PALEOREEFS—A DATABASE ON PHANEROZOIC REEFS

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ABSTRACT: A comprehensive relational database on pre-Quaternary Phanerozoic reefs is described. The database contains coded and standardized information on position/paleoposition, age, reef type, dimensions, environmental setting, paleontological and petrographical features, and reservoir quality of Phanerozoic reefs. At the time of submission, 3050 reef sites were included in the database. True reefs, mounds, and biostromes are considered. Although the database is incomplete, both in the quality of information provided for each reef and the quantity of reefs, the information contained is thought to reflect actual trends in the reef ecosystem. The reliability of statistical analyses based on the database varies through geologic time depending on the quantity and quality of data in each time slice but is reasonable on average.

INTRODUCTION

Paleontological and geological databases have become very popular in the last decade. The increasing speed and power of personal computers and suitable software offer the opportunity to organize and analyze huge amounts of data at low cost. Databases were already used for paleontological analyses in the early 1950s (Newell, 1952), but it was not before the late 1960s that paleontological databases were systematically developed and analyzed (see Benton, 1999, for review). Databases in geosciences have three main objectives:

1. Visual analysis of regional to global geographical, geological, or paleontological data with geographic information systems (GIS). This is a classical application in geography, but it is increasingly applied in geology (Laxton and Becken, 1996; Ziegler et al., 1998) and paleontology (e.g., http://www.odsn.de).

2. Statistical analyses. Evaluation of secular variations in the earth system, comparisons of different localities, or comparisons of features at different localities. Sophisticated statistical analyses have been applied to paleontological data since the early days of commercial computer production (e.g., Imbrie and Kipp, 1971). Bambach (1977), Raup (1976, 1978, 1991), Sepkoski (1978, 1979, 1981, 1992, 1993, 1996) and Benton (1993, 1995) have presented pioneer studies with relatively simple but comprehensive taxonomic databases. These studies have had a large impact on the development of ideas concerning temporal evolutionary patterns and the magnitude of extinction events.

3. Inventory of material and literature. In contrast to the former, these databases are often not especially designed for statistical evaluation. In geosciences, the data classically stored in this kind of databases may comprise rock property data (e.g., database of the Ocean Drilling Program, http://www-odp.tamu.edu/database/), inventory of specimens in a museum collection, and classification and taxonomic studies (e.g., Korn et al., 1994; Schmatz et al., 1995; Verrucchi and Minissale, 1997).

Many databases cover more than one major topic. For example, the most comprehensive paleontological database in Germany is a taxonomic database on goniatites (Korn et al., 1994). It is suitable for the identification of fossils and for statistical analysis of ammonoid diversity through time. ReefBase is another very comprehensive database, which is closely related to our database inasmuch as it combines reef data and geographic information. This database has been created by the International Center for Living Aquatic Resources Management (ICLARM) based in Manila, The Philippines. It currently contains data on more than 7000 modern coral reefs (http://www.reefbase.org/), and is thus far larger than our database.

Flügel and Flügel-Kahler (1992) made the first steps towards a database on ancient reefs by introducing a comprehensive literature collection, which formed the starting point for this project. Although the information in this "database" was limited to references, it could be used for plots of reef distribution on paleogeographic maps and the definition of ancient reef zones (Parrish, 1998, p. 117). Our activities towards a more detailed reef database started in late 1995. The development of our PaleoReef database was funded by the German Research Foundation (DFG) in the context and as an extension of the Priority Research Program "Global and Regional Controls on Biogenic Sedimentation", which lasted from 1991 to 1996. The goal of this project was a better understanding of geological and biological processes controlling the formation of reefs and changes in reef patterns during time. The program included more than 60 research projects dealing with Devonian to Holocene reefs and comprising a wide range of geological, paleontological, and biological topics (Reitner et al., 1996). Although significant contributions arose from the priority program, all participants in the final meeting in Göttingen, Germany (October 1996) agreed that one of the major unsolved problems is an objective comparison of reef attributes through time. This shortcoming was also emphasized in recent reviews on reef evolution (Wood, 1998, 1999). We were, therefore, encouraged to continue our work on the PaleoReef database. The state of the database as represented in this paper and dealt with in all the papers in this volume is as of late December 2000.

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DATABASE STRUCTURE

The Paleoreef database (PaleoReefs) combines visual analyses of paleogeographic reef distribution patterns and statistical analyses of reef attributes through time. Although PaleoReefs contains some taxonomic information and evaluates biodiversity, it is by no means a taxonomic database. It was the aim of the database project to collect as much information on as many Phanerozoic reefs as possible. However, few reefs older than Pleistocene are described in the detail that would be appropriate for an elaborate database. Additionally, the detailed information in many publications on fossil reefs is scarcely standardized enough to allow quantitative comparisons through time and space. Because we preferred to rely on measures that are comparable, we had to compromise our database structure. We have applied interval classifications (ordinal values) rather than detailed measures (scale values) to most fields in the database. The loss of information on particular reefs is balanced by the much larger quantity of reef data and the opportunity to consider reef data from inaccessible or poorly studied regions. If scale values were commonly available, we have provided both ordinal and scale values in the database.

Although a summary description of the database structure has already been provided by Kiessling et al. (1999), we repeat and extend the description herein, because the reef database plays an essential role in this book. The database and all programs connected with the database were created in Borland® Visual dBase 5.5, but they are also available in Microsoft® Access 97 format. At the time of copy deadline, 3050 post-Proterozoic and pre-Quaternary reefs are stored in the database.

The database contains information on outcropping reefs as well as on reefs known only from the subsurface (drilling and seismic exploration). True (ecological) reefs as well as reef mounds, mud mounds, and major biostromes were considered, but described separately. Three requirements are needed for a bioconstruction to be included in the database: (1) control on the formation by sessile benthic organisms (biological control), (2) lateral constriction of the structure, and (3) (inferred) rigidity of the structure. Although nearly all reefs in the database are probably additionally characterized by a higher rate of *in situ* carbonate production than the surrounding sediments, higher carbonate production is not included in our broad reef definition, as opposed to Wood (1998).

In order to permit a comparison of reef numbers through time and space, a minimum distance for a reef to be counted separately within the same time slice was chosen. Owing to the scale of even detailed paleogeographic maps, this distance was set to 20 km. If more closely spaced reefs were of different ages (e.g., different stage), from a different paleogeographic setting, and/or of significantly different composition, they were included separately.

Most reef data were extracted from published references (cf. Flügel and Flügel-Kahler, 1992), but personal communications, unpublished reports, and results from own fieldwork were also considered. The literature analysis focused on comprehensive papers providing either detailed descriptions of single reefs or dealing with reef distribution and characteristics on a regional scale. Currently, 2150 references are considered in the database. These references represent only a fraction of the vast amount of literature that deal with reefs and reef related sediments. Actually more than 14,000 references on reefs are stored in a separate database, but information was taken only from selected papers. The primary aim was to cover as much area as possible and to avoid large gaps on our reef distribution plots rather than to gather all available information on particular well described reefs.

Reef attributes were transformed into numerical codes to allow an objective and statistically meaningful analysis of the data. The database structure is summarized in Table 1; three examples of different reef types are provided in Table 2. Some reef attributes and their corresponding numerical codes are also depicted (Fig. 1). In case a reef attribute could not be defined with some certainty, the field remained blank and is treated as a missing value in statistical analyses.

The database structure can be summarized under seven main headings:

1. Reef identification
2. Age
3. Location
4. General attributes
5. Environment
6. Paleontology
7. Petrography

1. Reef Identification

The identification of each reef in the database is possible by a specific identification number for each reef. This four-digit number is necessary to link the main database with related datasets (e.g., references, paleopositions). A trivial name for each reef is also provided, to permit a quick assignment of its location. This field contains a short name of the reef or of the locality and the name of the country or U.S. state where the reef is situated. Each reef is connected with at least one reference, but it may be assigned to up to six references. Four-digit numbers code the references. They are linked to the reference database containing the whole citation.

2. Age

Several fields are included under this heading. Four fields are reserved for the stratigraphic age of the reef, including system, series, and stage. The system and series names are formalized, but there is no rigorous scheme for stage names. Because global correlations are still problematic for many stages, we often assigned regional stage names rather than international names. Substages were indicated whenever possible. One field indicates the lithostratigraphic setting of the reef site (formal formation name or informal unit).

Another field contains the chronostratigraphic age in millions of years (Ma), according to the geological time scale described earlier (Golonka and Kiessling, this volume). The most important field in this category is the time slice (supersequence). Thirty-two time slices were used encompassing the time between the earliest Cambrian and the late Miocene–Pliocene. The time slices correspond to supersequences as defined earlier in this volume (Golonka and Kiessling, this volume). Thus the time slices represent time intervals that may embrace several stages or cross system boundaries, but they may also cut stages. The philosophy behind this approach is a more natural subdivision of the geological record not biased by regional differences and not a priori influenced by biological evolution.

The last field within the age category quantifies the reliability of age determination given in the literature: 3 = age is likely to be exact and reliable on a substage level; 2 = age is likely to be correct, but stratigraphic resolution is not very high (no substage indicated); 1 = age determination doubtful, time slice may be incorrectly assigned (no stage indicated, or correlation with chronostratigraphy is disputed).

TABLE 1.—Reef database structure.

Category	Field name	Field type	Remarks
Reef ID	Reef Name	text	Locality, region and country names
	Reef number	numerical	Unique value for each reef
Age	System	text	e.g. Odovician
	Series	text	e.g. Upper
	Stage	text	e.g. Hirnantian
	Formation	text	e.g. Yaptikshor
	Time-Slice	ordinal	Number of supersequence (e.g. 5)
	Time	scale	Age of reef in million years (e.g. 444)
	Reliabilitity	ordinal	Reliability of age assignment (see definitions in text)
Position	Recent Latitude	scale	e.g. 32.1500
	Recent Longitude	scale	e.g.-104.3833
	Plate	ordinal	one of about 300 tectonic plates (e.g. 101)
	Paleolatitude	scale	e.g. 3.5355
	Paleolongitude	scale	e.g. -33.3600
Outcrop or subsurface data	Subsurface	ordinal	Only well or seismic data available (1) or outcrop studies possible (0)
Reef type	Type	ordinal	4 categories (see definitions in text)
Size	Thickness	ordinal	4 categories (see definitions in text)
	Thickness2	scale	metric thickness
	Length	ordinal	4 categories (see definitions in text)
	Length2	scale	metric length
	Length tract	scale	Length of reef tract in km
	Width	ordinal	4 categories (see definitions in text)
Environment	Environment	ordinal	Main environmental setting of reef. 4 categories (see definitions in text)
	Subenvironment	text	More detailed specification of environment (see definitions in text)
Bathymetry	Bathymetry	ordinal	2 categories (see definitions in text)
Biotic composition	Biota main	ordinal	14 categories (see definitions in text)
	Biota detailed	ordinal	91 categories (see definitions below)
Diversity	Diversity	ordinal	3 categories (see definitions in text)
	Diversity2	scale	number of species
Dominant guild	Guild	ordinal	3 categories (see definitions in text)
Bioerosion	Macroborings	ordinal	Macroborings present (1) or absent/unknown (0)
	Microborings	ordinal	Microborings present (1) or absent/unknown (0)
Zonation	Succession	ordinal	Degree of succession (see definitions in text)
	Lateral Zonation	ordinal	Lateral division (see definitions in text)
Petrography	Micrite	ordinal	Relative amount of micrite. 3 categories (see definitions in text)
	Sparite	ordinal	Relative amount of marine cement. 3 categories (see definitions in text)
	Debris	ordinal	Relative amount of debris in the reef. 3 categories (see definitions in text)
	Dolomite	ordinal	Intense dolomitization present (1) or absent (0)
	Reservoir	ordinal	Reef has reservoir potential (1) or not (0)
References	Ref1	numerical	Reference number 1 (linked to reference database)
	Ref2	numerical	Reference number 2 (linked to reference database)
	Others	text	Additional reference numbers ($\leq$ 5)
Remarks	Remarks	memo	Additional data for later reviews of data base (sometimes with abstracts)
Personal control	Control	logical	Control of reef attributes by personal studies (Flügel, Kiessling)

Structure of main table only. Other tables (references, paleolocalities, legends, calculated parameters) are joined to this table.

TABLE 2.—Examples from the Paleoreef database.

Category	Fields	EMSIAN MUD MOUND	HAUTERIVIAN REEF MOUND	MIOCENE CORAL REEF
1	Reef name	Hamar Lakhdad, Anti-Atlas, Morocco	Caudete, Spain	Cap Blanc, Mallorca, Spain
	Reef number	1565	2590	679
	References	962, 1421, 1627	1731	645, 670, 1194, 1757
2	Age/System	Devonian	Cretaceous	Tertiary
	Age/Series	Lower	Lower	Upper
	Age/Stage	lower Emsian	lower Hauterivian	Tortonian-Messinian
	Age/Time slice	9 = Kaskaskia I	23 = Upper Zuni I	32 = Upper Tejas III
	Age/Ma	398	130	7
	Age/Reliability	3 = exact and reliable age assignment	3 = exact and reliable age assignment	3 = exact and reliable age assignment
3	Location/Recent	31.3833° N, 4.0500° W	38.7333° N, 1.0500° W	39.4167° N, 2.7833° E
	Plate	714 = Northwest Africa	304 = Iberia	320 = Balearic Islands
	Location/Paleo	20.0639° S, 4.7912° E	22.4142° N, 2.4520° E	39.3528° N, 1.9269° E
4	Reef type	3 = mud mound	2 = reef mound	1 = reef
	Size/thickness	2 = more than 10 m, less than 100 m	1 = less than 10 m	3 = more than 100 m, less than 500 m
	Size/thickness2	46 m maximum thickness	8 m thickness	150 m maximum thickness
	Size/length	2 = more than 20 m, less than 100 m	1 = less than 20 m	2 = more than 20 m, less than 100 m
	Reef tract	5 km	45 km	20 km
	Lateral zonation	1 = low	1 = low	3 = high
5	Environment	1c = epeiric sea	1e = open marine shelf	2a = platform margin
	Bathymetry	2 = below fair weather wave base	1 = above fair weather wave base	1 = above fair weather wave base
6	Biota main	3 = microbes	1 = scleractinian corals	1 = scleractinian corals
	Biota detailed	56 = tabulate corals - crinoids - microbes	50 = corals - stromatoporoids (chaetetids) - algae (stromatolites) - rudists - (spicular sponges)	1 = corals - red algae - (foraminifera, microbes, sponges)
	Guild	3 = microbially induced carbonate precipitation	1 = constructor guild	1 = constructor guild
	Diversity	2 = moderate	3 = high (diverse assemblage of various reef builders)	1 = low (strongly dominated by *Porites*)
	Diversity2	17 coral species	0 = no taxonomic details	6 species of corals and algae
	Bioerosion/Macro	1 = present	1 = present	1 = present
	Bioerosion/Micro	0 = absent	1 = present	1 = present
	Succession	2 = moderate	1 = low	2 = moderate
7	Micrite	3 = abundant	2 = moderately abundant	2 = moderately abundant
	Sparite	2 = moderately abundant	1 = few	1 = few
	Reservoir potential	no	no	yes (high porosity)
	Dolomite	no	no	yes
	Debris potential	1 = low	2 = moderate	2 = moderate

Numbers in first column indicate categories as titled in the text. The lower Emsian example exemplifies the way how contradictory interpretations are treated. Although tabulate corals are the dominant group with reef building potential, mound formation was not controlled by them. Mound growth was rather driven by hydrothermal vents which had a direct or indirect (via microbes) effect of carbonate precipitation. The 48 mounds in the Hamar Lakhdad are treated as one reef owing to close spacing. References: 645 = Pomar (1991); 670 = Esteban (1979); 962 = Brachert et al. (1992); 1194 = Pomar et al. (1996); 1421 = Belka (1998); 1627 = Mounji et al. (1998); 1731 = Arias et al. (1995); 1757 = Perrin et al. (1995).

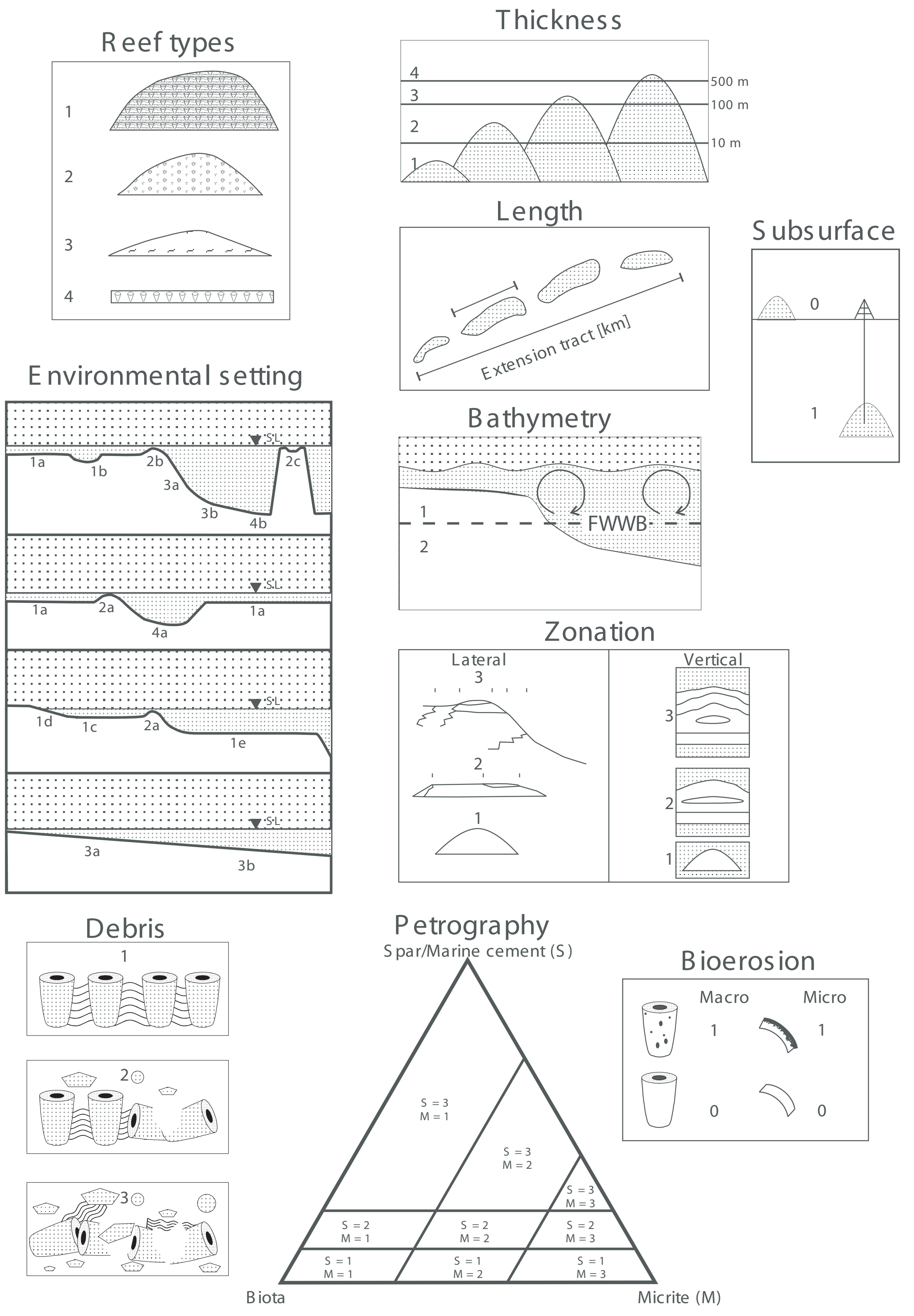

FIG. 1.—Examples of some reef attributes as quantified in the database and their corresponding numerical codes.

3. Location

Present-day coordinates are represented by two numbers referring to latitude and longitude (Greenwich coordinates). Southern and western coordinates are negative numbers. The correct assignment of a plate is crucial for the calculation of the paleogeographic reef position. Three-digit numbers represent the plates in the database. About 300 plates and terranes are distinguished in the plate-tectonic model (Golonka, this volume). Calculation of paleo-coordinates was done using PLATES and PALEOMAP software obtained through Mobil. The calculated paleo-positions are represented by two fields: paleolatitude and paleolongitude.

4. General Attributes

Outcrop.—

A one-digit number indicates whether the reef is exposed on the surface or covered by younger sediments. In the latter case geological and paleontological information is limited to core studies at most, but often is restricted to seismic exploration.

Reef Type.—

Four reef types were distinguished: 1 = true reefs, where the reef-building organisms form a rigid framework. True reefs are approximately equivalent to the "ecological" reefs of Dunham (1970). Syndepositional relief was present. 2 = reef mounds, where skeletal organisms are abundant but there is no evidence for a rigid framework. Micrite/cement and skeletal organisms are about equally important and the buildup is, or appears to be, matrix-supported. Syndepositional relief was present. 3 = mud mounds, where organisms are minor constituents of the buildup, which consists predominantly of carbonate mud. Mud banks without depositional relief (cf. Lees and Miller, 1995) and mounds with a predominance of cement were also included under mud mounds. 4 = biostromes, where dense growth of skeletal organisms is evident but there is no depositional relief. A rigid framework may be present or absent. Because the difference between small biostromes and fossiliferous beds may be problematic and small biostromes are too numerous to be counted, only major biostromes within a time slice were recorded in the database.

It should be noted that true reefs are not limited to buildups with a macrofossil or metazoan framework. Calcimicrobes or foraminiferans may form frameworks that are as rigid as that of modern coral reefs. Reef mounds and mud mounds are not clearly separated. We chose reef mounds if the density of skeletal organisms was high enough (about 30% of reef volume) to theoretically allow a buildup formation by baffling without a major contribution of microbes to matrix formation. The origin of matrix, whether inorganically precipitated, trapped, or formed by microbial activity, was not relevant to the assignment of the reef type. The separation of reef types can be compared with that of James and Bourque (1992): our reefs correspond to the reefs and calcimicrobial mounds of James and Bourque (1992). The reef mounds in the database are approximately equivalent to the skeletal mounds, and buildups classified as mud mounds correlate with stromatolitic and thrombolitic microbial mounds and mud mounds of James and Bourque (1992). Biostromal complexes, commonly referred to as stacked biostromes, have been counted as reef mounds in the database. The reef type was assigned to 90% of the database entries.

Size.—

The vertical and lateral dimensions of a reef body were registered. Because especially thickness values are often reported in some detail, we have combined scale and ordinal values for the fields. The ordinal values are: 1 = less than 10 m thick and less than 20 long; 2 = 10–100 m thick and 20–100 m long; 3 = 100–500 m thick or 100–1000 m long; 4 = more than 500 m thick or more than 1000 m long. The scale values report thickness and length of a reef in meters. Reef complexes containing stacked smaller buildups were described as one single reef mound at a given locality. For quantitative analyses the ordinal and scale values can be combined assuming a thickness of 5 m for class 1, 50 m for class 2, 250 m for class 3, and 650 m for class 4. If several reefs were described aligned in a laterally continuous tract, the length of the reef tract was recorded in kilometers and the reefs in the tract were marked as such.

Because closely neighboring reefs (less than 20 km apart) were not included separately in the database, the thickest reef in an area of 20 km diameter was stored. Additionally, the dimensions of the whole reefal complex rather than the measurements of smaller patch reefs within a buildup was stored. Therefore, a bias towards thicker reefs is continuously present. The thickness of major reef complexes that cross time-slice boundaries has been divided by their relative proportion in the time slices. For example, a 330 m thick Gzhelian to lower Sakmarian reef complex occurring at Kozhym River in the Pechora Urals (Antoshkina, 1998), has been classified as thickness = 3 for the Gzhelian–Asselian interval (Lower Absaroka II supersequence), but a thickness value of 2 was assigned for the lower Sakmarian interval (Lower Absaroka III supersequence). Thickness and length values were defined for 87% and 84% of the database entries, respectively. Because the width of reefs is rarely indicated in literature on outcropping reefs, we have not devoted a specific field to this measure. If the width of a reef is given, it is stored under remarks.

Lateral Zonation.—

The degree of lateral zonation in a reef or reef complex has been classified in three intervals: 1 = unzoned; 2 = moderate zonation; 3 = strong zonation. The lateral zonation is dependent largely on reef size, depositional environment, and prevailing organisms. This measure is thus regarded more as a general feature and should not be confused with the paleontologically defined vertical zonation (see below). A strong lateral zonation is given if the reef complex consists of a fore-reef apron, an inhomogeneous reef core, and a distinct back reef environment. Unzoned reefs are large uniform structures (mostly mud mounds) or small patch reefs. Because this field was introduced late in the database development, only 17% of the reefs contain an indication of lateral zonation.

5. Environment

Depositional Setting.—

We have separated four principal depositional settings for reefs, each subdivided into several environments.

1. Shelf or Platform
   - 1a: Within shallow carbonate platform
   - 1b: Intra-platform sag
   - 1c: Epeiric sea
   - 1d: Coastal, transitional, marginal marine
   - 1e: Open-marine shelf

2. Platform or shelf margin
   2a: Platform margin bordering shallow basins
   2b: Platform or shelf margin bordering deep basins
   2c: Atoll structure, seamounts

3. Slope or ramp
   3a: Upper slope or inner ramp
   3b: Lower slope or outer ramp

4. Basin
   4a: Moderately deep basin (above photic zone, < 200 m)
   4b: Deep basin

For some reefs it is difficult to assign the correct depositional environment, e.g., the difference between epeiric seas and open-marine shelves is not always precisely defined. The same is true for epeiric seas versus open-marine shelves and ramps (see Burchette and Wright, 1992 for a comprehensive discussion). Only ramps with a continuation into deeper-water settings were noted as such. Geometrical ramps within epeiric seas or in a marginal marine setting were included into environments 1c or 1d, respectively. The rough depositional setting could be assigned to 87% of the database entries, whereas only 77% contain a specification of the detailed environment.

Because the method of choosing the thickest reef in a 20 km circular area, environments bearing thicker reefs may be overrepresented in the database. As shown by Kiessling (this volume) these are mostly platform-margin and upper-slope settings.

Bathymetry.—

The determination of paleo–water depth is quite reliable, inasmuch as only two intervals were considered: 1 = above fair-weather wave base; 2 = below fair-weather wave base. A finer bathymetric classification is not feasible in most cases owing to lack of specific data. Reefs situated in shallow protected lagoons were assigned to class 1, although they may have grown below the local fair weather-wave base (cf. Liebau, 1984). The bathymetric setting could be determined for 80% of the database entries.

6. Paleontological Attributes

Biotic Composition.—

The biotic composition of reefs refers exclusively to reef-building organisms, in our database. Reef builders were defined as sessile organisms having the potential to contribute significantly to buildup formation by constructing, baffling, binding, or carbonate precipitation. Thus reef builders were considered, even if they did not contribute significantly to the buildup construction (e.g., bryozoans in Waulsortian mounds). Reef-dwelling or destructive organisms were not considered in these fields. Two fields in the database refer to the biotic composition of reef builders.

The quantitatively dominant reef-building group is listed in the first field. Fourteen groups of reef builders are considered: Microbes; algae; foraminifera; stromatoporoids, hydrozoans, chaetetids; archaeocyaths; "pharetronid" sponges; siliceous sponges; corals; pelecypods; worms, vermetid gastropods, problematic tubes; *"Tubiphytes" (=Shamovella)*; bryozoans; brachiopods; and pelmatozoans. In reefs with a pronounced horizontal and vertical zonation, the dominant reef builder in the reef core or climax stage was listed, even if the group is not dominant in the whole buildup. In mounds, the actual dominant biota responsible for mound formation is often difficult to determine. Recent evidence for microbial formation of micrite in most mud mounds is convincing (Monty et al., 1995), but skeletal macrobiota can also play a significant role in mound formation through baffling of external mud (Bosence et al., 1985). Additionally the true dominant biota responsible for mound growth may be a nonskeletal organism leaving almost no traces in the fossil record (cf. Wanless et al., 1995). Microbes were indicated as the dominant biota if there is evidence for automicrite formation as the dominant process in mound growth, but another (skeletal) group was listed if micrite is likely to come from external sources. Another problem arises if different reef-building groups are about equally abundant in a reef and no quantitative data are provided. In this case two closely spaced reefs of the same trend were assigned to two different dominant biotic groups. Despite all these pitfalls the dominant biota field is one of the most complete in the database; 92% of all reefs contain a value. The potential sources of error are likely to be balanced by the large amount of data.

In the second field considering biotic composition, all important reef builders in a buildup were considered. The combinations are coded by two-digit numbers. Ninety combinations of reef-building groups (= high-ranked communities) have been distinguished so far. There is also a code for reefs with evidently only one reef-building group (e.g., corals), in order to distinguish the entry from reefs lacking data on the detailed community composition. Information on community composition is available for 83% of the database entries.

Dominant Guild.—

Following the guild model of Fagerstrom (1987, 1991) the dominant guild in each reef was determined: 1 = constructor guild; 2 = baffler guild; 3 = binder/encruster guild. Bacterially induced carbonate precipitation was also allocated in class 3. Certain fossil groups can be always assigned to the same guild (e.g., stromatolites = binder guild), but most groups are classified into different guilds depending on growth form (cf. Fagerstrom, 1987, 1988) and their role in reef construction. In contrast to Fagerstrom (1991) we have not always assigned a particular growth form to the same guild. Rudists, for example, were only assigned to the constructor guild if they actually acted in constructing the reef framework. If they were loosely scattered in a micritic matrix (mud-stickers) they were rather assigned to the baffler guild, even though they may have been massive. The guild membership remains a matter of debate in many mud mounds. While the dominant macrobiota in a mound may indicate a baffling effect, bacterial precipitation of micrite is often likely to be major source of carbonate (Lees and Miller, 1995). Hence mud mounds were assigned to class 3 if a dominant baffling effect is not actually evident. The dominant guild could be evaluated for 78% of the database entries.

Diversity.—

The diversity field also refers exclusively to reef builders. Because the quality of published data is very heterogeneous, again a combination of scale and ordinal values was applied. The ordinal classes are rather coarse to allow inclusion of a maximum amount of data: 1 = low diversity (less than 5 species or one species strongly predominant); 2 = moderate diversity, 3 = high diversity. A reef was classified has highly diverse if it contained more than 25 species within one group (e.g., corals) or more than 20 species covering several groups (e.g., corals, rudists, and stromatoporoids). We also have assigned diversity values to reefs without detailed taxonomic listings. In these cases the author's diversity estimation was credited. In the scale field, the actual number of reef-building species described from the particular reef was stored, plus an extra for each mentioned but undescribed group. Thus a coral reef with 20 coral species described and red algae and coralline sponges mentioned as additional reef builders would receive a scale diversity value of 22. Diversity values could be estimated for 73% of the reefs on an ordinal level but for only 15% of the reefs on a scale level, mainly because the scale measure was introduced late in the database development.

Most microbial mounds and reefs were defined as low-diversity reefs. This may be a real bias in the database, because our knowledge of microbial diversity is seriously incomplete (Morris, 1998). Even if it turns out that microbial species diversity is high in many ancient mounds, however, the controlling factors of microbial diversity are likely to be quite different from those of metazoan diversity, and microbial diversity should probably be less weighted in ecological analyses than algal or metazoan diversity.

Bioerosion.—

Bioerosion is a major factor in the control of modern coral reefs (Goreau and Hartman, 1963; Hutchings, 1986). The intensity of bioerosion is said to indicate nutrient levels (Hallock, 1988). Microborings are also most valuable paleobathymetric indicators (Günther, 1990). However, the study of bioerosion in ancient reefs is still in its infancy (Vogel, 1993), and it was not feasible to consider more than binary (presence/absence) data for the classification of biological destruction.

We distinguished macroborings and microborings. Evidence provided in the original text or a figure showing boring traces was necessary for a positive indication in the bioerosion fields. Micritic rims were taken as evidence for microborers, although a recent study indicates that micritized grains may also form by carbonate recrystallization (Reid and Macintyre, 1998).

Succession.—

The degree of vertical zonation in a reef or reef complex has been classified with three intervals: 1 = unzoned; 2 = moderate zonation; 3 = strong zonation. A strong vertical zonation has been classified if the reef shows a fully developed ecological succession *sensu* Alberstadt et al. (1974) or if there are several incomplete ecological successions. If zonation is evident only by variable growth forms of a particular reef builder (e.g., Bjerstedt and Feldmann, 1985) or if not more than a pioneer and climax phase (*sensu* Copper, 1988) are observed, the vertical zonation was classified as moderate. As for the lateral zonation and the scale values, this field was introduced late in database development, and only 18% of the reefs contain an evaluation of succession.

7. Petrographical Features and Reservoir Potential

Petrography.—

The amount of micrite and spar (carbonate cements) was listed in two separate fields. For micrite no genetic interpretation was required for the evaluation, but for spar we tried to consider only marine or very early diagenetic cement. Both spar and micrite were quantified with respect to the proportion of biota, micrite, and spar using three intervals (1 = low; 2 = moderate; 3 = high). Low micrite content was noted if the reef contains less than abut 30% micrite, whereas high micrite content was indicated if more than 60% of a reef are formed by micrite. The class assignment for spar is different, because spar content is considerably lower than micrite content on average. Low spar content was indicated if spar contributed less than 10% to the reef volume, and high spar content was attested for a volume of more than 25%. Although spar content was intended to refer exclusively to early marine cements, we cannot disregard that later-stage cements were sometimes also considered, owing to poor data. Because in most cases neither micrite nor spar content are indicated in reef descriptions, we often had to estimate the content from general descriptions or plates. In about 35% of all reefs in the database micrite and spar content could not be confidently estimated and the fields had to remain blank. We also noted whether the reef was heavily dolomitized (binary value), because dolomitization reduces the reliability of paleontological data and provides information on reservoir quality.

Reservoir Quality.—

It is usually difficult to quantify precisely the reservoir quality of reefs from published data. In many cases, however, it can be evaluated whether a reef has a reservoir potential or not. Therefore, a binary field was included in the database saying whether a reef may have reservoir potential (meaning already productive reservoirs or reefs with high porosity and at least intermediate size) or not. Details on the reservoir characteristics of reefs (porosity, permeability) are provided under remarks, if indicated in the literature.

Debris.—

Many ancient and even modern reefs consist predominantly of debris formed by reef organisms and reworking of lithified reef rocks (Hubbard et al., 1998). Because the significance and amount of debris in reefs is thought to vary considerably through time, we tried to quantify the production of debris in reefs. Owing to the limited information on the absolute amount of debris produced by a reef, we quantified the relative debris production. This is measured by the ratio of *in situ* reef builders versus reworked and fragmented reef material. Again, poor literature data did not allow to separate more than three intervals: 1 = low; 2 = moderate; 3 = high debris potential. Low debris potential is supposed for reefs with a high proportion of autochthonous reef carbonates and/or lacking fore-reef debris. Less than 20% of the reef structure consists of reefal debris. Many reefs with low debris potential are from deeper-water environments, but reefs in protected lagoonal environments and buildups dominated by certain fossil groups (e.g., microbes) are also unlikely to produce high amounts of debris. Typical examples of reefs with low debris potential are the Upper Cambrian microbial buildups along the Llano River in Texas (Ruppel and Kerans, 1987), the Emsian Kes-Kes mounds in Morocco (Belka, 1998), and most Waulsortian mounds, but also small rudist mounds and biostromes (examples in Höfling, 1985; Scott, 1990). Examples of reefs with high debris potential (> 80% consist of reefal debris) are common in the Alpine Triassic (Zankl, 1977; Wurm, 1982), in Upper Jurassic and Tertiary coral reefs (Crevello et al., 1985; Joachimski and Scheller, 1987; Mankiewicz, 1996; Pedley, 1996), and in Cretaceous rudist complexes (e.g., Petta, 1977), but rare in Paleozoic reefs (Vopni and Lerbekmo, 1972). The debris potential could be estimated for 71% of the database entries.

The absolute amount of debris production is not relevant for this field. A reef 200 m thick can be classified as having high debris potential, as can a reef of less than 10 m thick, if they both consist almost exclusively of reworked boundstones. Thus the values in this field may be termed potential debris production or debris potential instead of debris production. The actual debris production of a reef can be calculated with the aid of reef dimensions (Kiessling et al. 2000).

Additional Information

If a detailed study was available, additional information is included under remarks (thickness of reef in meters, genera or species names, average porosity, etc.) in order to allow a later refinement of the database. Some 200 abstracts of recent papers are also included. Although the additional information has been kept short, about 2.5 MB of data have been collected in this field.

EVALUATION OF DATA COMPLETENESS AND QUALITY

Number of Reefs

As stated above, a database on recent reefs (ICLARM Reefbase) contains information on more than 7000 tropical and subtropical shallow-water reefs. Compared to this number our database with 3000 entries from the whole Phanerozoic appears very small. The mean number of reefs in one database time slice (supersequence) is 95, ranging between 31 and 271. Considering that the Holocene development of reefs took part in an extremely short geologic time interval (10,000 years) as compared to the mean duration of our time slices (17 million years), we cannot deny that our database is severely incomplete.

The pronounced difference is slightly diminished if we consider our 20 km distance requirement for reefs to be counted separately. This implies that every “reef” in a time slice lumps data of an area of around 315 km^2. Therefore, although we refer to reef numbers throughout most of the text, the numbers indicate reef sites rather than true reef numbers. If the criteron of 20 km spacing is applied to the ICLARM Reefbase and nonreefal coral communities are excluded, the number of modern reefs decreases to 1950. This number is still an order of magnitude higher than that of time slices with the most pronounced expansion of Phanerozoic reefs. For example, the number of Burdigalian to Serravallian (Upper Tejas II) reef sites in our database is 190. Hence, although the Miocene is characterized by a wider latitudinal expansion of coral reefs than the Holocene, less than 10% of the modern reef sites are represented in the Upper Tejas II supersequence. If we compare only reefal regions with both mid-Miocene and modern reefs, that is, excluding reefs in the Mediterranean and Paratethys, Upper Tejas II contains less than 8% of the modern reef sites. This implies that at least 92% of the Burdigalian to Serravallian reef sites are not represented in the database. Because we can assume that destruction of reef sites due to erosion or subduction is minor in the Miocene, this number reflects the incompleteness of the database owing to:

1. Incomplete description of reefs in well-studied regions (only the best examples in a region are described).

2. Occurrence of many reefs in the subsurface or in remote areas with few geological data (undiscovered reefs).

3. Incomplete consideration of published data.

For the specific example of the Miocene, we think that the occurrence of many reefs in the subsurface is mostly responsible for the limited dataset, because even 37% of the Upper Tejas II reefs included in the database occur in the subsurface. An incomplete description of reefs within a region is also a potential bias. Some reefs are regularly studied by geologists and are covered by a tremendous amount of literature, whereas less well exposed reefs in nearby areas are indicated only by a few words or traced on schematic maps (e.g., Guadalupian reefs around the Capitan reef). The incomplete consideration of references is especially important in older time slices during which reefs flourished in areas with difficult literature access (e.g., Russia and most of Asia). However, the bias of incomplete reference notice has been largely balanced by the data of the invited authors. Additionally, at least the presence of reefs is indicated for even the most unexplored areas, both onshore (e.g., Silurian of the Russian Far East; Bol’shakova et al., 1994) and offshore (e.g., Miocene of the Russell Basin, Solomon Islands; Hinz, 1995). We are now quite confident that there are no large gaps in the consideration of published literature, which is partly due to the filling of gaps by the authors in this volume.

In older time slices loss of reefs due to erosion or subduction becomes increasingly important. Taking calculated carbonate survival rates into account (Wilkinson and Walker, 1989), about 75% of the original Early Cambrian carbonate volume is considered to be lost. This translates into a complete loss of 41% of the reef sites in the Sauk I supersequence due to erosion or subduction (Kiessling, this volume). The subduction problem is especially important because modern oceanic atoll reefs contribute profoundly to the modern reef carbonate factory and are rarely recorded in pre-Cretaceous times. However, the few pre-Cretaceous oceanic atolls and terranes usually contain a rich reef record (Soja, 1991; Stanley and Beauvais, 1994), which gives a glance on the importance of this reef factory in the Phanerozoic.

In summary, the number of reef sites in the database reflects only around 6% of the real number in younger time slices and even less (down to 2.5%) in older time slices. How does this tremendous incompleteness affect our interpretations? The effects of incomplete knowledge would be minor if the bias were constant through time, that is, differences in the number of reef sites between time slices agree with true differences in reef expansion. Kiessling et al. (1999) have shown that this is the case on a semiquantitative level. However, a completely constant bias is unlikely. Time intervals with abundant reefal reservoirs are likely to be overrepresented in the literature and hence in the database. For instance, Copper (this volume) states that the maximum expansion of Devonian reefs is reached in the Givetian, whereas the database indicates a pronounced maximum in the Frasnian. This is probably because of the large number of reefal hydrocarbon reservoirs in the Frasnian of Alberta (Canada) and Timan–Pechora (Russia). Thereby a large amount of data is available from the subsurface. If there were no economic interest in Frasnian reefs, most of the subsurface reefs would be unknown. Scientific priorities may result in a similar bias that cannot be accounted for quantitatively.

Considering all the restrictions, we conclude that the true amount of reefs is not represented in the database. However, the database is probably the largest collection of data on ancient reefs and represents the current state of the art. We assume that all major reef provinces in the past are considered and that the actual variations of reef numbers though time can be analyzed with the aid of the database. This statement is supported by analyzing the shape of the reef abundance curve through time (Fig. 2). Besides significant changes in the Ordovician (due to stratigraphic revisions by Webby, personal communication 1998–2000) and in the Cretaceous (revision of supersequences by Golonka and Kiessling, this volume) the shape of the curve remained stable although more than 50% of data were added after the initial plot. In any case the variations lie well within the fluctuations predicted by the error bars.

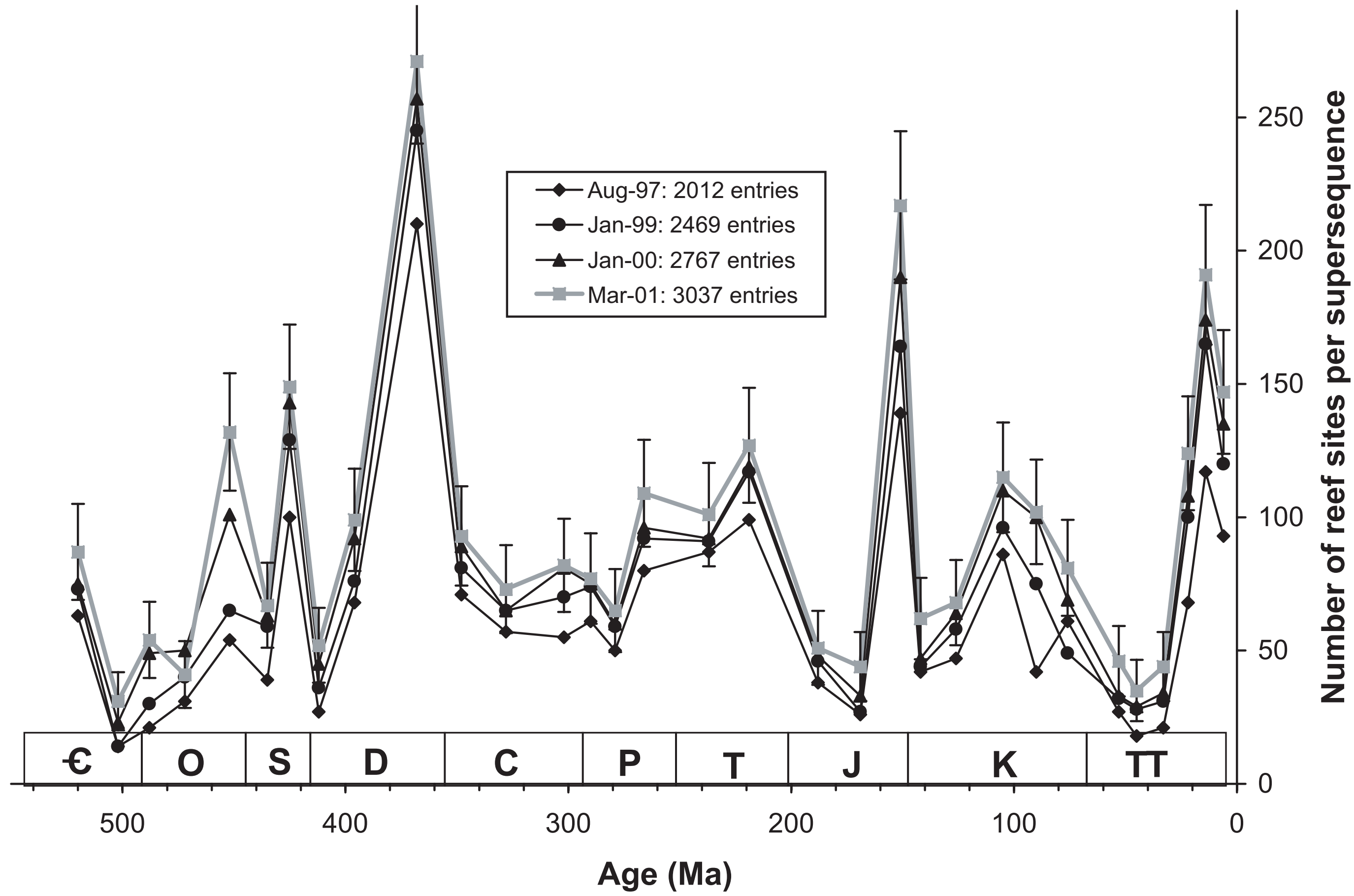

FIG. 2.—Stability of reef trends in the database as shown by reef numbers. The database project started in September 1995 and the whole Phanerozoic was first covered by August 1997. Since then data have been added whenever new relevant papers appeared or new data sources became available. Greater changes in the shape of the curve are due to stratigraphic misconceptions (Ordovician) or revision of the supersequences (Late Cretaceous) rather than sampling heterogeneities. Error bars for the March 2001 curve are calculated after Raup (1991).

Quality of Reef Data

Spatial Heterogeneity.—

High-quality reef data are heterogeneously distributed on a global scale. Better data on detailed reef attributes are available from regions with a classical interest in reef studies, such as North America and Europe. Reefs from other regions are often less well known, and many fields in the database (diversity, bioerosion, petrographic information) have to remain blank. Examples are the Early Cambrian reefs in Siberia and Mongolia or the Late Permian and Middle Triassic reefs in China. Only in the last decade have data on those reefs been published in international journals which have provided new and high-quality reef data (Flügel and Reinhardt, 1989; Liu et al., 1991; Wood et al., 1993; Rigby et al., 1994; Wang et al., 1994; Riding and Zhuravlev, 1995; Kruse et al., 1995, 1996; Lehrmann et al., 1998). There are still vast areas without any detailed description in easily accessible papers (e.g., Late Devonian reefs in the Timan-Pechora Province in Russia). Reef attributes from these areas are not well represented in the database and restrict the potential of pattern analysis. However, the comparison of reef attributes through time is presumably less affected by the spatial heterogeneity of data. Adequate descriptions of reefs can be found in all regions and time slices. Assuming that other reefs in the same area with the same biotic composition and age do not differ notably in main features, the negative influence of heterogeneous knowledge may be insignificant.

Temporal Heterogeneity.—

The quality of reef data is not uniformly distributed through time. This applies to the stratigraphy of reefs (Fig. 3) and the completeness of information on various reef attributes (Fig. 4). Moderate age control is mostly sufficient for the purpose of this book. However, 14% of all reefs in the database are considered to have poor age control, that is, they may be assigned to the wrong supersequence. The maximum percentage of reefs with poor age control is reached in Lower Tejas II (middle Eocene). In this supersequence several reefs are collected with no indication of a date more precise than "Eocene". If those reefs are actually Early or Late Eocene they must be assigned to Lower Tejas I or Lower Tejas III, respectively. With few exceptions, though, the age control is at least moderate for more than 80% of the reefs in a

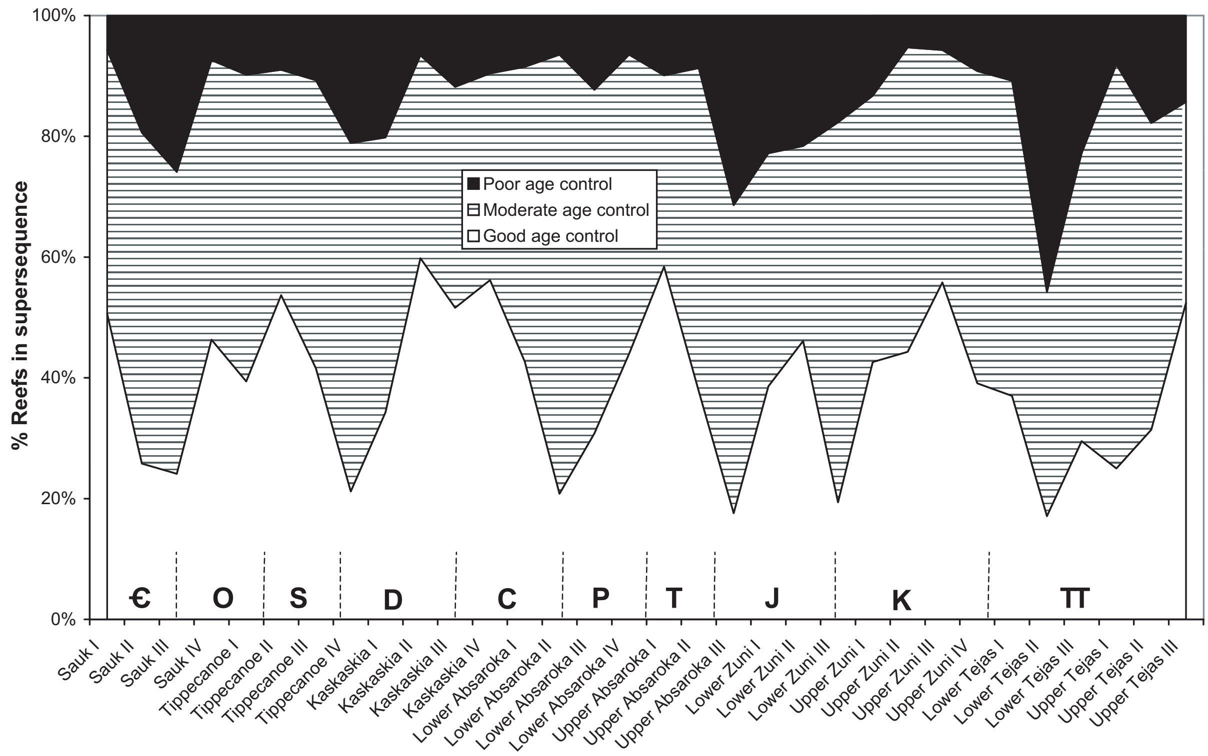

FIG. 3.—Distribution of the stratigraphic resolution in reefs through time. Most of the reef ages are reliable on a stage level (moderate age control), but notably fewer reefs contain reliable information on substages (good age control). The stratigraphic control on reefs fluctuates considerably but is not strongly dependent on economic interests.

supersequence. Poor age control is therefore unlikely to affect statistical evaluations on a supersequence level, but stage-level analyses should be interpreted with caution.

In terms of reef attributes, information on general features (reef dimensions and type) is best documented in the database. The information is uniformly good through time, and minor fluctuations are unlikely to affect the interpretations based on general features. The information on environmental setting (subenvironment and bathymetry), paleontology (community composition and diversity), and petrography (micrite and spar content) is less well documented in the database, and there are considerable variations between time slices. The information on petrographic attributes is weakest on average. The reef attributes are generally poorly documented in time slices with a large percentage of subsurface reefs (e.g., Tertiary) or time slices containing abundant reefs in remote regions (e.g., Silurian–Devonian). Because the heterogeneous knowledge of reef attributes through time and the fluctuating amount of reefs between time slices affect the confidence of calculated means, the statistical error for each mean in a time slice has been determined.

Statistical Errors.—

A standard application for the determination of statistical errors is the calculation of standard deviations and confidence intervals. Because the discussion of reef attributes though time (Kiessling, this volume) relies largely on mean values, the confidence of this measure is an important prerequisite in the evaluation. Owing to the prevalent coarse interval classification of most reef attributes, the standard deviations and confidence intervals are generally large. As an example we show the mean thickness of reefs together with the 95% confidence intervals (Fig. 5). The calculated errors depend largely on the amount of thickness data in each time slice. Hence the confidence interval is wide in time slices with few reefs (e.g., Paleogene) but narrow in time slices with abundant reef data (e.g., Late Triassic). This relation limits the stratigraphic resolution of statistical analyses. Statistical errors are moderate for most supersequences but blow up if attributes are analyzed at a stage level. Although we do not present error bars for all graphs, it should be noted that the curves based on mean values represent bands rather than well defined lines in all cases.

Systematic Errors.—

Because information on ancient reefs is heterogeneous not only between areas but also through time, the reliability of reef characteristics in the database as the basis for statistical analyses is a very important question. Systematic errors in particular time slices may be present, even on the rather coarse resolution of the reef attribute fields in the database. This may be due to biased information of the original author who compares his reef with others of the same age rather than through time. For example, a reef may be classified as highly micrite-containing if the amount is high compared with reefs of the same age (e.g., some Cretaceous reef mounds) but may be moderate in comparison with mounds consisting almost exclusively of micrite (e.g., Waulsortian mud mounds). Another possible bias is given by subjective evaluation of imprecisely stated information by the database compiler. Although the compiler of the database

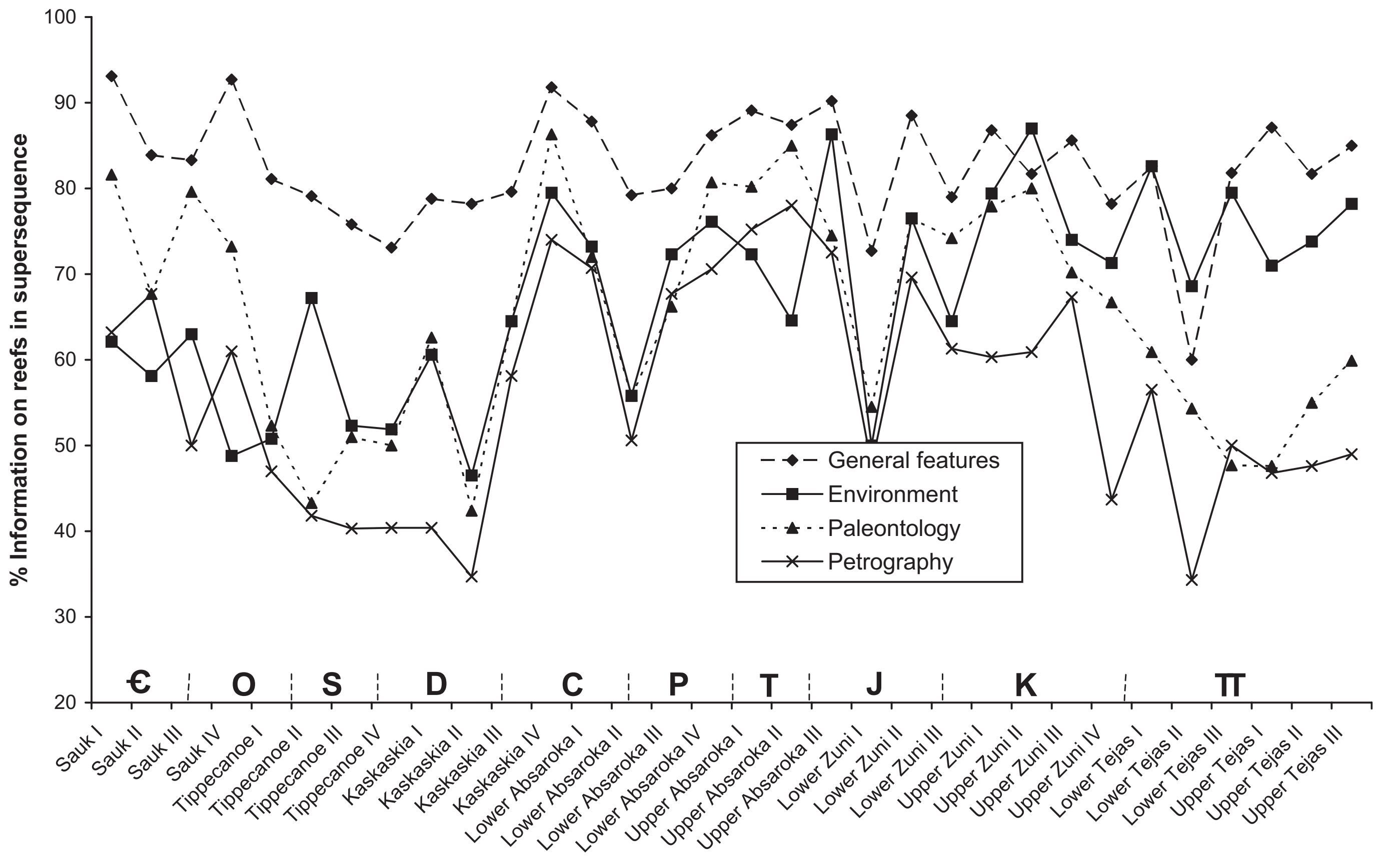

FIG. 4.—Distribution of the completeness of information in the database. General features (size, reef type) are best known, and their knowledge is most uniformly distributed through time. Petrographical attributes (micrite, spar content) are generally least well documented, on average.

(W. Kiessling) has tried to be as objective as possible, there is a great danger in subjective treatment of data:

- Classification can be biased with increasing knowledge of secular variations of particular reef attributes. For example, knowing that many Late Triassic reefs are highly diverse can influence the diversity assignment of taxonomically less well-described Late Triassic reefs.

- Although the original paper on a particular reef did not indicate a required attribute in the text or plate descriptions, the database compiler has tried to extract this information by reading "between the lines" or evaluating the figures and plates. Bias can be present especially when the latter method is used. If, for example, photographs of thin sections are utilized to evaluate the spar content of a reef, care must be taken to consider the different scale and to balance the restricted area figured.

The subjective bias is virtually inevitable, but it has been minimized by leaving fields blank rather than trying to assign all attributes to all reefs. Having the reef as such in the database was considered more important than to collect all information on it. The greatest danger of systematic errors is likely to appear in the assignment of reef types and in the determination of the dominant guild within a reef.

Predictions for the Database

Kiessling et al. (1999) have shown that the percentage of major reefs (> 100 m thick) as calculated from the database is surprisingly stable with an increasing amount of data. Here we provide another example to prove the predictive potential of the database. The percentage of deeper-water reefs in supersequences remains stable although 1462, 1816, 2149, and 2306 data entries were considered, respectively (Fig. 6). In spite of the fact that the database is and always will be incomplete, the observed trends are quite stable and statistical analyses based on percentage or mean values of reef attributes are, therefore, possible. However, some systematic changes are expected to occur with an increasing dataset. At the current state of database development we expect the following trends in the future:

- Both the mean thickness of reefs and the percentage of major reefs in a time slice are expected to decrease in the future. Although we are confident that we have included almost all the major Phanerozoic reef tracts, many smaller reefs are awaiting discovery or description.

- The stratigraphic resolution in reefs will be significantly enhanced with the application of multistratigraphic tools and better international stratigraphic correlations through the activities of International Commission on Stratigraphy.

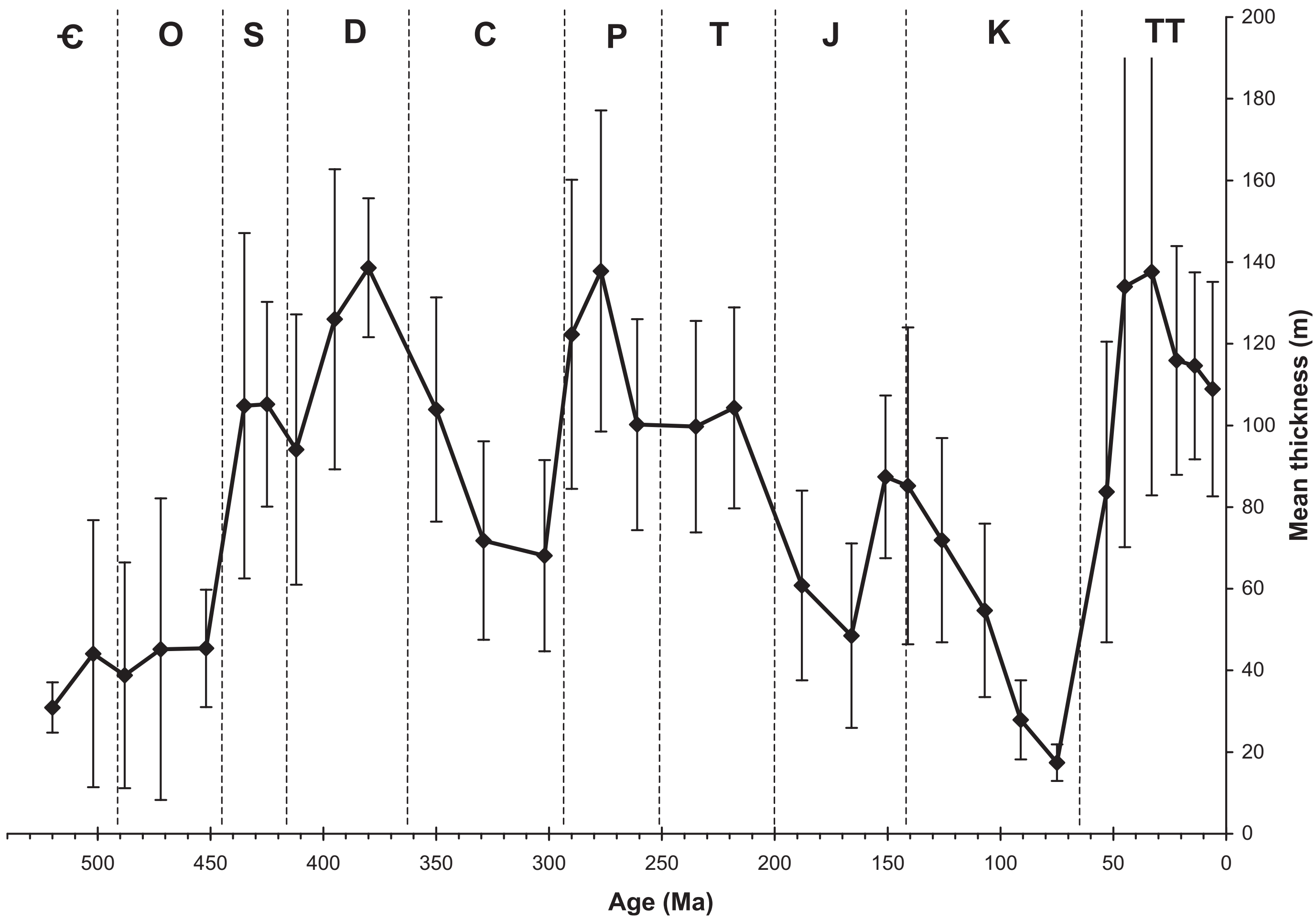

FIG. 5.—Mean thickness of Phanerozoic reefs per supersequence as calculated from the database. The 95% confidence interval is indicated.

- Paleopositions of reefs will change, especially in the Paleozoic, where paleogeographic reconstructions are still strongly debated.

- The mean diversity of reef builders will continuously increase as more taxonomic studies become available.

- The presence of bioerosion (both macroborings and microborings) is likely to be noted in much more reefs than now. Our simple approach of storing presence/absence data may turn out to be meaningless in the future and should be replaced by a semiquantitative field on the intensity of bioerosion.

The majority of percentages and means as calculated from the database are thought to be stable even with a vast increase of data. This is true for the relative amount of reef types, the relative distribution of environmental settings, the mean bathymetry of reefs, the relative dominance of reef-building groups, the relative dominance of guilds, the degree of lateral and vertical zonation, the mean micrite and spar contents, the mean debris potential, and the percentage of reefal reservoirs in a time slice. For all these measures the database can be used as a predictive tool; that is, the probability of reef attributes in unexplored reefs can be evaluated. Even the attributes with predicted future changes are likely to shift systematically with an increasing dataset; that is, the overall trends and patterns will remain essentially constant in the future. We conclude that further progress in database development will modify details of the results but that the major patterns are already visible.

CONCLUSIONS

Our database on Phanerozoic reefs currently contains more than 3000 entries, with information on reef stratigraphy, geographic position/paleoposition, dimensions, type, environmental setting, paleontology, petrographic features, and reservoir quality. The numbers of entries in the database reflects the number of reef sites rather than reef numbers, because only reefs with a minimum spacing of 20 km have been included separately. The amount of reef sites in the database is low compared with the number of Recent reef sites and presumably also in comparison with the true number of reef sites in a particular time slice. The incompleteness is due to (1) incomplete knowledge of preserved reef sites due to their occurrence in the subsurface, or in remote areas, or lack of scientific interest; (2) incomplete consideration of published literature in the database; (3) complete erosion or subduction of older reef complexes.

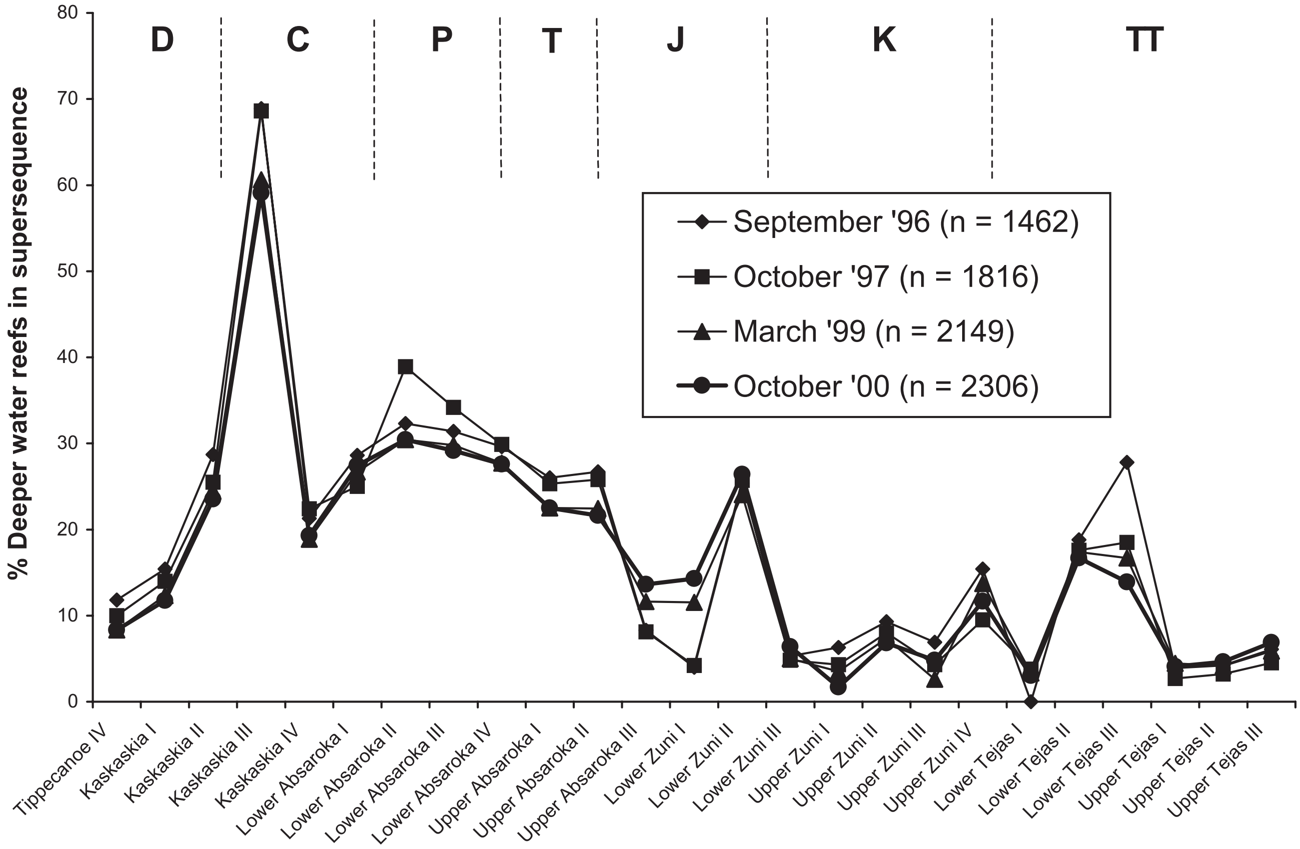

FIG. 6.—Comparison of three stages in database development. The percentage of deeper-water reefs (below fair-weather wave base) in each supersequence is indicated for three stages in database development (September '96, October '97, March '99, October '00). Note the stability of the overall trend in spite of a substantial increase of reef data.

Although missing reefs and missing data on reefs may form a substantial bias in evaluation of global distribution patterns, they are less relevant for the recognition of secular variations in the reef ecosystem and statistical analyses of the database entries (Kiessling, this volume). Reef attributes have been shown to remain essentially constant with an increasing dataset and are likely to remain constant in the future. We conclude that real trends in the reef ecosystem are reflected in the database.

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