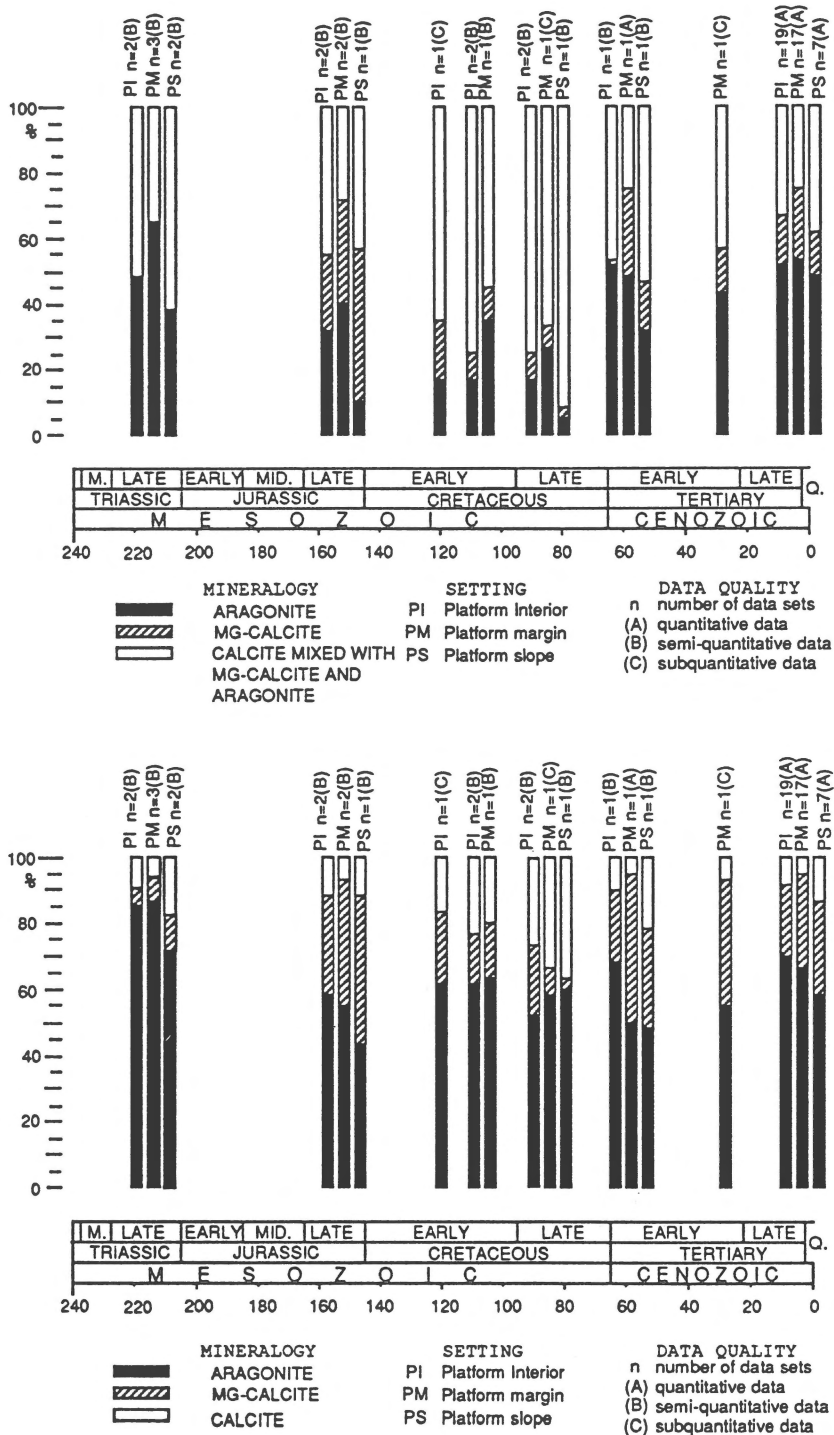


Fig. 3. Distribution of bulk skeletal mineralogy through the Meso-Cenozoic. 3A (above): distribution of aragonite, magnesian calcite and 'mixed mineralogy'. Note the abundance of metastable aragonite in the Triassic, of aragonite plus magnesian calcite in the Cenozoic and the pronounced maximum of 'mixed' in the Late Cretaceous. 3B (below): distribution of bulk skeletal aragonite, magnesian calcite and calcite. Note: decrease of aragonite after the Triassic and maximum for calcite in the Late Cretaceous.

whereas a mixture of aragonite and magnesian calcite occurs in *Merlia* (Hartman 1983, Vacelet 1988, Gautret & Cuif 1989). Only magnesian calcite occurs in *Acanthochaetetes*, which first appears in the Late Jurassic (Hartman 1983, Reitner & Engneser 1983).

The youngest **chaetetid** (in the strict sense) is known from the Late Miocene of SE Spain (Bodergat 1978). Although apparently less common than the stromatoporoids, chaetetids are regularly present from the Triassic to the Late Cretaceous (e.g. Flügel 1981, Turnšek et al. 1981, Tronchetti 1982, Scott et al. 1990).

West & Clark (1983) believe that an aragonitic skeleton for all Paleozoic forms is indicated by their recrystallisation patterns. Aragonitic skeletons have been observed in Permian, Late Jurassic and Early Cretaceous chaetetids (Wendt 1977, Termier & Termier 1974, Kazmierczak 1979). However, Reitner (in Füchtbauer 1988) observed also skeletons of magnesian calcite, and even calcite among the Mesozoic forms. Gautret & Cuif (1989a) have described Late Jurassic forms of particular microstructure and composition, which also may represent originally calcitic skeletons.

For the 'sclerosponges', a 100% aragonitic mineralogy is assumed for the Triassic and a 1/1 ratio aragonite/magnesian calcite for the younger Mesozoic (Fig. 1A).

Stromatoporata

Stromatoporoids in the strict sense, Spongiomorpha and the 'Heterastridiidae' and 'Ellipsactiniidae' make out the 'hydrozoa' (Flügel 1982a). Stromatoporata reach a high diversity in the Late Jurassic (Fig. 1A).

Wendt (1975, 1977) found aragonitic skeletal mineralogy for Permo–Triassic **Stromatoporoidea**. Stearn (1977) suggests an original magnesian calcite skeletal mineralogy for Mesozoic forms. The contradiction may be explained by the fact that the majority of Wendt's observations are on Disjectoporidae (the main Triassic stromatoporoids: Flügel 1982, Stanley 1988), that can be considered as remnants of a Paleozoic stock, for which also Stearn (1977) and Füchtbauer (1988) consider an aragonitic mineralogy. Stearn (1977) proposes a magnesian calcite mineralogy for typical Mesozoic forms. Wendt (1975) suggests an aragonitic mineralogy for a Jurassic *Actinostromaria*. Reitner (1987: 575) suspects a magnesian calcite mineralogy for Jurassic and Cretaceous forms of this genus. Gautret & Cuif (1989) suggest that

younger Mesozoic stromatoporoids earlier described by Hudson (1960) show a microstructure that points to calcite composition. The living sclerosponges *Calcifibriospongia* and *Astrosclera*, that strongly resemble stromatoporoids (Hartman 1983, Reitner 1987) have an aragonitic mineralogy.

For the **Spongiomorpha**, Wendt (1975, 1977) reports aragonitic mineralogy for Permian and Triassic forms.

The '**Ellipsactiniidae**' are important in the Late Jurassic–Early Cretaceous and the '**Heterastridiidae**' in the Late Triassic (Flügel 1982a). Reitner (1987) suggests that a form which may represent an *Ellipsactinia* has an original magnesian calcite mineralogy.

We assume a 100% aragonitic mineralogy for unspecified Triassic 'hydrozoa' and 100% magnesian calcite for the younger Mesozoic Stromatoporata.

Corals

Major modern carbonate-producing corals are the Scleractinia and, to a lesser extent, Octocorals and Milleporina and Stylasterina (Milliman 1974). The geologic record of the two latter groups is relatively poor (Bayer 1956, Boschma 1956, Frost 1981; Fig. 1A).

Milleporina and **Stylasterina** first appear in the early Paleocene (Boschma 1956; Fig. 1A). Milleporina have an aragonitic skeleton (Chave et al. 1962, Milliman 1974). Stylasterina principally also have an aragonitic skeleton (Lowenstam 1964, in Milliman 1974).

After scarce records in the Paleozoic and early Mesozoic, **Octocorals** appear somewhat more consistently in the Cretaceous (Fig. 1A). Their poor sedimentary record is probably caused by both early dissolution and the difficulty in recognizing skeletal elements consisting principally of magnesian calcite spicules only (cf. Bayer 1956: 167, Wallace & Schaefermann 1977, Frost 1981). Modern Octocorals generally have a high, sometimes intermediate, magnesium content (Clarke & Wheeler 1922, Keith & Weber 1964, Milliman 1974, Bayer 1956, Lowenstam 1964; Fig. 1A). Modern *Heliopora* has an entirely aragonitic skeleton (Bayer 1956, Milliman 1974) and this has also been found for early Helioporidae from the Cretaceous and Tertiary (Morycowa 1977). In the suborder Holaxonia (order Gorgonacea), a partial aragonite composition is commonly found, which may reach 50% in tropical forms of *Plexaura* (Lowenstam 1964).

Scleractinia are first found in the Middle Triassic and become important in Late Triassic reefs (Wells

1956, Flügel 1982, Stanley 1988). All modern representatives have an aragonite skeleton (Hill & Wells 1956, Chave et al. 1962, Keith & Weber 1964, Milliman 1974, etc.). The same has been found for a number of Middle Triassic forms (Montanaro-Gallitelli et al. 1973, Sorauf 1978).

For this study, unspecified Meso-Cenozoic corals are assumed to produce aragonite. In the rare cases where octocorals were reported they have been counted with the magnesian calcite producers.

Mollusks

Gastropods and Bivalves

Major contributors to shallow-water carbonates belong to the classes Gastropoda and Pelecypoda (Bivalvia) (e.g. Milliman 1974, Flügel 1981).

The number of families quoted for different geologic time intervals in Knight et al. (1960) suggests that the **Gastropoda** had a diversity peak in the Late Triassic (cf. fig. 6–18 in Füchtbauer 1988) and another one in Cenozoic time (Wilkinson 1979, Füchtbauer 1988). The skeletal mineralogy is predominantly aragonite, with an additional calcite layer in nine genera (Bøggild 1930, Bathurst 1971, Milliman 1974, Füchtbauer 1988). Amongst the latter, *Patella* has somewhat elevated magnesium values.

The class **Bivalvia** shows considerable diversity throughout the Meso-Cenozoic, with peaks in the Cretaceous and the Recent (Fig. 1A). Füchtbauer (1988: fig. 6–18) shows another diversity peak in the Triassic. Aragonite is again the dominant mineral of the shell, both in the Recent and in the geologic past (e.g. Bøggild 1930, Taylor et al. 1969, 1973, Bathurst 1971, Carter 1980; Fig. 1A). In two important orders (Mytiloidea and Pterioidea) a calcite layer occurs more or less consistently in recent and fossil forms (see also Newell 1938, Stehli 1956, Waskowiak 1962, Lerman 1965, Pilkey & Harris 1966, Pojeta 1966, Yochelson et al. 1967, Cox et al. 1969, Carter & Tevesz 1978, Waller 1978). Besides, a few recent representatives of the superfamily Chamacea (order Veneroidea) have a calcitic outer layer (Bøggild 1930, Kennedy et al. 1970).

Rudists

The extinct bivalve superfamily Hippuritacea ('**rudists**') was counted separately. It has great importance in Cretaceous platform environments (Cox et al. 1969, Scott 1988).

All rudist shells contain aragonite, but an outer calcitic layer is commonly present (Kennedy & Taylor 1968, Bathurst 1971, Skelton 1974, 1976, 1979, Al-Aasm & Veizer 1986). The Late Cretaceous family Hippuritidae has also calcite in the pillar and the beads (Al-Aasm & Veizer 1986), but most of the skeleton consists of aragonite (Kauffman & Johnson 1988). The Radiolitidae, which reach their peak also in the Late Cretaceous (e.g. Bilotte 1989), have a strongly dominant calcitic mineralogy (Kauffman & Johnson 1988). In the Caprinidae and Caprotinidae, the outer calcitic layer is thin, absent in the earlier portion of the shell or completely absent (Al-Aasm & Veizer 1986, Kauffman & Johnson 1988, Masse 1989; personal observations). Both families reach their greatest abundance in the Cenomanian (D'Orbigny in Philip 1978, Cox et al. 1965, Bilotte 1989). The oldest rudist families (Diceratidae, Requienidae) have a predominantly calcitic mineralogy (Kauffman & Johnson 1988).

The mineralogic composition of rudists as a whole, thus shows variation during the latest Jurassic–Cretaceous period (Masse 1989, Kaufmann & Johnson 1988; pers. comm. Skelton 1990). An aragonite maximum may be located in the Cenomanian.

Variations in the skeletal composition of Mesozoic–Cenozoic carbonate formations

The relative frequency of major carbonate platform biota shows considerable variation in the Mesozoic and Cenozoic (Fig. 2). The relative frequency of corals remains relatively stable, but tends toward a peak in the Recent. During the Mesozoic, calcareous sponges (in the strict sense), stromatoporoids and mollusks (in particular rudists) reach successive peaks. This confirms trends indicated by earlier studies of primary framebuilder development during the Triassic (Flügel 1982b, Stanley 1988) and Late Jurassic–Cretaceous (Scott 1988, Scott et al. 1990). Further notable is the proliferation of calcareous algae and, to a somewhat lesser extent, that of foraminifers in the Early Tertiary. These expansions follow the disappearance of rudists and stromatoporoid sponges at the end of the Cretaceous. The rise of codiacean green algae and corals is a more recent phenomenon (Frost 1981, Dullo et al. 1990; Fig. 2).

Table 3. Assumed percentages of clean minerals in category 'mixed mineralogy' (Figs 3A, B)

Environment	Period	Fossil group	Mixed % of 'mixed' ¹	Clean minerals			
				Aragonite	Mg-Calcite	Calcite	
Platform Interior	Late Triassic	Forams	21.50	6.50	5.00	3.75	
		Rudists	0.00	0.00		0.00	
		Other mollusks	30.50	26.50		6.50	
	Late Jurassic	Forams	13.00	2.00	4.50	1.50	
		Rudists	6.25	3.25		3.25	
		Other mollusks	24.75	21.00		5.25	
	Early Cretaceous (Aptian)	Forams	13.00	1.50	4.00	1.50	
		Rudists	5.50	3.00		3.00	
		Other mollusks	47.00	40.00		10.00	
	Early Cretaceous (Albian)	Forams	13.75	1.50	4.50	1.50	
		Rudists	26.00	14.00		14.00	
		Other mollusks	36.50	31.25		8.00	
	Late Cretaceous (Santonian)	Forams	23.00	0.00	11.50	2.25	
		Rudists	36.00	20.50		20.00	
		Other mollusks	16.25	14.50		3.75	
	Early Tertiary (Paleogene)	Forams	25.75	0.00	16.25	3.75	
		Rudists	0.00	0.00		0.00	
		Other mollusks	20.00	15.75		4.25	
	Recent	Forams	15.00	0.00	11.25	3.00	
		Rudists	0.00	0.00		0.00	
		Other mollusks	19.00	15.25		4.00	
Platform Margin	Late Triassic	Forams	14.50	1.50	8.00	0.75	
		Rudists	0.00	0.00		0.00	
		Other mollusks	19.75	16.50		4.25	
	Late Jurassic	Forams	5.50	0.00	2.50	0.25	
		Rudists	3.25	1.75		1.50	
		Other mollusks	18.00	14.75		3.75	
	Early Cretaceous (Albian)	Forams	9.00	0.00	3.50	0.25	
		Rudists	26.25	14.00		13.75	
		Other mollusks	20.75	17.50		4.50	
	Early Tertiary (Paleogene)	Forams	13.00	0.00	7.50	1.50	
		Rudists	0.00	0.00		0.00	
		Other mollusks	12.00	10.00		2.50	
	Early Tertiary (Oligocene)	Forams	23.00	0.00	15.50	5.25	
		Rudists	0.00	0.00		0.00	
		Other mollusks	18.00	14.75		3.75	
	Recent	Forams	9.00	0.00	7.75	1.25	
		Rudists	0.00	0.00		0.00	
		Other mollusks	16.00	12.75		3.25	
	Platform Slope	Late Triassic	Forams	30.50	0.75	7.50	13.00
			Rudists	0.00	0.00		0.00
			Other mollusks	31.00	28.25		7.00
Late Jurassic		Forams	13.00	0.25	3.25	5.00	
		Rudists	0.00	0.00		0.00	
		Other mollusks	40.50	34.00		8.50	
Late Cretaceous (Santonian)		Forams	13.00	0.00	3.50	3.75	
		Rudists	41.00	22.00		21.75	
		Other mollusks	39.00	33.25		8.25	
Early Tertiary (Paleogene)		Forams	30.75	0.00	12.25	3.75	
		Rudists	0.00	0.00		0.00	
		Other mollusks	23.00	21.25		5.25	
Recent		Forams	24.00	0.00	12.50	10.25	
		Rudists	0.00	0.00		0.00	
		Other mollusks	23.00	18.75		4.75	

¹ Includes agglutinated forams.

Changes in biotic mineralogy

The bulk skeletal mineralogic composition of Mesozoic and Cenozoic carbonate formations is shown in two diagrams. Figure 3A represents the relative abundance of aragonite, magnesian calcite and 'mixed mineralogy'. The last category includes the mollusks, where both aragonite and calcite contribute in varying proportions to the carbonate skeleton. This category further includes the foraminifers, where individual shells are monomineralic but mineralogy varies at a low taxonomic level. The category 'mixed mineralogy' thus is a rough measure of the abundance of calcite.

Figure 3B represents an attempt to 'unmix' this category and to estimate the percentages of pure aragonite, magnesian calcite and calcite (see also Table 3). Agglutinated foraminifer taxa were removed from the counts, whereas the relative frequency of the remaining foraminifer groups with specific mineralogy (Fig. 1C) was taken into account for each time-slice (Table 3). Since the aragonite percentage averaged over all rudist species from a certain time-slice is never much above 50% and generally less (Kauffman & Johnson 1988: fig. 9), a 'conservative' value of 50% aragonite was taken wherever rudists appear. For the remaining Mollusca, the ratio of ca. 0.2 for calcitic versus aragonitic mollusks, found by Dullo (1984, 1986) in modern carbonate platform deposits from the Red Sea, was consistently used.

Figure 3A shows a first-order trend in the form of a simple cycle: high abundance of metastable minerals (aragonite and magnesian calcite) in the Triassic and Cenozoic, low abundance of these minerals (and complementary high abundance of calcite) in the (Late) Cretaceous. Figure 3B shows a similar cycle. Maxima of metastable carbonate in the Triassic and Cenozoic are separated by a minimum of metastables (and a concomitant maximum of calcite) in the Late Cretaceous. In addition to the cyclic variation in the ratio of calcite to metastables, Figs 3A and B also show an increase of magnesian calcite after the Triassic. The maximum of metastables in the Triassic is basically an aragonite peak, whereas the maximum in the Cenozoic is the result of elevated contents of aragonite and magnesian calcite. A decrease in aragonite after the Triassic is most apparent for algae and sponges (s.l.), whereas it is also perceptible for the foraminifers and corals (Figs 1A–C, Tables 1, 3).

The Mesozoic–Cenozoic fluctuation in skeletal carbonate mineralogy is not dramatic, yet clearly recognizable, despite short-term variations and the asym-

metric increase in magnesian calcite mentioned above. The trend is a composite of various changes in the carbonate-producing biota. The increase of calcite during the Mesozoic is primarily caused by a reduction of aragonitic (and later partially magnesian-calcitic) framebuilders such as calcareous sponges and stromatoporoids and by their replacement by the partially calcitic rudists. An important number of 'new' calcitic or partly calcitic organisms originated in the Middle to Late Jurassic (coccoliths, planktonic foraminifers, rotaline benthic foraminifers, rudists: Table 1). Most of the Jurassic–Cretaceous calcareous sponges (including stromatoporoids) may have been calcitic, even though magnesian calcite was also present in this group (Reitner, in Füchtbauer 1988, Gautret & Cuif 1989). This faunal assemblage replaced a considerable part of the 'typical Triassic' aragonitic faunas that originated essentially in the Permo-Triassic interval (Involutinina and Robertinina among the foraminifers, aragonitic sponges and stromatoporoids, scleractinian corals: Table 1).

Present data suggest a calcite maximum in the Late Cretaceous (Figs 3A, B). In the Late Cenomanian, replacement of the largely aragonitic caprinid and caprothinid rudists by the relatively more calcitic radiolitids and hippuritids takes place. At the same time the last important aragonitic foraminifera (Involutinina) disappear, whereas the partially calcitic Rotaliina become important in the Late Cretaceous. This change may be heralded by an increase in calcitic organisms within the Aptian (Masse 1989).

The increase of metastables in the Cenozoic at first reflects the extinction of the rudists and an initial 'bloom' of calcareous algae and predominantly magnesian-calcitic foraminifera in the earlier Tertiary (Fig. 2). Later in the Tertiary, most metastables were contributed by the proliferation of aragonitic corals and codiacean green algae (Fig. 2).

The aragonite–calcite cycle appears not only in the estimates of bulk sediment mineralogy of Figs 3A and B. It is also present within two taxonomic groups that were prominent in the Meso-Cenozoic. Mineralogic, geochemical and structural characteristics of calcareous sponges (in the wide sense) are comparable, with dominant aragonite, for the Triassic and the Recent, and entirely different for the Jurassic–Cretaceous period (Gautret & Cuif 1989). For the mollusks, apart from the Hippuritoida, a trend towards a more calcitic mineralogy during the Mesozoic also exists for the important lamellibranch order Pterioidea (Waller 1978). Besides, a 'calcite maximum' may exist for the foraminifers

in the relative abundance of textulariines in the Cretaceous (Fig. 1C) and for the calcareous algae by the appearance of calcitic dasyclads in the same period (Masse 1989). If the, presently unquantified, portion of biocalcite produced by these groups can be further substantiated, the calcite maximum may extend to somewhat older levels and our curve would take a more symmetric outline (compare Figs 1A, C, 2).

We freely admit that our data base is small and of variable quality. Nonetheless, the cyclic trend is clear enough to present it for further evaluation.

Our 'Meso-Cenozoic wave' may ride on top of a unidirectional trend in the Phanerozoic that leads from calcite to aragonite (Wilkinson 1979, Lowenstam 1981), or the latter may essentially exist in a major increase of aragonitic invertebrates towards the end of the Paleozoic. It is even possible that the latter increase makes out part of an older, 'Paleozoic wave' in skeletal mineralogy, in which the contribution of aragonitic calcareous algae in its oldest part is underestimated. One difficulty in choosing between these possibilities is the difference in data bases. Wilkinson (1979), Lowenstam (1981) and other authors use taxonomic diversity as a basis; our data are a first attempt to estimate bulk sediment composition. It is as yet remarkable that the curve given by Füchtbauer (1988: 256), although dealing with a different data set (all invertebrate calcifiers) and method (species diversity) resembles our Figs 3A and B in the strong aragonitic maximum in the Triassic and the smaller maximum in the younger Cenozoic.

The remarkable coincidence of this aragonite-calcite wave with the aragonite-calcite cycle described for (inorganically precipitated?) ooids and marine cements (Sandberg 1983, 1985), may indicate that organic carbonate secretion is not independent of atmospheric and oceanic chemistry. A possible relation of the latter factors with an important Aptian faunal change and with Mesozoic-Cenozoic variation in sponge mineralogy, was previously suggested by Masse (1989) and by Gautret & Cuif (1989), respectively.

The increase of planktonic calcite fixation during the Mesozoic and Cenozoic is seemingly at variance with this idea. However, the present aragonite fixation by pteropods is about 15% (Fabry & Deuser 1991, Brummer & Van Eijden 1992). Thus, it is possible that the pelagic environments, too, experienced some increase in aragonite fixation since the Cretaceous.

The alternative to the above speculation is that the biogenic aragonite-calcite cycle is a coincidental effect of 'organic evolution'.

Conclusions

Estimates of bulk skeletal mineralogy of Mesozoic and Cenozoic shoalwater carbonate formations indicate a cyclic variation in the ratio of calcite to metastable carbonates (aragonite and magnesian calcite). This cycle parallels a similar one in the inorganic world of ooids and marine cements. It is possible that chemical variations of the atmosphere and the ocean influenced organic evolution.

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