Paleoceanographic evolution of backwater in the Nazca region, southeastern Pacific, during late Pleistocene

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ABSTRACT

The distribution of radiolarian assemblages in the surface sediments of the southeastern Pacific reflects the westward advection of the Chile Current away from the coast and its mixing with Subtropical Water. This oceanic process, occurring along the eastern section of the Nazca Ridge (~ 20° S), is influence by the trade wind field, disrupts the Subtropical Convergence and leaves backwater near the coast. Late Pleistocene glacial-interglacial fluctuations of this ocean circulation are reconstructed using radiolarian assemblages in core H96-Tg7 (17°14.04'S, 78°06.16'W). Glacial episodes exhibit more intense ocean circulation than interglacial episodes. Extreme southern incursions of Subtropical Water occurred during Marine Isotope Stages 11, 5 and 1, suggesting that extremely warm climate conditions occurred episodically.

Keywords: Chile Current, southeastern Pacific, trade wind field, radiolaria, glacial-interglacial episodes

RESUMEN

La distribución de conjuntos de radiolarios en los sedimentos superficiales del Pacífico suroriental refleja la advección que la Corriente de Chile efectúa occidentalmente hacia fuera de la costa, así como su mezcla con el Agua Subtropical. Este proceso, ocurre a lo largo de la porción oriental de la Cordillera Nazca (~ 20° S), y es influido por los vientos alisios, rompe la Convergencia Subtropical y deja agua reculada cerca de la costa. Fluctuaciones glacio-interglaciares de esta circulación oceánica, ocurridas durante el Pleistoceno tardío, son reconstruidas mediante conjuntos de radiolarios presentes en el núcleo H96-Tg7. (17°14.04'S, 78°06.16' W). Los episodios glaciares exhiben una circulación oceánica más intensa que los estadios interglaciares. Incursiones extremas del Agua Subtropical hacia el sur ocurrieron durante los Estadios Isotópicos Marinos 11, 5 y 1, sugiriendo que condiciones climáticas extremadamente calientes ocurren episódicamente.

Palabras clave: Corriente de Chile, Pacífico suroriental, radiolaria, vientos alisios, episodios glacio-interglaciares.

INTRODUCTION

At the southeastern extreme of the Subtropical Pacific (20° S and 78° W), the Chile Current, influenced by the southeast trade winds and coastal configuration, turns westward, away from the coast disrupting the Subtropical Convergence and leaving backwater near the coast (Figure 1). Within this region, near Nazca Ridge, the Chile Current meets the Peru Countercurrent mixing Subantarctic Water with Subtropical Water. This process develops an oceanic front, evidenced by temperature and salinity gradients, and determines the physical-chemical properties of the backwater. Thus, the oceanographic evolution of the backwater can be used to reconstruct the relative intensities of the Chile Current and the Peru Countercurrent.

The R/V “Hesperides” of the Spanish Navy collected the sediment core H96-Tg7 within the backwater region in 1996. Based on oxygen isotope stratigraphy the 398 cm long core spans the last ~ 430,000 yrs. including the very end of Marine Oxygen Isotope 11.

The oxygen isotope and radiolarian assemblage records allow us to infer over a longer period than previous studies (Molina-Cruz, 1984; 1991; and references therein), the oceanographic evolution of the backwater and the Chile Current and Peru Countercurrent system. The discussion of it and consequently the paleoceanography of the Nazca region, during the last ~ 400,000 yrs., is the focus of the present study.

OCEANOGRAPHIC SETTING

The eastern boundary currents of the South Pacific anticyclonic gyre directly influence the area of study (Figure 1). Therefore, it is worthwhile to differentiate the Chile Current from the Peru Current, because previously, these two currents were described together as the Humboldt Current (Gunter, 1936; White, 1969). The Chile Current arises in the Subantarctic region. Thus, it carries “equatorward”, along the coast of Chile, Subantarctic Water. When it reaches approximately 20° S, influenced by the southeast trade winds and coastal configuration, turns westward, away from the coast disrupting the definition of the Subtropical Convergence (S.C.) near the coast (Figure 1). As a consequence, these

Figure 1. Generalized circulation in the southeaster Pacific: continuous line arrows represent surface currents, broken line arrows represent subsurface currents. 1: Equatorial Undercurrent; 2: Peru Countercurrent; 3: North Equatorial Countercurrent; 4: South Equatorial Current; 5: Coastal Peru Current; 6; Oceanic Peru Current; 7: Chile Current; 8: Cabo de Hornos Current; 9: Circumpolar Current; 10: Falkland Current. E.F: Equatorial front; S.C.: Subtropical Convergence; P.F.: Polar front. The big dot off Peru shows the location of core H96-Tg7.

oceanographic dynamics leave backwater near the coast, over the Nazca Ridge.

Northwest of the backwater, along the Peruvian coast, equatorward flow also occurs. However, it is split into two branches: one coastal and one oceanic (Figure 1). These two branches constitute the Peru Current and are fed principally by upwelled water (Gunter, 1936; Smith, 1968). Between these two branches, the Peru Countercurrent flows poleward, carrying Subtropical-Tropical Water. However, sometimes the Peru Countercurrent forms an undercurrent and the two Peru currents merge to form a wider flow.

Pacific equatorial currents are largely dependent on the location of the trade wind system rather than the strength of its winds (Wyrtki, 1974). Thus, it is assumed that the evolution of the Peru Current and the Chile Current are most likely also dependent on the position of the trade wind system. In the Subtropical Southeastern Pacific, the southeast trade wind field is defined commonly between the equator and 20° S (Wyrtki and Meyers, 1975). However, annually, this wind-belt shifts approximately 6° of latitude. During the austral winter, the southeast trade wind field is in its northern position (inclusively crossing the equator), is more intense, and shows a well-defined SE direction. During this season, coastal upwelling along Peru and the development of the Peru Current are promoted, but the westward advection of the Chile Current is not well developed. On the contrary, during the austral summer, when the southeast trade wind field is in its southern position, is less intense, and shows an ESE direction, the Chile Current is advected more to the west, away from the coast (Bjerkness, 1966; Wyrtki, 1974). Thus, a backwater volume is increasing near the coast.

MATERIALS AND METHODS

Core H96-Tg7 was collected at 17°14.04'S, 78° 06.16' W and 3,120 m depth. Samples were taken, every 5 cm for oxygen isotope analysis and every 10 cm for radiolarian census counts.

Radiolarian assemblage analysis

Sediment samples for radiolarian assemblage counts were treated first with dilute HCl and then with H_2O_2, in order to eliminate $CaCO_3$ and organic matter. The remaining residue was washed on a 40-µm-sieve screen, and the coarse fraction mounted with Canada balsam on glass slides, following standard techniques (Moore, 1973, Molina-Cruz, 1978; Roelofs and Pisias, 1986). Approximately 400 specimens were identified to species level on each slide. Thirty-six species were identified within the core (Table 1).

Definition of radiolarian assemblages (Factors) was carried out by means of a Q-mode Factor Analysis (Klovan and Imbrie, 1971), including SE Pacific core top data set and down-core (H96-Tg7) samples. The core top data set is from Molina-Cruz, Ph.D. thesis (1978). Factor Analysis results of the top samples, define modern radiolarian assemblage distribution in relation to the major oceanic currents and their associated water masses (Figure 2). The species composition of each Factor is mathematically explained through the "Factor Scores" (Figure 3; Klovan and Imbrie, 1971). Factor Analysis down-core results are shown in Figure 4.

Oxygen isotope stratigraphy and age model

Isotope analysis were carried out at "Centro de Investigación Científica y Educación Superior de Ensenada" (CICESE) and Scripps Institution of Oceanography (SIO) with a VG Micromass 602 spectrometer. Test of planktonic foraminifera (*Globigerina bulloides*) were taken in the >250 µm size fraction. The analytical precision of laboratory standards was 0.12% for $\delta^{18}O$ calibration to PDB via the NBS-20 standard. The oxygen isotope record (Figure 4a) was correlated with the normalized SPECMAP standard profile through the CALIB 4.1 program (Stuvier and Reimer, 1993). Ages were derived from linear interpolation between isotopic events, assuming a constant accumulation rate (Calvo *et al.*, 2001).

RESULTS AND DISCUSSION

Radiolarian surface sediment distribution

The Q-mode Factor Analysis calculated 5 Factors (= radiolarian assemblages), accounting for 84% of the variance in the data set. Factor loadings of the core top assemblages define 5 independent geographic regions (Figure 2). Thus, it is possible to infer the oceanographic features which influence their distribution. Factor 3 shows the southern distribution. Because this is present in the Subantarctic region, it is called Subantarctic Factor (Assemblage). It accounts for 13% of the data variance. According to the Factor Scores (Figure 3), its predominant species are *P. pylonioum* (S21), *S. validispina* (S30), *E. delicatum* (S9) and *L. minor* (S20). All of these inhabit relatively cold waters (Molina-Cruz, 1977; 1978). The Subantarctic Factor is dominant only in the southern part of the Chile Current, south of 30° S. Thus, it does not cross the Subtropical Convergence (SC) and is not important in the Backwater region where core H96-Tg7 was collected.

Factor 4 is termed Chile Current Factor. It accounts for 10% of the variability and defines the westward advection of the Chile Current (Figures 1 and 2). Its predominant species are *Cenosphaera* sp (S3), *Stylatractus* spp (S29) and partially *E. delicatum* (S9) (it predominates more in the Subantarctic Factor). *Cenosphaera* sp. is a radiolarian species little discussed

Table 1. Taxonomic framework.

Code	***Species***	**Reference**	**Plate**	**Figures**
S1	*Amphirhopalum ypsilon*	Molina-Cruz, 1977	1	6
S3	*Cenosphaera (?)* sp	Molina-Cruz, 1977	5	12, 13
S8	*Dydymocirtis tetrathalamus*	Molina-Cruz, 1977	3	1, 2
S9	*Echinomma delicata*	Molina-Cruz, 1977	1	5
S10	*Euchitonia furcata*	Molina-Cruz, 1977	2	2
S13	*Hexacontium encanthum*	Molina-Cruz, 1977	2	3
S15	*Hymeniastrum euclidis*	Molina-Cruz, 1977	3	12
S16	*Larcopyle butschlii*	Molina-Cruz, 1977	3	10, 11
S18	*Larcospira quadrangula*	Molina-Cruz, 1977	3	3
S20	*Lithelius minor*	Molina-Cruz, 1977	3	13, 14
S21	*Phorticium clevei*	Molina-Cruz, 1978	9	1, 2, 3, 4
S22	*Porodiscus* sp A	Nigrini and Moore, 1978	14	1, 2a-b
S24	*Spongocore puella*	Molina-Cruz, 1977	5	4
S28	*Spongurus* spp	Molina-Cruz, 1977	1	2
S29	*Stylatractus* spp	Molina-Cruz, 1977	3	4,7
S30	*Stylodictya validispina*	Molina-Cruz, 1977	4	7
S33	*Tetrapyle octacantha*	Molina-Cruz, 1977	5	5, 6, 7
S35	*Acrosphaera murrayana*	Molina-Cruz, 1977	3	5, 6
S36	*Collosphaeridae*	Molina-Cruz, 1977	5	8-11, 14,15
N1	*Anthocyrtidium* spp	Molina-Cruz, 1977	6	8, 10
N4	*Botryostrobus aquilonaris*	Molina-Cruz, 1977	8	10, 11
N5	*Botryostrobus auritus-australis*	Molina-Cruz, 1977	7	15, 16, 17
N7	*Carpocanistrum papillosus*	Molina-Cruz, 1977	7	13
N8	*Carpocanistrum* spp	Molina-Cruz, 1977	6	12, 13
N10	*Cycladophora davisiana*	Molina-Cruz, 1977	7	19
N11	*Eucyrtidium acuminatum*	Molina-Cruz, 1977	7	3
N12	*Eucyrtidium hehagonatum*	Molina-Cruz, 1977	7	4, 5
N13	*Lamprocyclas maritalis*	Molina-Cruz, 1977	7	6, 7, 8, 9
N14	*Lamprocyclas junonis*	Molina-Cruz, 1977	7	2
N15	*Lamprocyrtis nigrinae*	Nigrini and Moore, 1978	25	7
N16	*Liriospyris reticulata*	Molina-Cruz, 1977	6	6
N17	*Liriospyris* sp	Molina-Cruz, 1977	6	1, 2, 3, 4
N21	*Peripiramides* spp	Nigrini and Moore, 1978	21	4a, b
N22	*Phormosphyris stabilis scaphipes*	Molina-Cruz, 1977	7	11, 12
N23	*Pterocorys zancleous*	Nigrini and Moore, 1978	25	11a, b
N26	*Theocalyptra bicornis*	Nigrini and Moore, 1978	24	1

Note: S codes= Spumellaria; N codes= Nassellaria

in the micropaleontological literature. Apparently, it is native of the Nazca region (Molina-Cruz, 1984). *Stylatractus* is a robust genus, which resists dissolution processes better than other genus. Thus enhancing its presence. Under the Chile Current, radiolarian remains are scarce and less well preserved than in other environments of the Southeast Pacific.

Factor 1 defines the Backwater region (Figure 2). Thus, it is termed the Backwater Factor. It accounts for the majority of the data variance (40%), as a result of "biased" data in the Factor Analysis. About 40% of the data employed in this analysis belong to core H96-Tg7 samples. The predominant species in the Backwater Factor (Figure 3) are *C. davisiana* (N10), *Spongurus* spp. (S28), *B. auritus-australis* group (N5) and partially *Cenosphaera* sp (S3) (although more predominant in the Chile Current Factor). *C. davisiana* is a subsurface water species, which increases its abundances at oceanic fronts and regions of strong water mixing (Molina-Cruz, 1984; Molina-Cruz and Martínez-Lopez, 1994). Thus, its presence in the Backwater region is coherent with the fact that Subantarctic Water (carried by the Chile Current)

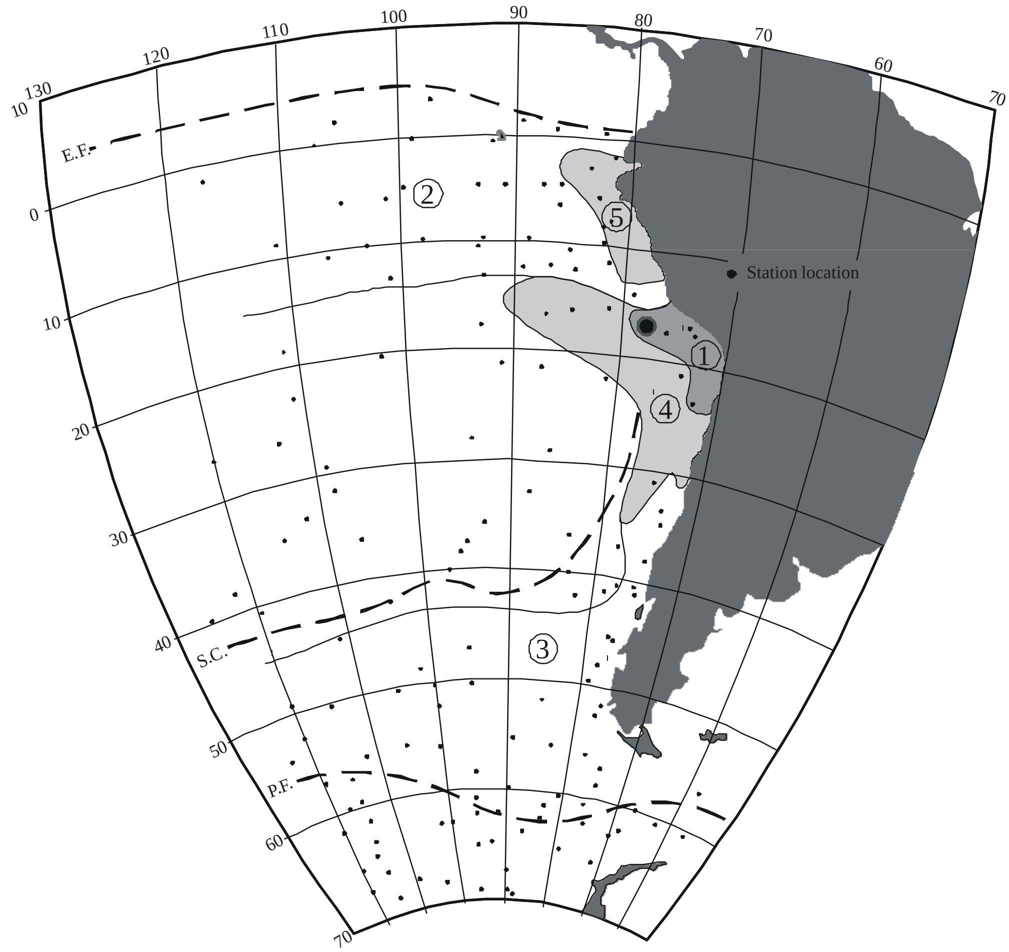

Figure 2. Regions in which each radiolarian factor (assemblage) has loading greater than or equal to 0.5. 1: Backwater Factor; 2: Subtropical Factor; 3: Subantarctic Factor; 4: Chile Current Factor; 5: Coastal upwelling Factor. The big dot off Peru shows the location of core H96-Tg7.

and Subtropical Water (carried by the Peru Countercurrent) meet at this region. *A. murrayana* (S35), the abundant radiolarian species in the coastal upwelling area off Peru (Molina-Cruz, 1977; 1984), is not predominant in the Backwater region.

Factor 2, termed the Subtropical Factor, accounts for 17% of the variance and dominates the subtropical Pacific, particularly the South Equatorial Current. Its distribution is disrupted along the coast of Peru, where an intense upwelling process occurs, i.e., where Factor 5 dominates (Figure 2). In spite of it, the distribution implies that Subtropical Water extends near the coast at about 14° S, probably carried by the Peru Countercurrent (Figsures 1 and 2). Consequently, it mixes with the Chile Current and the Backwater region. The predominant species in the Subtropical Factor (Figure 3) are *T. octhacantha* (S33), *Liriospyris* spp (N17) and *A. murrayana* (S35). The first 2 species have been before reported as subtropical species, while the last one is more associated with Factor 5, which distributes in coastal upwelling areas along Peru (Figure 2).

Stratigraphic results

Core H96-Tg7 (398 cm) spans the last ~400,000 years. All the Marine Isotope Stages (MIS) and most of the substages, back to the base of MIS 11, can be identified in the record (Figure 4). The average sedimentation rate is 1.06 cm/kyr for the whole core, but, in general, it is higher during glacial episodes (1.16 cm/kyr).

Down-core Factor loadings show glacial-interglacial fluctuations (Figure 4). Particularly, the Backwater Factor and the Chile Current Factor which trend in opposite direction. The Backwater Factor is generally larger during glacial episodes while the Chile Current Factor dominates interglacial episodes. Therefore, during glacial episodes, increased westward advection of the Chile Current occurred, increasing the production of backwater. These oceanographic dynamics probably occurred under a direct influence of the southeast trade winds, as occurs at present during the austral summer (boreal winter). During glacial episodes, the polar ice sheets became broader and the tropical-subtropical cli-

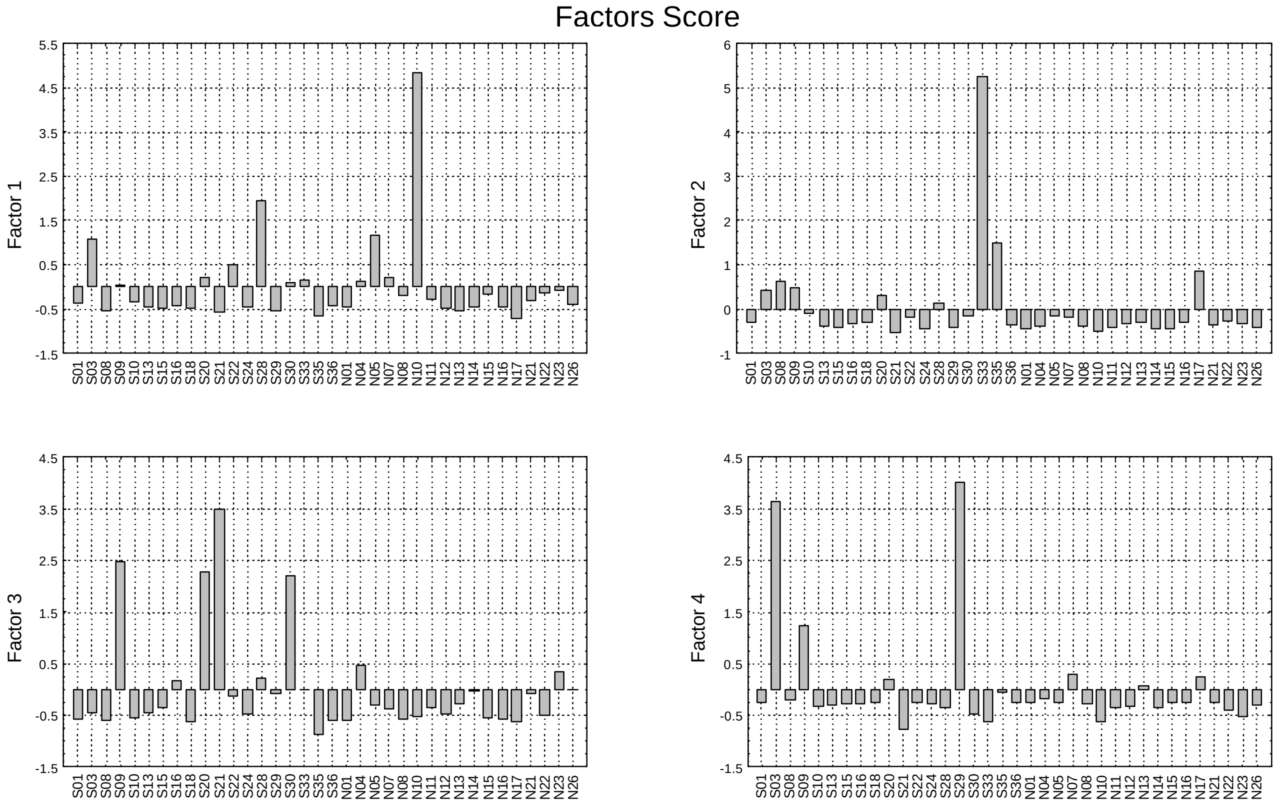

Figure 3. Factor Scores. The numbers at the base of each graph, preceded by an S (Spumellaria) or N (Nassellaria), correspond to the access code of the species listed in Table 1.

mate belt narrower, increasing thermal gradients and intensifying wind systems and oceanic currents. Furthermore, it is observed that the cold climate of the boreal hemisphere extends equatorward more than the one of the austral hemisphere (CLIMAP, 1976; 1981). During interglacial episodes, the trade wind field shifts north, similar to the present, during the austral winter (boreal summer). Thus, the westward advection of the Chile Current decreases as well as the amount of backwater. Under this scenario, the Chile Current is less intense and somewhat closer to the coast at this latitude.

The Subtropical Factor (Factor 2) shows a significant presence only during MIS 11, 5 and 1. Thus, it is somewhat in agreement with Calvo *et al.* (2001) paleoclimatic results. It appears that Subtropical Factor extreme southern advections, follows periodicities which last >100 kyrs. Our record is ~400 kyrs and thus is not long enough to analyze this in detail.

It is assumed that the Subtropical Factor shows extreme southern incursions only when wind strength or/ and oceanic circulation also diminishes in extreme; *i.e.*, during extreme interglacial episodes. Under this climate condition, backwater and coastal upwelling decrease, allowing advection of Subtropical Water toward the coast and probably a better definition of the Peru Countercurrent on the surface. This oceanographic condition has been proposed for the base of MIS 5 (Molina-Cruz, 1978). According to the record of the Subtropical Factor (Figure 4) and Calvo *et al.* (2001), this climate condition also occurred during MIS 11. It is important to observe that this scenario has occurred, mostly when the southeast trade wind field is in a northern position (boreal interglacial stage).

CONCLUSIONS

Radiolarian assemblage distribution in core top sediments reflects the oceanic circulation of the southeastern Pacific and its associated water masses, including: (1) the Subantarctic part of the Circumpolar Antarctic Current, (2) the Chile Current, (3) the backwater, (4) the South Equatorial Current and (5) the Coastal upwelling off Peru. Factor analysis of down-core assemblages indicates that the boundary between the Chile Current and the Backwater region has fluctuated during late Pleistocene. During glacial episodes, the Chile Current is advected further westward, away from the coast, because of the more southern position and greater strength of the southeast trade wind system. Conse-

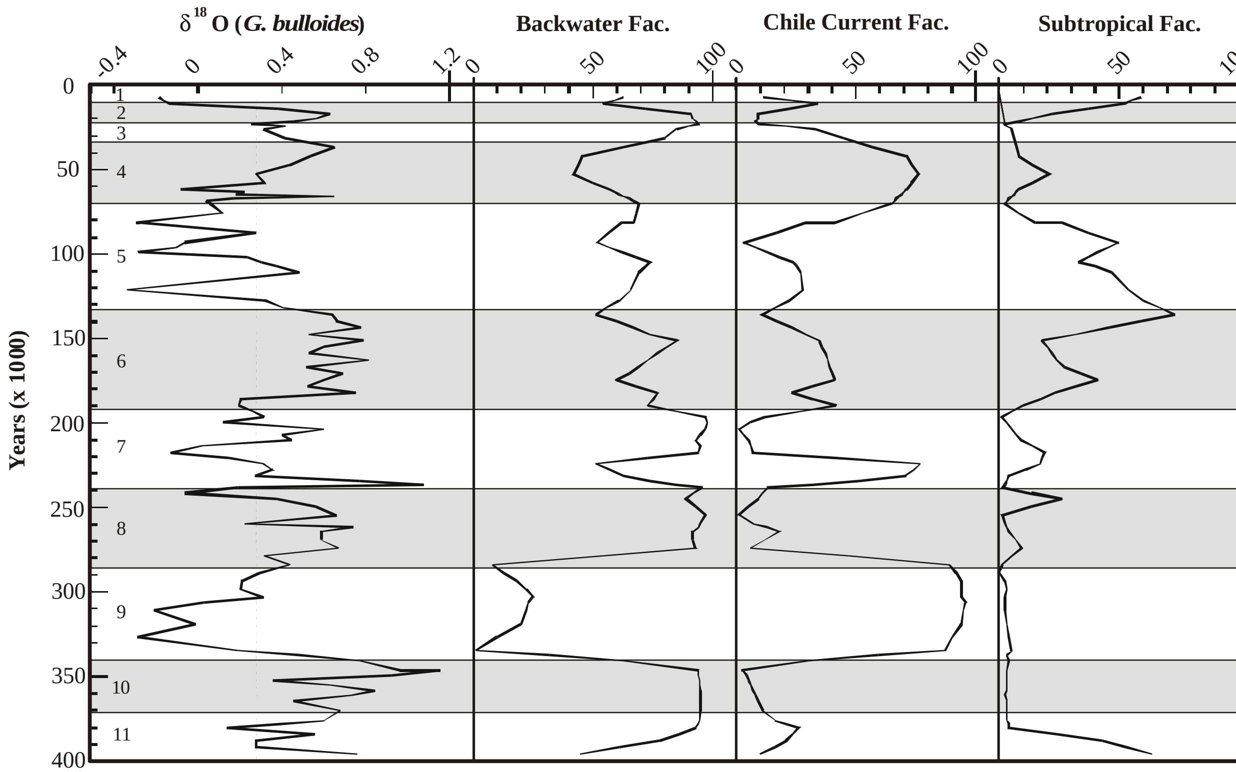

Figure 4. Down-core $\delta^{18}O$ (*G. bulloides*) and factor loadings (x 100) records of core H96-Tg7. Shaded intervals correspond to glacial stages.

quently, the Backwater Factor predominates at the location of core H96-Tg7. During interglacial episodes, the Chile Current is closer to the coast because of the more northern position of the trade wind system. Extreme Subtropical Water incursion into the Backwater region occurred during MIS 11, 5 and 1

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