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Osseous skeletal material and fish scales in marine sediments under the oxygen minimum zone off northern and central Chile

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Abstract

The significance of whale falls for the study of the biogeography, evolution and biodiversity of deep-sea biota has been recently recognized by international programs since large carcasses are known to give rise to biogenic chemosynthetic ecosystems. However, the plain accumulation of smaller bone material in the shallower settings of the continental shelf and upper slope under the hypoxic conditions of the Oxygen Minimum Zone (OMZ), has received much less attention. Here we describe new findings of skeletal material and fish scales in marine sediments under the OMZ off northern and central Chile which, combined with previous reports for the study area, lead us to suggest the existence of a band in the benthos of accumulation of bones and scales extending at least twenty degrees in latitude (18–38° S). Future studies should focus on the characterization of biotic communities living upon these resources in order to elucidate their peculiarities and importance in the Eastern South Pacific.

Keywords: bone remains; fish scales; paleoecology; tanatocoenosis; oxygen minimum zone; Chile

1. Introduction

Marine sediments bearing large amounts of skeletal remains of fishes and mammals are quite scarce in the world ocean (Brongersma-Sanders, 1948, 1957). In general, these deposits are associated with oxygen-deficient settings (e.g. oxygen minimum zones or OMZs, enclosed basins with poor bottom circulation, fjords etc.) (Soutar, 1967; Soutar and Isaacs, 1969; Shackleton, 1987). High mortalities and low degradation rates of organic matter in OMZs (Degens et al., 1964) apparently favor the preservation of skeletal remains of marine macro-organisms such as fish and mammals (De Vries and Pearcy, 1982). On the other hand, considerable pulses of labile organic matter to the seafloor, like those produced by large carcasses (e.g. whales) and its subsequent utilization by anaerobes, could provide an appropriate substrate for the establishment of ecosystems relying on reduced compounds for energy (Smith and Kukert, 1989; Smith et al., 2002; Goffredi et al., 2004).

Among important OMZ areas in the world where appropriate conditions for the accumulation of fish debris may occur are the Santa Barbara Basin (e.g. Soutar, 1967; Schimmelmann et al., 1994), the Gulf of California (Holmgren-Urba and Baumgartner, 1993), the Cariaco Basin, Venezuela (Hughen et al., 1996), some fjords with stagnant bottom water conditions

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(Josefson and Widbom, 1988; Sancetta, 1989; Tunnicliffe et al., 2001), some areas of the Black Sea (Crusius and Anderson, 1992), and the upwelling areas off Namibia (Shackleton, 1987) and Perú-Chile (De Vries and Pearcy, 1982; Ortlieb et al., 1994, 2000).

Several marine studies used variations in fish scale accumulation rate and abundance as records of historical changes in climatic and oceanographic conditions (Soutar, 1967; Soutar and Isaacs, 1969; Baumgartner et al., 1992; Holmgren-Urba and Baumgartner, 1993). De Vries and Pearcy (1982) were among the first to use fish skeletal remains (e.g., vertebrae) in addition to scales. Recently, O'Connell and Tunnicliffe (2001) and Tunnicliffe et al. (2001) studied small fish bones, teeth and scales in sediment profiles from Saanich Inlet, British Columbia, with the goal of reconstructing population dynamics prior to fishing impact.

Aside from its importance for paleo-environmental assessment, it has been recently realized that whale falls may also give rise to chemosynthetic ecosystems, and constitute a source of labile organic compounds (e.g. whale-bone oil). Anaerobic biodegradation and formation of hydrogen sulfide fuels vent-resembling communities, as first noted by Smith and Kukert (1989) in the Santa Barbara Basin. Subsequent findings in the deep sea corroborated these observations for several other whale falls and nekton falls (reviewed by Smith et al., 2002; Baco and Smith, 2003). However, the accumulation of smaller bone material in the shallower settings of the continental shelf and upper slope under hypoxic conditions of OMZs has received little attention (C. Smith, pers. commun.).

The aim of this study is to compile available information and report on new areas off Chile where large accumulations of skeletal material and fish scales, derived from fish, whales and other marine animals, occur. These may bear potential oceanographic importance for paleoecological, ecological, biodiversity, biogeography and evolutionary studies.

2. Materials and methods

Observations on skeletal material and fish scales in marine sediments off Chile derive from samples collected during several research trips and local fishing-fleet cruises (Table 1). The main sampling gear used from research vessels were a triangular dredge (Mar-Chile II Expedition, Gallardo, 1963) and an Agassiz trawl in 10–15 min trawlings (Sonne Cruise 156). Bottom otter-trawls were used from fishing vessels. All stations are located within or at the lower edge of the OMZ, which off Chile is usually located between 30–500 m at ~22° S and 80–300 m at ~36° S (Brandhorst, 1971; Strub et al., 1998). Samples were first preserved in buffered 4% formaldehyde solution and later transferred to ethanol. Smaller skeletal remains were analyzed under a low power stereomicroscope. For the identification of fish bone remains, the osteologic key for Chilean fishes of Falabella et al. (1995) was used.

3. Results

3.1. Previous findings

The presence of fish remains in marine sediments was noted during the H.M.S. Challenger (1872–1876) expedition, at several sites around the world, one off Chile was reported by Murray and Renard (1891). Gallardo (1963) recorded the finding of fish scales and bones of both fish and mammals under the OMZ off northern Chile (Table 1, Fig. 1). Shark teeth and squid beaks were also seen in greenish, muddy and hydrogen sulphide-containing sediments from the shelf break and upper slope. Within this collection the supra-occipital crest of horse mackerel *Trachurus murphyi* was abundant.

3.2. New findings

Trawling performed off Mejillones Bay in 2001 yielded a wealth of fish debris and other skeletal remains, especially at the shallower site (320 m; Table 1, Fig. 1). The collected material contained abundant fish bones (Fig. 2A–K) accompanied by squid beaks (Fig. 2L) and shark teeth (Fig. 2M). This material was in different stages of preservation and some formed conglomerates, probably with phosphoritic minerals (Fig. 2B,E). Most of the identified fish bones derive from horse mackerel, *T. murphyi*: the supra-occipital crest (Fig. 2A), upper jaw (Fig. 2C), assorted vertebrae (e.g. dorsal, caudal; Fig. 2D), pre-maxillary (Fig. 2F), cleitrum (Fig. 2G), operculum (Fig. 2H), gill arcs (Fig. 2I), dentary (Fig. 2J) and pre-operculum (Fig. 2K). The squid beaks (Fig. 2L) belong to the flying jumbo squid *Dosidicus gigas*, and the shark teeth (Fig. 2M) to the genus *Carcharhinus*. The largest osseous remain at this site was a whale inter-vertebral disc (Fig. 2N). The scarce benthic fauna consisted mainly of a gastropod (*Astyris* sp.) and some bivalves (*Nucula* sp. and *Limopsis* sp.), as well as a few polychaetes. In addition, large quantities of unidentifiable fish debris were found.

A striking decrease in skeletal remains was observed at the deeper site off Mejillones (500 m; Table 1), where only some fish bones (mainly *T. murphyi*) were found. Consistent with higher dissolved oxygen levels, as compared with the shallower site, i.e. 0.93 ± 0.04 vs. 0.08 ± 0.02 ml L^{-1} (mean $\pm$ SD; $n = 3$), the benthic fauna was more diverse, with more than 20 taxa present, i.e. mollusks, polychaetes, echinoderms, crustaceans and fishes (Hebbeln et al., 2001).

Table 1
Compilation of sites off Chile where skeletal material and fish scales have been observed in marine sediments

Locality	Position	Depth (m)	Type of skeletal remains	Source	Gear
1. Off Valparaíso	33°42′ S, 78°18′ W	2300	Assorted fish scales	Murray and Renard, 1891	D[a]
2. Off Mocha Island	38°06′ S, 78°02′ W	3100	fish bones shark teeth squid beaks		
3. Off Arica	18°29′ S, 70°32′ W	187	Assorted fish scales fish bones sea lion bones shark teeth squid beaks	Gallardo, 1963	TD[b]
4. Off Punta Pichalo	19°35′ S, 70°21′ W	268	Assorted fish scales fish bones sea lion bones shark teeth squid beaks	Gallardo, 1963	TD[b]
5. Off Iquique	21°03′ S, 70°16′ W	103	Assorted fish scales fish bones	R. De Pol (pers. comun.)	RC[c]
6. Off Bay of Mejillones	22°50′ S, 70°30′ W	500	Assorted fish scales squid beaks shark teeth	This study	AGT[d]
	22°51′ S, 70°29′ W	320	Assorted fish scales fish bones squid beaks shark teeth whale bones	This study	AGT[d]
7. Off Pichilemu	34°26′ S, 72°10′ W	160	Whale bone (vertebra)	This study	BOT[e]
8. Off Concepción	36°29′ S, 73°34′ W	240–300	Assorted fish bones whale bones	This study	AGT[f]
	36°25′ S, 73°23′ W	120	Assorted fish scales fish bones		RC[f]
9. Off Mocha Island	38°12′ S, 74°12′ W	250	Large carcass, probably a sperm whale	This study	BOT[e]

D, dredges; TD, triangular dredge; RC, Rumohr corer; AGT, Agassiz trawl; BOT, bottom otter trawling.
[a] H.M.S. Challenger, Expedition 1873–1876.
[b] AGS Yelcho, Mar Chile II expedition. Chilean Navy (1962).
[c] R/V Abate Molina; IFOP Chile (2002).
[d] R/V Sonne, SO-156 cruise in 2001, University of Bremen.
[e] Commercial trawling fleet (2003).
[f] L/C Kay Kay, University of Concepción (2003–2004).

Off south-central Chile, observations are scarce and relate mainly to a whale-fall, i.e., a whole skeleton, presumably of a large sperm whale that was retrieved at 38° S by a squat lobster commercial fishing vessel (Table 1, Fig. 1). Preliminary analysis of the fauna associated with these whale falls includes sedentary polychaetes, crustaceans, anthozoans, gastropods, polyplacophorans (including a new species: Schwabe and Sellanes, 2004) and fishes (J.S., unpublished results). In the area off Concepción, however, fish scales and bones are regularly observed in the sediments (J. Dıaz, pers. commun.), and occasionally pieces of whale falls are also registered (Table 1, Fig. 1).

4. Discussion

Although observations on whale falls, fish skeletal material, fish scales and other debris in sediments off Chile are still scarce (Table 1), due to the poor exploration of the benthic realm beyond the shelf break, these remains could be considered as good indicators of spatial and temporal changes in physical conditions of the water column (e.g. temperature, oxygen), ecosystem productivity, reproductive behavior and/or mass mortalities. In addition, the fossil records may have a potential importance for ecological/paleoecological studies (including chemosynthetic systems).

Off northern Chile, horse mackerel bones and squid beaks dominated the skeletal material in the sediments. Horse mackerel as well as the jumbo flying squid are characteristic species of the northern Chile upwelling areas where both organisms have high biomass and support fisheries (Arancibia et al., 1995; Clarke and Paliza, 2000). Obviously, this condition promotes a great contribution of their skeletal remains to the sediments. The combined effects of high organic matter flux,

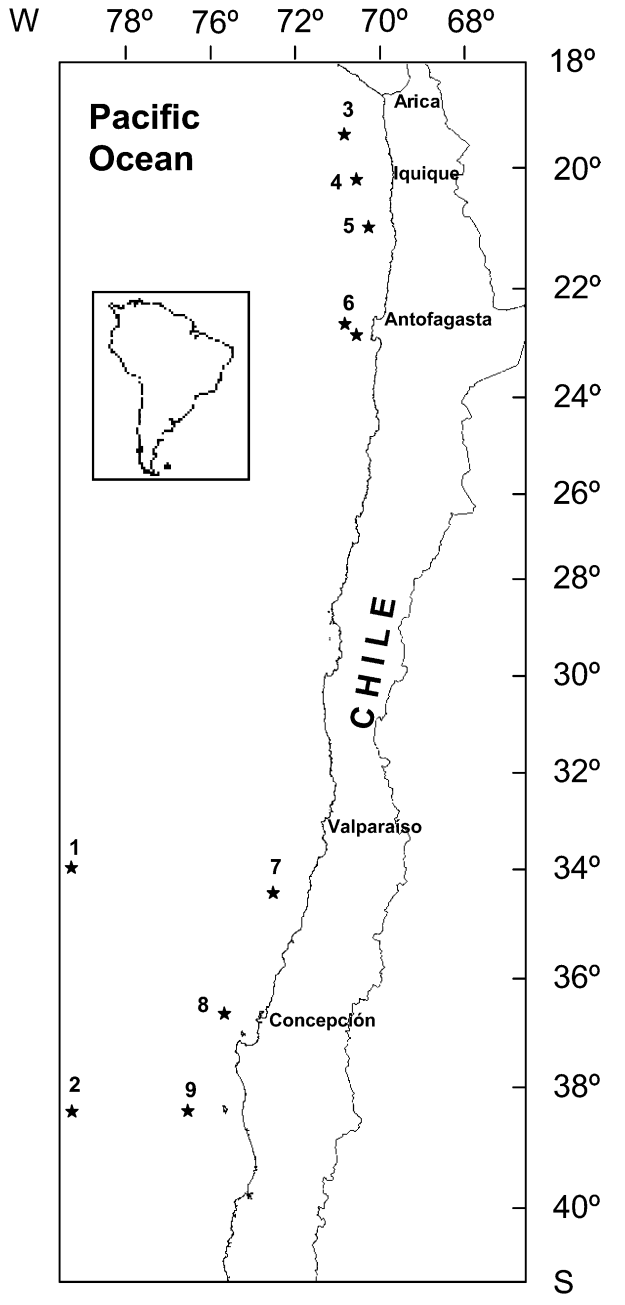

Fig. 1. Map of the Chilean coast, indicating the sites (★) where skeletal remains of fishes, marine mammals (e.g. whales) and others organisms have been found. See Table 1 for exact location of sites.

oxygen deficiency, and impoverished benthic fauna (Gallardo, 1963) would favor the preservation of skeletal material at the sediment surface. Furthermore, a sediment core collected with Rumohr corer off Iquique (21° S) contained layers of abundant fish scales and small vertebrae at various core depths (~7, 12 cm; Table 1).

In general, most of the skeletal material observed at all sites were large, fragile and very well preserved (e.g. Fig. 2C,G,I). These observations may suggest that predation and incorporation in fecal pellets of large mammals (i.e. sea lions) can be disregarded as a possible transport mechanism to reach the seafloor. Studies by Tollit et al. (1997) and Bowen (2000), for example, have shown that shredding, digestion and mechanical action in the digestive tract of sea lions produce almost unrecognizable bone fragments in the fecal material. Thus, the well-preserved bones, scales, beaks, etc. reported in this study may suggest the occurrence of periodical mass mortality events through time whose cause (i.e. lowered productivity and scarcity of food during El Niño events, Arntz and Fahrbach, 1991) needs to be further investigated.

Documented causes of mass mortalities are many (oxygen deficiency, red tides, sudden changes in temperature and salinity), and have been listed by Brongersma-Sanders (1957). Fish and squid strandings and massive mortalities are reported as episodic in central-south Chile and may be related to reproductive behavior or caused by alterations in oceanographic conditions (see Jara, 1992, and references therein). Temperature and oxygen levels are probably the most important factors behind these large mortalities because salinity is not expected to drastically change in the study area (18–38° S). Recently, massive strandings of jumbo flying squids (*Dosidicus gigas*) occurred at several points off Concepción, central Chile, i.e. between March and May 2003 at Coliumo, Santa Maria Island and Dichato, where thousands of *D. gigas* washed up on the beaches (e.g. http://www.planetark.com/envpicstory.cfm/news-id/20926).

In contrast to large accumulation of fish remains in the sediments, whale carcasses sink fast and provide a more localized huge pulse of labile organic matter for deep-sea organisms to exploit (Hall, 1999; Baco and Smith, 2003). Lipid-rich whale carcasses have been found to support a diverse animal community nourished by chemoautotrophic bacteria, which were previously thought to be restricted to hydrothermal vents (Smith and Kukert, 1989; Smith et al., 2002). Thus whale carcasses may act like islands in the deep sea and provide critical stepping-stones for organisms between vent communities, which are themselves insular and temporary habitats (Hall, 1999; Baco and Smith, 2003; Goffredi et al., 2004). The record of whale remains in sediments along the Chilean coast is spotty, ranging from a few bones observed in the north to a whole carcass at 38° S (Table 1); their role in supporting heterotrophic or chemosynthetic benthic communities in the area is still unknown.

In summary, the continental margin sediments off Chile under the OMZ constitute a promising setting for paleoecological studies as well as for biogenic chemosynthetic systems research. Further studies are thus necessary to learn more on the distribution of bone

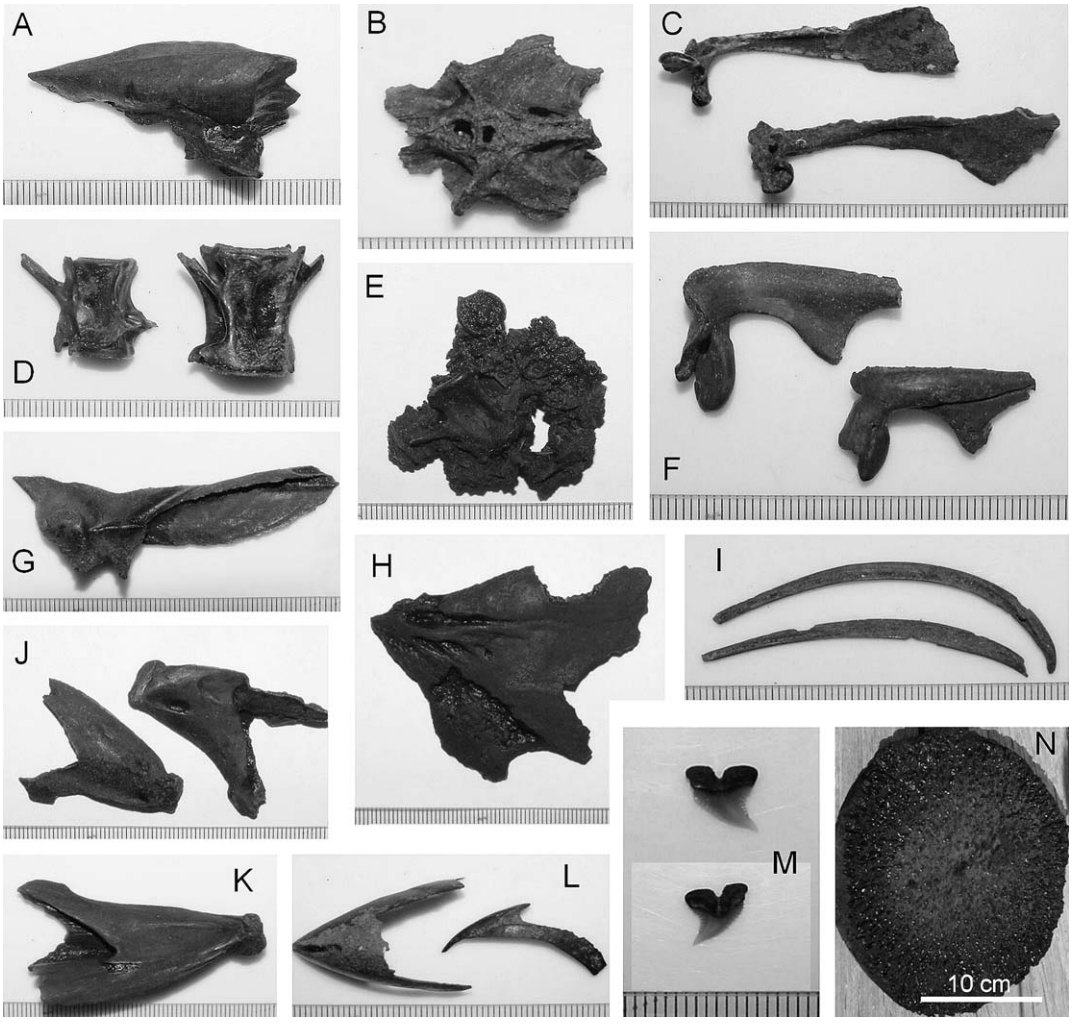

Fig. 2. Skeletal remains found off Mejillones Bay, northern Chile. Horse mackerel bones (*Trachurus murphyi*): (A) crest of the supra-occipital bone, (B and E) bone and phosphate mineral conglomerates, (C) maxillary, (D) vertebrae, (F) pre-maxillary, (G) cleitrum, (H) operculum, (I) gill arcs, (J) dentary and (K) pre-operculum. Other remains: (L) jumbo flying squid beaks (*Dosidicus gigas*), (M) shark teeth (*Carcharhinus* spp.), (N) whale inter-vertebral disc. All scales are in millimeters (distance between tickmarks = 1 mm), except for N, in which a 10 cm scale bar is given.

accumulations and their associated biota as well as their role in bio-elemental fluxes.

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