PERSPECTIVE

A REAPPRAISAL OF DOLOMITE ABUNDANCE AND OCCURRENCE IN THE PHANEROZOIC

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ABSTRACT: **Critical assessment of dolomite abundance throughout the Phanerozoic suggests that most large-scale dolomite has had an origin related to salinity-elevated seawaters. The distribution of such dolomite is not directly related to periods of major continental flooding but rather to periods when extensive peritidal sequences or large-scale evaporite basins/lagoons existed. The development of such depositional systems is controlled largely by eustasy, paleogeographic/tectonic setting, and paleoclimate.**

Extensive peritidal sequences are characteristic of mature, passive-margin carbonate platforms that formed during long periods of Earth history generally devoid of major continental glaciation (e.g., late Precambrian through early Paleozoic, and Mesozoic). Sea-level fluctuations of relatively low amplitude during such periods allowed extensive, cyclic peritidal-dominated platforms to develop. Such platforms typically lack raised rims, had depositional surfaces that stayed near sea level for tens of millions of years, and show little evidence of major drops in sea level that would have exposed the shelf for long periods. This would have allowed repeated replenishment of pore waters by Mg-rich marine fluids over very extensive supratidal surfaces. Also, since the cycles are very thin, the downward-moving brines could penetrate several cycles on the inner platform, causing massive dolomitization. In contrast, during major glacial periods (e.g., Middle to Late Mississippian to Early Permian and late Cenozoic) higher-amplitude, ice-driven fluctuations in sea level led to extensive meteoric-water flushing of shallow platforms, but related dolomitization has been of minor significance. Under conditions of elevated Mg/Ca ratio in hypersaline brines, however, large-scale dolomitization could occur in response to the formation of extensive evaporite basins/lagoons. Suitable climatic and paleogeographic/tectonic conditions have allowed such dolomitization at various times during the Phanerozoic, regardless of specific styles of eustatic sea-level change. Lack of massive dolomitization in Holocene carbonates may be because neither extensive peritidal sequences nor large-scale evaporite basins/lagoons are prevalent in modern carbonate environments.

INTRODUCTION

Despite a voluminous literature, the origin of dolomite continues to be a controversial topic in sedimentology. A symptom of the importance of this controversy is the frequency with which books and review papers have been published (e.g., Pray and Murray 1965; Friedman and Sanders 1967; Zenger 1972; Zenger et al. 1980; Morrow 1982a, 1982b, 1990a, 1990b; Land 1985; Machel and Mountjoy 1986; Hardie 1987; Shukla and Baker 1988; McKenzie 1991; Mazzullo 1992).

A range of models has been proposed to explain the origins of the numerous dolomites in the geological record (see review by Tucker and Wright 1990, Chapter 8) and, as each new model was proposed, a "band-wagon" effect sometimes resulted in the uncritical application of that model to various dolomite occurrences (see discussion in Machel and Mountjoy 1986 and Hardie 1987). With so little consensus on the controls and origins of dolomitization, Given and Wilkinson (1987) reassessed the abundance of Phanerozoic dolomite in the geological record. Their data showed two main features. First, dolomite abundance did not increase linearly through geological time, suggesting that such dolomites were not a direct product of any age-related process; and second, there is a correlation between dolomite abundance and periods of maximum continental flooding. They concluded that dolomitization may be enhanced during times of global transgression, higher atmospheric pCO_2, and lower calcite saturation state in shallow-marine settings. In addition, they made a strong case, as have other authors (e.g., Land 1985), that seawater is the only widely available fluid with sufficient magnesium to cause massive dolomitization.

In this paper data used in Given and Wilkinson's study are reexamined, particularly by looking at the facies association of major dolomites. From this reexamination it is suggested that dolomite abundance is not directly related to periods of maximum continental flooding, but rather to periods when extensive peritidal sequences or large-scale evaporite basins/lagoons existed. Review of dolomite abundance and occurrence in this study also leads me to concur with Friedman and Sanders (1967) and Friedman (1980) that most dolomite in the rock record formed under conditions of hypersalinity. Less dolomitization seems to have taken place when carbonate platforms were frequently flushed by meteoric fluids (i.e., during major glacial periods), arguing against mixing-zone processes as a significant mechanism for major dolomitization.

DATA SOURCES AND RELIABILITY

Early investigations into dolomite abundance and stratigraphic age were reported by Daly (1909), Chilingar (1956), Vinogradov and Ronov (1956), and Schmoker et al. (1985). The reliability of data in these studies was questioned by Given and Wilkinson (1987), who recognized the uneven sample distributions, apparent mathematical errors, and data omissions of previous studies. Given and Wilkinson retabulated dolomite/calcite ratios from all the readily available sources of data by first converting compositional values for individual samples into dolomite percentages, assuming calcite and dolomite stoichiometry, and then combining these values into stratigraphic units.

There are two groups of data sources for such a compilation. One is from retabulation of Chilingar's (1956) data (Fig. 1A), which has often been quoted as reflecting variations in Phanerozoic dolomite abundance (Tucker and Wright 1990; McKenzie 1991). Another is from data tabulations of Marschner (1968), Lumsden and Chimahusky (1980), Sperber et al. (1983), Langbein et al. (1984), and Baum et al. (1985) (Fig. 1B). The combined result of all the available sample analyses is presented in Figure 1C, which reflects the trend in Phanerozoic dolomite abundance better than Figure 1A. Although dolomite percentages for a given stratigraphic unit vary from one curve to another, all three tabulations show clearly that the percentage of dolomite in sedimentary sequences does not increase linearly with increasing stratigraphic age. Instead, both lower Paleozoic and upper Mesozoic units show similar high dolomite abundance (Fig. 1A). In an attempt to explain this distribution pattern, Given and Wilkinson plotted the curves of global sea level with the dolomite percentages from the above different tabulations and concluded that greater percentages of dolomite formation corresponded to periods of major continental flooding (Fig. 1D).

Even though both the quality and the quantity of the data were improved significantly in Given and Wilkinson's study, the nature of secular trends in dolomite distribution is still difficult to evaluate due to the small sample size and apparent uneven sample distribution (e.g., see Zenger 1989). For example, sample analyses from Cambrian, Early Ordovician, Middle Si-

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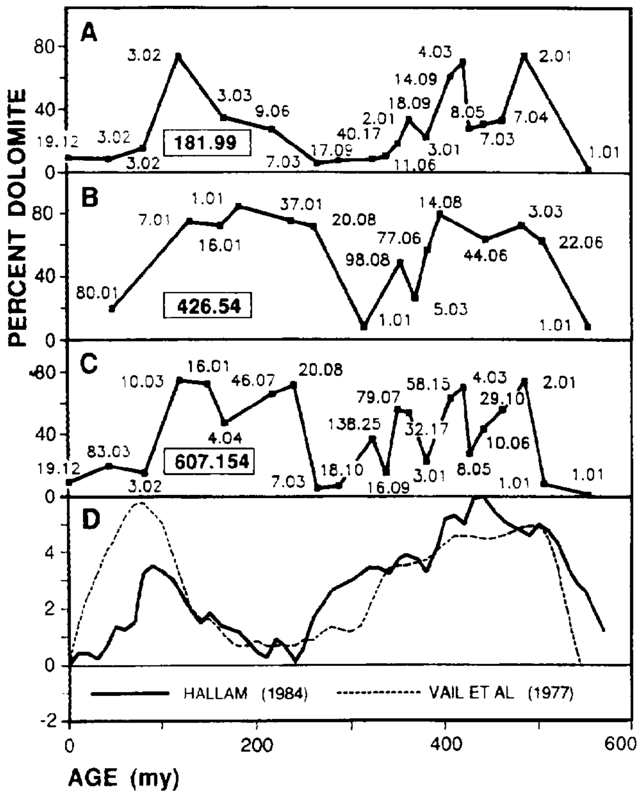

FIG. 1.—Correlation between Phanerozoic dolomite abundances retabulated by Given and Wilkinson (1987) and global sea level. **A)** Data from Chilingar (1956); dolomite abundances were determined by first converting compositional values for individual samples to percent dolomite, assuming calcite and dolomite stoichiometry (n = 181) and then lumping these values into stratigraphic units by geologic epoch (n = 99). **B)** Data from Marschner (1968), Lumsden and Chimahusky (1980), Sperber et al. (1983), Langbein et al. (1984), and Baum et al. (1985), tabulated as above. **C)** Summary of all available data (effectively a combination of data sources A and B). **D)** Estimates of global sea-level curves from Vail et al. (1977) and Hallam (1984).

lurian, Early Devonian, Middle Jurassic, and Late Cretaceous intervals are very limited, and analyses on Precambrian, Early and Late Triassic, Early Jurassic, and Early Tertiary samples are lacking (Fig. 1C).

Two major data sources are used in this study. One is from replotting of the period-average dolomite percentage compiled by Given and Wilkinson (1987). Another is from the author's involvement in a global dolomite reservoir project including systematic analysis of the published record of worldwide dolomite occurrences. For the purpose of this paper, a selection of published literature from worldwide major dolomite provinces is presented (see later for criteria for data tabulation). Although it may never be possible to evaluate the trends in dolomite abundance quantitatively, studies of both published and unpublished data allow cross-checking of the existing compilation and definition of the controls on dolomite distribution at various geological intervals. From the estimation of various published records of dolomite occurrences, several new data points are added to Given and Wilkinson's compilation, including the Late Precambrian through the Cambrian and also the Miocene (Fig. 2). Dolomite percentages for the Late Precambrian through the Cambrian are estimated from Vinogradov and Ronov (1956), Zhai and Zha (1982), Geldsetzer et al. (1988), Koerschner and Read (1989), and Jia (1991), and dolomite percentages for the Miocene are derived from author's unpublished data and systematic review of Miocene carbonates worldwide (see Sun and Esteban 1994). In addition, the global sea-level curve from Vail et al. (1977), paleoclimate from Fischer (1983), and volumes of evaporite from Holser (1984) are plotted along the histogram of dolomite percentage (Fig. 2).

DOLOMITIZATION AND EUSTASY

One of the key relationships of dolomite abundance throughout the Phanerozoic noted by Given and Wilkinson (1987) is that increased dolomite abundance corresponds to times of major continental flooding. Global highstand during the Cambro-Ordovician certainly corresponds to such a dolomitized interval, but less so with the maximum Phanerozoic flooding during Late Cretaceous time. Indeed, extensive dolomitization has occurred during periods of relatively low global sea level, as in the Late Permian and Triassic (Fig. 2). As first noted by Sibley (1991), however, there is an inverse correlation between percentage of dolomite and glaciation (i.e., periods with major ice sheets). Higher dolomite content generally corresponds to geological periods devoid of major continental glaciation, except, as stated above, for the Late Cretaceous (Fig. 2).

The explanation for the apparent link between dolomite abundance and ice-free periods may lie with factors such as pCO_2 and its influence on oceanic CO_3^{2-} concentration, which conceivably might favor dolomitization (Given and Wilkinson 1987; Mackenzie and Morse 1992). Indeed, the dolomite abundance curve does broadly follow the plots for CO_2 concentration in the paleo-atmosphere given by Berner (1991). However, such a hypothesis does not explain the apparent lack of dolomite during the maximum Phanerozoic flooding (i.e., Late Cretaceous) and the abundance of dolomite during times of relatively low global sea level (i.e., Late Permian and Triassic). Systematic review of the facies association of major dolomite occurrences worldwide indicates that the extensively dolomitized carbonate platforms that developed during ice-free periods have fundamentally different styles from the sparsely dolomitized carbonate platforms that developed during major glacial periods. The former consist predominantly of meter-scale peritidal cyclothems lacking evidence of prolonged subaerial exposure, whereas the latter are characterized by subtidal-dominated cycles and pronounced subaerial exposure surfaces capping the cyclothems (Wright 1992). Such a difference is believed to have been related to the amplitude of sea-level fluctuations (Koerschner and Read 1989; Wright 1992). Conceivably, variations in the amplitude of sea-level fluctuation between ice-free periods and major glacial periods may have exerted a dominant control on the extent of dolomite formation.

Dolomitization during Ice-Free Periods

Dolomitization Related to Peritidal Platforms.—Carbonate platforms developed during ice-free periods are characterized by two important attributes that relate to the potential for dolomitization. First, sea levels are generally higher and amplitudes of sea-level changes are small compared to major glacial periods, when higher-amplitude, high-frequency, ice-driven fluctuations in sea level are a dominant feature (Koerschner and Read 1989). Given the fact that typical rates of carbonate sedimentation far exceed potential rates of platform subsidence, most of the vertical space traversed during a sea-level fluctuation is filled with carbonate sediments, and accumulation continues until sea level falls below the platform surface. In the absence of ice buildups, no rapid falls or rises in sea level occur, resulting in a situation that would allow shallow carbonate platforms to prograde extensively, even cratonwide, to create keep-up-style platforms typically consisting of thick, stacked, meter-scale cyclic peritidal successions (Koerschner and Read 1989; Wright 1992). Such platforms typically lack raised rims, have depositional surfaces that stay near sea level for tens of millions of years, and show little evidence of major drops in sea level that would expose the shelf for long periods (Wright 1992). This would allow frequent inundation of extensive supratidal surfaces by storm-driven marine waters. Also, since the cycles are very thin, the downward-moving brines can penetrate several cycles on the inner platform, leading

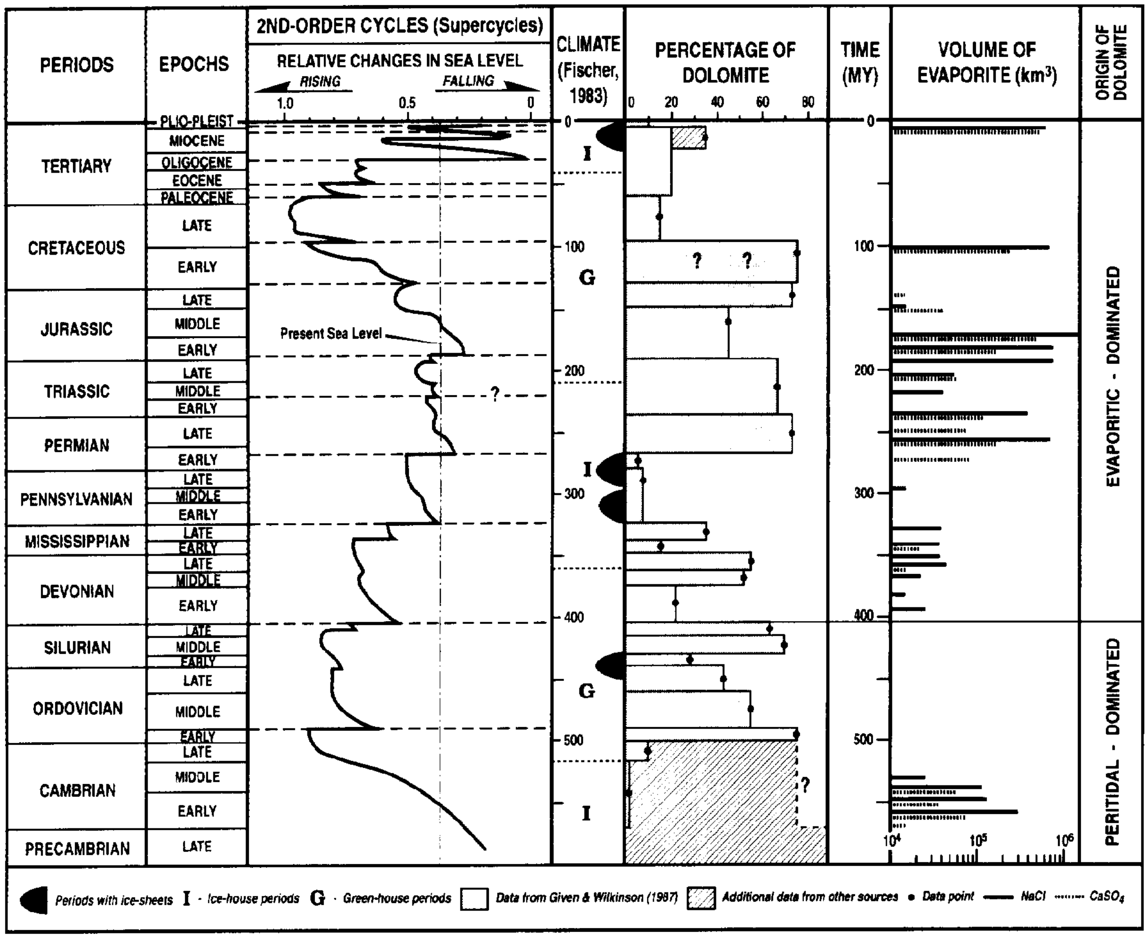

FIG. 2.—Dolomite abundance and global eustasy. Since the dolomite percent retabulated by Given and Wilkinson (1987) for each stratigraphic unit represents the average value for that period, the summarized data for the Phanerozoic dolomite abundances in Fig. 1C is better represented by a histogram. Additional data for the late Precambrian through the Cambrian are derived from Vinogradov and Ronov (1956), Zhai and Zha (1982), Koerschner and Read (1989), and Jia (1991), while dolomite percentage for the Miocene is derived from the author's unpublished data and review of Miocene carbonates worldwide (Sun and Esteban 1994). The second-order global sea-level curve is from Vail et al. (1977). The distribution of ice sheets through the Phanerozoic is from Fischer (1983). Volume of evaporite is from Holser (1984). Note that periods with major evaporite accumulation generally correspond to higher dolomite percentages for the late Paleozoic, Mesozoic, and Cenozoic, whereas late Precambrian and early Paleozoic dolomites are largely peritidal.

to repeated replenishment of pore waters by Mg-bearing marine fluids (Montañez and Read 1992b). If the premise is accepted that seawater is the only widely available fluid with sufficient magnesium to cause massive dolomitization, then carbonates with long residence time in seawaters and not extensively flushed through by meteoric water, as would occur if higher-amplitude sea-level falls took place, have the best chance to be extensively dolomitized.

A second effect of an ice-free global climate is salinity and Mg/Ca ratio, which are the two overriding controls on dolomitization (Liebermann 1967; Folk and Land 1975; Morrow 1978; Gaines 1980; Sass and Bein 1988). As discussed above, carbonate platforms developed during ice-free periods are typically very shallow and extensive, covering thousands or even hundreds of thousands of square kilometers. These "keep-up" platforms are able to maintain high productivity and seem commonly to have been capable of prograding into their surrounding basins. The predominance of thick, stacked peritidal sequences on such platforms suggests that depositional surfaces may have stayed near sea level for long periods. Any inundating waters are restricted in circulation, and if evapotranspiration is sufficiently high, salinity-elevated seawaters are generated. Even on small platforms like the Great Bahama Bank, seawaters of elevated salinity develop on the platform interior (e.g., Simms 1984; Whitaker and Smart 1990), and such waters can be refluxed into the platform, causing massive dolomitization (Simms and Hardie 1983; Simms 1984). The absence of evaporites in many dolomitized platform sequences has been used as an argument against their origin from higher-salinity seawater, but it is quite possible for platforms to generate saline waters without reaching the stage of evaporite precipitation (i.e., below gypsum saturation). For example, the massive Cretaceous dolomite of the Soreq Formation in Israel is interpreted as having formed at an early-diagenetic stage from slightly evaporated seawater whose salinity fluctuated and only sporadically reached the range of gypsum and anhydrite precipitation (Sass and Katz 1982; Sass and Bein 1988).

The effect of salinity on dolomitization has long been controversial. Theoretically, any solution supersaturated with dolomite is capable of precipitating dolomite as a cement, but to replacement carbonate sediments or limestones the solution must be undersaturated with respect to calcite and supersaturated with respect to dolomite. Badiozamani (1973) used thermodynamic arguments to show that although neither seawater nor meteoric waters have this property, certain mixtures of these two waters appear to be good candidates. Folk and Land (1975) argued that

TABLE 1.—*Examples of large-scale peritidal dolomite during ice-free periods*

Stratigraphic Age	Basin/Region	Country	Group/Formation	Facies Association	References
Late Precambrian	Bohai Gulf	N. China	Gaoyuzhuang-Wumishan	Cyclic peritidal carbonate	Guan 1981
	Tarim	W. China	Qigebulake	Cyclic peritidal carbonate	Ye and Liu 1991
	Guizhou	S. China	Danying	Stromatolite reef	Wu 1985
	Canadian Shield	Canada	NA	Stromatolite reef	Geldsetzer et al. 1988
Cambrian-Middle Ordovician	Bohai Gulf	N. China	Fujunshan/Liangjiashan	Cyclic peritidal carbonate	Zhai and Zha 1982
	Tarim	W. China	NA	Cyclic peritidal carbonate	Ulmishek 1984; Jia 1991
	Guizhou	S. China	NA	Peritidal carbonate	Wu 1985
	Canning	W. Australia	Nita	Cyclic peritidal carbonate	Karajas and Kernick 1984
	Appalachians	U.S.A.	Elbrook-Conococheague	Cyclic peritidal carbonate	Koerschner and Read 1989 Osleger and Read 1991
	W. Newfoundland	E. Canada	St. George	Cyclic peritidal carbonate	Pratt and James 1986
	Anadarko	U.S.A.	Arbuckle	Cyclic peritidal carbonate	Gao and Land 1991
	Permian	U.S.A.	Ellenburger	Cyclic peritidal carbonate	Loucks and Anderson 1985
	Appalachians	U.S.A.	Knox	Cyclic peritidal carbonate	Montanez and Read 1992a, b
Silurian	Michigan	U.S.A.	Niagaran	Tidal-flat carbonate	Sears and Lucia 1980
	Williston	U.S.A.	Interlake	Peritidal carbonate	Roehl 1985
	Appalachians	U.S.A.	Lockport	Restricted lagoon/tidalflat carbonate	Smosna et al. 1989
Late Triassic	Southern Alps	Italy	Dolomia Principale	Cyclic peritidal carbonate	Wilson 1975

dolomite, because of the difficulty of ordering required for crystallization, can form most easily by slow crystallization. Dilution of seawater by freshwater allows the Mg/Ca ratio to remain constant but slows the crystallization rate and reduces the concentration of competing ions. Morrow (1978) had a view completely opposite to that of Folk and Land (1975), believing that extensive precipitation of gypsum or anhydrite by evaporitic brines would raise Mg/Ca ratio to levels that more than compensate for the increased salinity. Using higher-salinity seawater (i.e., minimum salinity of four to six times that normal seawater), Liebermann (1967) succeeded in synthesizing dolomite at the low temperatures characteristic of coastal areas with restricted water circulation during periods of aridity. Gaines (1968, 1980) has shown experimentally that rate of dolomite formation decreases with decreasing salinity, and has suggested that in the shallow epeiric seas of relatively high surface/volume ratios, precipitation of calcite and aragonite might be sufficient to increase the Mg/Ca ratios to the point where dolomitization of the substrate might be possible kinetically. In a review of dolomite occurrence in the rock record and study of modern dolomite in sea-marginal ponds of the Red Sea, Friedman (1980) showed a close lateral, vertical, or temporal relationship between dolomite and evaporite deposits and concluded that most dolomites in the rock record formed under conditions of hypersalinity. Recently, Simms (1984) has shown that the reflux of hypersaline brines or bankwaters of only slightly elevated salinity produces a large-scale flow system that affects carbonate rocks up to several thousand meters thick over an area of thousands of square kilometers. Such flow systems would have been prevalent on ancient shallow platforms during periods of hydrographic restriction and climatic aridity, and consequently their dolomitizing potential would have been enormous. Clearly, dolomitization would be favored by salinity increase rather than decrease.

Evidence suggesting dolomitization by salinity-elevated seawater on peritidal-dominated platforms developed during ice-free periods comes largely from the facies association of the dolomites. A systematic review of large-scale peritidal dolomite in North America, China, Europe, and western Australia (Table 1) indicates that dolomite occurrences in meter-scale peritidal cycles is commonly restricted to the supratidal and intertidal zones of each shallowing-upward cycle, although the entire cycle can be completely dolomitized. The common association of dolomite with mud-cracked laminites, silicified evaporite nodules, and restricted subtidal facies suggests that reflux of evaporated seawater may have played a dominant role in causing dolomitization, although sulfate reduction in the tidal-flat sediments and brine mixing along the landward margin of the tidal flats may have also promoted dolomitization (Montañez and Read 1992b).

Dolomitization Related to Evaporitic Basins/Lagoons.—While platformwide dolomitization during ice-free periods can be linked tentatively to salinity-elevated seawater on peritidal-dominated platforms, not all extensive dolomitization during such periods was of peritidal origin. Such was the case for the late Paleozoic and Mesozoic, when the widespread epeiric seas essentially disappeared, resulting perhaps in part from displacements associated with continental drift. Massive dolomitization during such periods is related largely to the development of extensive evaporite basins or shelf lagoons (Table 2). The intimate link between dolomitization and evaporite precipitation was noted long ago by Friedman and Sanders (1967) and Friedman (1980). In fact, they even concluded that dolomite is an evaporite mineral. The distribution of such evaporite basins or shelf lagoons is controlled by regional tectonics and paleoclimate. Indeed, if it is accepted that salinity-elevated seawater is the most likely cause of extensive dolomitization, then its occurrence must be linked directly to areas and time intervals when evaporation was high. Conceivably, both global climatic factors and regional factors require consideration. The position of continental areas in relation to low-latitude arid belts and to other factors such as continentality and rain-shadow effects all influence regional climate. Studies of worldwide evaporite basins by Holser (1984) showed that the intensity of evaporite precipitation has varied with time. There have been periods when evaporite deposits were insignificant or absent over the whole Earth. In contrast, at other times widespread evaporite deposits were a prominent feature (i.e., Early Cambrian, Middle to Late Devonian, late Early Permian to Late Permian, Triassic through Early Jurassic, Late Jurassic, Early Cretaceous, and Miocene; Fig. 2). Lotze (1964) and Zharkov (1981, 1984) reached a similar conclusion. At these times extremely warm and arid climates must have been areally extensive. This may explain the apparent link between the higher dolomite content and periods of major evaporite accumulation for the late Paleozoic and Mesozoic (Fig. 2).

It is apparent from the above that massive dolomitization during ice-free periods is associated with either extensive peritidal carbonates or large-scale evaporite precipitation. However, not every carbonate platform that developed during ice-free periods was extensively dolomitized. For example, Early Devonian and Late Cretaceous strata contain little dolomite. Perhaps the paleoclimate and tectono-eustasy for such periods were unfavorable for the development of extensive peritidal carbonates or large-scale evaporite basins. Indeed, the Late Cretaceous is well-known as the period of maximum Phanerozoic continental flooding. Many shallow carbonate platforms were drowned by this flooding event and are overlain by widespread pelagic sediments (Jenkyns 1986). As a result, conditions favorable for dolomitization existed only in small inner-platform areas

TABLE 2.—*Examples of large-scale evaporite dolomite during ice-free periods*

Stratigraphic Age	Basin/Region	Country	Group/Formation	Facies Association	References
Middle-Late Devonian	Alberta	W. Canada	Keg River	Basinal evaporite	Schmidt et al. 1985
	Elk Point	Canada/U.S.A.	Keg River/Winnipegosis	Basinal evaporite	Kendall 1989
	Alberta	W. Canada	Wabamun	Restricted shelf evaporite	McCrossan and Glaister 1964
Late Permian	Permian	U.S.A.	San Andres	Lagoonal evaporite	Cowan and Harris 1986
	Zechstein	N.W. Europe	Zechstein	Basinal evaporite	Clark 1980
	Arabian Platform	Middle East	Khuff	Sabkha/lagoonal evaporite	Alsharhan 1989
Triassic	Southern Alps	Italy	Schlern/Serla (Ladinian)	Carbonate bank overlain by evaporite	Wilson 1975
	Guizhou	S. China	NA	Sabkha/lagoonal evaporite	Wu 1985
	Arabian Platform	Middle East	NA	Sabkha/lagoonal evaporite	Sharief 1983
Late Jurassic	Gulf of Mexico	U.S.A.	Smackover	Oolitic shoal with back-shoal evaporite	Saller and Moore 1986 Prather 1992
	Arabian Platform	Saudi Arabia	Arab	Subtidal carbonate overlain by supratidal evaporite	Wilson 1985 Mitchel et al. 1988
	Lower Saxony	N.W. Germany	Gigas	Sabkha/basinal evaporite	Schmidt 1965
Early-Middle Cretaceous	Comanche Platform	U.S.A.	Edwards	Lagoonal evaporite	Fisher and Rodda 1969
	South Florida	U.S.A.	Sunniland	Lagoonal evaporite	Halley 1985
	Campeche Shelf–Yucatan Platform	S.E. Mexico	NA	Lagoonal evaporite	Peterson 1983

where local restriction could generate salinity-elevated seawaters. In this regard, it would be instructive to learn whether those parts of ice-free periods lacking extensive dolomitization correspond to intervals when the global/regional paleoclimate was more humid. For example, the lack of dolomite in Middle Ordovician peritidal carbonates of the Virginia Appalachians has been attributed to a humid paleoclimate (Read and Horbury 1993).

Dolomitization during Major Glacial Periods

Periods with maximum glaciation during the Phanerozoic (i.e., Middle to Late Mississippian to late Early Permian, and late Cenozoic; Fig. 2) are associated with higher-amplitude sea-level changes and different styles of platform architecture (Koerschner and Read 1989; Wright 1992). For example, late Cenozoic carbonate platforms typically have raised rims, pinnacle/patch reefs, deep lagoons, limited development of peritidal facies, and upward-shallowing sequences that are capped by karst surfaces (Enos and Perkins 1977; Sun and Esteban 1994). They reflect a response to high-amplitude, ice-driven sea-level fluctuations of 100 m or more that occurred during late Cenozoic time (Enos and Perkins 1977; Beach 1982). Platforms through the Permo-Carboniferous are also well documented (e.g., Goldhammer et al. 1991; Horbury 1989; Walkden 1987; Walkden and Walkden 1990). The glacio-eustatic sea-level changes on the order of 10 ky frequencies and with 10–30 m amplitude began in the mid-Mississippian (late Dinantian) (Horbury 1989). At first the shorter Milankovitch rhythms (fifth-order cycles) were apparently missing (Fischer 1986), but subsequently became established throughout Pennsylvanian time with fourth-order and fifth-order cycles averaging 30 m and 6 m thick, respectively, in the well-documented Paradox Basin (Goldhammer et al. 1991) and Orogrande Basin (Algeo et al. 1992). As with the late Cenozoic platforms, peritidal carbonates are not a prominent component of these Permo-Carboniferous platform systems, even during the phases of falling sea level. The most plausible explanation for this appears to be that ice-induced sea-level falls during the major glacial periods are rapid, preventing the formation of a peritidal cap. Likewise, rapid sea-level rises induced by melting of continental ice sheets commonly lead to incipient drowning of subtidal-dominated platforms. Only reefal organisms like corals seem to be capable of keeping pace with some part of these glacio-eustatic sea-level rises, a fact probably contributing to the steep, reef-fronted margins of late Cenozoic platforms. Most of the cyclothems developed on the Permo-Carboniferous and late Cenozoic platforms are capped by paleokarsts and paleosols that developed on subtidal (not peritidal) deposits, providing clear evidence of extensive meteoric flushing. Despite frequent flushing by freshwater, dolomitization was considerably less developed in these platforms (Fig. 2), suggesting that dolomitization of platforms by marine-meteoric mixing processes is of minor significance. Sibley (1991) argued that rapid glacio-eustatic sea-level fluctuations reduced the length of time that carbonate sediments were in contact with dolomitizing fluids. In addition, predolomitization freshwater diagenesis reduces the potential for dolomitization by converting high-Mg calcite and aragonite to low-Mg calcite (Sibley 1980).

While high-amplitude sea-level fluctuations during major glacial periods were not favorable for the formation of stacked, cyclic peritidal sequences,

TABLE 3.—*Examples of large-scale evaporitic dolomite during major glacial periods*

Stratigraphic Age	Basin/Region	Country	Group/Formation	Facies Association	References
Late Ordovician	Williston	U.S.A.	Red River	Lagoonal evaporite	Longman et al. 1983 Derby and Kilpatrich 1985 Clement 1985
Carboniferous	Paradox	U.S.A.	Leadville/Paradox	Basinal evaporite	Baars and Stevenson 1983 Miller 1985; Roylance 1990
	Williston	U.S.A.	Mission Canyon	Lagoonal evaporite	Lindsay and Kendall 1985
	S.W. Wyoming	U.S.A.	Mission Canyon	Sabkha/lagoonal evaporite	Harris et al. 1988
Miocene	Mediterranean	Spain	(Late Miocene)	Basinal evaporite	Oswald 1992
	Gulf of Suez-Red Sea	Egypt	Upper Rudeis/Belayim	Basinal evaporite	Coniglio et al. 1988 Sun 1992
	Mesopotamian	Iraq, Syria, and S.W. Iran	Euphrates/Jeribe	Sabkha-lagoonal evaporite	Philip et al. 1972 Metwalli et al. 1974

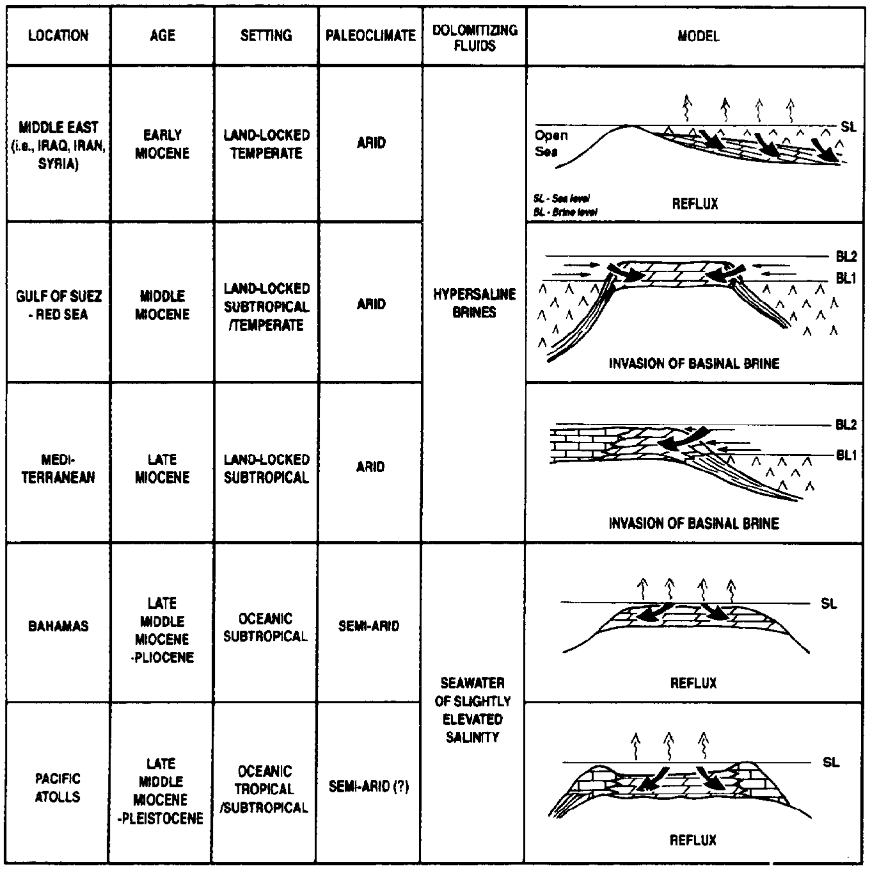

FIG. 3.—Sketch summarizing the dolomitizing mechanisms for late Tertiary carbonates in the Middle East, Gulf of Suez–Red Sea, Mediterranean, Bahamas, and Pacific.

they may locally have favored the formation of salinity-elevated seawater in evaporite basins or shelf lagoons. Indeed, ice-house sea-level oscillations tend to favor the formation of bucket-style platforms or atolls with hydrologically restricted interior lagoons (Wright 1992). Examples of extensive dolomitization related to basinal or lagoonal evaporites include the Carboniferous Paradox Basin, the Late Ordovician Williston Basin, the Late Miocene of the Mediterranean, and the Early to Middle Miocene of the Gulf of Suez and the Middle East (Table 3).

It is instructive to look at the well documented dolomites formed during the late Cenozoic, when high-amplitude sea-level fluctuations took place (McKenzie 1991). Two categories can be distinguished: dolomites associated with arid, land-locked, evaporite basins, and dolomites found in oceanic platforms or atolls (Fig. 3). Dolomitization in the first category is interpreted as having been caused by either reflux of lagoonal hypersaline brines or invasion of basinal hypersaline brines during the rise of brine level induced by hydraulic head (Oswald 1992; Sun 1992; Sun and Esteban 1994). A variety of origins has been proposed for the latter category, but most invoke modified seawater as the cause. Aissaoui (1988), Vahrenkamp et al. (1991), and Hein et al. (1992) have favored dolomitization caused by mixing-zone-induced seawater circulation, whereas thermal convective processes have been stressed by Aharon et al. (1987) and Saller (1984). However, stable-isotope data from these dolomites and the geometry of most dolomite bodies do not support either model. A remarkable similarity in carbon and oxygen isotopic signatures between late Cenozoic dolomites in the Bahamian platforms and Pacific atolls has been observed (Fig. 4). The carbon isotopic values (averaging 2–3‰) are typical of marine-derived carbon sources, while the oxygen isotopic values of 2–4‰ fall within the range expected for dolomitization from evaporated seawater (e.g., Sass and Bein 1988). Furthermore, if thermal convective processes are important in causing dolomitization, more dolomites should be found along atoll or platform margins, where thermally induced seawater circulation is most active. The fact that extensive dolomitization in most atolls or oceanic platforms takes place largely in the interiors or lagoons is inconsistent with the thermal-convection dolomitization model.

Vahrenkamp et al. (1991) have noticed the simultaneous formation of dolomites in the Bahamas, the Caribbean, and the Pacific during late Middle Miocene through Pleistocene. Massive dolomites are also present in some of the relatively flat-topped carbonate banks of Late Miocene age in Southeast Asia (Epting 1980; Sun and Esteban 1994). The timing of such dolomitization events apparently coincides with major climatic cooling and sea-level lowering (McKenzie 1991). Based on an analysis of eolian deposits, types of vegetation, and clay-mineral assemblages, Crowley and North (1991) suggested that there was a significant increase in climatic aridity in the late Cenozoic. All of the above evidence indicates that these late Tertiary dolomitizing events were related to global, climatically driven hydrologic systems. Perhaps global sea-level lowering and climatic aridity combined to provide conditions favorable for the generation of salinity-elevated seawaters on the interior of shallow platforms or atolls. Reflux of such waters into platforms may have been the main cause for massive dolomitization (Fig. 3). Persistent enrichment of ^{18}O in the Tertiary dolomites is consistent with such an explanation, although the absence of evaporite minerals in these dolomites has been used as an argument against their origin from evaporated seawater. The reflux origin of atoll dolomites has been favored by many other workers (e.g., Berner 1965; Schlanger 1965; Gross and Tracey 1966; Schofield and Nelson 1978; Ohde and Kitano 1981; and Goldstein et al. 1991).

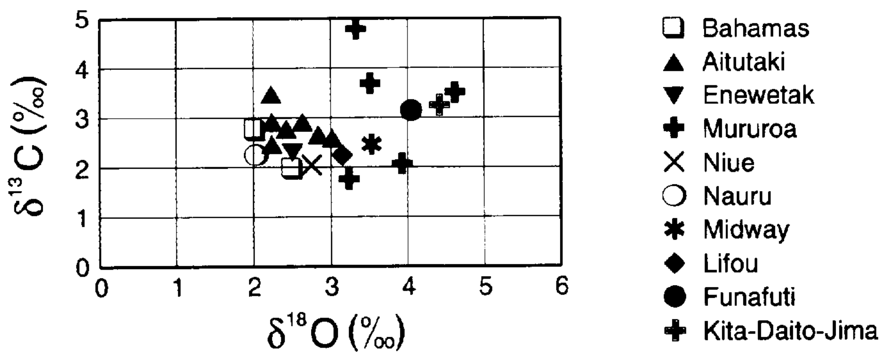

FIG. 4.—Compilation of carbon and oxygen isotopic data for the Bahama Bank and Pacific atolls. The data sources are: Bahamas (Dawans and Swart 1988), Aitutaki (Hein et al. 1992), Enewetak (Saller 1984), Mururoa (Aissaoui 1988), Niue and Nauru (Aharon et al. 1987), Midway (Major 1984), Lifou (Bourrouilh-Le Jan 1975), Funafuti and Kita-Datio-Jima (Berner 1965). Most data were reported as averages or were averaged here.

IMPLICATIONS FOR MODERN DOLOMITIZATION

Modern dolomites have been described from a wide range of diagenetic environments, including coastal marine environments (e.g., sabkhas, mud flats, and saline lakes), isolated platforms, deep-sea anoxic environments, and continental lakes, but these modern dolomite occurrences never approach the size of the massive dolomites common in the geologic record. Two factors are critical in explaining this paradox. First, as shown above, most massive ancient dolomites are associated with either extensive peritidal carbonates (i.e., during ice-free periods), or large-scale basinal/lagoonal evaporites. Neither are prevalent in modern carbonate environments. The lack of extensive Holocene peritidal sequences can be explained by the effect of late Cenozoic glaciation (see earlier discussion), whereas the absence of modern large-scale evaporite basins or restricted shelf lagoons is due mainly to unfavorable climatic and/or tectonic conditions.

Second, Holocene carbonates are less than a few thousand years old, a duration that may not be sufficient for massive dolomitization. Given that hypersaline brines are now generated only in areally restricted sabkhas, most modern carbonates have been residing in either nearly normal seawater or mixed meteoric water and seawater. Residence time is particularly important for dolomitizing fluids with relatively low Mg/Ca ratios (i.e., slightly evaporated seawater or mixed fluids). Active circulation of seawaters of elevated to nearly normal salinity has been measured beneath the modern Great Bahama Banks (Whitaker and Smart 1990), but dolomite formation is limited to thin supratidal crusts. Under conditions of elevated Mg/Ca ratio in hypersaline brines, however, rapid dolomitization can take place. For example, extensive dolomitization in the MacLeod evaporite basin of Western Australia has taken place over the past 5000 yr (B.W. Logan, personal communication 1992).

An additional clue about the lack of massive modern dolomites comes from a comparison between Holocene and late Tertiary carbonates. Massive late Tertiary dolomites have been documented from the Bahamian platforms (Vahrenkamp et al. 1991), Pacific atolls (Aharon et al. 1987; Aissaoui 1988; Hein et al. 1992), and Luconian Platform in Southeast Asia (Epting 1980). These dolomites are typically associated with shallow subtidal carbonates that provide no evidence of evaporite minerals. In all these cases, hydrographic restriction related to frequent global sea-level lowering and climatic aridity seem to be the two critical factors responsible for the massive dolomitization (see earlier discussion). Conceivably, the lack of massive modern dolomites may be caused by the Holocene transgression, the removal of hydrographic restriction, and a relatively humid climate.

CONCLUSION

This study presents an alternative approach to the understanding of dolomite abundance in the Phanerozoic by means of systematically analyzing the published record of major dolomites worldwide, and in particular, looking at the facies association of these dolomites. The preceding discussion is in no way meant to imply that the issue of the relative importance of various dolomitization processes is resolved, and many readers will undoubtedly take exception to some, or even most, of the ideas and speculations offered above. Although the origin of dolomites will continue to be controversial for many years, several aspects of dolomite formation seem to be indicated by the reappraisal of existing data in this study. Perhaps the most important one is that most large-scale dolomitization seems to have had an origin related to salinity-elevated seawaters. The distribution of such dolomites is not directly related to periods of major continental flooding but rather to periods when extensive peritidal carbonates or large-scale evaporite basins/lagoons existed. One might (and probably will) argue that many ancient dolomites are associated with neither peritidal carbonates nor evaporitic minerals. These exceptions are regarded as a reflection of complex local controls on dolomitization. Indeed, given appropriate hydrodynamic and geochemical conditions, dolomites can form in a wide range of diagenetic environments (e.g., coastal marine, lake, mixing zones, deep sea, burial). However, to produce major volumes of dolomite, particularly on a regional/platform scale, more critical and widely operative processes are needed. Seawater appears to be the only widely available fluid with sufficient magnesium to cause massive dolomitization. In this context, extensive peritidal-dominated platforms, or platforms associated with large-scale evaporite basins/lagoons, appear to be favorable places where the kinetic constraints of normal seawater can be overcome to produce dolomitization. Suitable eustatic, tectonic, and climatic conditions have allowed such depositional systems to develop at various times during the Phanerozoic. Sea-level fluctuations of relatively low amplitude during ice-free periods favored the development of extensive peritidal-dominated platforms, whereas higher-amplitude, ice-driven sea-level fluctuations during major glacial periods led to frequent meteoric flushing and reduced the length of time that carbonate sediments were in contact with dolomitizing fluids. Large-scale formation of evaporite basins/lagoons occurred during both ice-free and glacial periods, although there seems to have been more evaporite-related dolomitization during ice-free periods, reflecting the effects of paleogeography, tectonics, and climate.

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