Marine High Mg Calcite Cements in *Teredolites*-Bored Fossil Wood; Evidence for Cool Paleoclimates in the Eocene La Meseta Formation, Seymour Island, Antarctica

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The Eocene La Meseta Formation on Seymour Island, Antarctica, contains a diverse and abundant invertebrate and vertebrate fauna and, as such, is of key paleontological importance. Associated with this marine fauna is abundant angiosperm and conifer fossil wood, which commonly contains *Teredolites* borings. These borings are either infilled by clastic sediment, forming geopetal structures, or by calcite cements. The cements usually comprise two generations of radial-fibrous high-Mg calcite, post-dated by equant sparry calcite. The radial-fibrous cement is largely non-luminescent, non-ferroan calcite. However, within individual generations of radial-fibrous calcite there is a transition from non-ferroan non-luminescent to ferroan, orange-luminescent calcite at the margins of the fringing cement. These radial-fibrous cements have $\delta^{18}O$ values of between $-0.28$ and $1.9\%$ VPDB, $\delta^{13}C$ values of $1.72$ to $-42.59\%$, and Mg (ppm) values of between 18360 and 26735. On the basis of cement-fabric, stableisotope, and trace element data, these cements are interpreted as having precipitated from marine pore waters with total dissolved carbon derived from both methane oxidation and an inorganic marine carbon source. As HMC cements are diagenetically unstable, the preservation of these cements is remarkable, and must reflect very limited post-sea-floor diagenesis. In addition, the cement oxygen isotope data are consistent with previous results for molluscs from the La Meseta Formation. These data support the view that Antarctic climates deteriorated significantly by late early to early middle Eocene.

Regional Setting

The James Ross basin contains the thickest exposed onshore sequence of Late Cretaceous-Tertiary sedimentary rocks in Antarctica. Approximately 5–6 km of Cretaceous and Tertiary strata crop out, with the succession subdivided into three groups that broadly define a regressive megasequence; the generally deep marine Gostev Group of Aptian to Santonian age (Ineson et al., 1986), the shallow marine shelf Marambio Group of Santonian to Paleocene age (Macellari, 1988; Crame et al., 1991; Pirrie, 1989a, Pirrie et al., 1991a; Pirrie et al., 1997), and the Paleocene-Eocene and possibly Oligocene Seymour Island Group (Elliot and Trautman, 1982; Fig. 1). The Seymour Island Group comprises two formations, the Cross Valley Formation (and its probable lateral equivalent the “Wiman Formation”; Elliot and Hoffman, 1989) and the overlying Antarctic Peninsula (Fig. 1), contains a prolific invertebrate and vertebrate fauna and, as such, is one of the most important paleontological sites in Antarctica (e.g., Feldmann and Woodburne, 1988; Woodburne and Zinsmeister, 1982; Stilwell and Zinsmeister, 1992; Meyer and Oji, 1993; Doktor et al., 1996). Along with the autochthonous marine and allochthonous non-marine fauna, abundant fossil wood and leaves occur throughout the LMF and the underlying Tertiary and Cretaceous strata (e.g., Francis, 1986, 1989; Torres et al., 1994; Doktor et al., 1996). The wood commonly contains borings of the ichnogenus *Teredolites* (Kelly, 1988; Wiedman and Feldmann, 1988). In this paper, we aim to describe the petrography and geochemistry of calcite cements precipitated within *Teredolites* borings from the lower 180 m of the LMF on Seymour Island. These data are then interpreted in terms of the diagenetic history of the wood substrates and the paleoclimatic significance of the calcite cements. Based on textural and geochemical data, we can show that the wood cements are primary high Mg calcites that precipitated from marine pore waters. In addition, the calcite cements provide a reliable indicator of cool ambient waters for the LMF in the late early to early middle Eocene.
La Meseta Formation. The LMF crops out on Seymour Island (Elliot and Trautman, 1982; Fig. 2) and on nearby Cockburn Island (Askin et al., 1991). On Seymour Island, the LMF is estimated to be approximately 750 m thick (Sadler, 1988). Its lower contact is a marked unconformity with over 70 m of erosional relief (see Fig. 3). Although this contact has been interpreted as a fault-controlled incised valley system (Porebski, 1995), it is comparable in geometry to a Type 1 sequence boundary formed during lowstand (Sadler, 1988; Pirrie et al., 1991b). The majority of the LMF is of mid-late Eocene in age, although the lower part is late early Eocene, and the top of the formation may be as young as early Oligocene (Zinsmeister, 1984; Stilwell and Zinsmeister, 1992; Wrenn and Hart, 1988). The age of the lower 180 m of the LMF and the samples examined in this study are discussed in detail below.

Porebski (1995) described the sedimentology and interpreted the paleoenvironments of the LMF. He suggested that the formation represented deposition within: (1) a tidal ebb- and flood-affected estuary mouth; (2) mid-estuary channels and low-energy tidal shoals; and (3) ebb-dominated, marginal shallow-subtidal sand and mixed flats of a tide-dominated, wave-influenced estuary. The interpretation of estuarine conditions throughout the whole LMF contradicts previous observations that the base of the formation contains a shallow, normal-marine salinity fauna, overlain by strata interpreted as representing shallow complex tidal environments in the upper part of the formation (Stilwell and Zinsmeister, 1992). Molluscan fossil evidence indicates that much of the formation was characterized by normal marine salinities.

Previous Paleoclimatic Studies

Considering the potential importance of these Eocene strata for our understanding of climate change at relatively high paleolatitudes (approximately 60–65°S paleolatitude), there has been surprisingly little detailed work on their paleoclimatic significance. Most authors have assumed a temperate or even warm temperate paleoclimate on the basis of faunal evidence (e.g., Stilwell and Zinsmeister, 1992), with typical estimates of water temperatures being on the order of 10–15°C and minimum winter temperatures of 8°C (e.g., Meyer and Oji, 1993). Other authors have suggested a cool temperate paleoclimate on the basis of the vertebrate fauna (Case, 1992) and the flora (Case, 1988; Doktor et al., 1996). Gazdicki et al. (1992) presented results of stable isotope analyses of brachiopod, bivalve, and gastropod samples from the LMF. These authors state that the samples were well preserved, although they gave no discussion of techniques used to evaluate the sample preservation, nor were any data presented to support that view. Their oxygen isotope values are all very positive, ranging from 0.2 to 3.2‰ Vienna Peedee belemnite (VPDB). However, the Fe and Mn concentrations of these
samples are in most cases very high (up to 4500 ppm Fe and 820 ppm Mn), suggesting significant diagenetic alteration of the skeletal carbonates. Ditchfield et al. (1994) analyzed 15 bivalves and 2 nautiloids from the lower part of the LMF (see Fig. 3). All of these samples were considered to be unaltered on the basis of both petrographic and geochemical data, and have oxygen isotope values between −0.11 and 1.65‰ VPDB. Based on an estimated seawater δw value of 1.0, these isotope values correspond to calculated seawater temperatures between 5.9 and 12.8°C (Ditchfield et al., 1994).

THE ICHNOGENUS TEREDOLITES

The ichnogenus Teredolites, redefined by Kelly and Bromley (1984) for clavate borings in woody substrates, is commonly formed by members of the bivalve families Pholadidae and Teredinidae. In some cases, the borers produced a calcareous lining within the borings, or as in the bivalve Teredina, had an elongate siphonoplax, which is an extension of the shell (Kelly, 1988). Lined borings associated with wood of early Tertiary age from Seymour Island were first described by Sharman and Newton (1898). Wiedman and Feldmann (1988) included a description of Teredolites from the LMF and recognized that, in some cases, the borings were infilled by calcite cements. Teredolites-bored wood from the LMF was also figured by Stilwell and Zinsmeister (1992), and Pirrie (1989a, b) described the presence of Teredolites-bored wood from the Marambio Group on both James Ross and Vega islands. Kelly (1988), in a review of Cretaceous wood-boring bivalves from western Antarctica, described the bivalves Teredina jeffersoni sp. nov. from the Upper Cretaceous Marambio Group on Snow Hill Island and Xylophagella truncata sp. nov. from the Marambio Group on Vega and James Ross islands. In addition, he described Turnus kotickensis sp. nov. from the underlying Gustav Group on James Ross Island.

FIGURE 3—Stratigraphic and sedimentologic logs for sections DJ.226, DJ.227 and DJ.229, from the lower 200 m of the La Meseta Formation, Cape Wiman, Seymour Island. Histograms of measured δ18O values for the fossil wood cements along with data from Ditchfield et al. (1994) for Ostrea antarctica and Nucula from the same measured section are shown. δ18O values for mytilids and nautiloids from stratigraphically higher in Telm 3 are also shown (Ditchfield et al., 1994). Palynological zones 1 and 2 based on the work of Cocozza and Clarke (1992; see text for details) and the informal mapping units Telm 1–2 and Telm 3 from Sadler (1988) are indicated.
Infestation of wood can occur either while it is still floating, or after it has sunk to the seafloor. Although most commonly described from shallow marine environments (e.g., Lindqvist, 1986), *Teredolites* has also been identified both from Eocene marginal marine environments (Pint and Pickerill, 1985) and deep marine habitats. In fact, modern representatives of the bivalve family Pholadidae have been recorded living in water depths ranging from 2 to 2,790 m (Kelly, 1988); hence, they have little palaeoenvironmental significance. Recently, Savrda (1991) and Savrda et al. (1993) interpreted the distribution of *Teredolites*-bored logs in a sequence stratigraphic context. Savrda (1991) described an unusual abundance of allochthonous bored logs within the lower Paleocene Clayton Formation in Western Alabama. He interpreted this as being due to a three-fold process whereby, during sea-level rise, land areas were flooded, resulting in an influx of wood into marine and marginal marine environments. During the transgression, the wood was concentrated along erosive transgressive surfaces, and the low rates of sedimentation allowed concentration of the wood fragments in marine condensed sections.

**SAMPLE LOCATIONS, SEDIMENTOLOGY, AND AGE**

The samples examined in this study were collected during the 1988–89 Antarctic field season from detailed measured sections through the lower 180 m of the LMF at Cape Wiman, Seymour Island (Fig. 2). At Cape Wiman, the LMF unconformably overlies the Paleocene Sobral Formation and associated volcaniclastic sandstones assigned by Elliot and Hoffman (1989) to the “Wiman Formation” a probable lateral equivalent of the Cross Valley Formation (Fig. 2). The pronounced unconformity surface at the base of the LMF may correspond with the global late Ypresian (49.5 Ma) low stand of sea level (Sadler, 1988). Although common throughout the LMF, the fossil wood examined in this study was collected from two stratigraphic levels on measured sections DJ.227 and DJ.229 (Fig. 3). Sample DJ.227.8 was located at 150 m above the base of the LMF, corresponding to the upper levels of the informal mapping unit Telm 2 of Sadler (1988). Sample DJ.229.1 was collected at 176 m above the base of the LMF from the base of Telm 3 of Sadler (1988; Fig. 3). The bi-valve and nautiloid skeletal carbonate samples analyzed by Ditchfield et al. (1994) were collected either from exactly the same measured sections or laterally equivalent sections from the lower 200 m of the LMF at Cape Wiman (Fig. 3).

Section DJ.227 shows a coarsening and shallowing-upward sequence, with the lowest levels characterized by interbedded planar laminated, silty, mudstones, and thin, normally graded sandstones showing current-ripple cross laminations. Interbedded debris flows containing clasts of the underlying Paleocene sandstones occur within the lower 50 m of the section. The interbedded mudstones and sandstones are commonly channelized and show marked lateral variability. The number and thickness of sandstone interbeds increases up section, along with an increase in the intensity of bioturbation. Between 135 and 160 m there is a gradational change from the laminated, interbedded mudstones and sandstones below to massive, intensely bioturbated, very fine-grained sandstone with abundant concretions above. Many of the concretions yield bivalves and gastropods along with *Teredolites*-bored fossil wood fragments up to 20 cm long (Fig. 4). A series of channels, typically spaced 5–10 m apart vertically and up to 12.5 m wide and 0.6 m deep, occur between 150–160 m. The channelized units have irregularly scoured bases and are infilled by hummocky cross stratified, fine-to very fine-grained sandstones overlain by shell coquinas comprising bivalves and gastropods along with large fragments of *Teredolites*-bored fossil wood. Sample DJ.227.8 which is a fragment of bored, conifer wood (J. E. Francis, pers. comm., 1997), was collected from one of these channelized units.

Section DJ.229 represents a continuation of section DJ.227 from 160 to 180 m above the base of the LMF (Fig. 3). Poorly exposed trough cross-bedded, fine-grained sandstones, with molluscan shell lags, occur interbedded with laminated mudstones and silty sandstones. Interbedded sandstones show both wave and current ripples. Early diagenetic concretions contain gastropods, bivalves, and fossil fish along with abundant trace fossils. Fossil leaves and logs with *Teredolites* borings also occur. Sample DJ. 229.1, which is angiosperm wood (J.E. Francis, pers. comm., 1997), was collected from approximately 176 m above the base of the measured section (Fig. 3).

For the most part, section DJ.227 is sparsely fossiliferous. Comminuted shell debris is associated with the debris flow deposits at the base of the section, and in the lowest levels there are localized concentrations of both *Ostrea antarctica* Zinsmeister and *Chlamys* sp. A of Stilwell and Zinsmeister (1992). Small starfish (*asteroids*) also occur in the basal levels. A concretionary horizon at 170 m yielded a number of indeterminate gastropods and bivalve molds. Elsewhere on northwestern Seymour Island, both Telm 1 and 2 are characterized by assemblages of brachiopods, molluscs, echinoids, *asteroids*, crinoids, and arthropods (Sadler, 1988), along with leaf fragments and teleost fish (Doktor et al., 1996). Although poorly preserved, the fossil assemblage indicates normal marine salinities (Stilwell and Zinsmeister, 1992). Concentrations of fossil plant mat-
terial (i.e., both leaves and wood fragments) at certain levels may indicate close proximity to the paleoshoreline. Doktor et al. (1996) described a floral assemblage based on a collection of fossil leaves from Telm 1 and 2, which includes ferns (Cladophlebus sp.), conifers (Dacrycarpus ternarius, Araucaria nathorsti), and angiosperms (Nothofagus, Knightiophyllum, Dictyophyllium).

The coquinas exposed at the top of DJ.227 and base of DJ.229 represent the lowermost levels of Sadler’s (1988) Telm 3. They are composed predominantly of small bi-valves, with the shallow-burrowing venerid, Eurohoma lea, being particularly abundant. Other bivalves present include nuculids, arcids, mytilids, oysters, lucinids, and anomalodesmatans. The whole molluscan assemblage has a fully marine, but shallow-water, aspect.

Age of the La Meseta Formation

To date, there has been a general consensus that the LMF as a whole is largely late Eocene in age (e.g., Zinsmeister, 1984). However, more recently, micropaleontological work has suggested that the lowermost levels (approximately equivalent to Telm 1 and 2) are significantly older (i.e., late early Eocene or middle Eocene; Cocozza and Clarke, 1992; Stilwell and Zinsmeister, 1992). Abundant terrestrial vertebrates from Telm 5 of the LMF (i.e., higher in the section) are considered to be middle Eocene (Bartonian, 42–38 Ma) in age (Woodburne and Case, 1996). Vertebrate fossils, including some primitive whales, indicate that the very highest levels of the formation (Telm 6 and 7) may be early Oligocene in age (Fordyce, 1989; Stilwell and Zinsmeister, 1992).

Although the overall age of the formation may span much of the Eocene, the age of the samples described here can be more tightly constrained. Cocozza and Clarke (1992) described the results of palynological studies of 22 samples collected from the same measured section as described here. Three samples from the lower 30 m of section DJ.227 (palynological zone 1 on Fig. 3), yielded a dinoflagellate assemblage containing Deflandrea antarctica, Pau cisphaeridium inversibuccinum, Spiniadium macmurdense, Vozezhkovicia apertura, and Enigmadinium cylindrigeriferum. This assemblage was interpreted as indicating an age of no older than late Early Eocene (Askin et al., 1991; Cocozza and Clarke, 1992; Wrenn and Hart, 1988). Nineteen samples from the measured section from 45–168 m above the base of the LMF (palynological zone 2 on Fig. 3) included Phlanoperidium echinatum, Spiniferites multibrevis, and Thalassiphora fenestra, suggesting a possible middle to Late Eocene age (Cocozza and Clarke, 1992; see also Wrenn and Hart, 1988). The middle Eocene age for the overlying Telm 5 (Woodburne and Case, 1996) precludes a Late Eocene age for the overlying Telm 5 (Woodburne and Case, 1996).

Analytical Techniques

Multiple polished thin sections were prepared from both wood samples and examined by (1) standard petrography, (2) cathodo-luminescence (CL, using a Technosyl cold cathode luminescope at 15–20 kV and gun currents of 400–500 mA), and (3) following carbonate staining using the methodology of Dickson (1966). Fifteen carbonate powders were collected from the radial-fibrous calcite, along with a single calcite spar cement sample, by dental drill and analyzed at the University of Liverpool stable isotope laboratory (see Fig. 6). Organic material was removed by placing the powder samples in a low-temperature oxygen plasma asher for approximately 4 hours. Approximately 3 mg carbonate samples were reacted with 100% H3PO4 at 50°C. The CO2 liberated was analyzed on a modified VG Isogas SIRA 12 mass spectrometer. Results are expressed in standard δ notation as per mil relative to the VPDB standard. Overall reproducibility of results for both δ13C and δ18O is better than 0.1‰. Five representative samples were analyzed for Fe/Mn/Mg and Sr by ICP-AES at the University of Liverpool using 5 to 10 mg of carbonate in 1N HNO3 with identical dilution factors and comparison with matrix-matched standards. Analytical precision on results is better than ±5%. Representative carbonate samples were also examined using X-Ray Diffraction (XRD) to confirm the calcite mineralogy.

Petrography of the Boring-Fill Cements

Approximately 30 to 40% of the individual wood borings are infilled or partially infilled by detrital clastic sediment comprising monocrystalline and polycrystalline quartz, plagioclase, microcline, glauconite, hornblende, muscovite, and biotite; in partly-filled borings, these clearly form a geopetal layer (Fig. 5A). The detrital grains and glauconite have point-point or “floating” grain contacts and are surrounded by a microsparry to sparry non-ferronan calcite cement that is non-luminescent under CL. Rarely, the non-luminescent calcite cements are cross-cut by microfractures filled with very thin bright-orange luminescent calcite. Both the conifer and angiosperm wood is calcite-cemented, with variable preservation of the original growth rings. The rest of the borings are either totally or partially infilled by calcite cements (Fig. 5B). Although slightly variable between individual borings, most of the borings...
(D) Two generations of radial-fibrous HMC (rf1 and rf2) post-dated by sparry calcite cements (s). With carbonate staining, each generation of radial-fibrous HMC shows a transition from non-ferroan to weakly ferroan calcite. Sample number DJ.227.8b(5). Maximum field of view 3 mm. (E) Thin-section photomicrograph taken under CL. Note that the bright luminescent zones (B) correspond with the weakly ferroan luminescent zones within the cement fringes, while the non-ferroan calcite is non-luminescent. Sample number DJ.227.8c(1). Maximum field of view 8 mm. (F) Thin-section photomicrograph taken under CL showing zoned luminescence at the center of a boring. The last bright luminescent zone (B) corresponds to the micro-sparry to sparry calcite cement that post-date the radial-fibrous calcite (the outer apparently dark zone is pore space at the center of the boring). Sample DJ.227.8c(1). Maximum field of view 2 mm.
FIGURE 6—Diagram summarizing the petrographic characteristics and sample location for the carbonate powders analyzed for the stable isotopes δ¹⁸O and δ¹³C and trace/minor elements Mn, Fe, Mg, and Sr from the wood cements. Sketches which are based on thin sections examined in this study, indicate individual generations of radial fibrous calcite within the borings. Shaded areas represent borings infilled by sediment.

have three main phases of calcite cement visible in transmitted light (Fig. 5C). Two generations of radial-fibrous cement usually occur, post-dated by equant spar. The radial-fibrous cement fringes are typically 0.5–1.0 mm wide and comprise elongate stubby prismatic crystals with their long axes oriented at right angles to the substrate (Fig. 5D). In some cases, the radial-fibrous cements are also developed upon partial geopetal sediment infills. Several samples of the radial-fibrous cement fringes were gently powdered and examined by XRD; this confirmed a 100% calcite mineralogy. The radial-fibrous calcite cements are, in some cases, post-dated by an equant calcite cement that either totally or partially occludes the remaining porosity within the boring (see Fig. 5D). Based on carbonate staining, the first generation of radial-fibrous calcite shows a transition from non-ferroan calcite closest to the substrate to weakly ferroan calcite at the margin of the radial-fibrous cement fringe. The same pattern is repeated in the second generation of radial-fibrous calcite with a transition from non-ferroan to ferroan calcite. Locally, minor amounts of pyrite are associated with the ferroan radial-fibrous calcite. Most of the radial-fibrous calcite is, however, non-ferroan. The later equant spar calcite cement is usually non-ferroan.

Under CL, the majority of the radial-fibrous calcite is non-luminescent. However, the ferroan margins to the radial-fibrous calcite do show moderate- to bright-orange luminescence (Fig. 5E). In some cases, a single or alternating pair of non-luminescent and luminescent zones occur adjacent to the margin of the boring. The bivalve shells are either non-luminescent or show weak orange luminescence, while calcite cements that preserve the wood’s cellular structure show bright orange luminescence. Commonly, the equant calcite shows a zoned CL response with very fine-scale alternations between bright orange luminescent and non-luminescent calcite, typically with bright orange luminescent calcite forming the last-stage cement at the center of the boring or adjacent to the void space (Fig. 5F).

GEOCHEMISTRY OF THE BORING-FILL CEMENTS

The results of 16 stable isotope analyses are shown in Figures 6 and 7. Because of the very fine zonation seen under CL, it proved impossible in some cases to separate the individual non-ferroan non-luminescent and ferroan luminescent zones within the radial-fibrous calcite. However, where possible, samples from (1) predominantly non-luminescent radial-fibrous calcite, and (2) mostly non-luminescent radial-fibrous calcite with bright orange luminescent zones, were sampled separately from the same borings; the sample locations and petrography are summarized in Figure 6. The δ¹⁸O values for the radial-fibrous calcites show relatively little variation, ranging from −0.28 to 1.9‰ VPDB, with most values between 0.8 and 1.1‰ VPDB. The single sparly calcite cement that post-
dates the radial-fibrous calcite had a $\delta^{18}O$ value of $-3.24\%o$. The $\delta^{13}C$ values are highly variable, as can be seen in Figure 7, ranging from 1.72 to $-42.59\%o$. There is no systematic variation between the different generations of radial-fibrous calcite, nor is there any difference between the two separate wood samples analyzed.

Five representative calcite-powder samples were analyzed by ICP-AES for Fe/Mn/Sr and Mg (Fig. 6); these data are shown graphically in Figure 8. In all cases, Mn levels are low, ranging from 11 to 157 ppm. Fe values are variable, with values ranging from 123 to 1534 ppm. The low levels of Mn and higher values for Fe are consistent with the generally non-luminescent characteristics of the radial-fibrous cements. Sr values are relatively consistent, ranging between 762 and 1048 ppm. In contrast, Mg values are all very high, ranging between 18360 and 26735 ppm. These Mg values would equate with MgCO$_3$ values of 7.6 to 10.9 mole % MgCO$_3$, showing that all of the samples analyzed are high Mg calcites (HMC).

INTERPRETATION

On the basis of the cement texture, high MgCO$_3$ composition, and positive oxygen isotope values, we interpret the radial-fibrous calcite cements to be high-Mg calcite (HMC) marine precipitates. It is likely that, on the death of the boring bivalves, the radial-fibrous cements were precipitated within the borings from marine pore waters, preferentially nucleating upon both the calcite shell wall or lining and the geopetal infills. The distribution of the borings on all surfaces of the wood indicates that it was bored while the wood was still floating, or possibly repeatedly reoriented following reorientation on the seafloor. It is possible that some of the cements were also precipitated while the wood was floating, although the presence of radial-fibrous cements directly nucleated upon geopetal sediment inills indicates that the cements continued to grow while the wood was at the sea floor or during very shallow burial. This is also supported by the measured carbon isotope values. While the relatively narrow range in $\delta^{18}O$ values reflects that the cements were precipitated from marine pore waters with limited variation in composition and temperature, the very variable carbon isotope composition probably reflects carbon sourced from methane oxidation (the very negative values), and the more positive values reflect mixing with a marine inorganic carbon source (see, for example, discussion of similar values in Pirrie and Marshall, 1991; Kelly et al., 1995). The zonation from non-ferroan, non-luminescent to ferroan, luminescent within the radial-fibrous cements is interpreted to represent a repeated transition from oxidizing to reducing pore water conditions. It is possible that, following the initial phase of cement growth, either while the wood was within the water column or subsequently within the sediment, the wood underwent shallow burial, allowing the pore-water conditions to become reducing. Subsequent erosion and re-exposure of the wood to oxidizing near-surface conditions allowed the second phase of radial-fibrous cement to be precipitated, which again evolved during shallow burial from oxidizing to reducing conditions. As HMC cements are diagenetically unstable, the fact that the original cement mineralogy is preserved is in itself remarkable, and must reflect very limited post sea-floor diageneis.

The oxygen isotope data for the wood cements are very
similar to values from well preserved bivalves (Nucula, Mya, Eurhomaëla, Ostrea, and mytilids) and nautiloids from the lower 200 m of the LMF (Ditchfield et al., 1994; Figs. 3 and 7). Five samples of Ostrea antarctica from approximately 15 m above the base of the LMF section DJ.227 have δ18O values of between 0.67 and 1.25‰ (four samples range from 0.67 to 0.91; Ditchfield et al., 1994) (Fig. 3). Five Nucula bivalves from a shelf bank in section DJ.226, laterally equivalent to the top of section DJ.227, have δ18O values of between 0.58 and 0.71‰. Four samples of nautiloids and mytilid bivalves from the lower part of Telm 3, slightly above the stratigraphic position of the fossil wood, gave more positive δ18O values of between 1.29 and 1.36‰ (Ditchfield et al., 1994). The oxygen isotope values for the wood cements typically fall in the range between these data sets, which taken together can be interpreted as representing a cooling trend through the lower 200 m of the LMF. The carbon isotope values for the wood cements are, in most cases, significantly more negative than for the molluscs as would be expected.

Temperature of Cement Precipitation

If we assume that the HMC cements were precipitated in equilibrium with the surrounding marine pore waters then, by estimating the water isotopic composition, we can calculate likely temperatures for the precipitation of these cements. We have calculated paleotemperatures for these cements using a modified version of the Craig paleotemperature equation as given in Anderson and Arthur (1983):

$$T^\circ C = 16.0 - 4.14(\delta_1^\circ - \delta_w^\circ) + 0.13(\delta_8^\circ - \delta_w^\circ)^2$$

Where $\delta_1^\circ = \delta^{18}O$ (VPDB) of the analyzed carbonate at 25°C, and $\delta_w^\circ = \delta^{18}O$ (SMOW) of the water in which the carbonate was precipitated relative to Standard Mean Ocean Water. Estimating the likely composition of $\delta_1^\circ$ is, however, problematic because it has varied as a result of glaciation during geological time. If we assume on the basis of the associated fauna that the depositional setting for this part of the LMF was fully open marine with normal salinities, and we assume limited glaciation, then we can suggest a possible seawater $\delta_1^\circ$ value of $-1.0‰$ (cf. Shackleton and Kennett, 1975). However, if the sequence is in part estuarine, with significant freshwater runoff at this relatively high paleolatitude site, then the isotopic composition of the seawater is likely to have had a more negative isotopic composition. Barrera et al. (1987) estimated a seawater composition of $-1.4‰$ for the underlying Cretaceous succession on Seymour Island. We have calculated paleotemperatures based on values for $\delta_8^\circ$ of both $-1.0‰$ (normal marine salinity minimal glaciation) and for $\delta_8^\circ$ values of $-1.5‰$ (some freshwater runoff; Table 1). Calculated temperatures range between 5.1 and 13.2°C for $\delta_8^\circ$ of $-1.0‰$ and 3.4 to 11.1°C for $\delta_8^\circ$ of $-1.5‰$. It is important to note that these paleotemperature estimates are comparable with, or slightly cooler than, the estimates based on least altered bivalves from the same measured sections at the base of the LMF (Ditchfield et al., 1994). This suggests that the HMC radial-fibrous cements retain a reliable marine isotopic paleotemperature signature.

### TABLE 1—Radial-fibrous calcite cement $\delta^{18}O$ values and calculated paleotemperatures based on $\delta_8^\circ$ values of $-1.0$ and $-1.5$.

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<th>$T^\circ C$ at $\delta_8^\circ = -1.5$</th>
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### DISCUSSION

The late Paleocene-early Eocene was the apogee of Cenozoic warmth. During this interval, the tropics extended some 10–15° poleward, and both polar regions were populated with temperate forests (Frakes et al., 1992; Prothero, 1994). However, significant global cooling commenced very soon after this interval, in the latest early Eocene/earliest middle Eocene (i.e., approximately 50 Ma; Boersma et al., 1987; Stott et al., 1990). High-latitude sea-surface temperatures may have dropped by as much as 4–5°C at this time, and then again by a similar amount at the end of the middle Eocene (38 Ma; Prothero, 1994). Ehrmann and Mackensen (1992) also suggest that the early Eocene was relatively warm, but was followed by a long term cooling trend. The first record of ice-rafted debris in cores recovered from the Maud Rise and Kerguelen Plateau is dated at approximately 46 Ma (Ehrmann and Mackensen, 1992). This indication of climate change is supported by Woodburne and Case, (1996) who suggest that climatic deterioration may have commenced in Antarctica as early as 46–52 Ma, possibly linked to global cooling indicated by the presence of mesothermal non-seasonal climates in Australia and the beginning of the spread of Nothofagus rain forest.

The results obtained in this study support a cool-temperate paleoenvironmental setting for the LMF during the latest early to middle Eocene. As temperatures continued to decline, albeit in a series of pronounced steps, through the remainder of the Eocene (Stott et al., 1990), we can infer that the overlying LMF was deposited under even cooler climatic conditions. Warm-temperate interpretations of this unit (e.g., Stilwell and Zinsmeister, 1992) now seem inappropriate and greater credence can be given to cool-temperate reconstruction’s based on paleobotanical evidence (e.g., Case, 1988). A cool- or even cold-temperate paleoenvironment for the LMF also has important paleobiological implications. The Nothofagus rainforests were cool temperate, and in the northern Antarctic Peninsula region, formed the setting for a land vertebrate fauna that included polydolopid and microbiotheriid marsupials, a possible phororacoid bird, and several placental mammals (Askin, 1992; Case, 1988; Woodburne and Case,
1996). In the marine realm, a range of living invertebrate taxa have their earliest fossil records within the LMF. Examples include various decapod crustaceans, gastropods, bivalves, echinoderms, brachiopods, barnacles, and foraminifera; collectively they represent a phenomenon known as high-latitude heterochrony (Zinsmeister and Feldmann, 1984; Meyer and Oji, 1993; Crame, 1994). Many of these taxa have been displaced through time not only into lower latitudes but also into deeper water. Cool, shallow, sub-Antarctic waters in the middle-late Eocene may well have been an important source region for living outer-shelf and slope taxa. This may be taken as further evidence that cool as well as warm-water clades have been displaced progressively across the continental shelf through evolutionary time (Skelton et al., 1990, and references therein).

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REFERENCES


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