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Peruvian sediments as recorders of an evolving hiatus for the last 22 thousand years

Zeynep Erdem [a, *], Joachim Schönfeld [a], Nicolaas Glock [a], Marcus Dengler [a], Thomas Mosch [a], Stefan Sommer [a], Judith Elger [a, b], Anton Eisenhauer [a]

[a] GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstr. 1-3, 24148, Kiel, Germany
[b] Institute for Geosciences, Christian-Albrechts-Universität zu Kiel, Otto-Hahn-Platz 1, 24118 Kiel, Germany

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ABSTRACT

The Peruvian continental margin is characterized by the presence of one of the strongest and most distinct Oxygen Minimum Zones (OMZs) in today's oceans. Therefore, it has long been in the focus of oceanographic and geological investigations. Observations indicate that OMZs are expanding in relation with currently changing climate. To advance understanding of the temporal evolution of OMZs and climate change, complete paleoceanographic and palaeoclimatological reconstructions are needed. However, the development of paleoenvironmental scenarios for the period since the Last Glacial Maximum at this region was hampered by a ubiquitous hiatus and short-term interruptions of the stratigraphical record. In the present study, we combined the stratigraphical information from 31 sediment cores from the Peruvian margin located between 3 and 18°S and water depths of 90 to 1300 m within and below today's OMZ, in order to determine the extent of the hiatus and assess the responsible mechanisms. A widespread unconformity and related erosional features, omission surfaces and phosphorites, were observed in sediment cores from the area south of 7°S, depicting a prograding feature on the continental slope from south to north during the deglaciation. Combining recent oceanographic and sedimentological observations, it is inferred that, tide-topography interaction and resulting non-linear internal waves (NLIWs) shape the slope by erosion, carry sediments upslope or downslope and leave widespread phosphoritic lag sediments, while the Peru Chile Undercurrent (PCUC) transports the resuspended sediments southward causing non-deposition. This exceptional sedimentary regime makes the Peruvian margin a modern analogue for such environments. Overall, our compilation of downcore records showed that enhanced bottom currents due to tide-topography interaction were progressively evolving and affected a wider area with the onset of the last deglaciation. Elevated tidal amplitudes and variability of mid-depth water masses (i.e.; density changes) and hydrodynamics in relation with changing climate were potential reasons of this evolving feature of erosion and reworking. Additionally, erosion and non-deposition was observed widest and even was encountered on the continental shelf during the early Holocene, potentially indicating a strong phase of the PCUC mirroring today's El Niño-like conditions.

1. Introduction

The Peruvian continental margin is one of the key areas where the recently observed trend of expanding Oxygen Minimum Zones (OMZs) (Stramma et al., 2008) can be traced back in the geological record. Sediments from the Peruvian margin have been of interest for environmental reconstructions of high productivity areas and OMZs (e.g., Oberhänsli et al., 1990; Schrader, 1992; Rein et al., 2005). Short or long periods of non-deposition were observed in most of the sediment cores from continental shelf and slope off Peru. These gaps impeded the reconstructions of Late Pleistocene and Holocene paleoenvironmental conditions (Reimers and Suess, 1983; Froelich et al., 1988; Biebow, 1996; Skilbeck and Fink, 2006; Salvatteci et al., 2016). It has been suggested that the main reason for erosional intervals and hiatuses was the poleward flowing undercurrent (Reimers and Suess,

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* Corresponding author.
E-mail address: zerdem@geomar.de (Z. Erdem).

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1983; Suess et al., 1987; Reinhardt et al., 2002 and the references therein). Recently, it was found that the continental slope was critical for internal tides and breaking of internal waves were affecting the sedimentation on Peruvian continental margin (Mosch et al., 2012). In fact, these waves have been suggested as an important hydrodynamic energy source shaping the continental slope morphology, deposition and erosion of sediments (Cacchione et al., 2002; Pomar et al., 2012; Shanmugam, 2013; Lamb, 2014). Most of the previous work on internal waves was based on physical characteristics or the sedimentary structures created by the near-bottom enhanced oscillations in the fossil record. Meaningful examples where the interaction of internal waves with the sea floor has created a widespread unconformity have not been described to date. Furthermore, modern examples of NLIWs' interaction with seafloor topography are poorly documented. Previous works on the hiatus and erosional features concentrated on shelf and upper slope sediments off Peru and did not consider deposits from the middle or lower slope in the region. In the present paper, we present a compilation of sediment core and surface sediment studies (Table 1) including results from new cores recovered from greater depths. The aim of this study is: (1) to provide a modern analogue for a sedimentary regime which is current-dominated; (2) to show the importance of tide-topography interaction and resulting non-linear internal waves (NLIWs) on the sediment distribution, reworking and erosion; and (3) to understand the development of erosion in space and time and to elucidate the driving mechanism of the development of non-deposition since the Last Glacial Maximum (LGM).

2. Regional setting

The continental shelf and slope off Peru (Fig. 1) is characterized by one of the most pronounced oxygen minimum zones (OMZ) in today's world oceans (e.g., Fuenzalida et al., 2009). It is a tectonically active margin with a narrow continental shelf extending down to about 600 m water depth in places (Krissek et al., 1980; Strub et al., 1998). The northernmost area is characterized by marginal gulfs which are under influence of major rivers (Krissek and Scheidegger, 1983). The shelf between 7°S and 10°30′S is broad (~30 km) and the continental slope is steep with a pronounced shelf break (Reimers and Suess, 1983; Suess et al., 1987; Reinhardt et al., 2002). The shelf between 11 and 14°S is narrow (~15 km) and deeper compared with the north. The transition from shelf to slope is less pronounced (Reimers and Suess, 1983). South of 15°S, the continental shelf is narrower (<5 km) and the continental slope steepens again towards the Chilean margin (Krissek et al., 1980).

2.1. Physical oceanography

The Peruvian OMZ is maintained by the combination of a sluggish oceanic circulation and high primary productivity in the surface mixed layer, leading to elevated organic matter export and enhanced consumption of dissolved oxygen (e.g., Wyrtki, 1962). Highest productivity is observed at the continental margin between 5 and 15°S (e.g., Echevin et al., 2008). The major current system in the research area is Peru Current System (Gunther, 1936; Huyer et al., 1991; Strub et al., 1998), which is shaped by the topography of the continental margin. The Peru Current System is composed of the Peru-Chile Countercurrent (PCCC), the Peru-Chile Undercurrent (PCUC; or the Peruvian Undercurrent (PUC)), deep equatorward Chile-Peru Deep Coastal Current (CPDCC), and surface Peru Coastal Current (PCC). The subsurface currents PCCC and PCUC are fed by eastward equatorial subsurface currents (Montes et al., 2010; Czeschel et al., 2011). While the PCCC prevails 100–300 km offshore (Strub et al., 1995), the PCUC flows poleward above the continental slope and the outer shelf (Fig. 1; Strub et al., 1998; Chaigneau et al., 2013). The CPDCC is flowing equatorward beneath the PCUC carrying cold and low salinity Antarctic Intermediate Water (Chaigneau et al., 2013; and the references therein). The characteristics of the PCUC were documented by in situ measurements (Brockmann et al., 1980; Huyer et al., 1991; Czeschel et al., 2011; Chaigneau et al., 2013), and invoked by numerical modelling studies (Montes et al., 2010, 2011). It originates at around 3–5°S as a shallow water mass and prevails from 50 to 300 m water depths. The PCUC has a well-defined core between 50 and 200 m and flows with average velocities of 5–15 cm s^{-1} (Chaigneau et al., 2013). The current prevails over the shelf and upper continental slope in the northern and central part of the region (Brockmann et al., 1980; Huyer et al., 1991; Czeschel et al., 2011). On its way south, the current deepens, in accordance with potential vorticity conservation. It detaches from the continental slope south of 15°S but remains close to sea floor (Chaigneau et al., 2013). During ENSO phases and concomitant changes of equatorial subsurface currents, the PCUC shows pronounced variability. The current settles at greater depths and weakens during La Niña periods, whereas it flows at shallower depths and intensifies during El Niño periods (Shaffer, 1982; Huyer et al., 1991; Hill et al., 1998; Montes et al., 2011). Velocities of up to 30 cm s^{-1} were recorded between 9°S and 14°S in March 2010 which corresponds to El Niño period (Chaigneau et al., 2013).

Beside the deep currents, highly energetic baroclinic or NLIWs may exert an influence on the sediment distribution in relation to changes in sea floor topography. These waves are generated by tide–topography interaction and by internal wave reflection at the continental slope (e.g., Lamb, 2014). They are associated with

Table 1
Publications used as source for this compilation and review.

Information	Publications (author, year)
Continental shelf and slope morphology, Recent sediment distribution and characteristics as overview	Krissek et al. (1980), Krissek and Scheidegger (1983), Reimers and Suess (1983), Suess et al. (1987).
Recent sediment distribution and characteristics from certain areas and transects	Koide and Goldberg (1982), Henrichs and Farrington (1984), Kim and Burnett (1988), McCaffrey et al. (1990), Arthur et al. (1998), Levin et al. (2002), Böning et al. (2004), Muñoz et al. (2004), Gutiérrez et al. (2006), Sifeddine et al. (2008), Scholz et al. (2011), Mosch et al. (2012), Dale et al. (2015).
Phosphorite formation offshore Peru, phosphogenesis, phosphorite characteristics, their surface and downcore distributions	Veeh et al. (1973), Manheim et al. (1975), Burnett and Veeh (1977), Burnett (1980), Burnett et al. (1982), Froelich et al. (1988), Glenn and Arthur (1988), Garrison and Kastner (1990), Arning et al. (2009), Noffke et al. (2012).
Stratigraphical information; sediment cores, age models, dating points, sediment structures	Reimers and Suess (1983), Biebow (1996), Wolf (2002), Rein et al. (2004), Agnihotri et al. (2006), Skilbeck and Fink (2006), Chazen et al. (2009), Pfannkuche et al. (2011), Mollier-Vogel (2012), Mollier-Vogel et al. (2013), Salvatteci (2013), Salvatteci et al. (2016).