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# Early Miocene subtropical water temperatures in the southeast Pacific

Sven N. Nielsen\*, Johannes Glodny

Deutsches GeoForschungsZentrum (GFZ), Telegrafenberg, 14473 Potsdam, Germany

\* Now at Institut für Geowissenschaften, Christian-Albrechts-Universität zu Kiel, Ludewig-Meyn-Str. 10, 24118 Kiel, Germany. Fax: +49 431 880 5557. *E-mail address*: nielsen@gpi.uni-kiel.de.

## ABSTRACT

Cenozoic climate of western South America is strongly controlled by features like Andean uplift and the Humboldt Current. The first strontium isotope age data from central and southern Chile provide a latest Oligocene to late early Miocene age for classic warm-water mollusk faunas reaching as far south as 45°S. Comparison with the biogeography of congeneric living species indicates that sea surface temperatures off central and southern Chile during that time were at least 5°C higher than today; i.e., minimum annual mean sea surface temperatures for Darwin's Navidad fauna at 34°S are estimated as 20°C. As expected, the number of tropical taxa decreases towards the south but several are still present as far south as 45°S. The ages scatter relatively broadly between ~24 and ~16 Ma, partly even within individual localities. Shallow water and deeper water faunas are revealed to have similar ages. When considered in light of convincing micropaleontological evidence for late Miocene to early Pliocene depositional ages, the Sr-isotope data support a hypothesis that the mollusk fauna is reworked.

Keywords: Strontium isotope stratigraphy, climate, mollusks, Neogene, Chile

## 1. Introduction

Neogene sediments potentially recording paleoenvironmental conditions are known from a limited number of basins along the Chilean coast (Herm, 1969; Martínez-Pardo, 1990; Encinas et al., 2006; Le Roux et al., 2006). The classic mollusk fauna from the Navidad, Ranquil and Lacui Formations of central Chile (Fig. 1), known since Darwin's (1846) voyage on the *Beagle*, contains a number of species indicating a nearshore environment and tropical to subtropical water temperatures (Groves and Nielsen, 2003; Nielsen et al., 2004). Correlation of molluscan taxa from the Navidad Formation with Cenozoic faunas from Peru resulted in the proposal of a latest Oligocene to middle Miocene age for the Navidad fauna (DeVries and Frassinetti, 2003). Recent micropaleontological work (Finger et al., 2007), however, reveals that the Navidad, Ranquil and Lacui Formations are all late Miocene to early Pliocene in age and were deposited at bathyal depths. Ages based on planktic foraminifera are between 4.5 and 11 Ma (Zones N19a to N16a) for most of the localities (Finger et al., 2007); the investigated localities of the Navidad Formation are the same as those that yielded the apparently older mollusks of DeVries and Frassinetti (2003). The current explanation for the age discrepancy is that yet unknown older strata were reworked and displaced to greater depths (Finger et al., 2007). Here we test this hypothesis and check for the alternative possibility that some mollusk species survived much longer in Chile than in Peru. We analyze the strontium isotope signatures of several mollusks from these same localities and also test the hypothesis that the lesser known deep-water mollusk fauna of these formations might be contemporaneous with the microfossil biostratigraphic markers and therefore younger than the shallow-water mollusk fauna.

All of the specimens reported herein come from central to southern Chilean localities (Figs. 1, 2). The Navidad, Ranquil, and Lacui formations are coeval (Finger et al., 2007) and have been synonymised under the name Navidad Formation (Martínez-Pardo, 1990). However, the regional formation names are maintained here and the term Navidad Formation is used in its restricted original sense (Darwin, 1846; Encinas et al., 2006). The rich molluscan fauna of the three units, especially the Navidad Formation, has been the subject of numerous studies (e.g., Philippi, 1887; Tavera, 1979; Frassinetti and Covacevich, 1993; Nielsen et al., 2004; Nielsen, 2005; Nielsen and Frassinetti, 2007a). While depositional ages

younger than the molluscan fauna have been proposed based on planktic foraminifera (Finger et al., 2007), additional planktic foraminifera seem contemporaneous with the mollusks.

## **2. Geologic setting and sampling sites**

The geology of most of the investigated areas is still poorly described. All deposits are clastic sediments and most are situated at today's coastal bluffs. Only from the Navidad Formation a detailed study exists (Encinas, 2006; Encinas et al., 2006), which suggests deposition on the continental slope, based on sedimentary structures, trace fossils and microfossils. The deposits of the Ranquil Formation were briefly described by Tavera (1942) and García (1968), but no detailed sedimentological description is available. Similarly, the deposits of the Lacui Formation were briefly described in the geological map of Antinao et al. (2000) but detailed investigations are wanting. The deposits of both Ranquil and Navidad formations are very similar to those of the Navidad Formation and a similar depositional history is inferred here. No detailed sedimentological or other geological information was ever published about the islands of the Chonos Archipelago (see Fig 1).

Finger et al. (2007) reported late Miocene to early Pliocene planktonic foraminifera from the Navidad, Ranquil, and Lacui formations, supporting the data published by Ibaraki (1992) from Navidad. However, Finger et al. (2007) also correlated the mollusk fauna with well dated late Oligocene to middle Miocene occurrences in Peru (see also DeVries and Frassinetti, 2003) and concluded that the older mollusk fauna was reworked during the latest Miocene to early Pliocene. Reconstructions of the tectonic history of the Navidad and Arauco areas (Melnick and Echtler, 2006; Encinas et al., 2008; Fariás et al., 2008) support a history of tectonic downwarp and uplift as outlined by Finger et al. (2007).

Our localities are the same as those of Finger et al. (2007) and locality data including GPS points (Table 1), detailed strontium data for individual samples and localities (Table 2), and representative sample photos (Fig. 3) are given.

### *2.1. Navidad Formation*

The Matanzas locality (MAT; Figs. 1, 2, Table 1) referred to in this study, is a small fossiliferous lens of pale green sandstone exposed about 2 m above the base of the coastal cliffs about 1 km north of the village of Matanzas, that consist of more than 30 m of alternating sandstones and siltstones (Frassinetti and Covacevich, 1981; Nielsen, 2005). Punta Alta (PTA) is situated at the coastal cliff just below the road between Navidad and Matanzas. The fossiliferous lens consists of grey siltstone (Frassinetti and Covacevich, 1982). North of the Rapel River, to the north of a granite outcrop, fallen blocks of brownish grey sandstone were sampled (RAP), that probably were derived from different beds within the cliff (Nielsen et al., 2004). The locality name Punta Perro has been used for sandstone at the base of the coastal cliff immediately south of the mouth of the Rapel River (Covacevich and Frassinetti, 1986). Finger et al. (2007) distinguished several localities at Punta Perro and separated grey siltstone of the coastal platform (PPP) from overlying orange-brown to yellowish sandstone (PPN). The latter coincides with the locality of Covacevich and Frassinetti (1986).

All of these localities coincide with the coastal cliffs described by Tavera (1979) as belonging to the Navidad Member, the basal member of the Navidad Formation in his classification, which he considered as early to middle Miocene in age. However, the depositional age was recently shown to be late Miocene to early Pliocene (Finger et al., 2007). The three members were recently raised formally to formations which eliminated the homonymy of Navidad Member and Navidad Formation (Encinas et al., 2006). The localities sampled probably represent different stratigraphic levels within the Navidad Formation. Faunas of different ecological environments within the Navidad Formation have been reported (Nielsen, 2003; Nielsen et al., 2003; Finger, 2007), distinguishing a shallow-water fauna within brown sandstone and a deepwater fauna found in grey siltstone. However, displacement of sediment into a deep-water basin is indicated by sedimentological structures (Encinas et al., 2006) and mixed-depth assemblages of microfossils (Finger et al., 2007).

## 2.2. Ranquil Formation

The depositional age of the Ranquil Formation, like the Navidad Formation, has been dated using foraminifera as late Miocene to early Pliocene (Finger et al., 2007). The material used here is from Caleta Ranquil and from Punta El Fraile (Table 2, Fig. 2). The type locality of the formation is at Caleta Ranquil; mollusk specimens come from reddish-brown sandstone, with intercalated green glauconitic beds (RAN), grey siltstone (RQT), and a calcareous sandstone bed (RQK). At Punta El Fraile, two lithological units are distinguished: a grey siltstone unit (FRM) exposed along today's intertidal platform but often covered by sand, and a concordantly overlying reddish brown sandstone unit (FRA) that has not been dated in this study. The locality Lebu (LEB) is situated at the northern end of the village of Lebu, on the eastern side of the road North to Ranquil and Arauco, just beyond the cemetery. A shell-rich greenish calcareous sandstone is exposed in a crevice within light brown well-sorted unfossiliferous sandstone presumed to be of Eocene age (Groves and Nielsen, 2003; Nielsen et al., 2004). The few microfossils recovered from this locality point to a middle Miocene to early Pliocene age (Finger et al., 2007).

## 2.3. Lacui Formation

Sample material comes from three localities on the western coast of Chiloé Island (Fig. 2): a coarse light-grey sandstone at Puñihuil (PNH), a yellowish sandstone south of Chepu (CHE; Watters and Fleming, 1972), and a grey sandstone to siltstone just south of the village of Cucao (CUC). Micropaleontologically dated samples from Chepu (CHE) and Cucao (CUC) show late Miocene to early Pliocene depositional ages (Finger et al., 2007) similar to those of the Navidad Formation. No planktic foraminifera were recovered from Puñihuil (PNH).

## 2.4. Chonos Archipelago

Some data on the mollusk fauna from Ipún, Stokes and Lemo islands were presented by Frassinetti (2001, 2004). New collections made by SNN come from the same as well as additional localities on these islands.

## 3. Material and methods

### 3.1. The molluscan fauna

The classic Navidad fauna comes from sandstones and contains a number of typical tropical to subtropical molluscan taxa (Fig. 3), most of them living at or near the coast in shallow water. Several of these species occur in all of the sampled formations (Fig. 1). Several species of the mostly intertidal keyhole-limpet genus *Diodora* and the neritimorph *Heminerita chilensis* (actually a *Lisanerita*, see Vermeij et al., 2009) are especially indicative of rocky-coast, intertidal to shallow-water environments (Nielsen et al., 2004). The trochoid *Agathistoma antiqua* belongs to a genus that is restricted today to tropical America. Other members of exclusively tropical to subtropical gastropod families include *Strombus medinae* (Nielsen, 2005), *Xenophora paulinae* (Nielsen and DeVries, 2002), the cypraeid *Zonaria frassinettii* (Groves and Nielsen, 2003), the ficids *Ficus distans* and *Ficus gayana* (Covacevich and Frassinetti, 1980), the personid *Distorsio ringens*, the large terebrid *Terebra undulifera* and several species of architectonicids (Philippi, 1887; Nielsen and Frassinetti, 2007b). Additional warm-water taxa include species of the olivid gastropods *Olivancillaria* and *Lamprodomina* and the nautiloid cephalopod *Aturia cubaensis* (Watters and Fleming, 1972; Nielsen, 2004; Nielsen et al., 2009). Many of these warm-water taxa are relatively small in size compared to living or fossil congeners, which probably indicates that they were living at the tolerance limit of environmental conditions, maybe in waters almost too cold for them. However, there is no north-south trend in size, so it is more likely that most or all species represent normal sizes.

An entirely different fauna occurs in siltstones of the same formations, including the deep-water gastropods *Dalium*, *Struthiochenopus*, *Exilia*, *Borsonella Bathytoma*, *Cochlespira*, *Discotectonica*, *Falsilunatia*, *Nihonia* and *Ringicula* (Nielsen, 2005; Finger et al., 2007). None of these deep-water taxa

occur in association with the typical shallow-water fauna noted above. Only the nautiloid *Aturia* is found in both faunal associations, which may be explained by either the sinking of dead individuals into deep-water settings or the coastward drifting of gas-filled shells.

### 3.2. Selection and treatment of samples for Sr isotope stratigraphy

Shell material (cross-lamellar aragonitic, (aragonitic-) nacreous, and calcitic) of a variety of gastropods, bivalves and a cephalopod was analyzed (Table 3) to compare strontium isotope ratios of taxa with different shell structure from the same localities to check for possible material-dependent, alteration/recrystallization-related differences.

Microstructure of shell fragments was examined with scanning electron microscopy (SEM) to detect possible diagenetic effects involving recrystallization (Fig. 4). Non-recrystallized shell fragments were then examined under a stereomicroscope to select those devoid of sediment contamination. After initial cleaning of optically homogeneous samples in distilled H<sub>2</sub>O, the samples were rinsed with p.a.-grade ethanol and then leached with hydrochloric acid (3-6 sec. in 10% HCl, 20°C, in an ultrasonic bath) to remove secondary calcite and contaminants (McArthur, 1994; Bailey et al., 2000; Reinhardt et al., 2000). After another rinse in ultrapure distilled water, the shell material was dissolved in 2.5N HCl. Sr was isolated and recovered from the solutes by ion exchange using Dowex AG-50 cation exchange resin.

### 3.3. Analytics – Sr isotopes

Mass spectrometric analysis: Determinations of Rb and Sr isotope ratios were carried out on a VG Sector 54 multicollector TIMS instrument (GeoForschungsZentrum Potsdam). Sr was analyzed in dynamic multicollection mode. During the period of study, the value obtained for <sup>87</sup>Sr/<sup>86</sup>Sr of the NBS standard SRM 987 (now NIST 987) was 0.710255 ± 0.000020 (n = 11, 2σ SD). The <sup>87</sup>Sr/<sup>86</sup>Sr value for SRM 987 used for construction of the LOWESS dataset for conversion of Sr isotope data into ages is 0.710248 (McArthur et al., 2001), which requires application of a correction factor of 0.999990 for the Potsdam data. Calculation of ages and age errors was performed using the ‘Look-Up Table Version 4: 08/ 03’ (Howarth and McArthur, 1997; McArthur et al., 2001). The error intervals for our strontium isotope stratigraphy age data are based on typical 2σ<sub>m</sub> absolute uncertainties for single-analysis, first-measurement <sup>87</sup>Sr/<sup>86</sup>Sr values of ± 0.000030, as estimated from the reproducibility range for NBS SRM 987. To assess the possible in-situ radiogenic ingrowth of <sup>87</sup>Sr within shell material, we measured Rb and Sr concentrations for a number of samples. With Rb concentrations of <20 ppb and >10<sup>3</sup> ppm Sr, Rb/Sr ratios are far too low to have any detectable effect on <sup>87</sup>Sr/<sup>86</sup>Sr ratios since shell growth.

### 3.4. Sea Surface Temperatures

Modern distributions for several gastropod genera were taken from the OBIS database (<http://www.iobis.org>) in early 2007 and compared to modern sea surface temperature maps (Ocean Climate Laboratory, 1999). Occurrences with lowest sea surface temperatures from these distributions were then used to infer sea surface temperatures for the early Miocene of southern Chile because we interpret the tropical taxa to represent a fauna living at the lower limit of its temperature tolerance.

## 4. Results

### 4.1. Strontium Isotope Stratigraphy

Using strontium isotope ratios to correlate the Sr isotopic signature of marine fossils with the global Sr seawater evolution curve (McArthur et al., 2001; McArthur and Howarth, 2004), we dated a number of different mollusk shells of the Navidad Formation and its correlative units to the south. The results constitute the first strontium isotope data for the central and southern Chilean marine Neogene. All shell samples were carefully checked by SEM for mineralogical and microstructural integrity. The

sample preparation procedure ensures that contaminations by matrix sediments can be ruled out. All obtained  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (Table 2) can therefore reliably be converted to their corresponding latest Oligocene to early Miocene ages. The ages range from 24.27 (+0.90/-0.73) Ma to 16.10 (+0.64/-0.56) Ma. Two-sigma uncertainties on derived numerical ages are generally less than 1 Ma. Ages were obtained from different taxa presenting different shell microstructural characteristics (Table 3). Only the olivid *Lamprodomina dimidiata* was used from multiple outcrops for reference.

#### 4.2. Chilean early Miocene water temperatures

Geographic ranges of early Miocene warm-water gastropods suggest, not surprisingly, decreasing sea surface temperatures (SSTs) towards the south (Fig. 1). Many species belonging to exclusively tropical to subtropical taxa, including *Lisanerita chilensis*, *Strombus medinae*, *Ficus distans*, *Ficus gayana*, *Architectonica karsteni*, *Intitectonica inti*, and *Discotectonica navidadensis*, are restricted to the Navidad Formation and are not found in the coeval formations further south. Comparison of extant distributions of still living genera with modern SSTs suggests water temperatures of at least 20°C for the Navidad area (34°S) during the early Miocene. Some species occur as far south as Arauco (38°S) (e.g., *Zonaria frassinetti*, see Groves and Nielsen, 2003). Distinctly lower SSTs can be inferred towards Chiloé (42°S), where fewer warm-water taxa, such as *Distorsio ringens* and *Terebra undulifera*, occur. The Chonos Archipelago (44.5°S) yields even fewer warm-water taxa, which include *Sinum subglobosum*, *Echinophoria monilifera*, *Lamprodomina dimidiata*, and the architectonicid *Heliacus chonos* (Frassinetti, 2001; Nielsen and Frassinetti, 2007b). Annual average SSTs of at least 18°C seem reasonable for the early Miocene sea off Chiloé and the Chonos Archipelago, but only if *Distorsio* tolerated lower water temperatures than it does today. We are conservative in using the lowermost reasonable temperatures, even though *Distorsio* is a good argument for even higher temperatures as far south as 45°S.

### 5. Discussion

#### 5.1. Reworking of Early Miocene mollusks

Our obtained ages confirm previous correlations of these mollusks with latest Oligocene – middle Miocene mollusks of Peru (DeVries and Frassinetti, 2003; Finger et al., 2007). Our results indicate, however, considerably older ages for the here studied mollusk fauna compared to the late Miocene to early Pliocene planktic foraminifera from the same localities reported by Finger et al. (2007). It needs to be stressed in this context that most likely the Strontium isotope stratigraphy ages are not biased towards being ‘too old’. The mollusk shells are deposited in continent-derived sediments, which can be expected to develop diagenetic brines with  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios higher than seawater. The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of seawater increases monotonically in the during the Neogene. Both interaction of the shell material with seawater or diagenetic brines would thus raise  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios and result in erroneously young ages. We therefore regard our late Oligocene-early Miocene mollusk ages as accurate, and interpret the ages as evidence of reworking, both because of their broad range and the presence of younger microfossils derived from the same formations and localities (Finger et al., 2007). The shallow-water and deep-water mollusks are not consistently different in age (see Table 2). It is therefore concluded that these faunas coexisted, but at different depths. The deep-water mollusks were therefore reworked as the shallow-water ones and are not contemporaneous with the younger age-diagnostic planktic foraminifera reported by Finger et al. (2007). At the moment it cannot be explained how it is possible that macrofossils spanning a stratigraphic range of almost 8 Ma and having been subsequently redeposited are not mixed but occur in easily distinguishable faunas representing distinct environments with usually different lithologies. A possible explanation is that intermittent slumping caused fossil-bearing sediments from shallow water to become interbedded with fossil-bearing sediments from deeper water between 24 Ma and 16 Ma. However, to our knowledge there is no mechanism that would allow the entire sedimentary package to be displaced around 4.5 Ma, incorporating the early Pliocene planktic foraminifera reported by Finger et al. (2007) without leaving sedimentological evidence.

## 5.2 Climate, Paleooceanography and Tectonics

Our data clearly indicate that subtropical water temperatures persisted in southern Chile until at least ~16 Ma. However, no warm water mollusks with ages younger than ~16 Ma were found. Even more, we are not aware of any preserved marine mollusk fauna from central or southern Chile that has been dated with confidence for the time span between 16 and 5 Ma. It therefore appears that at around 16 Ma the critical conditions for occurrence and preservation of the Navidad fauna were no longer met, and that conditions for near-shore preservation of mollusk shells deteriorated after 16 Ma. This change may be due to climatic, paleoceanographic, or tectonic reasons or a combination of these, as outlined below.

The age range of 24.27 to 16.1 Ma for the Chilean tropical to subtropical fauna spans the early Miocene and predates the Miocene climate optimum observed both globally and around the Pacific at about 16 Ma (Tsuchi, 1990). Global climate from the late Oligocene until the middle Miocene was considerably warmer than it is today, with a marked cooling after ~16 Ma (Zachos et al., 2001). Disappearance of the Navidad fauna may thus be related to cooler water temperatures off Central and Southern Chile from the Middle Miocene onwards. However, this cooling alone does not explain the absence of younger, 'cooler' faunas after 16 Ma.

Global cooling at around 16 Ma does not necessarily imply local cooling in the southeast Pacific off Chile. Instead, contemporary interpretations of Antarctic Circumpolar Current (ACC) and Humboldt Current development suggest that cool waters may already have been present off Chile in the Early Miocene. Incipient opening of the Drake Passage occurred around 41 Ma (Scher and Martin, 2006), and its deepening allowed for initiation of the ACC. There is debate as to whether the ACC was fully established either in the Early Oligocene, between 34 and 30 Ma (Livermore et al., 2005) or in the latest Oligocene, at about 24 Ma (Pfuhl and McCave, 2005; Lyle et al., 2007). In any case, in the Early Miocene the ACC was active, in analogy to the present-day situation, and correspondingly extensive ice sheets developed over Antarctica. In a scenario similar to the present day situation, cool Antarctic water should have reached southern Chile at ~24 Ma at the latest, preventing subtropical temperatures as far south as our data show. Thus either the Circum-Antarctic waters must have been much warmer in the Early Miocene than they are today, or the overall pattern of oceanic circulation in the South Pacific must have been different from today's situation. Possibly in the Early Miocene, the Humboldt Current as the eastern branch of the South Pacific gyre was either weaker, or carried much lower proportions of ACC-derived cold waters along South-Central Chile than in the Holocene.

The apparent lack of any Middle and Late Miocene fossil record along the Chilean coast requires explanation. This apparent lack may be due to scarcity of preserved Middle to Late Miocene sediments with lack of recognition and description, or may indicate that there is a real hiatus in near-coastal sedimentation in this period. We hypothesize that tectonic processes at the Chilean active margin influenced the Neogene sedimentary record. A significant ecosystem change at ~16.5 Ma was reported from the Argentinean foreland of the Patagonian Andes by Blisniuk et al. (2005), who interpreted shifts in  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values as consequences of more than 1 km of surface uplift of the Southern Andes and related increased aridity resulting from development of a rain shadow. This major uplift should have resulted in increased precipitation and erosion on the western flank of the Andes, which likely would have triggered changes in subduction mode through increased sedimentation rates in the trench (Melnick and Echtler, 2006; Vietor and Echtler, 2006). Increased supply of sediments, possibly in conjunction with a drop in sea level, may have led to abandonment of Navidad-type depositional centers and to sediment bypass towards the deep ocean. A related shift from tectonically erosive to accretionary conditions along the offshore forearc of South-central Chile during the Pliocene was proposed to have led to inversion of existing forearc basins (Melnick and Echtler, 2006). Significant Late Miocene to Pliocene uplift is documented also by fission track data, both from the Navidad and Arauco areas (Farías et al., 2008; Glodny et al., 2008). It thus seems reasonable that Mid-Miocene and later tectonic processes along the

Chilean continental margin and in the Southern Andes had already stopped sedimentation in near-coastal Navidad-like basins at ~16 Ma, which would account for the lack of younger mollusk ages in our sample set and along the South-Central Chilean coast in general. Late-Miocene to Pliocene uplift of coastal areas and related basin inversion likely effected Navidad fauna reworking and intermingling with Late Miocene-Pliocene planktic foraminifera.

## 6. Conclusions

Several conclusions can be drawn from our combined faunal and isotopic data:

- 1) Warm surface water temperatures, at least 5°C warmer than today, existed off central and southern Chile during the whole early Miocene, and supported the Navidad fauna.
- 2) Shallow-water and deeper-water mollusk faunas of the investigated formations lived at the same time.
- 3) Early Miocene marine conditions in the Southeast Pacific differed from today's setting. Either circum-Antarctic waters were warmer, or their proportion in the Humboldt current was minor, or the Humboldt current was much weaker than at present.
- 4) Both the hypotheses of large-scale reworking of early Miocene sediments during the late Miocene-early Pliocene interval and the correlation of the Chilean Navidad Formation mollusks with late Oligocene to middle Miocene faunas in Peru (DeVries and Frassinetti, 2003; Finger et al., 2007) are supported by the new data.

Based on the presented results we hypothesize that displacement and redeposition of large amounts of sediments off the central and southern Chilean coast at about 4.5 Ma (Finger et al., 2007) likely correlate with basin inversion and associated reorganization of coast and/or continental slope stability. However, tectonic processes finally resulting in this continental margin reorganization might have started earlier, possibly shutting off sedimentation in near-coast depositional centers as early as ~16 Ma.

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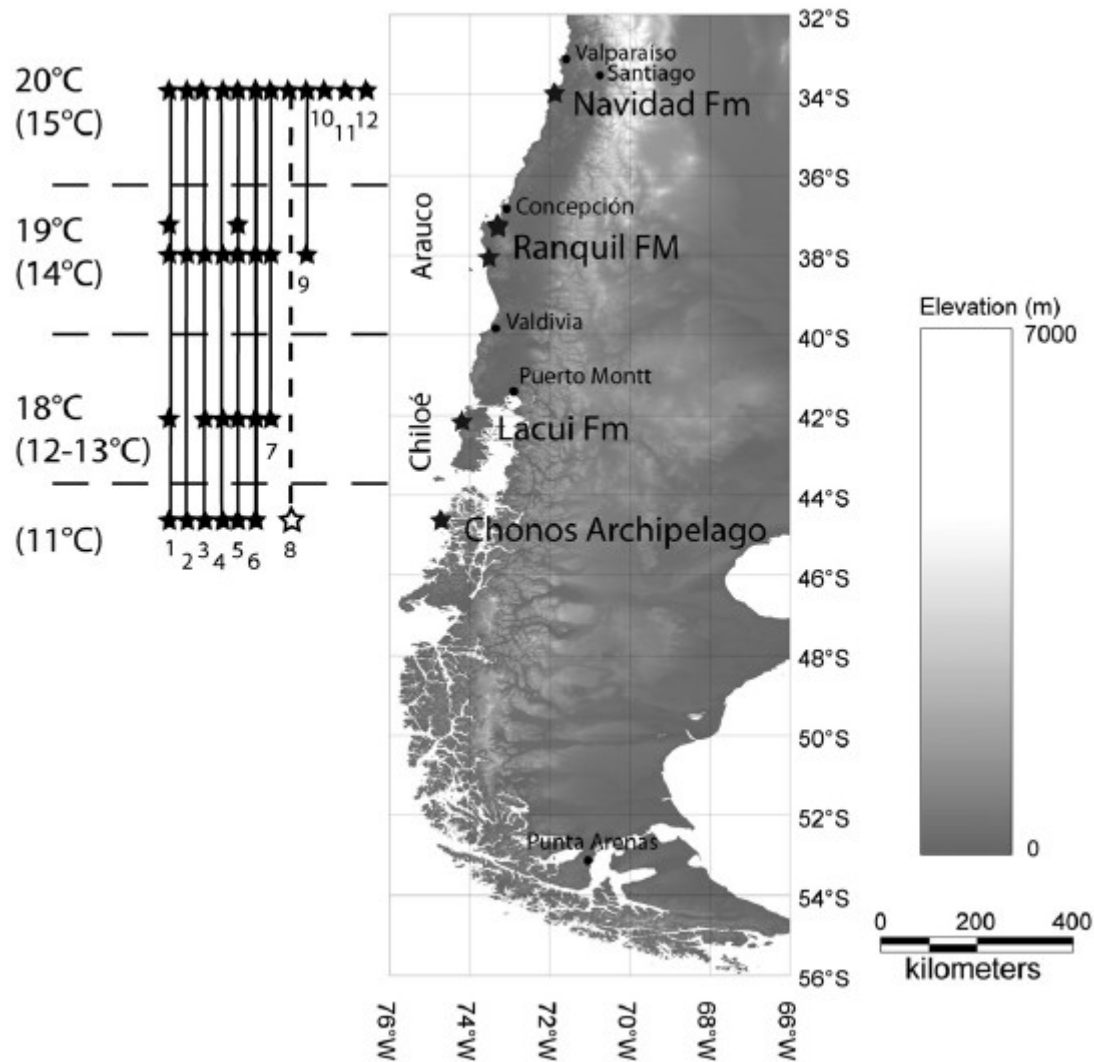
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## Figures



**Fig. 1.** Study areas in central Chile and geographic ranges for some early Miocene warm water mollusks and proposed approximate sea surface temperatures (SST). Modern annual average SSTs (in parentheses) from Ocean Climate Laboratory (1999). 1, *Aturia cubaensis*; 2, Architectonicidae; 3, *Sinum subglobosum*; 4, *Olivancillaria claneophila*; 5, *Lamprodomina dimidiata*; 6, *Distorsio ringens*; 7, *Terebra undulifera*; 8, *Xenophora paulinae*; 9, *Zonaria frassinettii*; 10, *Ficus* spp.; 11, *Strombus medinae*; 12, *Lisanerita chilensis*. Open star in 8 marks a shell fragment possibly belonging to this species. See Figure 2 for detailed maps and sampled localities.

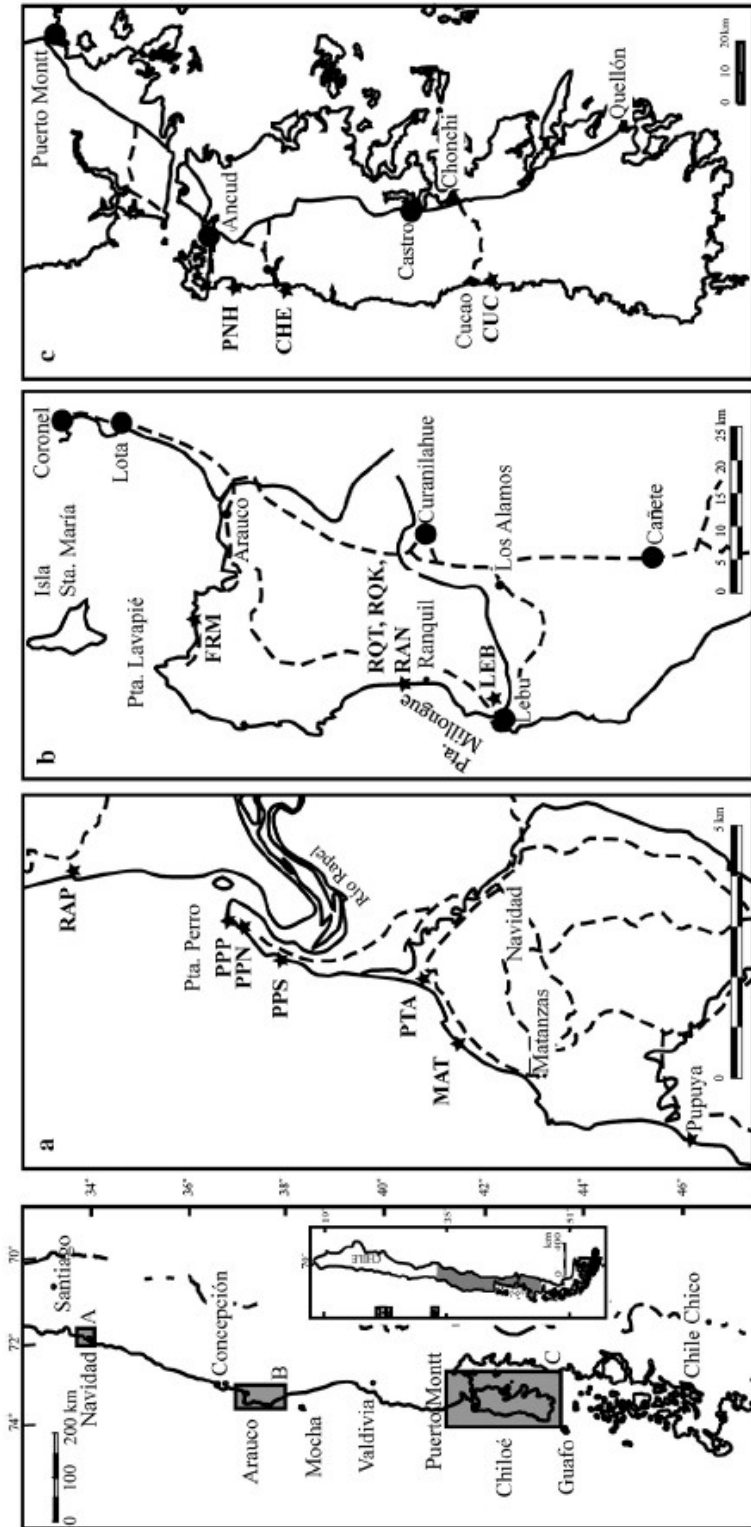
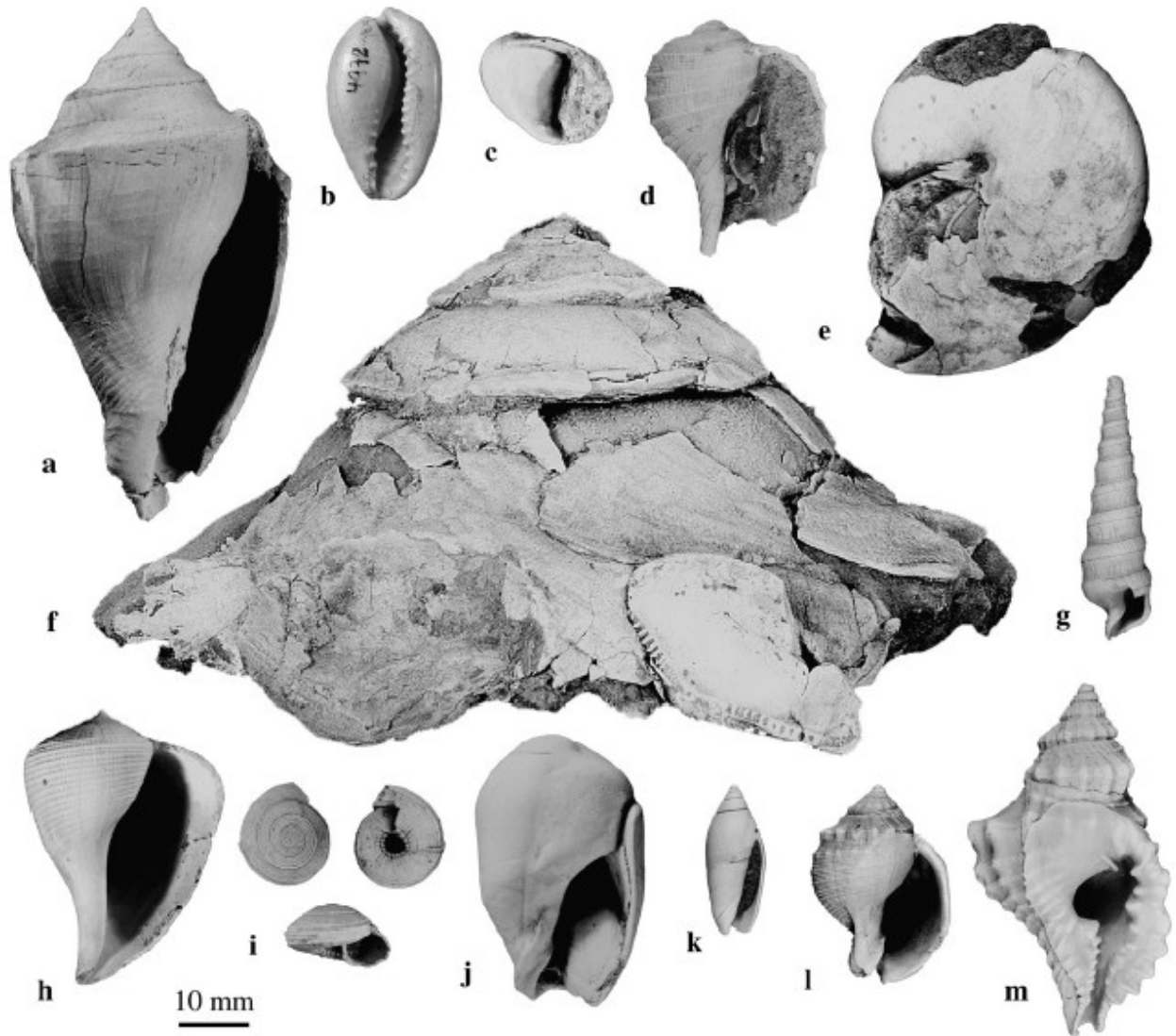
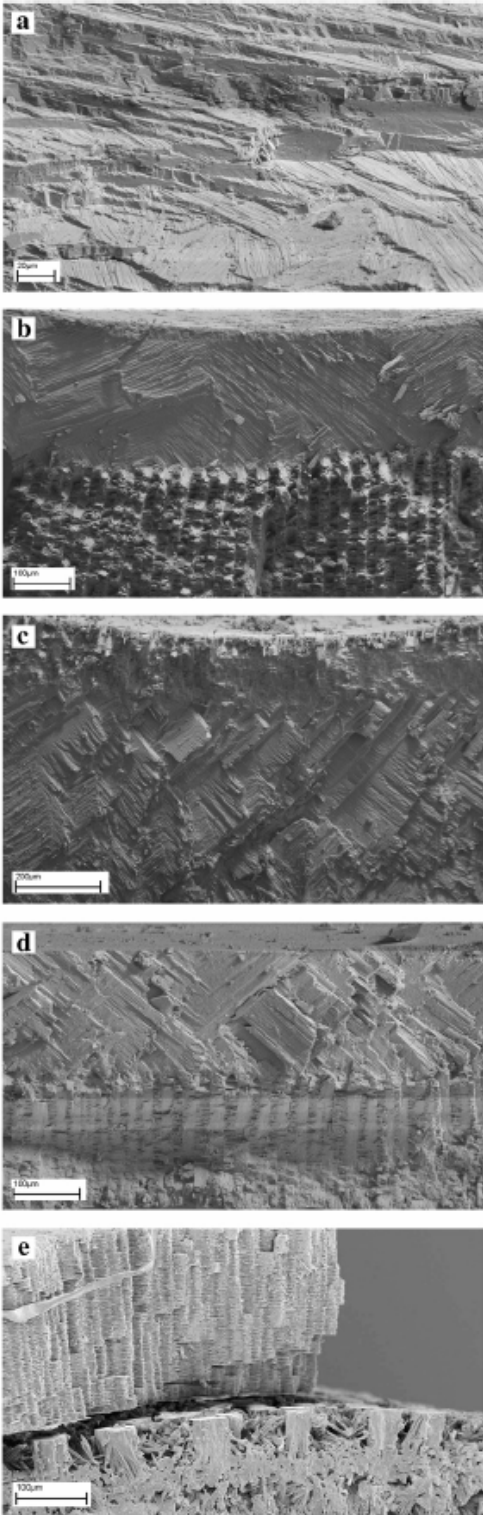


Fig. 2. Sample localities. A, Navidad Formation; B, Ranquil Formation; C, Lacui Formation.



**Fig. 3.** Typical warm water mollusc species from the early Miocene of Chile. a, *Strombus medinae*. b, *Zonaria frassinettii*. c, *Heminerita chilensis*. d, *Ficus distans*. e, *Aturia cubaensis*. f, *Xenophora paulinae*. g, *Terebra undulifera*. h, *Ficus gayana*. i, *Heliacus antu*. j, *Olivancillaria claneophila*. k, *Lamprodomina dimidiata*. l, *Echinophoria monilifera*. m, *Distorsio ringens*. a-d, f-m, Navidad Formation. e, Lacui Formation.



**Fig. 4.** Shell structure of species analyzed for strontium isotopic compositions. a, Undetermined pectinid, analysis PS1233/1234. b, *Lamprodomina*, PS1231. c, Undetermined turrid, PS1227. d, *Dalium*, PS1228. e, *Aturia*, PS1275. See Table 2 for locality and age data and Table 3 for shell structure.

## Tables

**Table 1.** Locality data for analyzed samples.

Fm	Locality	Long. / Lat.	Lithology
Navidad Fm	MAT	33.958°S / 71.888°W	Green sandstone
	PTA	33.952°S / 71.877°W	Grey siltstone
	RAP	33.852°S / 71.835°W	Brown grey sandstone
	PPP	33.910°S / 71.847°W	Grey siltstone
	PPN	33.914°S / 71.853°W	Brown sandstone
Ranquil Fm	RAN	37.507°S / 73.593°W	Brown sandstone with glauconite
	RQT	37.507°S / 73.593°W	Grey siltstone
	RQK	37.507°S / 73.593°W	Brown sandstone
	FRM	37.204°S / 73.511°W	Grey siltstone
	FRA	37.204°S / 73.511°W	Brown sandstone
	LEB	37.602°S / 73.644°W	Greenish sandstone
	Lacui Fm	PNH	41.896°S / 74.006°W
CHE		42.087°S / 74.057°W	Yellowish sandstone
CUC		42.724°S / 74.175°W	Grey sandstone



**Table 2.** Sr isotopic data and age results for analyzed taxa (see Table 3 for higher classification and shell structure). Navidad, Ranquil and Lacui formations, central to southern Chile. For sample localities see Figs. 1 and 2. Inferred water depth based on mollusk fauna from Finger et al. (2007, their Table 1). Data normalized to a  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.710248 for NIST SRM 987 (McArthur et al., 2001). NIST SRM 987 is measured at GFZ Potsdam as  $0.710255 \pm 0.000020$  ( $n = 11$ ,  $2\sigma$  SD) which results in a correction factor for the Potsdam data of 0.999990.

	Locality	Water depth	Taxon	Analysis	$^{87}\text{Sr}/^{86}\text{Sr}$ , $\pm 2\sigma_m$ (abs.)	$^{87}\text{Sr}/^{86}\text{Sr}$ normalized	age ( $\pm 2\sigma$ ) (in Ma)
Navidad Formation	RAP	shallow	Pectinidae	PS1233	$0.708654 \pm 0.000010$	0.708647	17.24 (+0.51/-0.63)
			Pectinidae	PS1234	$0.708639 \pm 0.000013$	0.708632	17.47 (+0.46/-0.59)
			<i>Lamprodomina</i>	PS1380	$0.708571 \pm 0.000010$	0.708564	18.33 (+0.45/-0.46)
	PPP	deep	<i>Struthiochenopus</i>	PS1272	$0.708575 \pm 0.000009$	0.708568	18.28 (+0.45/-0.46)
			<i>Lamprodomina</i>	PS1274	$0.708480 \pm 0.000007$	0.708473	19.51 (+0.54/-0.47)
			<i>Xenophora</i>	PS1277	$0.708571 \pm 0.000009$	0.708564	18.33 (+0.45/-0.46)
	PPN	shallow	<i>Olivancillaria</i>	PS1229	$0.708456 \pm 0.000009$	0.708449	19.84 (+0.67/-0.48)
			<i>Lamprodomina</i>	PS1231	$0.708427 \pm 0.000011$	0.708420	20.31 (+0.76/-0.57)
			<i>Olivancillaria</i>	PS1235	$0.708461 \pm 0.000013$	0.708454	19.77 (+0.65/-0.48)
	PPS	shallow	<i>Neobouchardia</i> (Brachiopoda)	PS1381	$0.708484 \pm 0.000009$	0.708477	19.46 (+0.52/-0.48)
PTA	deep	<i>Echinophoria</i>	PS1386	$0.708521 \pm 0.000010$	0.708514	19.96 (+0.48/-0.46)	
MAT	rocky coast	<i>Lamprodomina</i>	PS1230	$0.708227 \pm 0.000013$	0.708220	23.65 (+0.74/-0.73)	
Ranquil Formation	FRM	deep	Turridae	PS1227	$0.708280 \pm 0.000010$	0.708273	22.67 (+0.69/-0.57)
			<i>Dalium</i>	PS1228	$0.708227 \pm 0.000011$	0.708220	23.65 (+0.74/-0.73)
	RAN	shallow	Volutidae	PS1225	$0.708417 \pm 0.000010$	0.708410	20.50 (+0.73/-0.63)
			Pectinidae	PS1280	$0.708486 \pm 0.000007$	0.708479	19.43 (+0.51/-0.47)
			<i>Austrotoma</i>	PS1276	$0.708337 \pm 0.000009$	0.708330	21.82 (+0.53/-0.55)
	RQT	deep	cf. Olividae	PS1540	$0.7084247 \pm 0.0000085$	0.708418	20.35 (+0.75/-0.58)
	RQK	shallow	<i>Oliva</i>	PS1273	$0.708720 \pm 0.000007$	0.708713	16.10 (+0.64/-0.56)
LEB	rocky coast	Pectinidae	PS1278	$0.708194 \pm 0.000009$	0.708187	24.27 (+0.90/-0.73)	
Lacui Formation	PNH	indet.	Naticidae	PS1279	$0.708355 \pm 0.000010$	0.708358	21.42 (+0.54/-0.64)
	CHE	shallow	<i>Acanthina</i>	PS1388	$0.708683 \pm 0.000011$	0.708676	16.75 (+0.62/-0.63)
	CUC	shallow	<i>Lamprodomina</i>	PS1226	$0.708551 \pm 0.000011$	0.708544	18.57 (+0.47/-0.45)
<i>Aturia</i>			PS1275	$0.708682 \pm 0.000009$	0.708675	16.76 (+0.63/-0.62)	

**Table 3.** Higher classification and type of shell structure of molluscan taxa investigated in this study. Also included is the calcitic brachiopod of the genus *Neobouchardia* (see Table 2).

Shell structure	Class	Family	Genus
calcite	Bivalvia	Pectinidae	?
aragonitic nacre	Cephalopoda	Aturiidae	<i>Aturia</i>
aragonitic cross-lamella	Gastropoda	Volutidae	<i>Palaeomelon</i>
		Olividae	<i>Oliva</i>
			<i>Lamprodomina</i>
			<i>Olivancillaria</i>
		Turridae	?
			<i>Austrotoma</i>
		Tonnidae	<i>Dalium</i>
		Aporrhaidae	<i>Struthiochenopus</i>
Xenophoridae	<i>Xenophora</i>		
Naticidae	<i>Polinices</i>		