Evidence for an Early-Middle Miocene age of the Navidad Formation (central Chile): Paleontological, paleoclimatic and tectonic implications

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ABSTRACT. The age of the Navidad Formation in central Chile has always been controversial, mainly due to the conflicting age ranges indicated by its macro- and microfossils. Macrofossils are generally interpreted as having been reworked from older, Early to Middle Miocene strata, whereas a Late Miocene-Pliocene age has been accepted on the basis of planktonic foraminifer index species. The results of this study, however, indicate that the macrofossils occur *in situ*, which necessitates a complete revision of the geochronological data. It is concluded that the evidence for an Early to Middle Miocene age is overwhelming, and that the planktonic foraminifer index species must have appeared in the SE Pacific earlier than elsewhere. These include *Globoturborotalia apertura*, *Globorotalia puncticulata* (Deshayes), *Globorotalia spheriomizea* (Walters), *Neogloboquadrina pachyderma* (Ehrenberg), and *Neogloboquadrina acostaensis* (Blow). An Early to Middle Miocene age for the Navidad Formation correlates well with a reinterpretation of its depositional environment as a continental shelf instead of a deepwater continental slope, global and regional paleoclimatic events, and the tectonic development of the Andes Range.

Keywords: Foraminifer index species, Middle Miocene Climatic Optimum, Andean tectonics, Arid Diagonal.

RESUMEN. Evidencias de una edad miocena temprana-media de la Formación Navidad: Implicancias paleontológicas, paleoclimáticas y tectónicas. La edad de la Formación Navidad en Chile central siempre ha sido controversial, debido a los distintos rangos de edad indicados por los macro- y microfósiles. En general, se considera que los macrofósiles han sido retrabajados de estratos del Mioceno Temprano a Medio, y se aceptó una edad miocena tardía para esta unidad sobre la base de especies indicadoras de foraminíferos planctónicos. Sin embargo, los resultados de este estudio indican que los macrofósiles ocurren *in situ*, lo cual hace necesario una revisión completa de los datos geocronológicos. Se concluye que la evidencia por una edad miocena temprana a media es contundente, y que los foraminíferos planctónicos que indicarían una edad miocena tardía aparecieron más temprano en el SE del océano Pacífico que en otras partes. Estos foraminíferos incluyen *Globoturborotalia apertura*, *Globorotalia puncticulata* (Deshayes), *Globorotalia spheriomizea* (Walters), *Neogloboquadrina pachyderma* (Ehrenberg), y *Neogloboquadrina acostaensis* (Blow). Una edad miocena temprana a mediana correlaciona bien con la reinterpretación del ambiente deposicional como una plataforma continental en vez de un talud continental con agua profunda, eventos paleoclimáticos reconocidos a escala global y regional, y el desarrollo tectónico de los Andes.

Palabras clave: Especies indicadoras de foraminíferos, Óptimo Climático del Mioceno Medio, Tectonismo andino, Diagonal Árido.

1. Introduction

The Navidad Formation in central Chile (Fig. 1), since first described by Darwin (1846), has attracted considerable attention over the years due to its wealth of fossils, which include well preserved leaves and pollen (*e.g.,* Troncoso, 1991; Meón *et al.,* 1994; Hinojosa, 2005), microfossils such as foraminifera and ostracods (Osorio, 1978; Martínez-Pardo, 1990; Ibaraki, 1992; Finger *et al.,* 2003) and macrofossils ranging from gastropods to crustaceans and sharks (Philippi, 1887; Tavera, 1960; Nielsen *et al.,* 2004; Feldmann *et al.,* 2005; Suárez *et al.,* 2006). However, it is precisely this abundant variety of fossils that

has led to considerable debate on the age of this formation, which has been assigned to the Late Oligocene-Early Miocene based on invertebrate macrofossils (Tavera, 1979), the Late Miocene according to ostracods (Osorio, 1978) and the Middle Miocene-early Pliocene due to the presence of certain foraminifer index species (Encinas *et al.,* 2006; Finger *et al.,* 2007). Strontium dating of shells, on the other hand, has consistently yielded Early-Middle Miocene ages (Encinas, 2006). Nielsen *et al.* (2003), Encinas *et al.* (2008) and Finger *et al.* (2007) attributed this discrepancy to the reworking of older, shallow water micro- and macrofossils into deep water, where they were mixed with the younger foraminifers.
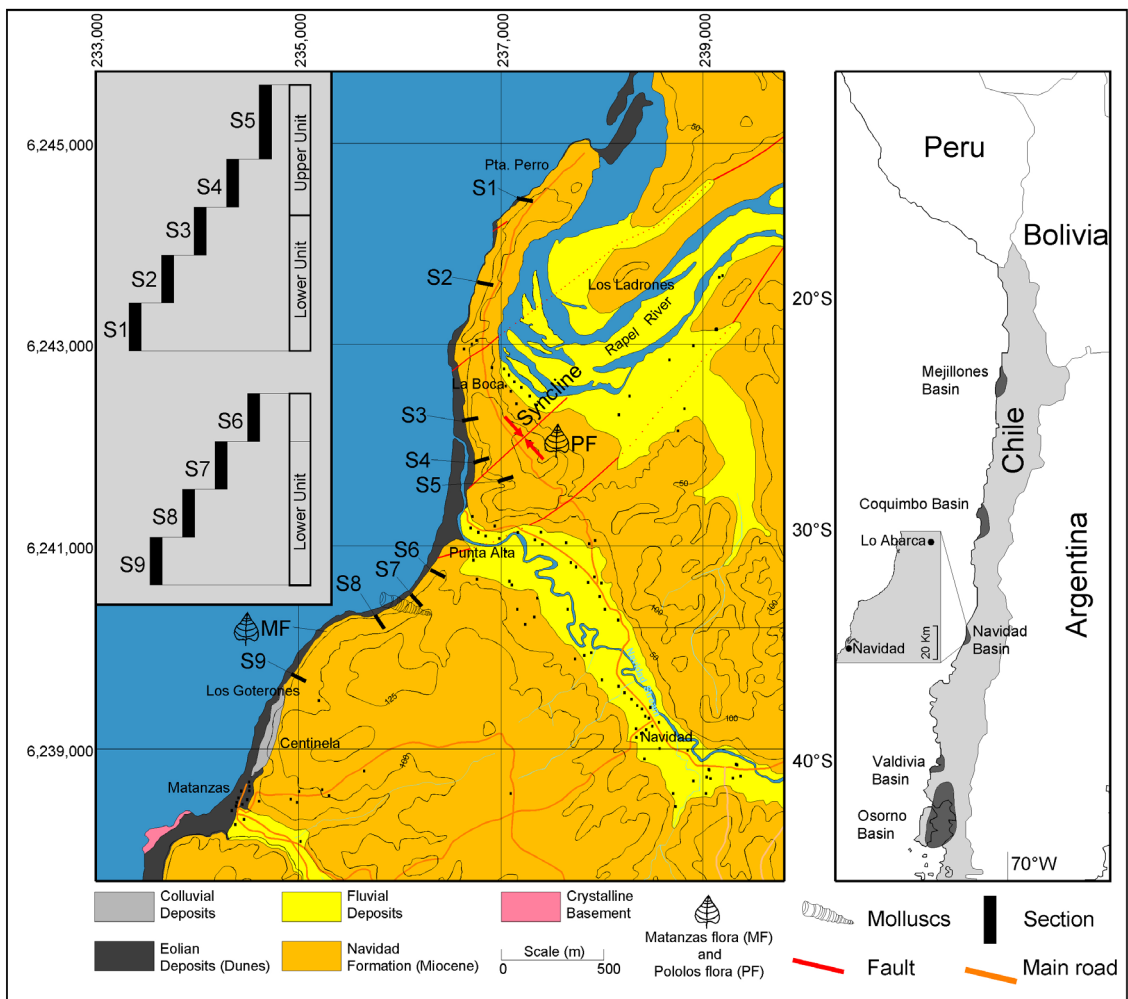

FIG. 1. Geological and locality map showing places mentioned in text. Locations of measured stratigraphic sections are indicated as S1-S9.

Not only the age of the Navidad Formation have been controversial, but also its stratigraphic extent and subdivision (Table 1) as well as its depositional environment. The latter has generally been interpreted as shallow marine (*e.g.,* Tavera, 1979), although Encinas (2006) and Encinas *et al.* (2008) proposed water depths reaching up to 1,500 m based on benthonic foraminifers. For the purposes of this paper, the stratigraphic nomenclature of Encinas *et al.* (2006) is accepted (Table 1), although the possibility that this may have to be revised in the future cannot be discarded.

2. The age of the Navidad Formation

Various methods have been used to determine the age of the Navidad Formation, which are critically summarized below.

2.1. Molluscs

In Peru, Navidad mollusc species such as *Miltha vidali* (Philippi), *Acanthina katzi* (Fleming), *Olivancillaria claneophila* (Duclos) and *Testallium cepa* (Sowerby) occur in well-dated strata of the Late Oligocene-Middle Miocene (Nielsen *et al.,* 2003), but not in younger successions (Vermeij and DeVries, 1997; DeVries and Frassinetti, 2003). Other Navidad species such as *Ficus distans* (Sowerby) are restricted in Peru to the Early-Middle Miocene (Covacevich and Frassinetti 1980), whereas *Eucrassatella ponderosa* (Philippi)*, Glycymeris ibariformis* (Frassinetti and Covacevich), and *G. colchaguensis* (Griffin and Nielsen) only occur in the Late Oligocene-Early Miocene (DeVries and Frassinetti, 2003). An Early Miocene age was also obtained by [87]Sr/[86]Sr dating of 2 samples of *O. claneophila* from the Navidad Formation at its type locality, which yielded 24.7±0.4 and 20.4±0.5 Ma (Encinas, 2006). The youngest age among these species as indicated by *Acanthina katzi* is about 13 Ma (Finger *et al.,* 2007, Fig. 9). There are no published reports of exclusively Late Miocene molluscs in the Navidad Formation. In our opinion, there is clear evidence that these fossils had not been reworked. Many of the shells are extremely well preserved (Nielsen and Glodny, 2006), bivalves often being articulated and some molluscs

TABLE 1. LITHOSTRATIGRAPHY AND AGE OF THE NAVIDAD FORMATION AS PROPOSED BY PREVIOUS AUTHORS AND THIS PAPER.

Epoch		Age	Ma	Darwin, 1946	Brüggen, 1950	Tavera, 1979	Encinas, 2006	This paper	
Pliocene		Piacenzian	2.6					?	?
			3.6		La Cueva Fm.		La Cueva Fm.	La Cueva Fm.	
		Zanclean					Rapel Fm.		
			5.3				Licancheu Fm.		
Miocene	L	Messinian	7.2						
		Tortonian					Navidad Fm.	Rapel Fm.	
			11.6					Licancheu Fm.	
	M	Serravalian	13.8					Navidad Fm.	Upper unit
		Langhian	16.0	Navidad Fm.	Navidad Fm.				
	E	Burdigalian	20.4			Navidad Fm.			Lower unit
		Aquitanian	23.0						
Oligocene	L	Chattian	28.4					?	?

having delicate ornamentation. At least one species, *Lucinoma promaucana*, clearly occurs *in situ* at a paleo-seep in the Navidad Formation (Contardo and Mena, 2012). This bivalve family presently lives at hydrothermal vents and cold-seeps (Campbell and Bottjer, 1995) and was also dominant in Oligocene to Neogene paleo-seeps in the North Pacific (Kiel *et al.,* 2010). The specific species *L. promaucana* has been recorded, apart from the Navidad Formation, only in the Oligocene of Argentina (Malumián *et al.,* 1978) and on Hereford Island in Chile, where Covacevich and Frassinetti (1986) assigned it tentatively to the Middle Miocene. It would be too great a coincidence to accept that this species was reworked from older rocks in such a way that it coincides exactly with the paleo-seep occurrence.

The strongest evidence, however, is that the matrix filling all the molluscs that we have observed is the same as that of the host strata (Fig. 2). If these fossils had been reworked from older (by at least 1.4 million years) rocks into Late Miocene sediments, the original material would have been consolidated and should thus have been preserved within the shells, thus differing from that of the younger host matrix. In addition, Nielsen (2003) and Nielsen *et al.* (2003) mention that molluscs of different ecological environments are separated into well-defined units, shallow water fauna being present in sandstone and deeper water fauna in siltstone. This separation of inner- and outer shelf fauna could more logically be explained by sea-level oscillations producing lateral shifts in facies belts than by reworking, which would have mixed deep and shallow water species indiscriminately. Finally, if the Navidad Formation were of Late Miocene age, we consider it to be very strange that no molluscs of this age have been found within the strata, as there is no evidence of any abnormal marine conditions that would have prevented their occurrence. We consider therefore the mollusc fossils to have been preserved *in situ* and to reflect the true age of the host strata.

2.2. Shark teeth

Suárez *et al.* (2006) recorded the teeth of various elasmobranch species from the Navidad Formation. Among these is *Carcharoides totuserratus* (Ameghino), an uncommon shark with a chronostratigraphical range restricted to the Late Oligocene and Early Miocene (Suárez and Marquardt, 2001).

2.3. Strontium dating

Twenty-nine out of 30 molluscs dated by Encinas (2006) yielded $^{87}Sr/^{86}Sr$ ages between 31.5 and 16.0 Ma, with only one age falling within the earliest Late Miocene (11.5±1.0 Ma). This sample was an oyster from the Lo Abarca sector (Fig. 1), which is probably not suitable for this kind of dating because oysters commonly occur in brackish water environments, in which the oceanic Sr content would be affected. In fact, Encinas (2006) mentions the presence of freshwater diatoms in samples from this sector.

Other Sr age determinations have been carried out on samples from the lower part of the Navidad Formation by K. Gregory-Wodziki and S. Pekar of the Columbia University as part of a pilot study. Twenty-four samples of shell material from the Navidad Formation yielded Sr ages between 23.0±0.6 and 20.2±0.6 Ma (K. Gregory-Wodziki, personal communiation to Suárez *et al.,* 2006). Furthermore, Nielsen and Glodny (2006) also reported 21 Sr ages that range between 24.3 and 16.1 Ma.

Additionally, we dated 8 molluscs between 22.5 and 18.9 Ma (Table 2). All the shells were in excellent condition, as shown by color conservation, unbroken ornaments and preserved articulation in the case of bivalves. They contained the same matrix-fill as the surrounding sediment.

The Sr ages obtained so far (a total of 83 samples dated in different laboratories) thus confirm the ages given by the generally accepted chronostratigraphic ranges of the Navidad mollusc species, being overwhelmingly Early Miocene.

2.4. Radiometric dating

Encinas (2006) dated 6 volcanic scoria and pumice clasts in the Navidad Formation using the K-Ar and Ar/Ar geochronological methods. Five of these are of Early to Middle Miocene age (22.2-15.9 Ma) and only one yielded 11.06±0.19 Ma. We also dated 2 pumice clasts by Ar/Ar, obtaining ages of 16.41±0.45 and 12.87±0.5 Ma. The generally well-rounded volcanic clasts occur in distinct, thin beds and therefore reflect specific, short-lived erosional events. Encinas (2006) argued that these clasts were also reworked from older strata. However, we contend that older beds would have been tilted by Andean uplift before the Late
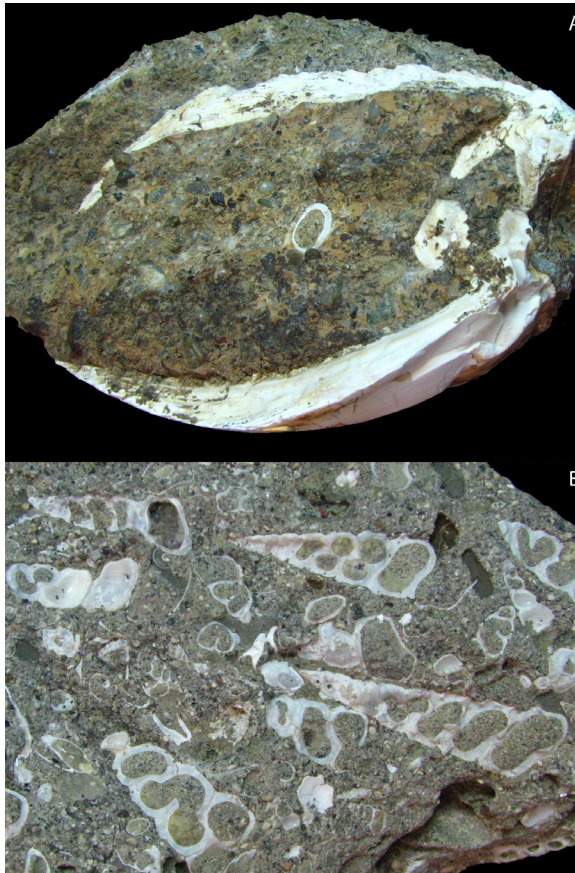
FIG. 2. Articulated bivalve (a) and gastropod (b) with trapped matrix similar to that of the surrounding host, which indicates that they are *in situ*. The material was left in the field at section S7 in figure 1.

Miocene, which upon erosion would have yielded volcanic clasts dispersed throughout the Navidad Formation. Conversely, if they were derived from surface scoria covering the landscape around volcanoes that erupted during the Early-Middle Miocene, the material would have been eroded rapidly during subsequent run-off events, arriving shortly thereafter in the Navidad Basin and thus reflecting the true age of the latter.

2.5. Diatoms

Only 2 of 15 samples analysed by Encinas (2006) for diatoms yielded index species, namely *Crucidenticula punctata* (Schrader) and *Craspedodiscus coscinodiscus* (Ehrenberg), which have age ranges of 12.8-11.3 Ma and 16.9-11.3 Ma, respectively (Barron, 2003). However, both samples came from the Lo Abarca sector, where the only Tortonian Sr-date of 11.5±1.0 Ma was also recorded. The Lo Abarca sector has mollusc species showing important differences with those of the type area at Navidad, which led Covacevich and Frassinetti (1990) to propose that these strata belong to a unit younger than the Navidad Formation. The diatoms may therefore not be diagnostic of the true age of the Navidad Formation, but in any case do not contradict an Early to Middle Miocene age.

TABLE 2. NEW $^{87}Sr/^{86}Sr$ AGES FOR THE NAVIDAD FORMATION, BASED ON THE CURVE OF McARTHUR AND HOWARD (2004).

Sample	Description	$^{87}Sr/^{86}Sr$	2 sem (%)	Age (Ma)
M1	Unidentified shell fragment	0.708371	0.0013	21.0
M2B	*Turritella*	0.708468	0.0012	19.4
M2A	*Turritella*	0.708543	0.0012	18.4
M3	Gastropods and scaphopods	0.708309	0.0014	21.9
M4	Gastropods	0.708500	0.0013	19.0
M5	Bivalves	0.708430	0.0015	19.9
M7	Gastropods and scaphopods	0.708486	0.0014	19.2
M8	Bivalves	0.708299	0.0010	22.1

Stratigraphic locations of samples are indicated in figure 3. Age error ranges vary between 0.07 and 0.20 Ma.

2.6. Ostracods

Osorio (1978) identified 7 ostracod species in the Navidad Formation, 4 of which do not occur after the Middle Miocene, namely *Bythocypris gibsonensis* (Howe and Chambers), *Parakrithe vermunti*, *Hermanites reticulata*, and *Cytheropteron stictum*. One species (*Munseyella bermudezi*) was assigned to the Late Miocene, and 2 species, namely *Krithe bartonensis* (Brady, Crosskey and Robertson), and *Bradleya normani* (Brady) belong to the Plio-Pleistocene. However, both *Munseyella bermudezi* and *Krithe bartonensis* have been recovered from Eocene strata elsewhere (Van den Bold, 1960; Elewa, 2004).

Encinas (2006) reported *Krithe producta* (Brady), *K. reversa* (Bold), *Legitimocythere acanthoderma* (Brady), *Bythoceratina* cf. *B. scabra* (Bold), *Cardobairdia glabra* (Bold), and *Bradleya normani*. *Krithe producta* occurs in Late Oligocene-Early Miocene deposits in Trinidad (Van den Bold, 1958), whereas the earliest known record of *Krithe reversa* is Middle Miocene (Coles *et al.*, 1994). Of the other species, *Legitimocythere acanthoderma* has occurred since the Early Miocene (Guernet, 1998), *Bythoceratina scabra* is present in the Eocene and Oligocene of Trinidad (Van den Bold, 1960), and *Cardobairdia glabra* has been reported from the Early Miocene-Pliocene of the Caribbean (Van den Bold, 1974). Therefore only one ostracod species, *Bradleya normani*, has not yet been reported from Middle Miocene or older strata.

2.7. Planktonic foraminifers

Finger *et al.* (2007) identified the following planktonic foraminifer index species that they considered to be younger than 11.6 Ma (Late Miocene): *Globoturborotalia apertura*, *Globorotalia puncticulata* (Deshayes), *Globorotalia spheriomizea* (Walters), *Neogloboquadrina pachyderma* (Ehrenberg), and *Neogloboquadrina acostaensis* (Blow). The last species was dated by Encinas (2006) at 12.1±0.7 Ma using $^{87}Sr/^{86}Sr$.

The generally accepted Late Miocene to Pliocene age of the 5 species listed above appears to be the only evidence against an Early-Middle Miocene age for the Navidad Formation, the latter being supported by mollusc fossils, Sr and radiometric dating, and shark teeth, which is not necessarily being contradicted by the ostracods and diatoms.

Other foraminifers identified in the Navidad Formation by Encinas *et al.* (2008), such as *Catapsydrax dissimilis* (Cushman and Renz), are also known from the Oligocene-Early Miocene (Cushman and Renz, 1947; Blow, 1959). This suggests that either all these alternative dating methods are unreliable, or that the 5 foraminifer index species above appeared earlier in the southeast Pacific than elsewhere. If this is correct, it means that other new fossil species described from the Navidad Formation are of Early-Middle and not Late Miocene age (*e.g.,* Nielsen and Frassinetti, 2003). This would also affect future fossil discoveries.

2.8. Lithostratigraphy

The Sr and radiometric dates are consistent with the stratigraphy of the Navidad Formation. Based on 9 measured stratigraphic profiles (Fig. 1), we subdivided the Navidad Formation into a lower and upper unit, with maximum thicknesses of 110 and 115 m, respectively (Fig. 3). The lower unit is composed of coarse- to medium-grained sandstone interbedded with lenticular, pebbly sandstones, whereas the upper unit has fine- to very fine-grained sandstones intercalated with shales and claystones. The frequency of invertebrate fossils, large pumice clasts and wood fragments decreases significantly from the lower to upper unit. Our Sr and radiometric dating indicates ages of 26-16 Ma for the lower unit and 16-12 Ma for the upper unit.

3. Implications for sedimentological environment, tectonism and paleoclimate

An Early to Middle Miocene age for the Navidad Formation has important implications for paleontological studies, the depositional environment of the Navidad Formation, as well as tectonic and paleoclimatic interpretations of the southeastern Pacific seaboard.

3.1. Depositional environment and tectonic events

Encinas (2006) and Encinas *et al.* (2008) considered the Navidad Formation to have been deposited on the continental slope in water depths up to 1,500 m, based on benthonic foraminifera (*Bathysiphon*, *Melonis*, *Osangularia*, *Pleurostomella*, and *Siphonodosaria*) together with trace fossils.
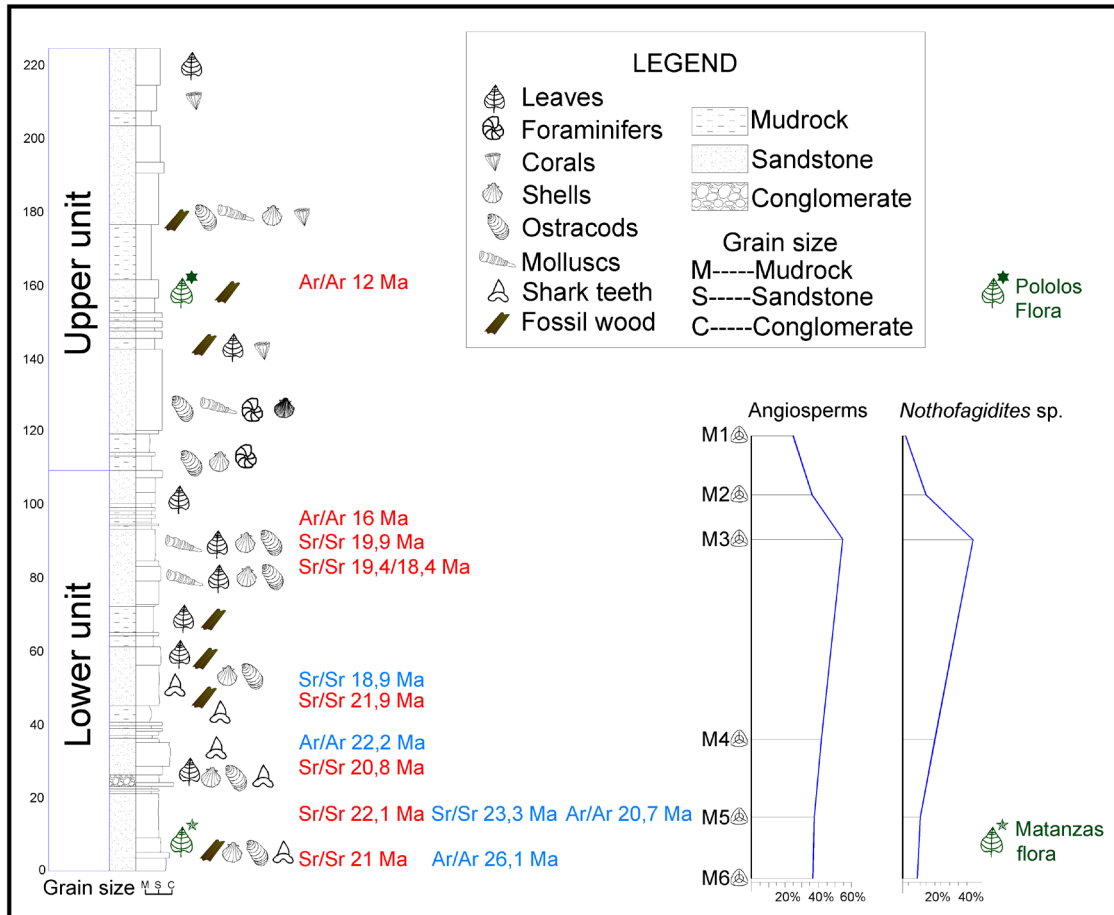
FIG. 3. Lithostratigraphy of the Navidad Formation showing subdivision into lower and upper unit and trends in pollen taxa. Dates shown in blue are those mentioned by Encinas (2006), in red are our own. Paleobotanic data shown in black are those of Hinojosa and Gutiérrez (2009).

Fossil benthonic foraminifers are commonly used in paleobathymetric studies based on the depth distribution of their closest living relatives (Lipps, 1993). However, these studies are most relevant for marine deposits post-dating the expansion of the Antarctic ice cap during the late Middle Miocene, when the oceans reached conditions similar to those of today. In the southeastern Pacific, major cooling only started during the Serravalian-Tortonian, *i.e.,* after about 13.8 Ma (Le Roux, 2012a). New benthonic foraminifer species that evolved at this time began to inhabit different water depths due to the thermal stratification of the ocean waters (Kennett, 1982; Lipps, 1993) and can therefore be used in such paleobathymetric studies. However, this is much more problematic in the case of pre-Serravalian species

(Kennett, 1982; Lipps, 1993; Encinas, 2006), where such depth differentiation probably did not yet exist. If an Early to Middle Miocene age is accepted for the bulk of the Navidad Formation, this would cast serious doubt on the subsidence to water depths of up to 1,500 m inferred by Encinas *et al.* (2008) at the beginning of Navidad deposition.

The trace fossil suite described by Encinas (2006) includes *Ophiomorpha nodosa* (Lundgren), *Skolithos linearis* (Haldeman), *Conichnus conicus* (Männil), *Macaronichnus segregates*, and *Thalassinoides* isp., considered to represent an upper shoreface environment (Pemberton *et al.,* 2001). *Diplocraterion parallelum* (Torell), *Lophoctenium* isp*., Zoophycus* isp., and *Chondrites* isp. also occur, which were attributed to a deepwater, continental slope environment

(Encinas, 2006; Encinas *et al.,* 2008). Whereas the last two ichnogenera are generally considered to be typical of the continental slope, it does not necessarily indicate water depths much greater than 150-200 m. Furthermore, *Diplocraterion parallellum* has been described from shallow water, restricted bay facies in Slovakia (Šimov and Olšavský, 2007), whereas dense concentrations of *Chondrites* have also been reported from shallow water settings, where they were linked to the burial of high quantities of organic matter during storm events (Vossler and Pemberton, 1988). Even *Zoophycos* ('*Spirophyton*') has been recorded in shallow subtidal deposits in South Africa (Boucot and Theron, 2001).

Encinas *et al.* (2008), using the planktonic foraminifer ages and water depth reconstructions based on benthonic foraminifers, proposed very rapid tectonic subsidence of at least 1,500 m at the beginning of the Tortonian (11.6 Ma), followed by equally rapid uplift to above sea-level at around 5 Ma. If our ages are correct, this would mean that such subsidence occurred around the Oligocene-Miocene transition and was inverted in the Early-Middle Miocene. However, we differ in our interpretation of paleowater depths for the Navidad Formation, considering the presence of wave ripples in the sandstones, the occurrence of delicate land insect wings and other body parts, and abundant, well-preserved fossil leaves, especially in the lower unit (Fig. 4). Pollen recovered by us from the Navidad Formation also consists of 99.7% continental palynomorphs and only 0.3% marine palynomorphs, which is inconsistent with a bathial environment. Taken together, these features suggest that the Navidad Formation represents a shallow coastal to outer shelf environment, in which sea-level oscillations or tectonic movements caused lateral migrations of facies belts. Finer-grained deposits and a decrease in the frequency of large wood and pumice fragments, leaves and palynomorphs in the upper unit indicate a general rise in sea-level commencing at about 16 Ma. This coincides with the beginning of marine transgression at around 15 Ma and the greatest depositional water depths recorded between 12-11 Ma in the Coquimbo Basin (Le Roux *et al.,* 2005), as well as a change from estuarine peat swamp conditions to deep marine embayments in the Valdivia and Osorno Basins (Fig. 1) during the Middle Miocene (Le Roux and Elgueta, 2000; Elgueta *et al.,* 2005). Tectonic subsidence accompanied by marine transgression during the Middle Miocene thus affected around 1,000 km of coastline between 30°S-40°S.

A general regressive succession commencing during the Late Miocene, is reflected in the shallow water deposits of the Licancheu Formation para-
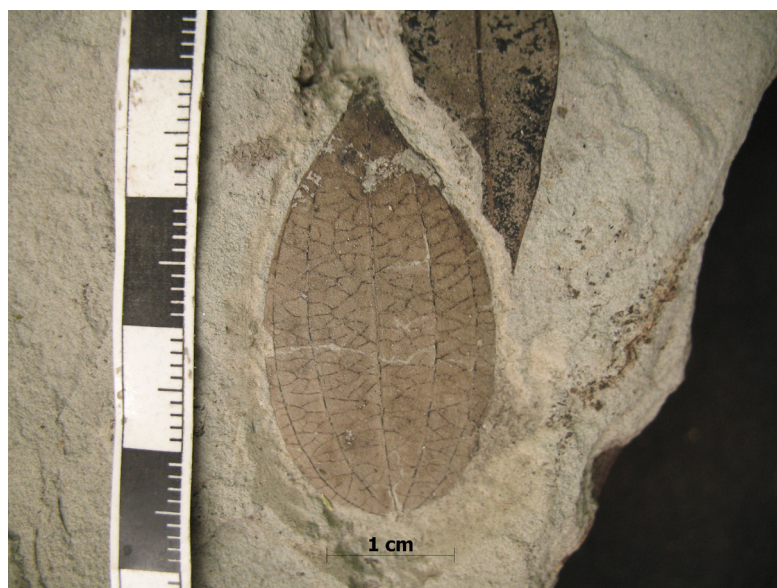

FIG. 4. Delicate, well preserved leaves (Melastomataceae) in the Navidad Formation, suggesting that deposition took place not far from land. Scale = 1 cm. The material was left in the field at the locality marked as 'Matanzas Flora' in figure 1.

conformably overlying the Navidad Formation. The latter was considered by Encinas (2006) to be of Pliocene age based on its stratigraphic position above the Navidad Formation, older Sr dates (not specified) being discarded by him because of 'probable diagenetic alteration'. However, the Licancheu Formation is in turn overlain by the Rapel and La Cueva Formations (both with paraconformable contacts), the latter yielding radiometric ages on pumice clasts between 7.7±1.0-2.7±0.3 Ma (Encinas, 2006). If a Late Miocene-Pliocene age is accepted for the La Cueva Formation, it is likely that the Licancheu Formation is Late Miocene. This implies that general marine regression and tectonic uplift could have started soon after 11 Ma along this part of the southeastern Pacific seaboard. Gregory-Wodzicki (2000), based on various lines of evidence, concluded that the Altiplano of the central Andes had attained no more than half its modern elevation by 10.7 Ma, and that surface uplift of 2,300-3,400 m occurred since the Late Miocene. Bissig *et al.* (2002) also recognized an important erosional surface in the high central Andes that formed in the interval 10-6 Ma.

3.2. Oceanic paleoclimatic conditions

Gastropods in the Navidad Formation include many warm-water genera such as *Nerita*, *Strombus*, *Sinum*, *Distorsio*, *Ficus*, *Zonaria*, *Olivancillaria*, *Terebra*, *Architectonica*, and *Heliacus* (Covacevich and Frassinetti, 1986; Groves and Nielsen, 2003; Nielsen *et al.,* 2004). Such (sub)tropical conditions were also identified elsewhere in the southeastern Pacific during the Early-Middle Miocene. Martínez-Pardo (1990) recorded a warming event between 18 and 11.5 Ma that extended north from 45ºS, based on the presence of foraminifers such as *Globoquadrina venezuelana* (Hedberg), *Globigerinita glutinata* (Egger), and the *Globorotalia mayeri-G. siakensis* plexus. These species are similar to those in tropical areas during the Early-Middle Miocene (Bertels, 1979; Srinivasan and Kennett, 1981; Kennett *et al.,* 1985), indicating that oceanic circulation and temperature gradients of marine waters in the southeast Pacific were more uniform than those prevailing today. Tsuchi (1992) recorded a Middle Miocene Climatic Optimum that culminated around 16 Ma in Japan and the southeast Pacific, which is also revealed by the presence of warm-water planktonic foraminifera in the Mejillones Basin (Martínez-Pardo, 1990;

Fig. 1) and the Coquimbo Basin (Martínez-Pardo, 1979). This is reinforced by the presence of typical equatorial diatoms such as *Actinoptychus senarius* (Ehrenberg), *Actinocyclus ellipticus* (Ehrenberg), and *Coscinodiscus oculoiridis* in the Coquimbo Formation (Martínez-Pardo and Caro, 1980), as well as at Mejillones (Martínez-Pardo, 1980). The sea surface temperature reached about 25ºC at this time (Loutit *et al.,* 1983).

Abrupt cooling of ocean water began at 15 Ma in Japan and Peru (Tsuchi, 1992), but seems to have spread to the southeastern Pacific mainly during the Late Miocene (Le Roux, 2012a). Such colder oceanic conditions are clearly recorded in the Licancheu and Rapel Formations, where Covacevich and Frassinetti (1986) noted a significant decrease in the total number of mollusc genera and species. An age of about 7 Ma for the La Cueva Formation would also coincide with the colder conditions and glaciations recorded between 7-5 Ma in West Antarctica and at Lago General Carrera in central Patagonia (Zachos *et al.,* 2001; Lagabrielle *et al.,* 2010).

3.3. Continental paleoclimatic conditions

From at least the late Paleocene to early Eocene, a subtropical, wet paleoclimate with high mean annual temperatures and a low mean variation range was recorded in southern Chile (Troncoso *et al.,* 2002). Towards the end of the Eocene, this Subtropical Gondwana Paleoflora of southern South America was replaced by Mixed Paleoflora, which in turn gave way to Subtropical Neogene Paleoflora indicating hot, humid conditions during the Early-Middle Miocene (Hinojosa and Villagrán, 1997, 2005). Maximum continental temperatures were reached between 17-15 Ma, as indicated by fossil leaves and pollen of Miocene deposits in Chile and Argentina (Hinojosa, 2005; Hinojosa *et al.,* 2011). After the Middle Miocene Climatic Optimum, pollen records suggest a marked decrease in temperature attributed to glaciation in West Antarctica and the beginning of uplift in the Andes (Zachos *et al.,* 2001). This Serravalian-Tortonian cooling (Le Roux, 2012b) was apparently manifested in Chilean Patagonia by varves with dropstones interbedded with conglomerates that were correlated with nearby conglomerates (30 km apart) dated at 12 Ma by zircons from an intercalated tuff (Suárez *et al.,* 2007).

Between 14-10 Ma, pulses of Andean uplift progressively formed a barrier to humid air masses from the east, generating the Arid Diagonal of South America (Riccardi and Rolleri, 1980). A northward shift in climate belts also increased the thermal gradient and strengthened the Southeast Pacific Anticyclone, so that the cold Humboldt Current came into being (Hinojosa and Villagrán, 1997; Zachos *et al.,* 2001).

Our palynological studies in the Navidad Formation show an increase in angiosperms towards the top of the lower unit (~16 Ma), together with a decrease in gymnosperms (Fig. 3). These Mixed Paleoflora (referred to as the 'Matanzas paleoflora' in figure 3) required conditions of high humidity with an annual precipitation of around 115 cm and mean annual temperatures of about 15ºC. In the upper unit (16-12 Ma), the relative proportion of angiosperms decreases, accompanied by an increase in gymnosperms. Belonging to the Subtropical Neogene Flora ('Pololos paleoflora' in figure 3), this suggests mean temperatures of 21-24ºC and a mean annual rainfall of 44-91 cm. There was thus a gradual increase in temperature and aridification between 16-12 Ma, which can be attributed to accelerated uplift in the Andes that prevented the spill-over of humid air from the east (Villagrán and Hinojosa, 1997; Hinojosa *et al.,* 2011). Finally, pollen with affinity to modern *Araucaria angustifolia* (Bertol) and *Araucaria araucana* (Koch) occur together in both the lower and upper units, but these species are presently separated by the Arid Diagonal. This supports the development of the Arid Diagonal during the period 14-10 Ma, *i.e.,* around the end of Navidad deposition. If the Navidad Formation were of Late Miocene-Pliocene age as argued by previous workers, these species would not have occurred together throughout the succession.

4. Conclusions

We consider the evidence pointing to an Early-Middle Miocene age for the Navidad Formation to be overwhelming, as Sr isotope and radiometric ages coincide with the chronostratigraphic ranges of macro- and microfossils, Andean tectonics and paleoclimatic events recognized worldwide. The only exception is the hitherto accepted Late Miocene-Pliocene age of five foraminifer species, which we consider should be revised in the light of

the data presented above. They apparently evolved in the southeastern Pacific during the Early Miocene before radiating elsewhere from the Late Miocene to Pliocene. However, a formal change in the accepted range of these species would require a detailed study of their exact stratigraphic distribution, together with specific dating of the beds in which they occur, which is beyond the scope of this paper.

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