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# STRATIGRAPHY, PALEOCEANOGRAPHY, AND EVOLUTION OF CRETACEOUS PACIFIC GUYOTS: RELICS FROM A GREENHOUSE EARTH

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**ABSTRACT. Many guyots in the north Pacific are built of drowned Cretaceous shallow-water carbonates that rest on edifice basalt. Dating of these limestones, using strontium- and carbon-isotope stratigraphy, illustrates a number of events in the evolution of these carbonate platforms: local deposition of marine black shales during the early Aptian oceanic anoxic event; synchronous development of oolitic deposits during the Aptian; and drowning at different times during the Cretaceous (and Tertiary).**

**Dating the youngest levels of these platform carbonate shows that the shallow-water systems drowned sequentially in the order in which plate-tectonic movement transported them into low latitudes south of the Equator (paleolatitude ~0°-10° south). The chemistry of peri-equatorial waters, rich in upwelled nutrients and carbon dioxide, may have been a contributory factor to the suppression of carbonate precipitation on these platforms. However, oceanic anoxic events, thought to reflect high nutrient availability and increased productivity of planktonic organic-walled and siliceous microfossils, did not occasion platform drowning. Neither is there any evidence that relative sealevel changes were the primary cause of platform drowning, which is consistent with the established resilience of shallow-water carbonate systems when influenced by such phenomena.**

**Comparisons with paleotemperature data show that platform drowning took place closer to the Equator during cooler intervals, such as the early Albian and Maastrichtian, and farther south of the Equator during warmer periods such as Albian-Cenomanian boundary time and the mid-Eocene. Initiation of one carbonate platform relatively close to the Equator, at paleolatitudes more northerly than those where others drowned, took place during the cool early mid-Aptian. These correlations are in accord with an interpretation that excess warmth in shallow peri-equatorial waters proved inimical for many carbonate-secreting organisms living on the platforms, allowing subsidence or eustatic sealevel rise to outpace sedimentation and guyots to form. A parallel may be drawn with the recent phenomenon of coral and foraminiferal bleaching, whereby photosynthetic symbionts succumb to prolonged high temperatures (>30°C) and the host organism dies. The fact that most Cretaceous guyots reside in the north Pacific may not be solely related to the age-distribution pattern of ocean floor but to their having run the gauntlet of a difficult and dangerous passage across the Equator. North Pacific guyots are relics from the Cretaceous (and Eocene) "greenhouse" Earth.**

## INTRODUCTION

Parts of the Pacific Ocean are strewn with individual features, clusters or chains of flat-topped Cretaceous seamounts whose summit depths typically lie between 1 and 2 km below sealevel. These features were termed "guyots" by Hess (1946), and their distribution, as originally mapped, was primarily "between latitudes 8°30′ north and 27° north and longitudes 165° west to 146° east", although scattered guyots were located up to 45° north and 165° west. Hess further noted that no guyots "have been found west and south of the above boundaries though this area has been at least as well explored as the former." Guyots therefore are predominantly known from the northwest Pacific, although features designated as guyots have now been found, albeit uncommonly, south of the Equator. The distribution of guyots, as presently mapped, suggests that about 80 to 90 percent of them lie north of the Equator (Menard, 1964; Vogt, 1989).

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Initially interpreted as erosionally truncated volcanic islands, dredging in 1950 revealed the presence of shallow-water limestones of Cretaceous age on the summits of certain guyots (Hamilton, 1956). Subsequent drilling and dredging (Heezen and others, 1973; Winterer, Ewing, and others, 1973; Matthews and others, 1974; Winterer and Metzler, 1984; Grötsch and Flügel, 1992; Lincoln, Pringle, and Premoli Silva, 1993; Winterer and Sager, 1995; Haggerty and Premoli Silva, 1995; Flood, 1998) demonstrated the common occurrence of Cretaceous shallow-water facies and fossils above the volcanic foundations of many guyots. The flat top is thus largely constructional rather than erosional. In the case of Resolution Guyot, in the mid-Pacific Mountains (fig. 1), the thickness of the Cretaceous shallow-water limestone cap is locally in excess of 1600 m (Sager, Winterer, Firth, and others, 1993) and records a long history of basement subsidence balanced by production of carbonate sediment in water depths of only a few meters. Guyots illustrate a later evolutionary phase in Darwin's (1842) theory of the origin of coral reefs and atolls: namely the phenomenon of drowning, whereby the rate of relative sealevel rise outpaces that of sediment production, and the edifice sinks into progressively deeper water to become mantled with pelagic sediment.

Because the shallow-water limestones that partly constitute guyots chiefly contain environmentally dependent faunas of limited stratigraphic worth, carbon- and strontium-isotope stratigraphy is here used to date critical events in the history of these carbonate platforms. Stratigraphic definition using these chemostratigraphic methods readily allows resolution to stage level and, locally, to zonal level, by comparison with well-calibrated reference curves derived from pelagic-carbonate sections containing planktonic micro- and nannofossils. Chemostratigraphy allows accurate dating of critical events in platform evolution such as the synchronous development of oolite and the deposition of black shales. Drowning is demonstrated to be sequential, in that the platforms drowned in the order in which plate-tectonic transport moved them northward into peri-equatorial latitudes.

## CRETACEOUS SHALLOW-WATER CARBONATE FACIES AND FAUNAS OF PACIFIC GUYOTS

The Cretaceous shallow-water facies found on north Pacific guyots are dominantly peritidal in nature. Principal facies recognized include cross-bedded oolitic, pelloidal, and oncolitic grainstones, locally with keystone vugs; wackestones and packstones containing algal-microbial (cyanobacterial) mats, bird's-eye vugs, desiccation cracks and calcretes, and black pebbles arranged in meter-scale sedimentary cycles indicating both deepening- and shallowing-upward trends. Pseudomorphs of gypsum have been recognized locally. Porosity can attain 40 percent in some lithologies, and the degree of lithification is highly variable.

Sponge, stromatoporoid, rudist, and coral bioherms occur locally, and these faunal constituents commonly occur as sand-sized or larger grains; other common faunal elements include echinoderms, red and green algae, gastropods, bivalves, bryozoans, large and small benthonic foraminifera, and ostracodes (Grötsch and Flügel, 1992; Strasser and others, 1995; Jenkyns and Strasser, 1995; Arnaud, Flood, and Strasser, 1995; van Waasbergen, 1995; Jansa and Arnaud Vanneau, 1995; Ogg, Camoin, and Jansa, 1995; Camoin and others, 1995). Planktonic foraminifera and nannofossils are rare (Erba and others, 1995; Sliter, 1995). Dolomitization occurs in the lower reaches of some sections, and clay-rich facies become more significant close to the contact with basaltic basement. Environments recognized include submarine shoals and beaches of skeletal, pelloidal, and oolitic sand; lagoons and marshes, periodically hypersaline, containing more clay-rich sediment; and inter- to supratidal flats containing finer-grained deposits. Paleo-water depths were typically in the range of a few meters.

The general facies associations compare closely with those of the present-day Bahama Banks (for example, Newell and others, 1959; Purdy, 1963; Bathurst, 1975) with

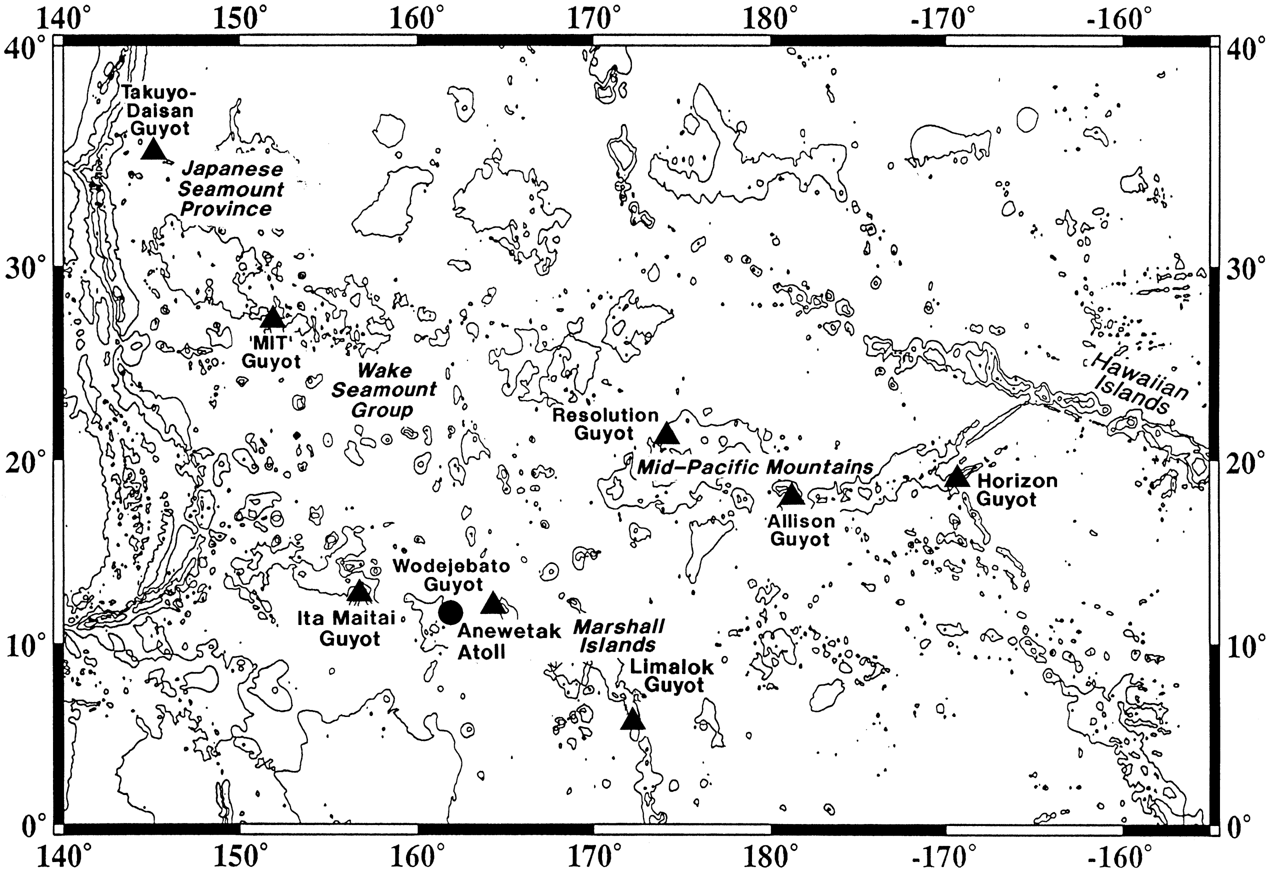


Fig. 1. The North Pacific, showing location of investigated atolls (filled circle), guyots (filled triangles), and principal seamount groups. Bathymetric contours at 2km. Allison, Horizon, and Resolution Guyots are part of the mid-Pacific Mountains; Limalok and Wodejebato Guyots and Anewetak Atoll lie in the region of the Marshall Islands; Ita Maitai Guyot is one of a group of seamounts lying to the west of the Marshall Islands; 'MIT' Guyot is an isolated feature close to the Wake Seamount Group, and Takuyo-Daisan is part of the Japanese Seamount Province.

the difference that the carbonate platforms/guyots sat and sit on oceanic crust in the center of a large ocean, whereas the Bahama Banks are installed on the Atlantic margin rooted on attenuated continental or transitional crust (Mullins and Lynts, 1977; Freeman and Ryan, 1987).

## METHODOLOGY

Samples of Cretaceous shallow-water carbonate from various guyots were sampled at the Core Repository in College Station and added to the shipboard collections already held in Oxford and Cambridge. Additional samples were obtained from the Core Repository at Scripps Institution of Oceanography. In Oxford, bulk limestone samples were analyzed for mineralogy using X-ray diffractometry and carbon- and oxygen-isotope ratios using a Prism mass spectrometer, as described in detail by Jenkyns (1995): the precision for both carbon- and oxygen-isotope ratios was better than 0.1 permil, PDB. Measurements on material from Wodejebato were made at the University of Michigan, using a Finnigan Mat 251 mass spectrometer with a Keil Carbonate device (precision: $\delta^{13}C \approx 0.01$ permil, $\delta^{18}O \approx 0.04$ permil, PDB).

Strontium-isotope ratios of material from Wodejebato, “MIT,” and Takuyo-Daisan Guyots were determined in Cambridge using a VG Sector 54 instrument, using the same techniques described in Wilson and others (1995). Microsamples of cements were also analyzed comprehensively for their isotopic chemistry in order to assess the possible impact of diagenesis on development of a reliable chemostratigraphy. The new data were added to the preliminary strontium-isotope analyses of material from Resolution and Allison Guyots initially undertaken at Oxford University and the University of North Carolina as described in detail in Jenkyns and others (1995) and Paull and others (1995). $^{87}Sr/^{86}Sr$ ratios of samples from Horizon Guyot and Ita Maitai Guyot were also analyzed at Oxford.

In this study, to ensure comparability, all data have been normalized to an $^{87}Sr/^{86}Sr$ value of NBS 987 = 0.710250, this being the long-term average determined in several different laboratories around the world for this standard (value determined at North Carolina over period during which initial analyses of Allison and Resolution Guyot were undertaken = 0.710250 ± 22, N = 104; value determined at Oxford over period analyses of Resolution Guyot were undertaken = 0.710260 ± 20, N = 27); values determined at Cambridge for the NBS 987 standard over the two periods during which analyses of Allison, Resolution, “MIT,” and Takuyo-Daisan Guyot were undertaken = 0.710251 ± 21, N = 139; and NBS 987 = 0.710253 ± 16, N = 76). Error bars in all graphs are shown as $\pm 20 \times 10^{-6}$ for all analyses unless precision was worse than this, in which case the greater value has been given.

## CHEMOSTRATIGRAPHY AND GUYOT EVOLUTION

This paper presents high-resolution comparative chemostratigraphy (C and Sr isotopes) for four Cretaceous drowned carbonate platforms (guyots) in the north Pacific Ocean drilled during ODP Legs 143 and 144. The guyots in question are: Resolution, Allison, “MIT,” and Takuyo-Daisan. New isotopic data are also presented for Horizon Guyot (DSDP Leg 17) and Ita Maitai (DSDP Leg 20) and published stratigraphies from Wodejebato and Limalok Guyots (ODP Leg 144) are reviewed and incorporated into a regional study. The location of these guyots is shown in figure 1.

Classic biostratigraphic techniques are of limited use in dating shallow-water guyot sediments because of the general lack of age-diagnostic faunas and floras. The common benthonic foraminifers in the peritidal deposits are facies fossils with ranges established half a world away in southern Europe (Arnaud-Vanneau and Sliter, 1995; Arnaud Vanneau and Premoli Silva, 1995); and planktonic foraminifera and nannofossils are confined to discrete horizons and commonly are badly preserved. Consequently, chemostratigraphy offers a more reliable means of pinpointing the timing of major events in Cretaceous guyot history because high-resolution reference curves now exist for the intervals in question (C-isotopes: Weissert and Lini, 1991; Erbacher, 1994; Marconi and others, 1994; Erbacher and Thurow, 1997; Ferreri and others, 1997; Weissert and others, 1998; Menegatti and others, 1998; Sr-isotopes: Jones and others, 1994; Bralower and others, 1997). The carbon-isotope reference curves are based on analyses of pelagic deep-sea sections, dated using nannofossils and planktonic foraminifera, in the Southern Alps and Apennines, Italy and the Swiss pre-Alps. The Sr-isotope curve of Jones and others (1994) derives from belemnites and oysters from Great Britain that are dated in terms of north European ammonite stratigraphy, that of Bralower and others (1997) from deep-sea oceanic (DSDP/ODP) sections that are dated with planktonic foraminifera and nannofossils. Relative to coeval pelagic sections, carbonate-platform sequences from guyots are stratigraphically expanded, which potentially affords a more detailed chemostratigraphic signature.

The events affecting guyots, before they became such, include synchronous deepening and shallowing, locally to emergence, across the carbonate platform, development of characteristic facies such as oolites, cyanobacterial laminites, calcretes, deposition of carbon-rich black shales, and the registering of strontium-, carbon, and possibly oxygen-isotope excursions. The most significant event affecting all platforms is the phenomenon of drowning, equivalent to guyot formation, whereby a shallow-water area (bank or carbonate platform) was unable to produce carbonate sediment rapidly enough to offset increase in water depth. Drowning resulted in the sediment-water interface being lowered into progressively deeper water, ultimately to accumulate pelagic sediment.

Two principal hypotheses have been recently entertained for the demise of these Pacific carbonate platforms: (1) “Death-by-Emergence-and-Submergence” which assumes that drowning was initiated by a short-term relative sealevel fall that left the platform high and dry followed by rapid relative deepening that outpaced subsequent carbonate production (Winterer and Sager, 1995; Winterer and others, 1995); (2) “Death-in-the Tropics” which assumes that the northward conveyor-belt motion of the Pacific Plate brought the platforms into peri-equatorial waters oceanographically unfavorable to skeletal and inorganic carbonate production (Larson and others, 1995; Wilson and others, 1998).

## THE ROLE OF METEORIC-WATER DIAGENESIS

In order for carbon isotopes in these shallow-water carbonate sequences to have stratigraphic worth, the role of meteoric-water diagenesis, in so far as it involved fluid interaction with organic-rich soils, must have been minor or at least involve the addition of a constant overprint throughout any one section. Studies on Pleistocene Bermudian and circum-Caribbean limestones by Gross (1964) revealed, in the progressively lithifying carbonates, the increasingly negative values of $\delta^{18}O$ and $\delta^{13}C$ resulting from the dissolution of skeletal aragonite under the influence of rain water containing absorbed atmospheric and soil-derived $CO_2$, and subsequent precipitation of low-magnesian calcite cement (reviews in Bathurst, 1975; Hudson, 1977; James and Choquette, 1984; Moore, 1989). These early studies of “Caribbean-style” diagenesis were, of course, undertaken on oceanic islands and carbonate banks subjected to major Pleistocene-Recent glacio-eustatic changes in sealevel. At times of low sealevel stands the carbonate cap would have been left high and dry, and the processes of meteoric-water diagenesis, lithification, and karstification could have been intense with great potential for geochemical change (for example, Lohmann, 1988).

In the early to mid-Cretaceous “greenhouse” world, where the presence of significant ice-caps is not generally accepted (for example, Crowell, 1982; Schlanger, 1986; Hallam, 1992; Frakes, Francis, and Syktus, 1992), eustatic sealevel changes forced by changes in the volume of ocean basins would have been perhaps as much as three orders of magnitude slower than glaciation-deglaciation (for example, ~2.0m/my, Schlager, 1981; Pitman and Golovchenko, 1983; Dewey and Pitman, 1998). Sealevel during this time is generally depicted as undergoing a long-term rise (Hancock and Kauffman, 1979; Haq, Hardenbol, and Vail, 1988; Hancock, 1989). Nonetheless, if the premise of a generally ice-free Cretaceous world is accepted, repeated dramatic and rapid relative sealevel falls promoting intensive meteoric-water diagenesis seem intrinsically unlikely, particularly in the center of a major ocean far removed from a continental margin. Inversion of this argument would lead to the prediction that an absence of meteoric-water cements in Cretaceous guyot carbonate sequences implies that major eustatic falls in sealevel were of negligible importance during the time span represented by these shallow-water carbonates. Minor meteoric-water diagenesis is, however, to be expected because the facies on guyots include those of intertidal and supratidal origin, of which the most extreme examples are the calcretes recorded from Resolution Guyot (Strasser and others, 1995). Some meteoric-water cemention has also been suggested for the upper part of the shallow-water section on Wodejebato Guyot, on the basis of carbon- and oxygen-isotope data (Camoin and others, 1998).

Data from calcitic cements and bulk sediment from the top 150 m of Allison, "MIT," Resolution, Takuyo-Daisan, and Wodejebato Guyots are illustrated in figure 2 and compared with Pleistocene cements and bulk sediment from Anewetak Atoll (Gross and Tracey, 1966; Saller and Moore, 1989, 1991). Clear compositional differences are apparent. These Pleistocene limestones are interpreted as having formed under the influence of meteoric-water diagenesis and clearly have a distinctly different isotopic composition with considerably lower values of $\delta^{18}O$ and $\delta^{13}C$. This is all the more remarkable because the mean $\delta^{18}O$ value of sea water during the Pleistocene would have been greater than during the Cretaceous, due to the build-up of relatively $^{16}O$-rich Antarctic ice during the Neogene and Quaternary (for example, Shackleton and Kennett, 1975; Hudson and Anderson, 1989). The striking difference between Pleistocene and Cretaceous cements, however, needs to be viewed with the understanding that Cretaceous platform carbonates, prior to meteoric-water diagenesis, may have possessed less metastable aragonite than their Pleistocene counterparts (Wilkinson, 1979; Sandberg, 1985; compare Milliman and others, 1993).

Marine cements, identified as such on the basis of their petrography and high magnesium contents ($\geq$7 mol percent $MgCO_3$) and rudistid aragonite from the upper Cretaceous (Maastrichtian) of Wodejebato Guyot, have $\delta^{18}O$ values close to those of bulk sediment from Allison, Resolution, "MIT," and Takuyo-Daisan Guyots (Wilson and Dickson, 1996; Wilson and others, 1998; fig. 2), again implying that the latter have not been isotopically altered by reactions with meteoric water. Röhl and Strasser (1995), in their study of cements from Allison and Resolution Guyots, presented isotopic data showing that most cements possessed signatures located "on a path from marine phreatic to burial," although they also assumed significant meteoric-water diagenesis. However, in their study of closely comparable facies, Haggerty and van Waasbergen (1995) noted that they could find no isotopic evidence for pervasive meteoric-water influence in the Cretaceous shallow-water carbonates of "MIT" and Takuyo-Daisan Guyots. Cretaceous guyot carbonates appear compositionally to be dominated by mixtures of skeletal components and early marine cements formed in warm shallow water and later cements formed in deeper colder water. These later cements possibly developed at bathymetric levels close to or below the thermocline to judge from the comparison with the isotopic signatures of deep-sea benthonic foraminifera from Cretaceous Pacific sites (fig. 2).

Oxygen-isotope values of shallow-water carbonates are affected, not only by the precipitation of various marine and minor meteoric-water cements but also by dissolution-precipitation reactions at progressively higher burial temperatures. These processes

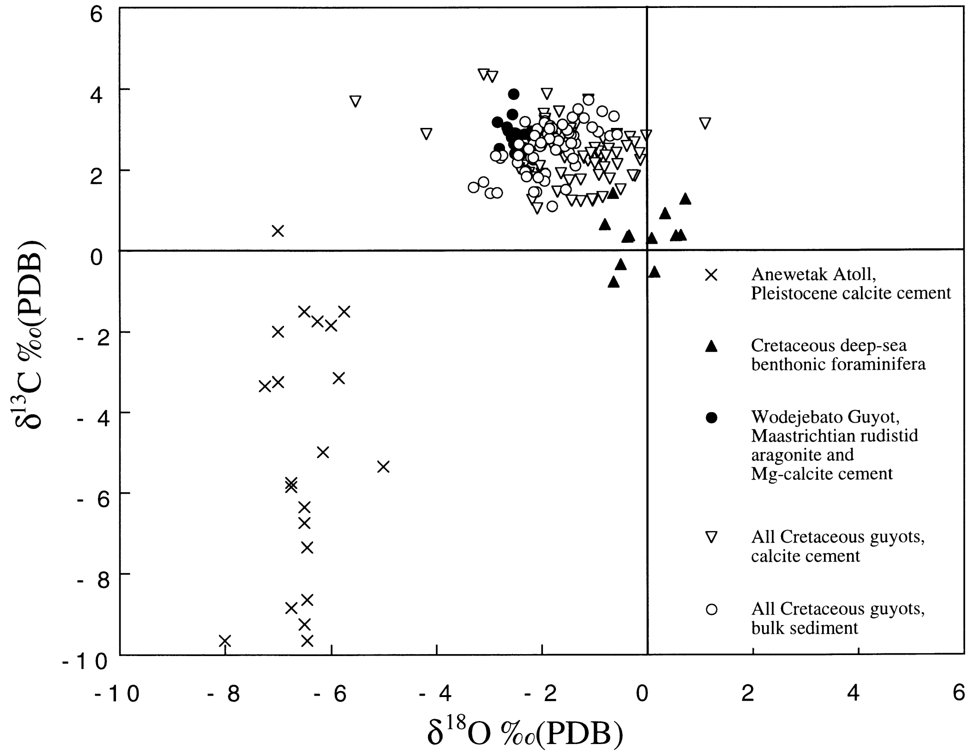


Fig. 2. Stable carbon- and oxygen-isotope data (referenced to the Pee Dee belemnite [PDB] carbonate standard) from the upper 150 m of the Cretaceous shallow-water carbonate platforms on Resolution, Allison, Wodejebato, "MIT," and Takuyo-Daisan Guyots (fig. 1) compared with Pleistocene cement data from Anewetak (Saller and Moore, 1991). Modified from Wilson and others (1998). Benthonic foraminiferal data from Pacific Cretaceous pelagic sections are after Douglas and Savin (1973, 1975). Note that the composition ($\delta^{18}O$) of those cement and skeletal elements retaining original metastable mineralogy (high-magnesian calcite, aragonite) indicates relatively high ambient temperatures, whereas the (low-magnesian) calcite cements suggest precipitation in somewhat cooler water, possibly close to or below the thermocline, and the benthonic foraminifera have registered cold sea-floor temperatures. Pleistocene cements from Anewetak, resulting from meteoric-water diagenesis, are compositionally very different to Cretaceous cements from guyots.

further conspire against unambiguous deciphering of stratigraphic change in $\delta^{18}O$ values (Scholle and Arthur, 1980; Land, 1980; Dickson and Coleman, 1980; Scholle and Halley, 1985).

Isotopic data suggest that the impact of soil-derived $CO_2$ on the guyot sediments during periods of diagenetic exposure is relatively small. Even if certain horizons developed when emersion persisted for great lengths of time, the isotopic signature of such would be a stratigraphically restricted phenomenon. Thus the carbon-isotope signature of these sediments should dominantly reflect that of primary marine bicarbonate to which has been added some later burial cement of modified marine origin. In other words, shallow-water guyot carbonates should record major changes in the carbon-isotope composition of the ocean-atmosphere system. As demonstrated below, this is indeed the case because major features in the Cretaceous carbon-isotope curve, documented from Tethyan and Atlantic sections, are reproduced in Pacific guyot carbonates (Jenkyns, 1995).

Major features and absolute values of $^{87}Sr/^{86}Sr$ compare well with reference curves established with diagenetically screened belemnites and oysters from Great Britain

(Jones and others, 1994; Jenkyns, 1995). Departures from this ideal are recognized by values that plot away from a consistent trend defined by the majority of data points. In their study of the Tertiary shallow-water carbonates of Anewetak, Quinn, Lohman, and Halliday (1991) demonstrate that both open- and closed-system diagenesis (solution of aragonite and precipitation of low-magnesium calcite, inversion of high-magnesian calcite to low-magnesian calcite) preserve the original $^{87}$Sr/$^{86}$Sr ratios unless "foreign" strontium has been introduced. Only if fluids were to be transported over considerable stratigraphic distance across unconformities might the stratigraphic value of the Sr-isotope values be compromised. Data from Anewetak and Kita-daito-jima atoll in the Philippine Sea show that the Neogene Sr-isotope curve, in terms of shape and absolute values, compares extremely closely with that generated from deep-sea pelagic oozes and chalks (Ludwig and others, 1988; Saller and Koepnick, 1990; Quinn, Lohman, and Halliday, 1991; Ohde and Elderfield, 1992).

In conclusion, it is apparent from previous studies that Cretaceous guyot carbonates potentially contain useful stratigraphic information in terms of their bulk carbon- and strontium-isotope values: the interpretation of oxygen-isotope data is open to debate.

## STRATIGRAPHIC ERROR

Stratigraphy of the guyots is arrived at by interpretation of isotopic data plotted against depth and comparison with reference curves from biostratigraphically well-dated sections. Replicate analyses of a number of bulk carbonate samples from the guyots showed that Sr-isotope ratios are all within error; analytical and/or compositional variability is hence thought to be of little significance. As argued above, the impact of diagenesis is apparently minor. However, because absolute values of both carbon and strontium isotopes may be compromised by diagenesis to some degree, at least locally, it is the shape of the curves rather than the absolute values attained at any given point that may be the most diagnostic feature: there do appear to be slight but systematic stratigraphical differences in $^{87}$Sr/$^{86}$Sr ratios from carbonates of equal age on different guyots, even though values lie within error limits.

Chemostratigraphic integrity is maintained by avoiding clay-rich lithologies and those containing more than a trace of dolomite, which could potentially give non-stratigraphic values of both carbon and strontium isotopes, as discussed by Jenkyns (1995) and Jenkyns and others (1995). Samples containing more than 3 percent dolomite, estimated by comparison with X-ray diffratograms of known dolomite-calcite ratios, have hence been eliminated from use in the isotope curves, as has the one sample containing phosphate. Dolomite is only abundant in the deeper levels of the section through Resolution Guyot. Furthermore, data points deriving from samples that lie close to the basaltic basement may have inherited strontium from the upper mantle and are hence suspect as stratigraphic indices. Samples that are deemed suspect are not included in the chemostratigraphic profiles, but there is no rigorous means of assessing exactly where in the section the influence of exotic strontium may be lost.

Stratigraphic uncertainties are also associated with the reference curves. The data of Jones and others (1994) through the Lower Cretaceous (Ryazanian through Albian intervals) derive from skeletal calcite (belemnites, oysters) collected against a stratigraphy calibrated by the north European (Boreal) ammonite zonation. In contrast, the data of Bralower and others (1997) on the Barremian through Turonian interval derive from a largely Tethyan nannofossil and planktonic foraminiferal stratigraphy. The problem of stratigraphic mismatch between zones and stages defined on different faunal/floral criteria is addressed by Bralower and others (1997). Wherever possible in this study, the Sr-isotope data of Bralower have been used as the primary reference curve for dating purposes. Dating of the uppermost surface of the shallow-water sections yields the oldest estimates for the age of platform drowning, but several lines of evidence suggest that erosion-induced uncertainties in these estimates are relatively minor (Wilson and others, 1998).

In order to encapsulate all the above sources of uncertainty, the dating of the drowning surface of each guyot has generally been fixed with an error bar of ±2 Ma.

## CHEMOSTRATIGRAPHY OF RESOLUTION GUYOT, MID-PACIFIC MOUNTAINS

*Carbon and oxygen isotopes.–* The carbon- and oxygen-isotope stratigraphy of Resolution Guyot, plotted against facies (symbols used shown in fig. 3), is shown in figure 4. The level of white dolomitized peloidal grainstone between about 1250 to 1300 m below sea floor (mbsf) has been dated, on the basis of strontium-isotope ratios, as early Tertiary in age (Flood and Chivas, 1995), and hence the Sr-isotope data from this lithology are not included in the profile given in figure 5.

The highest oxygen-isotope values are found in the upper 300 m of section (upper Albian). The oxygen-isotope profile shows a general trend of decreasing $\delta^{18}O$ values with depth, a common pattern in carbonate rocks that may be related to burial diagenesis at progressively greater temperatures in the presence of a continuously evolving pore fluid (Land, 1980; Scholle and Halley, 1985; Marshall, 1992). The saw-tooth pattern that is superimposed upon this overall trend involves some distinct negative excursions of up to 1 permil, some of which correlate with similar negative excursions in the carbon-

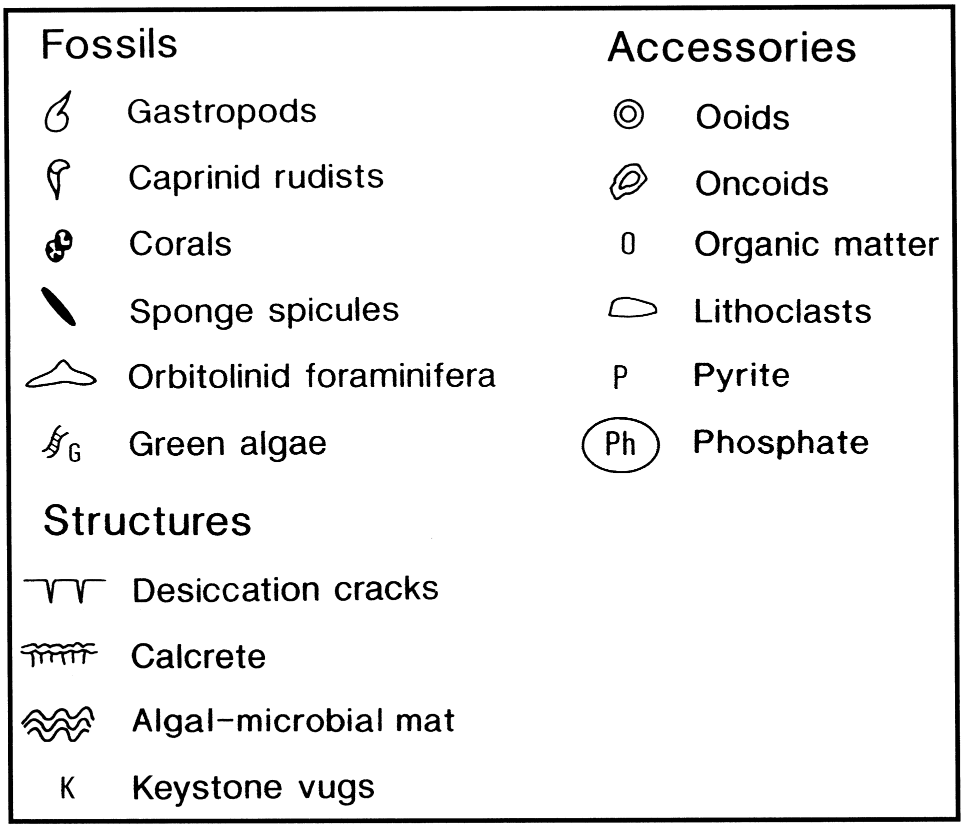


Fig. 3. Symbols used in lithostratigraphic columns in figures 4, 6, 7, 9, 11, and 12.

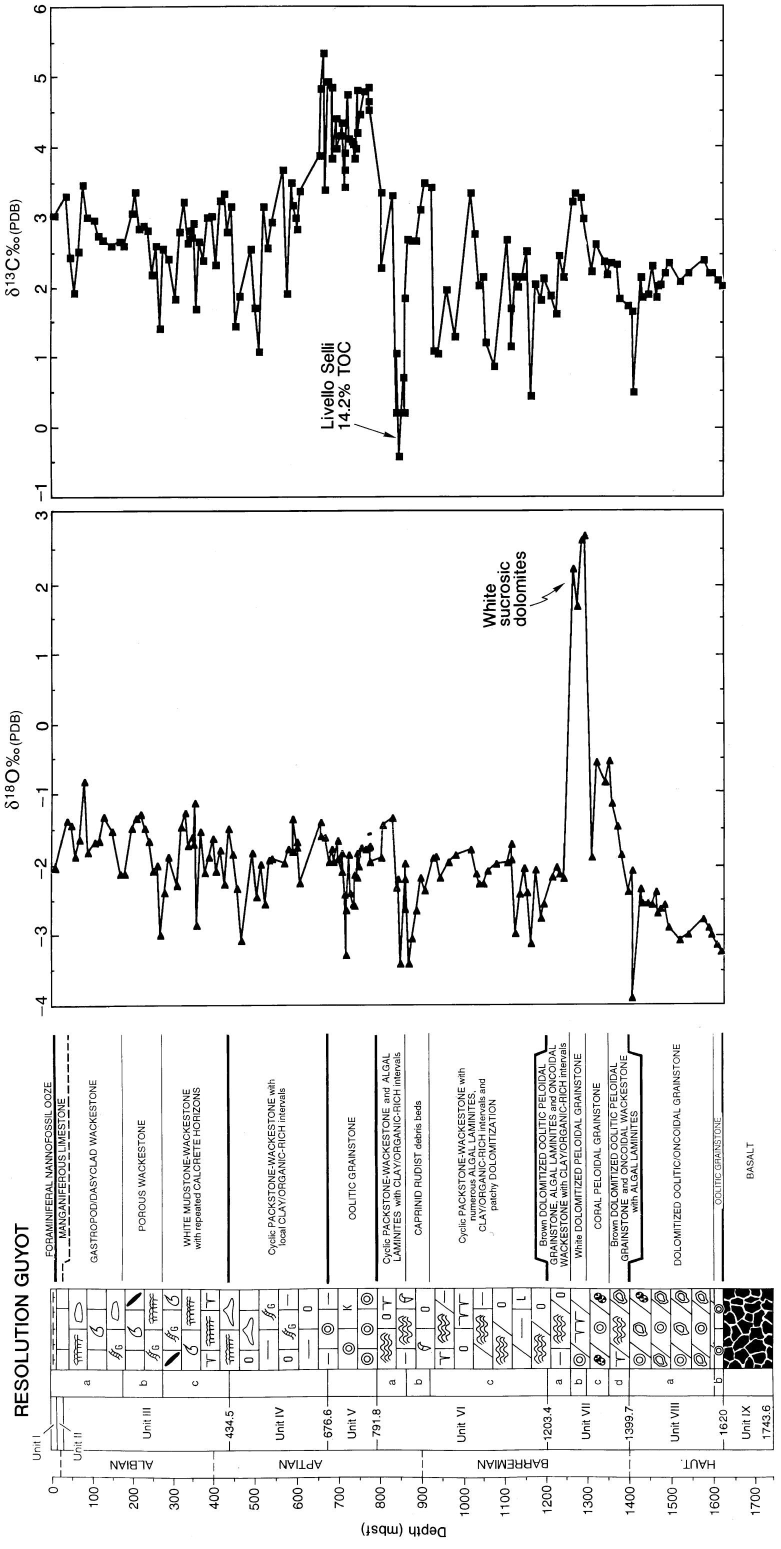


Fig. 4. Carbon- and oxygen-isotope stratigraphy and lithostratigraphy of Cretaceous platform carbonates, Resolution Guyot, mid-Pacific Mountains. Data (referenced to the Pee Dee belemnite [PDB] carbonate standard) are derived from bulk samples only. The cluster of relatively high $\delta^{18}O$ values reflects the presence of late diagenetic sucrosic dolomite. The "Livello Selli" or Selli Level is a laminated organic-rich black shale deposited during the early Aptian oceanic anoxic event. Modified from Jenkyns (1995).

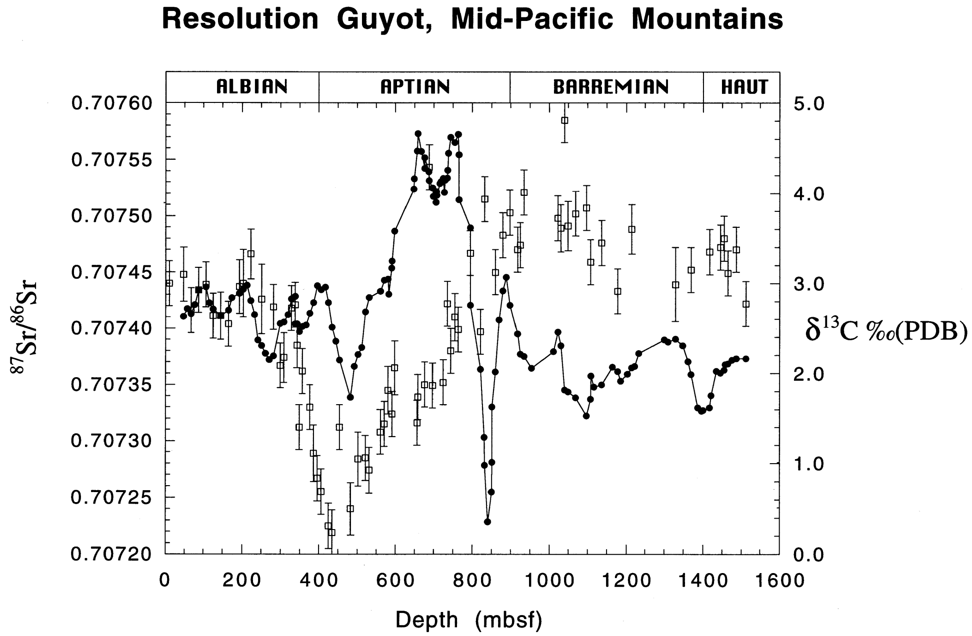


Fig. 5. Strontium- and carbon-isotope ($\delta^{13}C$ PDB) stratigraphy of Cretaceous platform carbonates, Resolution Guyot, mid-Pacific Mountains. Data are derived from bulk samples only; values from sucrosic dolomites are excluded because their $^{87}Sr/^{86}Sr$ ratios suggest a Tertiary age (Flood and Chivas, 1995). Carbon-isotope data (filled circles) have been smoothed with a five-point moving average. Significant features are a pronounced negative followed by a positive $\delta^{13}C$ excursion with a characteristic bifurcate peak in the early to mid-Aptian and a minimum in $^{87}Sr/^{86}Sr$ values close to the Aptian-Albian stage boundary. Where values in the carbon-isotope curve change abruptly (for example, at about 820 and 640 mbsf) hiatuses may be present, and the same holds for the strontium-isotope curve at around 400 mbsf. The onset and end of carbonate-platform deposition are dated as 128 ± 2 and 99 ± 2 Ma respectively, after translating the interpreted stratigraphy into the Gradstein and others (1994) timescale.

isotope profile; these may be explicable in terms of meteoric-water diagenesis affecting lithologies at these stratigraphic levels.

The carbon-isotope stratigraphy is characterized by a significant negative excursion from background values of 2 to 3 permil between sub-bottom depths of 1600 and 900 m to about −0.4 permil at a sub-bottom depth of about 840 m. This is followed upsection by an equally dramatic shift to values typically between 4 and 5 permil. Stratigraphically coincident with the position of this abrupt shift in the section from relatively low to relatively high $\delta^{13}C$ values is a level of marine laminated green to black carbon-rich shales. The positive excursion is characterized by two distinct maxima: 4.85 permil at 764 mbsf and 5.34 permil at 657 mbsf. The highest value attained (5.34 permil) is followed by values that decrease up-section to a background level of between 2 and 3 permil which define the upper parts of the section.

*Strontium isotopes.–* A relative minimum in strontium-isotope ratios ($^{87}Sr/^{86}Sr$ = 0.70720-0.70725) in the section through Resolution Guyot is achieved at around 425 to 435 mbsf (fig. 5).

*Guyot stratigraphy.–* The shallow-water carbonate sequence on Resolution Guyot has a thickness of some 1600 m. The combined carbon-isotope (smoothed) and strontium-isotope stratigraphy (fig. 5) is somewhat modified from that originally published by Jenkyns (1995) and Jenkyns and others (1995). In particular, the position of the Hauterivian-Barremian boundary is placed at 1400 mbsf, essentially presenting a compromise between the paleontological and strontium-isotope data (Winterer and Sager, 1995). Absolute-age determinations on basalts from the base of the section on Resolution Guyot yield values of 127.6 ± 2.1 Ma (Pringle and Duncan, 1995a), which falls just below the Barremian-Hauterivian boundary on the recent timescales of Obradovich (1993) and Gradstein and others (1994).

The position of the Aptian-Albian boundary on Resolution Guyot has also been modified from earlier publications in the light of the recent work of Bralower and others (1997), which accurately locates the position of the Sr-isotope minimum of these stages in the late Aptian. This stage boundary is now placed at 400 mbsf. There is a steep rise in the Sr-isotope curve beginning at around 450 mbsf, close to levels in the section where repeated calcrete levels developed, and it is suggested that there are numerous gaps in the section here (Jenkyns and others, 1995). Notably, the shape of the Sr-isotope excursion in the Bralower and others (1997) curve, which is calibrated against time rather than rock, is more symmetrical than that of Resolution Guyot. This is equally consistent with the presence of an incomplete sedimentary record in that part of the section lying between 450 and 300 mbsf.

As regards the major positive $\delta^{13}$C excursion, the relatively abrupt rise (about 820 mbsf) and fall (about 640 mbsf) in values, with cyclic packstone-wackestone facies, could be related to the presence of stratigraphic gaps. The most characteristic feature of this excursion namely the double-pronged $\delta^{13}$C 'spike', is diagnostic of the Aptian stage as initially defined by the analyses of Weissert and Lini (1991) and Weissert and Bréhéret (1991) from sections in the Southern Alps and Apennines of Italy and the Vocontian Trough in France.

A finer division of the Aptian was attempted by Jenkyns (1995), based on available carbon-isotope reference curves. Better-defined and calibrated curves from Tethyan pelagic sections now exist (Erbacher, 1994; Marconi, Wezel, and Longinelli, 1994; Erbacher and Thurow, 1997; Weissert and others, 1998; Menegatti and others, 1998). The principal features of these $\delta^{13}$C reference curves are as follows: the basal Aptian (*Globigerinelloides blowi* Zone) is characterized by relatively low $\delta^{13}$C values which increase abruptly through the interval characterized by the black shale of the Selli Level to reach a first peak in the *Leupoldina cabri* Zone and lowermost *Globigerinelloides ferreolensis* Zone; a decrease in values characterizes the rest of the *Globigerinelloides ferreolensis* Zone and values decline to a relative minimum in the *Globigerinelloides algerianus* Zone; $\delta^{13}$C values change little through the *Hedbergella trochoidea* Zone, then rise to a second peak in the *Ticinella bejaouaensis* Zone.

A detailed study of the carbon-isotope composition of wood and skeletal calcite from Aptian marine clastic sediments exposed in southern Britain reveals, however, at least three $\delta^{13}$C "spikes" in the isotopic profile of the stage (Gröcke, Hesselbo, and Jenkyns, 1999), creating a measure of ambiguity among the reference curves. A correlation between planktonic foraminiferal zones and part of the Aptian of Resolution Guyot, based on all these reference curves, is shown in figure 6. This scheme, representing a revision of Jenkyns (1995), is consistent with the strontium-isotope stratigraphy of Bralower and others (1997) which is resolved to zonal level. It seems likely that gaps in the upper Aptian stratigraphy of Resolution Guyot, around 400 mbsf (fig. 5), signify a loss to non-deposition or erosion of the carbonates that might carry characteristic high $\delta^{13}$C values (~4 permil in the *Ticinella bejaouaensis* Zone in European sections).

The top of the shallow-water carbonate section on Resolution Guyot, based on comparison of the Sr-isotope curve with the data of Jones and others (1994) and Bralower and others (1997), is placed close to the Albian-Cenomanian boundary (Jenkyns and others, 1995).

A summary history of shallow-water sedimentation on Resolution Guyot thus shows an onset during late Hauterivian and an end at around Albian-Cenomanian boundary time (128 ± 2 and 99 ± 2 Ma respectively on the Gradstein and others, 1994, timescale).

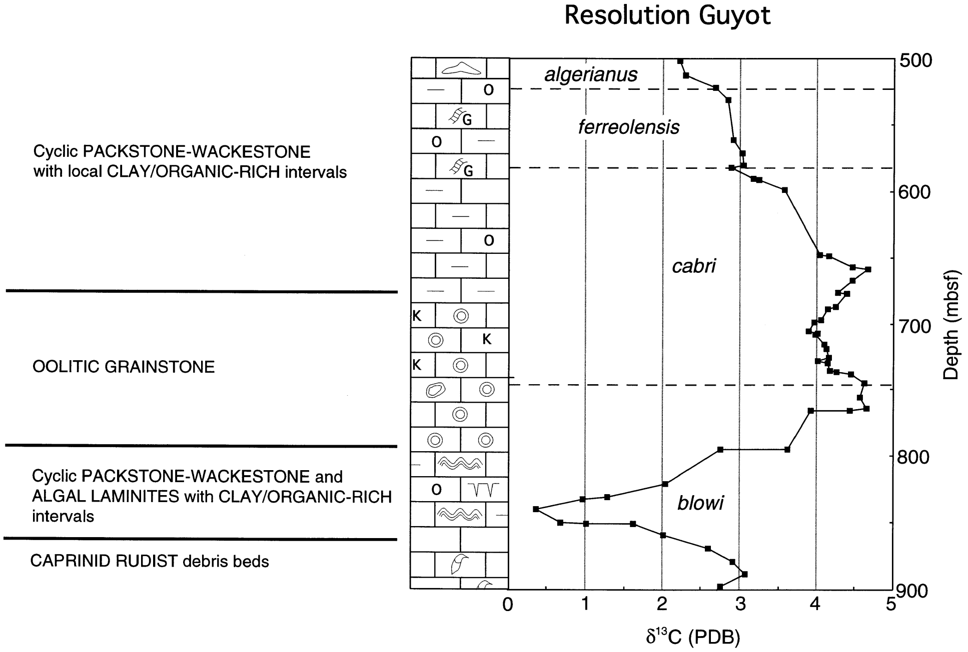


Fig. 6. Detail of part of the Aptian section through Resolution Guyot, with a suggested notional planktonic foraminiferal biostratigraphy calibrated against the smoothed carbon-isotope curve ($\delta^{13}$C PDB) of figure 4. The carbon-isotope reference curves for this proposed zonation derive from Tethyan pelagic sections described by Erbacher (1994), Marconi, Wezel, and Longinelli (1994), Erbacher and Thurow (1997), Weissert and others (1998), and Menegatti and others (1998) and are also consistent with strontium-isotope data calibrated against the reference curve of Bralower and others (1997). This suggested zonation differs from that suggested by Jenkyns (1995), but is not regarded as definitive.

## CHEMOSTRATIGRAPHY OF ALLISON GUYOT, MID-PACIFIC MOUNTAINS

*Carbon and oxygen isotopes.–* The carbon- and oxygen-isotope stratigraphy of Allison Guyot, plotted against facies, is shown in figure 7. Considerable scatter is present in the carbon-isotope data, although the majority of values lie between 2 and 3 permil; there are no diagnostic features as in the case of Resolution Guyot. A number of more negative excursions, some of which are correlative with lower $\delta^{18}$O values, are present in the section and may be diagenetic artifacts. Unusually low isotopic values from samples close to the base of the cored interval have probably been influenced by proximity to intercalated basaltic sills. The $\delta^{18}$O profile generally shows decreasing values with increasing depth, although values are relatively higher (close to $-1$ permil) in the 300 to 660 mbsf range (mid-Albian).

*Strontium isotopes.–* The Sr-isotope profile for Allison Guyot (fig. 8) shows a shift to more radiogenic Sr-isotope values from a minimum at the base of the cored interval. As with Resolution Guyot, clay and dolomite become more abundant in the lower part of the section, in this case below about 620 m, possibly compromising the stratigraphic integrity of Sr-isotopic values, even though samples containing these materials have been scrupulously avoided. Furthermore, proximity to intrusive igneous rocks may have altered original $^{87}$Sr/$^{86}$Sr values, because sediment found between the sills has particularly low Sr-isotope ratios (Jenkyns and others, 1995; not illustrated in fig. 8). However, unlike the samples from Resolution Guyot, the basal carbonates from Allison Guyot, up to a level of about 600 mbsf, contain relatively elevated concentrations of Fe and Mn and exhibit cathodoluminescence (Röhl and Strasser, 1995). If these elements are derived

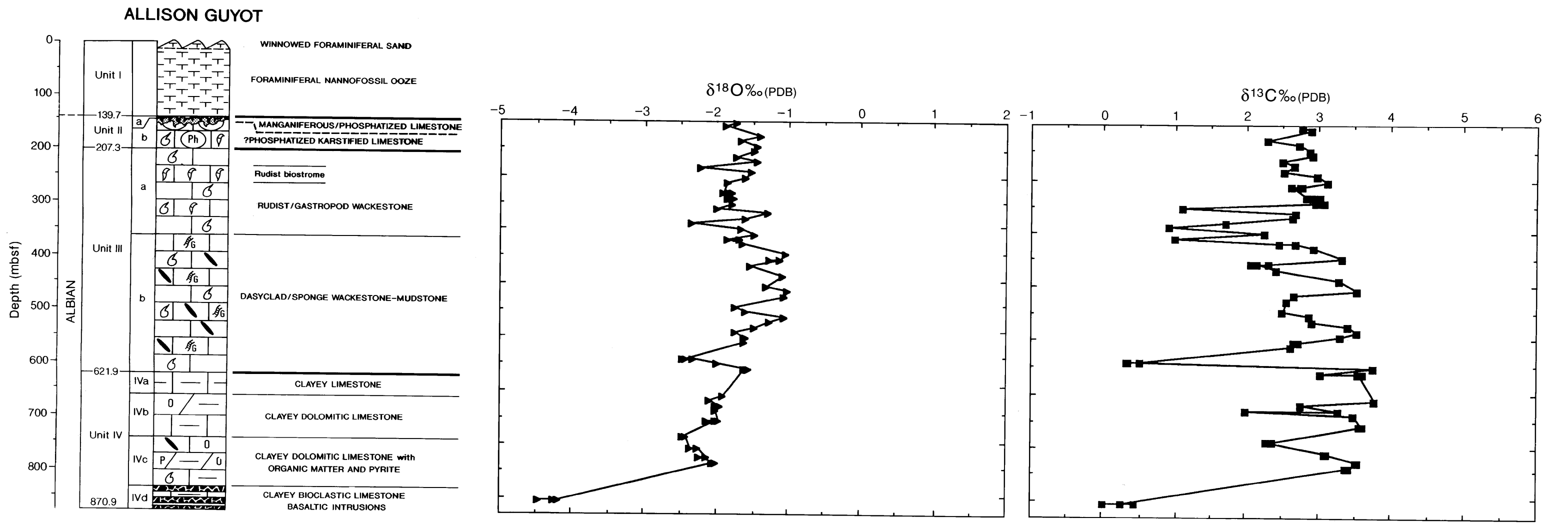


Fig. 7. Carbon- and oxygen-isotope stratigraphy and lithostratigraphy of Cretaceous platform carbonates, Allison Guyot, mid-Pacific Mountains. Data (referenced to the Pee Dee belemnite [PDB] carbonate standard) are derived from bulk samples only.

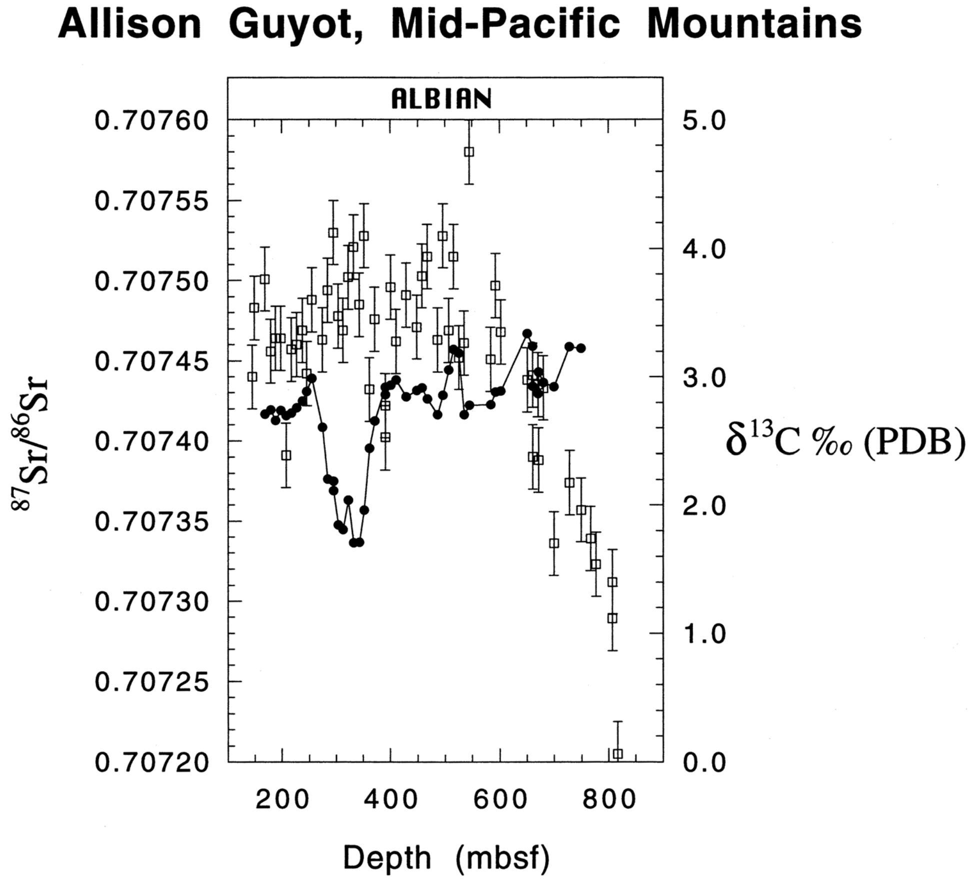


Fig. 8. Strontium- and carbon-isotope ($\delta^{13}C$ PDB) stratigraphy of Cretaceous platform carbonates, Allison Guyot, mid-Pacific Mountains. Data are derived from bulk samples only. Carbon-isotope data (filled circles) have been smoothed with a five-point moving average. A significant feature is the up-section rise in $^{87}Sr/^{86}Sr$ values followed by a plateau; such is characteristic of the Albian. The relatively steep rise in $^{87}Sr/^{86}Sr$ values at a depth of 700 to 800 mbsf is suggestive of the presence of hiatuses over this part of the section. The onset and end of carbonate-platform deposition are dated as 111 ± 2 and 99 ± 2 Ma respectively, after translating the interpreted stratigraphy into the Gradstein and others (1994) timescale.

from the volcanic basement, the possibility exists that the Sr-isotope ratios of the carbonates in this part of the section exhibit an upward-decreasing signature of mantle strontium (Jenkyns and others, 1995).

*Guyot stratigraphy.–* The total thickness of the shallow-water carbonate section of Allison Guyot, from its contact with basaltic sills below to its summit, is some 700 m. Unlike Resolution, "MIT," and Takuyo-Daisan Guyots, Allison Guyot possesses a substantial pelagic cap, namely 140 m of Paleocene-lower Oligocene foramininferal nannofossil ooze to sand (Sager, Winterer, Firth, and others, 1993). Available benthonic and planktonic foraminiferal data imply that the base of the section lies close to the Aptian-Albian boundary (Arnaud-Vanneau and Sliter, 1995; Sliter, 1995). This is in accord with the interpretation of the Sr-isotope data as primary, because the relatively low values could indicate the upper (that is, early Albian) limb of the negative excursion or trough characteristic of the late Aptian (Bralower and others, 1997).

The relatively steep increase in $^{87}Sr/^{86}Sr$ values at a depth of 700 to 800 mbsf is suggestive of the presence of unconformities over this part of the section. The absolute-age data from the basalts from Allison Guyot are compatible with the presence of older Albian strata. The best estimate for the age of the oldest igneous rocks drilled on Allison Guyot is 110.7 ± 1.2 Ma (Pringle and Duncan, 1995a) which would be placed by recent time scales in the earliest Albian (Obradovich, 1993; Gradstein and others, 1994). Although the basalts have been interpreted as intrusive, they are thought to have been emplaced penecontemporaneously with or just after the deposition of the enclosing clayey bioclastic limestone (Sager, Winterer, Firth, and others, 1993).

The carbon-isotope curve (fig. 8) shows no features that are reliably age-significant, although the negative excursion around 350 to 300 mbsf may ultimately prove to be a stratigraphically reproducible feature.

The top of the shallow-water carbonate section, based on comparison of the Sr-isotope curve with the data of Jones and others (1994) and Bralower and others (1997), is placed close to the Albian-Cenomanian boundary (Jenkyns and others, 1995). Such an age-assignment is in accord with data from dredge hauls across Allison Guyot, which recovered planktonic foraminifera, albeit associated with shallow-water grains, of latest Albian age, *Rotalipora appenninica* Zone (Grötsch and Flügel, 1992; Winterer and others, 1993).

A summary history of shallow-water sedimentation on Allison Guyot thus shows an onset during earliest Albian time and an end at around Albian-Cenomanian boundary time (111 ± 2 and 99 ± 2 Ma respectively on the Gradstein and others, 1994 timescale). Within the limits of error of strontium-isotope dating, cessation of shallow-water carbonate deposition can be judged to have taken place at approximately the same time on both Allison and Resolution Guyots.

## "MIT" GUYOT, NORTH PACIFIC

*Carbon and oxygen isotopes.*– The carbon- and oxygen-isotope stratigraphy of "MIT" Guyot, plotted against facies, is shown in figure 9. Some similarities to the profiles from Resolution Guyot are apparent, but note that the presence of a volcaniclastic-limestone breccia precludes the production of stratigraphically meaningful data from the middle of the sequence. In the base of the section, a bifurcate $\delta^{13}C$ positive excursion is present. Relatively high $\delta^{13}C$ values characterize both these peaks: 5.08 permil at 694 mbsf and 5.17 permil at 636 mbsf. Values generally decline above this stratigraphic level, apart from the case of a sample taken from just above the basalt/limestone breccia; values then peak again at 144 mbsf (3.4 permil), decrease to about 1 permil, then increase once again. The same general trend, with a two-pronged peak, is obtained if the isotopic data of Haggerty and van Waasbergen (1995) for 'MIT' Guyot are plotted on a vertical depth scale.

The oxygen-isotope profile shows relatively high values ($\delta^{18}O$ of $-2$ to $-1$ permil) close to the top of the section (middle Albian) and at a depth of 400 to 240 mbsf (upper Aptian).

*Strontium isotopes.*– If the two $^{87}Sr/^{86}Sr$ ratios from samples close to basaltic basement are discounted as being potentially altered from true stratigraphic values, the strontium-isotope profile (fig. 10) shows a decrease from around 0.70745 to below 0.70735 across the interval 700 to 300 mbsf. Stratigraphically higher, there is a flattening out of the curve before a rise in values beginning at around 230 mbsf to attain values between 0.70745 to 70750. This is the negative excursion, also seen in the section through Resolution Guyot.

*Guyot stratigraphy.*– The section of "MIT" Guyot comprises some 120 m of shallow-water limestone overlying basaltic basement, covered by about 300 m of a volcaniclastic limestone/basalt breccia, in turn capped by approx 350 m of limestone. The characteristic carbon-isotope excursion (fig. 10) dates the lowermost sediments as *Globigerinelloides blowi* Zone, lower Aptian, which is consistent with the recognition of the lower

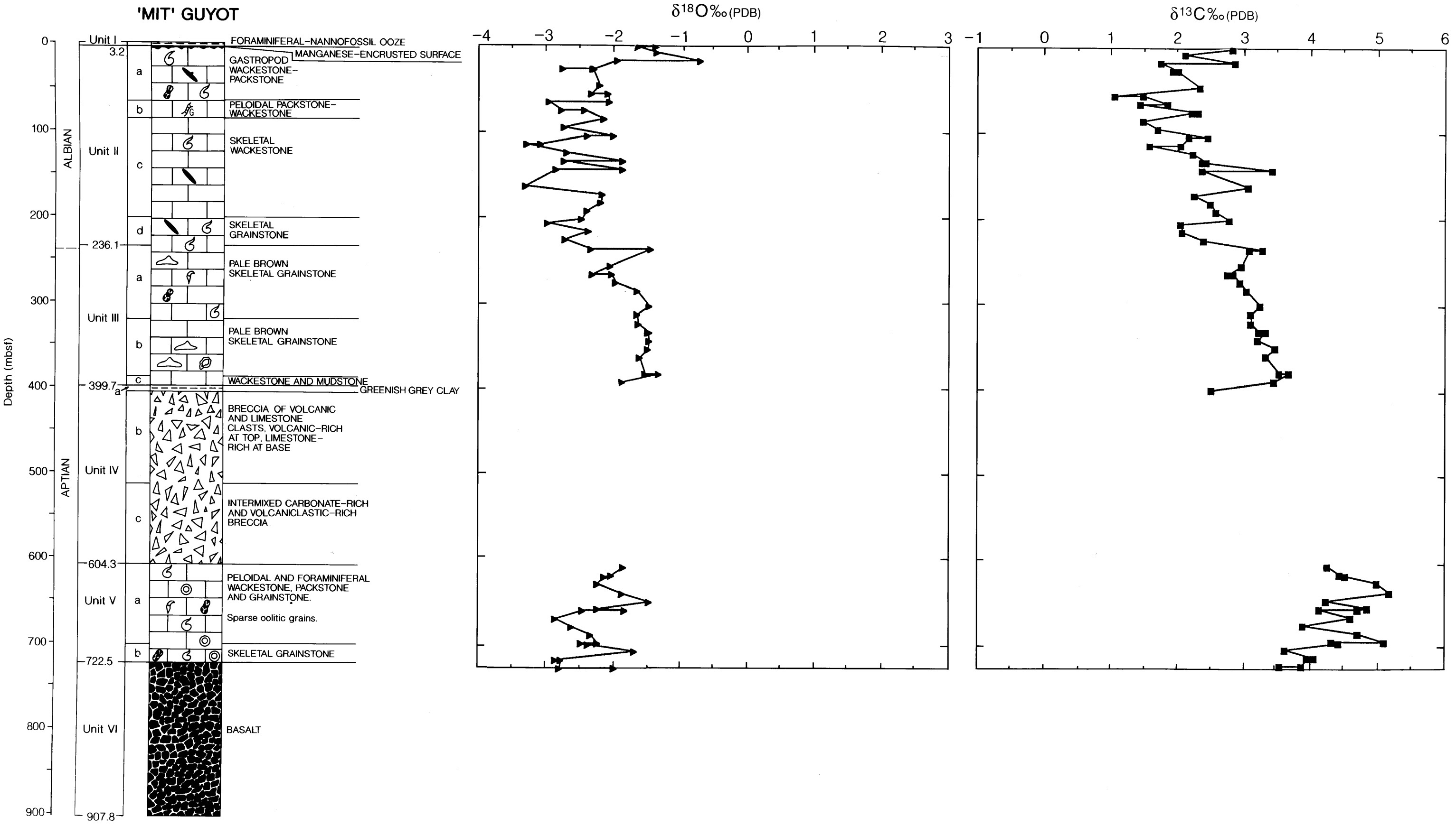


Fig. 9. Carbon- and oxygen-isotope stratigraphy and lithostratigraphy of Cretaceous platform carbonates, "MIT" Guyot, north Pacific. Data (referenced to the Pee Dee belemnite [PDB] carbonate standard) are derived from bulk samples only. Note the presence of a basalt/limestone breccia which interrupts the typical carbonate-platform succession. No isotopic data are included from this unit because of the unknown stratigraphical affinity of the carbonate clasts.

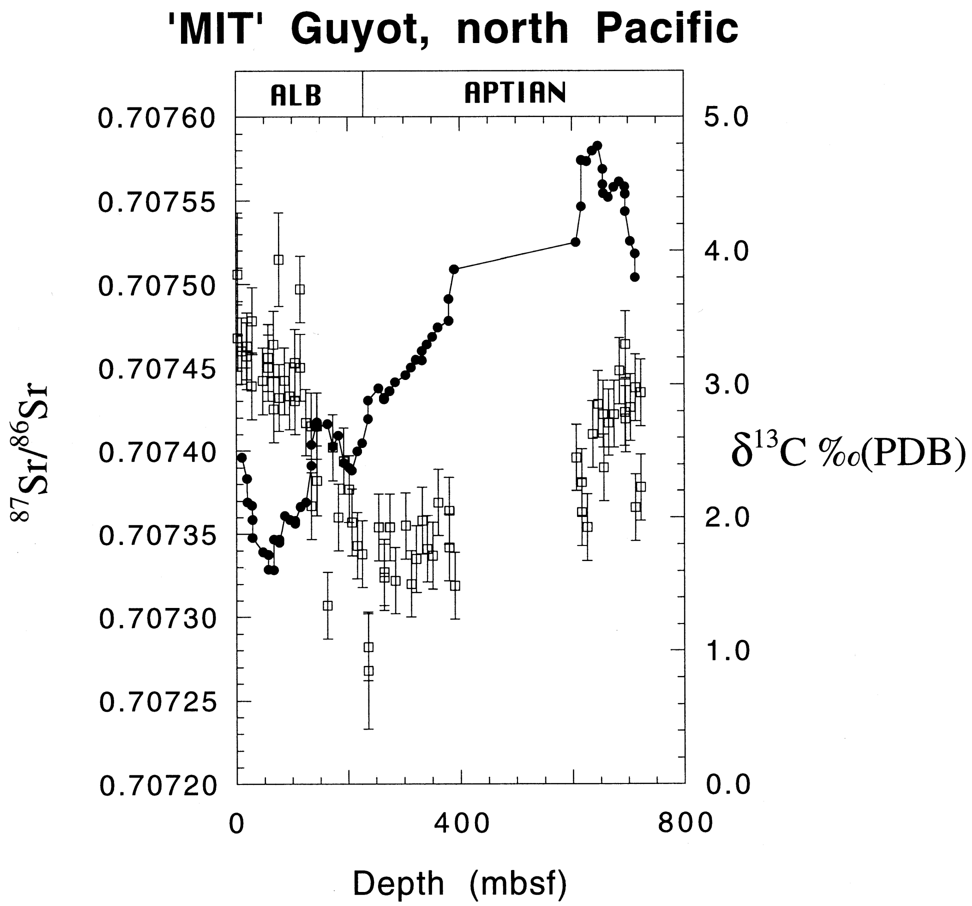


Fig. 10. Strontium- and carbon-isotope ($\delta^{13}C$ PDB) stratigraphy of Cretaceous platform carbonates, "MIT" Guyot, north Pacific. Data are derived from bulk samples only. Carbon-isotope data (filled circles) have been smoothed with a five-point moving average. Significant features are a pronounced positive $\delta^{13}C$ excursion with a characteristic bifurcate peak in the early to mid-Aptian and a minimum in $^{87}Sr/^{86}Sr$ values close to the Aptian-Albian stage boundary. The isotopic profiles compare closely with those of Resolution Guyot (fig. 3.). The onset and end of carbonate-platform deposition are dated as 119 ± 2 and 101 ± 2 Ma respectively, after translating the interpreted stratigraphy into the Gradstein and others (1994) timescale.

*Chiastozygus litterarius* nannofossil Zone (which corresponds with the mid- to upper part of the *Globigerinelloides blowi* Zone) at 700 mbsf (Erba, Premoli Silva, and Watkins, 1995; Erba and others, 1995). This stratigraphy is consistent with radiometric dating of a hawaiite from the upper lava sequence which gave an absolute age of 119.8 ± 0.8 Ma (Pringle and Duncan, 1995b), early Aptian on the Gradstein and others (1994) timescale.

The minimum in $^{87}Sr/^{86}Sr$ close to 250 mbsf (fig. 10) is placed close to the Aptian-Albian boundary, specifically in the latest Aptian, following Bralower and others (1997). Hence, the stage boundary itself on "MIT" Guyot is placed at 230 mbsf where values rise extremely steeply. This is not in accord with the placing of the stage boundary at 390 to 360 mbsf by Arnaud Vanneau and Premoli Silva (1995), based on their benthonic foraminiferal biostratigraphy. The plateau of Sr-isotope values at around 0.70745, characteristic of the data from the upper part of the platform-carbonate section from Resolution and Allison Guyots, is not present at the top of the section of "MIT." Therefore, cessation of shallow-water carbonate deposition is estimated as having occurred in early late Albian time (Wilson and others, 1998). This result is consistent with data from sparse planktonic microfossils in the uppermost levels of the platform carbonates (***Rotalipora subticinensis*** Subzone, about 20 mbsf below the platform top, Erba, Premoli Silva, and Watkins, 1995; Erba and others, 1995).

As with Resolution Guyot, a notional planktonic foraminiferal zonation for part of the Aptian of "MIT" Guyot, is shown in fig 11. This inferred zonation, which is based on the carbon-isotope Tethyan reference curves of Erbacher (1994), Marconi, Wezel, and Longinelli (1994), Erbacher and Thurow (1997), Weissert and others (1998), and Menegatti and others (1998) and the strontium-isotope curve of Bralower and others (1997) is broadly in accord with palaeontological data (Erba, Premoli Silva, and Watkins, 1995; Erba and others, 1995).

A summary history of shallow-water sedimentation on "MIT" Guyot thus shows an onset during early Aptian time and an end during early late Albian time (119 ± 2 and 101 ± 2 Ma respectively on the Gradstein and others, 1994, timescale).

### TAKUYO-DAISAN GUYOT, JAPANESE SEAMOUNT PROVINCE

*Carbon and oxygen isotopes.–* The carbon- and oxygen-isotope stratigraphy of Takuyo-Daisan Guyot, plotted against facies, is shown in figure 12. Values of $\delta^{13}C$ generally vary between 1.5 and 3.5 permil. Highest values are found between 100 and 25 mbsf (uppermost Aptian). The $\delta^{18}O$ values show the typical saw-tooth pattern that may reflect the local effect of diagenesis. The isotopic analyses made from bulk limestone samples

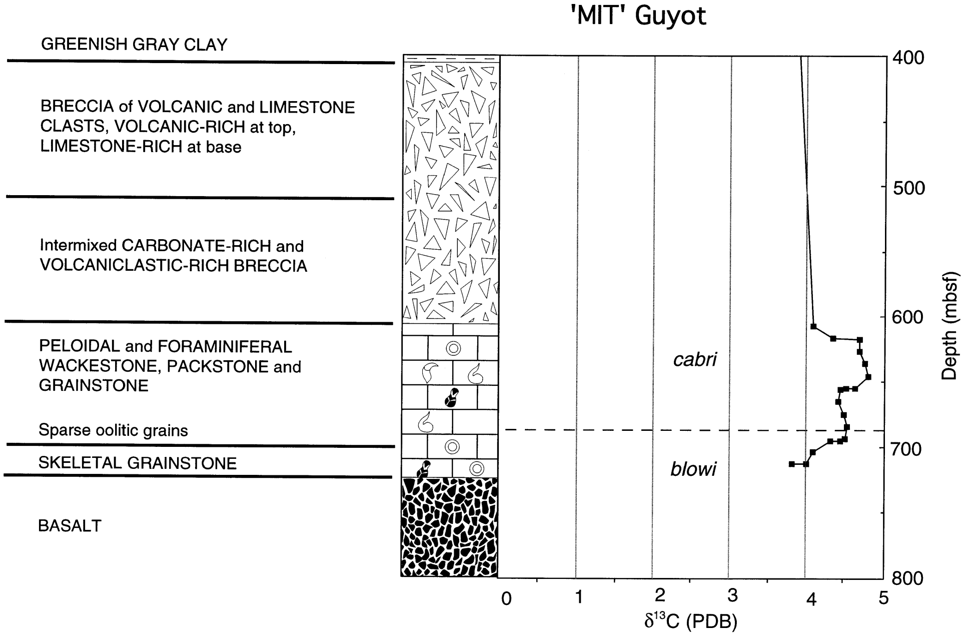


Fig. 11. Detail of part of the Aptian section through "MIT" Guyot, with a suggested notional planktonic foraminiferal biostratigraphy calibrated against the smoothed carbon-isotope curve ($\delta^{13}C$ PDB) of figure 9. The carbon-isotope reference curves for this proposed zonation derive from Tethyan pelagic sections described by Erbacher (1994), Marconi, Wezel, and Longinelli (1994), Erbacher and Thurow (1998), Weissert and others (1998), and Menegatti and others (1998). This proposed zonation is not regarded as definitive.

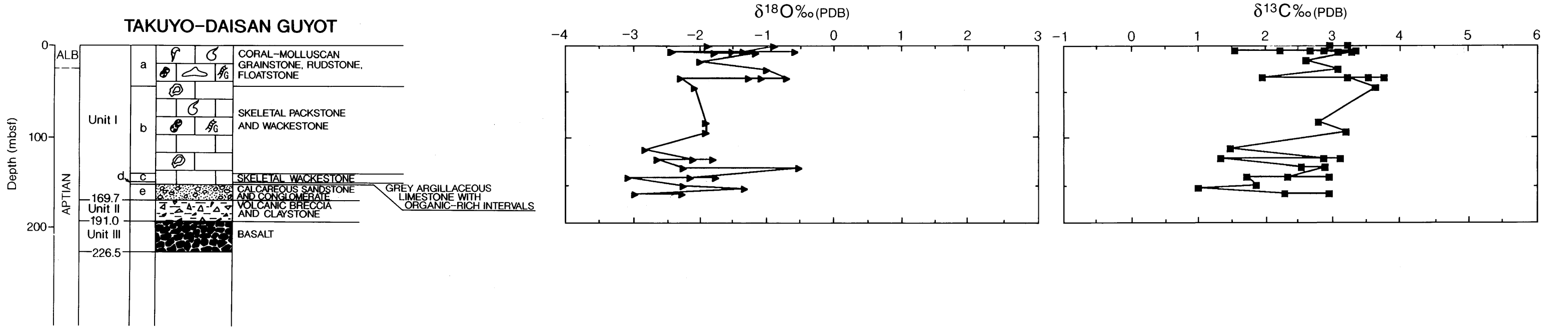


Fig. 12. Carbon- and oxygen-isotope stratigraphy and lithostratigraphy of Cretaceous platform carbonates, Takuyo-Daisan Guyot, Japanese Seamount Province. Data (referenced to the Pee Dee belemnite [PDB] carbonate standard) are derived from bulk samples only.

from this guyot by Haggerty and van Waasbergen (1995) are comparable with data presented here.

*Strontium isotopes.–* Ignoring values from samples close to basaltic basement, which may have incorporated non-seawater-derived strontium, the Sr-isotope profile (fig. 13) shows a clear declining trend from values of $^{87}Sr/^{86}Sr = 0.70735$ at around 140 mbsf to a minimum of between 0.70725 and 0.70730 at about 100 to 25 mbsf. Sr-isotope values then increase sharply again to the stratigraphic level defining the top of the carbonate platform.

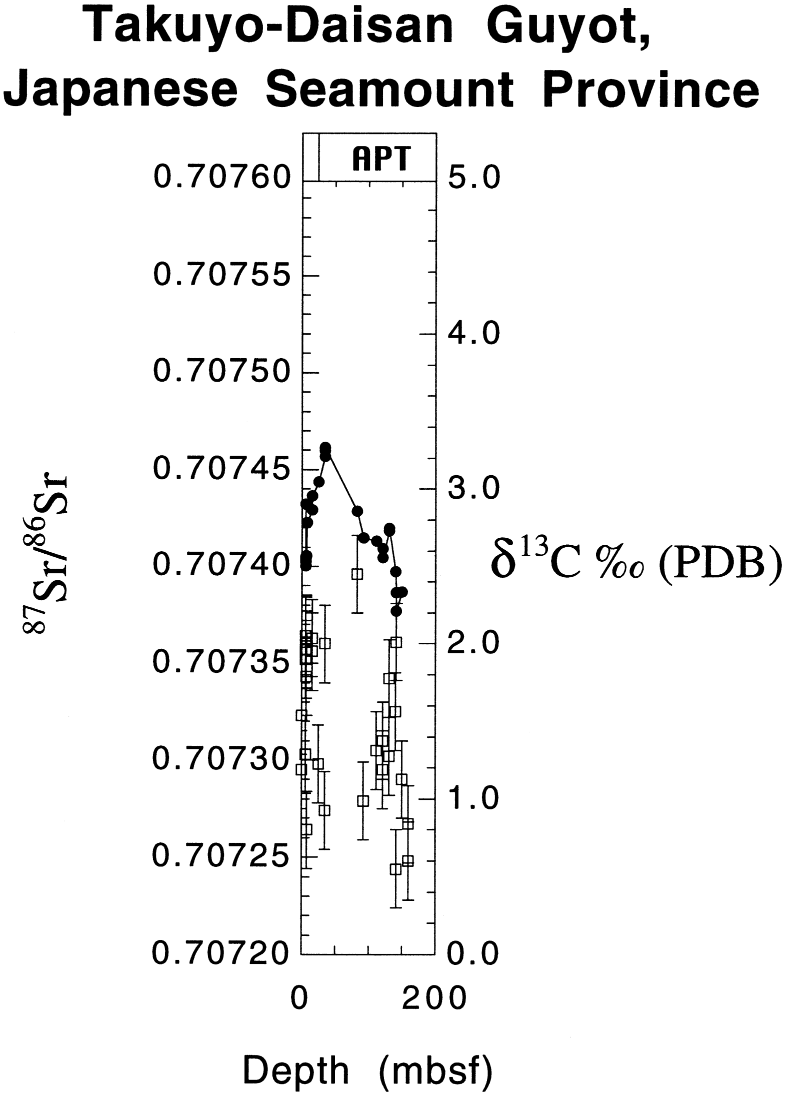


Fig. 13. Strontium- and carbon-isotope ($\delta^{13}C$ PDB) stratigraphy of Cretaceous platform carbonates, Takuyo-Daisan Guyot, Japanese Seamount Province. Data are derived from bulk samples only. Carbon-isotope data (filled circles) have been smoothed with a five-point moving average. A significant feature is a cluster of relatively low $^{87}Sr/^{86}Sr$ values diagnostic of the Aptian-Albian stage boundary. The onset and end of carbonate-platform deposition are dated as 118 ± 2 and 111 ± 2 Ma respectively, after translating the interpreted stratigraphy into the Gradstein and others (1994) timescale.

*Guyot stratigraphy.*– The total thickness of the shallow-water carbonate section of Takuyo-Daisan Guyot, from its contact with basaltic basement below to its summit, is some 170 m. The basal 30 m of the carbonate section contain nannofossils and planktonic foraminifera of late early Aptian age, *Globigerinelloides algerianus* to *Hedbergella trochoidea* Zones (Erba, Premoli Silva, and Watkins, 1995; Erba and others, 1995). This biostratigraphic assignment is broadly consistent with the Sr-isotope data (fig. 13) and further suggests that the relatively high $\delta^{13}C$ values (>3 permil) record part of the major Aptian positive isotope excursions. Absolute-age data from the basaltic basement of Takuyo-Daisan are not deemed reliable by Pringle and Duncan (1995b), but a dredged sample from nearby Takuyo-Daini Seamount gave an isochron age of 118 ± 1.1 Ma (late early Aptian on the Gradstein and others 1994 time scale). This is in accord with the isotopic and biostratigraphic data.

Values of $^{87}Sr/^{86}Sr$ lying between 0.70725 and 0.70730 (fig. 13) are characteristic of the latest Aptian. Hence the stage boundary itself is placed at 25 mbsf and the top of the carbonate platform is fixed as earliest Albian (Wilson and others, 1998). These age assignments differ fundamentally from that published in the biostratigraphic results of Leg 144 where the youngest shallow-water carbonate is attributed to the late Albian, *Rotalipora ticinensis* Zone. This biostratigraphic interpretation was based on very tentative recognition of poorly preserved planktonic foraminifera and some benthonic foraminiferal records (Arnaud Vanneau and Premoli Silva, 1995; Erba, Premoli Silva, and Watkins, 1995; Erba and others, 1995). However, the chemostratigraphy is in accord with the dating of the topmost carbonate unit as very early Albian by Ogg and others (1995) and Röhl and Ogg (1996), based on a comparison of interpreted sealevel cycles on Takuyo-Daisan Guyot with the global chart of Haq, Hardenbol, and Vail (1988).

A summary history of shallow-water sedimentation on Takuyo-Daisan Guyot thus shows an onset during early Aptian time and an end during earliest Albian time (118 ± 2 and 111 ± 2 Ma respectively on the Gradstein and others, 1994, timescale). This re-dating of the shallow-water carbonate section at Takuyo-Daisan is of fundamental importance for addressing the problem of carbonate-platform drowning.

### WODEJEBATO GUYOT, MARSHALL ISLANDS REGION

*Guyot stratigraphy.*– No new isotopic investigations have been undertaken on Wodejebato Guyot. Previous work, both biostratigraphic and chemostratigraphic, suggests that the shallow-water carbonate section (up to about 200-m thick) is of Campanian-Maastrichtian age. In the inner ridge of the Guyot (Site 877), the stage boundary is fixed at some 150 m below the top of the carbonate platform (Erba, Premoli Silva, and Watkins, 1995; Erba and others, 1995; Wilson, Opdyke, and Elderfield, 1995).

A summary history of shallow-water sedimentation on Wodejebato Guyot thus shows an onset in mid-Campanian time and an end during early late Maastrichtian time (76 ± 1 Ma and 69 ± 1 Ma respectively on the Gradstein and others, 1994, timescale).

### LIMALOK GUYOT, MARSHALL ISLANDS REGION

*Guyot stratigraphy.*– No new isotopic investigations have been carried out on Limalok Guyot, and its entire sedimentary history is post-Cretaceous. Biostratigraphic and chemostratigraphic studies show that the shallow-water carbonates are Paleogene in age (Erba, Premoli Silva, and Watkins, 1995; Erba and others, 1995; Nicora, Premoli Silva, and Erba, 1995; Wyatt, Quinn, and Davies, 1995).

A summary history of shallow-water sedimentation on Limalok Guyot thus shows an onset in late Paleocene time and a termination during the early mid-Eocene (57.5 ± 2.5 and 48 ± 2 Ma respectively on the Harland and others, 1990, timescale).

### HORIZON GUYOT, MID-PACIFIC MOUNTAINS

*Guyot stratigraphy.*– Horizon Guyot was drilled during Leg 17 of the Deep Sea Drilling Project at Site 171 (fig. 1). The sedimentary succession is composed of 134 m of shallow-water limestone resting on weathered vesicular basalt, overlain by a basaltic conglomerate and basalt and by Upper Cretaceous cherty chalk and volcanic siltstone of certain Turonian and probable late Cenomanian age (Winterer, Ewing, and others, 1973; Sliter, 1992). Drilling was so rapid and recovery so poor in the shallow-water carbonate section that lithological descriptions are largely lacking and much of the recovered material exists as macerated carbonate sand. Available material has, however, been analyzed, and a combined carbon-isotope (smoothed) and strontium-isotope stratigraphy for Horizon Guyot is shown in figure 14. The data ($\delta^{13}C \approx 3$ permil; $^{87}Sr/^{86}Sr$ lying between 0.70735-0.70745) are most consistent with an early Albian age for the entire shallow-water carbonate sequence, although an early Aptian age cannot be excluded: the time series is not long enough to be diagnostic. The presence of the mid-Albian planktonic foraminifer *Ticinella primula* in pelagic carbonate from a crack in a piece of basalt dredged from Horizon Guyot (Lonsdale and others, 1972) is compatible with both an early Aptian and early Albian age for the platform-carbonate sequence. The post-carbonate-platform history of this guyot was complicated by extrusive volcanic events: drowning, in this case of a volcanic island rather than a carbonate platform, may not have taken place until late Turonian or early Coniacian time (Winterer, Ewing, and others, 1973).

### ITA MAITAI GUYOT, WESTERN PACIFIC

*Guyot stratigraphy.*– Ita Maitai Guyot (fig. 1) was drilled during Leg 20 of the Deep Sea Drilling Project, but little shallow-water material was recovered (Hesse, 1973). Strontium-isotope analyses of two samples of oolite gave $^{87}Sr/^{86}Sr$ values of 0.707420 ± 21 and 0.707396 ± 17 (2 analyses from 96.5 mbsf) and 0.707454 ± 20; 0.707483 ± 20; 0.707476 ± 20 (3 analyses from 75.5 mbsf). $\delta^{13}C$ values of the same material range from about 3.5 to 3.1 permil (3 analyses of oolite from 96.5 mbsf gave values of 3.53, 3.53, and 3.46 permil; 3 analyses of oolite from 75.5 mbsf gave values of 3.12, 3.01, and 3.13 permil). Isotopic data from the Ita Maitai shallow-water section (Winterer and Metzler, 1984) show highest values of 3.72 permil in a calcareous silt stratigraphically below the oolite and values of 3.55 and 2.65 in progressively higher levels within the oolite. The $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ curves for Resolution, Allison, and “MIT” Guyots suggest that, if the age-span falls into the Early Cretaceous, the absolute isotopic values and trends indicate that the Ita Maitai oolite is most probably early Aptian or early Albian in age.

### THE EARLY APTIAN OCEANIC ANOXIC EVENT (SELLI EVENT) ON RESOLUTION GUYOT

Within the cyclically bedded packstones to wackestones of the mid-part of the section through Resolution Guyot (at 831.5 mbsf; fig. 4) there is a striking 10-cm thick intercalation of a black to green millimeter-laminated claystone whose total organic-carbon (TOC) values range from 0.5 to 14.4 percent (Baudin and others, 1995; Baudin, 1996; Baudin and Sachsenhofer, 1996; Jenkyns, 1995). Other organic carbon-rich layers (max TOC = 34 percent), commonly associated with fossil cyanobacterial mats, occur in stratigraphical proximity to this level over the interval 790 to 832 mbsf. This organic matter, which has a relatively high hydrogen index (183-821 mg HC/g TOC), is interpreted as being mainly algal and/or bacterial. The stratigraphic position of the black to green millimeter-laminated claystone relative to the $\delta^{13}C$ profile is identical to that of the Selli Level in the Italian Apennines and correlatives in southern France and Switzerland (Coccioni and others, 1987, 1989; Bréhéret, 1988; Weissert and Bréhéret, 1991; Erbacher, 1994; Erbacher and Thurow, 1997; Menegatti and others, 1998). This characteristic claystone on Resolution Guyot occurs at a stratigraphic level just above the

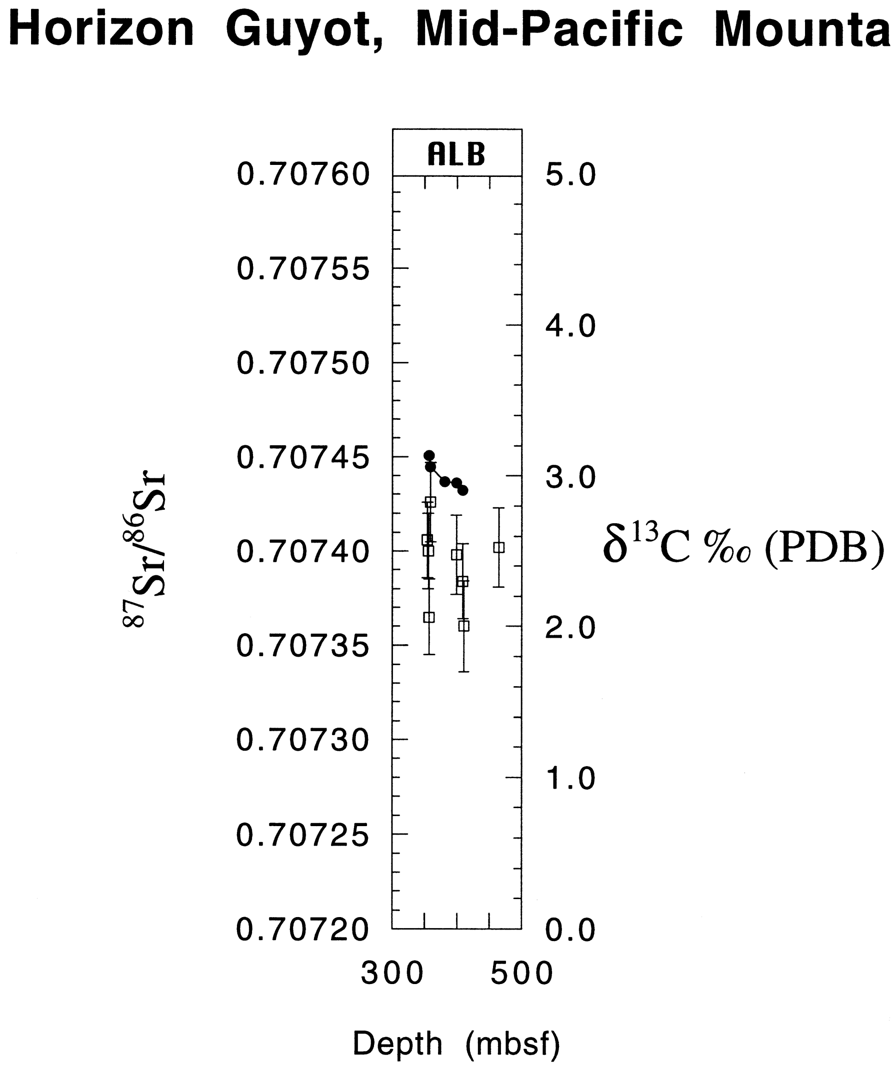


Fig. 14. Strontium- and carbon-isotope ($\delta^{13}C$ PDB) stratigraphy of Cretaceous platform carbonates, Horizon Guyot, mid-Pacific Mountains. Data are derived from bulk samples only. Carbon-isotope data (filled circles) have been smoothed with a five-point moving average. A significant feature is a cluster of $^{87}Sr/^{86}Sr$ values typical of the early Albian. A reliable drowning age cannot be established because of the presence of basalt above the platform carbonates and the probable persistence of a volcanic island until the Late Cretaceous (Winterer and Metzler, 1984).

position of a pronounced $\delta^{13}C$ minimum on part of the carbon-isotope curve that exhibits an extremely abrupt upward increase in values that define the beginning of the early Aptian, *Globigerelloides blowi*-Zone positive excursion (Jenkyns, 1995; figs 4, 6).

A geochemically similar coeval organic-rich facies to that described above was cored in a deep-water section on the flanks of Resolution Guyot (DSDP Site 463, Dean, Claypool, and Thiede, 1981, 1984; Mêlières, Deroo, and Herbin, 1981). This latter unit dominantly comprises lipid-rich kerogen derived from aquatic marine algae and bacteria. Given these stratigraphic and geochemical associations, the black to green laminated layer on Resolution Guyot is interpreted as a record of the early Aptian Oceanic Anoxic

Event or Selli Event (Coccioni and others, 1987, 1989; Sliter, 1989; Arthur and others, 1990; Jenkyns, 1999). Unlike other records of the Selli Event, however, the stratigraphic context of this layer, enclosed in peritidal carbonates, indicates that it was likely deposited in water of very modest depth ($\leq$10m).

Additional records of the Selli Event from the Pacific discovered to date are all in deep-water facies: DSDP Sites 167, Magellan Rise; 305, Shatsky Rise; 317, Manihiki Plateau (Sliter, 1989). These records, taken together with that of Resolution Guyot, show that coeval organic-rich facies were deposited over considerable range in latitude and water depth. In terms of depositional models, an increase in productivity of organic-walled microfossils such as dinoflagellates, seems the most attractive interpretation (Habib, 1982; Erba, 1994; Jenkyns, 1995; Baudin, 1996). This inferred change in productivity in turn implies a change in the nutrient balance of those parts of the ocean that were affected, possibly triggered by an increase in climatologically driven upwelling (Bralower and others, 1994; Jenkyns, 1999).

## PALEOCEANOGRAPHIC SIGNIFICANCE OF APTIAN CARBON-ISOTOPE VARIATIONS ON RESOLUTION GUYOT

The carbon-isotope profile of Resolution Guyot (figs. 4, 5) shows two striking features: a pronounced negative excursion from background values of around 2 permil to values close to zero, followed by a distinct positive excursion to values in excess of 4 permil, above which values decay to a background of about 3 permil. This positive excursion is characterized by a diagnostic peak that is known from other European Aptian sections in pelagic-carbonate facies (Weissert and Lini, 1991; Erbacher and Thurow, 1997; Weissert and others, 1998; Menegatti and others, 1998), from platform-carbonate successions (Ferreri and others, 1997) and from wood and skeletal calcite in shallow-marine clastics (Gröcke, Hesselbo, and Jenkyns, 1999). The significance of these excursions has occasioned much discussion. The carbon-isotope values of skeletal and inorganic carbonate primarily reflects the global partitioning of carbon into oxidized ($CO_2$, carbonate, bicarbonate) reservoir and the reduced (organic carbon) reservoir (for example, Scholle and Arthur, 1980; Berger and Vincent, 1986). Hence, global factors causing excursions toward lower values in the oxidized reservoir are conventionally interpreted as related to reduction in global biomass; erosion and oxidation of previously deposited organic matter, perhaps related to global regression; introduction of mantle carbon from vigorous volcanic degassing (for example, Scholle and Arthur, 1980; Weissert, 1989; Bralower and others, 1994); or release and oxidation of methane stored in sub-seafloor clathrates whose $\delta^{13}C$ values were around $-60$ permil (compare Dickens and others, 1995; Dickens, Castillo, and Walker, 1997). A change in the average global isotopic composition of organic matter to higher values and an increase in carbonate concentration in the ocean are additional factors acting in the same direction (Jenkyns, 1988; Spero and others, 1997). Local paleoceanographic factors include intensified upwelling and recycling of $^{12}C$-rich waters (Küspert, 1982). Excursions to higher values conversely may be interpreted as related to increases in global biomass and/or increase in global burial rates of organic carbon, as well as a decrease in global average $\delta^{13}C$ composition of organic matter and/or a decrease in oceanic carbonate concentration.

Uncertainty exists as to how the early Aptian negative $\delta^{13}C$ excursion is correlated with the pattern of transgressions and regressions, if at all. In one stratigraphically well-calibrated section from southern England this isotopic feature is found within strata indicative of relative deepening rather than shallowing (Gröcke, Hesselbo, and Jenkyns, 1999). However, on Resolution Guyot, the pattern is effectively the reverse, with movement of the $\delta^{13}C$ curve from relatively low to relatively high values coinciding with a change from peritidal facies to oolites (figs. 4, 6), suggestive of general deepening (Jenkyns and Strasser, 1995).

Bralower and others (1994) have recently viewed the negative excursion as a response to vigorous outgassing of mantle carbon ($\delta^{13}C \approx -7$ permil), an interpretation that gains some support from the marine strontium-isotope record. The trend to less radiogenic values commencing in the earliest Aptian, discussed by Jones and others (1994) and Ingram and others (1994), has been interpreted as a result of increased hydrothermal flux of strontium to the world ocean at this time, related to global increases in sea-floor spreading rates and/or emplacement of volcanic plateaus (see also Bralower and others, 1997). Other linkages can be envisaged: for example, vigorous volcanic degassing may have raised the $CO_2$ content of the atmosphere, causing global warming and allowing dissociation of marine clathrates, a combination of effects that would have greatly enriched the marine reservoir in $^{12}C$.

Cretaceous positive $\delta^{13}C$ excursions are conventionally interpreted as controlled by an increase in carbon-burial rates, and the global occurrence of carbon-rich shales (Selli Level) at the exact level of the onset of the excursion is persuasive in this regard. However, $\delta^{13}C$ values remain high at stratigraphic levels well above the Selli Level, suggesting either that the major sink for organic carbon that controlled global sea-water chemistry has not yet been identified or that other factors, such as those discussed above, are at work (discussion in Weissert and others, 1998; Menegatti and others, 1998).

In figure 15, the smoothed $\delta^{13}C_{carb}$ profile from Resolution Guyot is plotted against the $\delta^{13}C_{org}$ data of Baudin and Sachenhofer (1996) from the same section. Although the

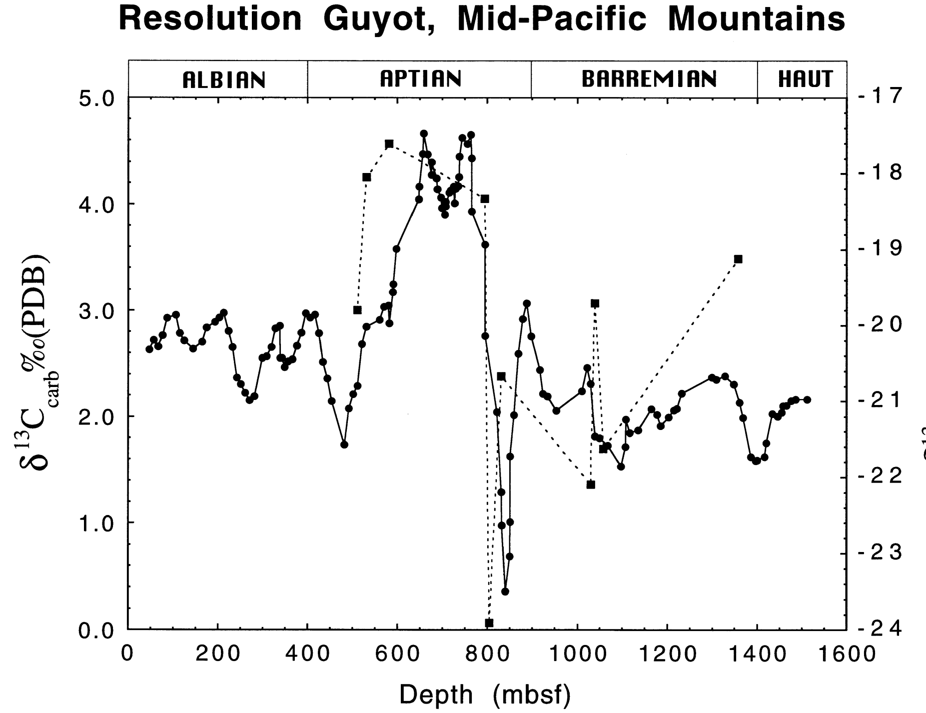


Fig. 15. Carbon-isotope stratigraphy of Cretaceous platform carbonates, Resolution Guyot, mid-Pacific Mountains. $\delta^{13}C_{carb}$ data (filled circles) are derived from bulk samples and smoothed with a five-point moving average; primary $\delta^{13}C_{org}$ data (filled squares) are derived from analysis of organic-rich levels in the section (Baudin and Sachsenhofer, 1996). Values are referenced to the Pee Dee belemnite [PDB] carbonate standard. Note the general correspondence in the curves but the displacement in the stratigraphic positions of minima and maxima.

latter data set is very limited, there is a strong correspondence, albeit with two important differences. The magnitude of the $\delta^{13}C_{org}$ shift, from the lowest to the highest values, is greater by some 2 permil than in the $\delta^{13}C_{carb}$ curve; and there is an apparent offset in the $\delta^{13}C_{org}$ profile to a higher stratigraphic level than comparable features in the $\delta^{13}C_{carb}$ curve, most notably in the relative position of their highest and lowest points. This offset is not an artifact of data smoothing.

Controls on the variation in the $\delta^{13}C$ composition of preserved organic matter are considerably more complex than those on carbonate and, as well as changes in the isotopic composition of the global inorganic carbon reservoir, include the following, either singly or in combination: (1) a temporary change in the nature of the marine primary productivity to organisms exhibiting greater selectivity for or against $^{13}C$; (2) differential syn- and post-depositional bacterial reworking of the organic matter; (3) changing levels of $CO_2$ in the ocean-atmosphere system; (4) variable recycling of bottom waters rich in oxidized organic matter (Küspert, 1982; Dean, Arthur, and Claypool, 1986; Arthur, Dean, and Pratt, 1988; Hollander and McKenzie, 1991; Lini, Weissert, and Erba, 1992; Freeman and Hayes, 1992). Both the relatively greater magnitude of the $\delta^{13}C_{org}$ excursion, when compared with that of $\delta^{13}C_{carb}$, and its later appearance in time, are phenomena previously reported in other sections and usually attributed to the mechanisms listed above.

The type of organic matter analyzed from Resolution Guyot is described as algal/bacterial throughout the section (Baudin and Sachenhofer, 1996), so there is no compelling evidence for mechanisms (1) and (2). Recycling of bottom waters rich in oxidized organic matter may be relevant to understanding the negative excursions in both $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$, but data are too few to determine whether or not the excursions are truly out of phase. However, as regards the greater positive shift in $\delta^{13}C_{org}$ relative to $\delta^{13}C_{carb}$, exemplified by the isotopic profiles between approx 800 and 600 mbsf on Resolution Guyot (fig. 15), drawdown of $CO_2$ in the ocean-atmosphere system consequent upon massive global carbon burial during an Oceanic Anoxic Event (in this case the early Aptian Selli Event) may be credited with causing an isotopic shift to higher values in particulate organic matter (compare Arthur, Dean, and Pratt, 1988; Freman and Hayes, 1992). Persistence of relatively low $CO_2$ values in the ocean-atmosphere system after the main carbon burial event/s may have led to elevated values of $\delta^{13}C_{org}$ being maintained when those of $\delta^{13}C_{carb}$ had begun to decline (fig. 15).

### COMPARATIVE CARBON-ISOTOPE STRATIGRAPHY OF "MIT" AND RESOLUTION GUYOTS

In figure 16, parts of the smoothed carbon-isotope curves generated for "MIT" and Resolution Guyots are plotted on an identical depth scale. The two definitive tie-points are the dual peaks of the composite Aptian $\delta^{13}C$ excursion, although some other features may be tentatively correlated. Positive excursions are more secure as correlation points because they should reflect regional or global oceanographic changes, whereas negative excursions may also represent local diagenetic artifacts, perhaps related to emergence and the introduction of isotopically light carbon from meteoric waters passing through humus-rich soils. Hence the correlative line in the lower Albian is fixed more tentatively. Although the facies are of shallow-water peritidal character and their original constituents were presumably subject to a wide range of "vital" and diagenetic effects, the carbon-isotope signature is so diagnostic that curve matching of the positive excursion is deemed definitive.

### REGIONAL DEVELOPMENT OF OOLITE ON CRETACEOUS GUYOTS

Two major packages of Cretaceous oolitic grainstone were cored on Resolution Guyot, the stratigraphically lower of which is partially dolomitized and rests on edifice basalt (fig. 4). The petrography of these grainstones is described in detail by Jenkyns and

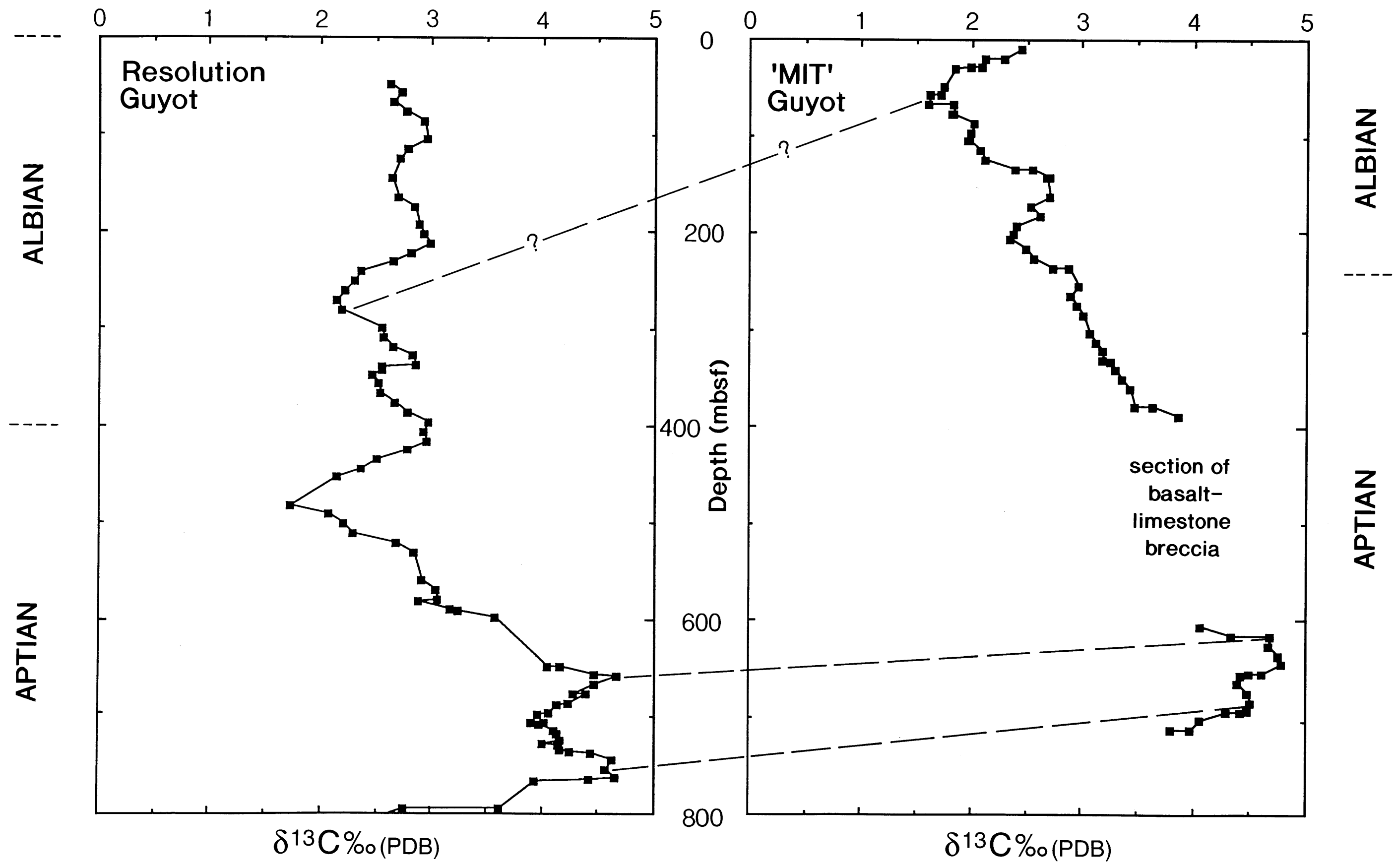


Fig. 16. Comparative smoothed (five-point moving average) carbon-isotope stratigraphy ($\delta^{13}$C PDB) for Resolution and "MIT" Guyots, plotted on the same thickness scale (meters below sea floor). Suggested tie-points are indicated: those at the two peaks of the bifurcate positive excursion are deemed secure; the tie-point at the level of the negative excursion less so, because diagenetic artifacts can produce anomalously low $\delta^{13}$C values.

Strasser (1995). Biostratigraphic data from rare planktonic and more abundant benthonic foraminifers, together with strontium- and carbon-isotope stratigraphy, suggest that the basal oolitic package can be assigned to the latest Hauterivian-Barremian (Arnaud-Vanneau and Sliter, 1995; Jenkyns, 1995; Jenkyns and others, 1995). The stratigraphically higher oolitic package can be tentatively dated to zonal level using the detailed carbon-isotope curve generated for Resolution Guyot (fig. 6). In terms of the planktonic foraminiferal biostratigraphic scheme, the oolitic section probably extends from the upper part of the *Globigerinelloides blowi* Zone into the *Leupoldina cabri* Zone of the Aptian.

Lower Aptian oolite-bearing grainstones also occur in the section cored through "MIT" Guyot (fig. 9), although they are not as oolite-rich as those of Resolution Guyot. The carbon-isotope profile suggests, using the planktonic foraminiferal biostratigraphic scheme, an age of *Globigerinelloides blowi* and *Leupoldina cabri* Zones for the oolitic facies on "MIT" Guyot (fig. 11). The oolitic facies on the two guyots are hence of equivalent age.

Earlier drilling records of possibly coeval oolitic facies from the Pacific Ocean include redeposited oolites of Barremian-Aptian age from Site 463 in a basinal section situated some 44 km to the east of Resolution Guyot (Thiede, Vallier and others, 1981; Ferry and Schaaf, 1981) and the redeposited Aptian-Albian ooids from Site 585 at the eastern margin of the Mariana Basin (Haggerty and Premoli Silva, 1986). Cretaceous shallow-water facies have been dredged from Ita Maitai Guyot close to Site 585, and cored oolitic material from Site 202 on this guyot (Hesse, 1973) is almost certainly of similar age, as supported by the chemostratigraphic data reported here (most probably early Aptian or early Albian). Other dredge-hauls have recovered Cretaceous oolite from a number of Pacific locations, but their age is uncertain (Lincoln, Pringle, and Premoli Silva, 1993; Shiba, 1993; Jenkyns and Strasser, 1995). The distribution of Cretaceous north Pacific oolite is illustrated in figure 17. All Cretaceous ooids from this region are dominantly possessed of micritic to radial structures in the cortex, presumably reflecting primary calcitic mineralogy (compare Sandberg, 1985).

The Aptian oolitic package on Resolution Guyot, which overlies and is underlain by more finer-grained intertidal-supratidal lithologies, signifies a modest increase in water depth (compare Kendall and Schlager, 1981). A recent analogue would be the formation of oolitic sand bodies in the Bahamas whose development is clearly related to the Holocene rise in sealevel (Hine, 1977; Harris, 1983). A possible mechanism promoting positive eustatic change during the Aptian would be desiccation of part or all of the proto-South Atlantic. Such a process has been credited with the potential to have moved eustatic sealevel upward by 10 m or more at rates of $10^3$ to $10^4$ m/my (fig. 18: Berger and Winterer, 1974; Burke and Sengör, 1988).

If the Aptian oolites reflect a genuine eustatic signal, then identical facies of identical age should be present across the Pacific, assuming a similar response of all guyot carbonates. A discrete level of Aptian oolitic grainstone is also recorded from the subsurface of Texas (Loucks and Bebout, 1984), and similar facies are recorded from parts of Mexico (Cupido Formation, Wilson and Ward, 1993). Further studies of Cretaceous circum-Pacific oolite are needed, particularly chemostratigraphic investigation of the oolitic Calera Limestone from the Franciscan of California, an accreted remnant of the sedimentary cover of a plateau or guyot from the vanished Farallon Plate (part of the paleo-Pacific Ocean) which is tentatively dated as Albian (Bailey, Irwin, and Jones, 1964; Wachs and Hein, 1974; Tarduno and others, 1985).

## COMPARATIVE OXYGEN-ISOTOPE STRATIGRAPHY OF PACIFIC GUYOTS

The $\delta^{18}O$ record of peritidal carbonates, as far as deciphering primary signals is concerned, must be suspect because of the potential impact of meteoric-water diagenesis

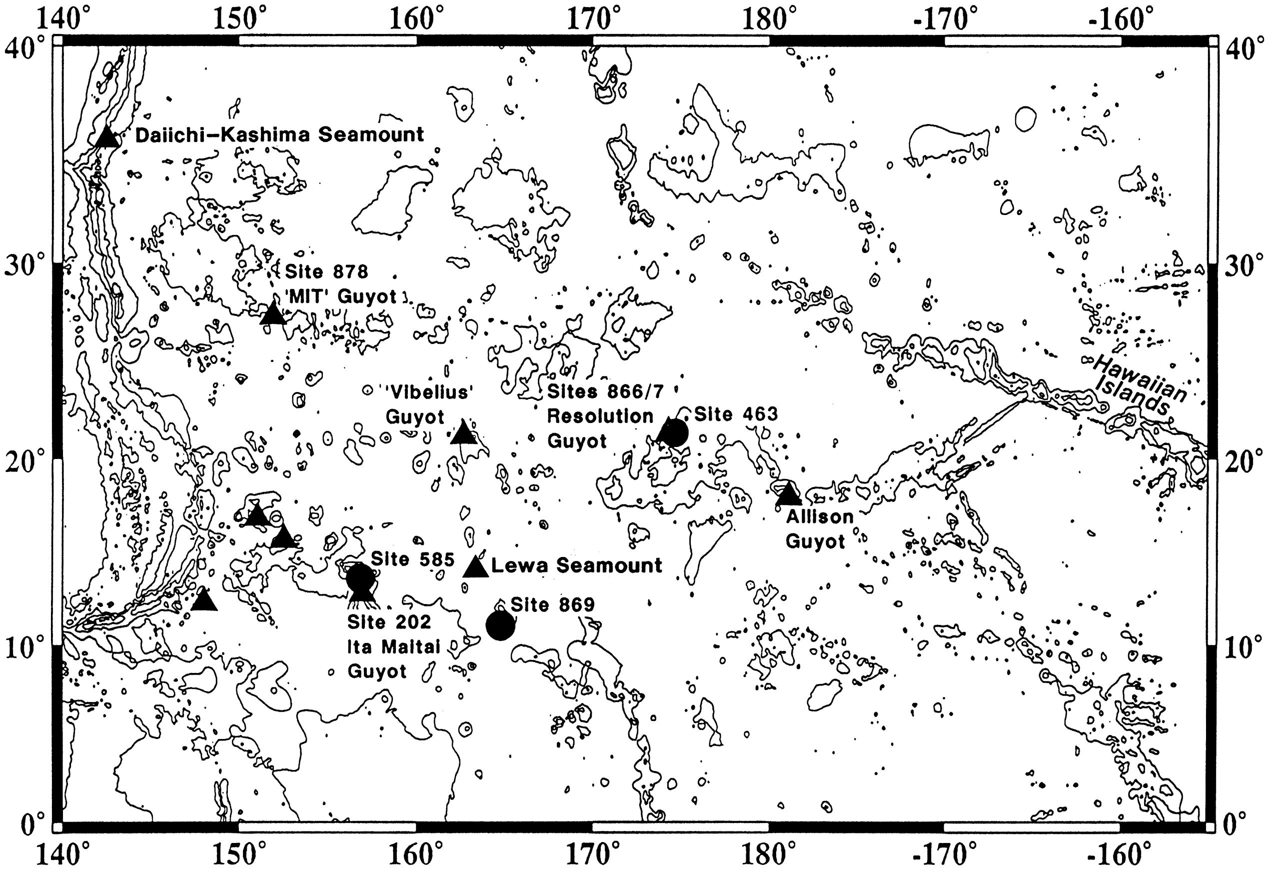
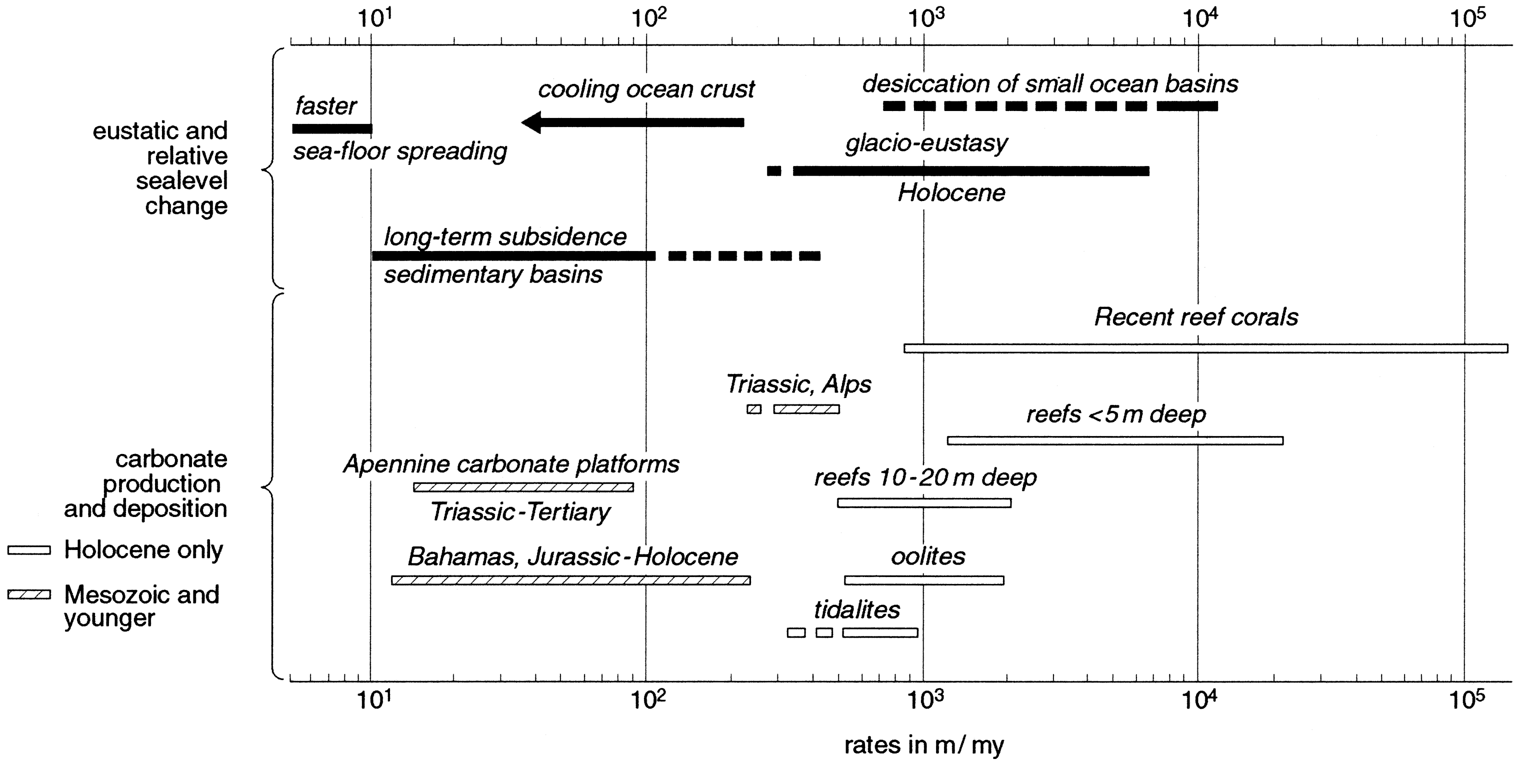


Fig. 17. Distribution of Cretaceous oolite across the north Pacific Basin as presently known from corings and dredgings. Bathymetric contour at 2 km. Those sites where redeposited ooids occur are shown as filled circles; where the ooids occur *in situ* within carbonate successions above volcanic basement their locations are shown as a filled triangle. Data from Hesse (1973), Haggerty and Premoli Silva (1986), Grötsch and Flügel, (1992), Lincoln, Pringle and Premoli Silva (1993), Shiba (1993) and Jenkyns and Strasser (1995).



After Schlager, 1981

Fig. 18. Rates of eustatic and relative sealevel change, long-term platform-carbonate deposition, and potential rates of shallow-water carbonate accumulation. Note how potential rates of shallow-water carbonate accumulation exceed, typically by several orders of magnitude, rates of relative and eustatic sealevel change. Modified from Schlager (1981).

and likely variation in cement-matrix ratios. Nonetheless, Resolution, and particularly Allison and "MIT" Guyots all show trends that correlate to some degree. "MIT" Guyot shows a trend of rising values from the base of the section ($\delta^{18}O$ of $-3$ to $-2$ permil) to peak in the mid-Aptian ($\delta^{18}O \approx -1.5$ permil), then decline across the Aptian-Albian boundary to reach a minimum in the early to mid Albian ($\delta^{18}O \approx -3$ to $-2$ permil), then rise again through the middle Albian to the early late Albian (fig. 9). Allison Guyot shows a progressive rising and falling trend centered on a maximum ($\delta^{18}O \approx -2$ to $-1$ permil), in the middle Albian (fig. 7). Broadly similar patterns may be discerned in the $\delta^{18}O$ profile on Resolution Guyot, although the dominant trend is for increasingly lower $\delta^{18}O$ values with depth (fig. 4). It is possible that trends registered on more than one guyot could relate to meteoric-water diagenesis, forced by regional episodes of emersion, producing carbonates with relatively negative $\delta^{18}O$ values. However, as noted above, evidence for pervasive meteoric-water diagenesis is not forthcoming in cements from these guyots. Hence it is perhaps more likely that the relative significance of marine cementation, above or below the thermocline, by virtue of the difference in temperature, could also have influenced the $\delta^{18}O$ signature of differing facies.

Alternatively, the stratigraphical oxygen-isotope changes in these sequences could represent a paleotemperature signal, albeit grossly modified. Support for this notion comes from the observation that the $\delta^{18}O$ profile of coeval pelagic carbonates from the Italian Apennines shows an identical pattern, although there is considerable data scatter: values decrease through the earliest Aptian from around $-4$ to $-2$ permil, then rise to a maximum in the mid Aptian ($\delta^{18}O \approx -1$ permil), then decline across the stage boundary to an early Albian minimum ($\delta^{18}O \approx -3$ to $-2$ permil), followed by a climb to a maximum in the middle Albian ($\delta^{18}O \approx -2$ per mil), followed by a subsequent decline toward the Albian-Cenomanian boundary (Erbacher, 1994). These data are in accord with a paleotemperature minimum in the mid-Aptian, for which there is sedimentary evidence in the form of glendonites (calcite pseudomorphs after the low-temperature form of $CaCO_3$, ikaite) from Arctic basins (Kemper, 1987).

## SEQUENTIAL DROWNING OF PACIFIC CARBONATE PLATFORMS

As underscored by Schlager (1981), the growth potential of healthy carbonate platforms exceeds any relative rise of sealevel caused by long-term geological processes, perhaps by as much as an order of magnitude or more (fig. 18). Thus the relative "health" of a platform, in terms of potential sediment production, is deemed the most critical factor if drowning is to take place (Schlager, 1999). The chemostratigraphic data show conclusively that the four former carbonate banks investigated in this study (Resolution, Allison, "MIT," and Takuyo-Daison) drowned at three different intervals of time. The estimated times of cessation of shallow-water carbonate deposition, based on the combined carbon- and strontium-isotope stratigraphy, and using the Gradstein and others (1994) time scale, are as follows: Takuyo-Daisan Guyot at 111 ± 2 Ma, "MIT" Guyot at 101 ± 2 Ma, Allison and Resolution Guyots at 99 ± 2 Ma. Wodejebato Guyot, a fifth well-dated Cretaceous shallow-water carbonate platform, drowned at 69 ± 1 Ma; and Limalok, a sixth guyot with a Paleocene-Eocene shallow-water section, drowned at 48 ± 2 Ma (Wilson, Opdyke, and Elderfield, 1995; Wilson and Dickson, 1996; Erba, Premoli Silva, and Watkins; Erba and others, 1995; Wyatt and others, 1995; Wilson and others, 1998).

Comparison with the present-day position of these guyots (Takuyo-Daisan furthest north; Limalok nearest to the Equator, fig. 1) illustrates the phenomenon of sequential drowning whereby the guyots formed in the order in which they crossed a given line of latitude. These dates of the timing of cessation of carbonate-platform sedimentation translate into the following paleolatitudes of atoll drowning, derived from a paleomagnetic reconstruction of Pacific Plate motion (Wilson and others, 1998):

Resolution Guyot: 10.7 ± 3.3° south.
Allison Guyot: 11.75 ± 3.25° south
"MIT" Guyot: 8.35 ± 3.35° south.
Takuyo-Daisan Guyot: 3.4 ± 3.5° south.
Wodejebato Guyot: 6.2 ± 2.2° south
Limalok Guyot: 8.15 ± 2.75° south

These findings support the hypothesis of "Death in the Tropics," whereby plate-tectonic transport of platforms through low latitudes proved fatal for the well-being of these shallow-water carbonate systems. Notably all platforms drowned in a narrow paleolatitudinal zone south of the Equator (~0-10° S).

### DROWNING OF PACIFIC CARBONATE PLATFORMS AND SEALEVEL CHANGE

The above results indicate that platform drowning and guyot formation did not result from some coeval eustatic or tectonic event. Furthermore, the dates are at odds with those proposed by Ogg, Camoin, and Jansa (1995) and Röhl and Ogg (1996), based on comparative sequence stratigraphy, of ~100 Ma for simultaneous drowning of Allison, "MIT" and Resolution Guyots. It has been suggested that the simultaneous or near-simultaneous drowning of Allison and Resolution Guyots records a regional, perhaps global, event. Such is the hypothesis of Grötsch and others (1993) and Fernd́andez-Mendiola and García-Mondéjar (1997) who attribute the facies change from platform carbonate to pelagic in Pacific guyots and Spanish and Slovenian carbonate platforms to emergence, karstification and subsequent drowning, attributed variously to eustatic or plate-tectonic effects.

One feature used to support the argument for sealevel change controlling development of guyots is the presence of highly irregular supposedly "karstic" topography, with variations in relief of 100 to 200 m, on the summits of many western Pacific guyots (van Waasbergen and Winterer, 1993; Winterer, 1998). If these features truly represent subaerially generated karst, then this could be a strong pointer to guyot formation by emergence and subsequent submergence (Winterer and others, 1995). Camoin and others (1998) also record local blocky spar cements, attributed to meteoric-water diagenesis, in the upper reaches of the platform carbonates on Wodejebato Guyot. However, as so few of the calcite cements examined in the top 150 m of Allison, Resolution, "MIT," and Takuyo-Daisan Guyots betray clear meteoric-water influence (fig. 3; Haggerty and van Waasbergen, 1995; Opdyke, Wilson, and Enos, 1995; Wilson and others, 1998), the possibility that formation of the irregular relief on the summit of the platform carbonates by subaerial dissolution appears remote. To maintain otherwise would imply that substantial subaerial dissolution of carbonate can take place without concomitant precipitation of significant calcite cement, a suggestion that contradicts current understanding of modern subaerial processes of limestone lithification (Bathurst, 1975; Hudson, 1977; James and Choquette, 1984; Lohmann, 1988; Moore, 1989).

A further problem with the "Death-by-Emergence-and-Submergence" hypothesis, conceeded by its proponents (van Waasbergen and Winterer, 1993; Winterer, 1998), is that it fails to explain why reefs and carbonate platforms were not re-established on subsiding karstified limestone topography at and just below sealevel, whereas they were formed initially on foundering volcanic pedestals whose rate of subsidence was presumably greater. As shown by Purdy (1974), reef biota selectively colonize karstic pinnacles when resubmergence of a corroded limestone landscape takes place. Indeed antecedent karst may, under certain conditions, exert a strong control on the morphology of present-day reefs and atolls, which have demonstrated the ability to keep pace with rapid rates of relative sealevel rise (MacNeil, 1954; Hopley, 1982; Schlager, 1981; Spencer, 1995).

Regional volcanism in and uplift of the mid-Pacific Mountains, and adjacent regions of the Pacific Plate, was suggested by Menard (1964) and Schlanger, Jenkyns, and Premoli Silva (1981), and these ideas have since been subsumed into the "Superplume Hypothesis" of Larson (1991). Uplift could have caused emersion of oceanic carbonate platforms in the mid-Pacific Mountains and elsewhere (Winterer and Metzler, 1984). However, regional Pacific volcanism began in earnest around 125 to 122 Ma (Larson, 1991) which would place any accompanying uplift well before cessation of carbonate deposition on "MIT," Allison, Resolution, Wodejebato, and Limalok Guyots.

In addition to the above problems, it should be noted that irregular topographies on guyots can be produced by merely physical processes of submarine erosion (Lonsdale, Normark, and Newman, 1972). Furthermore, the potential for the production of large-scale dissolutional geomorphic features is not restricted to meteoric waters and the subaerial environment. Submarine sinkholes have been found in pelagic drapes in the southern Straits of Florida at depths as great as 575 m, a level too deep to have been subaerially exposed by Neogene glacio-eustatic sealevel falls (Land, Paull, and Hobson, 1995). Moreover, a wide range of petrographic, geochemical, and hydrological data from both the guyots and living atolls suggests that the diagenetic histories of these mid-Pacific platforms is strongly influenced by the circulation of carbonate-undersaturated sea water, which has the potential to generate karst-like features (Swartz, 1958; Saller, 1984, 1986; Paull and others, 1995; Wilson and Dickson, 1996). Other models for the submarine generation of irregular topography on the summits of guyots are discussed by Haggerty and van Waasbergen (1995).

In summary: the hypothesis of emergence and submergence for guyot formation is rejected, because it contradicts (1) current understanding of the response of living atolls to these processes, (2) the broader picture of sequential drowning at low latitudes established for the guyots, and (3) the lack of geochemical or petrographic evidence indicating karstification in these drowned platforms (Wilson and others, 1998). In contrast, if other factors caused suppression of shallow-water carbonate production, a rapid pulse of relative sealevel rise could have outpaced sedimentation and helped to initiate drowning. This concept is explored below.

## DROWNING OF PACIFIC CARBONATE PLATFORMS AND PERI-EQUATORIAL UPWELLING

The present-day eastern equatorial region of the Pacific is an area of open-ocean upwelling, maintenance of nutrient-rich (N and P) near-surface waters and relatively high chlorophyll concentrations, and carbon fixation with respect to mid-latitude open-ocean areas (for example, Koblentz-Mishke, Volkovinsky, and Kabanova, 1970; Berger, 1989; Murray and others, 1994; Chavez and Smith, 1995; Barber and others, 1996; Bidigare and Ondrusek, 1996; Chavez and others, 1996). Despite elevated nutrient abundances and adequate insolation, planktonic biomass is lower than predicted, indeed lower than coastal upwelling systems, perhaps because another vital nutrient, iron, is in short supply (Martin and others, 1994), and concentrations of some dissolved species, particularly nitrate, remain high. Zones of elevated nitrate concentration occur between 3° to 8°N and 8° to 14°S in the eastern Pacific whereas farther west the distribution is more symmetrical about the Equator (Barber and Chavez, 1991; Wilkerson and Dugdale, 1992; Toggweiler and Carson, 1995); the same general distribution pattern characterizes dissolved phosphate (Levitus and others, 1993).

The area currently affected by equatorial upwelling is vast, extending from the coast of South America to the international date line (Wytki, 1981). Degassing of $CO_2$-rich upwelled waters ensures that the equatorial Pacific is also a major, probably the major single, source of carbon dioxide to the atmosphere (Tans, Fung, and Takahashi, 1990; Sundquist, 1993; Schneider and Müller, 1994).

Hence, if these mechanisms operated during the Cretaceous, plate-tectonic transport through equatorial waters would expose carbonate platforms to waters whose chemistry and biology was different from those farther south, and such waters could have been encountered well south of the Equator. The possible impact of nutrient-rich waters on shallow-water carbonate ecosystems has been explored by Hallock and Schlager (1986), Hallock (1988), and Wood (1993). These studies indicate that increasing plankton abundance decreases water transparency, limiting the depth range of light-dependent carbonate-producing organisms. The symbiotic relationship between zooxanthellae and corals is adapted to low nutrient concentrations and may break down under eutrophic conditions. Hence elevated nutrient levels encourage growth of non-calcareous algae and bioeroders at the expense of hermatypic corals and calcareous algae. This underpinning of reef and reef-related communities by algal symbiosis has probably been important throughout the Phanerozoic (Cowen, 1988), and Coates and Jackson (1987) suggest that most scleractinian corals possessed zooxanthellae by Jurassic time. A number of rudists may also have possessed zooxanthellae (Vogel, 1975; Cowen, 1983; Kauffman and Johnson, 1988; Gili, Masse, and Skelton, 1995). Hence the efficiency of a Cretaceous carbonate factory could have been greatly reduced in oceanic areas of high nutrient levels, and subsidence of ocean floor could potentially have outpaced sedimentation.

If, as is the case today, Cretaceous near-surface equatorial waters contained high $pCO_2$ levels, they would act against precipitation of non-biogenic aragonite, perhaps even favoring dissolution of fine-grained particles as well as adversely affecting the secretion and deposition of skeletal material (Sandberg, 1985; Buddemeier and Fautin, 1996; Gattuso and others, 1998). Total rates of carbonate generation may be more closely linked to physiochemical conditions in sea water rather than biological factors related to the ecological demands of variously calcifying taxa (Opdyke and Wilkinson, 1993). Kleypas and others (1999) suggest that a doubling of $CO_2$ from pre-industrial levels could cut biogenic aragonite precipitation by 14 to 30 percent. Similar chemical effects could also have affected the efficiency of Cretaceous carbonate factories and inclined the systems toward drowning.

## DROWNING OF PACIFIC CARBONATE PLATFORMS AND OCEANIC ANOXIC EVENTS

The possible link between platform drowning and high nutrient availability and plankton productivity of near-surface waters can be further explored in the context of oceanic anoxic events. Oceanic anoxic events reflect a switch in productivity from carbonate-walled biota (for example, planktonic foraminifera and nannofossils) to organic-walled and siliceous biota (for example, dinoflagellates and radiolarians) and presumably reflect elevated nutrient levels in near-surface waters over much of the world ocean (Erba, 1994; Jenkyns, 1999). A connection between oceanic anoxic events and platform drowning has been postulated by several authors (for example, Vogt, 1989; Philip and Airaud-Crumière, 1991; Rougerie and Fagerstrom, 1994). Some of these hypotheses were based on poor or incomplete knowledge of the relevant stratigraphy. There is no evidence, for example, of mass drowning of Pacific guyots during Cenomanian-Turonian boundary time when a major oceanic anoxic event took place (Schlanger and Jenkyns, 1976; Jenkyns, 1980, 1999; Schlanger and others, 1987; Arthur and others, 1990), and eustatic sealevel was extraordinarily high (Hancock and Kauffman, 1979; Haq, Hardenbol, and Vail, 1998; Hancock, 1989, 1993).

Another major oceanic anoxic event, similarly recorded in several Pacific deep-sea sites (Sliter, 1989; Bralower and others, 1993, 1994) took place during the early Aptian. However, the fact that this event was registered on Resolution Guyot as the Selli Level (fig. 4), and shallow-water carbonate deposition continued through the rest of the Aptian and Albian shows that, in this case at least, such events were not implicated in platform drowning. Duration of the Selli Event is estimated to have been half a million years or less (Bralower and others, 1994; Jenkyns, 1999), and Resolution Guyot is estimated to have subsided on average at about 57m/m.y. during the Aptian, using the Gradstein and others (1994) time scale (Jenkyns and others, 1995). The subsidence rate for "MIT" Guyot during the early Aptian, before deposition of the basalt/limestone breccia (fig. 9), is similarly estimated as about 60m/my. Hence if carbonate production shut down completely during the oceanic anoxic event, the environment is likely to have deepened by, at maximum, about 30 m (Wilson and others, 1998). The critical depth for most shallow-water carbonate producers lies in the 10 to 15 m range (Schlager, 1981). Hence an oceanic anoxic event, were it to eliminate all carbonate producers, could theoretically prove lethal to a carbonate platform. Manifestly this has not happened in the case of Resolution Guyot and it seems unlikely that skeletal carbonate production would be totally shut down under such conditions, particularly in relatively shallow-water conditions.

These observations suggest that, if oceanic anoxic events reflect high nutrient abundance in near-surface waters, nutrient excess was not necessarily the proximate cause of platform drowning (compare Hallock and Schlager, 1986). The only caveat to this conclusion would lie in the supposition that long-term exposure to nutrient-rich surface waters was the critical factor and the early Aptian oceanic anoxic event was of too short a duration to curtail carbonate production sufficiently and for long enough to facilitate drowning (Wilson and others, 1998). The history of Anewetak is significant in this context because this living atoll presently fluorishes in the north Pacific but apparently began life as a carbonate system very close to the Equator (0.30° ± 3.30° north, Wilson and others, 1998; fig. 21). In this region, the impact of upwelling might be expected to have been strong: this alone suggests that relatively high nutrient levels were not unfavorable to the development of oceanic carbonate platforms during this time. Other factors must have played a role in platform drowning.

Investigation of the behavior of European carbonate platforms during oceanic anoxic events shows that they may become flooded to a depth great enough to allow the temporary invasion of pelagic conditions but then build back up close to sealevel. Weissert and others (1998), for example, illustrate this phenomenon for the Aptian of part of the Alpine region. During the Cenomanian-Turonian oceanic anoxic event a change in facies to more pelagic sediments followed by ultimate recovery of the platform is documented from Croatia (Jenkyns, 1991; Gušić and Jelaska, 1993) and Spain (Drzewiecki and Simo, 1997). Although, in these cases, the effects of oceanic anoxic events are difficult to disentangle from eustatic sealevel rise, it is apparent that neither phenomenon necessarily causes definitive drowning and is not likely to have been primarily implicated in the formation of guyots.

### DROWNING OF PACIFIC CARBONATE PLATFORMS AND ELEVATED PERI-EQUATORIAL TEMPERATURES

Global sea-surface temperatures, established from climatic models and oxygen-isotope paleothermometry, are widely thought to have been considerably warmer in the Cretaceous than at present (Barron, 1983; Arthur, Dean, and Schlanger, 1985; Barron and others, 1993; Crowley, 1991). However, considerable temporal variation is documented throughout the Period, and tropical sea-surface paleotemperatures are particularly poorly understood. Global paleotemperature curves from a variety of locations (central Pacific, Australia, Antarctica, southern South Atlantic, northern and southern Europe) are in broad agreement and suggest a relatively cool mid and late Aptian (presence of mid-Aptian glendonites in Arctic basins, Kemper, 1987) and early to mid-Albian, with temperatures rising through the late Albian and the Cenomanian to peak in earliest Turonian time and then decline (Douglas and Savin, 1975; Arthur, Dean, and Schlanger, 1985; Kemper, 1987; Kolodny and Raab, 1988; Barrera, 1994; Ditchfield, Marshall, and Pirrie, 1994; Jenkyns, Gale, and Corfield, 1994; Frakes, Probst, and Ludwig, 1994; Pirrie and others, 1995; Huber, Hodell, and Hamilton, 1995; Podlaha, Mutterlose, and Veizer, 1998; Clarke and Jenkyns, 1999). The distribution of *Classopolis* pollen, thought to derive from a warmth-loving conifer, across the former Soviet Union equally suggests that the latest Aptian and early Albian were particularly cool compared with the ensuing Cenomanian stage (Vakhrameyev, 1982). The early to mid Paleocene is generally interpreted as warmer than the Maastrichtian, and the early Eocene was also characterized by global warmth (Haq, 1982; Buchardt, 1978; Shackleton, 1986; Adams, Lee, and Rosen, 1990; Spicer and Parrish, 1990; Zachos, Stoll, and Lohmann, 1994).

On the basis of $\delta^{18}O$ paleothermometry, some authors have suggested that the Maastrichtian Equator was characterized by relatively cool sea-surface conditions (~20°C, D'Hondt and Arthur, 1996). However, remarkably well-preserved metastable carbonates from the margin of Wodejebato Guyot yield Maastrichtian Pacific equatorial sea-surface temperatures *at least* as warm as those of today (~27-29°C, Wilson and Opdyke, 1996). These latter estimates, deriving from very shallow-water carbonates, are self-evidently more applicable to conditions on carbonate platforms than are estimates of paleotemperatures derived from planktonic foraminifera with complicated ontogenetic depth-habitat histories of calcification (compare Houston and Huber, 1998). As shown by Shackleton (1981), oxygen-isotope thermometry undertaken on certain recent planktonic foraminifera from deep-sea sediment can give temperatures cooler by several degrees than the ambient surface water, because calcification takes place at some depth below the sea surface. An additional complication in equatorial pelagic carbonates is diagenesis, which can produce $\delta^{18}O$ values higher than those characteristic of the originally secreted biogenic calcite (Schrag, DePaolo, and Richter, 1995). Exceptionally well-preserved Cretaceous planktonic foraminifera, which have been shown not to undergo significant migration to depth during ontogeny (upper Albian to lower Cenomanian of the subtropical western Atlantic, Norris and Wilson, 1998), yield sea-surface temperatures of 30° to 31°C. These figures compare well with those derived from the Maastrichian rudistid material of Wodejebato.

Given the general supposition, using oxygen-isotope paleothermometry and faunal/floral distributions, that the Maastrichtian was globally cooler than the preceding mid and Late Cretaceous stages (for example, Voigt, 1964; Naydin, Teys, and Zadorozhnyy, 1966; Douglas and Savin, 1975; Wolfe and Upchurch, 1987; Kolodny and Raab, 1988; Arthur, Dean, and Schlanger, 1985; Spicer and Parrish, 1990; Clauser, 1994; Ditchfield, Marshall, and Pirrie, 1994; Huber, Hodell, and Hamilton, 1995), it seems likely that equatorial sea-surface temperatures were above 30°C during the Albian-Campanian interval. This view is consistent with paleotemperature determinations from planktonic foraminifera from the Cretaceous of the Pacific (Price and others, 1998) and Atlantic (Norris and Wilson, 1998) as well as with extrapolated southern-hemisphere paleotemperature trends (Clarke and Jenkyns, 1999).

Estimates of Pacific peri-equatorial paleotemperatures for the early Eocene, based on isotopic investigations of surface-dwelling foraminifera, are in the range of 25°C (Zachos, Stott, and Lohmann, 1994; Bralower and others, 1995). However, these figures, predicated on certain paleoceanographic assumptions, may well reflect conditions in cooler upwelled waters that vented $CO_2$ and not be diagnostic of the shallow-water carbonate environment. The same caveats (position in the water column where calcification takes place, effects of diagenesis) apply as with Cretaceous paleotemperatures generated in the same way. In fact, the distribution of other key benthonic or terrestrial biotic elements (mangroves, zooxanthellate corals, molluscs, and larger foraminifers) suggests that mid-Eocene temperatures in low latitudes were greater than 25°C (Adams, Lee, Rosen, and others, 1990). Certainly the early to mid-Eocene seems to have been characterized by the warmest global paleotemperatures of the last 65 my (for example, Savin, 1977; Sloan and Rea, 1996).

High equatorial paleotemperatures could have been potentially lethal for many carbonate producers, as illustrated by the recent phenomenon of coral bleaching. Studies of Indo-Pacific reefs show that many corals are exposed to temperatures perilously close to their upper survival limit during summer months and that thermal excess can lead to loss of symbiotic zooxanthellae and, ultimately, death of the coral (Jokiel and Coles, 1990; Brown, 1997). Temperatures greater than ~30°C, maintained over as short a time as a few days, are potentially lethal for many corals. Even those heat-tolerant corals that have adapted to very warm conditions (for example, those in the Arabian Gulf, Kinsman, 1964) have succumbed to prolonged periods of warming (Glynn, 1993). In 1983 and 1987 the entire eastern equatorial Pacific, to a depth of 20m, was affected by coral bleaching (Glynn, 1993). Because several recent reef-dwelling carbonate-producing taxa (for example, foraminifers, sponges, hydrocorals, tridachnid clams) contain zooxanthellae or other symbiotic organisms they, too, are potentially at risk when temperatures rise, as are calcareous algae and other species that rely on the reef habitat for shelter and food. Detailed studies on the most abundant recent reef-dwelling algal-symbiont-bearing large foraminifera, *Amphistegina,* has also shown bleaching, loss in population density, and consequent reduction in carbonate production during periods of environmental stress (Williams and others, 1997).

Applying this model to the Cretaceous, and assuming that many carbonate producers were similarly susceptible (a number of rudists, for example, may have possessed zooxanthellae, Vogel, 1975; Cowen, 1983; Kauffman and Johnson, 1988; Gili, Masse, and Skelton, 1995), implies that exposure to elevated temperatures during equatorial crossings could well have crippled major biotic elements of the sediment factory. Destruction of corals and rudists on a carbonate bank could have also have changed a rimmed platform to an open platform (Ginsburg and James, 1974), opening it to the effects of wave- and current-induced erosion and hindering deposition. All these phenomena could readily have caused subsidence to outpace sedimentation, allowing carbonate platforms to drown and guyots to form.

If temperature were the critical factor in curtailing Cretaceous-Paleogene mid-Pacific carbonate production and assuming relatively uniform warming and cooling of the Cretaceous globe across the whole latitudinal range, closer proximity to the Equator would have been required to promote drowning during a "cool" period than a "warm" one. Assuming, furthermore, that equatorial sea-surface temperatures can be extrapolated from north European oxygen-isotope records, prediction matches observation (fig. 19). Takuyo-Daisan drowned nearest to the Equator (earliest Albian: cool) followed by "MIT" (early late Albian time: warmer) a little farther south, followed by Allison and Resolution Guyots farther south still (Albian-Cenomanian boundary time: warm). Global temperatures were relatively cool again in the early Maastrichtian, entirely compatible with the drowning paleolatitude of Wodejebato, relatively close to the Equator; Limalok drowned farther south during the interval of Eocene warmth. Since the paleolatitudinal positions of all investigated guyots at the time of drowning is in agreement with known global Cretaceous and Paleogene paleotemperature variations, the hypothesis that high equatorial temperatures were the proximate cause of platform drowning is particularly attractive. The opposite notion, namely that drowning was, in each case, related to a "cooling event" (Camoin and others, 1998) does not seem sustainable in the light of the present data.

The hypothesis of time-dependent equatorial thermal excess may be tested by viewing the distribution of Cretaceous rudistid "reefs" in the Caribbean, although the picture is complicated by a drastic reduction in taxa around Cenomanian-Turonian boundary time (Johnson and others, 1996). If we assume that the reconstructions of "reef lines" are robust, with the caveat that the reality and significance of rudistid "reefs" is still very much a matter for debate (Skelton and others, 1996), then reef distribution may be used as a proxy for paleotemperatures around the Cretaceous Equator. The Aptian "reef belt" is depicted as having a southern boundary close to the paleo-Equator (Johnson and others, 1996). A marked expansion of this belt took place during the early and middle Albian with a later contraction and northward movement of the southern boundary away from the Equator during the latest Albian, Cenomanian, Turonian, and Coniacian. This in turn was followed by expansion again and southerly advance of the same boundary toward the Equator during the Santonian through to Campanian-Maastrichtian time. The Maracaibo Platform, northwestern Venezuela, which was positioned a few degrees north of the Equator during the mid-Cretaceous, was initiated during the Aptian and drowned during the late Albian (Vahrenkamp and others, 1993). These paleobiogeographic and sedimentary histories are compatible with published global paleotemperature curves (fig. 19). The thermal regime around the Cretaceous Equator was, during latest Albian, Cenomanian, Turonian, and Coniacian times, apparently so extreme that it was inimical to many reef-dwelling taxa and consequently curtailed production of carbonate sediment. The apparent absence of guyot carbonates of Cenomanian-Santonian age in the north Pacific (fig. 20) may in part reflect this temperature excess.

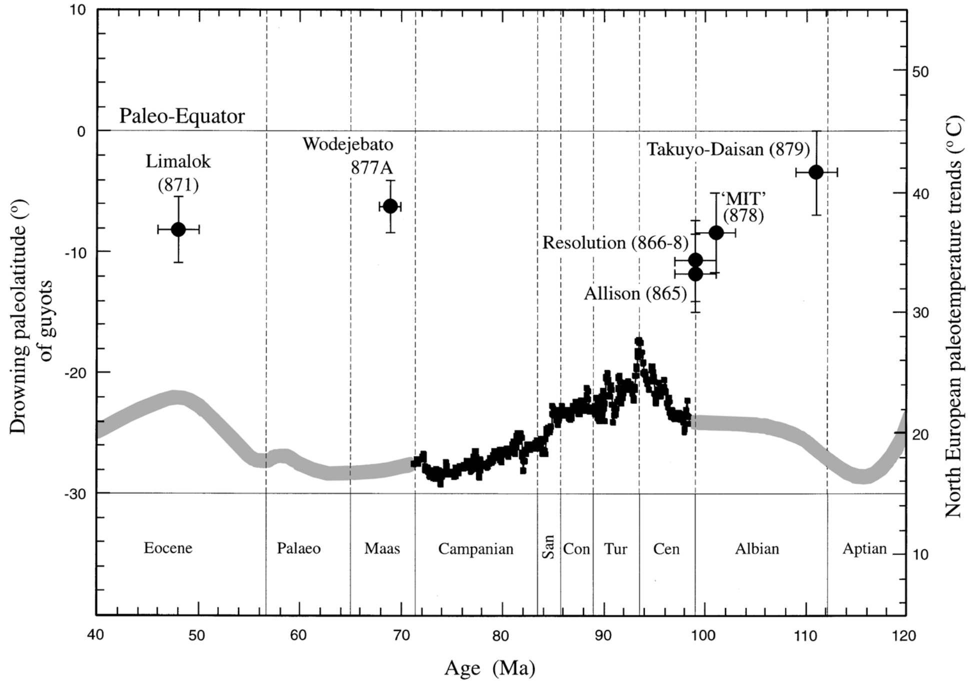


Fig. 19. Paleolatitudes of guyots at the time of formation: that is, at the time of carbonate-platform drowning. Data from Wilson and others (1998). Paleotemperature trends from northern Europe are derived from Arthur, Dean, and Schlanger (1985) who give a general curve, based on oxygen-isotope data from Cretaceous belemnites and inoceramids; from Kemper (1987) based on a regional study of Cretaceous climate-sensitive facies; from Jenkyns, Gale, and Corfield (1994) who give oxygen-isotope data and paleotemperature curves from the English Chalk, and Buchardt (1978) who gives oxygen-isotope data and a paleotemperature curve for the Tertiary of the North Sea. These trends, albeit with higher absolute values, are assumed to be applicable to the Cretaceous and Tertiary peri-equatorial Pacific. Note how drowning took place closer to the Equator during cooler intervals and vice versa. Tertiary time scale after Harland and others (1990); Mesozoic time scale after Gradstein and others (1994).

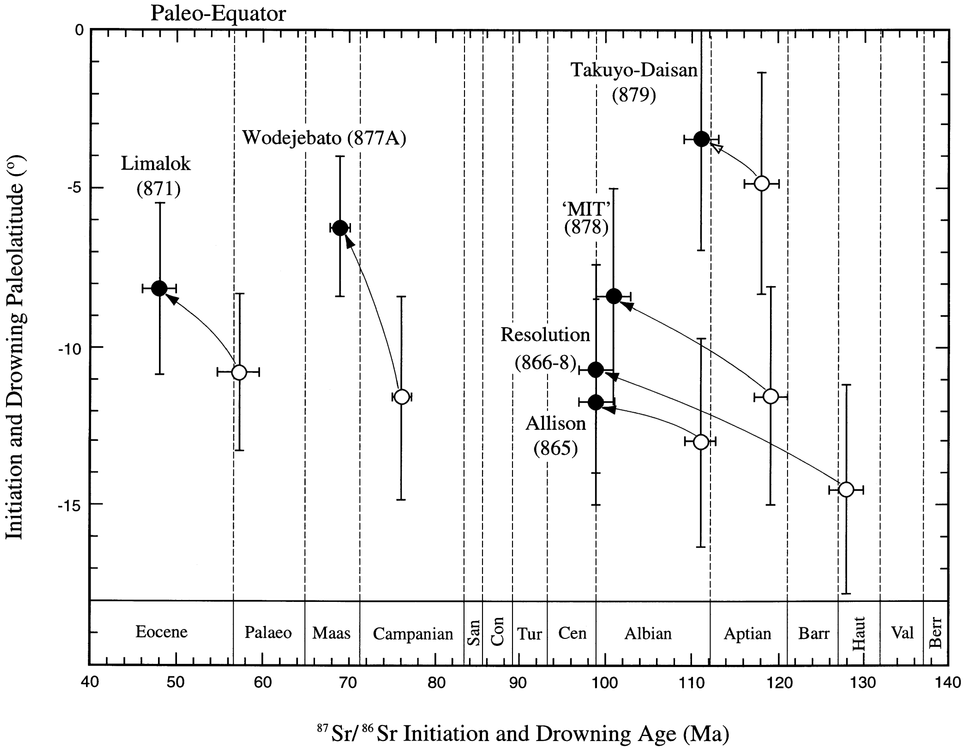


Fig. 20. Palaeolatitudes of guyots at the time of carbonate-platform initiation (unfilled circles) and drowning (filled circles). Data from Wilson and others (1998). Note how Takuyo Daisan was initiated as a carbonate-platform system at latitudes more northerly than those at which the other investigated guyots drowned. Note also the absence of shallow-water guyot carbonates of Cenomanian-Santonian age, interpreted as related to excessive peri-equatorial warmth. Tertiary time scale after Harland and others (1990); Mesozoic time scale after Gradstein and others (1994).

Once the carbonate factory was effectively crippled, other factors, such as pulses of sealevel change or intensified upwelling, could have provided the *coup de grace* that resulted in definitive drowning.

### ONSET OF CARBONATE-PLATFORM DEPOSITION AND ELEVATED PERI-EQUATORIAL TEMPERATURES

Another approach is to look at the paleolatitudes where carbonate platforms were initiated on guyots in order to discover whether those edifices that began to accumulate shallow-water sediment nearest to the Equator did so during a relatively cool interval. The timing of the onset of carbonate-platform sedimentation translates into the following paleolatitudes (Wilson and others, 1998):

Resolution Guyot: 14.50° ± 3.30° south.
Allison Guyot: 13.00° ± 3.30° south
"MIT" Guyot: 11.55° ± 3.45° south.
Takuyo-Daisan Guyot: 4.80° ± 3.50° south.
Wodejebato Guyot: 11.60° ± 3.20° south
Limalok Guyot: 10.80° ± 2.50° south

As shown in figure 20, the shallow-water carbonate system of Takuyo-Daisan became established at a paleolatitude more northerly than the drowning paleolatitude of all the other investigated guyots. This is explicable if global paleotemperatures were particularly depressed around the mid-Aptian (fig. 21). Such a circumstance has been suggested by Kemper (1987), based on a regional study of the occurrence and distribution of glendonites in shallow-water Cretaceous sediments and is in accord with palynological data from the former Soviet Union (Vakhrameyev, 1982) and established regional oxygen-isotope trends. Takuyo-Daisan drowned as it approached the Equator and global temperatures rose. Similar short-lived carbonate platforms apparently characterized other guyots of the Japanese Seamount Provice (fig. 1) because they typically possess only thin deposits of shallow-water limestones (Winterer and others, 1993).

As noted above, Anewetak Atoll apparently began life as a carbonate system very close to the Equator (0.30° ± 3.30° north, Wilson and others, 1998; fig. 21). The age of the volcanic basement of Anewetak is given as 75.9 ± 0.6 Ma (Lincoln, Pringle, and Premoli Silva, 1993), which would be placed in the mid-Campanian on the timescale of Gradstein and others (1994). However, biostratigraphy (Todd and Low, 1960) and strontium-isotope stratigraphy (Saller and Koepnick, 1990) suggest that shallow-water carbonate sedimentation, at least locally, began considerably later, during late Eocene time (~40 Ma), signifying the presence of a considerable hiatus in deposition. Hence,

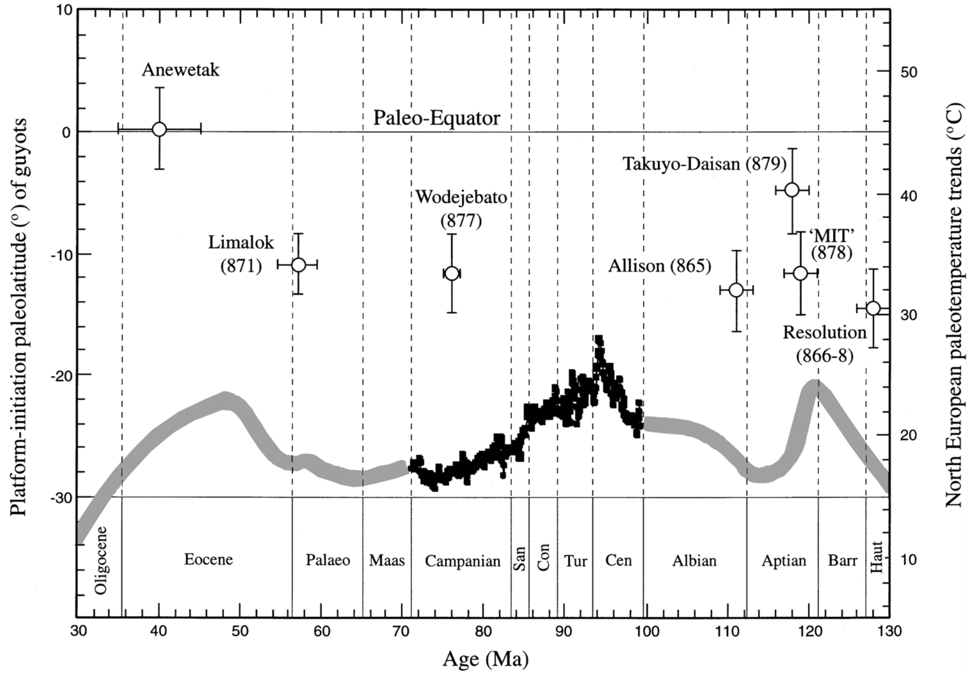


Fig. 21. Paleolatitudes of guyots at the time of carbonate-platform initiation. Data from Wilson and others (1998). Paleotemperature trends from northern Europe are derived from Arthur, Dean, and Schlanger (1985) who give a general curve based on oxygen-isotope data from Cretaceous belemnites and inoceramids; from Kemper (1987) based on a regional study of Cretaceous climate-sensitive facies; from Jenkyns, Gale, and Corfield (1994) who give oxygen-isotope data and paleotemperature curves from the English Chalk, and Buchardt (1978) who gives oxygen-isotope data and a paleotemperature curve for the Tertiary of the North Sea. These trends, albeit with higher absolute values, are assumed to be applicable to the Cretaceous and Tertiary peri-equatorial Pacific.

Note how Takuyo Daisan began its carbonate production relatively close to the Equator during the cool mid-Aptian, at paleolatitudes more northerly than those where other platforms drowned to produce guyots (fig. 19). Takuyo Daisan drowned as it approached the Equator and global temperatures rose. Anewetak was able to initiate carbonate production close to the Equator during the late Eocene when global temperatures were cooling dramatically and exists as an atoll to the present day. Tertiary time scale after Harland and others (1990); Mesozoic time scale after Gradstein and others (1994).

Anewetak may have existed as a purely volcanic island during the intervening period between eruption of the lava pile and initiation of large-scale platform-carbonate deposition. However, nearby Wodejebato (fig. 1), whose basement age is ~83 Ma, earliest Campanian (Pringle and Duncan, 1995b) has a platform-initiation and drowning age of ~76 Ma, late Campanian and ~69 Ma, early late Maastrichtian, respectively (Wilson and others, 1998). Thus a short-lived fringing reef of similar Late Cretaceous age could be predicted to have developed around Anewetak. Poor recovery in the lowest levels of the critical Enewetok core hampers investigation of this problem (Todd and Low, 1960). Furthermore, strontium-isotope stratigraphy is not helpful, because the $^{87}Sr/^{86}Sr$ values of the latest Cretaceous are effectively the same as those of the late Eocene (Hess, Bender, and Schilling, 1986; Howarth and McArthur, 1997). It is possible that carbonate-platform sediments of latest Cretaceous age do exist atop part of the igneous basement of Anewetak.

Subsequent to the formation of any short-lived Late Cretaceous carbonate platform on Anewetak, a volcanic island must have persisted as a significant subaerial feature, while conditions continued to be unfavorable for accumulation of shallow-water carbonates as the edifice approached and ultimately crossed the Equator. Because Limalok drowned at ~48 Ma, early mid-Eocene (fig. 18), equatorial proximity was apparently not favorable for shallow-water carbonate sedimentation at this time. However, by the latest Eocene, global temperatures were declining, with the likely first appearance of ice sheets on Antarctica (Miller, 1992; Zachos, Stott, and Lohman, 1994). The presence of somewhat cooler equatorial waters at this time, similar in temperature to those of today, could have permitted initiation of the carbonate-platform on and around the long-lived volcanic island that developed into Anewetak Atoll.

## CONCLUSIONS: THE PERI-EQUATORIAL DANGER ZONE AND DISTRIBUTION OF ATOLLS AND GUYOTS

As originally noted by Hess (1946), guyots are a characteristic feature of the northwest Pacific, being relatively rare elsewhere in the world ocean. The maps of Menard (1964) and Vogt (1989) suggest that some 80 to 90 percent of Cretaceous Pacific guyots reside north of the Equator as would be predicted if an equatorial crossing were instrumental in their formation. This figure is meaningful, even though there is more Cretaceous and pre-Cretaceous ocean crust to the north of the Equator than there is to the south ($37.5 \times 10^6 km^2$ versus $23.2 \times 10^6 km^2$, Sclater, Jaupart, and Galson, 1980). Furthermore, not all Cretaceous guyots are necessarily drowned carbonate platforms. Menard (1964) documents a number of other possible origins: some may be erosionally truncated volcanoes, as originally suggested by Hess (1946); others may be calderas filled with pelagic sediment. The section drilled on one guyot during ODP Leg 144 (Lo-En Guyot) is composed of pelagic sediment resting directly on volcanic basement, and hence the edifice lacks a continuous carbonate-platform cap (Premoli Silva, Haggerty, Rack and others, 1993). Furthermore, some of the guyots in the Wake Seamount Group (fig. 1) seem to be entirely volcanic (Winterer and others, 1993). Guyots lying in the more southerly reaches of the Pacific or situated in other oceans may be of this type.

A case can be made for both inimical water chemistry and thermal excess in peri-equatorial regions as the proximate cause of the drowning of Pacific Cretaceous carbonate platforms and the creation of guyots. Presently available data do not allow us to choose definitively between these two hypotheses, and the two mechanisms may well have acted in concert. However, since Resolution and "MIT" Guyots survived the early Aptian oceanic anoxic event–and its impact is definitely registered by deposition of organic-rich shale (Selli Level) on the former guyot–the proposed phenomenon of nutrient excess and high productivity is deemed of lesser importance. The presence of upwelled $CO_2$-rich near-surface peri-equatorial waters could have acted as a chemical deterrent to precipitation of calcium carbonate. However, the fact that Anewetak

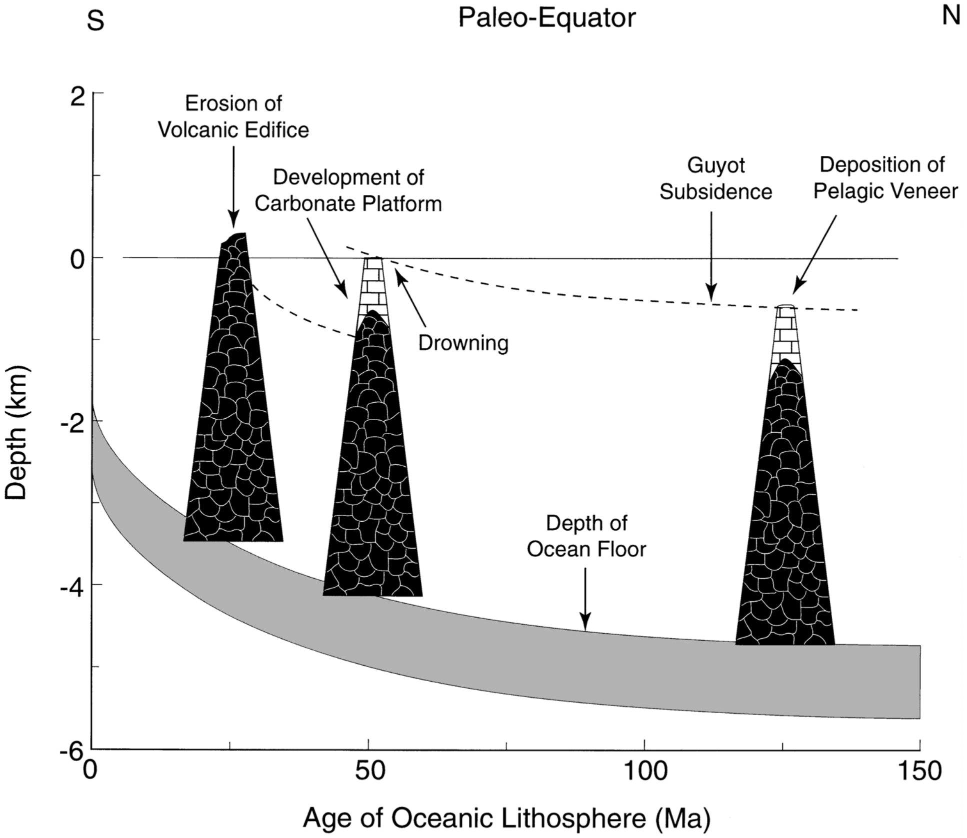


Fig. 22. Model to illustrate formation of north Pacific guyots. Eruption of volcanic edifice above sealevel is followed by erosion, subsidence, and, if surface temperatures are not excessive, subsequent development of a carbonate platform. As this platform approaches the Equator and ambient sea-surface temperatures rise, the rate of carbonate production declines, allowing subsidence to outpace sedimentation and guyots to form. A veneer of pelagic sediment is deposited atop the drowned carbonate platform.

became established as a carbonate platform close to the Equator during the late Eocene or earlier militates against inimical water chemistry as being an invariable obstacle to deposition.

On balance, it seems that running the gauntlet of the equatorial high temperatures characteristic of the Cretaceous (and Eocene) "greenhouse" Earth was the principal hazard encountered by volcanically floored carbonate platforms as plate-tectonic transport conveyed them into the peri-equatorial danger zone. Here, carbonate secretion and precipitation became increasingly difficult until drowning took place and guyots formed (fig. 22). Submarine processes of dissolution could then operate as the guyot sank into progressively deeper water. Plate movement pushed the edifices into the north Pacific as a mantle of pelagic sediment settled upon the drowned shallow-water carbonate surface.

## ACKNOWLEDGMENTS

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