Recording of ocean-climate changes during the last 2,000 years in a hypoxic marine environment off northern Chile (23°S)

Registro de cambios océano-climáticos durante los últimos 2000 años en un ambiente marino hipóxico en el norte de Chile (23°S)

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ABSTRACT

Atmosphere-ocean interactions are particularly strong along the Chile-Peru coast and largely account for the extreme aridity of the Atacama Desert. Near the center of the driest part of this coastal desert, we found that the embayment Bahía Mejillones constitutes an unusually favorable setting for the formation and subsequent preservation of a sedimentary record of the successive oceanographic conditions of the last few thousand years. This work deals with relative abundance of various bio-indicators, including fish scales, foraminifers and phytoplankton, with a centimetre-scale resolution, in several gravity cores taken from 80 to 120 m depth, in a low-oxygen environment. We use this information to document ocean-climate changes at decadal to centennial time scales in the region. Radiocarbon dating on the bulk organic-rich sediment provides the chronological framework for the observed paleoceanographic changes. We interpret that an episode of relatively warmer water, with a stratified water column and enhanced anoxic (< 0.1 ml $l^{-1}O_2$) conditions at the bottom of the bay, might correlate with the Warm Medieval Interval (11th-15th centuries) of the northern hemisphere. A younger episode, characterised by cooler water, richer in planktonic foraminifers and anchovy remains, with dysoxic (0.1 to 0.3 ml $l^{-1}O_2$) or suboxic (> 0.3 ml $l^{-1}O_2$) conditions at the bottom of the water column, may correspond to the Little Ice Age (16th to mid-19th centuries). During the first millennium of our era, two thin sedimentary layers which present similarities with the bed assigned to the warm episode are interpreted as possible remnants of very strong, or " mega " El Niño events. The study confirms that Bahía Mejillones sediments did record ocean-climate changes with a very high time-resolution, and thus deserve a closer attention to investigate the ocean-atmosphere interactions over the last few thousand years.

Key words: bioindicators, paleoceanography, paleoclimatology, Northern-Chile, low-oxygen sediments.

RESUMEN

Las interacciones océano-atmósfera son particularmente fuertes a lo largo de la costa de Chile y Perú y explican en gran parte la extrema aridez del desierto de Atacama. Cerca del sector más seco del desierto costero, hemos encontrado que la bahía semi-cerrada de Bahía Mejillones constituye un sitio particularmente favorable para la formación y subsecuente preservación de registros sedimentarios de las condiciones oceanográficas sucesivas de los últimos miles de años. Este estudio analiza la abundancia relativa de varios bioindicadores, incluyendo escamas de peces, foraminíferos y fitoplancton, con una resolución de un centímetro, en muestras de testigos de gravedad obtenidas desde los 80 a 120 m de profundidad, en un ambiente muy pobre en oxígeno. Luego, se utiliza esta información para documentar cambios océano-climáticos en escalas decenales a seculares en la región. Fechamientos por radiocarbono, realizados sobre el componente orgánico del sedimento, proveen el marco cronológico para los cambios paleoceanográficos observados. Interpretamos que un episodio caracterizado por temperaturas relativamente cálidas, con una columna de agua estratificada y condiciones reforzadas de anoxia ($< 0,1$ ml $l^{-1}O_2$) en el fondo de la bahía, podría ser coetáneo con el Intervalo Cálido Medieval (siglos XI-XV) del hemisferio norte. Un episodio más reciente, caracterizado por aguas frías, rico en foraminíferos planctónicos y remanentes de anchoveta, con condiciones disóxicas (0,1 to 0,3 ml $l^{-1}O_2$) o subóxicas ($> 0,3$ ml $l^{-1}O_2$) en la base de la columna de agua, podría corresponder a la "Pequeña Edad del Hielo" (siglo XVI a mediados del s. XIX). Durante el primer milenio de nuestra era, dos delgadas capas sedimentarias que presentan similitudes con la capa atribuída al episodio cálido son interpretadas como manifestaciones probables de eventos El

Niño de intensidad muy fuerte (o "mega" El Niño). El estudio confirma que los sedimentos de Bahía Mejillones registraron efectivamente cambios oceano-climáticos con una resolución temporal muy alta, y en consecuencia, ameritan una mayor atención para investigar las interacciones atmósfera-océano durante los últimos miles de años.

Palabras clave: bioindicadores, paleoceanografía, paleoclimatología, Norte de Chile, sedimentos con bajos niveles de oxígeno.

INTRODUCTION

The Atacama desert and its climate-ocean interaction

The desert of Atacama in northern Chile (ca., 18°S to 30°S), considered as the most arid place on earth, owes its lack of precipitation to a singular interaction of oceanic and atmospheric processes under particular geographic conditions. The northbound cold Humboldt Current and the eastern branch of the southeast Pacific anticyclonic cell combine their effects to strongly reduce the evaporation of oceanic water and limit the onshore transfer of humid air. The two orographic factors that reinforce the aridity of the Atacama desert are the Andean Cordillera, which acts by blocking all the humidity from the Atlantic-Amazonian domain, and the 1000-m-high coastal escarpment of northern Chile, which forms an effective barrier for the Pacific coastal fogs. Geological evidence indicates that aridity has been predominant in the region during the Quaternary, and possibly since the end of the Miocene (Mortimer & Saric 1975, Mortimer 1980, Alpers & Brimhall 1988). Indeed, the major peculiarity of the Atacama desert lies in the fact that it has experienced an almost uninterrupted aridity during at least several hundreds of thousand years. This situation has been explained by the quasi-permanency, at distinct time scales of the principal interactive factors of orographic, atmospheric and oceanic nature (Trewartha 1961, 1981, Rutllant 1977,1978, 1985, Ortlieb 1995a, Romero & Gonzalez [1]).

In modern times, rainfall over the Atacama desert and its coastal rim is limited to an interannual mean of a few mm per year (Almeyda 1948, Miller 1976). Exceptional showers, with amounts of 30 to 40 mm rainfall, did occur in three or four opportunities during the 20th century (Vargas 1996). These rare rainfall episodes are caused by circulation anomalies that are somehow related to El Niño phenomenon (Vargas et al. in press). A recent historical compilation of rainfall events during the last two centuries (Ortlieb

1995b) confirmed that these were generally coeval with ENSO events, although they were not as strongly linked to the ENSO system as are the rainy winters of central Chile, or the summer rains along the coast of northern Peru. In particular, it was shown that no clear relationship seems to exist between the strength of El Niño events and the amount of the exceptional rainfalls in northern Chile. No data are available for the last few centuries, since the area was practically devoid of inhabitants before the 19th century.

The reconstruction of climate variations at longer, centennial to millennial, time scales, is particularly difficult in northern Chile, due to the aridity itself. The water is so scarce that it is practically an abiotic desert, where organic matter is extremely rare and consequently radiocarbon dating can hardly be used for geochronological setting. Recent work on sequences of Late Quaternary alluvial or sheetflood deposits in the Antofagasta area (Vargas 1996, Vargas & Ortlieb 1998) confirmed that this kind of deposits, which may document former rainy episodes or periods, does not include material that can be radiocarbon-dated.

Because of difficulties to trace climate variations on land and since present-day ocean-climate interactions are remarkably strong in the northern Chile area, we thought that the nearshore marine sediments could record oceanographic variations that may help to reconstruct the regional climatic evolution. Depending on the quality of the paleoceanographic record, this approach might compensate for the scarcity of onshore paleoclimatic data, and might also offer an opportunity to study the variability of the interaction between atmospheric and oceanographic processes for the last centuries/millennia.

Paleoceanographic studies on recent sediments had not yet been conducted in northern Chile and the knowledge about present-day planktonic biodiversity in this part of the eastern Pacific is limited (Boltovskoy & Theyer 1970, Boltovskoy 1976, Zapata & Gutierrez 1995, Marchant et al. 1998). Therefore, basic information may be required to establish the basis for more profound

[1] ROMERO H & GONZALEZ P (1988) Estructura y procesos de interacción oceano-atmósfera en los climas chilenos. Simposio Recursos vivos y pesquerias en el Pacífico sudeste, Viña del Mar, Comisión Permanente del Pacífico Sur. Libro resúmenes: 84-85.

studies. This study aimed to evaluate the potential of Bahía Mejillones as a site for paleoceanographic/paleoclimate studies and to propose a tentative paleoceanographic interpretation based on the bio-indicators analysis of the marine sediments accumulated in the last 2000 years at this site.

Oceanographic features of Bahía Mejillones

Eastern oceanic boundary systems, like the margins of the western Sahara/Mauritania, Namibia, California and Peru, are known to be characterised by strong coastal upwelling. The record of former upwelling conditions have been studied through sedimentary coring of the continental shelf and/or the continental slope of these regions (e.g., Diester-Haas 1978, Thiede & Suess 1983, Curry et al. 1992). Off central Peru, where the shelf may be relatively wide, several studies, at different time scales, have been developed in the course of the last two decades (DeVries & Schrader 1981, 1997, Schrader 1992). Off northern Chile, where the upwelling activity is also very strong, the narrow continental platform and steep slope (which plunges into the 8000 m deep Peru-Chile Trench), do not constitute the best area to look for high-resolution sedimentary record of former oceanic conditions. This may partly explain why paleoceanographic and paleo-upwelling studies have not been previously attempted.

In spite of the apparently non favourable conditions off northern Chile, there is a small limited area, with a particular geographical setting that makes it potentially suitable for coring bottom sediments. Bahía Mejillones (23°05' S), 60 km north of Antofagasta, is one of the few places along the eastern Pacific coast with an embayment open towards the north, on the lee-side of a large peninsula (Fig. 1). This geographical position could constitute a favourable factor for paleoceanographic records because the bay is not under the direct effect of the northbound coastal currents, and thus may act as a sedimentary depocenter of the remains of an active primary productivity known to occur close-by, at Punta Angamos (Martín & Farías 1978, Navea & Miranda 1980, Rodriguez et al. 1991, Marín et al. 1993). Off central and south Peru, as off northern Chile, the oxygen minimum zone (less than 0.5 ml l^{-1} O_2) is found at varying depths, commonly 200 to 400 m below sea surface (Guillén & Calienes 1981, Guillén et al. 1989, Emeis et al. 1991, Strub et al. 1998), or at a shallower depth, like in Bahía Mejillones (120 m maximum depth) (Navea & Miranda 1980, Morales et al. 1996, Escribano

1998). From a time series of oxygen profiles obtained at 15 days intervals between June 1996 and August 1997 at the center of the 15 km wide bay (Escribano 1998), oxygen levels as low as 2 ml l^{-1} were found near, or just below a 30-m depth. Nearly anoxic (less than 0.1 ml l^{-1} O_2), and at least dysoxic (between 0.1 and 0.3 ml l^{-1} O_2), conditions are recorded almost year round below 80 m, except during a month or two during strong El Niño events as observed in May-June 1997 (Fig. 2). In this paper, we shall use the term "hypoxic" to refer to dissolved oxygen concentrations below 0.3 ml l^{-1}, thus including both categories "dysoxic" and "anoxic", as defined by Kaiho (1994).

The combination of the location of Bahía Mejillones, close to one of the major upwelling centers of the northern Chilean coast susceptible to induce high levels of primary productivity and
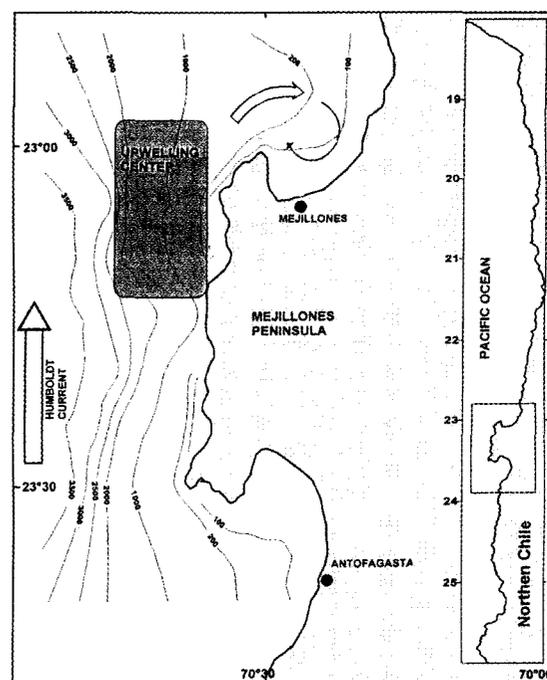
Fig. 1. Sketch map of the Peninsula of Mejillones, limited to the north and south by the embayments of Mejillones and Antofagasta, respectively. The arrows illustrate the major flow of the Humboldt Current and the expected gyre inside bay of Mejillones area. Isolines (m) show the bathymetric morphology of the area.

Ubicación de la Península de Mejillones limitada en el norte y el sur por las bahías de Mejillones y Antofagasta, respectivamente. Las flechas ilustran los flujos mayores de la Corriente de Humboldt y el giro esperado dentro de la bahía de Mejillones. Las isolíneas (m) muestran la morfología batimétrica del área.
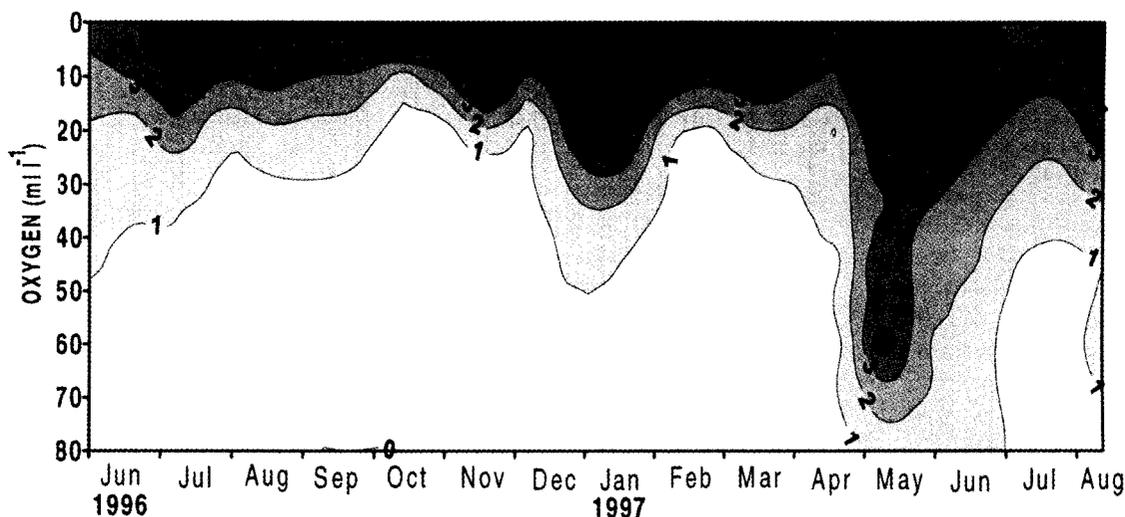
Fig. 2. Vertical and temporal distribution of dissolved oxygen in Bahía Mejillones, during 1996/1997. Redrawn from Escribano (1998).

Distribución vertical y temporal de oxígeno disuelto en Bahía Mejillones, durante 1996/1997. Gráfico reconstruído desde Escribano (1998).

phytoplankton biomass, and of the geometry and orientation of the embayment may account for enhanced hypoxic conditions if the decay of large amounts of phytoplankton that sink to the bottom of the embayment consume most of the available oxygen.

All the above features, which may have been pervasive in the course of the last centuries, are favourable for the formation of sedimentary records of past conditions. By limiting strongly the bioturbation at the sediment interface, the hypoxia indirectly constitutes a major requirement for detailed studies of recent paleoceanographic evolution. It is only in the areas devoid of bioturbation that stratigraphic analysis of sedimentary columns at fine scales can be envisaged. The permanency through time of the hypoxia is also important, because episodes of oxic conditions (even of short duration) may enable bioturbation phenomena that can result in a mixing of the superficial layer down to several mm below the interface, and thus in the perturbation of the sedimentary stratigraphy.

MATERIAL AND METHODS

The gravity cores

Sediment cores were taken from the bottom of Bahía Mejillones (Fig. 3) in order to analyse the biological remains included and preserved within

the greenish muds that accumulated in the last two millennia. Only some of the cores collected in the bay were analysed. The general methodological approach, the first radiocarbon results and preliminary analyses performed on the first two cores that were opened (cores 1 and 2A, see location Fig. 3), have been indicated with some details in Ortlieb et al. (1994).

In the present work we compile all the available relevant information, indicate new radiometric data, and provide results on bioindicator analyses performed with a high resolution (every 10 mm) on two particular cores. The first one, core 5A, was collected with a 1-inch-diameter gravity corer (Phleger type), during the first campaign (April 1993), at a 115 m depth. The second one, core 24, was obtained during a second campaign (October 1993), with the help of a 3-inch corer, at a 80 m depth. The third campaign (June 1996), during which cores 31 to 33 were collected was mostly used for geochemical analyses (Valdés 1998). Location of the cores is indicated in Fig. 3.

The cores collected were initially kept in plastic liners, of 1 or 3 inches in diameter (cores 1 to 5, and 21 to 33, respectively). Those which were not open, were kept at low temperature (<10 °C). The first step in the processing of the cores consisted in opening them, by cutting the liner (using an electrical circular saw) and then separating the sedimentary column longitudinally in two halves. A brief description of the core, accompanied with photographs, was then completed. In the case of
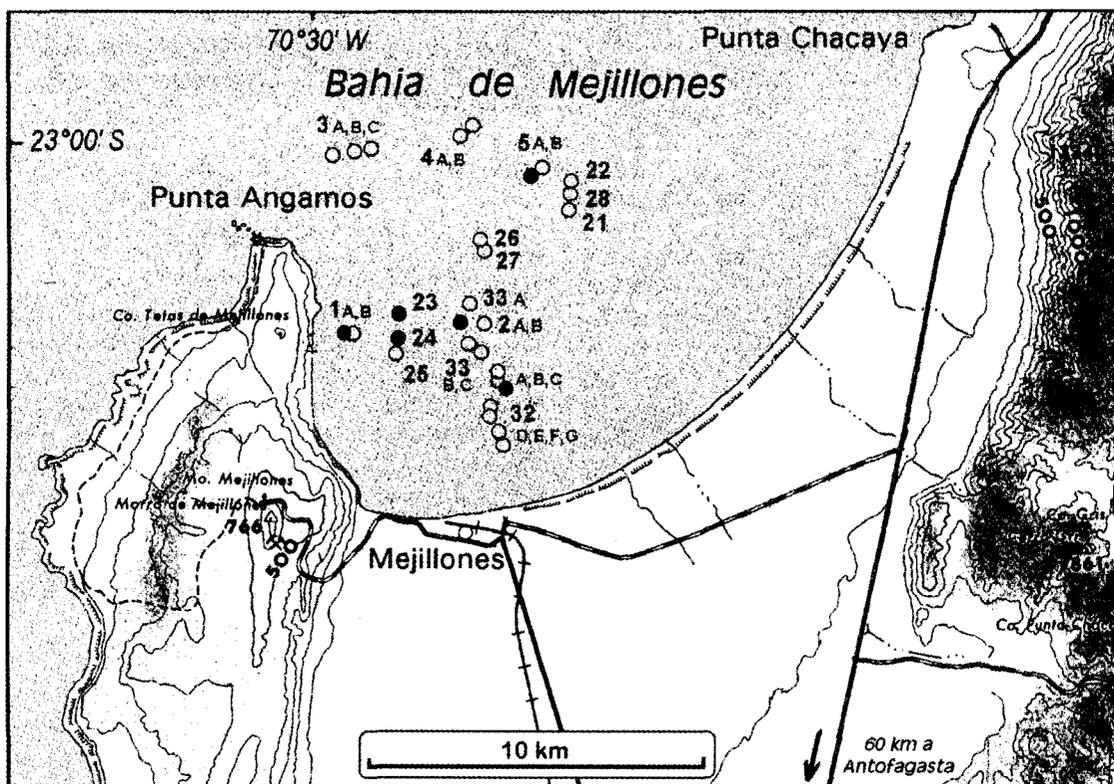
Fig. 3. Location of the gravity cores extracted from Bahía Mejillones. Filled circles designate the cores studied and mentioned in this work. Cores 1 to 5 are 1 inch diameter, and all the others are 3 inch diameter.

Localización de los testigos de gravedad extraídos en Bahía Mejillones. Círculos cerrados designan los testigos estudiados y mencionados en este trabajo. Los testigos 1 a 5 tienen un diámetro de 1 pulgada (75 mm), y todos los otros miden 3 pulgadas de diámetro.

core 23, an anomalous slump structure, which indicated that the stratigraphy had been altered in the lower third of the column, was noticed (Fig. 4). In the case of cores 5A and 24, at this stage, we proceeded with the separation of samples, 10 mm apart.

In the small diameter core 5A, the two halves were used, so that the 10 mm thick samples measured approx. 50 mm³. In core 24, one half was cut every 10 mm for bio-indicators studies while the other half was reserved for dating purpose, and cut every 50 mm. It may thus be noted that the volume of every 10 mm sample from core 24 was nearly 4 times as much as core 5A samples. From cores 5A and 24, 33 and 95 samples, respectively, were separated. Obviously, this sampling tech-
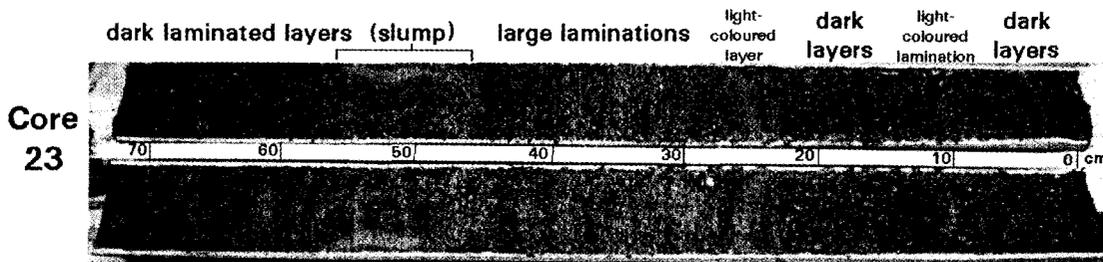
Fig. 4. Photograph of core 23 (see location Fig. 3), showing a slump feature between 460 and 570 mm below surface. This slump is correlated with an angular discordance visible in several other cores (see core 24, Fig. 7). Top of core is at right.

Fotografía del testigo 23 (ver localización en Fig. 3), mostrando una disrupción entre los mm 460 y 570 bajo la superficie. Esta disrupción está asociada con una discordancia angular visible en varios otros testigos (ver testigo 24, Fig. 7). El tope del testigo está a la derecha.

nique leads to a much higher resolution than the procedure used previously (Ortlieb et al. 1994). In the case of cores 1 and 2 previously studied, the sampling had been made (1 to several mm thick subsamples) in each section representative of the different layers observed downcore, layers distinguished mainly by their differences in colour and/or texture.

Another technique, applied in this study only on one core (32C), consists in taking an X-ray radiography of the open core. The equipment used was a conventional medical device, with the following settings : exposure during 0.16 s, distance : 1 m and voltage 50 kv. The X-radiographs enable a much finer description of the stratigraphy and the variations of the sedimentological characteristics than the naked eye or photographs.

Preparation of the samples

Every 10 mm thick samples of cores 5A and 24 were gently washed with tap water over sieves with 63, 125 and 500 mm mesh-size. The fractions kept on the sieves were dried up in an oven at 80°C, during 24 h. The fractions 125-500 and >500 mm were observed under microscope to separate fish and any other macroscopic invertebrate remains. The subsamples 125-500 mm were thereafter used for the micropaleontological study. These subsamples were re-hydrated and treated with perchlorethylene. The floating foraminifers were extracted until a number of approximately 250 individuals were gathered. In the core 24, the study of phytoplankton was made on very small samples that were taken out of each 10 mm thick slice of sediment previous to any sieving. The technique used for the separation and counting of the phytoplankton remains, based on the method described by Barcena & Flores (1990), considered subsamples of 2 mg of dry sediment, diluted in 100 ml of distilled water, and deposited on 18 x 18 mm coverglasses. The counting of the cell density (valves g^{-1}) was performed on a 7.5 mm^2 area.

Radiochronological analyses were performed either on the sediment that filled the corer nose (cores 1A, 5A, 3C), or on 50 mm (half-)slices (core 24). The measurements were made on the organic matter of the bulk sediment, after mild acid attack to eliminate the carbonates (essentially foraminifer tests). In two cases when the amount of organic matter carbon was not sufficient for the radiochronological analysis, a second 50 mm thick sample immediately below (or above) the other sample was taken. The radiocarbon analyses were performed by traditional scin-

tillation counting in the former Geochronological laboratory of ORSTOM at Bondy (France). Attempts to use foraminifers for AMS (Accelerator Mass Spectrometry) dating were not successful, essentially because of the limited amount of material available. All the radiocarbon results indicated here are conventional ages BP (Before Present = before 1950 AD), without correction or calibration.

Organic remains

The sediment accumulated at the bottom of the bay is essentially of organic origin (Ortlieb et al. 1994). The hard parts of organisms that are preserved are foraminifer tests, siliceous phytoplankton frustules and fish remains (both phosphatic bones and scales). We thus intended to determine these different kinds of accumulated remains and to analyse the variation of their abundance downcore. At the same time, we explored which material or species, may be used as indicators of particular past oceanographic conditions.

The foraminifers, which are well preserved in sediments of Bahía Mejillones, have proved to be good bio-indicators in many paleoceanographic studies, providing that a minimum knowledge is available for the present situation in the geographic area (e.g., Boltovskoy et al. 1991, Kaiho 1994). Unfortunately, in our case, there is a scarcity of background information. Some of this information was derived from a series of samples on the bottom of the same bay, which included a preliminary taxonomic analysis (R. Martinez, unpublished work). There is also a work on recent foram assemblages from the area of Tocopilla (Zapata & Gutierrez 1995), which was published (in early 1997), that is after our study on cores 5A and 24 was completed. Thus, we carried out a preliminary taxonomic determination of the forams and used most general characteristics taken from the literature for the interpretation of former oceanographic conditions.

For the analysis of phytoplankton, the identification of the material was performed according to the technique of Müller-Melchers & Ferrando (1956) and was based on a reasonable knowledge of the modern microflora in the area (Rivera 1981, 1983, Rodríguez et al. 1996). The main problem faced, that still awaits for a satisfactory solution, was related with technical difficulties like the sampling interval (time scale), the representativeness of each subsample, and the measurement of the relative abundance of the numerous species. Phytoplankton remains are so abundant that the extrapolation of the patterns ob-

tained from small subsamples induces a very large uncertainty.

Fish remains have been studied for a long time in sediments off California, at time-scales that vary from millennial to decadal scales (Soutar 1967, 1971, Soutar & Crill 1977, Soutar & Isaacs 1969, Baumgartner et al. 1989, 1992). In this study, fish scales and bones were determined by comparison with a reference collection of modern material from the most common fishes of the area (FAREMAR, Universidad de Antofagasta). The methods used in the study of fish remains and the problems for evaluating their abundance variation downcore are indicated with some details in another work[2]. The problem for this kind of material is the opposite of that for phytoplankton remains: the diameter of the cores (particularly for the 1'' cores) is too small to enable a validated statistical analysis of the fish remains in 10-mm thick samples. Nevertheless, even if some species are found with only one or two scale/sample, we surmise that their presence, by itself, is relevant information. Of course the converse is not necessarily true : in a statistically small sample, absences is not definitive evidence that a given species was not present.

RESULTS

Characteristics and structure of the sediments

In the embayment of Mejillones the superficial bottom sediments grade from fine sands, close to the surf zone, to dark greenish muds in the deeper, central part of the bay. All the sediments cored confirmed the previous works on the benthos of the bay (Ramorino & Muñiz 1970; Zúñiga et al. 1974) which had shown that below 50 m depth, the muds are practically devoid of mollusc shells, and showed evidence of low-oxygen conditions. This is consistent with the measurements reported in Fig. 2, according which, below 50 m, the mean amount of dissolved oxygen is less than 1 ml l^{-1} year round, except during (strong) El Niño events.

In the cores, all taken at depths of more than 60 m, the sediments are, on the whole, relatively homogeneous in texture and colour. However, some bedding is present and the colour and texture of the different layers vary slightly from one to another. In the larger part of the cores, the colour varies between olive grey (5 Y 3/2) to

greyish olive (10 Y 4/2). The lighter-coloured layers that include yellowish "nodules" of organic matter are either moderate olive brown (5 Y 4/4), or light olive brown (5 Y 5/6) in some cores, but may be locally moderate yellow (5 Y 7/6).

Microscopic observations of the sieved sediments indicated that the sand (quartz) fraction is extremely reduced. The only core in which a sandy layer was found and even included small pebbles was core 3A. This particular core, which was obtained near the shelf break, at about 140 m depth (Fig. 3), probably registered coastal sands that were laid during the last glacial low seastand (ca. 20,000 BP). In the other cores, coming from within the embayment, the sediment is predominantly an organic-rich diatomaceous mud. The lithic components (which have not been quantified with precision but seem to be less than 10 % in dry weight) are most probably brought by eolian action. In some opened cores, like core 5A, the presence of micas was noted in two distinct dark small layers: they are interpreted as possible indicators of continental runoff into the embayment.

The structure of the sediment is grossly laminated (Fig. 4 and 5). To the naked eye, the predominant feature of the opened cores is the succession of layers that are defined by slight differences in colour and texture. These layers are commonly several cm-thick but some laminations, with a thickness of the order of a few mm (or less), may also be observed. The existence of
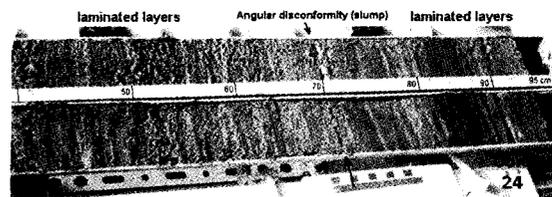
Fig. 5. Photograph of the lower half of core 24, with indication of an angular discontinuity within the laminated sediments (700 mm below surface). This discontinuity most probably corresponds to a strong earthquake that occurred at ca. 1200 ± 100 BP. Top of core is at left.

Fotografía de la mitad inferior del testigo 24, con indicación de una discontinuidad angular dentro de los sedimentos laminados (700 mm bajo la superficie). Esta discontinuidad probablemente corresponde a un fuerte sismo que ocurrió aproximadamente a los 1200 ± 100 BP. El tope del testigo está a la izquierda.

[2] KONG I, J VALDES, P IRATCHET & L ORTLIEB. Restos de peces pelágicos en sedimentos hipóxicos de Bahía Mejillones (23°S), Norte de Chile, y su uso para la reconstrucción de condiciones océano-climáticas pasadas (manuscript).

these layers and fine laminations and their sharp boundaries constitutes one of the major evidences that bioturbation, if any, was limited during and after their respective deposition.

The X-radiography technique applied to the core 32C confirmed the laminated character of the major part of the sedimentary column. As shown in Fig. 6, the X-ray analysis provides altogether a much more precise and detailed image of the core stratigraphy, as well as information on "density" and textural differences between layers. In the example taken from the top of core 32C, it appears for instance that few-mm-thick layers may be identified and that some beds are more neatly stratified than others. We interpret that the less well-defined layers (bottom of Fig. 6) may have registered some diagenetic alteration, as a superimposed phenomenon after deposition of the laminated sediment (which are still visible in the radiographs). However, even in this case, where the laminations are less conspicuous, it seems that no bioturbation did occur, neither during or after the sedimentation.

No detailed sedimentological studies were made on the core material, at this stage. The abundance of organic matter within the sediment, the presence of diatomaceous (?) sheath in many beds, as well as the so-called "nodules", small yellowish balls that contain diatoms, polychaetes and forams (of undetermined origin) that are concentrated in some layers (of brighter colour), make it difficult to complete classical granulometric analyses. We assume that most of the terrigenous input in the bottom sediment is of eolian origin, and consists in very fine detrital debris eroded from the isthmus of Mejillones peninsula. This hypothesis is currently being tested in the framework of a doctoral thesis (G. Vargas).

Geochronological data and sedimentation rates

In a previous work (Ortlieb et al. 1994), a first evaluation of the sedimentation rates was made by dating (by conventional ^{14}C measurements) the sediment at the base of the cores, using the material collected in the corer nose. The base of core 1A (ca. 35-400 mm below sediment-water interface) thus yielded a radiocarbon age of 1100 ± 60 BP. At the base of core 5A, the 50 mm thick layer of sediment that immediately underlied sample 5A-1 (Fig. 7), gave a result of $2,080 \pm 80$ BP. Finally, the base of core 3C (ca. 400-450 mm below interface) yielded a result of 8140 ± 80 BP. The last mentioned (core 3C) radiocarbon age may not be representative of the age of the deposition of the sandy sediment if, as proposed above,
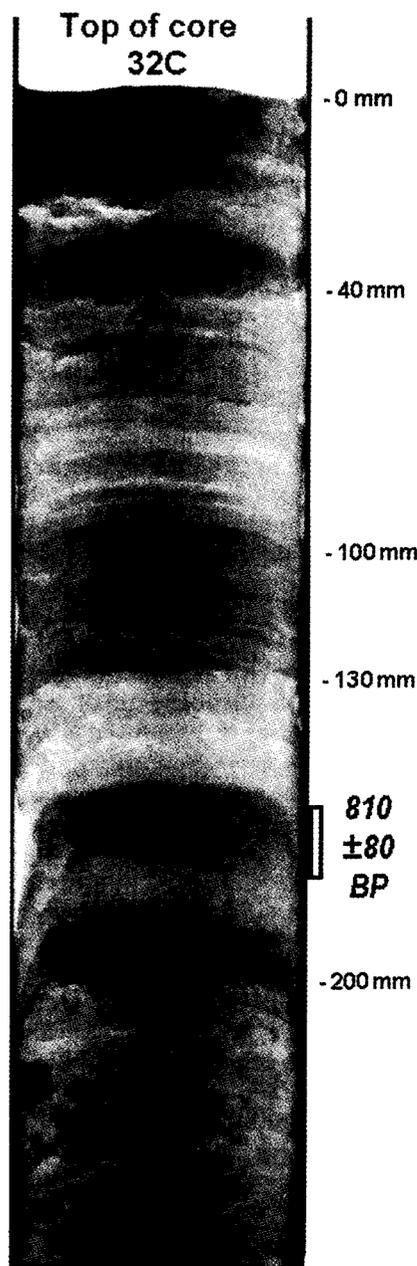
Fig. 6. X-ray photograph of the top of core 32C, showing the sedimentary structure of the layers deposited during the last 9 centuries (from Valdés,1998). The laminations and sharp limits between layers of different densities confirm the general lack of bioturbation during the last centuries and suggest a series of ocean-climate changes in the Bahia Mejillones area.

Fotografía de rayos-X de la zona superior del testigo 32C, mostrando la estructura sedimentaria de las capas depositadas durante los últimos 9 siglos (Valdés 1998). Las laminaciones y abruptos límites entre capas de distinta densidad confirman la falta general de bioturbación durante los últimos siglos y sugieren a serie de cambios climáticos y oceanográficos en el area de Bahía Mejillones.

the episode of sedimentation was coeval with a late glacial low stand of sea level (120 m below present datum). In the two other cases (cores 1A and 5A), we observe that at a similar depth (400 mm) below the present sea bottom, apparent ages vary from ca. 1000 and ca. 2000 BP, between a peripheric, relatively shallow, sector (80 m depth) and the centre of the bay (115 m depth). A rough evaluation of the accumulation rates during the last millennia thus gives values of the order of 200 to 400 mm 10^{-3} year, respectively in the outer part and near the rim of the bay. Such·values are comparable to those measured in some localities of the central Peru upper continental slope, which vary between 300 and 3200 mm10^{-3} year (DeMaster 1979, Koide & Goldberg 1982, Reimers & Suess 1983).

In order to obtain an idea of the sedimentation rate variation through time at a single site, we used several 50-mm-sections of the half core 24. The radiocarbon results for the sections 160-250 mm, 360-450, 810-850 and 910-950 are indicated in Fig. 7. They are internally consistent and suggest at first sight that the accumulation rate varied much through time. Intermediate values calculated between the dated sections, and which indicate rates of 200 mm 10^{-3} y (at the bottom) and 270 mm 10^{-3} y (at the top), are fully compatible with the mean values calculated for cores 1A and 5A. Other intermediate values calculated in the central part of the core yielded rates of 740 mm 10^{-3} y and 1800 mm 10^{-3} y, and thus suggest that there were episodes during which the sedimentation processes were accelerated. The overall mean sedimentation rate for the whole core 24 is 480 mm 10^{-3} y (calculated with the radiocarbon result of the 910-950 mm section).

Another attempt to refine the chronological study of core 24 by dating more intermediate 50 mm core sections was unsuccessful. Radiocarbon analyses performed some two years after the core was opened, on samples that had not been kept in refrigerated, air-tight, sealed bags, provided apparent ages that were inconsistent both internally and with the first set of results. This can be interpreted as the result of an oxidation and an accelerated diagenesis of the different carbon-bearing components of a (normally hypoxic/anoxic) sediment.

In other cores from the study area, some additional radiochronological data are available. For now, we shall only mention that AMS dating performed on small 20-mm thick samples (instead of 50- or 100-mm sections) enabled us to bracket the age of a particular feature visible in several cores (e.g., 230 and 240, see Fig. 4 and 5, respectively). This feature is a conspicuous
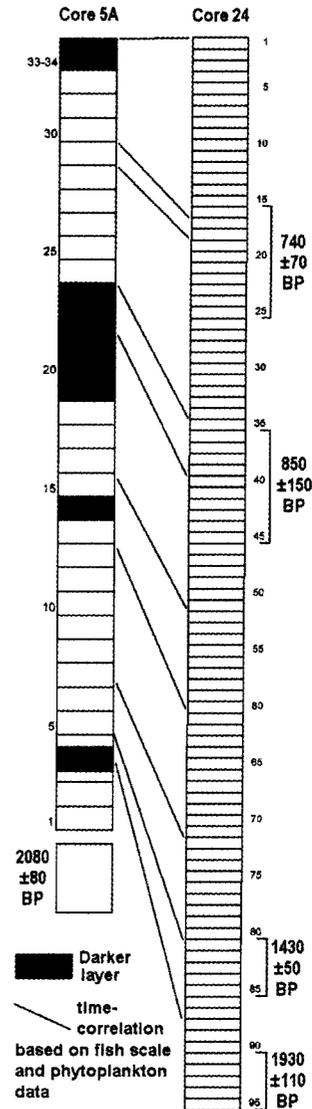
Fig. 7. General description and geochronological results of cores 24 and 5A . The proposed lateral correlation between distinct layers of cores 24 and 5A is essentially based on relative abundance of fish remains. Numbers refer to samples # and represent distance in cm from top (Core 24) or from base (Core 5A) of cores. Radiocarbon dates indicated were obtained from decarbonated bulk organic matter (traditional counting) and are expressed as uncorrected ages before present.

Descripción general y resultados geocronológicos de testigos 24 y 5A. La correlación lateral propuesta para las distintas capas de los testigos 24 y 5A está esencialmente basada en la abundancia relativa de remanentes de peces. Los números corresponden a las muestras y representan las distancias en centímetros de la cima (testigo 24) o de la base (testigo 5A) del testigo. Los fechamientos por radiocarbono indicados fueron obtenidos a partir de materia organica total decarbonatada (análisis tradicional) y están expresados como edades no corregidas antes del presente.

Core 24
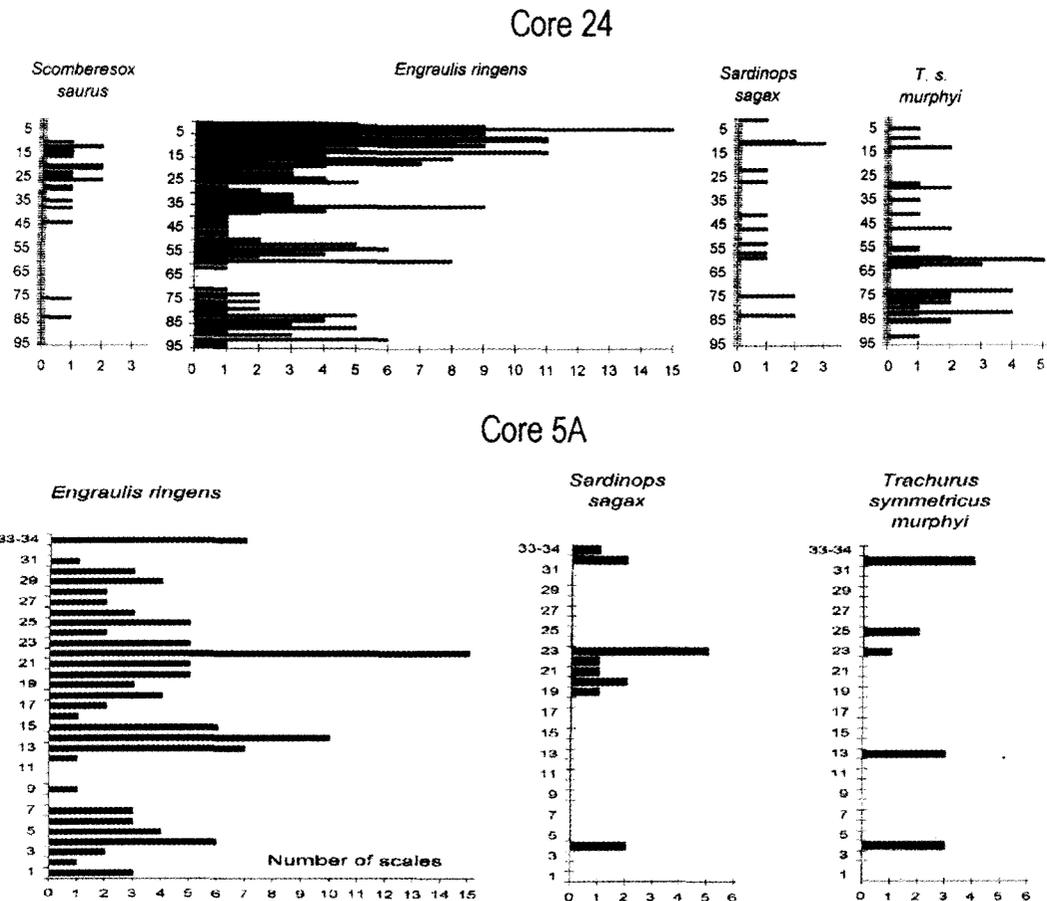
Core 5A

Fig. 8. Variation of fish scales abundance in cores 5A and 24. Note the coincidence between peak of abundance of the three species in core 5A: inferred correlations and basis for paleoceanographic reconstruction.

Variación en la abundancia de escamas de peces en los testigos 5A y 24. Note la coincidencia entre los picos de abundancia de las tres especies en el testigo 5A: bases y correlaciones para la reconstrucción paleoceanográfica.

stratigraphic unconformity that is found at several decimetres below the core tops and which is interpreted as the manifestation of a large seismic event. In core 32C Valdés and co-authors [3] report two AMS ^{14}C results of 1150 ± 100 BP and 1230 ± 60 BP, for two layers which are 20 and 40 mm, respectively above and below, the seismically induced discordance. A third AMS ^{14}C result is indicated on the radiograph of the upper part of the same core 32C (Fig. 6): 810 ± 80 BP [3]. All these results from core 32C are consistent with the dates obtained in core 24, thus consolidating the chronological framework for the whole study. Other radiochronological analyses are currently

underway on other cores from the area (Valdés 1998).

Biological remains: variations along core 5A and 24

Fish scales : The variation of number of fish scales along the cores 5A and 24 is interpreted to be significant albeit their low absolute abundance in the small samples. As indicated in Fig. 8, the maximum number of scales of any species is 15, both in core 5A and 24 (although samples are of different sizes). By far the most abundant species

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[3] VALDES J, L ORTLIEB & R ESCRIBANO (1997) Fechamiento de sedimentos marinos recientes en el norte de Chile (23°S); implicaciones paleoclimaticas (y paleosismologicas). XVII Congreso de Ciencias del Mar, Santiago. Abstr.: 156.

is anchoveta (*Engraulis ringens*), which also predominates today, except during El Niño years when sardine (*Sardinops sagax*) displaces anchoveta.

In core 5A, three species were recognised at the specific level: *E. ringens, S. sagax* and *Trachurus symmetricus murphyi. E. ringens* is almost present all along the core, while the two other species are limited to specific 10-mm-thick horizons or thicker layers (e.g. samples 5A-19 to -23). There is a remarkable coincidence between the abundance peaks of the three species and the dark layers of core 5A (5A-3 or -4, 5A-14, 5A-19 to -23 and 5A-33/34) (see Figs. 7 and 8). The dark layers thus seem to correspond to episodes, of varying duration, during which the specimens of one or several species are more abundant. Unlike what has been indicated in the study of core 2A (Ortlieb et al 1994), there is an apparent positive correlation between *E. ringens* and *S. sagax*.

In core 24, a fourth species was identified: *Scomberesox saurus*, but this species is represented by, at most, only one or two scale(s) in some samples. It is clearly more abundant in the upper part of core 24 (Fig. 8). At odds with core 5A, there is a remarkable abundance of *E. ringens* remains in the more recently laid sediments of core 24 (upper 110 mm). But below samples 24 - 24-25, the variations in abundance of *E. ringens* suggest a good correlation with those observed (at a different length scale) in core 5A (Fig. 8). *S. sagax* and *T. symmetricus murphyi* are, on the whole, slightly more abundant and more commonly represented in core 24 samples than in core 5A. The downcore variation in abundance of these two species is not as well marked as in core 5A but suggests some correlations with the fluctuations of *E. ringens* in core 24, and hence with core 5A (Fig. 7).

The fish scales data thus appear to be representative enough to enable a tentative lateral correlation within the sedimentary sequences across the embayment. Major concentrations of fish scales of all the species are observed in the darker layers. It may be assumed that the relative abundance of fish scales reflects a relative abundance of fishes formerly living in the water column (Shackleton 1988). As will be discussed later, the fact that the dark beds, richer in organic matter, and apparently coeval with enhanced anoxic conditions at the bottom of the bay, are also those where a maximum relative abundance of fish scales is observed should be significant.

Benthic foraminifers : In Core 5A samples, benthic foraminifers are generally abundant. Total numbers counted in each sample vary from 120 and almost 300 individuals (Fig. 9). The predominant species of benthic foraminifers is *Bolivina seminuda*, a species known to support very low levels of oxygen (e.g. Boltovskoy et al. 1991). We shall refer here to *B. seminuda* for different forms that other authors may identify as *B. dilatata* (Barmadwidjaja et al. 1992) and/or *B. punctata* (Zapata & Gutierrez 1995). Relative abundance of *B. seminuda* downcore seems to be closely linked to some sedimentological variations: abundance maxima are coincidental with the darker layers of the core (5A-18 to -20, 5A-13/14, 5A-3). Near the top of the core, which also consists in a rather dark layer, is observed a steady increase of *B. seminuda* abundance. The minimum abundance of *B. seminuda* is observed in samples 5A-28 to -30, i.e. immediately below the upper layer of the core (i.e. before the 20th century).

Bolivina costata is the benthic species that shows less variability along core 5A, but its abundance is limited to a few tens of individuals in every sample (maximum 50 individuals at the base of the core). Among the much less abundant benthic foraminifers, found in separate segments of core 5A, we shall mention: *Buliminella elegantissima, Nonionella auris* and *Nonionella pulchella* (Fig. 10), which are observed in the less dark layers, and *Cassidulina limbata* that is more abundant in the darker layers.

In core 24, benthic foraminifers show larger variations of abundance than in core 5A. *B. seminuda* remains the most abundant species in some sectors of the core but is absent in other samples. Like in core 5A, *B. costata* is almost constantly present all along core 24, but in major density. The other benthic species vary in abundance in a similar way than in core 5A, and support the lateral correlation proposed in Fig. 7.

The benthic foraminifer data thus suggest that low-oxygen conditions (possibly dysoxic : 0.1-0.3 ml l^{-1} O$_2$) were practically constant in the outer (and slightly deeper) part of the bay, while in the inner area of core 24 the conditions possibly oscillated between dysoxic and suboxic (0.3-1.5 ml l^{-1} O$_2$).

Planktonic foraminifers : Planktonic foraminifers are less numerous than the benthics along core 5A. Total number of counted individuals varied between 3 and 55 (Fig. 9). The minimum abundance of planktonic foraminifers (< 10 individuals) coincide with the darker layers of the central part of the core (5A-18/23).

The most abundant planktonic species is *Globigerina bulloides* (Fig. 10), with a maximum number of individuals of 20 (5A-26, 5A-6). Minimum abundance of this species is noted in the darker layers (5A-33/34, 5A-19/22, 5A-3).

Globiquerina bulloides is a subpolar planktonic foraminifer that indicates upwelling conditions and implies a high abundance of phytoplankton (Imbrie & Kipp 1971, Thiede 1975, Naidu & Malmgren 1996, Hughen et al. 1993[4]).

Neogloboquadrina pachyderma (Fig. 10) and *Globigerina falconensis* are the two other species that are almost always present downcore. *Globiquerina falconensis*, an eurythermal species, does not vary clearly with the major sedimentological units recognised in core 5A: it

is absent in some of the darker layers (5A-19/29, 5A-22/23) and also in the lighter-coloured segments (5A-7/8, 5A-28, 5A-30). *N. pachyderma* is represented, with only a few individuals, in most of the samples by both the dextral and sinistral (right- and left-coiling) forms, the former being predominant. The sinistral form is totally absent in the darker layers (5A-32/34, 5A-18/24, 5A-12-14, 5A-3) and also in three other isolated samples (5A-29, 5A- 9/10, 5A-5). The dextral form is most abundant (but with only 9 individuals) in the

Benthic and planktonic foraminifers in core 5A
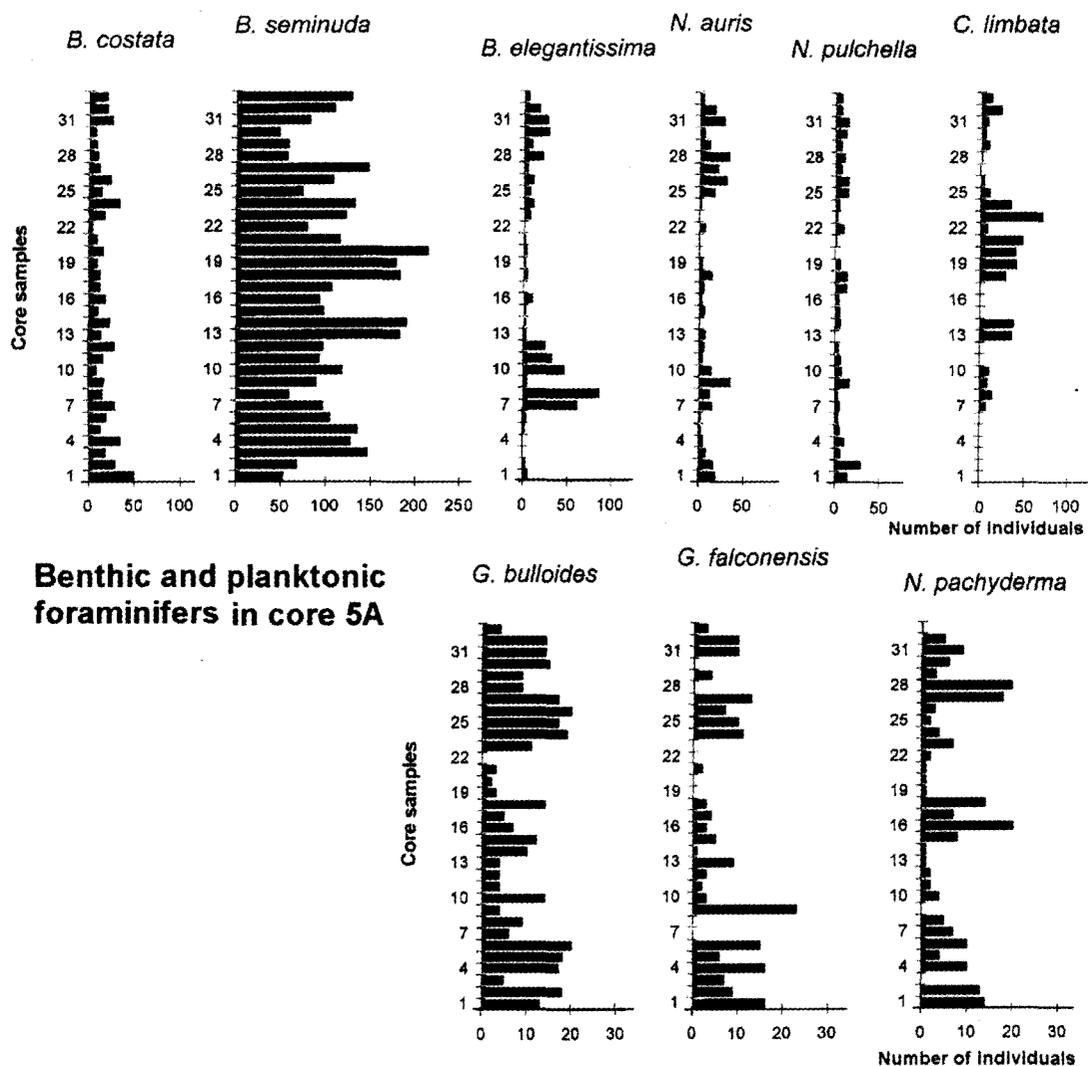
Fig. 9. Variation of abundance of benthic and planktonic foraminifers in core 5A.

Variación en la abundancia de foraminíferos planctónicos y bentónicos en el testigo 5A.

[4] HUGHEN K, TJ OVERPECK & LC PETERSON (1993) The nature of varved sedimentation in the Cariaco Basin and its paleoclimatic significance. Eos, Transactions of the American Geophysical Union, 74: 362.

less dark layers 5A-1, 5A-16 and 5A-27/28. The sinistral form of *N. pachyderma*, abundant in polar and subpolar regions, is considered as a useful proxy for sea surface temperatures since this form is normally found in areas where, during part of the year, the temperature is 8°C or lower (Thunnell & Mortyn 1995). The episodic occurrence of sinistral *N. pachyderma* in sedimentary records is generally interpreted to indicate either seasonal variations (winter sedimentation) or episodes of intense upwelling of cold deep waters (Thiede 1975, Oberhänsli 1991, Little et al. 1997).

Other planktonic foraminifers identified in the sediment of core 5A include *Globorotalia hirsuta, Globoquadrina hexagona, Globigerina* cf. *G. siphonifera* and *Globorotalia* sp. All these species are present in a very small number of individuals, and only in a few samples downcore. We failed to identify *Neogloboquadrina dutertrei*, a common planktonic foraminifer of the Peruvian coast that has been used in paleo-upwelling studies (Thiede 1975, Wefer et al. 1983).

In core 24, the planktonic foraminifers are, unexpectedly, more abundant than in core 5A.
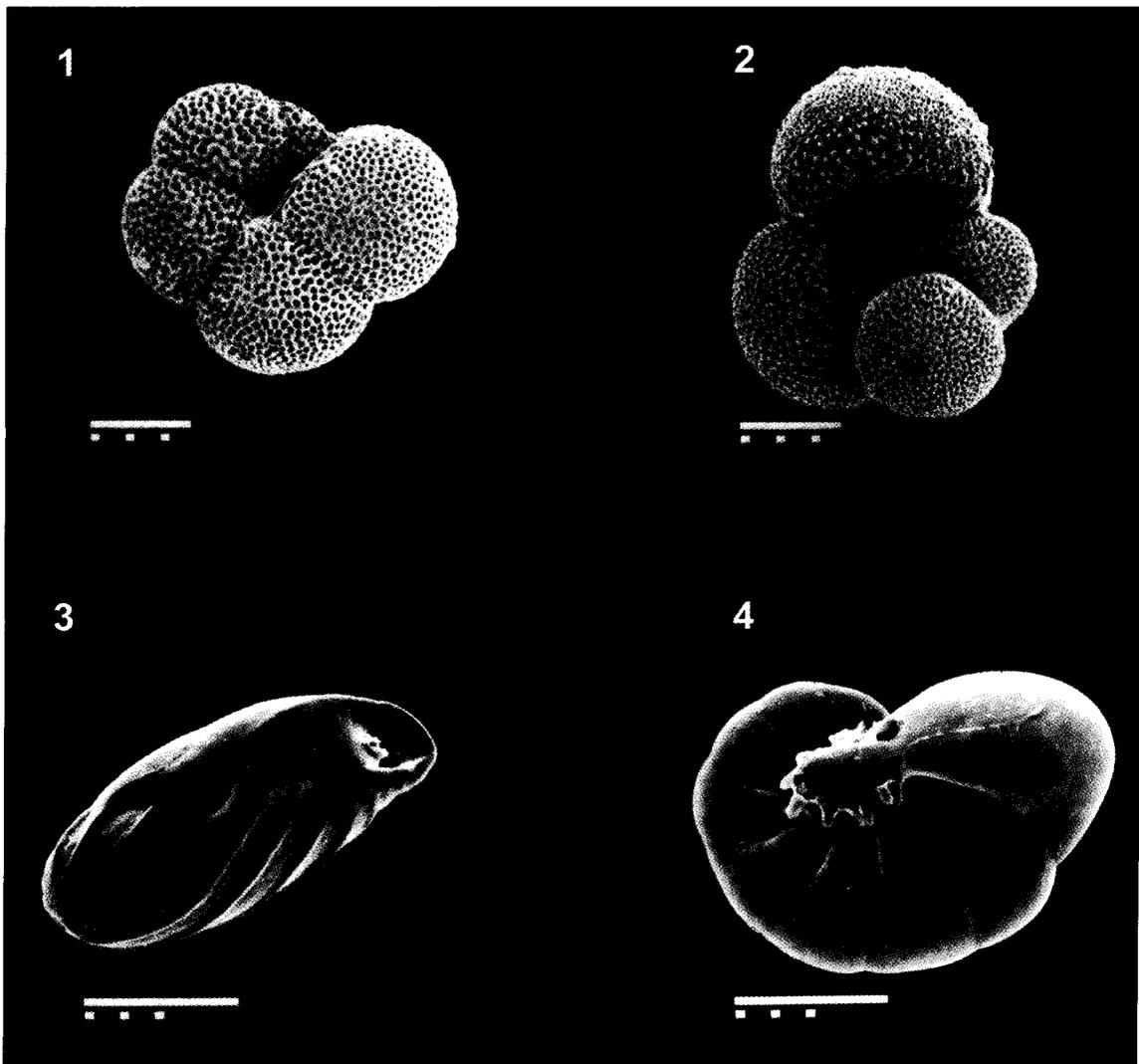
Fig. 10. Some of the common (planktoni: 1 & 2, and benthi: 3 & 4) foraminifers found in the sediments of Bahia Mejillones. 1. *Neogloboquadrina pachyderma* (dextral form). 2. *Globigerina bulloides*. 3. *Buliminella elegantissima*. 4. *Nonionella pulchella*.

Algunos de los foraminíferos (planctónicos : 1 & 2, y benticos : 3 & 4) comunes encontrados en los sedimentos de Bahía Mejillones. 1. *Neogloboquadrina pachyderma* (forma dextral). 2. *Globigerina bulloides*. 3. *Buliminella elegantissima*. 4. *Nonionella pulchella*.

Their abundance varies more than in core 5A, both in amplitude and from sample to sample. In core 24, *G. bulloides* and *N. pachyderma,* which are the most abundant species, present several common peaks. However, as no separation between sinistral and dextral forms of *N. pachyderma* was performed in core 24, it was not possible to fully assess a lateral correlation between both cores that would take into account the relative peaks of abundance of these forms of the planktonic species.

From the overall foraminifer data, it can be stressed that, in core 5A, the darker layers observed near the base, at the centre and at the top of the sedimentary record are characterised by peak abundance of the benthic foraminifer *B. seminuda* (and the presence of a few individuals of *Cassidulina limbata*) and the total absence of sinistral forms of *N. pachyderma.* In a general way, the darker layers are poor in planktonic foraminifers (Fig. 11). Reducing conditions at the bottom of the water column, that favour the predominance of *B. seminuda,* thus appear to be linked to a strong limitation of influx of open oceanic water masses and, particularly, of cold-temperate water.

Phytoplankton variation : Even though several species could be well identified, it was clear that the variation of total abundance of phytoplankton in cores 5A and 24 was determined by two groups of species: *Chaetoceros* spp. and *Thalassiosira spp,* together accounting for more than 90% of total abundance in both cores (Fig. 12). These two genera are widely recognised as typical bio-indicators of upwelling conditions (e.g. Schuette & Schrader 1981). Thus, it may be said that increases in phytoplankton abundance represent, not only periods of potentially higher primary productivity, but also periods characterised by more frequent, or more intense upwelling events. Conversely, decreases in phytoplankton abundance might indicate periods of perhaps warmer, or more El Niño-like conditions. Variation along the cores appears to reveal such alternate periods, although how they associate with the other bio-indicators (fish remains and forams) is not yet well established.
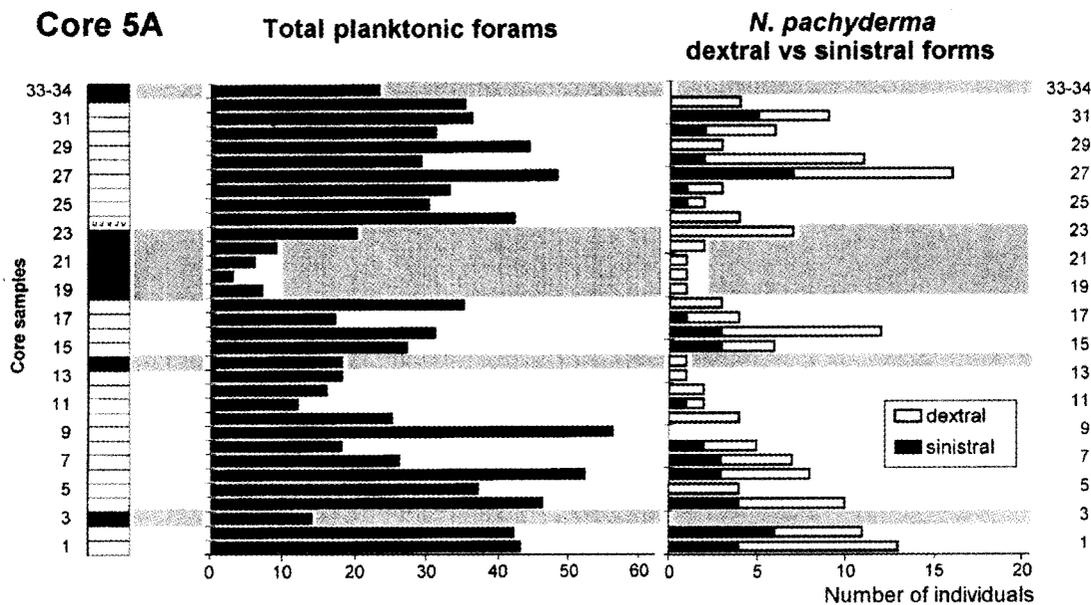
Fig. 11. Coincidence between the relative deficit of planktonic foraminifers, the lack of *Neogloboquadrina pachyderma* sinistral form (cold water), and the dark layers of core 5A. The long interval covered by samples 19 to 23, as well as the dark layers of samples 3-4 and 13-14, are interpreted as reflecting warmer water and reduced oxygen availability at the interface. Samples 19 to 23 might correspond to a several century period, like the Warm Medieval Epoch.

Coincidencia entre el déficit relativo de foraminíferos planctónicos, la falta de *Neogloboquadrina pachyderma* forma sinestral (agua fría), y las capas oscuras del testigo 5A. El intervalo largo cubierto por las muestras 19 a 23, así como las capas oscuras de las muestras 3-4 y 13-14, son interpretadas como un reflejo de condiciones cálidas y de disponibilidad reducida de oxígeno en el interface sedimento-agua. Las muestras 19 a 23 podrían corresponder a un período de varios siglos, como el Intervalo Cálido Medieval.
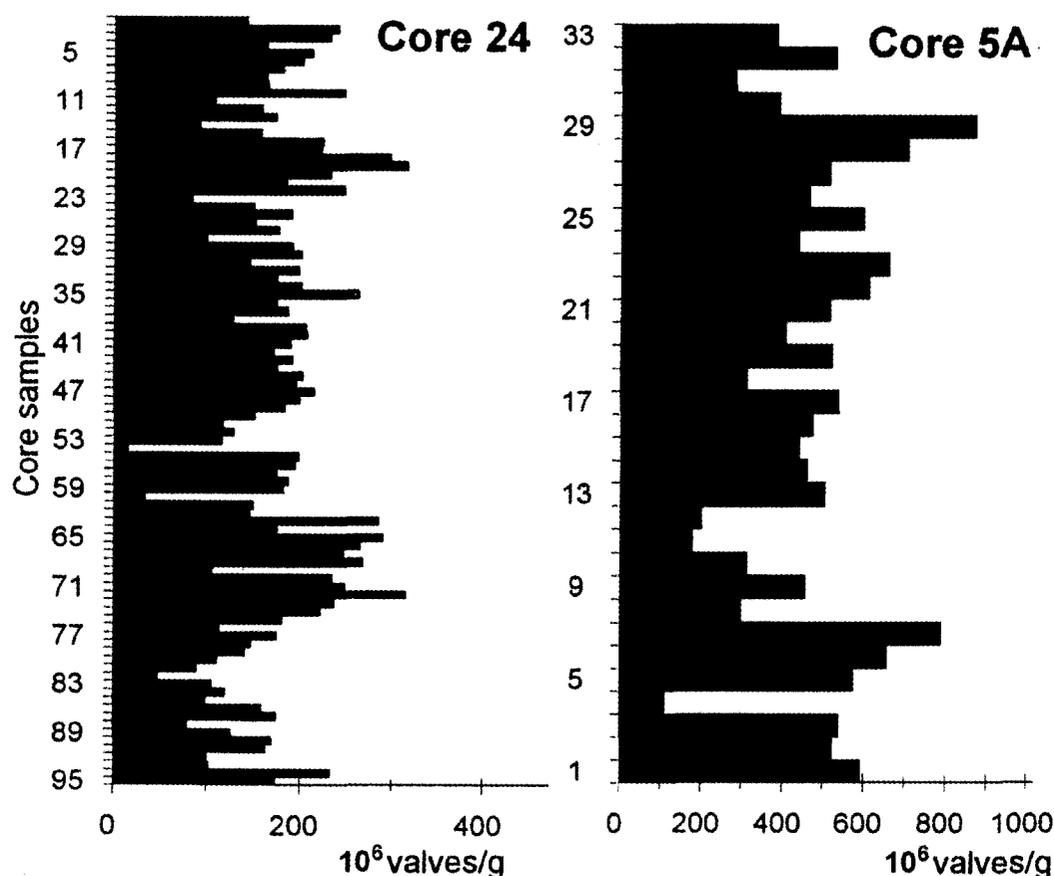
Fig. 12. Variation in total abundance of phytoplankton (millions of valves per gram of dried sediment) in cores 5A and 24.

Variación en la abundancia total de fitoplancton (millones de valvas por gramo de sedimento seco) de los testigos 5A y 24.

DISCUSSION AND CONCLUSIONS

The comparison of the available data from cores 24 and 5A supports the interpretation that both cores encompass a period of deposition of about 2000 years (Fig. 7). The difference in length of the two cores points to a 1 : 3 ratio between the accumulation rates of core 5a with respect to core 24. Core 5A, obtained in the outer part of the bay, thus has a much lower time-resolution but, for different reasons, is easier to interpret in terms of regional paleoceanographic evolution. The cores from the centre of the embayment, like cores 24 and 32C, are in the area that can be interpreted as a " depocenter " most probably due to the circulation pattern within the bay, which still remains to be understood. Those cores from the centre of the bay thus should provide more detailed information, with a higher time-resolution. Actually, on-going studies are focused on cores from this area, and consider the

problem of lateral correlations. These studies which bear on geochemical and mineralogical composition and include X-radiography and thin section analyses must be completed before a consolidated reconstruction of the paleoceanographic evolution of the centre of the embayment can be obtained.

Nevertheless, the results obtained in the present study, based on a correlation between the variation of different bio-indicators within cores 5A and 24, are strong enough to elaborate a preliminary interpretation of the paleoceanographic evolution of the bay. This reconstruction will be based mainly on some sedimentological characters and on the bio-indicator variations observed in core 5A.

It is important to note here that a stratigraphic and paleoecological approach at a centimetre-scale level is totally unusual in marine coastal sediments. This was made possible because of the exceptional lack of bioturbation observed in the

sediment of Bahía Mejillones. The relative homo-geneity of the sediments cored, and the range of variation in the composition of the different kinds of bio-indicators strongly suggest that the low-oxygen conditions were continuous during at least the last 2,000 years. Nevertheless, the relative abundance of different bio-indicators in the dark and lighter coloured layers of core 5A suggests that different oceanographic conditions were reg-istered, altogether at the surface, within the water column and on the bottom of the bay.

In the discussion of the results, we shall first synthesise the information provided by the dif-ferent bio-indicators in the darker layers and propose an interpretation of the corresponding prevailing conditions. Subsequently, we shall address the characteristics of the lighter-col-oured layers and suggest a paleoclimatic inter-pretation.

A warm Medieval episode in Bahía Mejillones?

The 50-mm-thick dark bed observed near the middle of the core 5A (samples 19-23) is charac-terised by: (i) the presence of sardine, which suggests rather warm surface temperature; (ii) a strong deficit in planktonic foraminifers, and a total lack of sinistral forms of *Neogloboquadrina pachyderma*, which both suggest a limitation of the influx of cool water in the bay, either because upwelling of deep cold water was reduced or because the bay was under the predominant influ-ence of poleward warm water masses; and (iii) an important variation of the benthic foraminifers *Bolivina seminuda* and *Cassidulina limbata*. The peaks of abundance of these two species suggest episodes of low levels of oxygen at the bottom, condition which is possibly related to an increase of upwelling activity and an intensification of the degradation of organic matter (due to enhanced primary productivity).

Based on the lateral correlation proposed be-tween cores 5A and 24 and on two radiocarbon dates obtained in core 24 (Fig. 7), we interpret that this episode of warmer sea surface temperature, with a minimum oxygenation of the bottom, oc-curred some 8 centuries ago, i.e., during what is known in the northern hemisphere as the Medieval Warm Epoch (11th-15th centuries, Lamb 1977). Although the effects of this climatic fluctuation

remain to be defined in the Southern Hemisphere, it is worth noting the coincidence between this warmer climatic episode and anomalous recon-structed oceanographic conditions in Mejillones bay. Modern situations like the strong ENSO event of 1982-83, during which the thermocline (15°C) was lowered down to 50 m and the sea surface temperature was several degrees warmer than usual, are useful to interpret past warmer conditions that may have lasted decades or centuries.

Two short-lived warm episodes

Two other short events observed in the lower half of core 5A (samples 3 and/or 4, and 13 and/or 14) present similar characteristics to those of the samples 19-23. The fish scales, and the plank-tonic and benthic forams contents, as well as the colour of these particular layers closely resemble that of the longer-lasting warm event of the mid-dle of core 5A. Therefore, we assume that these two layers also depict short warm events. By extrapolation from the radiocarbon data of core 24, these two events might have occurred at ca. 1000 BP and ca. 1400 BP (Fig. 13). Interestingly, the conspicuous presence of mica in the sediments of these two dark layers, furthermore suggests strong terrigenous inputs at that time. As core 5A is located in the outer part of the bay (ca. 5 km from the shore), and as the sedimentary column is normally devoid of sands and other terrigenous material, it is interpreted that these inputs are related to strong rainy episodes, possibly stronger than the "heaviest" rainfalls known from the short (only 2 centuries long) historical record (Ortlieb 1995b). It should be recalled that under present-day conditions, exceptional rainfalls in northern Chile are coincident with ENSO events (Ortlieb 1995b, Vargas 1996, Vargas et al. in press). When the radiochronological control of the sedimentary record of Mejillones bay will be consolidated (through calibration studies, control of the effect of upwelled "old" carbon, ^{210}Pb measurements, etc.), it may be possible to assess the existence and the date of particular events sometimes re-ferred to as "mega El Niño" events. For now, we notice that at least one of the dark layers possibly related to an anomalously strong El Niño epi-sodes (ca. 1000 BP) seems coeval with the last Holocene beach-ridge of the Colan area in north-

[5] ORTLIEB L, R FOLLEGATI, O ZUÑIGA, R ESCRIBANO, I KONG, L RODRIGUEZ, Ph MOURGUIART, L MARTIN & M FOURNIER (1995) A paleoceanographic record of Little Ice Age and Warm Medieval Interval conditions in northern Chile? Preliminary data from gravity cores in Bahía Mejillones (23° lat. S). Symposium on Water, Glaciers and Climatic change in the tropical Andes, La Paz, Bolivia, ORSTOM-Bolivia, Universidad Mayor de San Andrés, SENAMHI & CONAPHI. Abstr. 1: 277-278.

Preliminary paleoclimate interpretation
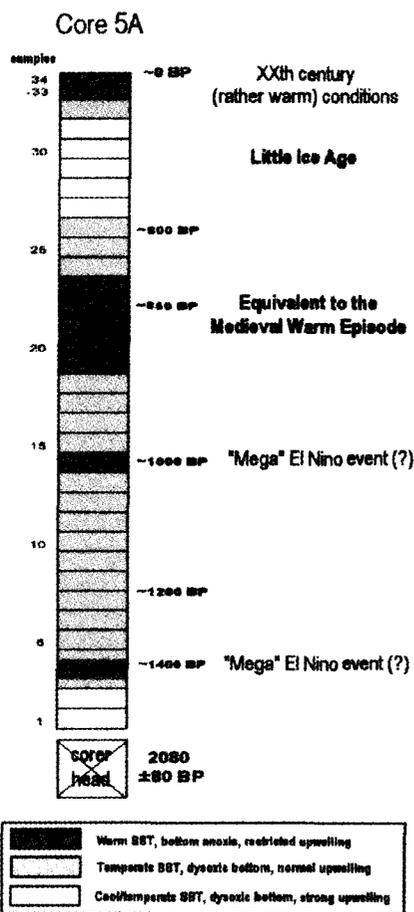
Core 5A

Fig. 13. Paleoceanographic and paleoclimatic interpretation proposed for core 5a, on basis of sedimentological and biostratigraphic data from both cores 24 and 5A. According this interpretation, the Little Ice Age would have been characterised by cool SST and strong upwelling, while an episode which may be coeval with the Warm Medieval Epoch was marked by warmer SST and enhanced hypoxic conditions at the bottom. In the preceeding millenium, two short episodes evidenced by terrigenous input and biological indicators of warm SST are interpreted as possible manifestations of " mega-El Niño " events.

Interpretación paleoceanográfica y paleoclimática propuesta para el testigo 5A, fundada en datos sedimentologicos y bioestratigráfico de ambos testigos 24 y 5. Según esta interpretación, la Pequeña Edad del Hielo hubiera sido caracterizada por aguas superficiales frías y una fuerte surgencia, mientras un episodio que sería coetáneo del Intervalo Cálido del Medievo hubiera sido marcado por aguas superficiales más cálidas y condiciones hipóxicas en el fondo. Durante el milenio anterior, se interpreta que dos episodios cortos con evidencias de aportes terrígenos y con bioindicadores de aguas superficiales cálidas podrían constituir posibles manifestaciones de eventos " mega-El Niño ".

ern Peru, dated ca. 1010 AD, and interpreted as one of the last "mega El Niño" events of the the last 5,000 years (Ortlieb & Macharé 1993, Ortlieb et al. 1995, Ortlieb et al. [5]).

Little Ice Age conditions in Mejillones Bay

The top of the sedimentary column of core 5A (i.e. the upper 15 mm, sample 33-34) can be considered as the fourth dark layer of the core. It is characterised by a reduced abundance of planktonic forams, no sinistral coiling *Neogloboquadrina pachyderma*, numerous scales of *Engraulis ringens* and a relative peak of abundance of *Bolivina seminuda*. This recent assemblage, which may correspond to the last century or so, points to a relatively warm episode, albeit not as warm as the " Warm Medieval Epoch". On a global scale, between the "Warm Medieval Epoch" and the 20th century, occurred a cool period known as the Little Ice Age (16th -19th centuries, Lamb 1977, Bradley & Jones 1992). In the core 5A, this period would be represented by samples 27-31 which are ligther-coloured, and show maximum peaks of phytoplankton and of *N. pachyderma* (both total number and sinistral forms, see sample 27) abundance. These layers which are also characterised by a lack of scales of *S. sagax* and *T. s. murphyi*, seem to have been deposited during relatively cool conditions and strong upwelling activity. A relative diversity of benthic forams and the progressive diminution of abundance of *B. seminuda* and of *B. costata* suggest that the lower part of the water column and the interface were experiencing dysoxic conditions, i.e., with some higher levels of oxygen than before and after that episode. This interpretation of cooler water and enhanced upwelling must still be confirmed by a more precise study on the phytoplankton indicators. A cooler state of the Bahia Mejillones environment, which may be depicted in some aspects at least by modern "La Niña" events, should be better understood to enable a proper reconstruction of the Little Ice Age conditions in the area.

The other periods within the last 2,000 years

Between the few dark layers of the core and at the base of core 5A, assemblages of fish remains, phytoplankton and foraminifers, as observed in either isolated samples or in groups of two or three samples, point to varying but relatively cool water conditions. The benthic foraminifer assemblages tend to be more diversified (less predominant *B. seminuda*), the planktonic forams (includ-

ing left-coiling *N. pachyderma)* and the phyto-
plankton are more abundant, and *Sardinops sagax*
and *Trachurus symmetricus murphyi* are totally
absent. We tend to interpret that these assem-
blages of bio-indicators correspond to intermedi-
ate conditions, cooler than those prevailing dur-
ing the deposition of the darker layers but not as
cold as during the layers 27-31.

Perspectives for future studies

The present study relied heavily on the contrast
between bio-indicator compositions of darker *vs.*
lighter-coloured sediments, as they were observed
macroscopically. But X-ray radiographs, that were
not performed on cores 5A and 24, provide a
much more precise tool to distinguish successive
layers and laminations (see Fig. 6). Future studies
on Bahía Mejillones cores thus should systemati-
cally involve X-radiographs. Additional refine-
ments in the sedimentological analyses of the
cores will also include petrographical thin sec-
tions cut vertically downcore, analyses of the
microscopic texture and composition (including
lithic elements of eolian or alluvial origin and
organic matter components) at a sub-millimetre
scale. Such studies should determine through dif-
ferent indicators (not only the bio-indicators used
here in a preliminary way, but also mineralogical
and geochemical indicators) ocean-climate situa-
tions, such as episodes of enhanced upwelling, or
of El Niño-like (or La Niña-like) conditions
(Vargas, doctoral thesis at Bordeaux I University).

As mentioned above, the part of the study deal-
ing with foraminifers should be considered as
preliminary. Both for planktonic and benthic
forams, more detailed taxonomic and ecological
studies are required. In the case of the benthic
forams, for instance, an analysis of presently
living organisms, with measurements of physico-
chemical parameters of the water-sediment inter-
face, is deeply needed. With respect to the plank-
tonic forams, it would be most useful to document
the relationship between the different water
masses that interfere in Bahía Mejillones area and
their respective composition in zooplankton
populations. In both cases, for benthic and plank-
tonic forams, we also need to work on time-series
that encompass recent El Niño and La Niña events,
so as to document a wide spectrum of modern
conditions that may provide proxies for contrasted
past conditions.

One of the parallel approaches which should be
encouraged in a near future, is a stable isotope
study on both planktonic and benthic forams
downcore. In a recent work based on stable iso-
tope measurements on planktonic foraminifers
and on carbonate variation, Keigwin (1996) inter-
preted that in the Sargasso Sea the sea water was
about 1°C cooler than nowadays both during the
Little Ice Age (LIA) and about 1700 years ago,
and that the sea was 1°C warmer during the Me-
dieval Warm Period (ca. 1000 AD). Paleo-
temperature data based on ^{18}Oxygen measure-
ments on Florida corals also indicate a 1 to 2 °C
lowering of sea surface temperature during the
LIA, between 1680 and 1750 AD [6]. These esti-
mates coincide with other indications of global
sea surface temperature variations during the last
millennium (Bradley & Jones 1993). Obviously,
it would be interesting to determine if the same
range of temperature difference can be assessed
in the southeastern Pacific, namely at Bahía
Mejillones.

Regarding the other bio-indicators, several im-
provements are also expected in a near future.
The fish remains should be studied in box-cores
instead of small-diameter gravity cores, to enable
more representative, statistically significant, stud-
ies. For the phytoplankton, it was stressed that
much more detailed studies are needed for more
precise reconstructions of the primary productiv-
ity evolution and of the upwelling conditions
through time. In a sediment which can be de-
scribed as a diatomitic mud, it is clear that the
data presented here (total number of valves per g,
every 10 mm downcore) is only a very prelimi-
nary approach. Beside the fact that taxonomic
analyses will be performed at the genus/species
level, future studies should be carried on much
thinner samples than the 10-mm sampling inter-
val considered in this study.

Concluding remarks

The sediments accumulated on the bottom of
Mejillones bay, at a depth of over 80 m are green-
ish, organic-rich, diatomitic muds in which are
preserved foraminifers and fish remains, and
where no macro-infaunal elements were observed.
The lack of remnants of benthic organisms that
normally cause bioturbation is of utmost impor-
tance for paleoceanographic reconstructions. It
implies that this locality may have recorded, with

[6] PATZOLD J & G WEFER (1992) Bermuda coral reef record of the last 1000 years. 4th International Conference
on Paleoceanography, Kiel. Abstr. 224-225.

an unusual detail, the evolution of the biological productivity (from diatoms to fishes) of the embayment. In fact the area of Bahía Mejillones is, up to now, the first one along the coast of western South America that offers an opportunity to study the evolution of paleoceanographic conditions throughout the last few thousand years, at a (sub-)decadal time scale. More to the south, in Concepcion-Arauco area, where relatively shallow and suboxic environments were recognised (Salamanca 1989, Arntz et al. 1991, Gallardo 1992, Gallardo com. pers.), the concentration of dissolved oxygen at the bottom has not been sufficiently low to prevent bioturbation by benthic organisms. Another important difference between Mejillones embayment and other sites to the south, like the Concepcion area, is its extreme aridity. The general lack of rainfall, at present and in the past, explains an exceptionally low input of terrigenous material to the embayment which itself affected both the physico-chemical conditions of the marine environment and the composition of the benthic community. The scarcity of rainfall events, thus, also played a role in the lack of bioturbation at the bottom of the bay.

On the other hand, the existence of the strong upwelling centre at Punta Angamos, which controls a high primary productivity, and thus the accumulation of organic matter, indirectly enhances the low-oxygen conditions at the bottom of the embayment. The high sedimentation rates favour the preservation of manifestations of past oceanographic changes and make possible an exceptional high resolution record.

In this study we did not aim to reach a very high resolution. We tried to demonstrate, through a sampling every centimetre in two cores, that the abundance variations of the major biological remains have a real potential for paleoceanographic reconstructions. The fish scales, diatoms and planktonic foraminifers, proved to be useful indicators of physical conditions of the upper part of the water column and of past upwelling regimes. The benthic foraminifers and some sediment characteristics gave information on the degree of hypoxia of the bottom of the embayment and, secondarily, on the stratification of the water column. Through this study, it was also shown that the hypoxic conditions observed nowadays in Mejillones embayment had been pervasive during, at least, the last two millennia. More detailed studies involving box-cores and longer piston cores are planned, and more sophisticated studies are currently being performed on a series of cores. Bahía Mejillones area should soon become a case-study for the reconstruction of the variations of wind intensity, upwelling intensity, primary pro-

ductivity, and sea surface temperature during the last few millennia.

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