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Quaternary climate modulation of Pb isotopes in the deep Indian Ocean linked to the Himalayan chemical weathering

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ABSTRACT

We use reductive sediment leaching to extract lead (Pb) from the authigenic fraction of marine sediments and reconstruct the Pb isotope evolution of the deep central Indian Ocean over the past 250 thousand years at ∼3 kyr resolution. Temporal variations define a binary mixing line that is consistent with data from ferromanganese nodules and which records mixing between two well-defined endmembers through time. The unradiogenic endmember appears to represent a widely-distributed Pb source, from mid-ocean ridges or possibly volcanic aerosols, while the radiogenic endmember coincides with the composition of Ganges–Brahmaputra river sediments that are indicative of the Himalayan weathering inputs. Glacial–interglacial Pb isotope variations are striking and can be explained by an enhancement of Himalayan contributions by two to three times during interglacial periods, indicating that climate modulates the supply of dissolved elements to the ocean. While these changes could accurately record variations in the continental chemical weathering flux in response to warmer and wetter conditions during interglacials, the relative proportions of Pb derived from the Ganges and Brahmaputra appear to have been constant through time. This observation may point towards particulate-dissolved interactions in the estuary or pro-delta as a buffer of short timescale variability in the composition (and potentially flux) of the fluvial inputs. In addition, the changes are recorded at 3800 m water depth, and with the lack of deep water formation in the Bay of Bengal, a mechanism to transfer such a signature into the deep ocean could either be reversible scavenging of dissolved Pb inputs and/or boundary exchange on the deep sea fan. Unless the mechanism transferring the Pb isotope signature into the deep ocean was itself highly sensitive to global climate cycles, and with the absence of a precessional signal in our Pb isotope data, we suggest that the Indian climate and its influence on basin-scale chemical weathering were strongly modulated by glacial versus interglacial boundary conditions.

1. Introduction

Continental weathering and erosion are fundamental processes that influence the earth's elemental cycles, ocean chemistry, atmospheric composition and climate (e.g. Raymo et al., 1988). However, potential feedbacks between climate and chemical weathering remain poorly understood because of the multiple controls on weathering rates (e.g. White and Blum, 1995; Dupre et al., 2003; Riebe et al., 2004; West et al., 2005). The Himalayan orogen, via the Ganges and Brahmaputra rivers, provides a significant source of both sediments (∼1000 million tons/year) and dissolved elements (∼100 million tons/year) to the oceans (Galy and France-Lanord, 1999; Milliman and Farnsworth, 2013), making it a good target for investigating climate-weathering links (note that for brevity, we are using 'weathering' to refer to the combined effect of in-situ chemical weathering and the dissolved transport of its products). Changes in Himalayan weathering have previously been invoked to explain changing ocean chemistry and climate during the Cenozoic (e.g. Edmond, 1992; Richter et al., 1992), but we lack direct evidence on its temporal evolution and its response to climate change over both million-year and glacial–interglacial timescales.

Past weathering rates may be obtained by analysing sedimentary archives recovered from the ocean basins. Isotopic tracers with oceanic residence times significantly longer than the mixing time of the oceans (e.g. Sr, Li isotopes) can provide evidence on the

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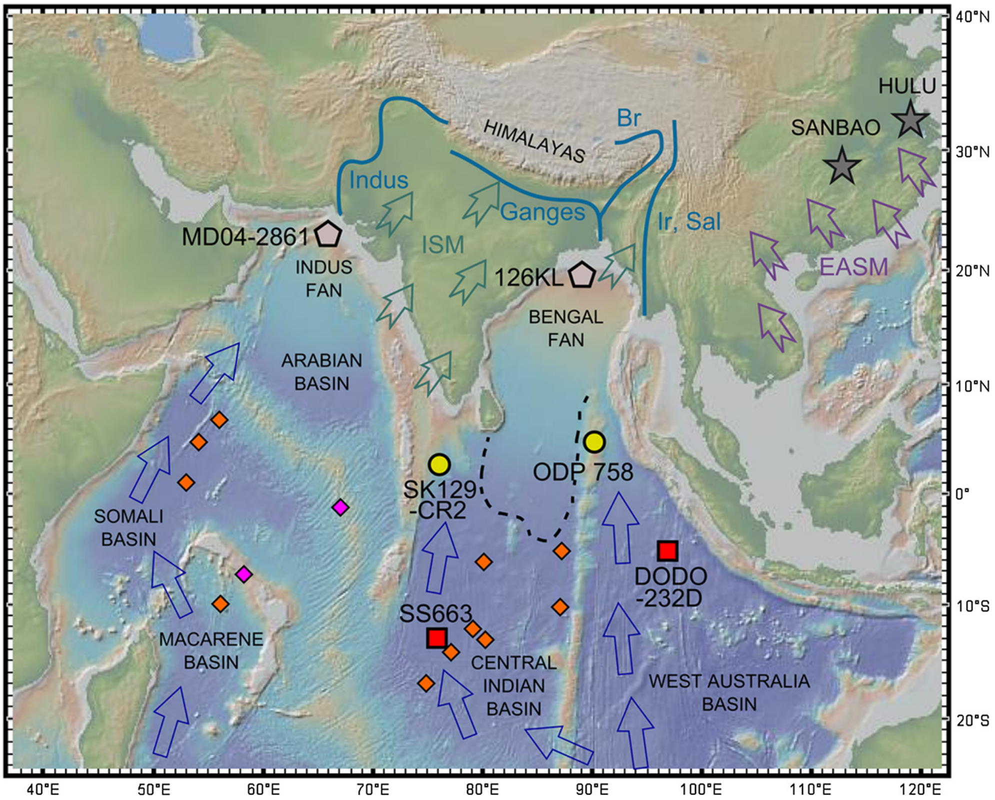

Fig. 1. Location map for studied cores SK129-CR2 (3°N, 76°E, 3800 m depth) and ODP 758 (5°N, 90°E, 2925 m depth) (yellow circles). Ferromanganese crusts with existing Pb isotope records are SS663 (Frank and O'Nions, 1998) and DODO-232D (Frank et al., 2006) (red squares). Ferromanganese crusts and nodules whose surface layers were analysed for Pb isotopes are also plotted (von Blanckenburg et al., 1996, pink diamonds; Vlastelic et al., 2001, orange diamonds, their N-Indian domain). Blue arrows show schematic representation of the deep circulation (after Mantyla and Reid, 1995; You, 2000) and dotted line shows the extent of the Bengal Fan. Also shown are sediment cores SO93-126KL (Kudrass et al., 2001) and MD04-2861 (Caley et al., 2011) (grey pentagons); Chinese speleothems from Sanbao and Hulu caves (Wang et al., 2001, 2008; Cheng et al., 2009) (grey stars); major rivers (Br=Brahmaputra, Ir=Irrawaddy, Sal=Salween) and schematic representation of Indian Summer Monsoon (ISM) and East Asian Summer Monsoon (EASM) (green and purple arrows). Base map from GeoMapApp. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

globally-integrated weathering signal over a timescale comparable to their residence time (Richter et al., 1992; Misra and Froelich, 2012). However, for any forcing occurring on timescales comparable to or shorter than their residence times, such tracers will show a muted amplitude of change and a phase lag behind that forcing (Richter and Turekian, 1993). In addition, these tracers cannot provide evidence on the geographic distribution of the weathering, making it difficult to link changes in weathering fluxes to specific continental source regions. For this purpose, we require isotopic tracers with oceanic residence times shorter than the mixing time of the oceans (e.g. Nd, Hf, Pb isotopes). Such tracers have a non-uniform geographical distribution that in part reflects the location of the inputs (von Blanckenburg, 1999; Frank, 2002; Goldstein and Hemming, 2003) and should respond rapidly to climatically-controlled changes in weathering inputs.

Since lead (Pb) has a deep water residence time of ~50–200 years (Schaule and Patterson, 1981; Cochran et al., 1990; Henderson and Maier-Reimer, 2002), its isotopic composition is expected to be particularly sensitive to local weathering inputs. Lead isotope measurements on the authigenic fraction of marine sediments have therefore been used to trace regional weathering intensity and/or provenance through time (e.g. von Blanckenburg and Nagler, 2001; Reynolds et al., 2004; Foster and Vance, 2006; Haley et al., 2008; Gutjahr et al., 2009; Crocket et al., 2012). In the Indian Ocean, the Pb isotope signature advected by deep waters from the Southern Ocean is overwhelmed by local sources of Pb in the central Indian Ocean (Vlastelic et al., 2001), indicating the potential of Pb isotopes for tracing the local weathering sources. On million year timescales, Frank and O'Nions (1998) proposed a link between Himalayan weathering changes during the Neogene and the Pb isotopic composition of the deep central Indian Ocean recorded by ferromanganese crust SS663 (Fig. 1). However, with the exception of a further study on crust DODO-232D (Frank et al., 2006), this approach remains under-exploited for investigating weathering in the Himalayan system, and in particular has not been applied on shorter timescales.

In this study, we reconstruct the Pb isotopic evolution of the deep Indian Ocean over glacial–interglacial and shorter timescales, aiming to better constrain the Himalayan Pb contribution and assess Himalayan weathering changes in response to glacial–interglacial cycles. More specifically, we (i) test the use of acid-reductive leaching to extract past seawater Pb isotopic composition from ocean sediments; (ii) reconstruct temporal variability in the Pb isotopic composition of the central Indian Ocean from 0–250 ka BP; (iii) assess the sources of Pb and the mechanisms for generating that temporal variability; and (iv) consider the implications of our high resolution record for past changes in the Himalayan weathering inputs.

2. Regional setting

Our study is based on two marine sediment cores from the deep central Indian Ocean (Fig. 1). Core SK129-CR2 (3°N, 76°E, 3800 m water depth) is located on the east side of the Chagos–Laccadive Ridge in the Central Indian Basin (Banakar, 2005) and core ODP 758 (5°N, 90°E, 2925 m water depth) is located on Ninetyeast Ridge (Farrell and Janacek, 1991). Deep waters at both sites are supplied by northward-flowing Circumpolar Deep Water