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## Oxygen isotope systematics in *Diploastrea heliopora*: New coral archive of tropical paleoclimate

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**Abstract**—*Diploastrea heliopora* forms dense, robust, dome-shaped coral colonies throughout the reef ecosystems of the tropical Pacific and Indian Oceans. This slow-growing (2 to 6 mm/yr) coral has the potential to yield continuous paleoclimate records spanning up to 1000 yr for the warmest waters on Earth, the Indo-Pacific Warm Pool, and has a long fossil history as a single recognizable species. Despite the potential of *Diploastrea* to be an important new paleoclimate archive, little is known about the systematics of geochemical tracers incorporated into its skeleton. To fill this knowledge gap, we compared skeletal  $\delta^{18}\text{O}$  signatures in live *Diploastrea* and *Porites* colonies from Southwest Lagoon, near Amédée Lighthouse, New Caledonia (at the southern latitudinal limit for *Diploastrea*) and Alor, Indonesia (in the core area of the Indo-Pacific Warm Pool). We designed a new microsampling technique to minimize smoothing and distortion of the isotopic records due to the complex calyx architecture and slow growth of *Diploastrea*. High-resolution isotope profiles from the septal portion of the *Diploastrea* corallite are attenuated, whereas those restricted to the central columella are similar in quality to those extracted from the well-established *Porites* coral archive. The  $\delta^{18}\text{O}$ -temperature relationship for the columellar portion of *Diploastrea* ( $-0.18\text{‰}/^{\circ}\text{C}$ ) is in good agreement with that derived for a nearby *Porites* ( $-0.19\text{‰}/^{\circ}\text{C}$ ; Quinn et al., 1996), on the basis of comparison with an in situ sea surface temperature record from Amédée Lighthouse. There is a measurable difference of  $0.3 \pm 0.1\text{‰}$  between the kinetic/biological disequilibrium offsets from seawater  $\delta^{18}\text{O}$  composition for *Diploastrea* and *Porites*. Despite this offset in mean  $\delta^{18}\text{O}$ , *Diploastrea* accurately records the regional differences in mean temperature and salinity between New Caledonia and the Indo-Pacific Warm Pool. Additional tests show that *Diploastrea* records El Niño–Southern Oscillation (ENSO) interannual variability in sea surface temperature and salinity across the southwestern Pacific, indicating that it should yield dependable paleo-ENSO records. Based on these results, we propose that *D. heliopora* has the potential to provide an important new coral archive of tropical paleoclimate. Copyright © 2003 Elsevier Science Ltd

### 1. INTRODUCTION

Massive corals are useful paleoclimate archives because they are widely distributed throughout the tropics, can be accurately dated, and contain a wide array of geochemical tracers within their skeletons (Dunbar and Cole, 1999; Gagan et al., 2000). The quality of the evolving network of coralline paleoclimate records will inevitably depend upon its length, accuracy, and ability to resolve events spanning seasonal to century time scales. So far, most studies of past climate have used the coral genus *Porites* because it is abundant throughout the climatically influential Indo-Pacific region and can be sampled at high temporal resolution because it grows quickly (8 to 24 mm/yr). At present, however, continuous geochemical records from *Porites* do not extend beyond the past ~300 to 400 yr (Druffel and Griffin, 1993; Linsley et al., 1994; Quinn et al., 1998; Hendy et al., 2002). The same age barrier has been met in published studies of *Pavona* from the equatorial eastern Pacific (Dunbar et al., 1994) and *Montastrea* from the Caribbean (Watanabe et al., 2000; Winter et al., 2000).

Recently, there has been a concerted effort to develop iso-

topic techniques appropriate for exceptionally slow-growing (0.2 to 1.0 mm/yr) coralline sponges (Böhm et al., 2000), which can live for > 400 yr (Swart et al., 1998). Although coralline sponges appear to be well suited for recording century- to decade-scale climate changes (Böhm et al., 1996; Moore et al., 2000), they lack annual density bands and must be dated radiometrically, thus potentially limiting their accuracy as recorders of seasonal to interannual climate variability. Also, coralline sponges are not abundant in the fossil record, which limits their ability to provide time slice reconstructions of Late Quaternary climates.

On the other hand, the massive annually banded coral *Diploastrea heliopora* is known to live for up to 1000 yr (T. Corrège, unpublished data) and has inhabited the tropical reef ecosystems of the Indian Ocean, Caribbean Sea, and Tethys Sea since the Oligocene as a single distinctive species (Veron, 2000). Today, *Diploastrea* is common throughout the tropical Indian and Pacific Oceans and grows slowly (2 to 6 mm/yr), even in the warm waters of the Indo-Pacific Warm Pool, where the coral *Porites* tends to grow quickly and die relatively young. *Diploastrea* is known to be less prone to boring organisms and grazing fish than *Porites* (Veron, 2000). The robust, dense skeleton of *Diploastrea* is also well preserved in Late Quaternary raised coral reefs within the Warm Pool region,

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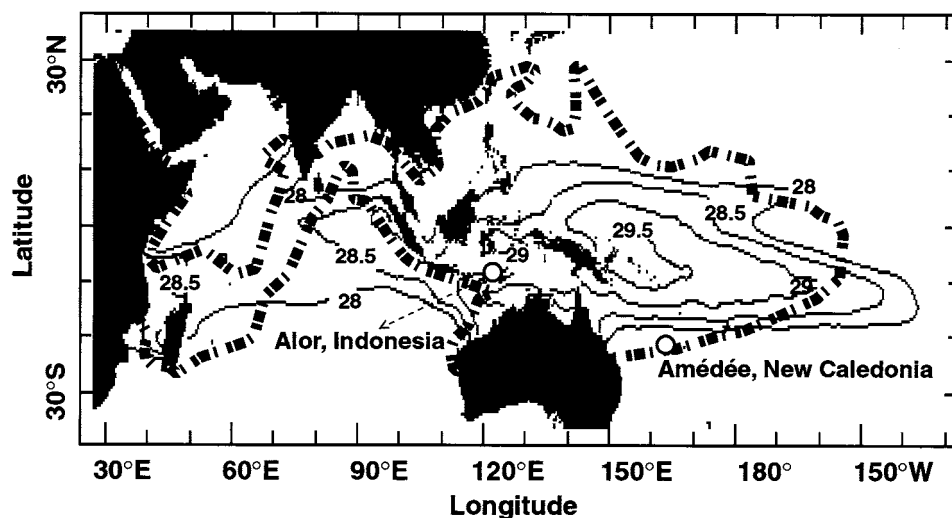


Fig. 1. Location of sampling sites for comparison of oxygen isotope ratios in *Diploastrea heliopora* and *Porites*: Southwest Lagoon near Amédée, New Caledonia, and Pantai Putih, Alor, Indonesia. Dashed line shows the known range of *D. heliopora* (Veron, 2000) in relation to the Western Pacific Warm Pool (mean sea surface temperature > 28°C; [http://iridl.ldeo.columbia.edu/SOURCES/NOAA/NCEP/EMC/CMB/GLOBAL/Reyn\\_SmithOIv2/climatology/sst](http://iridl.ldeo.columbia.edu/SOURCES/NOAA/NCEP/EMC/CMB/GLOBAL/Reyn_SmithOIv2/climatology/sst)).

including Indonesia (Chappell and Veeh, 1978; Pirazzoli et al., 1991; Hantoro et al., 1994), Papua New Guinea (Chappell, 1974), and Vanuatu (Burr et al., 1998; Cabioch et al., 1998).

Despite the potential of *D. heliopora* to advance our understanding of tropical climate variability, little is known about its geochemistry, with the exception of a study of radiocarbon variability in a fossil *Diploastrea* from the raised reefs of Espiritu Santo, Vanuatu (Burr et al., 1998). In this study, we test the ability of  $\delta^{18}\text{O}$  in *Diploastrea* to record the full range in the temperature and oxygen isotopic composition of seawater (Epstein et al., 1951; Weber and Woodhead, 1972) across its known range of survival (Fig. 1). We experimented with microsampling protocols for *Diploastrea* specimens from two different physiographic and oceanic settings: the Southwest Lagoon, near Amédée Lighthouse, New Caledonia, at the southern latitudinal limit for *Diploastrea*, and Alor, Indonesia, in the core area of the Indo-Pacific Warm Pool. The oxygen isotope systematics for the coral *Porites* are reasonably well established for the western Pacific region, so we produced oxygen isotope records for pairs of *Diploastrea* and *Porites* from both oceanic settings to compare the quality of the isotopic signals recorded by the two corals.

## 2. STUDY AREA

### 2.1. Southwest Lagoon, New Caledonia

A continuous core of *D. heliopora* was collected on March 29, 1996, using an underwater hydraulic drill in the Southwest Lagoon of New Caledonia, 15 km northwest of Amédée Lighthouse (22°29'S, 166°27'E; Fig. 1). This specimen of *Diploastrea* grew in an open, well-flushed reef environment at a depth of ~3 m below mean low tide. We compared the oxygen isotope record for the *Diploastrea* with the oxygen isotope record of Quinn et al. (1996) for a *Porites* growing in a similar reef environment 4 km from Amédée. Sea surface temperature (SST) and sea surface salinity (SSS) have been monitored

almost continuously at Amédée Lighthouse since February 28, 1967, by the Institut de Recherche pour le Développement. The in situ SST record is used to establish the temperature dependence of  $\delta^{18}\text{O}$  in *D. heliopora*. Mean SST at Amédée during the calibration period (1980 to 1996) was 23.4°C, with a mean seasonal range of 5.2°C. New Caledonia is located on the southeastern pole of the Asian-Australian monsoon system and receives annual average rainfall of 1050 mm, with an average monthly maximum of 150 mm in March and a minimum of 40 mm in September. Despite the seasonal rainfall, SSS at Amédée from 1980 to 1996 was a relatively constant 35.7 psu, with an average seasonal range of 0.6 psu.

### 2.2. Alor, Indonesia

An underwater hydraulic drill was deployed to retrieve vertical cores from live colonies of *D. heliopora* and *Porites* on September 13 and 14, 1999, from the fringing reef at Pantai Putih, Alor, Indonesia (8°14'S, 124°24'E; Fig. 1) for comparison with the coral  $\delta^{18}\text{O}$  records from New Caledonia. The *Diploastrea* and *Porites* were located ~50 m apart in similar water depths (tops of colonies 2.5 to 3.5 m below mean low tide) to ensure that both coral specimens grew in comparable reef environments. The ocean water surrounding Alor is among the warmest on Earth; mean SST for the  $1^\circ \times 1^\circ$  box centered at 124.5°E, 8.5°S (Integrated Global Ocean Services System nmc blended ship and satellite data; Reynolds and Smith, 1994) was 28.3°C (2.3°C range) for the calibration period from 1985 to 1999, which is 4.9°C warmer than the mean SST of New Caledonia. Monsoon rainfall is higher in Alor than in New Caledonia, averaging 2000 mm/yr, and highly seasonal, with an average monthly maximum of 245 mm in March and a minimum of 16 mm in September. Mean SSS in Alor (34.3 psu), estimated from National Oceanic and Atmospheric Administration, National Center for Environmental Prediction satellite

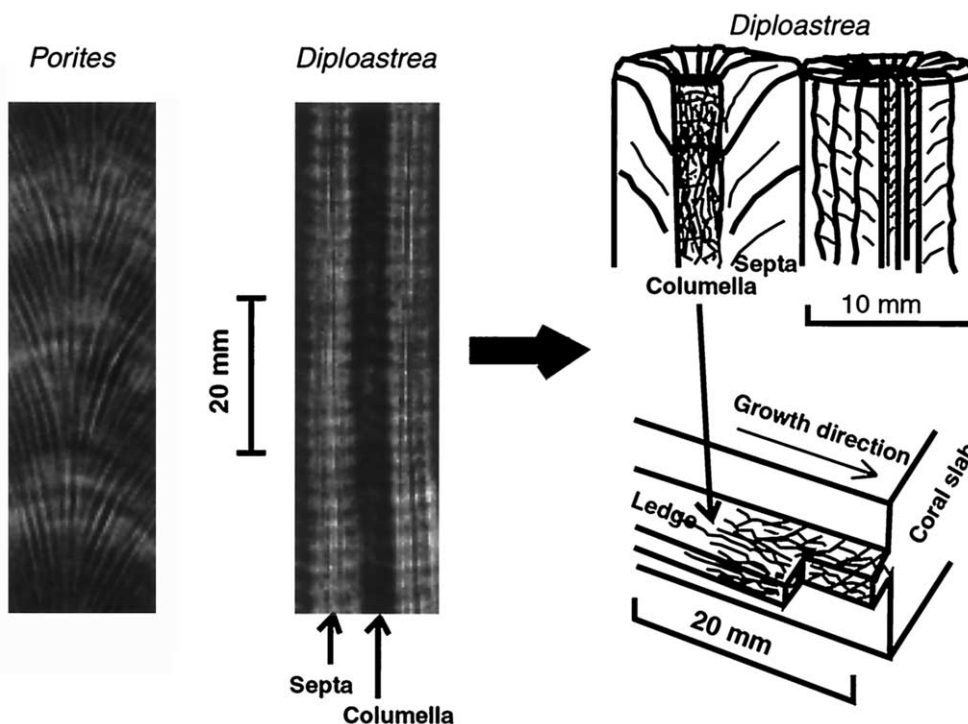


Fig. 2. X-radiograph positive prints of coral density banding showing difference in growth rates for the *Porites* from Alor (~20 mm/yr, left) and *Diploastrea heliopora* from New Caledonia (~3 mm/yr, right). Couplets of high skeletal density (dark bands) and low skeletal density (light bands) represent one annual growth increment. Far right: schematic diagram of coral ledge configuration and micromilling technique used for high-resolution microsampling of transects within the columellar and septal areas of *Diploastrea*.

data, is substantially lower (1.4 psu) than the mean salinity at Amédée, New Caledonia.

### 3. MATERIALS AND METHODS

#### 3.1. Skeletal Architecture and Sampling Considerations

Colonies of *D. heliopora* are easily identified in the reef environment by their dome-shaped habit, smooth growth surfaces, and convex corallites (Veron, 2000). Individual corallites are 10 mm in diameter. Each corallite comprises a straight, prominent columella (3 mm in diameter) surrounded by radiating septa that thicken toward the corallite wall. Upper growth surfaces of septa slope downward from the columella at an angle of 45°, forming 5-mm-high cone-shaped tops. The important point is that the sloping growth surfaces in the septal region of the corallite are not perpendicular to the main direction of coral growth. Thus, it became clear that microsampling of both columellar and septal skeletal elements would produce a complex paleo-environmental record reflecting a mixture of carbonate material precipitated over a period of several months.

To address this issue, we designed a microsampling approach to investigate the nature of the isotopic signals retrieved from the columellar compared to septal areas of *D. heliopora*. All cores were slabbled at 7 mm thickness parallel to the axis of maximum growth and X-rayed. In addition to showing the position of the columellar and septal areas of *Diploastrea*, the X-rays revealed distinct density band couplets that are 4 to 5 times narrower than those in *Porites* growing in the same reef setting (Fig. 2). To test for the potential effect of signal smoothing in the septal area of *Diploastrea*, we prepared two parallel sampling transects, one restricted to the columella and the other restricted to the septal area of the corallite. The experiment was carried out on the *Diploastrea* from New Caledonia, where seasonal variations in SST are large and any smoothing of the  $\delta^{18}\text{O}$  signal in the septal region should be obvious. We adopted the ledge microsampling technique of Gagan

et al. (1994), whereby a 2-mm-thick ledge is prepared and ultrasonically cleaned before microsampling (Fig. 2). This was accomplished by immersing the coral slab in distilled water and focusing a powerful ultrasonic beam repeatedly onto either side of the ledge to remove surficial contaminants and, in the case of *Porites*, to disintegrate dissepiments. Horizontal dissepiments are precipitated near the base of the living coral tissue at depth within the skeleton of *Porites* and, if they are not selectively removed, can potentially cause substantial smoothing of the isotopic record (Barnes and Lough, 1993; Gagan et al., 1994).

#### 3.2. Microsampling Technique

Computer-controlled microsamples of 100  $\mu\text{m}$  in thickness were collected from both columellar and septal transects in the New Caledonia *Diploastrea* to ensure that the records were comparable at 25 samples per annual growth increment, on the basis of the width of density band couplets observed in X-radiographs. In the first instance, the anastomosing network of skeletal elements forming the columella was shaved continuously along a strip with a 2 mm  $\times$  2 mm cross-sectional area centered within the columella. To obtain a clean cut and samples of equal mass (400  $\mu\text{g}$ ), we used a slowly rotating (90 rpm), 2-mm-diameter end-mill bit that traverses slowly (0.2 mm/s) across the cutting surface. After the sample powder was collected, an additional 1 mm was cut and discarded to ensure that the next sample was collected from a flat cutting surface. An identical protocol was used to collect microsamples from a septal transect adjacent to the columellar sampling transect.

Microsamples for the *Diploastrea* and *Porites* specimens from Alor were collected in the same manner and at a frequency (25 samples/yr) comparable to that used for the *Diploastrea* from New Caledonia. The sampling frequency for the *Porites* from New Caledonia is 12 samples/yr (Quinn et al., 1996).

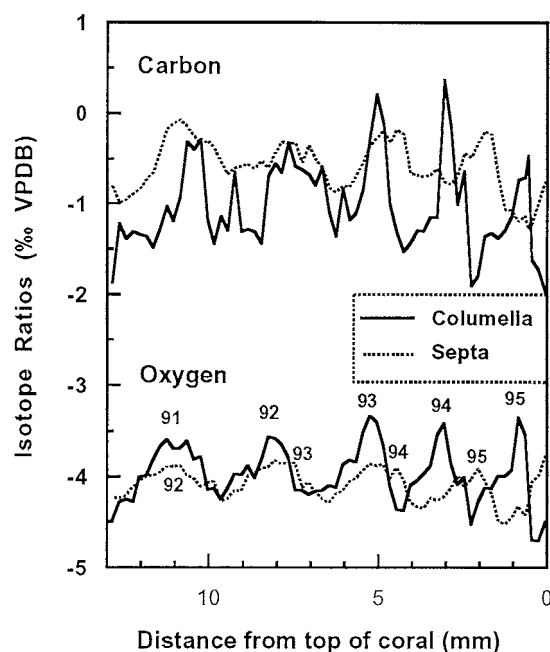


Fig. 3. Comparison of seasonal range in skeletal  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  for high-resolution sampling transects from the columellar (solid line) and septal (dashed line) areas of the *Diploastrea heliopora* from Amédée, New Caledonia. The smoothing and offset of the seasonal  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  signals in the septal area is caused by the  $\sim 45^\circ$  slope and thickening of septal skeletal elements through time (averaging of signal). Years are labeled in  $\delta^{18}\text{O}$  profile (1991 to 1995) to show  $\sim 6$ - to 12-month offset (one half to one seasonal cycle) between data collected from septal and columellar transects. VPDB = Vienna Pee Dee belemnite.

### 3.3. Oxygen and Carbon Isotope Analysis

Sample aliquots of 180 to 220  $\mu\text{g}$  were analyzed for oxygen ( $\delta^{18}\text{O}$ ) and carbon ( $\delta^{13}\text{C}$ ) isotope ratios by reacting the powders with 103% phosphoric acid at  $90^\circ\text{C}$  using an automated individual-carbonate reaction device (Kiel device) coupled to a Finnigan MAT 251 mass spectrometer. Isotopic ratios are expressed in conventional delta notation in per mil units relative to Vienna Pee Dee belemnite through measurements of the isotopic ratio of  $\text{CO}_2$  gas derived from National Bureau of Standards NBS-19 ( $\delta^{18}\text{O}$ :  $-2.20\text{‰}$ ,  $\delta^{13}\text{C}$ :  $1.95\text{‰}$ ) and NBS-18 ( $\delta^{18}\text{O}$ :  $-23.00\text{‰}$ ,  $\delta^{13}\text{C}$ :  $-5.00\text{‰}$ ). Average internal precision for NBS-19 was  $0.04\text{‰}$  for  $\delta^{18}\text{O}$  and  $0.04\text{‰}$  for  $\delta^{13}\text{C}$  ( $n = 158$ ) during the course of the measurements.

The oxygen isotopic analysis of seawater followed a modified version of the  $\text{H}_2\text{O}-\text{CO}_2$  equilibration technique (Epstein and Mayeda, 1953) described by Socki et al. (1992). Three-milliliter water samples were equilibrated with 7 ml of  $\text{CO}_2$  gas for  $\sim 40$  h at  $25.0 \pm 0.1^\circ\text{C}$ . The equilibrated  $\text{H}_2\text{O}-\text{CO}_2$  gas was then injected into a vacuum line for  $\text{CO}_2$  extraction. The  $\delta^{18}\text{O}$  value of the purified  $\text{CO}_2$  was measured on a Finnigan MAT 251 mass spectrometer and expressed relative to Vienna Standard Mean Ocean Water (SMOW).

## 4. RESULTS AND DISCUSSION

### 4.1. Oxygen Isotope Ratios in Columella Compared to Septa

Figure 3 shows  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  profiles for the columella and septa in the same corallite of the *D. heliopora* from New Caledonia over five annual growth increments (1991 to 1995). The results demonstrate that the seasonal range in  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  from the septal sampling transect is significantly attenu-

ated relative to that of the columella. In addition, the position of the isotopic seasonal cycle is offset between the columellar and septal sampling transects in terms of its distance from the outer growth surface of the coral. Isotopic signals extracted from skeleton residing midway within the living tissue layer at the time the coral was collected are offset by about one half of a seasonal cycle (6 months). Signals that have passed through the entire tissue layer are offset by about one full seasonal cycle (12 months).

The smoothing and offset in position of the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  records extracted from the septa of *Diploastrea*, relative to that from the columella, is likely to be caused by two factors: corallite geometry and calcification at depth within the tissue layer. The  $45^\circ$  inclination of the growth surfaces of septa relative to the direction of coral growth means that each microsample contains skeleton precipitated over a longer period of time compared to microsamples collected within the columella. An additional smoothing process could involve the thickening of septa through time as they pass through the tissue layer, as has been observed to some extent for *Porites* (Barnes and Lough, 1993). In *Diploastrea*, the bulk of septal calcification appears to occur near their outer edge and base, where the septa thicken and interlock with other septa along the walls of adjacent corallites. This basal thickening of the septa in *Diploastrea* and their  $45^\circ$  inclination may explain the offset of about one half of a seasonal cycle between isotopic profiles produced from septal and columellar transects. The specimen from New Caledonia grows at 3 mm/yr (see section 4.2). Thus, for the case of the *Diploastrea* used in this experiment, the septal record reflects the concentration of calcification toward the base of the septa, 1.5 to 3.0 mm down from the top of the columella, a distance that is equivalent to about one half to one seasonal cycle in  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ .

These results agree with studies of *Montastrea* in which it has been found that skeletal structures may calcify at different times and that the amplitude of the seasonal  $\delta^{18}\text{O}$  profile produced by bulk sampling is significantly reduced and irregular (Pätzold, 1992; Leder et al., 1996; Watanabe et al., 2002). However, attenuation of isotopic signals in *D. heliopora* can be avoided because the large corallite and distinct separation of columellar and septal structures allow samples to be collected from specific skeletal elements. The results indicate that calcification in the columella may be primarily restricted to the area at the top of the corallite. Therefore, only columellar skeletal elements should be sampled to minimize any smoothing and distortion of the isotopic signal caused by the complex corallite architecture and slow growth of *Diploastrea*.

### 4.2. Skeletal Calcification Rate and Oxygen Isotope Disequilibrium

It has been shown that corals do not precipitate their skeletons in isotopic equilibrium with ambient seawater (Weber and Woodhead, 1972; Land et al., 1975; Goreau, 1977; Erez, 1978; Swart, 1983; McConnaughey, 1989a, 1989b; Heikoop et al., 2000). The result of this isotopic disequilibrium in corals is the simultaneous depletion of the heavy isotopes  $^{13}\text{C}$  and  $^{18}\text{O}$  during the  $\text{CO}_2$  hydration and hydroxylation reactions involved in calcification (McConnaughey, 1989a, 1989b). In the case of oxygen isotopes, it has been suggested that this kinetic offset

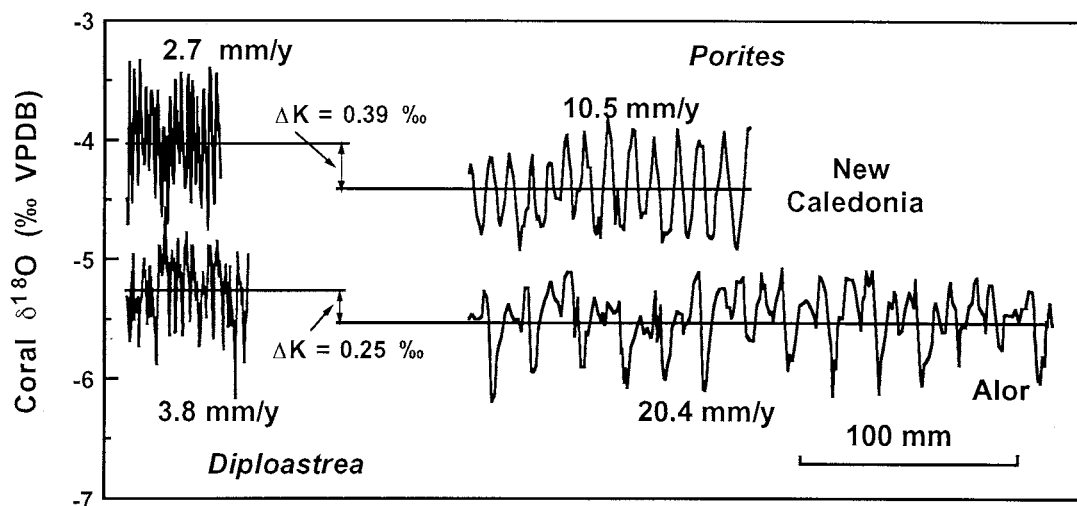


Fig. 4. Comparison of columellar skeletal  $\delta^{18}\text{O}$  records and growth rates for *Diploastrea heliophora* and *Porites* corals from Amédée, New Caledonia, and Pantai Putih, Alor. Horizontal lines show mean  $\delta^{18}\text{O}$  values for each record. The difference in the disequilibrium offset from seawater  $\delta^{18}\text{O}$  composition for *Diploastrea* and *Porites* ( $\Delta K$ ) is 0.39‰ at New Caledonia and 0.25‰ at Alor. Data for *Porites* from New Caledonia are from Quinn et al. (1996). VPDB = Vienna Pee Dee belemnite.

from equilibrium is constant within a given coral genus (Weber and Woodhead, 1972). However, there is evidence that kinetic isotope or “vital effects” are not necessarily constant within a coral genus, or even within individual coral colonies (McConnaughey, 1989a; Aharon, 1991; de Villiers et al., 1995; Wellington et al., 1996; Cohen and Hart, 1997; Guilderson and Schrag, 1999; Linsley et al., 1999).

A key question is whether biologic controls on  $^{18}\text{O}/^{16}\text{O}$  fractionation are sufficiently constant within a coral genus across its known range of survival to use a given coral for paleoclimate reconstruction. This study was designed to determine if the  $\delta^{18}\text{O}$  values for slow-growing *D. heliophora* are consistently offset from those of the faster growing *Porites*. It has been shown that faster growing parts of coral skeletons, or faster growing coral colonies, tend to be more strongly depleted in  $^{18}\text{O}$  (e.g., McConnaughey, 1989a). Thus, differences in the mean  $\delta^{18}\text{O}$  values of *Diploastrea* and *Porites* growing in identical reef environments should be indicative of the difference in the effect of biologically mediated fractionation of  $^{18}\text{O}/^{16}\text{O}$  for the two coral genera.

Annual skeletal extension rates were estimated for the paired specimens of *Diploastrea* and *Porites* from New Caledonia and Alor on the basis of the distance between  $\delta^{18}\text{O}$  maxima (Fig. 4), which correspond to winter SST minima. The average annual extension rate for the New Caledonia *Diploastrea* was 2.7 mm/yr (range 2.1 to 3.4 mm/yr), whereas the nearby *Porites* grew 4 times faster (10.5 mm/yr, range 6.2 to 13.4 mm/yr; Quinn et al., 1996). In Alor, the average annual extension rate for the *Diploastrea* was 3.8 mm/yr (range 2.4 to 6.4 mm/yr), whereas the adjacent *Porites* grew 5 times faster (20.4 mm/yr, range 16.8 to 23.2 mm/yr). Such large differences in coral extension rate (3 to 23 mm/yr) should result in significantly different kinetic fractionation of  $^{18}\text{O}$  (McConnaughey, 1989a).

The average  $\delta^{18}\text{O}$  values for the *Diploastrea* and *Porites* (Quinn et al., 1996) from New Caledonia are  $-4.03\text{‰}$  and  $-4.42\text{‰}$ , respectively, giving a difference of 0.39‰ (Fig. 4).

For comparison, the average  $\delta^{18}\text{O}$  values for the *Diploastrea* and *Porites* from Alor are  $-5.27\text{‰}$  and  $-5.52\text{‰}$ , respectively, giving a difference of 0.25‰. Disregarding the possibility that part of the difference in the mean  $\delta^{18}\text{O}$  values for the *Diploastrea* and *Porites* from New Caledonia may be due to interlaboratory calibration differences (Ostermann and Curry, 2000), the results suggest that the disequilibrium offset in  $\delta^{18}\text{O}$  between *Diploastrea* and *Porites* is  $0.3 \pm 0.1\text{‰}$ .

The results agree with kinetic isotope disequilibrium models (McConnaughey, 1989a, 1989b), which predict that slow-growing corals should approach isotopic equilibrium and be preferentially enriched in  $^{18}\text{O}$ . The difference in mean  $\delta^{18}\text{O}$  for *Diploastrea* and *Porites* is surprisingly small, however, considering the vast difference in their extension rates. One possibility is that the relatively high skeletal bulk density of *Diploastrea* is compensating in part for the reduction in extension rate. The *Diploastrea* examined in this study both have bulk densities of  $1.8 \text{ g/cm}^3$  (determined gravimetrically), which are 50% greater than densities typical for *Porites* ( $1.2 \pm 0.2 \text{ g/cm}^3$ ), as measured throughout the Great Barrier Reef, Australia (Lough and Barnes, 1997). Applying these densities to the coral specimens from New Caledonia and Alor yields calcification rates (density times extension rate) of 0.49 to 0.68  $\text{g/cm}^2/\text{yr}$  for *Diploastrea* and 1.26 to 2.45  $\text{g/cm}^2/\text{yr}$  for *Porites*. Clearly, the difference in bulk density between the coral genera is insufficient to compensate completely for the four- to five-fold difference in calcification indicated by coral extension rates. Another possibility is that the columellar skeletal elements of *Diploastrea* may calcify at a mean rate similar to the bulk calcification rate of *Porites*. Regardless of the exact controls for the offset in  $\delta^{18}\text{O}$ , the consistent results across a range of environmental settings suggest that this offset is sufficiently constant in *Diploastrea* to allow this coral to be explored further for the purposes of paleoclimate reconstruction.

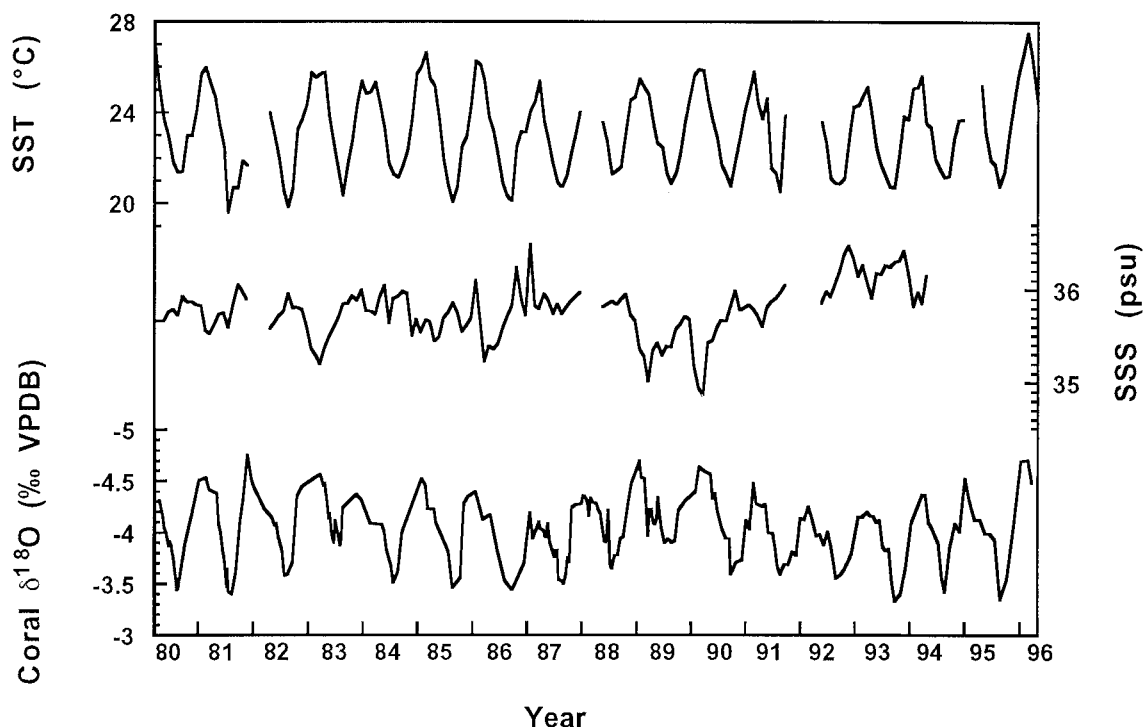


Fig. 5. Time series of columellar skeletal  $\delta^{18}\text{O}$  in *Diploastrea heliopora* compared with mean monthly sea surface temperature (SST) and sea surface salinity (SSS) measured in situ at Amédée, New Caledonia. The timing and pattern of skeletal  $\delta^{18}\text{O}$  and reef SST correlate during periods when SSS and presumably seawater  $\delta^{18}\text{O}$  are relatively constant. Coral  $\delta^{18}\text{O}$  values are reversed on the y axis for direct comparison with SST (warmer upward). VPDB = Vienna Pee Dee belemnite.

#### 4.3. Temperature Dependence of $\delta^{18}\text{O}$ in *Diploastrea*

We calibrated the relationship between  $\delta^{18}\text{O}$  in *Diploastrea* and in situ measurements of temperature at Amédée Lighthouse by comparing minima and maxima in coral  $\delta^{18}\text{O}$  with corresponding peaks and troughs in SST for 15 seasonal cycles from 1980 to 1995 (Fig. 5). Distance along the coral sampling transect was converted to time assuming that each peak and trough in the coral  $\delta^{18}\text{O}$  profile corresponds to the average arrival time of summer and winter SSTs, respectively. The Analyseries computer program (Paillard et al., 1996) was used to interpolate linearly between summer and winter anchor points in the coral record to produce a resolution of 12 samples/yr to match the resolution of the in situ SST record.

The least squares regression equation for the temperature dependence of  $\delta^{18}\text{O}$  for the New Caledonia *Diploastrea* ( $\delta^{18}\text{O}_c$ ) is

$$\delta^{18}\text{O}_c = 0.23 - 0.18 \times T(^{\circ}\text{C}) \quad (r = 0.94). \quad (1)$$

The slope of the  $\delta^{18}\text{O}$ -temperature calibration ( $-0.18\text{‰}/^{\circ}\text{C}$ ) is in good agreement with that derived for the *Porites* from Amédée ( $-0.19\text{‰}/^{\circ}\text{C}$ ; Fig. 6) analyzed at high sample resolution by Quinn et al. (1996). Seasonal variations in  $\delta^{18}\text{O}$  recorded by the *Diploastrea* and *Porites* in New Caledonia are likely to be driven primarily by variations in temperature because the effect of SST variations on coral  $\delta^{18}\text{O}$  is large relative to those brought about by variations of  $\delta^{18}\text{O}$  in seawater ( $\delta^{18}\text{O}_w$ ). In the tropical Pacific,  $\delta^{18}\text{O}_w$  is strongly related to

SSS with the following regression equation (Fairbanks et al., 1997):

$$\delta^{18}\text{O}_w = -9.14 + 0.273 \times \text{SSS} \quad (r^2 = 0.92). \quad (2)$$

Applying this  $\delta^{18}\text{O}_w$ -SSS relation to the in situ salinity record for Amédée yields average seasonal variations in  $\delta^{18}\text{O}_w$  of  $0.16\text{‰}$ . Although the seasonal variation in  $\delta^{18}\text{O}_w$  is not small relative to the mean seasonal range in  $\delta^{18}\text{O}_c$  for the *Diploastrea* ( $0.82\text{‰}$ , 1980 to 1996) and *Porites* ( $0.77\text{‰}$ , 1980 to 1992), its influence on the  $\delta^{18}\text{O}_c$ -SST calculation is negligible. This is because the difference in SSS in February (35.63 psu) and August (35.83 psu), which are the times of the SST maxima and minima used for the  $\delta^{18}\text{O}_c$ -SST calculation, corresponds to only  $0.06\text{‰}$  change in  $\delta^{18}\text{O}_w$ . The results suggest that high-resolution measurements of  $\delta^{18}\text{O}$  in the columellar skeletal elements of *D. heliopora* will yield estimates of seasonal variations in paleotemperature comparable with those extracted from *Porites*.

#### 4.4. Reconstructing Regional Differences in Temperature and Salinity

One of the goals of this study was to establish if the different disequilibrium offsets from seawater  $\delta^{18}\text{O}$  composition for *D. heliopora* and *Porites* affect the ability of either coral genus to record regional differences in mean SST and SSS. Examining the combined effect on coral  $\delta^{18}\text{O}$  of the difference in SST and

Table 1. Comparison of differences in mean SST and SSS for Amédée, New Caledonia, and Alor, Indonesia, and differences in mean  $\delta^{18}\text{O}$  recorded by *Diploastrea heliopora* and *Porites*.

Location/calculations	SST	SSS	$\delta^{18}\text{O}$ ( <i>Porites</i> ) (‰)	$\delta^{18}\text{O}$ ( <i>Diploastrea</i> ) (‰)
New Caledonia	23.4°C	35.7 psu	-4.42	-4.03
Alor, Indonesia	28.3°C	34.3 psu	-5.52	-5.27
Measured $\Delta_{\text{(New Caledonia-Alor)}}$	4.9°C	1.4 psu	1.10	1.24
Calculated $\Delta\delta^{18}\text{O}$	0.88‰ <sup>a</sup>	0.38‰ <sup>b</sup>	1.26	1.26
Difference (measured-calculated)	—	—	0.16	0.02

<sup>a</sup> Calculated  $\Delta\delta^{18}\text{O} = \Delta_{\text{(New Caledonia-Alor)}} \times (0.18\text{‰/°C})$ .

<sup>b</sup> Calculated  $\Delta\delta^{18}\text{O} = \Delta_{\text{(New Caledonia-Alor)}} \times (0.27\text{‰/psu})$ . The accuracy of the calculated  $\Delta\delta^{18}\text{O}$  (on the basis of the difference in mean salinity between New Caledonia and Alor) was checked with spot measurements of  $\delta^{18}\text{O}_w$  at Amédée, New Caledonia, and Pantai Putih, Alor, from September to December 1999. The mean  $\delta^{18}\text{O}_w$  for Amédée was  $0.53 \pm 0.06\text{‰}$  ( $n = 4$ ), whereas the  $\delta^{18}\text{O}_w$  value for Pantai Putih was  $0.02 \pm 0.02\text{‰}$  ( $n = 2$ ). The measured difference in  $\delta^{18}\text{O}_w$  of  $0.51\text{‰}$  is consistent with the calculated  $\Delta\delta^{18}\text{O}$  of  $0.38\text{‰}$ .

SST = sea surface temperature, SSS = sea surface salinity.

SSS between New Caledonia and Alor provides a good test. According to the  $\delta^{18}\text{O}$ -SST relation (Eqn. 1), the 4.9°C difference in mean SST between New Caledonia and Alor should produce a shift in coral  $\delta^{18}\text{O}$  of 0.88‰ (Table 1). Likewise, according to the  $\delta^{18}\text{O}$ -SSS relation (Eqn. 2), the difference in mean SSS between the two regions (1.4 psu) should shift the coral  $\delta^{18}\text{O}$  by an additional 0.38‰ (Table 1). Therefore, the combined effect of the difference in mean SST and SSS on coral  $\delta^{18}\text{O}$  would be to lower Alor coral  $\delta^{18}\text{O}$  by 1.26‰ relative to coral  $\delta^{18}\text{O}$  from New Caledonia.

The regional difference in mean coral  $\delta^{18}\text{O}$  indicated by the *Diploastrea* records from New Caledonia and Alor is 1.24‰,

which is essentially the same as the calculated difference of 1.26‰ (Fig. 7; Table 1). The regional difference in mean  $\delta^{18}\text{O}$  indicated by the pair of *Porites* is only 1.10‰, which is 0.16‰ less than the anticipated difference. Although it is not possible to quantify the significance of this mismatch for *Porites*, some of the 0.16‰ difference may be due to interlaboratory differences in calibration to NBS-19 (Ostermann and Curry, 2000). However, it is also possible that differences in oxygen isotope disequilibrium among individual species within the genus *Porites* are responsible for some of the mismatch. This cannot be the case for the coral genus *Diploastrea*, which comprises only one species throughout its known range of survival. The results suggest that slow-growing colonies of *Diploastrea* appear to faithfully track regional differences in mean SST and  $\delta^{18}\text{O}_w$  at least as well as *Porites*.

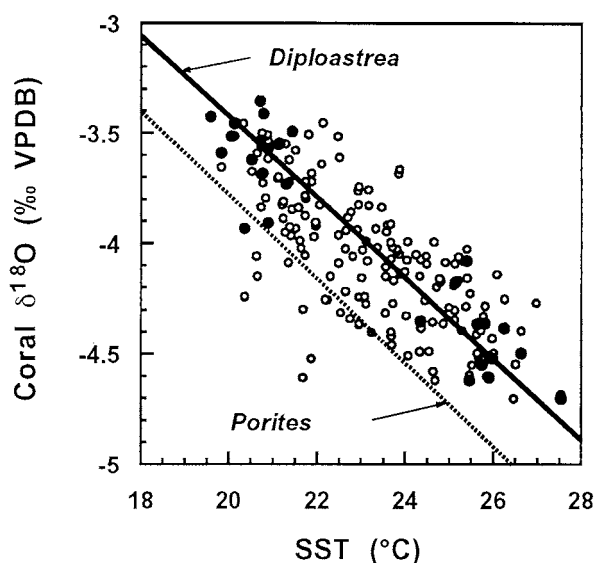


Fig. 6. Least squares linear regression of columellar skeletal  $\delta^{18}\text{O}$  and sea surface temperature (SST) for *Diploastrea heliopora* from Southwest Lagoon near Amédée, New Caledonia, over the period from 1980 to 1996. The  $\delta^{18}\text{O}$ -SST relationship of  $-0.18\text{‰/°C}$  for the *Diploastrea* was derived using 2 months defining each maximum and minimum (solid circles) in the columellar skeletal  $\delta^{18}\text{O}$  profile. Open circles are data points excluded from the regression analysis because of chronological uncertainties in spring and autumn produced by simple linear interpolation between  $\delta^{18}\text{O}$  maxima and minima. The  $\delta^{18}\text{O}$ /SST slope for *Diploastrea* is similar to that published for a nearby *Porites* (dashed line,  $-0.19\text{‰/°C}$ ) from Amédée (Quinn et al., 1996). VPDB = Vienna Pee Dee belemnite.

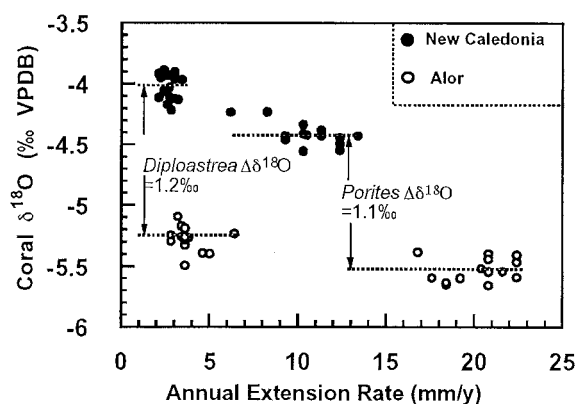


Fig. 7. Summary of annual average columellar skeletal  $\delta^{18}\text{O}$  for *Diploastrea heliopora* and *Porites* compared to coral annual extension rate. Despite the different kinetic disequilibrium effect on  $\delta^{18}\text{O}$  for *Diploastrea* and *Porites*, both corals record a similar shift in coral  $\delta^{18}\text{O}$  ( $\Delta\delta^{18}\text{O}$ ) between New Caledonia and Alor. The magnitudes of the shifts in coral  $\delta^{18}\text{O}$  (1.2‰ for *Diploastrea*, 1.1‰ for *Porites*) are consistent with the shift of 1.3‰ for coral  $\delta^{18}\text{O}$  calculated using the measured difference in mean sea surface temperature and sea surface salinity between New Caledonia and Alor (see Table 1). VPDB = Vienna Pee Dee belemnite.

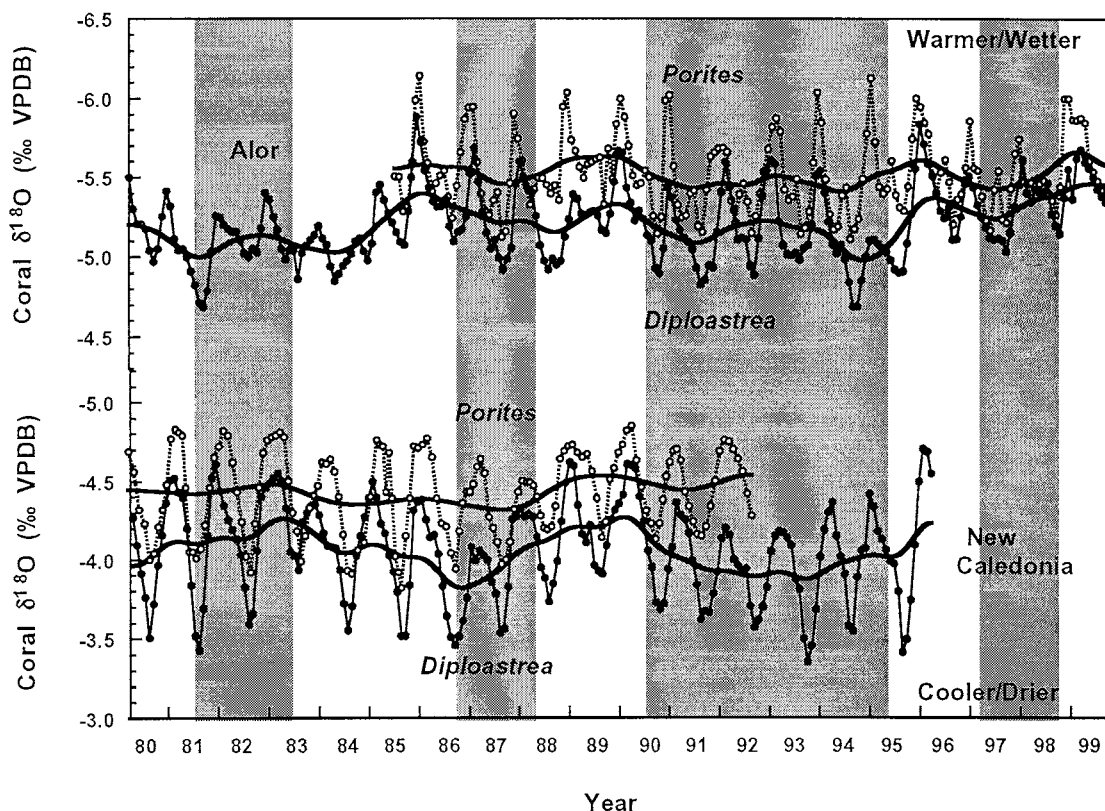


Fig. 8. Comparison of El Niño–Southern Oscillation-related interannual variability in  $\delta^{18}\text{O}$  for *Diploastrea heliopora* (solid lines with closed circles) and *Porites* (dashed lines with open circles) from New Caledonia and Alor. The coral records are interpolated to a resolution of 12 samples/yr (Paillard et al., 1996) and then smoothed with a 48-point running average (thick solid lines) to remove the annual cycle in  $\delta^{18}\text{O}$ . Coral  $\delta^{18}\text{O}$  values are reversed on the y axis to show warmer/wetter conditions upward. Shading indicates periods of cooler sea surface temperature and higher salinity (higher  $\delta^{18}\text{O}$  values) in the western Pacific region associated with El Niño events. VPDB = Vienna Pee Dee belemnite.

#### 4.5. Reconstructing the El Niño–Southern Oscillation (ENSO) in the Western Pacific

The ability of  $\delta^{18}\text{O}$  in the coral genera *Porites* and *Pavona* to monitor interannual climate fluctuations in the tropical Pacific region, such as the ENSO, has been demonstrated with live coral specimens (e.g., Cole et al., 1993; Dunbar et al., 1994; Evans et al., 1998; Guilderson and Schrag, 1999; Urban et al., 2000) and fossil corals for time slices since the Last Interglacial (Hughen et al., 1999; Corrège et al., 2000; Tudhope et al., 2001). This study was designed to directly compare records of *Diploastrea* and *Porites* in the ENSO-sensitive area of the southwestern Pacific (Rasmusson and Carpenter, 1982; Ropelewski and Halpert, 1987) to judge the ability of *Diploastrea* to record interannual climate variability. El Niño events (when eastern equatorial Pacific SSTs are unusually warm) are typically associated with cooler SSTs (Rasmusson and Carpenter, 1982) and below average monsoon rainfall (Ropelewski and Halpert, 1987) in the southwestern Pacific region. In contrast, changes in SSTs in the southwestern Pacific are less marked during La Niña events (when the eastern equatorial Pacific is cooler than average), but rainfall is enhanced because of a more vigorous summer monsoon. The effect of ENSO-induced changes in SST and the amount of  $^{18}\text{O}$ -depleted rainfall diluting the surface ocean drives coral  $\delta^{18}\text{O}$  in the same

direction, thus increasing the significance with which  $\delta^{18}\text{O}$  detects ENSO events.

Figure 8 shows the timing and magnitude of ENSO-induced variability in  $\delta^{18}\text{O}$  for the *Diploastrea* and *Porites* from New Caledonia and Alor over the period 1980 to 1999. The regional effect of the ENSO on the coral  $\delta^{18}\text{O}$  is evident. During the strong El Niño events of 1986 to 1987 and 1992 to 1994, the combined effect of cooler SST and reduced monsoon rainfall (higher  $\delta^{18}\text{O}_w$ ) served to increase coral  $\delta^{18}\text{O}$  simultaneously at New Caledonia and Alor. Lower coral  $\delta^{18}\text{O}$  values are evident at both sites for the 1988 to 1989 La Niña, when warmer SSTs and higher monsoon rainfall (lower  $\delta^{18}\text{O}_w$ ) prevailed. The Alor *Diploastrea* also records the very strong El Niño event from 1982 to 1983, but evidently, the effects of this event were not as pronounced in the coral records or instrumental records (Fig. 5) for subtropical New Caledonia. The results indicate that *D. heliopora* records ENSO climate variability in a manner similar to *Porites*.

#### 5. SUMMARY AND CONCLUSIONS

On the basis of our examination of skeletal  $\delta^{18}\text{O}$  in *D. heliopora* from New Caledonia and Alor, Indonesia, it appears that this slow-growing, long-lived, reef-building coral has the potential to provide an important new archive of tropical cli-



mate variability. Individual colonies of *Diploastrea* are known to grow 3 to 4 m high and could potentially double the typical time span of existing coral paleoclimate records. The concentration of *Diploastrea* in the Indo-Pacific region, particularly in the Warm Pool, means that these long records will describe temperature and rainfall variability for a key component of the global climate system. The tough, dense, dome-shaped colonies of *Diploastrea* preserve well in the fossil record, offering the potential for long paleoclimate records for time slices from the distant past.

Specific conclusions from this study are as follows:

1. Seasonal oxygen isotope and carbon isotope signals extracted from the septal portion of the skeleton of *Diploastrea* were significantly smoothed and distorted relative to signals from the columellar area of the corallite. Microanalysis of the columellar portion of *Diploastrea* produced isotopic data similar in quality to that extracted from the *Porites* coral archive. Bulk sampling of the complex skeletal architecture of *Diploastrea* will undoubtedly produce artifacts in paleoclimate reconstructions and should be avoided.
2. Oxygen isotope ratios analyzed in the columellar skeleton of *Diploastrea* exhibit a  $\delta^{18}\text{O}$ -temperature dependence that is similar to that reported for *Porites*. The slope of the  $\delta^{18}\text{O}$ -temperature calibration for *Diploastrea* ( $-0.18\text{‰}/^{\circ}\text{C}$ ) is in good agreement with that derived for a nearby *Porites* ( $-0.19\text{‰}/^{\circ}\text{C}$ ; Quinn et al., 1996), on the basis of comparisons with an in situ SST record from Amédée Lighthouse, New Caledonia.
3. There is a measurable difference of  $0.3 \pm 0.1\text{‰}$  between the kinetic/biologic disequilibrium offsets from seawater  $\delta^{18}\text{O}$  composition for *Diploastrea* and *Porites*. Despite the difference in the disequilibrium offset of the  $\delta^{18}\text{O}$  records for *Diploastrea* and *Porites*, the columellar skeletal  $\delta^{18}\text{O}$  of *Diploastrea* is capable of accurately recording regional differences in mean temperature and salinity throughout the southwestern Pacific. We also tested the ability of *Diploastrea* to record the combined effect on skeletal  $\delta^{18}\text{O}$  of changes in SST and precipitation in the ENSO-sensitive southwestern Pacific region. The results suggest that *Diploastrea* records interannual climate variability as well as *Porites* and that it should yield a dependable paleo-ENSO signal.

Further experiments with *D. heliopora* should result in improved paleoclimate reconstructions. The potential for interspecies offsets in isotope ratios among coral records is now well known; thus, a key advantage to working with *Diploastrea* is that a single species represents the genus throughout its entire environmental range of survival and long fossil history. Furthermore, intercomparison of geochemical records among *Porites* has not been straightforward, because the positioning of sampling transects within a coral core is a matter of interpretation and can potentially affect the quality of the resulting geochemical record. The individual corallites of *Diploastrea* are long and straight, thus offering the opportunity to produce continuous records spanning centuries from a single corallite. Microsampling restricted to the columella of *Diploastrea* should improve the standardization and intercomparison of coral geochemical records produced in different laboratories.

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