

TEXT-FIGURE 14

Principle coordinates plot from NMDS analysis showing the relationships between localities based on the 52 dominant (common and abundant) species occurrences.

by S. N. Nielsen 2000 & 2001 and K. L. Finger 2003. UCMP MF9009.

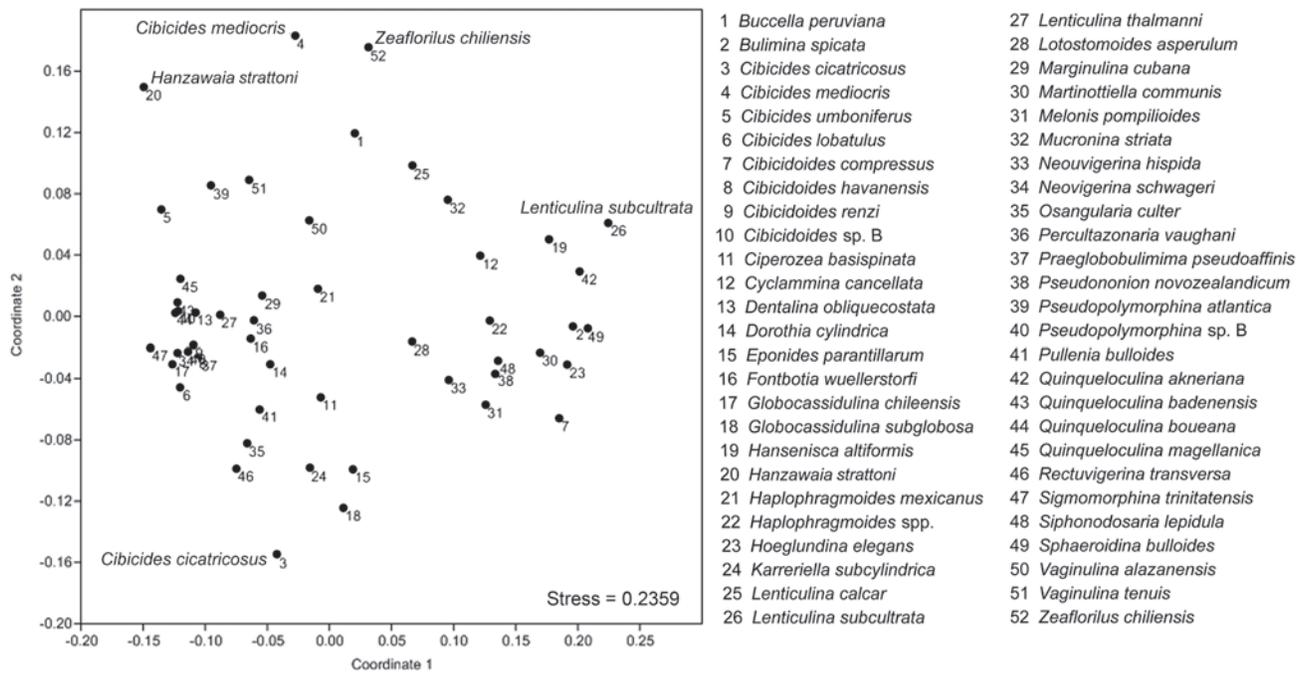
**PPT:** Navidad Formation. Top of grey siltstone interval, approximately 15m stratigraphically above PPP, coastal bluff, Punta Perro, Cardinal Caro Province, Libertador General Bernardo O'Higgins Region, 33°54'16"S, 71°50'9"W. Collected by A. Encinas, 2006. UCMP MF9006.

**PTA:** Navidad Formation. Fossiliferous lens of grey siltstone similar to that of PPP and PPN, at top of a 20-m thick siltstone interval that overlies a 30-m thick interval of massive microconglomerates and medium- to coarse-grained sandstones, coastal bluff almost below dirt road, Punta Alta, south of Las Brisas, Libertador General Bernardo O'Higgins Region,

33°56'23"S, 71°51'4"W. Collected by S. N. Nielsen 2002 and K. L. Finger 2003. UCMP MF9011.

**RAN:** Ranquil Formation. Brown massive sandstones with intermittent beds of glauconitic sandstone, overlying RQT and transected by RQS, coastal bluff of Punta Huenteguapi, Ranquil, Arauco Peninsula, Arauco Province, Biobío Region, 37°30'25"S, 73°35'28"W. Collected by S. N. Nielsen 2000–2002 and K. L. Finger 2003. UCMP MF9023.

**RAP:** Navidad Formation. Grey, reddish-brown and dark-brown sandstones in an undifferentiated blockfall from steep cliffs along the coast north of Río Rapel, San Antonio Province, Valparaíso Region, 33°53'20"S, 71°49'34"W. Collected by S. N. Nielsen, 2000 & 2002. UCMP MF9004.



TEXT-FIGURE 15  
Principle coordinates plot from NMDS analysis showing relationships between species based on same data matrix as text-figure 14.

**RQK:** Ranquil Formation. Highly fossiliferous sandstone boulders restricted to the northernmost part of the beach, Punta Huenteguapi, Arauco Peninsula, Arauco Province, Biobío Region, 37°30'20"S, 73°35'26"W. Derived from the top of the sequence that is no longer present on the top of the bluffs. Collected by S. N. Nielsen 2001 & 2002 and K. L. Finger 2003. UCMP MF9022.

**RQS:** Ranquil Formation. Gastropod-rich sandstone displaced from upper part of adjacent bluffs and scattered on beach, Arauco Peninsula, Arauco Province, Biobío Region, 37°30'18"S, 73°35'24"W. Collected by K. L. Finger 2003. UCMP9020.

**RQT:** Ranquil Formation. Grey mudstones to siltstones like FRM, intertidal platform of Punta Huenteguapi, Ranquil, Arauco Peninsula, Arauco Province, Biobío Region, 37°30'18"S, 73°35'24"W. Collected by S. N. Nielsen 2001 & 2002 and K. L. Finger 2003. UCMP MF9021.

**VAL:** Santo Domingo Formation. Dark grey mudstone to siltstone, bluff behind roadside house approximately 20km south of Valdivia, Valdivia Province, Los Lagos Region, 39°55'43"S, 73°07'32"W. Collected by S. N. Nielsen, 2001. UCMP MF9026.

**METHODS**

**Sample processing**

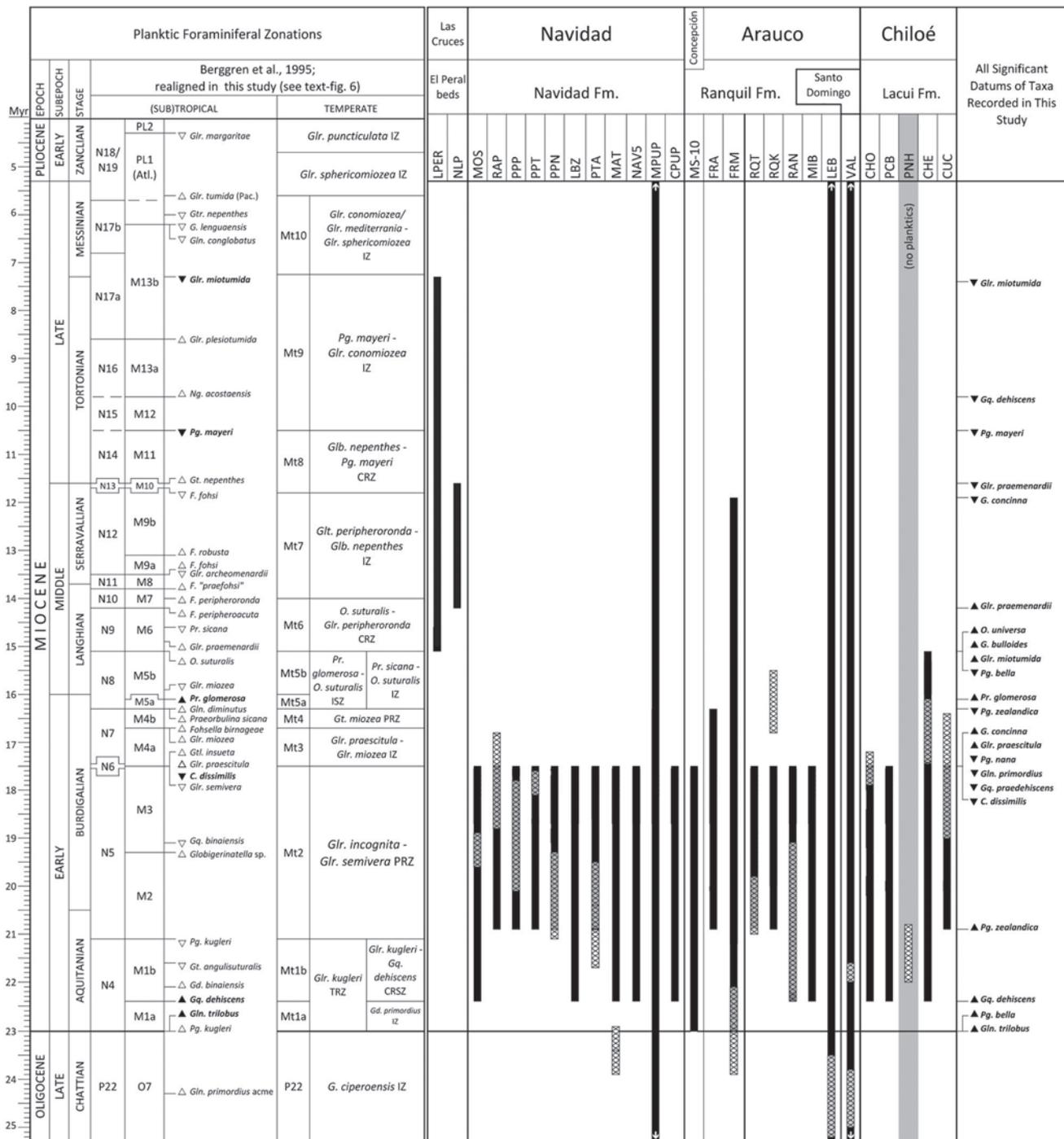
Foraminifera were processed from 46 sedimentary rock samples representing 32 localities by (1) soaking in water or hydrogen peroxide until most of the sediment had disaggregated, (2) washing the residue over a U.S. Standard 230-mesh (63-µm openings) sieve and (3) drying by funneling through fast-flow filter paper, followed by oven-drying at 30°C. Specimens were then picked with a 000 sable hair brush and sorted by species onto 63 60-grid micropaleontological slides, from which primary types and hypotypes were selected and transferred onto single-hole slides for reference and imaging. Five localities

were excluded from this study because they had poor yields of foraminifera with no unique species, reducing the number of localities to 27. After species identifications and counts were made, assemblage data from sites that were sampled multiple times were composited (i.e., one assemblage per site).

Both assemblage and individual species slides are in the microfossil collection of the University of California Museum of Paleontology (UCMP) in Berkeley. Primary types and hypotypes were imaged with a succession of three environmental scanning electron microscopes (ESEMs) at the UC Electron Microscope Laboratory. A photomicroscope setup with the 30-year old Infinite Focus system (Irvine Optical Corporation) was also utilized, as in some cases it produced more revealing and useful, albeit lower resolution, images. That system involves time-lapsed photomicrography of a specimen on a motorized stage as it slowly passes through a plane of illumination. Similar images were subsequently obtained with a Leica IC80 HD microscope camera, which is an integrated digital system that is considerably more efficient, and the auto-blend (photostacking) feature of Adobe Photoshop.

**Taxonomic procedure**

The primary resources initially used in this study for identifying planktic foraminifera Kennett and Srinivasan (1983), Bolli and Saunders (1985), Jenkins (1985), and Scott, Bishop and Burt (1990). Also referred to were studies on planktic foraminifera of Oligocene and Miocene deep-sea core sections, including Brönnimann and Resig (1971), Spezzaferri and Premoli-Silva (1992), Chaisson and Leckie (1993), Leckie, Farnham and Schmidt (1993), and Majewski (2010). Identifications of benthic species were based primarily on the type descriptions and figures in the *Catalogue of Foraminifera* (Ellis and Messina 1940 et seq.), revisions of the nine early European works on Tertiary to Recent foraminifera listed in table 2, *Atlas of Cosmopolitan Deep-water Benthic Foraminifera* (van Morkhoven, Berggren and Edwards



TEXT-FIGURE 16

Biostratigraphic correlation of Chilean samples based on concurrent ranges of planktic foraminifers that have first or last occurrences in the Miocene. Arrow at top of bar indicate range continues post-Miocene; arrow at bottom of bar indicate species appears earlier in Tertiary. Species in bold and preceded by a solid datum triangle are those found in this study. Light grey columns are samples that yielded no markers. Cross-hatched bars indicate Sr ages from Nielsen and Glodny (2009) and Encinas (unpublished) and shaded grey where they overlap the biostratigraphic range; that for NAV5 and PPT were obtained from tests of *Paragloborotalia bella* and *Pg. zealandica*, respectively; all others were derived from gastropod shells collected near the microfossil locality they are associated with. See Figure 8 caption for abbreviation keys.

1986), *Benthic Cenozoic foraminifera from Ecuador* (Whittaker 1988), the recent tome on deep-water uniserial taxa (Hayward et al. 2012), and the new *Atlas of Benthic Foraminifera* (Holbourn, Henderson and MacLeod 2013). Literature on the modern

foraminifera of Chile was also perused for this purpose (see following subsection).

Many of the benthic species identified in this study were originally described from the Pacific (Oligocene–Recent), Caribbean

Genus	"Shallow"		"Deep"		
	Neritic		Bathyal		
	I	O	U	M	L
<b>Ammobaculites</b>			SCC		
<i>Ammodiscus</i>	SCC				
<i>Amphicoryna</i>	SCC				
<b>Anomalinoidea</b>			SCC		
<b>Bathysiphon</b>					SCC
<i>Bolivina</i>	SCC				
<i>Buccella</i>	SCC				
<i>Bulimina</i>	SCC				
<i>Buliminella</i>	SCC				
<i>Cancris</i>	SCC				
<i>Cassidulina</i>	SCC				
<i>Cassidulinoides</i>	SCC				
<b>Chilostomella</b>			SCC		
<i>Cibicides</i>	SCC				
<i>Cibicidoides</i>	SCC				
<i>Cornuspira</i>	SCC				
<i>Cyclammina</i>	SCC				
<i>Dentalina</i>					
<i>Eggerella</i>		SCC			
<i>Eggerelloides</i>					
<i>Ehrenbergina</i>	SCC				
<i>Elphidium</i>	SCC				
<i>Eponides</i>	SCC				
<i>Favulina</i>	SCC				
<i>Fissurina</i>	SCC				
<i>Fontbotia</i>	SCC		(undivided)		
<b>Gaudryina</b>			SCC		
<i>Gavelinopsis</i>	SCC				
<i>Glandulina</i>					
<i>Globobulimina</i>	SCC				
<i>Globocassidulina</i>			SCC		
<i>Globulina</i>	SCC				
<i>Gyroidina</i>	SCC				
<i>Hanzawaia</i>		SCC			
<i>Haplophragmoides</i>	SCC				
<i>Hoeglundina</i>	SCC				
<i>Karreriella</i>	SCC				
<i>Lagena</i>	SCC				
<b>Laticarinina</b>					SCC
<i>Lenticulina</i>	SCC				
<i>Martinottiella</i>	SCC				
<i>Melonis</i>	SCC				
<i>Milamina</i>	SCC				
<i>Miliolinella</i>	SCC				
<i>Nodosaria</i>	SCC				
<i>Nonionella</i>	SCC				
<i>Nonionoides</i>	SCC				
<i>Oolina</i>	SCC				
<i>Oridorsalis</i>	SCC				
<b>Osangularia</b>					SCC
<i>Planulina</i>	SCC				
<b>Pleurostomella</b>					SCC
<i>Pseudoparrella</i>	SCC				
<i>Pullenia</i>	SCC				
<i>Pyrgo</i>	SCC				
<b>Quadriformina</b>					SCC
<i>Quinqueloculina</i>	SCC				
<i>Rectuvigerina</i>	SCC				
<i>Reophax</i>	SCC				
<b>Rhabdammina</b>					SCC
<b>Robertina</b>					SCC
<i>Rosalina</i>	SCC				
<i>Saracenaria</i>	SCC				
<i>Sigmoilina</i>	SCC				
<i>Sphaeroidina</i>		SCC	size increase		
<i>Spiroloculina</i>	SCC				
<i>Stainforthia</i>	SCC				
<i>Textularia</i>	SCC				
<i>Trifarina</i>	SCC				
<i>Triloculina</i>		SCC			
<b>Tritaxis</b>					SCC
<i>Trochammina</i>	SCC				
<i>Uvigerina</i>	SCC				
<i>Valvulineria</i>	SCC				
<b>Virgulinea</b>					SCC
<i>Zeaflohilus</i>	SCC				

TEXT-FIGURE 17

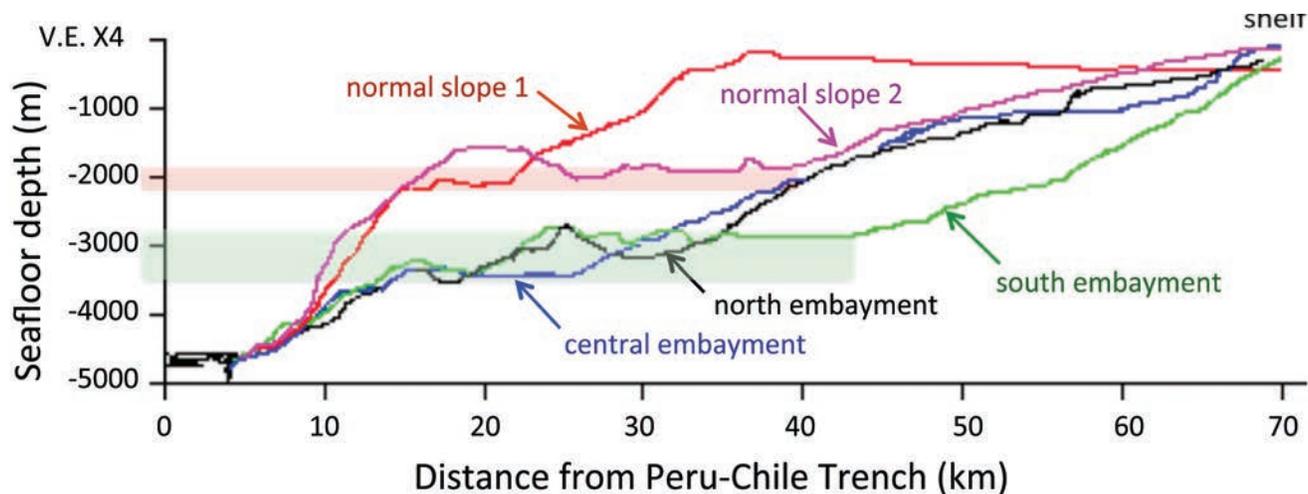
Modern upper-depth limits of 76 foraminiferal genera represented in the Chilean Neogene that are common in the global fauna. Based on modern global data from Murray (1991, 2006). Modern provincial data from Ingle, Keller and Kolpack (1980), Zapata and Moyano (1997), Zapata and Varela (1975), and Figueroa et al. (2005, 2006). Key: Genera in bold = restricted to bathyal depths; dark grey cells = global common; light grey cells = global infrequent; SCC = south-central Chile (provincial) UDL.

(Oligocene and Miocene), Mediterranean (Miocene–Recent) Car Nicobar Island in the Andaman Sea (Pliocene), and the Vienna Basin of the Central Paratethys (Oligocene–Miocene). A few species were first described from the Atlantic and polar regions, or from pre-Oligocene strata.

**Previous taxonomic studies on the modern Chilean fauna**

Marchant, Zapata and Hromic (2007) provide a thorough bibliography of studies on the modern foraminifera of Chile. Those most pertinent to the present study are discussed below.

The earliest report on the modern foraminifera off central Chile describes species occurring in littoral sands from the coasts of South America (i.e., Brazil to Ecuador; d’Orbigny 1839c). Of the 81 new species described in that study, 56 were from the Atlantic and 25 were from the Pacific. D’Orbigny’s only sample taken off Chile is from Bahía de Valparaíso (33°S), which yielded 12 new species [brackets denote current generic assignment]: *Rotalina* [*Buccella*] *peruviana*, *Globigerina* *bulloides*, *Truncatulina* [*Planulina*] *depressa*, *Truncatulina* [*Planulina*] *ornata*, *Rosalina* [*Valvulineria*] *araucana*, *Valvulina* [*Nonionella*]



TEXT-FIGURE 18

Modern slope profiles off south-central Chile. Horizontal bands show depth ranges where slopes level out. (Modified from Geersen et al. 2011).

*auris*, *Valvulina* [*Cancris*] *inflata*, *Bulimina pulchella*, *Bulimina* [*Praeglobobulimina*] *ovula*, *Bolivina plicata*, *Bolivina punctata*, and *Quinqueloculina araucana*. Of these, only *Buccella peruviana* and *Bulimina ovula* occur in my samples. Nine other species identified herein were described by d'Orbigny (1839c) from the southwest Atlantic — one from Patagonia and eight from the Falkland Islands.

Additional species were documented in H. B. Brady's (1884) tome on the foraminifera collected by the *Challenger* Expedition (1873–1876). That global venture included sample stations west of Chiloé and throughout the archipelago of southern Chile. Egger (1893) subsequently worked on samples from the Gazelle Expedition (1874–1876) that were collected off northern Chile (north of Valparaíso). Bandy and Rodolfo (1964) studied 32 trawl and core samples from depths of 179–6250 m off Peru and Chile, but only as far south as Valparaíso (32.3°S). The foraminifera off south-central Chile were included in studies by Khusid (1971, 1974, 1977, 1979a, b) and Saidova (1969, 1971, 1975). Boltovskoy and Theyer (1970) analyzed 20 samples taken at depths of 44–260 m off central Chile (29°57'–42°16'S). A few years later, studies focused on specific locations off Chile began appearing in South American journals (e.g., Zapata and Varela 1975). Resig (1981) analyzed 121 core-top samples taken from depths of 82–2286 m on the northern Nazca plate (0–27°S) and on the continental margin from 2–20°S. More pertinent to the present study is the analysis by Ingle, Keller and Kolpack (1980) of bottom samples collected from depths of 135–4500 m along three transects off central Chile (31.5–39.2°S).

In the last two decades, several marine biologists in central Chile have studied the modern foraminifera of the Chilean margin (e.g., Zapata and Moyano 1997; Zapata and Cear 2004; Figueroa et al. 2005, 2006; Marchant, Zapata and Hromic 2007). Zapata (1999) studied benthic foraminifera in Cumberland Bay (33°41'S, 78°50'W), Robinson Crusoe Island, in the Juan Fernandez Archipelago ~670 m west of the mainland at San Antonio. His samples taken from depths down to 20 m yielded 85 species, but he noted the degree of affinity with the Chilean province was only 35% and, therefore, suggested that they were different subprovinces. Zapata and Cear (2004) provided the most thorough report on littoral foraminifera off the coast of northern Chile (18°28'–31°56'S), having documented 151 species

from depths of 1–170 m. Nearly half of the species illustrated in that study resemble those that occur in the Chilean Miocene, but I retain the same binomina for only 20 of them. Most pertinent among the studies by the Chileans is that of Figueroa et al. (2005, 2006), who recorded 117 species of calcareous benthic foraminifera from multicores taken at depths of 125–3485 m in the south-central Chilean province (i.e., from Valparaíso to the southern end of Chiloé Island).

#### Taxonomic problems

Subjective synonymies are the nemesis of foraminiferal taxonomy. Early workers were often unaware of publications in foreign languages, as evidenced by the lack of comments comparing their new species with previously described forms. Also, as discussed by Lipps (2002), synonymies invaded the foraminiferal literature in the 19<sup>th</sup> Century, partly because British workers rejected d'Orbigny's concept of foraminiferal taxonomy. Attitudes changed when H. B. Brady's (1884) *Challenger* tome recognized many of d'Orbigny's genera.

In the first half of the 20<sup>th</sup> Century, J. A. Cushman pioneered the application of benthic foraminifera in the North American oil industry, and he soon became the most prolific authority on their taxonomy. Unfortunately, he and his contemporaries tended to view foraminifera as highly provincial and mostly ignored species that had already been described in foreign languages. This resulted in a multitude of synonyms that inundate the topical literature. Murray (2007) estimates that for the modern fauna as many as 25% of the species names are synonyms.

It has become increasingly evident that many species of benthic foraminifera have much wider geologic and geographic ranges than previously envisioned. In addition, it appears that many named varieties, subspecies, and species that may have utility in local biostratigraphic correlations are simply ecophenotypes (i.e., invalid taxa). Wide geographic distributions are probably due primarily to the dispersal of propagules by oceanic currents (Alve and Goldstein 2003, 2010). To a lesser degree, testate specimens are dispersed by water masses, detached algae, and migrating marine animals (i.e., fish, birds, mammals). As colder, denser water flows from high latitudes toward the equator, the oceans become increasingly stratified. This phenomenon enhances the cosmopolitan nature of the deep-water fauna,

TABLE 1  
Comparison of bathymetric zonation schemes.

Benthic Environment	Depth Zone	Depth ranges (in m)	
		E Pacific Margin	Passive Margin
Inner shelf	inner neritic	0–50	0–30
Outer shelf	outer neritic	50–135	30–100
Shelf/slope break	---	135–150	100–200
Upper slope	upper bathyal	150–500	200–600
Upper-middle slope	upper-middle bathyal	500–1500	*600–
Lower-middle slope	lower-middle bathyal	1500–2000	–1000
Lower slope & rise	lower bathyal	2000–4000	1000–2000
Abbyss	abyssal	>4000	>2000

\* Undivided middle slope.

which preliminary genetic data supports (Pawlowski et al. 2007). Neritic and marginal-marine foraminifera, on the other hand, can be transported freely by surface currents or winds and their geographic distribution can be assisted by adherence to floating wood and algae or highly mobile marine animals (Murray 1991; Culver and Buzas 2002). Ingestion by the latter vector is another possibility, as there is some evidence that foraminifera can survive passage through the digestive tracts of marine animals (e.g., Brand and Lipps 1982).

It is both a blessing and a curse that foraminifera are so abundant and diverse, and that they have received so much attention by the scientific community. Their numerous applications are well established in the earth sciences, especially in biostratigraphy, paleoecology, paleoceanography, paleoclimatology, and environmental science. Their great temporal and spatial diversity of morphotypes, and the different opinions of taxonomists, unfortunately have resulted in the conundrum of synonyms previously noted. Boltovskoy (1965) expounded on this taxonomic quagmire that may forever plague foraminiferology. His pessimistic view would likely have been greater had he lived long enough to learn that DNA sequencing has revealed several cryptic species of benthic and planktic foraminifera (Gooday and Jorissen 2012, and references therein). Early monographs revised with better images of type specimens (table 2) certainly have been a great asset in deciphering synonymies and detecting misidentifications in the literature, but the taxonomic study of the Foraminifera remains a formidable task. Those who have already provided these valuable resources have sealed many of the cracks in the foundation of foraminiferology and they are commended for their extraordinary efforts. Nevertheless, Linnaean taxonomy is typological, aligning species concepts with primary type specimens. As concluded by Scott (2011) in reference to planktic foraminifera, “Typological practices served well for the zonal biostratigraphic studies promoted by Loeblich et al. (1957). That and allied research, which focused on discovery of homotaxial stratigraphic markers, made little demand on knowledge of populations. Its legacy is a host of poorly described taxa.” This certainly rings true for benthic foraminifera as well.

#### Identifications made in this study

In the present study, I initially identified taxa by comparing specimens with illustrations in notable papers on Oligocene to Holocene faunas and modern publications bearing high-quality images of contemporaneous specimens. Most useful among those illustrating the modern Chilean fauna were those of Ingle, Keller and Kolpack (1980) and Resig (1981). I utilized the *Catalogue of Foraminifera* (Ellis and Messina 1940 et. seq.) extensively to confirm species identifications, to construct synonymies, and to select other comparative species worthy of mention.

TABLE 2  
Early foraminiferal monographs and their latest revisions, and the number of their benthic species recognized in this study.

Original Work	Location	Age	Latest Revision
Fichtel & Moll 1798	mostly Europe	Tertiary–Recent	Rögl & Hansen 1984
Orbigny 1826	Italy & Adriatic	Pliocene & Recent	Véneç-Peyré 2005
Orbigny 1839a	Cuba	Recent	Le Calvez 1977
Orbigny 1839b	Canary Islands	Recent	Le Calvez 1974
Orbigny 1846	Vienna Basin	Miocene	Papp and Schmid 1985
Karrer 1865	New Zealand	Late Tertiary	Hornibrook 1971
Stache 1865	New Zealand	Late Tertiary	Hornibrook 1971
Schwager 1866	Car Nicobar	E–M Pliocene	Srinivasan and Sharma 1980
Brady 1884	global	Recent	Jones 1994

This compilation is the only extensive documentation of fossil foraminifera from Chile and it serves as the definitive reference to the Miocene fauna of this region. As with any study of similar scope, further sampling may recover additional species, but the large number of assemblages perused throughout the course of this study suggests that they are most likely to be relatively rare occurrences.

#### Applied statistics

Species diversity and assemblage similarity measurements used a variety of applications provided by the PAST software package of Hammer, Harper and Ryan (2001). I applied the Simpson and Fisher  $\alpha$  diversity indices to each assemblage by using its species richness and numbers of specimens. The Simpson index indicates dominance and ranges from 0 (all taxa equally present) to 1 (a monospecific assemblage). Fisher’s  $\alpha$  is a diversity index defined by  $S = \alpha n / (1 + \alpha n)$ , where  $S$  is the number of taxa and  $n$  is the number of specimens. To detect faunal similarities and differences between areas and geologic units, I applied cluster analyses and non-linear multidimensional scaling (NMDS) with presence-absence matrices that were reduced in size first by the exclusion of all species that do not account for at least 1% of one assemblage, then by the exclusion of all species that do not account for at least 5% of one assemblage. I used the similarity coefficients of Jaccard and Simpson, as well as Ward’s method, in the cluster analyses, and the correlation coefficient (Pearson’s  $r$ ) for the NMDS.

#### RESULTS

The 27 assemblages analyzed in this study are represented by more than 16,000 specimens that were picked and sorted on 60-grid micropaleontological assemblage slides (UCMP50438–50499), from which I isolated representative specimens on single-holed slides (UCMP50000–50437) for imaging and reference. Table 3 shows the relative abundances of benthic foraminifera present in each of the 27 assemblages. Table 4 simply indicates the presence/absence of planktic foraminiferal species in each assemblage because many specimens were diagenetically distorted or had obscured features. There was also a wide range of transitional or variant forms. The recorded fauna comprises 336 benthic and 24 planktic species. Table 5 presents the numerical calculations and diversity indices for each assemblage. Compositing assemblages obtained by resampling sites resulted in a wide range of specimen counts (165–2133; mean 610, median 471) and benthic species richness (20–138; mean 60, median 63). Planktic:benthic (P:B) ratios range 0–0.68 (mean 0.20, median 0.14).

Thirty-one benthic species occur at more than half the 27 localities. The most widespread (number of localities in parentheses) are *Lenticulina subcultrata* (26), *Quinqueloculina akneriana* (23), *Sphaeroidina bulloides* (22), *Glandulina laevigata* (22), *Bulimina spicata* (21), *Cibicidoides compressus* (20), *Hoeglundina*

TABLE 3

Relative abundance of benthic species vs. localities checklist. VR = 1 specimen; R ≥ 2 specimens if <1%, or 2 specimens if ≥1%; F = 1–5%; C = 5–25%; A = 25–50%; VA >33%.

SECTOR	North													Central							South								
	AREA	Navidad												Conc	Arauco						Valid	Chiloé							
		Las Cruces																											
GEOLOGIC UNIT	El Peral beds		Navidad Fm.												Ranquil Fm.							Lacui Fm.							
LOCALITY	NLP	LPER	MOS	RAP	PPP	PPT	PPN	LBZ	PTA	MAT	NAV5	MPUP	CPUP	MS10	FRA	FRM	RQT	RQK	RAN	MI8	LEB	VAL	SDom	CHO	PCB	PNH	CHE	CUC	
<i>Allomorpha pacifica</i>																													
<i>Alveophragmium orbiculatum</i>																													
<i>Ammobaculites agglutinans</i>																													
<i>Ammobaculites exilis</i>																													
<i>Ammodiscus incertus</i>																													
<i>Amphicoryna badensis</i>																													
<i>Amphicoryna cf. A. scalaris</i>																													
<i>Anastamosa brevilocula</i>																													
<i>Anastamosa lamellata</i>																													
<i>Anomalinoidea salinasensis</i>																													
<i>Astacolus crepidulus</i>																													
<i>Astacolus cymboides</i>																													
<i>Astacolus jordai</i>																													
<i>Astacolus cf. A. mayi</i>																													
<i>Astacolus mexicanus</i>																													
<i>Astacolus multicameratus</i>																													
<i>Astacolus novambiguus</i>																													
<i>Astacolus sp. A</i>																													
<i>Astacolus sp. B</i>																													
<i>Bathysiphon giganteus</i>																													
<i>Bathysiphon sp.</i>																													
<i>Biloculinella labiata</i>																													
<i>Bolivina advena</i>																													
<i>Bolivina aenariensis</i>																													
<i>Bolivina alazanensis</i>																													
<i>Bolivina arta</i>																													
<i>Bolivina pukeuriensis</i>																													
<i>Bolivina tumida</i>																													
<i>Buccella peruviana</i>																													
<i>Bulimina alazanensis</i>																													
<i>Bulimina spicata</i>																													
<i>Cancris auriculus</i>																													
<i>Cassidulinoides californiensis</i>																													
<i>Cassidulinoides porrectus</i>																													
<i>Ceratobulimina jonesiana</i>																													
<i>Chilostomella ovoidea</i>																													
<i>Chrysalogonium deceptorium</i>																													
<i>Chrysalogonium equisetiformis</i>																													
<i>Chrysalogonium rudis</i>																													
<i>Cibicides cicatricosus</i>																													
<i>Cibicides mediocris</i>																													
<i>Cibicides umboniferus</i>																													
<i>Cibicides walli</i>																													
<i>Cibicides sp.</i>																													
<i>Cibicoides bradyi</i>																													
<i>Cibicoides compressus</i>																													
<i>Cibicoides havanensis</i>																													
<i>Cibicoides renzi</i>																													
<i>Cibicoides sp.</i>																													
<i>Ciperozea basispinata</i>																													
<i>Ciperozea multicostata</i>																													
<i>Ciperozea ongleyi</i>																													
<i>Cornuspira libella</i>																													
<i>Cornuspira planorbis</i>																													
<i>Cornuspira veleronis</i>																													
<i>Cornuspiroides foliaceus</i>																													
<i>Criboelphidium hauerinum</i>																													
<i>Cribrammina subvalvularis</i>																													
<i>Cristellariopsis petersonae</i>																													
<i>Cyclammina cancellata</i>																													
<i>Dentalina aciculata</i>																													
<i>Dentalina albatrossi</i>																													
<i>Dentalina flintii</i>																													
<i>Dentalina mutsui</i>																													
<i>Dentalina obliquecostata</i>																													
<i>Dentalina striatissima</i>																													
<i>Dorothia cylindrica</i>																													

TABLE 3  
Continued.

SECTOR	North														Central							South						
	AREA		Navidad												Conc	Arauco						Vald	Chiloé					
	GEOLOGIC UNIT		El Peral beds	Navidad Fm.												Ranquil Fm.							SDom	Lacui Fm.				
LOCALITY		NLP	LPER	MOS	RAP	PPP	PPT	PPN	LBZ	PTA	MAT	NAV5	MPUP	CPUP	MS10	FRA	FRM	RQT	RQK	RAN	MIB	LEB	VAL	CHO	PCB	PNH	CHE	CUC
<i>Eggerella bradyi</i>																												
<i>Eggerelloides scabrus</i>						VR																						
<i>Ehrenbergina fyfei</i>				R		F	F			F		F		R	F			VR							VR		VR	
<i>Ellipsopolymorphina zuberi</i>																R	F	VR										
<i>Elphidium macellum</i>												VR																VR
<i>Enantiodentalina muraii</i>						R				VR				R					R						VR			
<i>Eponides orientalis</i>																									R			
<i>Eponides ouachitaensis</i>																				VR								
<i>Eponides parantillarum</i>			R	F	VR	VR		F				F		F		R		F	R	F					F	VR	F	
<i>Eubuliminella bassendorffensis</i>																			F									
<i>Falsocibicides</i> sp.	F		VR						R											R		F						VR
<i>Favulina famosopunctata</i>																									F			
<i>Favulina hexagona</i>						VR				VR														R				
<i>Favulina melo</i>																							F		VR			
<i>Favulina squamosa</i>																VR					VR					VR		
<i>Fijinionion obesum</i>	F																									F		
<i>Fingerina brevis</i>						R				R	VR			R	F													
<i>Fingerina weaveri</i>			R		R	F				R				R														
<i>Fissurina ambicarinata</i>																			R									
<i>Fissurina cuculatta</i>																	R											
<i>Fissurina marginata</i>							VR																					
<i>Fissurina</i> cf. <i>F. marginata</i>																										VR		
<i>Fissurina</i> cf. <i>F. obvia</i>														R														
<i>Fissurina</i> sp.							VR																					
<i>Fontbotia wuellerstorfi</i>	F	R				R										R					VR							VR
<i>Fursenkoina vicksburgensis</i>																				VR								
<i>Gaudryina</i> sp.																			VR									
<i>Gavelinopsis alhamensis</i>													VR											VR	VR			
<i>Glandulina dentalinoides</i>				VR																					F			
<i>Glandulina laevigata</i>	F	R	VR	VR	F	F			F		F	R	F	R	R	F	C	F	R	F	R	R	R	R	VR	VR		
<i>Glandulina simplex</i>																									F			
<i>Globbulimina pacifica</i>				F		F	F			F	F	VR	R	F	F		VR	F			F			VR				
<i>Globocassidulina chileensis</i>																										F	VA	VR
<i>Globocassidulina quadrata</i>																												
<i>Globocassidulina subglobosa</i>				F		R						F	VR	F							VR		F	R		F	C	F
<i>Globulina pirula</i>																											VR	
<i>Guppyella crassa</i>				F	VR	F	F			F				R	VR		VR	VR						F	VR			
<i>Gyroidina laevigata</i>		R														R						R	F			R	F	
<i>Gyroidina</i> sp.																												
<i>Gyroidinoides umbonatus</i>						R						F									VR		R					
<i>Hansenisca altiformis</i>				F		F	F		VR	F	R	C	R	F	F		VR	F	VR	F	F	VR	C	R			R	
<i>Hansenisca soldanii</i>		R														F	F	R	R	R							F	
<i>Hanzawaia</i> cf. <i>H. nipponica</i>						R																						
<i>Hanzawaia strattoni</i>					C			C	F		F	VR				F						VR	R	R	C	VR	F	F
<i>Haplophragmoides impressus</i>				R		R									R													F
<i>Haplophragmoides mexicanus</i>	R			C		F	R			F						VR								R				
<i>Haplophragmoides pulicosus</i>																	R											
<i>Haplophragmoides</i> spp.				F	R	R	R			VR			C	F	F	F	F	R	VR	VR			F	R			C	
<i>Hemirobulina pedum</i>																	VR	VR				VR	R		R			
<i>Hemirobulina similis</i>	VR									F		VR		F	F			F	VR					VR	R			
<i>Hemirobulina yabei</i>				VR		R								VR														
<i>Hidina variabilis</i>						F				R	VR				VR		VR	F										
<i>Hoeglundina elegans</i>	R	VR	F		F	F	VR			F	F	F	R	F	F	R	F	F	R	F	R	F	R	F				
<i>Homalohedra</i> sp. A																												
<i>Homalohedra</i> sp. B																											F	
<i>Hyalinonetrion distomum</i>	VR					VR				VR						R				VR					R	R		
<i>Hyalinonetrion ingens</i>	R				R	VR							F			VR								R	VR			
<i>Hyalinonetrion multilaterum</i>																						VR						
<i>Karriella biglobata</i>																												
<i>Karriella bradyi</i>																	F	VR									VR	
<i>Karriella subcylindrica</i>	R	R								F				R		F	F	F	R	R	C							
<i>Karrerulina apicularis</i>						F								R		VR								R				
<i>Laevidentalina advena</i>						R	R	VR					VR	VR		VR		VR										
<i>Laevidentalina communis</i>						R				VR					F	VR			VR					R				
<i>Laevidentalina elegans</i>	R		R		F	F	VR			F	R	R	R	F	F	VR		F		R				R	F	F	R	R
<i>Laevidentalina inflexa</i>						R	VR									VR		R	R									
<i>Laevidentalina inornata</i>	R	VR				R	R			R		VR		VR	VR	F	F				R	VR		VR				

TABLE 3  
Continued.

SECTOR	North														Central							South							
	AREA		Navidad												Conc	Arauco						Valid	Chiloé						
GEOLOGIC UNIT	Las Cruces		Navidad Fm.														Ranquil Fm.							SDom	Lacui Fm.				
	LOCALITY	NLP	PPER	MOS	RAP	PPP	PPT	PPN	LBZ	PTA	MAT	NAV5	MPUP	CPUP	MS10	FRA	FRM	ROT	ROK	RAN	MIB	LEB	VAL	CHO	PCB	PNH	CHE	CUC	
<i>Laevidentalina cf. L. planata</i>								VR																					
<i>Laevidentalina roemeri</i>																					R				VR				
<i>Laevidentalina sp. A</i>					VR							VR																	
<i>Laevidentalina sp. B</i>																	VR												
<i>Lagena cf. L. alcocki</i>																						VR							
<i>Lagena alternans</i>												VR	VR			R	VR	R	VR	R	R						VR		
<i>Lagena bassensis</i>												R										VR		VR	R				
<i>Lagena filicostata</i>						VR	VR		VR																				
<i>Lagena perlucida</i>																						F							
<i>Lagena semistriata</i>																R								VR	VR				
<i>Lagena striata</i>	VR				R	VR			VR		R		F		R	VR		R	F	VR			F						
<i>Lagena cf. L. striata</i>					VR					VR								R		VR									
<i>Lagena striatula</i>															VR														
<i>Lagena substriata</i>						VR				VR								VR	VR	R									
<i>Lagena sulcata</i>														R		R	VR			R									
<i>Lagena vilardeboana</i>										VR										VR									
<i>Lagena sp. A</i>					R				R																VR				
<i>Lagena sp. B</i>																									VR				
<i>Lagena sp. C</i>										VR																			
<i>Lagena sp. D</i>																					VR								
<i>Lagena cf. L. enderbiensis</i>																					VR				VR				
<i>Lagena sp.</i>																					VR								
<i>Laticarinina pauperata</i>																R		R											
<i>Lenticulina calcar</i>	F		C	F	F	F		VR	F	R		VR		F			VR		VR				F				R		
<i>Lenticulina douglasi</i>			F		R				F			F		VR		VR	R									VR	VR		
<i>Lenticulina foliata</i>						VR										VR					VR					VR			
<i>Lenticulina cf. L. gibba</i>											R							R				R			VR	R			
<i>Lenticulina glaucina</i>															VR		VR												
<i>Lenticulina grandis</i>							R																						
<i>Lenticulina halophora</i>				VR	R				R				R		VR	F								R	VR		F		
<i>Lenticulina miyagiensis</i>																		VR			VR								
<i>Lenticulina neopolita</i>																		R			R								
<i>Lenticulina nuttalli</i>														VR															
<i>Lenticulina stellata</i>	VR																		R				F						
<i>Lenticulina subcultrata</i>	R	R	C	C	F	F	R	F	F	F	F	C	F	C	C	C	C	C	F	C		R	F	C	F	F	F		
<i>Lenticulina tangens</i>																						R							
<i>Lenticulina thalmani</i>			F		VR			C		VR								R											
<i>Lenticulina variabilis</i>					R									VR										R					
<i>Lenticulina sp. A</i>																						R							
<i>Lenticulina sp. B</i>																	VR												
<i>Lenticulina sp. C</i>																						R							
<i>Lenticulina sp. D</i>		VR									VR				VR								VR						
<i>Lingulina sirakawaensis</i>			VR		R																								
<i>Lotostomoides asperulum</i>	R		R		R	R		R		F	F	F	VR				F		R	R									
<i>Lotostomoides pyrulus</i>			VR		R	F		F	R	F	F				R	VR	R	VR	R	R									
<i>Marginulina cubana</i>			VR		F			F						C															
<i>Martinottiella communis</i>	F	F	F		F	F		F		R	F	R	C		VR	F	R	VR				F	F	F	VR	F			
<i>Martinottiella juncea</i>						F									R														
<i>Martinottiella pallida</i>				VR	R													F					F						
<i>Melonis affinis</i>											F							F							VR				
<i>Melonis barleeanum</i>				VR		R	VR		R		F				R		R										VR		
<i>Melonis pompilioides</i>			R		F	F		F		F		F	C	R	VR	F	R	F	F			F				VR			
<i>Milolinella suborbicularis</i>			R	F	R																						R		
<i>Mucronina acuta</i>						R																VR							
<i>Mucronina compressa</i>	F	R	R		R	F							F	VR	F	VR						R							
<i>Mucronina spatulata</i>			VR		R																								
<i>Mucronina striata</i>	F	F	F		F	F		F	VR		F	F	C								R		F	VR					
<i>Neolenticulina peregrina</i>	R				R			VR				VR			R	VR	R												
<i>Neovigerina auberiana</i>			F		R			VR			VR							VR		F									
<i>Neovigerina gallowayi</i>					F																								
<i>Neovigerina hispida</i>	C	C	R		F	R		F				R		VR	VR	VR	F	R	F	F				VR					
<i>Neovigerina schwageri</i>											C	F												R			VR		
<i>Neugeborina longiscata</i>	R	F	R		R	F		R		R	R	F	VR	R	R	F	F	R	R	C		R	R	R					
<i>Nodosaria splendidula</i>		VR	VR												R	R		R			R		R		VR	R			
<i>Nonionella miocenica</i>				VR						VR	R	F	F							VR									
<i>Nonionella stella</i>						R												R	F				F						
<i>Nummoloculina contraria</i>						R																							

TABLE 3  
Continued.

SECTOR	North											Central						South									
	AREA	Navidad										Conc	Arauco					Valid	Chiloé								
GEOLOGIC UNIT	Las Cruces	Navidad Fm.										MS10	Ranquil Fm.					SDom	Lacui Fm.								
	LOCALITY	NLP	LPER	MOS	RAP	PPP	PPT	PPN	LBZ	PTA	MAT		NAV5	MPUP	CPUP	FRA	FRM		RQT	RQK	RAN	MIB	LEB	VAL	CHO	PCB	PNH
<i>Nummulopyrgo globulus</i>	VR				R																						
<i>Obesopleurostomella brevis</i>															VR		VR			VR							
<i>Oolina laevigata</i>	VR											R					R	VR			VR	R					
<i>Oolina laevigata?</i>						VR																					
<i>Orbitina parri</i>																					R			VR			
<i>Oridorsalis umbonatus</i>	F				R	F			R		F		R	R	VR	VR	R	R	R			R		R			
<i>Orthomorphina jettitschkai</i>					R									VR										VR			
<i>Orthomorphina perversa</i>									VR															VR			
<i>Osangularia culter</i>	F														R		F	R	VR	F					F		
<i>Pandaglandulina obliquiesurata</i>			R		R	R			R		VR	R	F	R	R		R	VR	VR			R					
<i>Paracassidulina lobatula</i>										R	R							F									
<i>Parafissurina inermis</i>															R												
<i>Percultazonaria encinasi</i>			F	R	R	F	R	F	F	F			R		F		F		F				F				F
<i>Percultazonaria cf. P. mamilligera</i>																R											
<i>Percultazonaria obliquispina</i>											F		F		VR	R	VR	VR	VR	R				R			VR
<i>Percultazonaria vaughani</i>	VR				R				R			C															
<i>Planocassidulina curvicamerata</i>																								VR			
<i>Planularia cassis</i>						R																					
<i>Planulina sp.</i>	VR																		VR								
<i>Plectofrondicularia californica</i>	F	F											VR														
<i>Plectofrondicularia digitalis</i>			R	R	R	R	VR		R	F	F		F	F	R		R				VR		VR				
<i>Pleurostomella alternans</i>															R	VR	VR		VR								
<i>Polymorphina fistulosa</i>																			VR								
<i>Polymorphina sp.</i>																			R		R						
<i>Praeglobobulimina ovata</i>																		VR									
<i>Praeglobobulimina ovula</i>																			VR					F			
<i>Praeglobobulimina socialis</i>	F	C				R					R	F		F	C			F	R								
<i>Praeglobobulimina spinescens</i>									R		R																
<i>Prismatomorphia tricarinata</i>	VR																										
<i>Procerolagena sp.</i>					VR				VR																		
<i>Protoglobobulimina pupoides</i>					F				F					F	F		F			R				VR			
<i>Pseudoclavulina mexicana</i>	F	F	F		R				F				R	F	R	F	F		R		VR		VR				
<i>Pseudolingulina digitata</i>													VR														
<i>Pseudolingulina nielsenii</i>													VR														
<i>Pseudonodosaria aequalis</i>	VR				R	R												VR		R				R			
<i>Pseudonodosaria comatula</i>			F		R	F			F		F		R		R		F						R				
<i>Pseudononion communis</i>	F	F				VR																					
<i>Pseudononion cuevaensis</i>				F	VR									VR				F					F	R			F
<i>Pseudononion novozealandicum</i>			F		F	F			F		C	C	F	F	C	VR	F		F	F			VR		R		F
<i>Pseudononion ranquilensis</i>																				VR							
<i>Pseudoolina? sp.</i>						VR													VR								
<i>Pseudoparrella naraensis</i>			VR							VR	R																
<i>Pseudopolymorphina atlantica</i>				R	R		C	R						VR		VR		F		F					R		
<i>Pseudopolymorphina sp. A</i>	VR					VR																					
<i>Pseudopolymorphina sp. B</i>										VR																	C
<i>Pseudotriloculina cf. P. cyclostoma</i>												R							R								
<i>Pullenia bulloides</i>	F			R							R				F		R		R	F		R					
<i>Pullenia subcarinata</i>	R				R										R	VR	VR	R	F	R	R	VR		VR			
<i>Pygmaeoseistrion asperoides</i>											VR	VR			F				VR	VR							
<i>Pygmaeoseistrion gibberum</i>															R												
<i>Pygmaeoseistrion globulohispidum</i>															R												
<i>Pygmaeoseistrion hispidum</i>															R			R									
<i>Pygmaeoseistrion cf. P. hispidum</i>						VR																					
<i>Pyramidulina acuminata</i>	R			R	R										R	F				R				VR			
<i>Pyrgo clypeata</i>	R			VR	VR				VR				R		R	VR	F	R	VR	F	VR	F			R		
<i>Pyrgo depressa</i>	F		R	F	F	F		VR	F		R	F	R	R	F	VR	R		F				F	R			F
<i>Pyrgo lunula</i>																											
<i>Pyrgo murrhina</i>		F	F	VR											R		F	VR		F							
<i>Pyrgoella sphaera</i>	R		VR		R								VR		VR		R						VR				
<i>Quadriformina glabra</i>										VR																	
<i>Quinqueloculina akneriana</i>	R	R	C	C	F	F			F	F	R	F	F	C	F	VR	R	R	F	VR		R	F		F	VR	F
<i>Quinqueloculina badenensis</i>				C							VR												R				
<i>Quinqueloculina benwestonensis</i>									F		R				R		R										
<i>Quinqueloculina boueana</i>				F				C																			
<i>Quinqueloculina cf. Q. flexuosa</i>																				R	VR			R			
<i>Quinqueloculina magellanica</i>				VR																			C				F
<i>Quinqueloculina opulenta</i>											VR																

TABLE 3  
Continued.

SECTOR	North											Central							South									
	AREA		Navidad									Conc	Arauco						Valid	Chiloé								
GEOLOGIC UNIT	El Peral beds		Navidad Fm.									Ranquil Fm.							S.Dom	Lacui Fm.								
	LOCALITY	NLP	LPER	MOS	RAP	PPP	PPT	PPN	LBZ	PTA	MAT	NAV5	MPUP	CPUP	MS10	FRA	FRM	RQT	RQK	RAN	MIB	LEB	VAL	CHO	PCB	PNH	CHE	CUC
<i>Quinqueloculina suborbicularis</i>																												
<i>Quinqueloculina</i> sp. A									R		F																	
<i>Quinqueloculina</i> sp. B														R	R					VR			R					
<i>Ramulina globulifera</i>						VR			VR																			
<i>Ramulina pulchra</i>						VR	VR								R					VR								
<i>Rectuvigerina transversa</i>											C				F	F	VR	VR				F	VA		F			
<i>Reophax agglutinatus</i>																VR												
<i>Reophax</i> sp.																							R					
<i>Rhabdammina abyssorum</i>	VR					F	R																R		VR			
<i>Robertina subteres</i>														VR														
<i>Rosalina rugosa</i>				VR						VR																		
<i>Rotalinoides margaritifera</i>											R												F	R				
<i>Saracenaria schencki</i>					F	F	F		F	R	VR	R	F	F	R	F	F	VR	R					VR	VR	VR		VR
<i>Sigmoidella</i> sp.				VR																VR							VR	
<i>Sigmoilinita tenuis</i>				VR		R			F				VR					VR	VR					R				
<i>Sigmoilopsis schlumbergeri</i>	F																											
<i>Sigmomorphina trinitatensis</i>										C													F		C	VR	VR	
<i>Sigmopyrgo vespertilio</i>						VR																						
<i>Siphoglobulina</i> sp.																							R					
<i>Siphonodosaria insecta</i>																				VR	VR							
<i>Siphonodosaria lepidula</i>				F		F	C		F		VR	F	F	F	F	F	F	R	F	F	R			F			R	
<i>Siphonodosaria pomuligera</i>	VR	R					VR		VR	F														F		F		
<i>Siphonodosaria sentifera</i>																							R					
<i>Sphaeroidina bulloides</i>	F	F	R	R	F	F	VR		F	C	F	C	F	F	F	C	F	R	C	C		C		F		R		
<i>Spiroloculina incisa</i>		VR			R	R	VR									R	F	F	VR	R	F		R					
<i>Spiroloculina robusta</i>	R					R	VR																					
<i>Stainforthia</i> cf. <i>S. complanata</i>														VR														
<i>Strictocostella pupa</i>	R	R	R							R												VR						
<i>Textularia agglutinans</i>	VR					R	VR		VR			VR	F							VR			R					
<i>Textularia lythostrota</i>						F	VR		R		VR				R										R			
<i>Textularia miozea</i>							R				R		R					R										
<i>Textularia schencki</i>						VR																			F			
<i>Textularia</i> sp. A																										F		
<i>Textularia</i> sp. B	VR																											
<i>Textularia</i> sp. C																			VR									
<i>Textularia?</i> sp.										VR															VR			
<i>Toddostomella hochstetteri</i>	R												R		VR													
<i>Tollmannia costata</i>						R	VR																					
<i>Trifarina angulosa</i>											R		VR										F	R		F		
<i>Triloculina</i> cf. <i>T. brochita</i>																												VR
<i>Triloculina lucermuloides</i>				R		R				VR	VR	R	R	F				R						R				
<i>Triloculina oblonga</i>																VR												
<i>Triloculina striatotriginula</i>																VR												
<i>Triloculina trigonula</i>						R	R							VR		F				R				F				
<i>Triloculina</i> sp.						R																						
<i>Triloculinella bornemanni</i>	R					VR																	R					
<i>Triloculinella</i> sp. A	R	F				VR										R							VR			VR		
<i>Triloculinella</i> sp. B																VR		R		F			VR					
<i>Triloculinella striata</i>	F																											
<i>Tritaxis challengeri</i>							R																					
<i>Trochamminopsis quadriloba</i>																F	VR							VR				
<i>Uvigerina hispidocostata</i>												F	R	F									R					
<i>Uvigerina kemensis</i>						R	F			F																		
<i>Uvigerina peregrina</i>																				VR								VR
<i>Vaginulina alazanensis</i>						R				VR	VR		C	VR				R					R		R			C
<i>Vaginulina</i> cf. <i>V. spinata</i>						F																						VR
<i>Vaginulina tenuis</i>						F	R			VR	VR	VR			VR					R				C				VR
<i>Vaginulinopsis</i> cf. <i>V. chetae</i>																									VR			
<i>Vaginulinopsis costatus</i>																											VR	
<i>Vaginulinopsis lueneburgensis</i>									R		VR				R												VR	
<i>Vaginulinopsis subelegans?</i>													VR										R		R	R	F	R
<i>Vaginulinopsis</i> sp. A																							VR					
<i>Vaginulinopsis</i> sp. B	VR																											
<i>Vaginulinopsis</i> sp. C																VR												
<i>Valvulinera ecuadorana</i>				VR		F							F	R														
<i>Virgulinita pertusa</i>																												
<i>Vulvulina pacifica</i>																												
<i>Zeafflorilus chilensis</i>						C	R		VA	C	VR	C	R		VR	F		R	C			C	R	C			A	C

TABLE 4

Planktic species presence vs. localities checklist. Relative abundances: VR = 1 specimen; R ≥2 specimens if <1%, or 2 specimens if ≥1%; F = 1–5%; C = 5–25%; A = 25–50%; VA >33%.

GEOLOGIC UNIT	Las Cruces		Navidad													Conc	Arauco							Vald	Chiloé				
	El Peral beds		Navidad Fm.														Ranquil Fm.							SDom	Lacui Fm.				
	LOCALITY		NLP	LPER	MOS	RAP	PPP	PPT	PPN	LBZ	PTA	MAT	NAV5	MUPU	CPUP	MS10	FRA	FRM	RQT	RQK	RAN	MIB	LEB	VAL	CHO	PCB	PNH	CHE	CUC
<i>Catapsydrax dissimilis</i>						X									X			X	X	X	X								
<i>Globigerina concinna</i>						X	X			X		X									X								
<i>Globigerina praebulloides</i>	X	X	X		X					X	X	X		X		X	X	X	X	X	X	X	X	X	X			X	
<i>Globigerina venezuelana</i>	X	X	X	X	X	X	X			X	X	X		X	X	X	X	X	X	X	X						X		
<i>Globigerinella obesa</i>	X		X	X	X	X	X			X	X	X			X	X	X	X	X	X	X	X				X	X		
<i>Globigerinoides primordius</i>	X	X	X		X	X	X	X	X	X	X			X	X					X		X							
<i>Globigerinoides trilobus</i>			X	X	X		X			X	X	X		X	X				X	X	X						X	X	
<i>Globoquadrina dehiscens</i>			X	X	X	X	X	X	X	X	X			X		X	X	X		X	X				X	X		X	
<i>Globoquadrina praedeheiscens</i>			X		X												X			X									
<i>Globorotalia miotumida</i>	X	X																											
<i>Globorotalia cf. Glr. miozea</i>										X																			
<i>Globorotalia praemenardi</i>	X																												
<i>Globorotalia praescitula</i>						X	X																						
<i>Globoturbotalita brazieri</i>			X	X	X	X				X	X					X		X		X						X			
<i>Globoturbotalita connecta</i>										X		X																	
<i>Globoturbotalita woodi</i>	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X		X	X
<i>Orbulina universa</i>	X	X																											
<i>Praeorbulina glomerosa</i>	X																												
<i>Paragloborotalia mayeri plexus</i>								X			X							X	X	X	X								
<i>Paragloborotalia bella plexus</i>					X		X				X	X				X									X				
<i>Paragloborotalia nana plexus</i>											X	X							X					X	X				X
<i>Paragloborotalia zealandica plexus</i>			X		X	X				X								X	X										X

(none)

*elegans* (20), *Dentalina striatissima* (19), *Hansenisca altiformis* (19), *Laevidentalina elegans* (19), *Martinottiella communis* (19), *Neugeborina longiscata* (18), *Saracenaria schencki* (18), *Siphonodosaria lepidula* (17), *Globocassidulina chileensis* (16), *Pseudononion novozealandicum* (16), *Pyrgo depressa* (16), and *Zeaflorilus chiliensis* (16).

Only five species are relatively abundant (>25%) in any assemblage: *Cibicides umboniferus* (LBZ), *Ciperozoa basispinata* (MIB), *Globocassidulina chileensis* (PNH), *Rectuvigerina transversa* (VAL), and *Zeaflorilus chiliensis* (PPN, CHE). Forty other species are common (5–25%) at one or more localities. Of these 45 species that are at least 5% at one locality, 26 are restricted to one locality, and two were recorded at multiple localities but restricted to one formation; the remaining 17 are less constrained (table 6).

Benthic species previously known from Miocene–Holocene deposits in the middle latitudes predominate in all assemblages from Neogene outcrop and well samples examined during the course of this study. Both benthic and planktic microfaunas in temperate zones typically include taxa also known to occur in subpolar and subtropical latitudes, and the samples studied herein are no exception. Many benthic species or their homeomorphs inhabiting the deep waters off Chile occur in the provincial Neogene and some are members of the cosmopolitan deep-water fauna documented by Morkhoven, Berggren and Edwards (1986).

Boltovskoy (1980) claimed that less than 2.5% of Neogene bathyal benthic foraminiferal taxa have provincial or regional utility as guide fossils because the fauna has remained fairly stable from

Oligocene to Holocene. This is reflected in the distribution of the type ages for the identified species (or comparative ‘cf.’ species) in Chile, 97% of which are Oligocene or younger (51% Quaternary, 38% Neogene and 8% Oligocene). This is also apparent in the known ranges presented in the Systematic Taxonomy section, nearly all of which are post-Eocene.

Table 5 includes the results of the statistical measurements of diversity, as well as the P:B values calculated for each of the 27 assemblages. Thirteen of the Fisher  $\alpha$  values are within the normal range of 5–16 for open-marine environments (Murray, 1973), but the rest range higher, up to 32.66, and the 27 assemblages average 18.21. Considering that the normal range is based on modern assemblages, and the values obtained from fossil assemblages may have been lowered by post-mortem disaggregation of weakly agglutinated species, the majority of the Chilean values are abnormally high for fossil assemblages. I performed linear regressions to examine the relationships between the number of specimens, species richness, and Fisher  $\alpha$  (text-figure 10). As more specimens are observed, the number of species counted increases to a point where only very rare components of the assemblage are likely to be found. Following Phleger (1954), foraminiferologists have traditionally placed that at 300 specimens — the number derived from an analysis of heavy mineral frequencies (Dryden 1931) and later extended to zoological studies (Fisher, Corbett and Williams 1943). Even though diversity indices are based on that logarithmic trend, Fisher  $\alpha$  correlated much better with species richness than with species number, possibly because the richness value is a factor of the number, not vice versa.

TABLE 5  
Numerical and statistical data tally for the 28 foraminiferal assemblages.

Sector	Geologic Unit	Area	Locality	Sample Site	No. of Samples	No. of Slides	Benthics							Number of Planktic Specimens	P:B	
							No. of Specimens	No. of Species	Diversity Indices							
									Dominance	Simpson	Fisher $\alpha$	Evenness	Equitability			
NORTH	El Peral beds	Las Cruces	Laguna el Peral	NLP	1	1	425	73	0.030	0.970	25.38	0.618	0.888	44	0.10	
				LPER	1	1	165	36	0.048	0.952	14.20	0.714	0.906	11	0.07	
	Navidad Fm.	Navidad	Mostazal	MOS	2	3	575	65	0.040	0.960	18.84	0.542	0.853	281	0.49	
			Río Rapel	RAP	2	2	472	45	0.085	0.915	12.23	0.392	0.754	277	0.59	
			Punta Perro	PPP	4	7	2135	138	0.017	0.983	32.97	0.555	0.881	647	0.30	
				PPT	1	1	533	67	0.027	0.973	20.26	0.668	0.904	301	0.56	
				PPN	1	1	472	21	0.423	0.577	4.51	0.204	0.478	103	0.22	
			Las Brisas	LBZ	1	1	163	20	0.223	0.777	7.64	0.348	0.667	6	0.04	
			Punta Alta	PTA	2	3	697	88	0.024	0.977	26.66	0.608	0.889	185	0.27	
			Matanzas	MAT	2	2	539	38	0.083	0.917	9.33	0.465	0.790	61	0.11	
			Navidad #5	NAV5	1	2	461	68	0.034	0.966	22.02	0.575	0.869	126	0.27	
SE of Matanzas	MPUP	2	2	491	46	0.064	0.936	12.43	0.486	0.811	6	0.01				
Camino de Pupuya	CPUP	1	3	865	78	0.029	0.971	20.79	0.607	0.885	111	0.13				
CENTRAL	Ranquil Fm.	Arauco	Concepción	Quiriquina Island	MS10	1	1	299	63	0.036	0.964	24.37	0.594	0.874	68	0.14
			Punta El Fraile	FRA	3	5	1081	109	0.049	0.951	30.24	0.428	0.819	381	0.35	
				FRM	1	1	272	66	0.033	0.967	27.72	0.612	0.883	52	0.19	
			Punta Huntiguapi	RQT	2	4	1226	105	0.024	0.976	27.49	0.541	0.868	193	0.16	
				RQK	1	2	876	56	0.125	0.875	13.33	0.247	0.652	95	0.11	
				RAN	3	4	851	92	0.063	0.937	26.20	0.362	0.775	269	0.32	
			Caleta Ranquil	MIB	1	2	558	69	0.044	0.956	20.72	0.501	0.837	160	0.29	
	Lebu	LEB	2	2	663	39	0.262	0.738	9.06	0.221	0.588	8	0.01			
S. Dom. Fm.	Valdivia	Valdivia	VAL	1	2	788	62	0.094	0.906	15.77	0.365	0.756	9	0.15		
SOUTH	Lacui Fm.	Chiloé Island	Punta Chocoi	Punta Chocoi	CHO	1	2	475	51	0.065	0.935	14.49	0.457	0.801	163	0.34
			Playa Chaumán	PCB	1	2	462	80	0.033	0.967	27.93	0.554	0.865	86	0.19	
			Puñihuil	PNH	1	2	463	35	0.216	0.784	8.79	0.258	0.619	0	0.00	
			Chepu	CHE	1	1	194	33	0.251	0.749	11.42	0.281	0.637	37	0.19	
			Cucao	CUC	1	2	411	38	0.087	0.913	10.22	0.470	0.793	4	0.01	
Totals (cols. 6–8, 15) & averages (cols.9–14, 16):					41	61	16,609	62	0.093	0.907	18.19	0.471	0.791	3,684	0.21	

The Q-mode cluster analysis produced a dendrogram (text-fig. 11) that groups some assemblages from the same geologic units, but there are many geologically and geographically incongruent pairings. The associated R-mode clustering (text-fig. 12) resulted in groupings that for the most part are paleobathymetrically inconsistent, as expected. The relationships between the five units are shown in another dendrogram (text-fig. 13), where the Navidad and Ranquil formations are differentiated from the other three, but the latter's groupings are perplexing. The NMDS plot (text-fig. 14) more clearly distinguishes the geologic units, although those of the Navidad group show considerable overlap. Each of the three primary units (Navidad, Ranquil, and Lacui formations) overlaps the other two, perhaps related to similarities in age and environment. The NMDS on the 52 common species (text-fig. 15) yielded high stress values ( $S = 0.2399$  for localities;  $S = 0.4937$  for species) that indicate poor ordinations. Similarly poor values had been obtained prior, when the NMDS was performed on the larger 172-species dataset that excluded all rare species (which produced a very cluttered species plot).

## DISCUSSION

### Age of the units

In Peru, Navidad molluscs such as *Miltha vidali*, *Acanthina katzi*, *Olivancillaria claneophila*, and *Testallium cepa* occur in Late Oligocene–Middle Miocene sections (Nielsen et al. 2003), but not in younger successions (DeVries and Frassinetti 2003).

Other Navidad species such as *Ficus distans* are restricted in Peru to the Early–Middle Miocene, whereas *Eucrassatella ponderosa*, *Glycymeris ibariformis*, and *G. colchaguensis* only occur in the Late Oligocene–Early Miocene. Encinas (2006) obtained Early Miocene ages of  $24.7 \pm 0.4$  and  $20.4 \pm 0.5$  Ma from  $^{87}\text{Sr}/^{86}\text{Sr}$  analyses of two *O. claneophila* specimens from the Navidad Formation. Among these particular species in the Navidad group, *A. katzi* (Finger et al. 2007, fig. 9) ranges the youngest, to about 13 Ma. Encinas (2006) reported Sr isotope dates in the range of 31.5 Ma (Early Oligocene) to 16.0 Ma (early Middle Miocene) for 29 of 30 mollusc specimens from the Navidad group, but only a few of the younger samples are from the same localities as the microfossil assemblages reported here. Nielsen and Glodny (2010) presented  $^{87}\text{Sr}/^{86}\text{Sr}$  ages obtained from molluscs collected at 14 of the Navidad group localities in the general proximity of where the foraminiferal samples were taken. Text-figure 16 shows the chronostratigraphic ages (derived from both analytical data sets) that represent 18 of the foraminiferal sample localities. Those ages range from between 25.1 and 15.6 Myr Ma, or latest Oligocene (Chattian) to early Middle Miocene (Langhian), but all but one (LEB) are represented by at least one chronostratigraphic date extending into or restricted to the Early Miocene. Evidence for being in this lower, warmer interval of the Miocene may also be the presence of benthic genera like *Rectuvigerina*, which in California has its last occurrence at about 14 Ma (Finger 1992).

TABLE 6  
Dominant (common and abundant) species in each assemblage.

SECTOR	AREA	GEOLOGIC UNIT	SAMPLE	DOMINANT (COMMON TO ABUNDANT) SPECIES
				Abundant (25–33%) and very abundant (>33%) occurrences indicated in <b>bold</b> . The most constrained of these occurrences are indicated as being restricted to a single *locality or **formation.
NORTH	Las Cruces	El Peral beds	NLP	<b>**Neouvigerina hispida</b>
			LPER	<b>**Neouvigerina hispida</b> , <i>Praeglobobulimina socialis</i>
	Navidad	Navidad Fm.	MOS	<i>Cibicides umboniferus</i> , * <i>Haplophragmoides mexicanus</i> , * <i>Lenticulina calcar</i> , <i>Lenticulina subcultrata</i> , <i>Quinqueloculina akneriana</i>
			RAP	<i>Cibicides umboniferus</i> , * <i>Dentalina obliquecostata</i> , <i>Hanzawaia strattoni</i> , <i>Lenticulina subcultrata</i> , <i>Quinqueloculina akneriana</i> , * <i>Q. badenensis</i> , <i>Zeafflorilus chiliensis</i>
			PPP	No species >5% of the assemblage
			PPT	<i>Cibicoides compressus</i> , * <i>Siphonodosaria lepidula</i>
			PPN	<i>Cibicides mediocris</i> , <i>Cibicides umboniferus</i> , <i>Hanzawaia strattoni</i> , * <i>Pseudopolymorphina atlantica</i> , * <i>Quinqueloculina boueana</i> , <b><i>Zeafflorilus chiliensis</i></b>
			LBZ	<i>Cibicides cicatricosus</i> , <b><i>Cibicides umboniferus</i></b> , * <i>Lenticulina thalmani</i> , <i>Zeafflorilus chiliensis</i>
			PTA	No species >5% of the assemblage
			MAT	<i>Cibicoides compressus</i> , <i>Cyclammina cancellata</i> , <i>Rectuvigerina transversa</i> , <i>Sigmomorphina trinitatensis</i> , <i>Sphaeroidina bulloides</i> , <i>Zeafflorilus chiliensis</i>
			NAV5	<i>Hansenisca altiformis</i> , * <i>Neouvigerina schwageri</i> , <i>Pseudononion novozealandicum</i>
			MPUP	<i>Cibicoides compressus</i> , <i>Cyclammina cancellata</i> , <i>Haplophragmoides</i> spp., <i>Lenticulina subcultrata</i> , * <i>Percultazonaria vaughani</i> , <i>Pseudononion novozealandicum</i> , <i>Sphaeroidina bulloides</i>
	CPUP	<i>Vaginulina alazanensis</i>		
CENTRAL	Concepción	Ranquil Fm.	MS10	<i>Cibicides mediocris</i> , <i>Lenticulina subcultrata</i> , <i>Marginulina cubana</i> , * <i>Martinotiella communis</i> , * <i>Melonis pompilioides</i> , * <i>Mucronina striata</i> , <i>Quinqueloculina akneriana</i>
			FRA	<i>Cibicoides compressus</i> , <i>Lenticulina subcultrata</i> , <i>Pseudononion novozealandicum</i>
	Arauco		FRM	<i>Cibicoides compressus</i> , * <i>Dorothia cylindrica</i> , <i>Lenticulina subcultrata</i> , <i>Praeglobobulimina socialis</i> , <i>Sphaeroidina bulloides</i>
			RQT	<i>Cibicoides compressus</i> , * <i>Glandulina laevigata</i> , <i>Lenticulina subcultrata</i>
			RQK	<i>Buccella peruviana</i> , * <i>Ciperozoa onglyei</i> , <i>Zeafflorilus chiliensis</i>
			RAN	<i>Cibicides umboniferus</i> , <i>Cibicoides compressus</i> , <i>Ciperozoa basispinata</i> , <i>Lenticulina subcultrata</i> , <i>Sphaeroidina bulloides</i>
			MIB	<i>Cibicoides compressus</i> , <b>**<i>Ciperozoa basispinata</i></b> , * <i>Karriella subcylindrica</i> , * <i>Neugeborina longiscata</i>
			LEB	<i>Cibicoides compressus</i> , <i>Zeafflorilus chiliensis</i>
Valdivia	Santo Domingo	VAL	<i>Hansenisca altiformis</i> , <b><i>Rectuvigerina transversa</i></b> , <i>Sphaeroidina bulloides</i>	
SOUTH	Punta Chocoi	Lacui Fm.	CHO	<i>Cibicoides mediocris</i> , <i>Hanzawaia strattoni</i> , <i>Lenticulina subcultrata</i> , * <i>Vaginulina tenuis</i> , <i>Zeafflorilus chiliensis</i>
	Chiloé Island		PCB	<i>Cibicides cicatricosus</i> , <i>Cibicides lobatulus</i> , <i>Cibicoides renzi</i> , <i>Sigmomorphina trinitatensis</i>
			PNH	* <b><i>Globocassidulina chileensis</i></b> , * <i>Pseudopolymorphina</i> sp. B
			CHE	<i>Cibicoides compressus</i> , <i>Cibicoides mediocris</i> , <b><i>Zeafflorilus chiliensis</i></b>
			CUC	<i>Cyclammina cancellata</i> , <i>Haplophragmoides</i> spp., <i>Vaginulina alazaensis</i> , <i>Zeafflorilus chiliensis</i>

Finger et al. (2007) previously addressed the discordant interpretations that were the impetus for undertaking this study. In that report, I identified several species of planktic foraminifera in the Navidad, Ranquil, and Lacui formations that indicate Late Miocene and Early Pliocene ages. Several colleagues agreed with those identifications, and many of those index species had been reported by others who previously worked in the region, some having collected from the same localities examined in the present study; hence, the identifications were thought to be accurate. In 2010, I had the opportunity to show my images of these species to Martin Crundwell, who is intimately familiar with the mid-

latitude Miocene planktic fauna and the excellent stratigraphic sections in New Zealand, from which many were first described. Crundwell kindly provided his taxonomic opinions and argued for an Early–Middle Miocene age. I subsequently followed his suggestion that I peruse George Scott’s publications on the Miocene globorotaliids, and I also asked Scott to examine the images. He confirmed the inaccuracy of some of my identifications, but he was unable to assign several definitively to species. It became obvious that some of the Chilean Miocene taxa could not be reliably speciated because of their relative rarity and stratigraphic isolation, which preclude a contextual

TABLE 7

Upper-depth limits of 383 foraminiferal taxa living off the central Chilean margin between 33–44°S. Data compiled from Ingle, Keller and Kolpack (1980) and Figueroa (2005, 2006). Species found in the present study are indicated in bold; five of those species reported by Ingle, Keller and Kolpack (I) are typically deep-water, but they were purported to occur much shallower by Figueroa (F).

**Shelf-edge or Shelf***Ammodiscus flavidus**Ammodiscus incertus**Ammonia beccarii****Amphicoryna scalaris******Amphicoryna separans****Anomalina vermiculatra**Asteriginata pacifica**Astrononion gallowayi**Bolivina alata**Bolivina compacta**Bolivina costata**Bolivina earlandi**Bolivina interjuncta**Bolivina interjuncta bicostata**Bolivina ordinaria**Bolivina plicata**Bolivina pseudoplicata**Bolivina punctata**Bolivina pygmaea**Bolivina* aff. *B. rankini**Bolivina seminuda****Buccella peruviana****Bulimina demudata**Bulimina elongata**Bulimina exilis**Bulimina marginata**Bulimina patagonica**Bulimina pulchella**Buliminella curta**Buliminella elegantissima**Cancris inflatus**Cancris sagra**Cassidulina auka**Cassidulina californica**Cassidulina depressa**Cassidulina crassa**Cassidulina cushmani**Cassidulina laevigata**Cassidulina limbata**Cassidulina minuta**Cassidulina pulchella**Cassidella seminuda**Cassidulinoides parkerianus**Cassidulinoides tenuis**Cibicides aknerianus**Cibicides dispars**Cibicides fletcheri**Cibicides lobatulus**Cibicides ornatus**Cibicides pseudoungerianus**Cibicides refulgens**Cibicides variabilis**Cribrorotalia meridionalis**Cribrostomoides hancocki**Cribrostomoides jeffreysi**Cribrostomoides subglobosus**Cribrostomoides subinvolutum****Cyclammmina cancellata*** (F)*Darbyella argentinensis**Dentalina baggi****Dentalina communis****Dentalina consobrina emaciata**Dentalina strigosa**Discorbis bertheloti**Discorbis corus**Discorbis floridanus**Discorbis isabelleanus**Discorbis mira**Discorbis orbicularis**Discorbis parkerae**Discorbis peruvianus**Discorbis williamsoni**Ehrenbergina hystrix glabra**Ehrenbergina pupa**Eilohedra levicula**Elphidium alvarezianum**Elphidium articulatum**Elphidium discoidale**Elphidium excavatum**Elphidium macellum**Epistominella exigua**Epistominella pacifica**Eponides bradyi****Favulina hexagona******Favulina melo****Fissurina earlandi**Fissurina elliptica**Fissurina laevigata**Fissurina lagenoides**Fissurina lucida****Fissurina marginata****Fissurina quadricostulata****Fontotia wuellerstorfi*** (F)*Glabratella pileolus****Globoassidulina subglobosa****Globobulimina pacifica**Globulina australis**Guttulina problematica**Goesella flintii****Gyroidina soldanii****Haplophragmoides columbiensis**Haplophragmoides planissimus****Hoeglundina elegans******Hyalinonetrina distomum****Lagena gracilis**Lagena interrupta**Lagena isabella**Lagena laevis****Lagena striata******Lagena sulcata****Lagena villardeboana****Laticarinina pauperata*** (F)*Lenticulina adelinensis**Lenticulina calcar**Lenticulina melvilli**Lenticulina orbicularis**Lenticulina reniformis**Marginulina curvata**Marginulina hancocki****Marginulinopsis*** sp.***Melonis affinis******Melonis pompilioides*** (F)*Miliammina fusca****Martinottiella communis****Miliolinella lutea**Miliolinella subrotunda**Morulaeplecta bulbosa**Nonion mexicanum**Nonioniella auris****Nonionoides grateloupi******Nonionella miocenica****Nonioniella turgida**Notorotalia clathrata**Oolina caudigera**Oolina costata**Oolina inornata**Oolina costata****Oridorsalis umbonatus****Parafissurina lateralis**Parafissurina quadrata**Patellina corrugata**Planulina ornata**Poroepionides lateralis****Praeoglobulimina affinis******Praeoglobulimina ovata******Praeoglobulimina ovula****Pseudononion japonicum****Pullenia bulloides*** (F)***Pullenia subcarinata******Pygmaeosestron aspera****Pyrgo elongata****Pyrgo murrhina****Pyrgo patagonica**Pyrgo peruviana**Pyrgo quadrata**Pyrgo ringens**Pyrgo subsphaerica**Pyrgo vespertilio**Quinqueloculina angulata**Quinqueloculina arctica**Quinqueloculina gregaria**Quinqueloculina lamarckiana**Quinqueloculina patagonica****Quinqueloculina seminulum****Remaneica helgolandica**Reophax dentaliniformis**Reophax pilulifer**Reophax scorpiurus**Robulus rotulatus**Saccamina atlantica**Sigmoilina* sp.*Sigmomorphina williamsoni**Spirillina densepunctata**Spirillina vivipara**Spiroloculina asperula**Stainforthia complanata**Stainforthia riggi**Textularia clava**Textularia conica**Textularia cuyleri****Trifarina angulosa****Trifarina carinata****Triloculina trigonula****Trochammina globigerinaformis**Trochammina inflata**Trochammina ochracea**Trochammina plana**Trochammina squamata**Tubinella finalis****Uvigerina auberiana****Uvigerina bifurcata**Uvigerina flintii****Uvigerina peregrina****Uvigerina striata**Valvulineria inflata****Zeaflorilus chiliensis***

TABLE 7  
Continued.**Upper Bathyal**

*Alveophragmium subglobosum*  
*Ammobaculites foliaceus*  
*Amphitremoidea granulosa*  
***Anomalinoidea* sp.**  
*Astrononion tumidum*  
*Bolivina* cf. *B. danvillensis*  
*Bolivinita minuta*  
*Bolivina spissa*  
*Bulimina inflata*  
***Bulimina striata mexicana***  
*Buliminella tenuata*  
***Cancris auriculus***  
*Cassidulina delicata*  
*Cassidulina gemma*  
*Cassidulina obtusa*  
***Chilostomella ovoidea***  
*Cibicides elmaensis*  
*Cibicides mckannai*  
*Cyclammina pusilla*  
***Dentalina elegans***  
*Discorbis peruvianus*  
*Discorbis williamsoni*  
*Eggerella advena*  
*Eggerella scabra*  
*Ehrenbergina healyi*  
*Fissurina laevigata*  
*Fissurina staphyllearia*  
*Fissurina susanae*  
*Gaudryina rugosa*  
***Glandulina laevigata***  
*Glandulina ovula*  
*Globocassidulina* sp.  
*Glomospira gordialis*  
*Gyroidina turgida*  
***Hanzawaia basiloba***  
*Hoeglundina pleurostomata*  
*Involutina* sp.  
*Oolina apiculata*  
*Lagena elongata*  
*Melonis guadalupe*  
***Melonis sphaeroides***  
*Miliolinella lutea*  
*Nodosaria calomorpha*  
*Nodosaria* sp.  
*Nonion scapha*  
*Nuttallides* sp.  
*Oolina globosa*  
*Oolina margaritae*  
*Oolina villardeboana*  
*Praeglobbulimina pyrula*  
***Pullenia bulloides* (I)**  
***Pullenia quinqueloba***  
***Pyrgo depressa***  
*Recurvoides turbinatum*  
*Rhabdammina linearis*  
***Sigmoilinita tenuis***  
***Sphaeroidina bulloides* (F)**  
*Spiroplectammina bififormis*  
*Stainforthia fusiformis*  
*Textularia goesi*  
*Trifarina fluens*  
***Triloculina trigonula***  
*Uvigerina incilis*  
***Uvigerina peregrina dirupta***  
*Valvulineria inequalis*

**Upper Middle Bathyal**

*Alveophragmium scitulum*  
***Ammodiscus tenuis***  
*Bolivina pseudospissa*  
*Bolivina subspinescens*  
*Bulimina auriculata*  
***Bulimina pyrula spinescens***  
*Cassidulina laevigata carinata*  
*Cassidulinoidea bififormis*  
*Chilostomella oolina*  
*Cibicides moyanoi*  
***Cibicidoides bradyi***  
***Cibicidoides spiralis***  
*Dentalina* spp.  
***Eggerella bradyi***  
*Eggerella pusilla*  
*Fissurina alveolata*  
*Fissurina annectens*  
*Fissurina fimbriata*  
*Fissurina orbignyana*  
*Fissurina solida*  
*Fissurina spinosa*  
*Fissurina staphyllearia*  
*Fissurina susanae*  
*Fissurina wiesneri*  
***Fontbotia wuellerstorfi* (I)**  
***Glandulina laevigata***  
***Globocassidulina subglobosa quadrata***  
*Globobulimina pyrula*  
*Gyroidina gemma*  
*Gyroidina lamareckiana*  
***Gyroidina neosoldanii***  
*Gyroidina subtener*  
***Hansenisca altiformis***  
*Haplophragmium canariensis*  
*Hormosina globulifera*  
*Karrieriella novangliae*  
*Lagena longispina*  
*Lagena nebulosa*  
***Melonis barleeanus***  
***Melonis pompilioides* (I)**  
*Miliolina alveoliniformis*  
*Oolina apiculata*  
***Protolobbulimina pupoides***  
*Pyrgo nasuta*  
*Pyrgo serrata*  
*Quadriformina camerata*  
*Rectoglandulina rotundata*  
*Reophax distans*  
*Reophax excentricus*  
*Robulus argentinensis*  
*Robulus orbicularis*  
*Saracenaria* sp.  
*Tritaxis fusca*  
*Trochammina inflata*  
*Uvigerina ampullacea*  
*Uvigerina borbotara*  
*Uvigerina canariensis*  
*Virgulinella rotundata*

**Lower Middle Bathyal**

*Ammobaculites cylindroides*  
***Astacolus* sp.**  
*Bulimina barbata*  
***Bulimina rostrata***  
*Cassidulinoidea cornuta*  
*Cassidulinoidea bradyi*  
*Cassidulina oblongata*  
*Cibicidoides kullenbergi*  
***Cyclammina cancellata* (I)**  
*Cystammina galeata*  
*Ehrenbergina undulata*  
*Eponides tumidulus*  
*Fissurina auriculata*  
*Glomospira charoides*  
*Gyroidina zelandica*  
*Lagena amphora*  
*Lagena gracillima*  
***Pleurostomella* sp.**  
***Pseudoglandulina* sp.**  
*Reophax guttifer*  
***Rhabdammina abyssorum***  
***Robertina* sp.**  
*Robulus papillosus*  
***Rosalina columbiensis***  
*Textularia tenuissima*  
*Trifarina bradyana*

**Lower Bathyal**  
*Adercotryma glomeratum*  
*Alveophragmium wiesneri*  
*Bathysiphon filiformis*  
*Cassidella schreibersiana*  
*Cassidulina oblonga*  
*Cassidulina tenuata*  
***Cibicides robertsonianus***  
*Cystammina pauciloculata*  
***Dentalina advena***  
*Ehrenbergina trigona*  
*Epistominella pulchella*  
*Fissurina exculpta*  
***Gyroidina* aff. *G. neosoldanii***  
*Hormosina ovivula*  
*Hyperammina subnodosa*  
***Karrieriella apicularis***  
*Lagena digitale*  
***Lagena gibbera***  
*Lagena sacculus*  
***Laticarinina pauperata* (I)**  
*Lenticulina convergens*  
*Oolina striatopunctata*  
***Osangularia mexicana***  
*Reophax fusiformis*  
***Sphaeroidina bulloides* (I)**  
*Uvigerina peregrina asperula*  
*Uvigerina senticosa*  
*Valvulineria herricki*

understanding of where their particular morphologies fit among the species used to subdivide the Miocene. I have carefully reexamined my Chilean specimens in light of the comments from both experts and Scott's pertinent publications. Although some taxonomic uncertainties remain, the apparent indications better agree with data from other sources, most notably molluscan biostratigraphy and strontium isotope chronostratigraphy. Nevertheless, unsettling discrepancies still challenge the integrity of the planktic taxonomy and biostratigraphy of these geologic units.

Other types of data mostly support the molluscan and isotopic indications of ages in the Late Oligocene–Early Miocene interval. Suárez, Encinas and Ward (2006) identified the teeth of various elasmobranch fishes in the Navidad Formation, including *Carcharoides totuserratus*, an uncommon shark that has this range (Suárez and Marquardt 2001). Encinas (2006) dated six volcanic scoria and pumice clasts in the Navidad Formation by K/Ar and Ar/Ar analyses and found five were of Early to Middle Miocene age (22.2–15.9 Ma); the exception yielded an age of 11.06±0.19 Ma (earliest Late Miocene), which is 3.9 Myr younger than the biostratigraphic range, and, therefore, assumed to be unreliable.

The affinity of the El Peral beds with the Lo Abarca Formation could only be postulated based on the regional sequence because the former are silty mudstones with foraminifera, but no molluscs, and the latter, described by Covacevich and Frassinetti (1990), was primarily a limestone with molluscs but no foraminifera. Covacevich and Frassinetti (1990) differentiated the Lo Abarca Formation as younger than the Navidad Formation at Punta Perro by comparing their molluscan faunas. Encinas et al. (2006, 2010) reported that the beds overlying the basal conglomerate of the Lo Abarca stratotype yielded two diatom markers that have a concurrent range of 12.2–11.3 Ma (Serravallian) in the equatorial Pacific (Barron, 2003). That interval encompasses the Sr age of 11.5±1.0 Ma obtained from an oyster shell collected at that same level (Encinas, personal comm.). The two foraminiferal assemblages from the Laguna el Peral area, 5 km northwest of the Lo Abarca stratotype, are also noticeably different from those of the Navidad Formation. This is readily apparent in their dominance by *Neouvigerina hispida*, which is not a dominant constituent of any assemblage in the Navidad group (see table 3). The presence of *Globorotalia miotumida* in NLP and LPER indicates a younger Miocene age of 15.0–7.3 Myr, but LPER also has *Globorotalia praemenardii*, which has a more restricted range of 14.2–11.6 Myr (Middle Miocene). This range overlaps those obtained for the type Lo Abarca Formation, supporting the notion that the El Peral beds belong to that unit, and dispelling Martínez and Parada's interpretation of the LPER locality as Pliocene, which they based on benthic foraminifera.

For the Navidad Formation in its type area along Punta Perro, Martínez-Pardo and Osorio (1964), Cecioni (1970), Osorio (1978), and Ibaraki (1992a, 1992b) suggested a Late Miocene age. Ibaraki (1992a) was the first to apply modern planktic foraminiferal biostratigraphy in her interpretation, and her identification of *Neogloboquadrina acostaensis* (10.9 Ma FAD in Berggren et al. 1995) placed the unit in the Tortonian. Shuto (1990), Tsuchi et al. (1990), and Tsuchi (2002) also assigned the Navidad at Punta Perro to the Late Miocene, presumably based on Ibaraki's report, even though it was associated with a subtropical molluscan assemblage recorded by Covacevich and Frassinetti (1980), which suggests that it preceded the global Mid-Miocene cooling event. Tsuchi (2002) correlated the molluscs with one of the relative abundance spikes of warm-water planktic

foraminifera that he used to determine warm episodes in the Pacific Neogene, notably that recognized at ~5.7 Ma in Japan, Ecuador, Peru, and the Caleta Herradura de Mejillones section near Antofagasta, northern Chile. Although Finger et al. (2007) did not recognize *Ng. acostaensis* in their Punta Perro samples, they reported the species from five other localities representing the Navidad (NAV5), Ranquil (FRA, RQK), and Lacui (CHO, CUC) formations. Their identifications of *Globoturborotalia apertura* and *Ng. pachyderma* at another five localities (PTA, MAT, MOS, RQT, MIB, PCB) also indicated a Late Miocene age. The youngest index species they reported were *Globorotalia sphericomiozea* (5.6 FAD in Berggren et al., 1995) at PTA and *Gl. puncticulata* (4.6 Ma FAD in Berggren et al. 1995) at six localities (PPP, PPT, PTA, FRA, RQK, CUC) that were therefore referred to the Early Pliocene. They noted longer concurrent range zones extending upward into the Late Miocene for 12 other planktic assemblages (LPER, NLP, CPUP, LBZ, MOS, PPN, RAP, MS10, FRM, LEB, RAN, CHE). Finger et al. (2007) concluded that faunal similarities among all of these localities suggested similar ages within the Late Miocene to Early Pliocene interval.

Of the 21 planktic foraminifer species with Miocene datums that were recognized in ODP Site 1237, off southern Peru (text-fig. 9), I recognized only *Catapsydrax dissimilis*, *Globigerinoides primordius*, *Gln. trilobus*, *Globoquadrina dehiscens*, and *Globorotalia praemenardii* in the outcrop samples from central Chile. All three species have datums in the Early Miocene.

Gutiérrez et al. (2013) recently challenged the deduction by Finger et al. (2007) that the Navidad Formation was a Late Miocene–Early Pliocene deep-water deposit, by insisting that the unit is an Early to Middle Miocene shallow-water deposit. There are two plausible explanations for the age disagreement: (1) reworking, as proposed by Finger et al. (2007), and (2) misidentification of index species by Finger et al. (2007). Gutiérrez et al. (2012) did not consider the latter possibility, but instead assumed the planktic markers had to have evolved much earlier in the Southeast Pacific than elsewhere. Modern microfossil biostratigraphy, honed by several decades of deep-sea core studies, immediately dismisses that hypothesis because the voluminous amount of global data show that any regional differences in first appearance datums are on a much shorter time scale, and such diachronous events certainly would have been detected by foraminiferal biostratigraphers and paleoceanographers long ago.

It is now apparent to me that the younger age determinations are incorrect, and the result of misidentifications. This can be attributed partly to the preservational state of most specimens and the absence of any extended or continuous stratigraphic sequences that would put their morphologic variability into temporal perspective. The most common planktic species in the Navidad group are *Globigerina venezuelana*, *Globigerinella obesa*, *Globoquadrina dehiscens*, and *Globoturborotalia woodi*, all of which have long ranges in the Miocene. Of these, only *Gq. dehiscens* has a Miocene datum, being its first occurrence just above the base of the Miocene; hence, none of these four species is useful in restricting an assemblage to a single subepoch or age. Although less abundant, the most informative species in the Navidad group are *Catapsydrax dissimilis* (N6 LAD), *Globigerinoides primordius* (N4A–N5 FAD), *Globoquadrina dehiscens* (N4 FAD), transitional forms between *Paragloborotalia nana* (N6 LAD), *Neogloboquadrina continua*, (N6 FAD), *Pg. bella* (N4–N8), and the *Pg. zealandica* group (N5–N7). For the El Peral beds they are *Orbulina universa* (N9 FAD), *Globorotalia miotumida* (N9 FAD), and



*Gl. praemenardii* (N10–N13). *Catapsydrax dissimilis* is present in seven of the Navidad group assemblages, often in association with what were previously thought to be younger taxa, including the orbulines. Whereas *C. dissimilis* is highly resistant to dissolution (Kennett and Srinivasan 1983), reworking seemed a logical explanation for its presence. All of the specimens identified as *Orbulina universa* have since been reexamined, and only those in the two El Peral assemblages tested positive for calcium carbonate, revealing that the other porous, nonspinose spheres (Pl. 16, Fig. 14) were the predominant radiolarians in the washed sample residues representing 11 localities in the Navidad and Ranquil formations.

Finger et al. (2007) erroneously reported five species of planktic foraminifera in the Navidad group that have first appearance datums in the Late Miocene or Early Pliocene. These were *Neoglobobulimina acostaensis* (N16 FAD), *Ng. pachyderma* (N16 FAD), *Globobulimina apertura* (N16 FAD), *Globobulimina sphericomiozea* (N16 LAD), and *Globobulimina puncticulata* (N19 FAD). As previously noted, these were identified on the basis of their illustrations in Kennett and Srinivasan (1983), Bolli and Saunders (1985), and Jenkins (1985). In addition, *Ng. acostaensis* had been reported by Ibaraki (1992a) from Punta Perro and by Osorio and Elgueta (1990) from the ENAP Labranza #1 well drilled west of Temuco, where they also recorded *Gt. apertura* and *Ng. pachyderma*. Marchant and Pineda (1988) and Marchant (1990) also recorded *Ng. pachyderma* in the vicinity of Valdivia. I have carefully reexamined these species in my assemblages, with particular reference to the detailed descriptions, morpho-statistical analyses, and excellent images provided by Scott (1983, 2011), Scott, Bishop and Burt (1990), and Scott et al. (2007). My revisions are as follows: (1) the rare specimens that appear identical to *Gt. apertura* are large-apertured variants within the *Gt. woodi* populations they are associated with; (2) the specimens previously referred to *Ng. acostaensis*, *Ng. continuosa*, and *Ng. pachyderma* are now ascribed to various transitional forms in *Pg. bella*, *Pg. nana*–*Ng. continuosa*, and *Pg. nana*, respectively; (4) the rare specimens identified as *Gl. sphericomiozea* now confer with *Gl. miozea*; (5) what was thought to be *Gl. puncticulata* are now recognized as juvenile *Pg. zealandica*, and (6), as noted above, the specimens in the Navidad group that had been ascribed to *Orbulina universa* are actually radiolarians. The features that distinguish each of these species are discussed in the Systematic Taxonomy section.

Excluding the assemblages devoid (VAL) and nearly devoid (PNH) of planktic foraminifera, and two with only long-ranging species (MPUP, LEB), each of the 21 assemblages from the Navidad group begin or end in the Early Miocene; 19 of those ranges are restricted to that subepoch, whereas two others (FRM, CHE) range into the Middle Miocene (text-fig. 16). I did not find any species with a Late Oligocene LAD. Seventeen of 18 localities had a  $^{87}\text{Sr}/^{86}\text{Sr}$  age coincident with the Early Miocene (text-fig. 16); the exception yielded an isotopic age considerably younger than the biostratigraphic range and was therefore considered unreliable. One isotopic age (RQK) ranges into the Middle Miocene, whereas two (MAT, FRM) cross over the boundary into the latest Oligocene. The Sr age obtained for MAT, however, is 0.5 My older than that indicated by the foraminifera. Two Sr dates were obtained for VAL, one Early Miocene and the other latest Oligocene. The only other Sr age restricted to the latest Oligocene was from LEB, which, as noted above, did not yield any planktic foraminifera useful in constraining the biostratigraphic age within the latest Oligocene–Miocene interval. In summary, 16 localities yielded Sr-isotope ages that at least partly overlap the concurrent range

indicated by planktic foraminifera. Overall, the analytical data place nearly all of the material collected from the Navidad group within the Burdigalian stage of the late Early Miocene.

### Depositional paleoenvironment

Previously, Finger et al. (2007) attempted to end the disagreement among regional workers about the depositional depth of the units by determining which taxa are regionally restricted to deep water according to the depths reported in Ingle, Keller and Kolpack (1980) and van Morkhoven, Berggren and Edwards (1986), and then identifying the deepest minimal depth zone indicated within each assemblage. The findings led to two conclusions that are repeated here. First, all samples yielded mixed-depth assemblages of benthic foraminifera, indicating the prevalence of downslope transport and contributing to the faunal heterogeneity between sample sites. Ingle, Keller and Kolpack (1980) previously documented this phenomenon in their study of transects taken off Valparaíso (33°S), Cabo Carranza (36°S), and Valdivia (39°S), as did Resig (1990) in her foraminiferal study of 21 drill sites along the Peru margin (DSDP Legs 18 and 112, respectively). Such downslope displacement of sediments is a common phenomenon on tectonically active margins (e.g., Shipp, Weimer and Posamentier 2011; Slatt and Zavala 2012). The second conclusion was that all of the sampled units were deposited at deep bathyal depths.

If a fossil assemblage has undergone significant bathymetric mixing, it may yield anomalously high values of species richness and diversity that reflect the conglomeration of taxa from different depth-related biofacies. Most of the benthic foraminiferal assemblages in this study yielded numbers that are unusually high for a modern *in situ* temperate assemblage, despite any taphonomic loss that may have occurred. From another perspective, the depths interpreted for the fossil assemblages have a narrower range than those from which the modern fauna was sampled, yet the total number of species in the fossil fauna is not much less than that of the modern provincial fauna. This similarity in species richness could be explained by the paleobathymetric mixing that is evident in the fossil assemblages.

Reworking is most readily recognized by the presence of significantly older fossils that show a poorer state of preservation, but the only reliable evidence of this phenomenon is a single Cretaceous globotruncanid test recovered from the FRA locality and the association of *Praeorbulina* with slightly younger species in LPER. Each assemblage appears more likely to be the product of mixing unconsolidated sediments that had accumulated along a depth transect of downslope displacement.

The paleobathymetric study has been expanded to incorporate data on the modern fauna reported in South American journals. Of those, Figueroa et al. (2005, 2006) provide the most bathymetric data for the provincial fauna, including many neritic occurrences shallower than those reported by Ingle, Keller and Kolpack (1980). Combined, these three reports total 108 genera and 374 species (table 7).

On the generic level, the Chilean fauna is similar to those from other Neogene locations in temperate and subtropical zones, particularly the diverse and well-studied units of the Caribbean and New Zealand, but many of the benthic species are recorded only from one of these three regions. Regardless of unrealized synonymies, this clearly indicates that many species did not have wide geographic or temporal ranges.

Typical modern outer neritic and deeper benthic foraminiferal assemblages have 30 to 60 species per thousand specimens (Murray 1973). The 27 Chilean assemblages have species:specimen ratios that equate to 44 to 223 species per thousand specimens, with an average of 122. Accordingly, species diversity indices range well above the normal, as previously mentioned. These disparities are also evident in the wide variation of species that dominate each assemblage (table 6). Despite the mixing, the premise that the Navidad, Ranquil, Santo Domingo, and Lacui formations have similar faunas that may have been contemporaneous is borne out by the multivariate statistical analyses (text-figs. 11–15), which do not clearly distinguish them from each other.

Text-figure 17 shows the modern provincial and global UDLs of 76 common genera, all of which are represented in the Chilean Miocene. It suggests that most, if not all, of these genera have been recorded from neritic depths; in the south-central Chilean province, however, 14 of the genera are represented by species found only at bathyal depths: *Ammobaculites*, *Anomalinoidea*, *Bathysiphon*, *Chilostomella*, *Gaudryina*, *Globocassidulina*, *Laticarinina*, *Osangularia*, *Pleurostomella*, *Quadriformina*, *Rhabdammina*, *Robertina*, *Tritaxis*, and *Virgulinella*. One or more of these are represented in 23 of the 27 assemblages (the exceptions are PPN, LBZ, MAT, and CHO); thus, despite any inconsistency in species identifications between different workers, and some seemingly anomalous UDLs, the evidence strongly favors deposition at bathyal depths.

Modern benthic foraminifera off central and northern Chile were first reported in geographically broader works by d'Orbigny (1839c), Gay (1854), and Brady (1884). The Southeast Pacific margin was first isolated for study by Bandy and Rodolfo (1964), who examined foraminifera in 32 trawl and core samples taken from depths of 179–6250m off Peru and Chile, but only as far south as Valparaiso (32.3°S). Ingle, Keller and Kolpack (1980) analyzed the fauna in bottom samples collected from depths of 135–4500m along three transects off central Chile (31.5–39.2°S). Resig (1981) analyzed 121 core-top samples taken from depths of 82–2286m on the northern part of the Nazca plate (0–27°S) and on the continental margin off Guayaquil, Ecuador (2°S) to Iquique (20°S), Chile. Recently, several marine biologists have focused on the modern foraminiferal fauna off Chile (e.g., Zapata and Cear 2004; Zapata and Moyano 1997; Figueroa et al. 2005, 2006; Marchant, Zapata and Hromic 2007). A study by Zapata (1999) of the benthic foraminifera down to 20m depth in Cumberland Bay (33°41'S, 78°50'W), Robinson Crusoe Island, Juan Fernandez Archipelago (~670m west of the mainland at San Antonio), yielded 85 species but he noted the degree of affinity with the Chilean province was only 35% and suggested that they were different subprovinces. Zapata and Cear (2004) provided the most thorough report on littoral foraminifera off the coast of northern Chile (18°28'–31°56'S). They documented 151 species from depths of 1–170m, but only 20 of those species are recognized in the Miocene fauna, and about half appear to be different species. From the south-central Chilean province extending from Valparaiso to Chiloé, Figueroa et al. (2005, 2006) recorded 117 species of calcareous benthic foraminifera from multicores taken at depths of 125–3485m. Hence, Ingle, Keller and Kolpack (1980) and Figueroa et al. (2005, 2006) are the source of the 374 provincial upper-depth limits (UDLs) listed in table 7, which serves as the foundation for extrapolating provincial modern bathyal UDLs into the regional fossil record (table 8).

Considering that the average time range of a Cenozoic benthic foraminiferal species is estimated to be 15–25 million years

(Buzas and Culver 1984), it is not surprising that 63 (22%) of the Chilean Miocene benthic species are provincially extant, nor that about half of those have been provincially recovered only from bathyal depths. Deep-water deposition is further supported by 21 genera represented in the Chilean Miocene that have been recorded only at bathyal depths off south-central Chile (text-fig. 17). Other species UDLs noted in the systematics section are extrapolated from the modern cosmopolitan deep-water fauna documented by van Morkhoven, Berggren and Edwards (1986), Hayward et al. (2012), and Holbourn, Henderson and MacLeod (2013).

Table 8 shows the distribution of 63 species assigned bathyal UDLs in this study. The 27 assemblages range 4–33 bathyal species with an average of 16; the numbers of middle or lower bathyal indicators per assemblage range 1–21 and average 9. Among these are the seemingly anomalous inner shelf records of *Cyclammina cancellata*, *Fissurina* sp., *Favulina hexagona*, *Fontbotia wuellerstorfi*, *Laticarinina pauperata*, *Martinottiella communis*, *Melonis pompilioides* (f. *spheroides*), *M. barleeanus*, *Oridorsalis umbonatus*, *Pullenia bulloides*, *Pyrgo murrhina*, and *Triloculina trigona*. These 12 taxa are included in table 8 in their otherwise bathyal depth zones, deepening the paleobathymetric interpretations for three localities (MOS, RQK, CHE), from lower middle bathyal to lower bathyal. Excluding those 12 species from the set of 63 bathyal depth indicators would result in 4 upper middle bathyal, 5 lower middle bathyal, and 18 lower bathyal paleodepth zone interpretations. The 559 bathyal indications (332 being middle and lower bathyal) in table 8 should erase any lingering doubts about the deep-water interpretation for the units, as it is unlikely that any significant number of the 63 species consistently had anomalously shallow occurrences. Their association with neritic species is considered here to be evidence of downslope displacement and bathymetric mixing with final deposition on the continental slope, most likely at middle to lower bathyal depths.

The paleobathymetric interpretation of the foraminifera fits the modern depositional scenario off south-central Chile, where earthquakes trigger slumps and debris flows that evolve into turbidity currents and mudflows that rework and funnel slope sediments through deep submarine canyons (Raitzsch, Volker and Huebeck 2007). Displaced sediments accumulate in topographic depressions and where the seafloor levels out; in the latter case off south-central Chile, these depocenters are at depths between 1900–2200m for normal slopes and between 2800–3600m for slope embayments (text-figure 18).

An argument can be made about the accuracy of the temporal consistency of depth zones assigned to the Chilean assemblages, as the UDLs are based on extrapolation from the Holocene to the Early Miocene, a span of more than 16 Myr that includes the late Middle Miocene global cooling event, and it often assumes that similar congeneric morphotypes lived at similar depths. In addition, UDLs vary geographically — there are no isobathyal species. With the exception of polar emergence, those geographic differences should rarely exceed a few hundred meters or one bathymetric zone. All of the assemblages, except LBZ, are interpreted to have been deposited in the lower middle bathyal (1500–2000m) or lower bathyal (2000–4000m) zone, but the margin of error is unknown. All of the Chilean assemblages have indications of deep-water deposition, well below 500m. It is noteworthy that ODP Site 1237, drilled at a water depth of 3212m, yielded a Neogene fauna characterized by *Chrysalogonium* spp., *Cibicoides mundulus*, *Globocassidulina subglobosa*, *Gyroidinoides soldanii*, *G. orbicularis*, *Laticarinina pauperata*,

*Melonis affinis*, *Oridorsalis umbonatus*, *Planulina wuellerstorfi*, *Pullenia bulloides*, *Pyrgo murrhina*, *Rectuvigerina striata*, *Siphonina tenuicarinata*, *Stilostomella abyssorum*, *Stilostomella subspinoso*, and *Vulvulina spinosa* (Shipboard Scientific Party 2003). Most of those species, as well as very similar taxa and possible synonyms, are identified in the present study. Regardless of purported or verified shallow-water occurrences, these species and many of those identified in the present study are typically found at bathyal depths.

#### Comparison with other American Cenozoic faunas

There are numerous well-documented Oligocene, Miocene, and Pliocene benthic foraminiferal faunas in the lower-latitude Americas. They have many genera, but comparatively fewer species (including likely synonyms), in common with the Chilean Early Miocene. These studies include the faunas of six formations spanning the Middle Oligocene to Lower Miocene of Puerto Rico (Galloway and Heminway 1941), the Oligocene Ciperó Marl in Trinidad and Tobago (Cushman and Stainforth 1945), the Early Miocene La Boca Formation of Panama (Blacut and Kleinpell 1969), the lower Pliocene of southeastern Mexico (Kohl 1985), the middle to Late Miocene Buff Bay Formation of Jamaica (Robertson 1998), and the late middle to Late Miocene Gatun Formation of Panama (Collins et al. 1996, Coates et al. 2009). Of additional utility in comparing with the Caribbean taxa is the compendium by Bolli, Beckmann and Saunders (1994) on the Cretaceous to Miocene foraminiferal biostratigraphy of Trinidad, Venezuela, and Barbados. The most thorough study on a contemporaneous fauna from the Pacific side of South America is Whittaker's (1988) work on benthic foraminifera from the Late Oligocene to Pliocene sequences in Ecuador, which provides taxonomic and distributional data for 130 species. Many of the Ecuadorian Miocene taxa, particularly the deep-water species, occur in the Chilean Neogene. Although Natland et al. (1974) recognized 200 species of foraminifera from Tertiary sequences in the Magallanes Basin in southern Patagonia, they only provided information on those 25 species determined to be of biostratigraphic utility in their study, and none of them is recognized in the present study.

#### Biogeography

Biogeographic inferences are difficult to make for benthic foraminifera because species identifications in the literature reflect worker subjectivity on intraspecific variation and provincial vs. cosmopolitan distributions, as well as their experience and taxonomic skills, available resources (i.e., imaging, literature, collections, colleagues, time), and the amount of time and effort devoted to identifying specimens. Some relevant comments are included in the beginning of the Systematics section of this report. Considering that ocean currents and other vectors effectively transport tests and propagules, I find it difficult to conceive any bona fide marine microfossil species can be restricted to its type locality and horizon, although it might appear that many are, especially if they lack adequate type-figures and subsequent workers apply other names without recognizing their synonymies, or if similar coeval facies had not been studied elsewhere. Many workers have been misled by Cushman's profuse contributions in which he had a propensity to designate a new species if it was found in a different region or epoch than a very similar or identical morphotype already described. As expected, the vast majority of species in the Chilean Miocene fauna were originally described from the Oligocene–Holocene, and their regional distributions are widely scattered across the globe. Although many of the modern offshore Chilean species or their homeomorphs are

recognized in the Chilean Neogene, the provincial foraminiferal fauna was unknown until the second half of the 20<sup>th</sup> Century, well after the vast majority of common Neogene species had already been described elsewhere.

Many of the Neogene benthic foraminiferal species in Chile appear to have wide geographic ranges, which suggests that oceanic pathways connected these disparate regions. The Mediterranean basin was not silled off from the North Atlantic in the Early Neogene, and transoceanic migration, particularly via the deep water masses, could have distributed benthic species. This might explain why many of the same species are recognized in both the Mediterranean and Caribbean regions. Deep-water straits across Central America would have enabled the Caribbean foraminifera to migrate to and from the subtropical Northeast Pacific. Coates et al. (2009) reported that benthic foraminifera indicate that the deepest parts of the Chucunaque-Tuira and Sambu basins in the Darien province of Panama were at lower-bathyal depths during the Middle Miocene, but the basins shallowed as the Panama arc began colliding with South America, rising to neritic depths in the Early Pliocene and emerging at 4.8 Ma. Similarities between the Miocene foraminifera of Car Nicobar and Chile, on the other hand, could be due to oceanic pathways of cold, deep water masses emanating from the Southern Ocean.

Modern water masses of the Southeast Pacific are described by Strub et al. (1998). Off central Chile today, cold, nutrient-enriched subpolar water is transported northward by the Peru-Chile Current (PCC). The Coastal Current (CC) also flows northward but is significantly affected by an admixture of low-salinity waters from the Chile fjord region. In between them, 100–300km offshore, the Peru-Chile Counter Current (PCCC) transports subtropical surface water to the south. The poleward-flowing Gunther Undercurrent underlies these surface-water masses at depths of 100–400m and transports relatively low-oxygen and high-salinity water masses southward along the shelf edge. At depths of 400–1000m is the northward-flowing Antarctic Intermediate Water (AAIW), which is relatively high in oxygen and low in salinity. It overlies the southward-flowing, nutrient-rich Pacific Central Water (PCW). If a similar pattern of stratification and circulation existed in the Oligo-Miocene, it could have provided both northerly and southerly pathways for potential foraminiferal migration.

The Chilean Neogene benthic foraminiferal fauna has relatively few species in common with the well-documented Neogene deep-water basins of Japan and California. This suggests that Oligocene and Early Miocene, foraminiferal migration across the Equator may have been more difficult in the Pacific than in the Atlantic. Although van Morkhoven, Berggren and Edwards (1986) designated a select number of deep-water Neogene foraminifera as cosmopolitan, they presented relatively few data from the Southeast Pacific in their study. The present study indicates that many other species may belong to the cosmopolitan deep-water fauna.

#### CONCLUSIONS

The benthic foraminiferal faunas of the Navidad, Ranquil, Santo Domingo, and Lacui formations (the Navidad group) cannot readily be distinguished from each other due to similarities in geologic age, depositional history, and species composition. Most of the species (excluding very rare ones) occur in two or more of these units. Only the northernmost strata in this study, the El Peral beds, yielded assemblages that do not correlate with the Navidad group, but instead may belong to the nearby Lo Abarca Formation. I conclude that all of the Navidad group localities are

Early Miocene, based primarily on the presence of the planktic species *Catapsydrax dissimilis*, *Globigerinoides primordius*, *Paragloborotalia bella*, and *Paragloborotalia zealandica* s.l., as well as strontium-isotope chronostratigraphy and molluscan biostratigraphy. The results of statistical analyses of the benthic foraminiferal data weakly correlate with geography and geology of the areas studied due to their faunal similarities. Foraminiferal assemblages from the El Peral beds differ from the those of the Navidad group by the dominance of benthic species not found in the other units and by the presence of orbulines, *Globorotalia miotumida*, and *Gl. praemenardii*, which indicate Middle and Late Miocene ages.

Benthic foraminifera indicate that all of the samples were deposited on the lower “half” of the continental slope between 1000 and 2500m. Downslope displacement and deep-water deposition on the forearc of the Peru-Chile trench is supported not just by the tectonic setting, but also by the recognition of deep-dwelling (psychrospheric) ostracodes, partial Bouma sequences, and the *Zoophycos* ichnofacies. All of these findings imply that the well-studied gastropods of the Navidad group are not *in situ*.

This report fulfills the need for a guide to the Neogene foraminifera of south-central coastal Chile, and it is anticipated that it will impact future studies on the stratigraphy, sedimentology, and paleontology of the region. In addition, the abundance of cosmopolitan deep-water species in this fauna extends its utility of this publication to Neogene foraminiferal studies elsewhere in the mid-latitudes.

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#### SYSTEMATIC TAXONOMY

The 27 Chilean Neogene localities yielded a foraminiferal fauna consisting of 336 benthic and 22 planktic species. All assemblage and type specimen slides have been deposited in the microfossil collections at the UCMP (University of California Museum of Paleontology). The taxa identified in this study represent 162 genera, and are systematically arranged according to the supraspecific framework provided by Loeblich and

Tappan (1987) and subsequent revisions above the rank of family (Lee 1990, 2000; Loeblich and Tappan 1992, 1993; Sen Gupta 1999; Cavalier-Smith 2002), including that for the suffix of superfamilies (ICZN 4<sup>th</sup> Ed. 1999, Art. 29.2). The subdivisions of the Foraminifera should be recognized as uncertain because they are not fully consistent with molecular phylogenetic data (Adl et al. 2005). Ten new species described are *Karrieriella biglobata*, *Cornuspira libella*, *Pseudolingulina nielseni*, *Cristellariopsis petersonae*, *Percultazonaria encinasi*, *Percultazonaria obliquispina*, *Astacolus novambiguus*, *Fissurina ambicarinata*, *Globocassidulina chileensis*, and *Pseudononion ranquilensis*. One new (substitute) name, *Lenticulina neopolita*, is proposed for an objective junior synonym. Among the benthic fauna are 19 species conferred (cf.) to another species, and an additional 46 left in open nomenclature because they are not represented by any specimens that are distinct and well preserved enough to warrant their establishment as new species.

#### Format of this section

For each species, reference to its original designation and description is included. Many include a synonymy based on comparison with published images.

*Distinguishing features:* Primary characteristics used to distinguish (1) relatively new (post-Loeblich and Tappan 1987) genera from similar genera represented in this study, and (2) selected species that may not be readily distinguished from others identified in this study.

*Type age and locality:* The general age and locality designated for the holotype. If a type locality was not indicated, the first reported localities are noted.

*Stratigraphic range:* For benthic species, this is a minimum range based only on the type level, the present study, and ages indicated in the global studies by van Morkhoven, Berggren and Edwards (1986), Jones (1994), and Hayward et al. (2012). For planktic species, the stratigraphic range is indicated by the age range corresponding to the Paleogene (P) and Neogene (N) zones of Blow (1969, 1979) that define the first and last appearances of the species. Ranges of planktic species are derived from Kennett and Srinivasan (1983) and Bolli and Saunders (1985), which vary slightly from each other. Revised datums presented by Berggren et al. (1995) are incorporated, especially if they specified their relevance to the temperate zone. Age ranges of deep-dwelling benthic species are based on van Morkhoven, Berggren and Edwards (1986), Jones (1994), and Hayward et al. (2012). For any other benthic taxon, the known age indicated is that between its type age and its occurrence in the Chilean Miocene.

*Upper depth limit:* The shallowest depth zone in which the species has been recorded. Derived primarily from bathymetric ranges presented in Bandy and Rodolfo (1964), Hayward et al. (2012), Ingle, Keller and Kolpack (1980), van Morkhoven, Berggren and Edwards (1986), Figueroa et al. (2005, 2006), Hayward et al. (2012), and Holbourn, Henderson and MacLeod (2013). In a few cases, California UDLs recorded by Ingle (1980) are incorporated, but only if shallower than the other determinations, since they tend to be deeper in California than in most other regions, or if data for a particular species was not presented in any of the three primary references. If the UDL is based on another species, that probable synonym, isomorph, or comparable morphospecies is indicated. Numerical depths are assigned to depth zones according to the Southeast Pacific scheme of Ingle, Keller and Kolpack (1980).