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ABSTRACT

Marine high-productivity zones along the continents are of great economic importance, and they account for most organic carbon burial. The carbon cycle in many coastal zones is influenced by the sediments and dissolved nutrients introduced by rivers. However, there is little direct evidence for a regional marine response to changes in river dynamics. Here we present a suite of high-resolution records of organic and inorganic paleoceanographic proxies, which together demonstrate that past changes in Indus River discharge have strongly affected productivity patterns in the coastal northeastern Arabian Sea. Anthropogenic activity, including the building of dams and irrigation facilities during the past century, has drastically decreased the discharge rate of the Indus River. Between A.D. 1890 and 1998, the period over which this reduction occurred, primary productivity off the Pakistan coast seems to have decreased by more than one-third. Over the same period, the regional oxygen minimum zone weakened, increasing the supply of oxygen to the sediments, leaving the expected imprint on a suite of redox-sensitive elements and reducing the preservation of organic matter.

INTRODUCTION

Primary productivity and sedimentation patterns in the northeastern Arabian Sea, one of the world's major high-productivity areas, are characterized by large seasonal contrasts due to reversing monsoons. During boreal summer, southwesterly monsoon winds induce strong upwelling and thus high productivity, particularly in the western Arabian Sea (Prell and Kutzbach, 1992). During boreal winter, northeasterly winds trigger convective turnover of water masses and stimulate a second productivity maximum throughout a single monsoon cycle in the eastern Arabian Sea (Haake et al., 1993; Reichart et al., 1998).

The monsoons also play a significant role in the global hydrological cycle and dominate the water discharge of large rivers in the tropical to subtropical latitudes (Kale, 2007; Kudrass et al., 2001). Suspended loads and nutrients through riverine input can have a significant impact on the biogeochemistry and thus the productivity in the marine realm (Syvitski et al., 2005). In the Arabian Sea, freshwater is mainly supplied by the Indus River (Pakistan). The Indus River is one of the largest contributors of sediment and water to the world oceans, and drains an area of ~950,000 km^2 (Ittekkot and Arain, 1986). Nearly 90% of the water reaching the river mouth is supplied from glaciers located in the Himalaya and Karakoram mountain ranges. The total freshwater runoff is ~100 km^3/yr (Karim and Veizer, 2002), carrying ~100 × 10^6 t/yr of sediments (Milliman et al., 1984). However,

starting more than 100 yr ago, and particularly over the past 70 yr, series of barrages and irrigation facilities, resulting from urbanization, have been built. As a consequence, water and sediment discharge were diminished drastically, by as much as 70%–90% (Ittekkot and Arain, 1986; Inam et al., 2007). This perturbation of the natural ecosystem makes it ideal to study

the influence of varying freshwater and nutrient supply on oceanographic conditions like variations in primary productivity and subsequent burial of organic matter in the Arabian Sea (in the vicinity of the Indus River mouth). It also enables us to assess trends in Indus River discharge rates over the past centuries.

STRATIGRAPHY AND SAMPLING

We use a well-preserved sediment core (SO130–288MC) that was recovered at the flank of the Indus Canyon off the Indus mouth (23°07.37N, 66°29.83E; 569 m water depth; Fig. 1). The 54-cm-long undisturbed core was retrieved from the center of an oxygen minimum zone (OMZ). The sediments are in most parts dark colored and indistinctly laminated. The uppermost 5 cm consist of nearly nonlaminated, brownish sediments.

The age model is based on ^{210}Pb dating of a neighboring core (SO130–285MC), which could be well correlated to SO130–288MC (Fig. DR3 in the GSA Data Repository[1]). The ^{210}Pb activ-
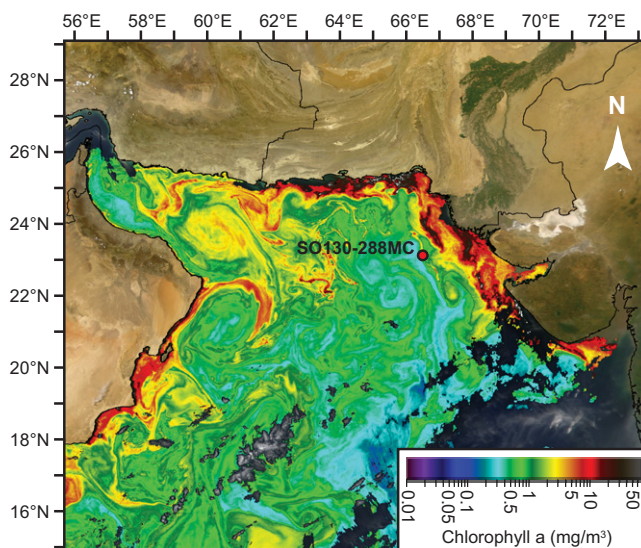

Figure 1. Location of sediment core SO130–288MC in northeastern Arabian Sea and Indus River (Pakistan) system. Sea-viewing Wide Field-of-view Sensor image from 4 October 2002, displaying productivity (chlorophyll a concentration) in Arabian Sea (SeaWiFS Project, NASA–Goddard Space Flight Center, ORBIMAGE; http://oceancolor.gsfc.nasa.gov/SeaWiFS/Gallery_Images/S2002277080416.L2_HBHR.ArabianSea.jpg).

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[1]GSA Data Repository item 2012123, details regarding the methodologies used and the results of age dating, sea-surface temperatures, TOC measurements (Figures DR1–DR3), and organic matter composition and grain sizes (Tables DR1–DR2), is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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ity (Fig. DR1) indicates a constant sedimentation rate of 0.7 mm/yr, in agreement with slope-wide sedimentation rates (Cowie et al., 1999). The ^{210}Pb age model is reliable for the uppermost 12 cm, equivalent to 170 yr. Beyond the ^{210}Pb dating limit, we assume constant sedimentation rates for the entire core, thus spanning the past 650 yr from A.D. 1998 to ca. 1350. (For a full description of methods, see the Data Repository.)

Marine Sediment Proxies for Productivity and OMZ Decline

We used clusters of organic and inorganic proxies to discriminate between early diagenetic and climate sensitive processes in the sediments (Fig. 2). Redox-sensitive elements (e.g., van der Weijden et al., 1999) show a characteristic depth succession of solid phase peaks. Mn and Fe are enriched in the uppermost part of the sedimen-

tary sequence. The distributions of Mn and Fe reflect the diagenetic status rather than changes in the supply of both elements and coincide with the interval where the sediments are not laminated. Both are indicative of suboxic conditions. U and Cd, elements that are fixed in anoxic parts of sediment, typically below the iron redox boundary, are not enriched until below a depth of ~5 cm (Fig. 2). This depth succession of the enrichments of redox-sensitive elements indicates non-steady-state diagenesis, as described by Reitz et al. (2004). A shift to lower total organic carbon (TOC) input is likely to have induced this non-steady-state diagenetic period.

The concentration of the biomarker tetrahymanol parallels the U/Al profile (Fig. 2). Tetrahymanol is synthesized by marine ciliates (Sinninghe Damsté et al., 1995). The diet of ciliates is sulfide-oxidizing bacteria living at the transition of suboxic to anoxic environments (Thiel et al., 1997). Therefore, the relatively low concentration near the sediment surface further indicates an increase in oxygen contents in the bottom water, in concert with the distribution of the redox-sensitive trace metals.

Sediment $\delta^{15}N$ values are within a range of 7.5‰–8.8 ‰. The lowest values occur in the near-surface sediments, which are also seen in nearby locations within OMZ sediments (Fig. 2; Cowie et al., 2009). TOC varies between 2.5% and 4.1%. The highest TOC contents were encountered in the interval with highest $\delta^{15}N$ values. Productivity-indicating biomarkers like alkenones (Fig. 2; Volkman et al., 1995) and diols (not shown; Sinninghe Damsté et al., 2003) suggest, in concert with TOC, a phase of enhanced productivity lasting more than 200 yr and indicate a distinct decline of TOC burial during the past century. The hydrogen index (HI) is lowest in this uppermost interval (Fig. 2). A microscopic study indicates that the contribution of hydrogen-poor terrestrial organic matter (OM) in all samples is low (<2%) and rather constant (Table DR1). This excludes the possibility that variable HI values are caused by variable input of OM from different sources; instead, HI values express the preservation state of OM (Lückge et al., 2002).

DISCUSSION

Paleoproductivity in the Arabian Sea is usually discussed in the context of monsoon circulation, but the role of the Indus River, responsible for the enormous supply of water, sediments, and nutrients to the sea, is overlooked. Today, the Indus River is one of the most intensively used rivers worldwide. Since the end of the 19th century, irrigation facilities and dams have changed the water budget and sediment load dramatically. The freshwater supply declined by more than 70% (to 90%) during this period (Fig. 2; Milliman et al., 1984; Inam et al., 2007). As a
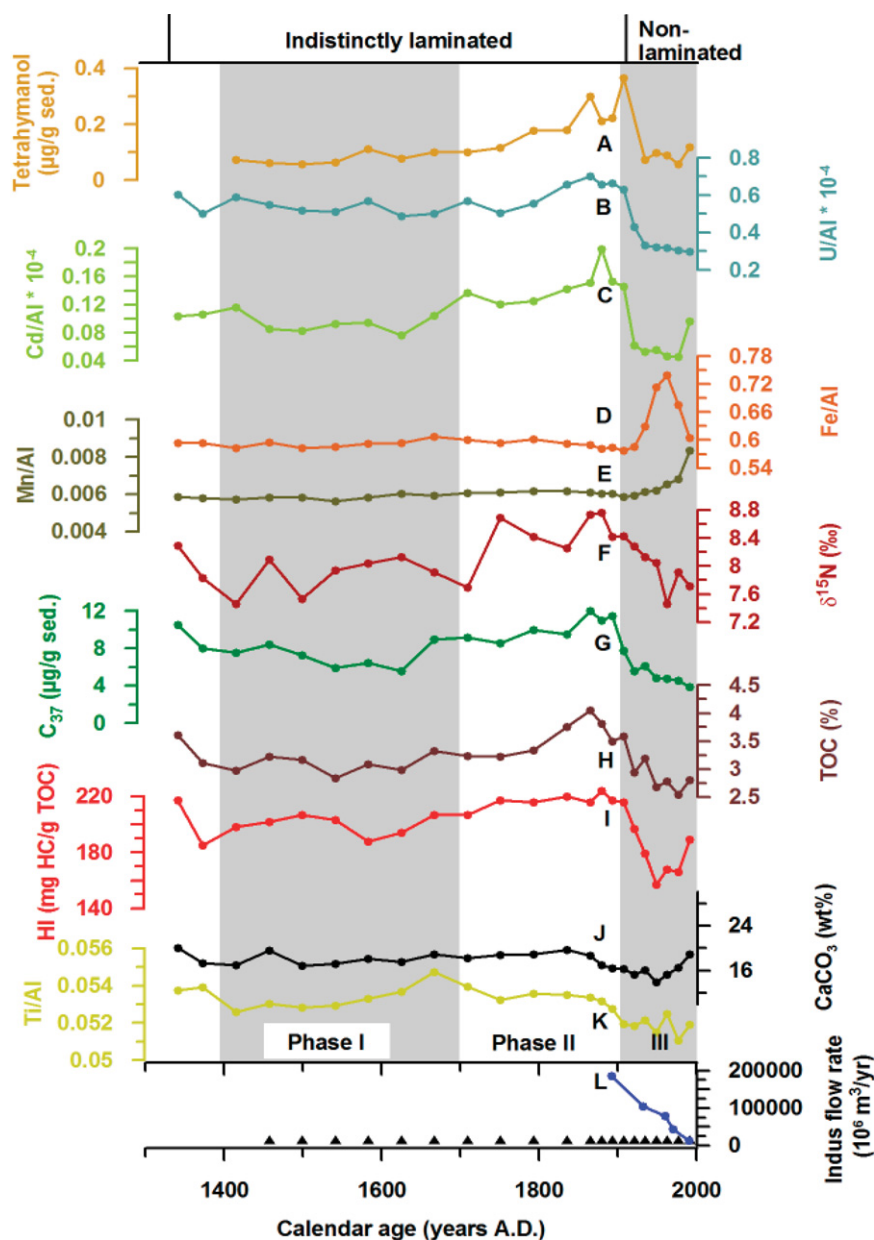

Figure 2. Inorganic and organic geochemical data from core SO130–288MC. A: Tetrahymanol provides biomarker for ciliates living at suboxic to anoxic interfaces. B–E: Redox state of sediments. B: Uranium. C: Cadmium. D: Iron. E: Manganese (normalized to Al). F: $\delta^{15}N$ is characteristic for oxygen-minimum zone conditions during deposition of sediments. G: C_{37} alkenones are biomarkers for haptophyte algae and provide, like total organic carbon (TOC), a proxy for primary productivity in the ocean. H: TOC. I: HI (hydrogen index) is measure of preservation state of organic matter. J: CaCO$_3$ (wt%) mirrors increase in uppermost interval of sediments. K: Titanium (normalized to Al) reflects changes in discharge rates of terrigenous fraction. L: Indus River discharge rates are documented for past 120 yr (Milliman et al., 1984; Inam et al., 2007). Black triangles denote sampling locations for ^{210}Pb analyses.

consequence, the Indus Canyon, which has fed the huge Indus fan with rather coarse-grained material, is becoming inactive. Sedimentation is restricted to fine-grained material that is delivered primarily to the continental slope (Prins and Postma, 2000; Clift et al., 2008).

During these past decades, the Ti/Al ratio, which is not affected by postdepositional alteration, also declines significantly in the core (Fig. 2). Sediment type studies in the Arabian Sea (von Rad et al., 1999; Prins and Postma, 2000) demonstrated that Al is an indicator of clay detritus derived from the continent. Lückge et al. (2001) proposed that variations in the Ti/Al ratio in sediments off the Makran coast are mainly the result of changes in fluvial discharge rates. The shape of the Ti/Al profile and its temporal correlation with discharge rates during the past decades suggest that variations in the composition of sediments are directly linked to changes in the drainage pattern of the Indus River. Because of the vicinity of the core to the Indus mouth, river runoff transporting suspended material is the most likely source for sediments (Clift et al., 2008). Eolian transport, which is the major terrigenous sediment source in the distal part of the Arabian Sea (Sirocko et al., 1993), is of minor importance. Metivier and Gaudemer (1999) and Clift et al. (2008) demonstrated that sediment buffering in river terraces and floodplains reacts on much larger time scales (10^5–10^6 yr). Changes in natural sediment buffering are therefore likely of minor importance. Grain-size analyses do not show significant grain-size variations (Table DR2), and changes in eolian versus fluvial input can be neglected (Prins and Postma, 2000). We can assume that variations in Ti/Al since ca. A.D. 1900 are most likely caused by damming and irrigation facilities. These processes had the effect of reducing the water and sediment transport, and thus changed the geochemical signature of transported material.

The radiometric dating provides evidence that sedimentation rates were constant within 20% uncertainty. The sedimentation rates are probably kept constant due to increasing $CaCO_3$ contents (from 13% to 19%) in the uppermost interval (Fig. 2). It seems to be likely that lower organic carbon productivity has resulted in less corrosive bottom water, leading to a better preservation and accumulation of $CaCO_3$. Changes due to enhanced erosion because of intensified land use seem to be unlikely since in this case we should expect increasing sedimentation rates.

The TOC and productivity-indicating biomarker records (Fig. 2) suggest that marine productivity declined during the phase of diminished discharge. Milliman et al. (1984) postulated that the drastic decrease of river discharge may have consequences for the nutrient supply and thus productivity in the Arabian Sea. Significant decreasing summer and/or winter monsoon activities that may lower the marine productivity and may explain lower TOC concentrations are not known from this period. Anderson et al. (2002) found that summer monsoon wind strength increased during the past 400 yr. Accordingly, Goes et al. (2005) reported for recent years that decreasing Eurasian snow cover is favorable to stronger southwestern monsoon, and thus increasing productivity. Studies on corals present evidence for rather constant northeastern monsoon activity during the past decades (Tudhope et al., 1996). Dahl and Oppo (2006) noted that sea surface temperatures (SSTs) are sensitive to the strength of the monsoon winds. Alkenone-based SSTs show more or less constant values, including the suggested period of diminished river discharge (Fig. DR2), and further support our conclusion that variations of marine hydrographical processes had minor influences on productivity changes. Instead, it is more likely that decreasing nutrient supply due to decreasing discharge from the Indus River has led to a regional decline in productivity. This may also explain the pattern that can be seen in the distribution of the redox-sensitive elements (Fig. 2). Because the log ^{210}Pb activity decreases linear with depth (Fig. DR1), we can exclude that sedimentation was disturbed by any postsedimentary processes. Instead, the geochemical patterns most likely document synsedimentary changes due to declining marine productivity. Low HI values in the sediments of the past ~100 yr argue for more intense degradation of OM. Decreasing marine productivity is probably accompanied by a slight weakening of the OMZ and/or an intensification of the decay of OM. Sedimentary δ^{15}N values vary in concert with productivity, as expressed by TOC and alkenones. The range in δ^{15}N is typical of marine high productivity areas affected by water-column denitrification (Cowie et al., 2009). The decline in δ^{15}N over the past century suggests that the reduction in river flow and the concurrent reduction in coastal productivity reduced the local intensity of water-column denitrification, through a contraction in the OMZ volume and/or a decrease in the volume-normalized denitrification rate through reduced organic matter supply (Suthhof et al., 2001; Reichart et al., 1998).

PALEOCEANOGRAPHIC IMPLICATIONS

The geochemical records show that significant environmental changes have occurred during the past centuries. Our data suggest that the sedimentary history of core SO130–288MC can be subdivided into three phases (Fig. 2). Ice core data from the Tibetan Plateau and tree ring records from Karakoram (Treydte et al., 2006) describe a dry and cold period, probably with relaxed monsoons, between A.D. 1400 and ca. 1700 (Mann et al., 2009). Gupta et al. (2003) demonstrated that, during that time, summer monsoon intensity and thus upwelling were less intense in the western Arabian Sea. This cool period, which correlates with colder temperatures in the North Atlantic (Gupta et al., 2003), was probably accompanied by low Indus discharge rates, as indicated by low Ti/Al ratios. During this period, which was characterized by lower snow-line elevations in the Karakoram and Himalaya mountains (Kuhle, 1999), runoff was lower because of reduced precipitation and increased retention as snow. During this time coastal productivity was relatively low, as indicated by TOC and biomarkers. During a second phase, from A.D. 1700 to ca. 1900, the southwest monsoon was intensified (Chauhan et al., 2010), and the freshwater input from the Indus River was high. During this phase, marine productivity was high. During the third phase, from ca. A.D. 1900 to 1998, marine productivity declined, although monsoon strength remained favorable for enhanced production and/or preservation of marine organic matter (Gupta et al., 2003; Anderson et al., 2002).

CONCLUSIONS

Paleoproductivity proxies in the northeastern Arabian Sea are usually discussed in the context of monsoon circulation, but the impact of the Indus River on coastal productivity, redox conditions, and sedimentation may be substantial. Our study suggests that the human-driven hydrological changes on land over the past century may have had a significant effect on offshore productivity and TOC burial. Anthropogenic redistribution of the Indus flow appears to have altered the chemical and physical conditions of the coastal sedimentary environment. Our results provide further motivation for investigating the impacts of human activities on the transport rates of water, sediment, and dissolved constituents to the coastal areas of oceans; specifically, monitoring the sedimentation offshore the Indus River might improve our understanding of the human perturbation of this drainage system. The devastating floods that followed heavy monsoon rains in the summer of 2010 in Pakistan might be used as a test case for the implications of changing Indus River discharge on the marine offshore ecosystem, helping to improve flood management strategies. Our results also give a sense of the scale of locally driven human changes in this coastal system, relative to those driven by past climate change.

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