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A WARM INTERGLACIAL EPISODE DURING OXYGEN ISOTOPE STAGE 11 IN NORTHERN CHILE

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Abstract — Combined palaeontological, morphostratigraphic and geochronologic data from emerged Middle Pleistocene coastal deposits in Mejillones Peninsula (23°S), northern Chile, strongly suggest that climatic conditions were particularly warm during the Oxygen Isotope Stage 11 high seastand episode. An anomalous warm-water molluscan assemblage from localities assigned to that interglaciation included several extralimital species, presently living only north of 6°S (or 14°S), that were not present in the area during subsequent Middle and Late Pleistocene, or Holocene, interglacial episodes. Only two of these extralimital species may be found nowadays at the 23°S latitude, in a protected locality, immediately after the occurrence of strong El Niño events. Many of the species of the thermally anomalous molluscan assemblage (TAMA) are the same as those which lived in a closed shallow lagoon near Santa, north-central Peru (9°S) during a brief mid-Holocene episode. The new findings thus indicate that lagoonal and protected embayments were significantly warmer than the open marine environment ca. 400 ka. Actually, the co-occurrence of cool water fauna in exposed sectors of the coastline at that time suggests that the coastal upwelling activity and the Humboldt Current effects were not strongly reduced. The warm-water conditions prevailing in lagoons and protected bays during the Mid-Brunhes episode may reflect particularly warm air temperatures and distinct ocean–atmosphere relationships than those prevalent nowadays. These data support the hypothesis that the Oxygen Isotope Stage 11 was the warmest interglaciation, at least in the southern hemisphere. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Sea Level and Climatic Variations During the Last Million Years

During the last million years, the inter-related climatic and sea level fluctuations were strongly controlled by astronomical forcing (Milankovitch cycles of 23–19, 40 and 100 ky), with a predominance of the 100 ky cycle on the glaciations/interglaciations rhythm (e.g. Shackleton and Opdyke, 1973; Hays *et al.*, 1976; Imbrie and Imbrie, 1980; Imbrie *et al.*, 1992; Liu, 1992, 1995). It is commonly admitted that the interglacial episodes have been characterised by a sea level position close (within a few meters) to the present datum, and by global climatic conditions that compared with those experienced in the Holocene. The oxygen-isotope composition of plankton foraminifers from the world oceans indicates that, from one interglacial stage to the other, the sea surface temperature (SST) was in the same range, at least during the last half-million years (Shackleton and Opdyke, 1973; Hays *et al.*, 1976).

Oxygen Isotope Stage 7 is generally considered as having been a little colder than stages 1 (Holocene), 5, 9 and 11 (Shackleton, 1987), but no consensus was met as to which of the latter was the warmest isotopic stage. Discrepancies are observed between deep-sea core data from the various oceans and at distinct latitudes. According to many deep-sea records, the only, or major, episode warmer than the Holocene would have occurred at the beginning of the last interglacial, during Oxygen Isotope Substage 5e (Shackleton and Opdyke, 1973; Kellogg, 1977; Shackleton, 1987). An indirect confirmation of a relatively higher global temperature during the early stage of the last interglaciation is provided by widely scattered evidence for a higher sea level than nowadays at ca. 120 ka. A slightly more elevated "eustatic" sea level stand at that time (some 5–7 m above present datum?) is classically interpreted as a consequence of major global sea water volume than nowadays, a minor size of the polar ice sheets, warmer air temperature and SST. The paleo-position of "eustatic" sea level during former interglaciations is difficult to assess for Middle Pleistocene times (700–140 ka): it can be established with some precision for Oxygen Isotope Substage 5e, but it is increasingly less precise for Oxygen Isotope Stages 7, 9 and 11. In numerous coastal areas of the world, regional and local tectonic instability as well as glacio-isostatic effects hamper a precise reconstruction of paleo-sea level position from emerged terraces and reef tracts.

A Warmer Interglacial Episode During Oxygen Isotope Stage 11?

In a recent review on multiple evidence for warmer than usual Pleistocene interglacial stages, Burckle (1993) concluded that Oxygen Isotope Stage 11 probably had been warmer than the present and the last three previous interglacial episodes. The most convincing evidence for such interpretation comes from the southern hemisphere, and includes: carbonate-rich layers in the southern Pacific Ocean at ca. 400–500 ka (Kennett, 1970), particularly high rate of opal accumulation during Oxygen Isotope Stage 11 in the southern Atlantic Ocean (Charles *et al*., 1991), greater fluxes of North Atlantic Deep Water (NADW) into the Southern and Indian oceans during Oxygen Isotope Stage 11 (Oppo *et al*., 1990; Hodell, 1993). On the basis of radiolarian and other data from the southern Indian Ocean, Morley (1989) and Howard and Prell (1992) also determined that Stage 11 had been the warmest, and longest, interglacial stage in the last half-million years.

As in the northern hemisphere deep sea record, the indications for a particularly warm Stage 11 are scarce (e.g. Ruddiman and McIntyre, 1976; Ruddiman *et al*., 1986, 1989; Aksu *et al*., 1992) or lacking. It may be hypothesised that during that particular interglaciation, anomalous warm climatic conditions were restricted to the southern hemisphere, and were not a global feature. From an orbital point of view, the Oxygen Isotope Stage 11 interglaciation actually corresponds to an eccentricity low (413 ky component) that, according to the Milankovitch theory, should have been rather colder than observed. It is the '400 ka problem' of Imbrie and Imbrie (1980), and the 'Isotopic Stage 11 problem' of Imbrie *et al*. (1993) which pointed that the $\delta^{18}O$ response in the deep oceans was, for some reason, not proportional to the postulated forcing.

Paleoceanographic records of this particular interglaciation from nearshore environments may be of great value, since they may provide some interesting clues to solve the paradox of the Mid-Brunhes climate (Jansen *et al*., 1986). In apparent contradiction with some of the deep sea record from the northern hemisphere, it may be mentioned that some indication for exceptionally warm conditions were provided by coastal faunas from northwestern Alaska. There, the Anvilian emerged coastal deposits contain a series of molluscan species that are either extinct and/or of warmer water than the present fauna (MacNeil *et al*., 1943; Hopkins, 1967); this unit had been assigned to the Early Pleistocene (Hopkins *et al*., 1974) until a radiometric age determination and aminostratigraphic analyses strongly suggested that it was of Middle Pleistocene age, and probably coeval with Oxygen Isotope Stage 11 (Kaufman *et al*., 1991; Kaufman and Brigham-Grette, 1993).

In this note we present paleontological data from the northern coast of Chile that supports the hypothesis of a warm interglacial period assigned to Oxygen Isotope Stage 11. The faunal assemblage, characterised by the predominance of extralimital species from the Panamic Province (Fig. 1), strongly suggests much warmer conditions than during any other Quaternary high seastand episode, including the present one.

QUATERNARY MARINE DEPOSITS OF MEJILLONES PENINSULA

Regional Geological Setting

The subduction of the Nazca Plate below the South American continent is responsible for uplift motions along the coast of northern Chile and southern Peru. The neotectonic behaviour of the northern Chile coast is documented by marine terraces formed during Pliocene and Pleistocene high seastands on the narrow coastal plain lying at the foot of the Coastal Cordillera. Thick accumulations of alluvium generally hide the highest lying emerged wave-cut platforms (Ortlieb *et al*., 1996a). Plio-Pleistocene marine-abraded surfaces and Quaternary beach-ridge series are well preserved in Mejillones Peninsula, a 60 × 40 km large crustal block located immediately north of Antofagasta (23°S; Figs 1 and 2). The peninsula is crossed by major fracture zones which are partly active, and several faulted blocks show differential uplift motions (Okada, 1971; Ferraris and Di Biase, 1978; Armijo and Thiele, 1990). The peninsula exhibits three exceptional sequences of regressive beach ridges formed on gentle slopes that extend on hundreds of km^2 from an elevation of the order of 200 m and the present coastline (Ortlieb, 1993; Ortlieb *et al*., 1995). The two major series of beach ridges are found on the north (Pampa Mejillones) and south (Pampa del Aeropuerto) sides of the wide isthmus linking the coastal plain to the peninsula. As a result of the extreme aridity of the area, the sediments and faunal remains of the beach ridges are generally very well preserved. The abrasion terraces and beach ridges document the Quaternary uplift of distinct sectors of the peninsula (Ortlieb, 1993; Ortlieb *et al*., 1995, 1996b), and also provide an unusual insight into palaeoceanographic conditions during succeeding episodes of interglacial high sea-stands.

The age of the emerged Pleistocene coastal deposits in the area is still actively debated. We shall mention briefly the previous morphostratigraphic interpretations and present some results of on-going morphostratigraphic and geochronologic studies. For this purpose, three key areas will be considered: the coastal region along the northern half of Antofagasta Bay; Pampa del Aeropuerto; and Pampa Mejillones.

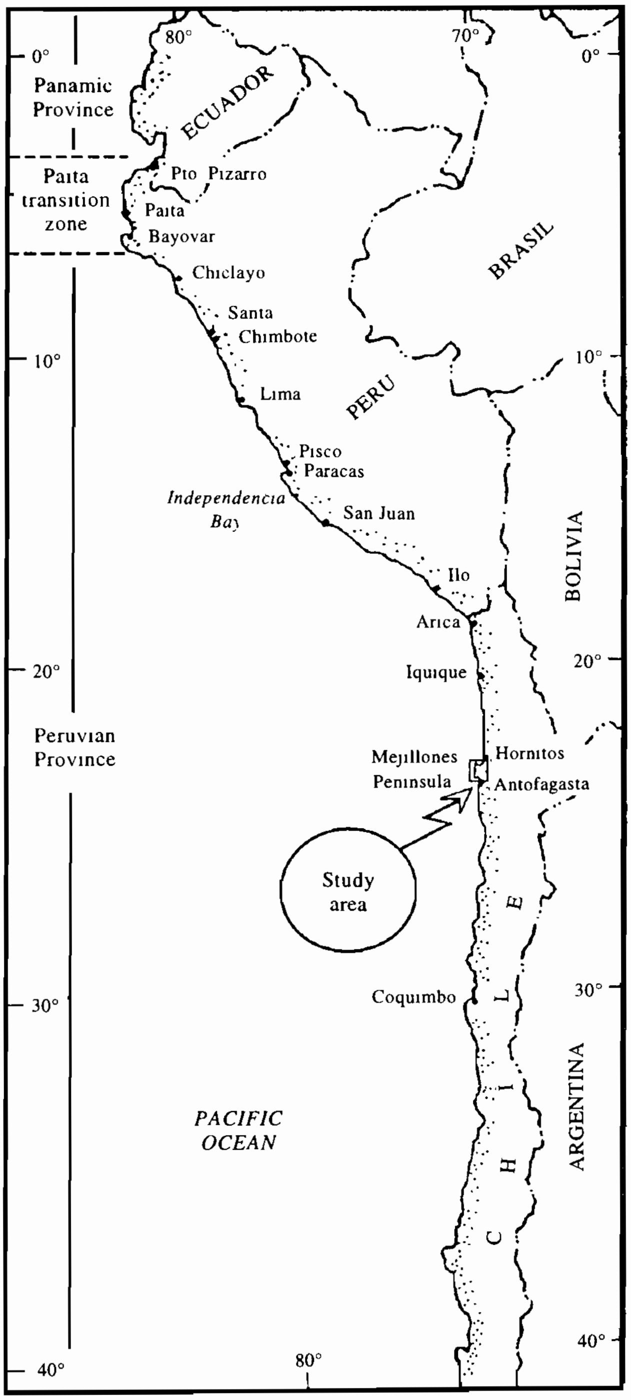

FIG. 1. Locality map of the Peru–northern Chile coasts, with indication of the boundaries of marine faunal provinces.

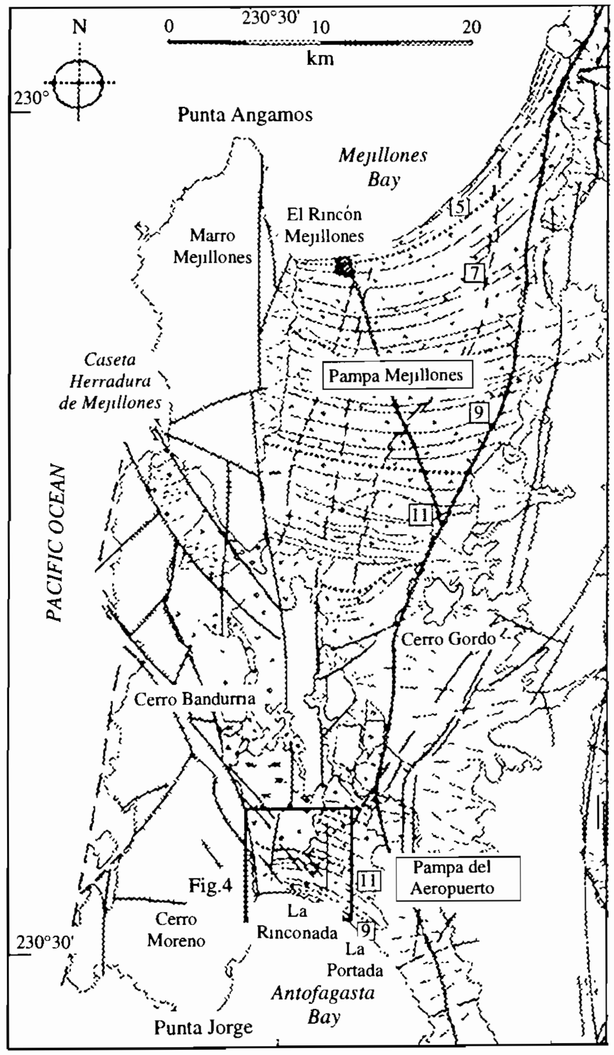

FIG. 2. Sketch map of Mejillones Peninsula, and location of the study area, near La Rinconada, north of Antofagasta Bay. The sets of Pleistocene beach ridges that form Pampa Mejillones and Pampa del Aeropuerto are assigned to successive interglacial episodes identified by the respective number of Oxygen Isotope Stage (5, 7, 9, 11), according the interpretation proposed by Ortlieb *et al.* (1996b).

Quaternary Marine Deposits along Antofagasta Bay

Antofagasta Bay is bordered to the northeast by a vertical seacliff that cuts an ~40 m thick sequence of Pliocene marine calcarenites, coquina and sandstones (La Portada Formation; Ferraris and Di Biase, 1978) covered by Pleistocene unit that is a few meters thick and composed of marine deposits and alluvium. The Pleistocene coastal sediments are loosely consolidated sands with interlayered coquina beds. They correspond to a single marine terrace unit.

New geochronological data recently obtained on mollusk shells from this last unit, at the locality called La Portada (Fig. 3), strongly suggest an Oxygen Isotope Stage 9 age (Ortlieb *et al.*, 1995). Two sets of 14 valves of each of the two dominant species (*Mulinia* cf. *edulis* and *Mesodesma donacium*) yielded mean allo/isoleucine ratios of 0.66±0.10 and 0.67±0.12, respectively. These values compare with the mean A/I ratio of 0.71 yielded by samples (from the same bivalve species) on the third emerged terrace at Hornitos (22°55′S; Ortlieb *et al.*, 1996a) and can be assigned regionally to the Stage 9 interglacial episode. Furthermore, three U/Th age determinations (obtained at GEOTOP, Université du Québec à Montréal) on shells from the same locality yielded the following results: 282±9 ka for one measurement through the TIMS (thermal ionisation mass spectrometry) technique, and 275±11 ka and 288±12 ka (mean = 282 ka) for two measurements by alpha-spectrometry. These concordant results, and additional morphostratigraphic arguments (Ortlieb *et al.*, 1995), thus strongly suggest that the Quaternary marine terrace that cuts and overlies the

Pliocene La Portada Formation was formed during Stage 9, ca. 300–330 ka.

To the west of La Portada, the seacliff height diminishes progressively as a result of a recent westward tilting of the Plio-Quaternary beds. This attitude is related to a half-graben structure limited westwards by an active major crustal fault. The N–S trending La Rinconada fault separates the uplifted Cerro Moreno block to the west and the Pampa del Aeropuerto plain (Fig. 2). The tilt of the Plio-Quaternary sequence in the northern Antofagasta Bay is accompanied by a series of recent normal faults (which systematically downthrow the western compartments) that belong to a complex *en échelon* system (NNW–SSW and N–S trends; Armijo and Thiele, 1990; Ortlieb *et al.*, 1995).

At the southwestern extremity of the Mejillones Peninsula, several marine abraded platforms were cut at elevations reaching up to about +150 m. Electron Spin Resonance (ESR), U/Th and allo/isoleucine analyses were performed on molluscs from the three lower terraces at Juan Lopez but provided only preliminary results which did not lead yet to a well established chronostratigraphy (Ratusny and Radtke, 1988; Radtke, 1989; Ortlieb *et al.*, 1995). Nevertheless, the faunal content of the deposits associated to two terraces tentatively assigned to the Oxygen Isotope Stages 7 and 9, was studied.

Along the southeastern shore of Antofagasta Bay, the last interglacial high seastand was recorded at elevations varying between +6 (Punta Coloso, Fig. 3) and +15 m (north of Antofagasta; Ortlieb *et al.*, 1994, 1995). Other terrace deposits were tentatively assigned to Oxygen Isotope Stages 7, 9 and 'older than 11' (Ortlieb and Guzmán, 1994; Ortlieb *et al.*, 1994, 1995; Fig. 3). The

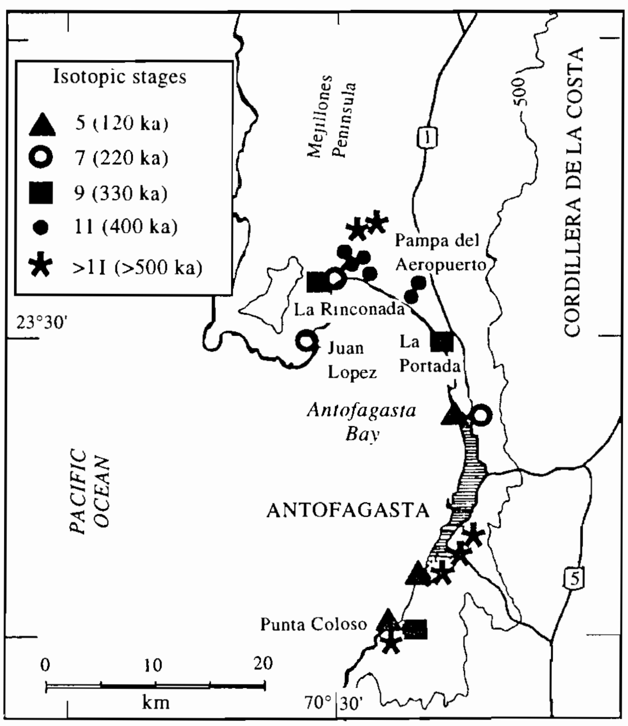

FIG. 3. Sampled localities of Pleistocene marine terraces and associated deposits, around Antofagasta Bay. The faunal content of these deposits is indicated in Table 1.

oldest Pleistocene terrace identified in the surroundings of Antofagasta lies at ca. +100 m elevation (Ortlieb *et al.*, 1995). These Early Pleistocene deposits, as well as some lateral equivalents in the northwestern Pampa del Aeropuerto plain, at ca. +200 m (Fig. 3), are the oldest Quaternary marine units, with characteristic Quaternary fauna (Herm, 1969), that crop out in the Antofagasta Bay area.

The Pleistocene Beach Ridges at Pampa del Aeropuerto

Pampa del Aeropuerto is a wide, slightly deformed, elevated coastal plain that slopes southward from the centre of the isthmus, at ca. +200 m elevation, toward the Antofagasta embayment. It is covered by a series of beach ridges disposed in a concentric way and grossly parallel to the present coastline. The beach ridges are well preserved and display beach cusp structures (visible on aerial photographs), that compare with those formed on the present beach at La Rinconada (Fig. 4). The sequence of regressive shorelines may be split into several sets that were most probably formed during succeeding episodes of interglacial high sea stands.

The age of the sets of beach ridges is still a matter of discussion. A Pliocene age was suggested on the geological map (Ferraris and Di Biase, 1978), while several authors had envisaged, without any precise study of the emerged marine deposits, that the whole beach ridge sequence might be as young as Late Pleistocene (Okada, 1971; Armijo and Thiele, 1990). However, the assignation of the Quaternary unit at the top of the seacliff at the locality of La Portada (see above) to the Oxygen Isotope Stage 9 implies that the Pampa del Aeropuerto beach ridges sets are necessarily older than 330 ka. In the northern part of Pampa del Aeropuerto, the oldest beach ridges of the sequence are observed either at the foot of a major (50 m high) paleo-seacliff (Pleistocene marine limit) or in offlap disposition upon Pliocene marine units. It is thus inferred that the older part of the beach–ridge sequence is of Early Pleistocene (or early Middle Pleistocene?) age, and that the whole beach–ridge sequence was formed in the lapse of several hundred thousand years.

The geometry of the coastal features of the area indicates that the Pampa del Aeropuerto plain was steadily uplifted until a strong deformation phase which occurred at the end of the Middle Pleistocene. This deformation included the faulting of the Plio-Pleistocene units by the NNW–SSE en *échelon* system, the dipping of recent Quaternary units (last three interglacial coastal deposits) below sea level at La Rinconada, and the upwarp of a small faulted block northwest of La Rinconada. It is on top of this southward tilted fault block and in the vicinity of a major NNW–SSE trending fault trace which cuts the western part of Pampa del Aeropuerto, that were found the outcrops of the anomalously warm faunal assemblage studied here. The lateral correlation between individual beach ridges across the large NW-trending fracture zone indicates clearly that

FIG. 4. Aerial photograph of Pampa del Aeropuerto, in the southern part of the isthmus of Mejillones peninsula (Instituto geogiáfico Militar, Hycoon 10089). The La Rinconada tilted fault block is visible to the left. Note the continuity of the beach ridges across the large NNW–SSE trending fault zone that separates the La Rinconada block from the rest of Pampa del Aeropuerto. Sample localities are indicated by black dots.

the block faulting and the tilting occurred recently, well after the deposition of the sedimentary units. The set of beach ridges studied here actually predates the marine terrace unit which caps the seacliff at La Portada and which is correlated with Oxygen Isotope Stage 9. Consequently, the former unit is tentatively assigned to the previous interglacial cycle, i.e. Oxygen Isotope Stage 11 (ca. 400 ka).

Quaternary Marine Deposits of Pampa Mejillones

The northern part of the isthmus of Mejillones Peninsula is another large (400 km^2) plain slowly dipping northward, toward Mejillones Bay (Fig. 2). It is bounded to the west by the N–S trending Mejillones fault and extends eastward to the foot of the Coastal Cordillera. Pampa Mejillones plain reaches a maximum elevation of +220 m and is almost totally covered with beach ridges sub-parallel to the present coastline of Mejillones Bay. This series of regressive shorelines have a major extension than its counterpart on the southern side of the Mejillones Peninsula. The ridges, also very well preserved and disposed in successive sets, are several tens of metres wide, some 2 to 5 m high and may be more than 20 km long. They consist of coarse, fossiliferous, loosely consolidated sediment. The ridges are separated by wide shallow troughs, now generally covered by a sheet of eolian sand. Like in Pampa del Aeropuerto, the geometric disposition of the ridge sequence shows that after a relatively long period of steady uplift, the plain suffered a strong tectonic deformation with major N–S trending normal faulting. The vertical displacement produced by these faults are of several meters, and may locally reach 20 m (Armijo and Thiele, 1990; Ortlieb *et al.*, 1995).

The precise chronostratigraphy of the series of beach ridges is yet unresolved. Herm (1969) showed that the ridges were post-Pliocene, and interpreted that a major discontinuity in the geometry of the beach ridge sets marked a limit between 'Middle Pleistocene' Serena II and 'Early Pleistocene' Serena I deposits. Alternatively, Ferraris and Di Biase (1978) mapped the northern half of

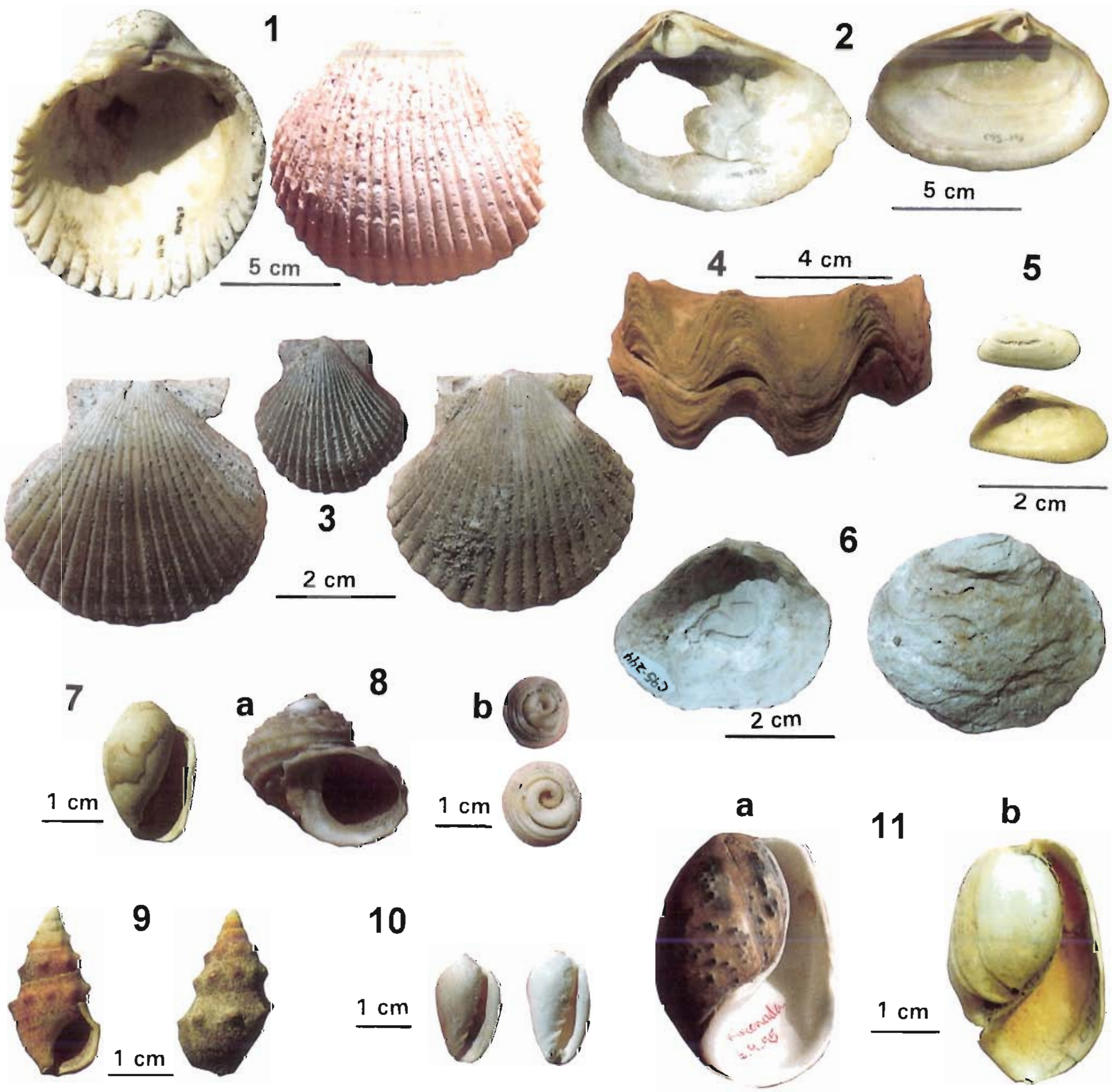

FIG. 5. Some of the most abundant extralimital species of the TAMA (thermally anomalous molluscan assemblage) of the 400 ka deposits at La Rinconada locality. All these species have been found living today in the Panamic province and/or in the Paita Transition Zone (see Fig. 1). (1) *Trachycardium* cf. *procerum* (Sowerby, 1833), right valves, interior and exterior views; (2) *Mactra velata* (Philippi, 1849), right (large, fragmented) and left (medium size) valves, interior views; (3) *Argopecten circularis* (Sowerby, 1835), two right valves, medium size, and a juvenile left valve, exterior views; (4) *Ostrea megodon* (Hanley, 1846), whole individual with articulated valves; (5) *Donax peruvianus* (Deshayes, 1855), small left valve (exterior) and right valve (interior); (6) *Anomia peruviana* (d'Orbigny, 1846), upper valves of medium size individuals (interior and exterior); (7) cf. *Melampus* sp., undetermined individual (out of three, not well preserved shells); (8) *Turbo* cf. *fluctuosus* (Wood, 1828): (a) apertural view of medium size individual; (b) two calcarcous operculums; (9) *Cerithium stercusmuscarum* (Valenciennes, 1833), apertural and abapertural views; (10) *Prunum curtum* (Sowerby, 1832), apertural view of two individuals; (11) *Bulla punctulata* (A. Adams *in* Sowerby, 1850): (a) apertural view of a recent individual (from La Rinconada locality, collected in Sept. 1995); (b) apertural view of a fossil sample from the ca. 400 ka deposit near La Rinconada.

the beach–ridge sequence as Pleistocene (a so-called 'Mejillones Formation') and the southern half of the plain as Pliocene (La Portada Formation). This interpretation has been accepted by some recent workers (e.g. Flint *et al*., 1991). According to another interpretation (Okada, 1971; Armijo and Thiele, 1990), the whole series of beach ridges might have been formed during the regression subsequent to the last high seastand (Oxygen Isotope Stage 5). In 1993, Ortlieb proposed to divide the sequence of beach ridges in a series of sets which might be coeval with as many successive interglacial (and/or interstadial) episodes. This hypothesis was based upon a preliminary air-photo interpretation of discontinuities between the successive sets of beach ridges, and on a few previously available geochronological results (Radtke, 1987, 1989) on the youngest deposits of the Pampa Mejillones sequence (at El Rincón). This interpretation was subsequently slightly modified when we discovered that the deposits cropping out between +150 and up to +200 m in the southern part of Pampa Mejillones were characterised by a warm-water faunal composition similar to that of the youngest set of beach ridges at Pampa del Aeropuerto, near La Rinconada (Ortlieb *et al.*, 1995, 1996b).

U-series and aminostratigraphic analyses performed on shells collected across the Pampa Mejillones sequence did not yet allow precise and conclusive age determinations (Hillaire-Marcel *et al.*, 1995; Ortlieb *et al.*, 1995). High $^{234}U/^{238}Th$ ratios (>1.2), indicators of a non-marine origin of the uranium, and evidence for late diagenetic uptake of this element seriously limit the possibility to calculate the age of the Pampa Mejillones ridges. On the other hand, aminostratigraphic studies did not prove to be entirely reliable. A shallow burial of the molluscan material apparently produced differences in the thermal history of the samples, even if the samples generally yielded increasing allo/isoleucine ratios with the elevation of the ridge sets across the plain. Several measurements in localities with the anomalous warm-water fauna (above +150 m), thus produced allo/isoleucine ratios of the order of 0.9, value compatible with an Oxygen Isotope Stage 11 age in this region (Ortlieb *et al.*, 1995; *in preparation*). Immediately to the northeast of Mejillones Bay, in the area of Chacaya-Hornitos (see Ortlieb *et al.*, 1996a), the three lowermost conspicuous staircased marine terraces were tentatively correlated with Oxygen Isotope Stages 5, 7 and 9.

Thus, difficulties were met in the establishment of a solid chronostratigraphy of the exceptional series of beach ridges at Pampa Mejillones, but the available data suggest that the major part of the sequence was formed during the Middle Pleistocene. A lateral correlation based on paleontological grounds is proposed between two sets of warm-water mollusc bearing deposits from the northern and southern isthmus of Mejillones Peninsula. At Pampa del Aeropuerto, the chronological constraint is better assessed than at Pampa Mejillones and leads us to infer that both anomalous molluscan assemblages are coeval with Oxygen Isotope Stage 11.

THE WARM-WATER MOLLUSCAN ASSEMBLAGE AT LA RINCONADA

The surface of the strongly tilted fault block found 3 km north of La Rinconada is covered by a series of coastal sediments deposited previously to the tectonic deformation, which now lie at increasing elevations, between below +10 m and +80 m, from south to north. On the La Rinconada block, and across the faulted zone that separates the block from the Pampa del Aeropuerto plain, the Pleistocene coastal sediments are one to several meters thick, and lie upon Pliocene beds. They vary between fine sands to pebbly coarse sands, and also include irregularly cemented biocalciruditic coquina beds. In places, a superposition of distinct units points to a depositional regressive sequence, with lagoonal or beach deposits overlying subtidal sediments with *in situ* fauna (articulated shells of pelecypods in living position).

The varied sedimentary units contain distinct faunal assemblages that are either typically warm-water forms (open or closed lagoons, shallow marine environments), or a mix of warm and cold-water forms (nearshore environments and exposed beach). Some beds corresponding to subtidal environments are the only ones that include rather cold-water forms identical to the Holocene fauna of the area (*Argopecten purpuratus* [Lamarck, 1819], *Choromytilus chorus* [Molina, 1782], *Transennella pannosa* [Sowerby, 1835], *Petricola rugosa* [Sowerby, 1834], *Thais chocolata* [Duclos, 1832]). The variety of sedimentary facies and of associated faunal assemblages suggest multiple changes in the palaeogeography of the area, and in the nearshore conditions, within a single episode of interglacial high seastand.

From west to east of Pampa del Aeropuerto plain, a major lateral change is observed in the faunal composition of the same beach ridge set. In sharp contrast to the 'warm' fauna found upon and near the La Rinconada block, the beach deposits of the eastern and central area of the coastal plain bear a cool-water fauna (*Mulinia* cf. *edulis* [King, 1831], *Mesodesma donacium* [Lamarck, 1818], *Glycymeris ovatus* [Broderip, 1832], *Calyptraea trochiformis* [Born, 1778], *Crepipatella dilatata* [Lamarck, 1822], and *Oliva peruviana* [Lamarck, 1811]). This fauna is similar to that found in the older (higher elevated) beach–ridge sets and in the younger marine terrace deposit (Oxygen Isotope Stage 9) at La Portada. As there is no doubt that the deposits bearing cool-water fossils are coeval with those from the La Rinconada area (see Fig. 4), the variation in the faunal composition must be attributed to paleogeographic factors. Cool nearshore conditions were prevalent in the non-protected part of the Antofagasta embayment. It was only in the northwesternmost part of Antofagasta Bay, near La Rinconada, protected from the cool waters of the Humboldt current, that lagoons with restricted circulation could form.

A 'Thermally Anomalous Molluscan Assemblage' (TAMA)

Table 1 compares the composition of molluscan faunas sampled on the La Rinconada block (and adjacent areas; Fig. 4), on the modern beach and in the older and younger Pleistocene deposits (from other interglacial episodes) around Antofagasta Bay (Fig. 3). The fauna upon the 'La Rinconada block' differs significantly from altogether the modern assemblage and the fossil content of the other Late and Middle Pleistocene emerged marine deposits. Because of the predominance of warm-water elements, it constitutes a 'thermally anomalous molluscan assemblage' (= TAMA) as referred to by Valentine (1955), Zinsmeister (1974), DeVries and Wells (1990), Ortlieb *et al.* (1990) and Roy *et al.* (1995).

A number of extralimital species of this TAMA had not

TABLE 1. Comparison of the molluscan fauna around Antofagasta Bay, between deposits assigned to the major high seastands of Oxygen Isotope Stages 5 (ca. 120 ka), 7 (ca. 220 ka), 9 (ca. 330 ka) and 11 (ca. 400 ka), as well as with older (early Middle Pleistocene or Early Pleistocene?) units and with the present day living fauna (Holocene). In bold are indicated the warmer water species only found in the deposits assigned here to the 400 ka high seastand episode. Identification of the species is based on Morris (1966), Keen (1971) and Marincovich (1973). Author and date of the species designation were omitted for the sake of conciseness

Chronostratigraphic units	Hol.	5e	7	9	**11**	>11
GASTROPODS:						
Aeneator fontainei	X	P	P		P	P
Bulla punctulata	(X)				**P**	
Calyptraea (T.) trochiformis	X	V	A	V	V	V
Cancellaria (S.) buccinoides	X	P		P		P
Cerithium stercusmuscarum	—				**A**	
Collisella spp.	X	P	P	P		P
Concholepas concholepas	X	V	A	A	A	V
Crassilabrum crassilabrum	X	V	P	P	P	V
Crepidula spp.	X	A			P	P
Crepipatella dilatata	X	V	P	V	V	A
Crepipatella dorsata	X	V	P	V	V	V
Crucibulum quiriquinae	X	P	P	V	A	P
Diodora saturnalis	—				P	P
Fisurella costata	X	A	P	?		A
Fissurella crassa	X	P				A
Fissurella latimarginata	X	P	P			?
Fissurella maxima	X	P	P	P		P
Fissurella peruviana	X	P			P	P
Fissurella spp.	X	P	P	P	P	A
Liotia cancellata	X	?	?	?	P	?
Littorina (A.) peruviana	X	V				P
cf. *Melampus* sp.	—				P	
Mitra orientalis	X			P		A
Mitrella unifasciata	X				P	P
Nassarius dentifer	?	P				
Nassarius gayi	X	A	P	P	A	V
Nucella (A.) crassilabrum	?		P		P	P
Oliva (O.) peruviana	X	V	A	V	V	V
Olivella sp.	—				**V**	
Polinices (P.) uber	X		P	P	A	
Priene rude	X	V		P	P	P
Priene scabrum	X	A	P	P	V	A
Prisogaster niger	X	V	P	V	V	A
Prunum curtum	—				**A**	
Rissoina inca	X	?	P	?	P	P
Scurria spp.	X	A	P	P		P
Sinum cymba	X	?	P	P	P	
Siphonaria (T.) lessoni	X	P			P	P
Tegula (C.) atra	X	V	A	A		V
Tegula (C.) euryomphala	X	?	P	A	V	V
Tegula (C.) luctuosa	X	P	P		V	
Tegula (C.) tridentata	X	V	P	P	A	V
Thais (S.) chocolata	X	P		V	V	V
Thais haemastoma	X					
Trigonostoma tuberculosum	X		P			
Trimusculus peruvianus	X	P		P		
Turbo* cf. *fluctuosus	—				**P**	
Turritella cingulata	X	A	P	V	V	V
Xanthochorus buxea	X	P			P	P
Xanthochorus cassidiformis	X	P	P	A	P	P

V = Very abundant, A = Abundant, P = Present, X = extant, (X) = exceptionally present, — = not present in the area, ? = probably present, but not collected. Hol. = Holocene (Present). 5e, 7, 9, 11, >11 = Oxygen Isotope Stages

TABLE 1. Continued

PELECYPODS:						
Anomia peruviana					**A**	
Arcopsis solida	—				**P**	
Argopecten circularis	—				**P**	
Argopecten purpuratus	X	V	V	V	V	A
Aulacomya ater	X	P	P	P		P
Barbatia pusilla	X	P			P	P
Brachidontes granulata	X	P	P		P	P
Cyclocardia* cf. *spurca beebei	—				**P**	
Carditella tegulata	X	P	A	P	A	P
Chama pellucida	X	V	P	P	A	V
Chione (L.) peruviana	—	P				
Choromytilus chorus	?	V	A	P	A	V
Cumingia mutica	?				P	
Cyclinella subquadrata	—			P		
Diplodonta inconspicua	X				P	?
Donax peruvianus	(X)				**P**	
Ensis macha	X	P				
Eurhomalea lenticularis	?	A			P	
Eurhomalea rufa	X	V	P	A	A	P
Gari solida	X	P		P		P
Glycymeris ovatus	X	V	A	A	V	A
Mactra velata	—				**A**	
Mesodesma donacium	X	V	P	V	A	P
Mulinia cf. *edulis*	—	P	P	V	V	V
Mysella spp.	X	P			?	
Nucula cf. *exigua*	X		P			
Ostrea cf. *columbiensis*	—		V			
Ostrea megodon	—				**V**	
Perumytilus purpuratus	X	V	A			P
Petricola (P.) rugosa	X				A	
Protothaca (P.) thaca	X	V	V	P	A	A
Protothaca sp.	—				**P**	
Raeta (R.) undulata	—				?	P
Semele solida	X	P	P	V	V	P
Semimytilus algosus	X	P				P
Tagelus dombeii	X	A	P	P	A	P
Trachycardium* cf. *procerum	—				**V**	
Transennella pannosa	X	P	A	V	V	V
Venus antiqua	?	P			P	

V = Very abundant, A = Abundant, P = Present, X = extant, (X) = exceptionally present, — = not present in the area, ? = probably present, but not collected
Hol. = Holocene (Present). 5e, 7, 9, 11, >11 = Oxygen Isotope Stages

been mentioned previously in any other Pleistocene marine deposit of northern Chile. These species are: *Bulla punctulata* (A. Adams *in* Sowerby, 1850), *Cerithium stercusmuscarum* (Valenciennes, 1833), *Olivella* sp., *Prunum curtum* (Sowerby, 1832), *Turbo* cf. *fluctuosus* (Wood, 1828), *Anomia peruviana* (d'Orbigny, 1846), *Arcopsis solida* (Sowerby, 1833), *Argopecten circularis* (Sowerby, 1835), *Cyclocardia* cf. *spurca beebei* (Hertlein, 1958), *Donax peruvianus* (Deshayes, 1855), *Mactra velata* (Philippi, 1849), *Ostrea megodon* (Hanley, 1846), and *Trachycardium* cf. *procerum* (Sowerby, 1833; Fig. 5). These species are mostly Panamic species which nowadays live between the Gulf of California and northern Peru (Table 2). Their modern distribution range is generally limited to 6°S (or 14°S for *Trachycardium* cf. *procerum* and *Bulla punctulata*). Two species of the TAMA, however, pertain to the Peruvian province and range from Ecuador to southern Peru (*Prunum curtum* and *Donax peruvianus*).

The most common species found, often *in situ*, in the La Rinconada deposits, is *Trachycardium* cf. *procerum*. This species presently lives in the Panamic Province and the Paita Transition Zone (Olsson, 1961; 4–6°S). Episodically, though, it is observed along the northern half of the Peruvian coast (DeVries, 1986; Díaz and Ortlieb, 1993; Perrier *et al.*, 1992, 1994). Keen (1971) mentioned, erroneously, that the southernmost limit of its present distribution was northern Chile. *Trachycardium* cf. *procerum* was present, and locally abundant, in coastal lagoons of southern Peru during the last interglacial (Díaz

TABLE 2. Geographic distribution of the main warm-water molluscan species found in the Middle Pleistocene deposits of the La Rinconada area, with indications of the southernmost occurrences during the Pleistocene and Holocene along the coasts of Peru and Chile, according to varied sources and our own observations

Species	Present distribution range	Late Quaternary occurrence
GASTROPODS		
Bulla punctulata (A. Adams *in* Sowerby, 1850)	Baja California to N. Peru (Isla Lobos) (1,2,3). Exceptional at Antofagasta (a few beach drift samples collected in 1995 at La Rinconada)	One mention south of 6° S (possibly after an ENSO event) near Pisco (14°S) (4)
Cerithium stercusmuscarum (Valenciennes, 1833)	Baja California to N. Peru (Puerto Pizarro) (1,2)	Present in IS 5 deposits at Ilo (16°S) and in a Holocene palaeo-lagoon at Santa (9°S) (5, 6,7)
Olivella sp.	(extant ?)	(see text)
Prunum curtum (Sowerby, 1832)	Ecuador to N. Chile (Iquique) (1, 2, 3). Rare in southern Peru and northern Chile	
Turbo* cf. *fluctuosus (Wood, 1828)	Baja California, Nicaragua to N. Peru (Paita) (1,2)	Present in IS 5 deposits at Ilo (5, 6)
PELECYPODS		
Anomia peruviana (d'Orbigny, 1846)	California to N. Peru (Paita–Sechura) (1, 2, 8, 9)	Present in Holocene palaeo- lagoons (7) and in IS 5 deposits near San Juan Marcona (3); first mention for the Quaternary south of 16° S
Arcopsis solida (Sowerby, 1833)	Baja California to N. Peru (Paita) (1), or to central Peru (Chimbote) (2)	First mention for the Quaternary south of 9°S
Argopecten circularis (Sowerby, 1835)	Baja California to N. Peru (Paita) (1, 2, 3).	Present in a Holocene palaeo-lagoon at Santa (5, 6, 7, 12).
Cyclocardia* cf. *spurca beebei (Hertlein, 1958)	Gulf of California to Panama (1, 8)	(see text)
Donax peruvianus (Deshayes, 1855)=*Donax marincovichi* (Coan, 1983; 10), or = *Donax obesulus* (Reeve, 1854; 3, 7).	Ecuador to N. Chile (2, 3, 8, 10)	Modern distribution in N Chile linked to ENSO anomalies (6, 11).
Mactra velata (Philippi, 1849)	Gulf of California to N. Peru (Sechura) (3, 8) (or Chiclayo) (9)	First mention for the Quaternary south of 6°S.
Ostrea megodon (Hanley, 1846)	Baja California to N. Peru (Paita) (1, 8, 9) or central Peru (Chimbote) (2)	First mention for the Quaternary south of 9°S
Trachycardium* cf. *procerum (Sowerby, 1833)	Baja California to central Peru (Independencia Bay) (3) , or to Chile [doubtful!] (1, 2)	Present in IS 5 deposits at Ilo and also in a Holocene palaeo-lagoon at Santa (5, 6, 7, 12).

IS 5: Oxygen Isotope Stage 5 (last interglacial, 120 ka).

Sources: (1): Keen (1971); (2): Alamo and Valdivieso (1987); (3): DeVries (1986), (4) Paredes *et al.* (1988); (5): Ortlieb *et al.* (1990); (6): Díaz and Ortlieb (1993), (7): DeVries and Wells (1990), (8): Olsson (1961), (9): Peña (1971), (10): Coan (1983); (11) Tomicic (1985), (12): Perrier *et al* (1994).

and Ortlieb, 1993; Ortlieb *et al.*, *in press*), but has not been mentioned in any Late or Middle Pleistocene deposit in northern Chile. It was also relatively abundant in a mid-Holocene lagoon deposit near Santa in north-central Peru (9°S; Rollins *et al.*, 1986; DeVries and Wells, 1990; Perrier *et al.*, 1992, 1994).

Anomia peruviana is an epibenthic form strictly limited to the Panamic Province and the Paita Transition Zone (Olsson, 1961; Keen, 1971). Along the Peruvian coast, the species was only mentioned in late Pleistocene sediments at 15°30′S (DeVries, 1986) and in the Holocene TAMA of Santa (Rollins *et al.*, 1986; DeVries and Wells, 1990).

Arcopsis solida is a small pelecypod found in the intertidal area on sandy and rocky coastlines. Its range encompasses the Panamic Province and Paita Transition Zone, with a southernmost limit near Chimbote (Keen, 1971; Alamo and Valdivieso, 1987). To our knowledge, the species was not mentioned south of 6°S in any Holocene or Pleistocene deposits.

Argopecten circularis is the common scallop shell in the Panamic Province, with a wide bathymetric range (Keen, 1971). Its southern limit is presently at Sechura. The southernmost occurrence of the species is in the mid-Holocene paleo-lagoon deposit at Santa (Rollins *et al.*, 1986; DeVries and Wells, 1990).

Cyclocardia cf. *spurca beebei* is a poorly documented species. The samples of *Cyclocardia*, or *Cardita*, collected at La Rinconada could not be properly identified. They resemble *Cyclocardia velutinus* (Smith 1881) and/or *C. compressa* (Reeve 1843), that are cold-water species (extending southward to Magellan Straits; Soot-Ryan, 1959; Ramorino, 1966). *Cardita spurca beebei* lives nowadays in the warm-water between western Mexico and Panama (Olsson, 1961), while *Cardita* (*Cyclocardia*) *spurca* (Sowerby 1832) is a Chilean form extending northward to Lima (Olsson, 1961; Keen, 1971).

Donax peruvianus (which may correspond to *D. obesulus* [Reeve, 1854], according to Coan (1983) and/or to *Donax marincovichi* [Coan, 1983]) is generally found on exposed sandy coasts. In northern Chile it is reported as presently living (?) at Arica (18°30′S) and Iquique (20°S). Actually the only locality in northern Chile where we collected samples of *D. peruvianus* recently (in 1993–1995) is the sector of La Rinconada. The occurrence of the species is apparently limited to the months (and years?) that follow strong (or very strong) El Niño events, for example in 1982–1983 (Tomicic, 1985).

Mactra velata is a very large Panamic pelecypod that commonly lives on mud flats and ranges southward to northern Peru (7°S, according to Peña (1971)). To our knowledge, the species was not recorded south of 6°S in any Holocene or Pleistocene deposits.

Ostrea megodon has a wide ecological range occurring from shallow waters and about a 110 m depth (Keen, 1971). It is distributed between Baja California and northern Peru (6°S). According to Alamo and Valdivieso (1987), it may be found presently at Chimbote (9°S). It was locally very abundant in Early (?) and Middle Pleistocene 'tablazo' (marine terrace) deposits of northern Peru (Olsson, 1961; DeVries, 1986). It may be noted that the species was not present in the mid-Holocene TAMA of Santa.

Bulla punctulata is an opisthobranch gastropod which presently inhabits protected sandy or muddy environments north of Bayovar (6°S), although a small isolated population was described at Bahia Independencia (14°S; Paredes *et al.*, 1988). It was also found in the Holocene TAMA of Santa (DeVries and Wells, 1990). Its southernmost limit, presently, must be extended southward to Antofagasta, since we collected (in 1995) a few samples of live animals, on the beach at La Rinconada. To our knowledge, *Bulla* was not previously described in any Pleistocene deposit south of 6°S.

Cerithium stercusmuscarum normally lives in shallow embayments and coastal lagoons in the Panamic Province and the Paita Transition Zone. It was present in mid-Holocene lagoonal deposits near Santa and Chimbote (9°S). Some samples were also found in paleo-lagoon units assigned to the Oxygen Isotope Stage 5 in southern Peru (at Ilo, 18°S; Ortlieb *et al.*, 1990, *in press*).

Olivella sp., which abounds in some beds at La Rinconada, could not yet be identified. The species presents several significant morphological differences with *O. columellaris* (Sowerby, 1825), the most frequent species found in Holocene or Pleistocene deposits of northern Peru. To our knowledge, no other *Olivella* were described in Quaternary deposits from southern Peru or Chile.

Prunum curtum is a small and uncommon gastropod that lives on sandy or muddy substrates of the Peruvian coast. Its present distribution range may extend to northern Chile (DeVries, 1986; Alamo and Valdivieso, 1987), although it was not mentioned by authors that worked in Iquique (e.g. Marincovich, 1973).

Turbo cf. *fluctuosus* is a gastropod that lives on rocky substrate, below low tide level. It is rare in the southern end of its range, i.e. the Paita Transition Zone (Keen, 1971). Its southernmost occurrence during the Pleistocene was in southern Peru, at Ilo (Ortlieb *et al.*, 1990; Díaz and Ortlieb, 1993).

A few isolated individuals of other bivalves (*Protothaca* sp., *Panope* sp.) and gastropods (*Chorus* sp.) were found. Their identification is still pending. As they were encountered less frequently than all the others, cool or warm-water species, we consider that they were episodical forms, and of less significance than the rest of the TAMA species mentioned here.

Thus, the Middle Pleistocene TAMA of the La Rinconada block is composed mostly of elements which presently live north of 6°S, or 9°S. A few forms of the TAMA may be found episodically or in reduced number in particular localities of south-central Peru (Paracas embayment, Independencia Bay), particularly after occurrences of El Niño events (Paredes *et al.*, 1988). Many of the fossil species found at La Rinconada are presently living in the Bay of Bayovar, some 2000 km to the north (Fig. 1). In some way, present conditions in this bay within the Paita Transition Zone (SST annual range of 17–21°C) should help to reconstruct the paleoenvironment of the La Rinconada area at 400 ka. On the other hand, one of the typical modern biotopes defined in the Paracas Bay area (14°S, SST annual range of 16–20°C), characterised by the assemblage *Donax peruvianus–Prunum curtum–Bulla punctulata–Mesodesma donacium* (Paredes *et al.*, 1988) from relatively protected sandy and silty environments may also represent a modern equivalent of one of the facies found at the La Rinconada site. Finally, there is a striking similarity between the fauna of the La Rinconada site and the mid-Holocene TAMA at Santa, north-central Peru (DeVries and Wells, 1990; Ortlieb *et al.*, 1990; Perrier *et al.*, 1992). In the paleolagoon of Santa the warm-water assemblage developed during more than 2000 years (6500–4300 BP), behind a large beach ridge, while a cool fauna co-existed in the nearshore area exposed to the effects of the Humboldt Current system (DeVries and Wells, 1990; Perrier *et al.*, 1994). A similar situation may have occurred at La Rinconada during Oxygen Isotope Stage 11, although probably during a much longer lapse. In both cases (Santa and the study area), it can be inferred that the shallow depth and warmer than present climatic conditions allowed for the survival and perpetuation of species which would not have lived in the cool, open, nearby ocean waters.

Paleogeographic and Paleoclimatic Interpretation

The Middle Pleistocene deposits of southern Pampa Mejillones, above +150 m, which also present a warm-water faunal assemblage, exhibit some of the same extralimital species (*Olivella* sp., *Cyclocardia* cf. *spurca beebei*, *Mactra velata*, *Ostrea megodon* and *Trachycardium* cf. *procerum)* of the La Rinconada TAMA. A few other species, also characteristic of the Panamic Province but not present at La Rinconada locality, like *Cyclinella subquadrata* (Hanley, 1845) and *Dosinia ponderosa* (Gray, 1838) are present in the oldest deposits of Pampa Mejillones. In both coastal plains, the TAMA indicate that during the presumed Oxygen Isotope Stage 11, the oceanographic conditions were such that numerous species that require warm water could live in protected environments both north and south of the Mejillones Peninsula. In the La Rinconada sector, like in southern Pampa Mejillones, permanent (or semi-permanent) coastal lagoons were formed behind the beach ridges. At La Rinconada, nowadays, without any lagoonal or closed environment (SST annual range 14–20°C), there is evidence that the morphological disposition of the coast is favourable to the episodical development of small communities of molluscs that are beyond their northern distributional range: *Bulla punctulata* and *Donax peruvianus* were found recently there, hundreds of kilometres south of their usual southernmost limit. In the case of Pampa Mejillones, it is interpreted that the Mejillones embayment was much more protected, in relation to the Present, from the cool water upwelled to the west and northwest of the peninsula, some 400,000 years ago. Before the 150–200 m slow uplift of the isthmus occurred, the coastline was much more profoundly indented than today, thus making possible the existence of protected biotopes.

Favourable palaeogeographic conditions for the formation of coastal environments with limited communication with the open oceans were possibly present in both cases, north and south of the peninsula. In these shallow lagoons, the solar radiation and the air temperature probably played a key role in maintaining warm-water conditions during most of the year. Also, winter air temperatures may have been significantly warmer than today (closer to the present-day summer temperatures). It is possible that a distinct seasonal range of air temperature variation could have been as important, or even more important in allowing the formation of the TAMA than a net increase of annual temperature.

A greater influence of atmospheric factors in relation to the oceanographic parametres is suggested. This is based on the strong evidence that coevally with the development of the TAMA, 'normal' cool water fauna was contemporaneously present on the exposed stretches of the coast, particularly on the northeastern shore of Antofagasta Bay. The cool-water component of the TAMA and the faunal content of the deposits in the eastern half of Pampa del Aeropuerto indicate clearly that the open sea temperature could not have been very different from the present-day conditions.

The mid-Holocene TAMA of Santa was here repeatedly referred to as a recent equivalent of the La Rinconada anomalous assemblage. Another equivalent situation was observed in Late Pleistocene lagoonal deposits of southern Peru (Ilo, 17°30′S), where warm-water forms (including: *Trachycardium* cf. *procerum* and *Cerithium stercusmuscarum)* were found with normal cool-water species (Ortlieb *et al.*, 1990; Díaz and Ortlieb, 1993). At Ilo, a complex story of coastal changes related to sea-level variations (within the last interglaciation) and tectonic deformations resulted in the formation of several lagoonal episodes, during which a relatively 'warm' fauna could develop (Ortlieb *et al.*, 1990, *in press*). There, also, it seems that the warm-water forms were closely linked to the existence of lagoonal environments. At Ilo, like at Santa, it was hypothesised that the introduction of the species in the lagoonal environment was possibly controlled by some coastal southbound currents, and/or by short-lived anomalies in the nearshore conditions like those accompagnying the El Niño occurrences (Díaz and Ortlieb, 1993). Larval transport of some species outside their normal distribution range has been one of the mechanisms invoked to explain the TAMA phenomenon (Zinsmeister, 1974). In any case, some relationship is demonstrated between the El Niño induced modifications on the coastal environment and the appearance of anomalous species in favourable sites (Tomicic, 1985; Paredes *et al.*, 1988; Díaz and Ortlieb, 1993).

CONCLUSION

Morphostratigraphic and geochronologic studies recently performed in the Mejillones Peninsula area provide a new insight into the chronostratigraphic framework of the Middle Pleistocene coastal landforms and associated deposits in northern Chile. As a result, the identification of the remnants of the last three or four interglacial high seastands begins to be well assessed (Ortlieb *et al.*, 1995). The coastal features and sediments formed during Oxygen Isotope Stage 11 (ca. 400 ka) are not commonly preserved along the narrow coastal plain of northern Chile, between Antofagasta (24°S) and Iquique (21°S), but they are well developed in Mejillones Peninsula. It was discovered that the faunal composition of some of the deposits assigned to the 400 ka high seastand was exceptional, with respect to that of the other interglacial high seastand episodes. The most protected areas in two sectors of the peninsula are characterised by thermally anomalous molluscan assemblages (TAMA) which include a series of warm-water species that commonly live now in the Panamic Province and in the Paita Transition Zone (4–6°S). For most of these species, the 400 ka deposits at Mejillones Peninsula constitute the southernmost limit of occurrence during the Quaternary. Some of these species are found, at 23°S, about 2000 km further south than their modern end-limit.

The TAMA species at La Rinconada locality are generally lagoonal forms, or species that live in protected shallow water embayments. As evidenced in a few other cases of TAMA on the Peruvian coast (two modern ones in Paracas Bay and at Independencia Bay, one in the mid-Holocene at Santa, and another one in last interglacial deposits at Ilo), the anomalous assemblages of extralimital species are restricted to areas with limited circulation where the water temperature can be significantly higher than in the nearby open ocean. Besides, it may be noted that the modern occurrence of extralimital species is favoured during the months and years following strong El Niño events. Short-lived oceanographic and climatic anomalies may also have played a role in the southward transport of warm-water species along the Peruvian and Chilean coast in the past.

However, the fauna of the coastal deposits assigned to the Oxygen Isotope Stage 11 is not uniformly characteristic of warm water conditions. The exposed sectors of the coast were coevally inhabited by cool water species that do not differ significantly from those presently living in the area. Therefore, it may be inferred that the Humboldt Current and the coastal upwelling system were probably as active at that time as they are today. It was only in protected environments, physically separated by a sandy barrier from the cool nearshore waters, that Panamic molluscs could live. This suggests that ocean–atmosphere interactions were on a distinct mode than at present. The winter air temperature was probably higher by several degrees, and the solar radiation may also have been stronger than today. Atmospheric conditions which may be comparable to those prevailing at present in summer, may have lasted much longer in the yearly cycle.

The studied emerged coastal deposits assigned to Oxygen Isotope Stage 11 in Mejillones Peninsula are the only localities, among all the studied Quaternary marine units of northern Chile, that include a number of panamic species. It is stressed, for instance, that none of these warm-water species were found in any of the numerous Late Pleistocene (Oxygen Isotope Stage 5e) deposits. The warmer character of the ca. 400 ka interglaciation in relation with the subsequent Middle–Late Pleistocene interglacial episodes and the Holocene probably reflects a particular atmospheric circulation mode that may concern essentially the southern hemisphere, and not necessarily the whole globe.

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REFERENCES

Aksu, A.E., Mudie, P.J., de Vernal, A. and Gillespie, H. (1992). Ocean-atmosphere responses to climatic change in the Labrador Sea: Pleistocene plankton and pollen records. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **92,** 121–138.

Alamo, V.V. and Valdivieso, V. (1987). *Lista sistemática de moluscos marinos del Perú*. Instituto del Mar del Perú, Boletín extraordinario, 205 pp.

Armijo, R.and Thiele, R. (1990). Active faulting in northern Chile: ramp stacking and lateral decoupling along a subduction plate boundary? *Earth and Planetary Science Letters*, **98**, 40–61.

Burckle, L.H. (1993). Late Quaternary interglacial stages warmer than present. *Quaternary Science Reviews*, **12**, 825–831.

Charles, C.D., Froelich, P.N., Zibello, M.A., Mortlock, R.A. and Morley, J.J. (1991). Biogenic opal in Southern Ocean sediments over the last 450,000 years: Implications for Quaternary surface water chemistry. *Paleoceanography*, **6,** 697–728.

Coan, E. (1983). The Eastern Pacific Donacidae. *The Veliger*, **25,** 273–298.

DeVries, T.J. (1986). The geology and paleontology of the tablazos in northwest Peru. Ph.D. dissertation, Ohio State University, Columbus (Ohio), 964 pp.

DeVries, T.J. and Wells, L.E. (1990). Thermally-anomalous Holocene molluscan assemblages from coastal Peru: evidence for paleogeographic, not climatic change. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **81,** 11–32.

Díaz, A. and Ortlieb, L. (1993). El Fenómeno 'El Niño' y los moluscos de la costa peruana. *Bulletin de l'Institut Francais d'Etudes Andines*, **22,** 159–177.

Ferraris, F. and Di Biase, F. (1978). Hoja Antofagasta, región de Antofagasta. *Carta Geológica de Chile* n°30, Instituto de Investigaciones Geológicas, Chile. 48 pp., 1 map 1:250.000.

Flint, S., Turner, P. and Jolley, E.J. (1991). Depositional architecture of Quaternary fan-delta deposits of the Andean fore-arc: relative sea-level changes as a response to aseismic ridge subduction. *International Association of Sedimentologists, Special Publication*, **12,** 91–103.

Hays, J.D., Imbrie, J. and Shackleton, N.J. (1976). Variations in the Earth's orbit: pacemaker of the ice ages. *Science*, **194**, 1121–1132.

Herm, D. (1969). Marines Pliozän und Pleistozän in Nord und Mittel- Chile unter besonderer Berucksichtigung der Enwicklung der Mollusken-Faunen. *Zitteliana (München)*, **2**, 159 pp.

Hillaire-Marcel, C., Ghaleb, B., Cournoyer, L. and Ortlieb, L. (1996). Allo/isoleucine (A/I) and Th/U measurements in mollusk shells from Michilla and Mejillanes Bays, northern Chile. *II Annual Meeting of the International Geological Correlation Program*, Project 367 (Antofagasta, 19–28 Nov., 1995). Abstracts volume, p. 47. ORSTOM, Antofagasta, Chile.

Hodell, D.A. (1993). Late Pleistocene paleoceanography of the South Atlantic sector of the southern ocean: Ocean Drilling Program hole 704-A. *Paleoceanography*, **8**, 47–67.

Hopkins, D.M. (1967). Quaternary marine transgressions in Alaska. *In*: Hopkins, D.M. (ed.), *The Bering Land Bridge*, pp. 47–90. Stanford University Press, California.

Hopkins, D.M., Rowland, R.W., Echols, R.E. and Valentine, P.C. (1974). An Anvilian (early Pleistocene) marine fauna from western Seward Peninsula, Alaska. *Quaternary Research*, **4**, 441–471.

Howard, W.R. and Prell, W.L. (1992). Late Quaternary surface circulation of the southern Indian ocean and its relationship to orbital variability. *Paleoceanography*, **76**, 43–54.

Imbrie, J. and Imbrie, J.Z. (1980). Modeling the climate response to orbital variations. *Science*, **207**, 943–953.

Imbrie, J., Boyle, E.A., Clemens, S.C., Duffy, A., Howard, W., Kukla, G., Kutzbach, J., Martinson, D.G., McIntyre, A., Mix, A.C., Molfino, B., Morley, J.J., Peterson, L.C., Pisias, N.G., Prell, W.L., Raymo, M.E., Shackleton, N.J. and Toggweiler, J.R. (1992). On the structure and origin of major glaciation cycles, 1: Linear responses to Milankovitch forcing. *Paleoceanography*, **7**, 701–738.

Imbrie, J., Boyle, E.A., Clemens, S.C., Duffy, A., Howard, W., Kukla, G., Kutzbach, J., Martinson, D.G., McIntyre, A., Mix, A.C., Molfino, B., Morley, J.J., Peterson, L.C., Pisias, N.G., Prell, W.L., Raymo, M.E., Shackleton, N.J. and Toggweiler, J.R. (1993). On the structure and origin of major glaciation cycles, 2: The 100,000-year cycle. *Paleoceanography*, **8**, 699–735.

Jansen, J.H.F., Kuijpers, A. and Troelstra, S.R (1986). A Mid-Brunhes climatic event: Long-term changes in global atmosphere and ocean circulation. *Science*, **232**, 619–622.

Kaufman, D.S., Walter, R.C., Brigham-Grette, D.M. and Hopkins, (1991). Middle Pleistocene age of the Nome River glaciation, northwestern Alaska. *Quaternary Research*, **36**, 277–293.

Kaufman, D.S. and Brigham-Grette, J. (1993). Aminostratigraphic correlations and paleotemperature implications, Pliocene-Pleistocene high-sea-level deposits, northwestern Alaska. *Quaternary Science Reviews*, **12**, 21–33

Keen, A.M. (1971). *Sea Shells of Tropical West America: Marine Mollusks from Baja California to Peru*. Stanford University Press, Stanford, 1064 pp.

Kellogg, T.B. (1977). Paleoclimatology and paleo-oceanography of the Norwegian and Greenland seas: The last 450,000 years. *Marine Micropaleontology*, **2**, 235–249.

Kennett, J. (1970). Pleistocene paleoclimates and foraminiferal biostratigraphy in subantarctic deep-sea cores. *Deep Sea Research*, **17**, 125–140.

Liu, H.S. (1992). Frequency variation of the Earth's obliquity and the 100-kyr ice-age cycles. *Nature*, **358**, 397–399.

Liu, H.S. (1995). A new view on the driving mechanism of Milankovitch glaciation cycles. *Earth and Planetary Science Letters*, **131**, 17–26.

MacNeil, F.S., Mertie, J.B. and Pilsbry, H.A. (1943). Marine invertebrate faunas of the buried beaches near Nome, Alaska *Journal of Paleontology*, **17**, 69–96.

Marincovich, L. (1973). Intertidal mollusks of Iquique, Chile. *National History Museum of Los Angeles County, Scientific Bulletin*, **16**, 1–49.

Morley, J.J. (1989). Variations in high-latitude oceanographic fronts in the southern Indian Ocean; An estimation based on faunal changes. *Paleoceanography*, **4**, 547–554.

Morris, P. (1966). *A Field Guide to Shells of the Pacific Coast and Hawai, Including Shells of the Gulf of California*. Houghton Miffin Co., Boston, 297 pp.

Okada, A. (1971). On the neotectonics of the Atacama fault zone region. Preliminary notes on late Cenozoic faulting and geomorphic development of the Coast Range of northern Chile. *Bulletin of the Department of Geography Kyoto University*, **3**, 47–65.

Olsson, A.A. (1961). *Mollusks of the tropical eastern Pacific, Panamic Pacific Pelecypoda*. Paleontological Research Institute, Ithaca, New York. 574 pp.

Oppo, D.W., Fairbanks, R.G. and Gordon, A.L. (1990). Late Pleistocene Southern Ocean $\delta^{13}C$ variability. *Paleoceanography*, **5**, 43–54.

Ortlieb, L. (1993). Vertical motions inferred from Pleistocene shoreline elevations in Mejillones Peninsula, northern Chile: Some reassessments. *II International Symposium on Andean Geodynamics* (Oxford, 1993), Extended Abstract volume, pp. 125–128.

Ortlieb, L., DeVries T. and Díaz, A. (1990). Ocurrencia de *Chione broggi* (Pilsbry and Olsson, 1943) (Pelecypoda) en depósitos litorales cuaternarios del sur del Perú: implicaciones paleoceanográficas. *Sociedad Geológica del Perú, Boletín*, **81**, 127–134.

Ortlieb, L. and Guzmán, N. (1994). La malacofauna pleistocena de la región de Antofagasta: variaciones en la distribución biogeográfica y potencial paleoceanográfico. Actas VII Congreso Geológico Chileno (Concepción, 1994), 1, pp. 498–502.

Ortlieb, L., Guzmán, N. and Candia, M. (1994). Moluscos litorales del Pleistoceno superior en el área de Antofagasta, Chile: Primeras determinaciones e indicaciones paleoceanográficas. *Estudios Oceanológicos*, **13**, 51–57.

Ortlieb, L., in coll. with J.L. Goy, C. Zazo, Cl. Hillaire-Marcel and G. Vargas (1995). *Late Quaternary Coastal Changes in Northern Chile*. Guidebook for a fieldtrip. *II annual meeting of the International Geological Correlation Program*, Project 367 (Antofagasta, 19–28 Nov. 1995), ORSTOM, Antofagasta, Chile. 175 pp.

Ortlieb, L., Zazo, C., Goy, J., Dabrio, C. and Macharé, J (*in press*). Pampa del Palo: An anomalous composite marine terrace in the uprising coast of southern Peru. *Journal of South American Earth Sciences*, **9**.

Ortlieb, L., Zazo, C., Goy, J. L., Hillaire-Marcel, C., Ghaleb, B. and Cournoyer, L. (1966a). Coastal deformation and sea-level changes in the Northern Chile subduction area (23°S) during the last 330 ky. *Quaternary Science Reviews*, **15**.

Ortlieb, L., Goy, J.L., Zazo, C., Hillaire-Marcel, C., Ghaleb, B., Guzmán, N. and Thiele, R. (1996) *Quaternary morphostratigraphy and vertical deformation in Mejillones Peninsula, Northern Chile. 3rd International Symposium on Andean Geodynamics*. (St Malo, September 1996), Abstract volume, 211–214.

Paredes, C., Tarazona, J., Canahuire, E., Romero, L. and Cornejo, O. (1988). Invertebrados macro-bentónicos del área de Pisco, Perú. *In*: Salzwedel, H. and Landa, A. (eds), *Recursos y dinámica del ecosistema de afloramiento peruano*, Instituto del Mar del Perú, volumen extraordinario 1, pp. 121–132.

Peña, G.M. (1971). Zonas de distribución de los bivalvos marinos del Perú. *Anales Cientificos, Universidad Nacional Agraria La Molina*, **9**, 127–138.

Perrier, C., Ortlieb, L. and Hillaire-Marcel, C. (1992). Coastal evolution and El Niño impact in Santa area, NW Peru, based on isotopic composition of Holocene mollusk shells. *In*: Ortlieb, L. and Macharé J. (eds), *Paleo-ENSO records* *symposium*, extended abstracts, International symposium on Former ENSO phenomena in western South America: Records of El Niño events (Lima, 4–7 march 1992), ORSTOM and CONCYTEC, Lima. pp. 237–243.

Perrier, Ch., Hillaire-Marcel, C. and Ortlieb, L. (1994). Paléogéographie littorale et enregistrement isotopique (^{13}C,^{18}O) d'événements de type El Niño par les mollusques holocènes et récents du nord-ouest péruvien *Géographie Physique et Quaternaire*, **48,** 23–38.

Radtke, U. (1987). Paleo sea levels and discrimination of the last and the penultimate interglacial fossiliferous deposits by absolute dating methods and geomorphological investigations, illustrated from marine terraces in Chile. *Berliner geographische Studien*, **25,** 313–342.

Radtke, U. (1989). Marine Terrassen und Korallenriffe. Das Probleem der Quartären Meeresspiegelschwankungen erläntert an Fallstudien aus Chile, Argentinien und Barbados. *Düsseldorfer geographische Schriften*, **27,** 245 pp.

Ramorino, L. (1966). Pelecypoda del fondo de la Bahía de Valparaíso. *Revista de Biología Marina (Chile)*, **13,** 175–285.

Ratusny, A. and Radtke, U. (1988). Jungere ergebnisse Küstenmorphologischer untersuchungen im "grossen Norden" Chiles. *Hamburger Geographische Studien*, **44,** 31–46.

Rollins, H.B., Richardson III, J.B. and Sandweiss, D.H. (1986). The birth of El Niño: geochronological evidence and implications. *Geoarcheology*, **1**, 3–15.

Roy, K., Jablonski, D. and Valentine, J.W. (1995). Thermally anomalous assemblages revisited: Patterns in the extraprovincial latitudinal range shifts of Pleistocene marine mollusks. *Geology*, **23,** 1071–1074.

Ruddiman, W.F. and McIntyre, A. (1976). Northeast Atlantic paleoclimatic changes over the past 600,000 years. *In*: Cline, R.M. and Hays, J.D. (eds), *Investigation of Late Quaternary Paleoceanography and Paleoclimatology*, Geological Society of America Memoir 145, pp. 111–146.

Ruddiman, W.F., McIntyre, A. and Raymo, M.E. (1986). Paleoenvironmental results from north Atlantic sites 607 and 609. *Ocean Drilling Program Scientific Results, Proceedings*, **94,** 855–878.

Ruddiman, W.F., Raymo, M.E., Martinson, D.G., Clement, B.M and Backman, J. (1989). Pleistocene evolution of northern hemisphere climate. *Paleoceanography*, **4,** 353–412.

Shackleton, N.J. (1987). Oxygen isotopes, ice volume and sea level. *Quaternary Science Reviews*, **6,** 183–190.

Shackleton, N.J. and Opdyke, N.D. (1973). Oxygen isotope and paleomagnetic stratigraphy of Equatorial Pacific core V28-238: Oxygen isotope temperatures and ice volume on a 10^5–10^6 year scale. *Quaternary Research*, **31,** 805–816.

Soot-Ryan, T. (1959). Pelecypoda. Reports of The Lund University, Chile Expedition 1948–1949, 35, 1–87.

Tomicic, J.J. (1985). Efectos del fenómeno El Niño 1982–83 en las comunidades de la Península de Mejillones. *Investigaciones Pesqueras (Chile)*, **32,** 209–213.

Valentine, J.W. (1955). Upwelling and thermally anomalous Pacific coast Pleistocene molluscan faunas. *American Journal of Science*, **253,** 462–474.

Zinsmeister, W.J. (1974). A new interpretation of thermally anomalous molluscan assemblages of the California Pleistocene. *Journal of Paleontology*, **48,** 84–94.