



# Cool early Albian climates; new data from Argentina

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## Abstract

Previous studies on the stable isotope geochemistry of dimitobelid belemnites from Antarctica and Australia indicated cool climatic conditions during the early Albian in the shelf seas around the Gondwanan margin. In this paper new analyses from diagenetically unaltered specimens of *Dimitobelus* cf. *stimulus* from early Albian deposits of the Rio Mayer Formation of Lago San Martin, southern Argentina are presented. Oxygen isotope values for diagenetically least altered samples give values ranging between  $\delta^{18}\text{O} +0.07$  and  $+0.96$  ‰PDB, which equate to a mean palaeotemperature of 9.5 °C (assuming  $\delta_w$  of  $-1.2$ ‰ SMOW). These data are consistent with a model of cool early Albian shelf seas in the Southern Hemisphere.

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## 1. Introduction

The possibility of intervals of cool climatic conditions, with the development of polar glaciation, during the otherwise greenhouse climate of the Cretaceous is controversial (Sellwood et al., 1994; Stoll and Schrag, 2000; Huber et al., 2002). Results that have been used to support the possibility of cool climatic intervals in the Cretaceous include: data from palaeobotanical studies (e.g. Francis and Poole, 2002), stable isotope analyses (Rich et al., 1988; Gregory et al., 1989; Ditchfield et al., 1994; Pirrie et al., 1995; Stoll and Schrag, 2000), sequence stratigraphic boundaries and linked  $\delta^{18}\text{O}$  increases (Miller et al., 1999, 2003), dropstones interpreted to be of glacial origin (Frakes and Francis, 1988; Frakes et al., 1992), global climate models (Price et al., 1998) and sedimentary structures interpreted to be the result of cryoturbation (Constantine et al., 1998). However, oxygen isotope data from planktonic and benthic foraminifera from numerous Deep Sea Drilling Project (DSDP) and Ocean Drilling Programme (ODP)

sites indicate that Cretaceous ocean temperatures were much higher than at present and incompatible with intervals of polar glaciation (Clarke and Jenkyns, 1999; Huber et al., 1995, 2002). To resolve this controversy additional data sets are needed. Possibly the most widely documented potential icehouse interval in the Cretaceous is a major cooling event during the late Aptian and early Albian (e.g. Pirrie et al., 1995). In this study new stable isotope data from dimitobelid belemnites from early Albian deposits in Argentina are presented. These data are comparable with previous data for dimitobelid belemnites from Antarctica (Ditchfield et al., 1994) and Australia (Pirrie et al., 1995) and are consistent with the interpretation of cool climatic conditions in the high palaeolatitudes of the Southern Hemisphere during the early Albian.

## 2. Regional setting and previous work

Samples of the belemnite *Dimitobelus* cf. *stimulus* were selected for analysis from the palaeontological collections of the Museo de La Plata, Universidad de la Plata, Argentina. The samples were collected from early

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E-mail address: [dpirrie@csm.ex.ac.uk](mailto:dpirrie@csm.ex.ac.uk) (D. Pirrie).

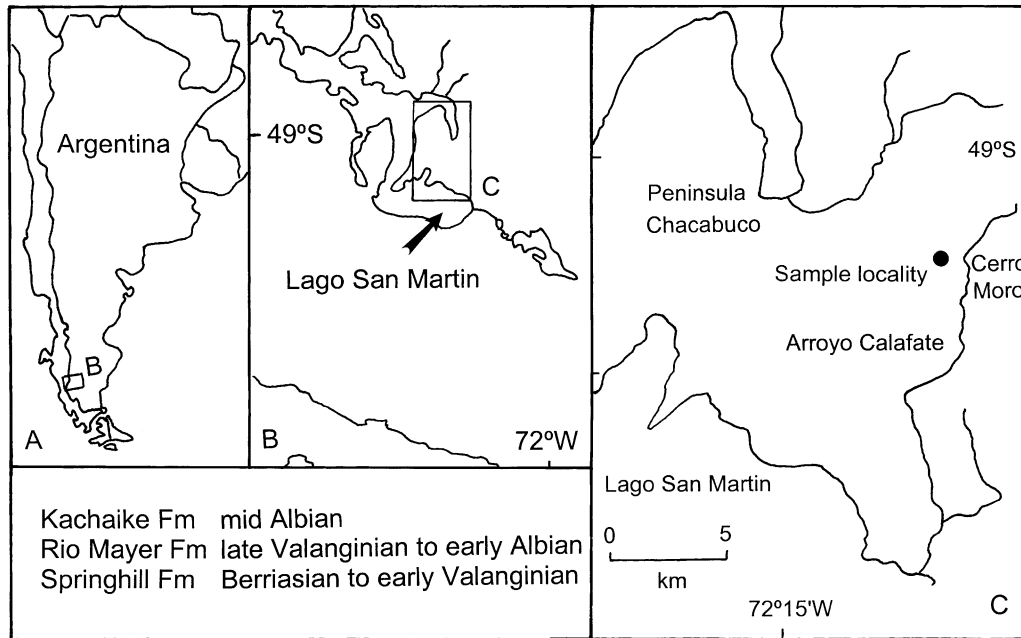


Fig. 1. Sketch map showing the location of the sampled interval in the Rio Mayer Formation in the Arroyo Calafate.

Albian levels of the Rio Mayer Formation, Lago San Martin, southern Argentina (Riccardi and Aguirre Urreta, 1987; Riccardi, 1988) (Fig. 1). The sampled locality (49°02'S, 72°08'W) is documented by Riccardi (1971). The succession is exposed on the eastern limb of a broad anticline that covers a core of Palaeozoic rocks which are exposed on the western and eastern shores of Peninsula Chacabuco. The regional dip of the Mesozoic succession is 5–25°ESE. Although thick (ca. 3 m) essexite sills occur 50 m above the sampled levels, there is no evidence for any diagenetic alteration of the belemnites as a result of the emplacement of the sills. The Cretaceous sediments in the area (see Riccardi, 1988) overlie Jurassic volcanic rocks of the El Quemado Complex and consist of Berriasian–early Valanginian continental to marine sandstones of the Springhill Formation; the late Valanginian–early Albian marine black shales of the Rio Mayer Formation; and the mid Albian shallow marine to continental sandstones of the Kachaike Formation.

The early Albian levels of the Rio Mayer Formation have been divided into two assemblage zones on the basis of its ammonoids (see Riccardi and Medina, 2002): the index species are, from the base, *Aioloceras argentinum* and *A. rollerii*. The samples studied were collected from the *argentinum* Assemblage Zone, which is characterised by: *A. argentinum* (Bonarelli), *Maccoyella bonarellii* (Leanza), *Puzosia recteradiata* (Collignon), *Rossalites imlayi* (Leanza) and perhaps *Douvilleiceras* sp., *Phylloceras* sp. and *Protanisoceras* sp. The *argentinum* and *rollerii* zones are coeval with the *Mammillatum* Standard Superzone, which most probably correlates

with the upper *Chalensis* and lower *Auritiformis* Standard zones (see Riccardi and Medina, 2002). This correlation is based on several genera and species that link the Patagonian faunas with those from Madagascar and Tethys (Riccardi and Medina, 2002).

There are very few previously published oxygen isotope palaeotemperature studies for the Cretaceous of southern Argentina. Bowen (1961, 1963) presented results from a number of samples that are poorly constrained stratigraphically. Among these Cretaceous samples several from near Lago San Martin gave  $\delta^{18}\text{O}$  values of between  $-2.8$  and  $-3.5\text{‰}$ , which would equate to much higher palaeotemperatures than reported here. The lack of diagenetic screening casts doubt on the reliability of these preliminary data, although it is also possible that they were collected from a different stratigraphic level in the Cretaceous succession exposed at Lago San Martin.

### 3. Palaeobiogeography of the Dimitobelidae

The Dimitobelidae are unusual as a distinct and easily recognisable group of belemnites that have a wholly Gondwanan distribution pattern (Whitehouse, 1924). Reviews of the biogeography of the Dimitobelidae include Stevens (1965), and more recently Doyle (1988, 1990, 1992) and Doyle and Pirrie (1999). It is generally held that the group is representative of a marine Austral Realm that developed towards the close of the Early Cretaceous period and continued through to the end of the Cretaceous. The Dimitobelidae are

representative of the boundaries of the realm, and comprise the genera *Peratobelus*, *Tetrabelus* and *Dimitobelus* (including the subgenus *Dimitocamax*).

Doyle (1988, 1990) has pointed out the presence of at least two distinct faunas within the dimitobelid-dominated Austral Realm, defined on the basis of the presence or absence of the genus *Tetrabelus*. This genus is only known from the Aptian/Albian of southern India and James Ross Island, Antarctica.

The second fauna is dominated by *Dimitobelus* itself, which is geographically widespread within Gondwana. Apart from the largely endemic New Zealand species (Stevens, 1965), Albian *Dimitobelus* species are remarkably uniform across Gondwana, with the most widespread being the group comprising *D. diptychus*, *D. stimulus*, and *D. stimulus* var. *extremis* (Doyle, 1987, 1990). The importance of this group to biogeographers and palaeoclimatologists is its overall uniformity and consistency, with the same closely related taxa occurring in close geographical association. As such the *D. diptychus* group is common in Argentina, the Antarctic Peninsula and Australia, and is also present in other Gondwanan territories (Stevens, 1965; Ludbrook, 1966; Doyle, 1987, 1988, 1990; Riccardi, 1988). Pirrie and Marshall (1990), Ditchfield et al. (1994) and Pirrie et al. (1995) have used belemnites from this dominant group in their palaeotemperature studies, and the use of belemnites from the same group in this study validates comparison of the oxygen isotope composition and calculated palaeotemperatures across all three studies, and therefore latitudinally, across Gondwana.

However, although belemnites have been used widely in palaeotemperature studies, partly because the rostra are considered to be diagenetically stable low Mg calcite, some work has shown an apparent offset between the oxygen isotopic composition of belemnites (which are typically heavier) and benthic organisms from the same sections (e.g. Voigt et al., 2003). In most studies though, there is no evidence for an isotopic offset between belemnites and other molluscan taxonomic groups from the same sections and this has been taken to indicate that there are no significant vital effects during calcification of the belemnite rostra. The isotopic offset reported in some studies may reflect a limitation of our understanding of belemnite palaeobiology. Despite the fact that belemnites most commonly occur within sedimentary rocks, interpreted to have been deposited within shelf environments, the life habitats and water depth at which the rostra calcified is equivocal. Isotopic studies on Jurassic belemnites have indicated that at least some taxa were nektobenthonic within a shelf setting (Anderson et al., 1994). However, belemnite biogeography studies (e.g. Doyle, 1992) suggest that, while some belemnites were shelf dwelling, other taxa were nektonic and it is possible that the rostra were calcified in deep water environments. Palaeogeographical

studies of the Dimitobelidae suggest that this family of belemnites was predominantly restricted to shelf settings (Doyle and Pirrie, 1999), although in the James Ross Basin, Antarctica, dimitobelids occur in the deep marine slope apron and submarine fan complex of the Kotick Point and Whisky Bay formations (Doyle, 1987; Ineson, 1989). However, these belemnites are commonly fragmentary and abraded and may have been resedimented within high concentration turbidity currents sourced from the adjacent shelf (DP, pers. obs., 2002). In addition to understanding the depth at which the calcification of the rostra occurred, another factor that needs to be considered when interpreting the palaeoclimatic significance of the data is the oxygen isotopic composition of the seawater in which the taxa lived. Although the Austral Basin was semi-restricted in the Hauterivian there was improved oceanic circulation by the Aptian–Albian, allowing the migration of a more diversified marine fauna. While some recent work on the Western Interior Seaway in the US has demonstrated that some ammonites were tolerant of somewhat brackish-water conditions (Cochran et al., 2003), there is no evidence to suggest that belemnites were anything other than fully marine organisms. Consequently, it is assumed that the belemnite rostra were calcified within open marine conditions. Thus, whilst oxygen isotope data from dimitobelid belemnites cannot be considered to necessarily reflect sea-surface temperatures (SST) it is highly likely that they are indicative of shelf sea temperatures.

#### 4. Analytical methods

Ten belemnite rostra of the species *Dimitobelus* cf. *stimulus* were examined in this study. Half of each rostrum was thin sectioned and examined using standard petrography, cathodoluminescence (CL) (using a Technosyn cold cathode luminoscope at 15–20 kV and gun currents of 400–500  $\mu$ A) and after carbonate staining (following Dickson, 1966). Using the petrographic data (see below) as a guide, single subsamples of carbonate powder were collected from non-luminescent non-ferroan areas of each rostrum using a dental drill for stable isotope and trace element geochemistry. Samples for stable isotope analysis had any organic contamination removed by roasting the carbonate powder in a low temperature plasma oven for 3 h. CO<sub>2</sub> gas was generated for analysis by reacting the sample with 100% orthophosphoric acid at 25 °C. The liberated CO<sub>2</sub> was analysed using a modified VG Isogas SIRA 12 mass spectrometer at the University of Liverpool stable isotope laboratory. Results are reported in standard  $\delta$  notation relative to vPDB. Reproducibility for both  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  is better than

0.1‰. Carbonate powder subsamples were analysed by ICP for Fe, Mn, Mg and Sr.

### 5. Sample preservation and geochemistry

The rostra are largely composed of radially arranged clear calcite that is both non-ferroan and non-luminescent. Inclusion-rich calcite occurs at the centre of the rostra and within widely spaced growth lines. The majority of each of the rostra are non-luminescent and non-ferroan. Minor orange luminescent ferroan calcite cements occur within microfractures cross-cutting the rostra, replacing both individual growth lines and the centre of the rostra and also occurring as cements around the edge of the rostra. Subsamples for trace element and stable isotopic analysis were drilled from areas away from the ferroan calcite cements in parts of the rostra composed of non-luminescent non-ferroan calcite. The trace element geochemistry of the subsamples have Mn values of less than 34 ppm and less than 84 ppm Fe although there is an apparent weak covariance between the Fe and Mn data (Fig. 2A). Sr values vary from 1680 to 2373 ppm, with Mg ranging from 1093 to 1576 ppm (Table 1). The trace element data are consistent with the interpretation that the belemnite rostra are unaltered (Marshall, 1992). Measured  $\delta^{18}\text{O}$  values range between +0.07 and +0.96‰ vPDB, with a single outlying value of -1.88‰ (C210).  $\delta^{13}\text{C}$  ranges between +0.38 and +2.47‰ (Table 1, Fig. 2B). Based on the thin section petrography, trace element geochemistry and isotopic composition, all of the samples except C210 are considered to represent diagenetically minimally altered original low Mg calcite.

### 6. Palaeotemperature calculations

Palaeotemperature values for calcite samples can be calculated using a modified version of the Craig palaeotemperature equation, as given in Anderson and Arthur (1983) and used in previous studies (e.g. Pirrie et al., 1995):

$$T\text{ }^{\circ}\text{C} = 16.0 - 4.14(\delta_c - \delta_w) + 0.13(\delta_c - \delta_w)^2$$

where  $\delta_c = \delta^{18}\text{O}$  (vPDB) of the analysed carbonate at 25 °C and  $\delta_w = \delta^{18}\text{O}$  (SMOW) of the water in which the carbonate was precipitated relative to the 'Standard Mean Ocean Water' international standard. While  $\delta_c$  is measured,  $\delta_w$  has to be estimated. This is problematic because (1)  $\delta_w$  varies within the present oceans and (2) average  $\delta_w$  has varied throughout geological time (Hudson and Anderson, 1989). It is important to note that temperature decrease and global ice-volume build up (and consequent oceanic  $^{18}\text{O}$  enrichment), will have a similar effect on  $\delta_c$ . For periods of limited or no glaciation, global average  $\delta_w$  values are estimated to be -1.2‰ SMOW (Shackleton and Kennett, 1975; see discussion in Hudson and Anderson, 1989). In this study palaeotemperatures have been calculated using a  $\delta_w$  value of -1.2‰. Calculated palaeotemperatures range between 7.7 and 10.9 °C (mean 9.5 °C) (Table 2).

### 7. Discussion

These new data suggest relatively cool temperatures for the early Albian of Argentina at a palaeolatitude of approximately 58°S. These data can be directly compared with previous work on dimitobelid belemnites

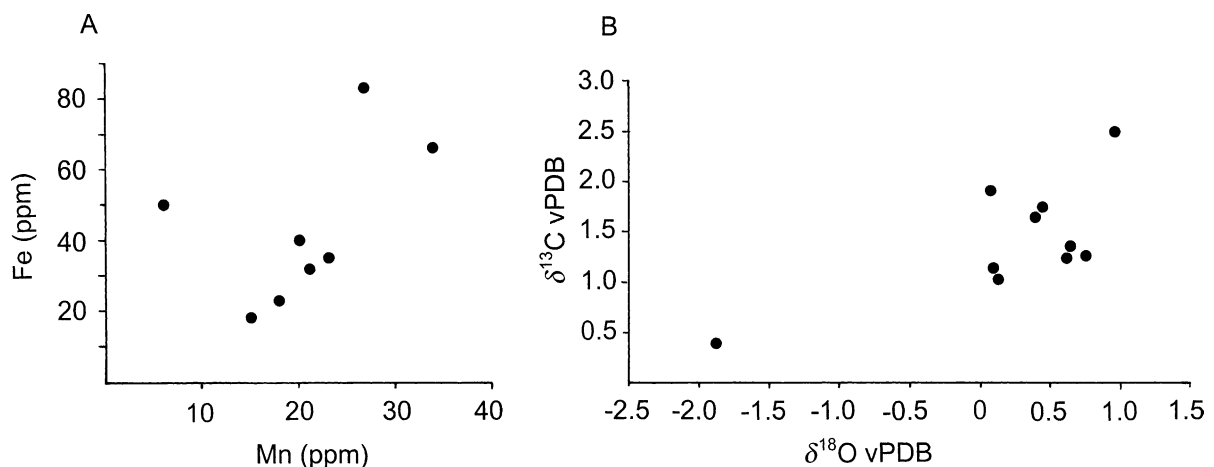


Fig. 2. (A) Fe vs. Mn cross plot; although there is covariance between Fe and Mn, all of the values are low and are compatible with skeletal carbonates showing minimal diagenetic alteration. (B)  $\delta^{18}\text{O}$  vs.  $\delta^{13}\text{C}$  cross plot for *Dimitobelus* cf. *stimulus* from Argentina; the outlying sample (C210) is considered to be diagenetically altered.



Table 1

Stable isotope and trace element geochemistry for *Dimitobelus* cf. *stimulus* from the early Albian Rio Mayer Formation, Lago San Martin, Argentina; bd, below detection limits

Sample	$\delta^{18}\text{O}$ (‰)	$\delta^{13}\text{C}$ (‰)	Mn (ppm)	Fe (ppm)	Sr (ppm)	Mg (ppm)	$T$ (°C)
C210	-1.88	+0.38	27	83	2373	1181	—
C211	+0.64	+1.33	18	23	1744	1425	8.8
C212	+0.09	+1.12	15	18	1729	1093	10.9
C215	+0.96	+2.47	bd	bd	1807	1360	7.7
C216	+0.45	+1.72	21	32	1901	1284	9.5
C220	+0.12	+1.01	bd	bd	2209	1323	10.8
C222	+0.4	+1.62	20	40	1791	1233	9.7
C223	+0.76	+1.24	23	35	1680	1312	8.4
C227	+0.07	+1.89	34	66	1945	1576	10.9
C231	+0.61	+1.22	6	50	2027	1240	8.9

Calculated palaeotemperatures are also given assuming a  $\delta_w$  value of  $-1.2\text{‰}$ . Note that sample C210 is considered to be diagenetically altered based on the anomalously low  $\delta^{18}\text{O}$  value and is not used to calculate a palaeotemperature.

belonging to the *D. diptychus* group from Antarctica and Australia (Fig. 3). Ditchfield et al. (1994) examined specimens of *Dimitobelus* from the Kotick Point Formation, James Ross Basin, Antarctica. During the Albian, the James Ross Basin was located at a palaeolatitude of ca.  $65^\circ\text{S}$ . Recent palynological biostratigraphic studies have revised the age of the Kotick Point Formation, which is now considered to be mainly early Albian in age, although the uppermost part of the formation may span up into the mid Albian (Riding and Crame, 2002). Based on thin section petrography, and isotopic composition, 10 samples of *Dimitobelus* (most probably *D. stimulus*, one of the members of the *D. diptychus* group) were considered by Ditchfield et al. (1994) to be diagenetically unaltered and had a range in  $\delta^{18}\text{O}$  values of between  $+0.13$  and  $+1.40\text{‰}$ . Using a  $\delta_w$  value of  $-1.2\text{‰}$  (SMOW) calculated palaeotemperatures for these data range between  $6.1$  and  $10.7^\circ\text{C}$  (Table 2) and have a mean of  $8.5^\circ\text{C}$ .

Pirrie et al. (1995) analysed the stable isotope geochemistry of 17 samples of *Dimitobelus stimulus* and *D. diptychus* from the early–mid Albian Gearle Siltstone, Carnarvon Basin, Western Australia. The Gearle Siltstone was deposited at a palaeolatitude of  $55^\circ\text{S}$  during the Albian. All of the samples showed partial replacement by light blue luminescing quartz, while the rest of the rostra comprised clear, non-luminescent non-ferroan calcite other than orange

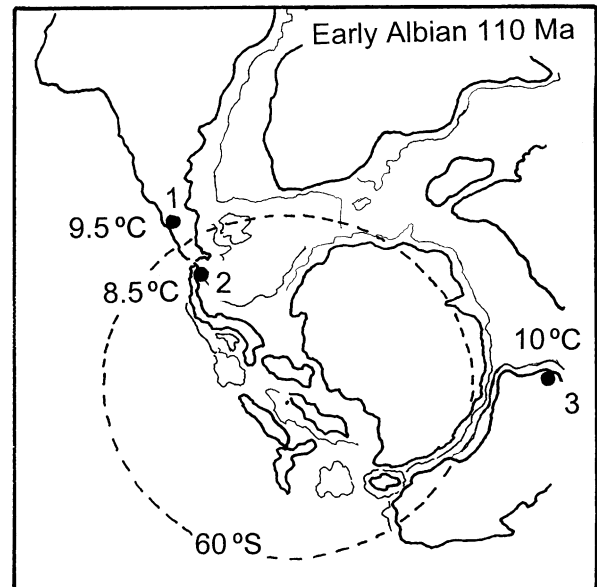


Fig. 3. Schematic plate tectonic reconstruction for the early Albian showing the sampling locations in: (1) Lago San Martin (Argentina), (2) Antarctica (James Ross Basin) and (3) Australia (Carnarvon Basin). Average calculated palaeotemperatures assuming a  $\delta_w$  of  $-1.2\text{‰}$  are also shown.

luminescent calcite infilling very thin microfractures that cross-cut the rostra. Carbonate staining guided sampling of non-ferroan calcite that was considered to be diagenetically unaltered. The samples have a range in  $\delta^{18}\text{O}$  values between  $-0.02$  and  $+0.85\text{‰}$ . Using a  $\delta_w$  value of  $-1.2\text{‰}$  (SMOW) calculated palaeotemperatures for these data range between  $7.8$  and  $11.3^\circ\text{C}$  (mean  $10.1^\circ\text{C}$ ) (Table 2).

Together these data suggest that shelf seawater temperatures around the Gondwanan margin during the early Albian were relatively cool, assuming of course, that the *Dimitobelidae*, and in particular, the *D. diptychus* group, were shelf-dwelling nekto-benthonic organisms. Erbacher et al. (2001) have previously recorded positive  $\delta^{18}\text{O}$  values for both benthic and planktonic foraminifera in the early Albian. These data were attributed to either cool water temperatures and/or high salinities. Although cool, the palaeotemperature estimate for the dimitobelid data is probably not cold enough to support the presence of significant polar glaciation at this time, although limited montane glaciation was possible at intervals in the Cretaceous

Table 2

Comparison of the measured oxygen isotope composition, calculated palaeotemperatures and palaeolatitudes for Lago San Martin (Argentina), the James Ross Basin (Antarctica) (Ditchfield et al., 1994) and the Carnarvon Basin (Australia) (Pirrie et al., 1995)

Location	Stratigraphy	Palaeolatitude	$\delta^{18}\text{O}$ (range)	$T$ °C (range)	$T$ °C (mean)
Lago San Martin (Argentina)	Rio Mayer Fm (early Albian)	$58^\circ\text{S}$	$+0.07$ to $+0.96$	$7.7$ – $10.9$	$9.5$
James Ross Island (Antarctica)	Kotick Point Fm (early to mid Albian)	$65^\circ\text{S}$	$+0.13$ to $+1.40$	$6.1$ – $10.7$	$8.5$
Carnarvon Basin (Australia)	Gearle Siltstone (early to mid Albian)	$55^\circ\text{S}$	$-0.02$ to $+0.93$	$7.8$ – $11.3$	$10.1$

(cf. Miller et al., 2003). The data also support low latitudinal temperature gradients. Huber et al. (2002) suggested a sea-surface latitudinal temperature gradient in the late Albian of 0.25 °C per degree of latitude, while the early Albian belemnite data presented here suggest a slightly lower latitudinal temperature gradient of, at most, 0.16 °C per degree of latitude, although a linear latitudinal gradient is unlikely. Clearly, there was no significant temperature variation between South America and Antarctica in the early Albian. However, what is clear is that the shelf seas of Gondwana were relatively cool during the early Albian, a time during which a distinct marine Austral realm was present.

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