Provenance and temporal variability of ice rafted debris in the Indian sector of the Southern Ocean during the last 22,000 years

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Ice rafted debris (IRD) records were studied in two sediment cores (SK200/22a and SK200/27) from the sub-Antarctic and Polar frontal regime of the Indian sector of Southern Ocean for their distribution and provenance during the last 22,000 years. The IRD fraction consists of quartz and lithic grains, with the lithic grains dominated by volcaniclastic materials. IRD content was high at marine isotope stage 2 but decreased dramatically to near absence at the Termination 1 and the Holocene. The concentration of IRD at glacial section of the core SK200/27 was nearly twice that of SK200/22a. Moreover, IRD were more abundant at the last glacial maxima (LGM) in SK200/27 with its peak abundance proceeding by nearly two millennia than at SK200/22a. It appears that an intensification of Antarctic glaciation combined with a northward migration of the Polar Front during LGM promoted high IRD flux at SK200/27 and subsequent deglacial warming have influenced the IRD supply at SK200/22a. Quartz and lithic grains may have derived from two different sources, the former transported from the Antarctic mainland, while the latter from the islands of volcanic origin from Southern Ocean. Sea-ice, influenced by the Antarctic Circumpolar Current is suggested to be a dominant mechanism for the distribution of lithic IRD in the region.

1. Introduction

The Southern Ocean exerts a strong influence on the global climatic system mainly due to the presence of the Antarctic Circumpolar Current (ACC), driven by the westerly winds that encircle Antarctica. The oceanography of the Southern Ocean also plays an important role in the distribution of icebergs and is a crucial factor in reconstructing the waxing and waning of Antarctic ice sheets and the regional palaeoclimate record (Ehrmann and Mackensen 1992). The sedimentary records of ice rafted debris (IRD) in the Southern Ocean offer potential proxy indicators to investigate the dynamic behaviour of Antarctic ice sheets and Antarctic climate (Hayes *et al.* 1975; Grobe and Mackensen 1992; Zachos *et al.* 1992). Large changes in an ice margin, for example, the surge and breakup of an ice stream would generate icebergs and deposition of IRD on the sea bed. IRD records have the advantage of being more continuous and more easily dated than the more ice-proximal glaciogenic sediments. The timing of IRD deposition relative to glacial–interglacial climatic cycles is significant in understanding the processes by which the IRD carrying icebergs produced. By determining the

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geochemistry of IRD, it is possible to infer the provenance of the icebergs that carried it, and hence the ice margin that produced the icebergs.

Terrigenous fraction makes up a considerable proportion of total sediment accumulation in the Southern Ocean, and its origin is less understood than the biogenic deposits (Fischer and Wefer 1999; Walter *et al.* 2000). Although the IRD forms only a small proportion of the terrigenous sediment fraction, its temporal distribution provides important insights into ice-sheet dynamics and the extent of cold surface water masses that control the distribution and survival of both icebergs and sea ice in relation to the climate changes (Diekmann *et al.* 2004; Diekmann 2007). The occurrence of discrete IRD layers in the Southern Ocean has challenged the notion of Antarctic ice sheet stability during the last glaciation. Within the Indian sector of the Southern Ocean, IRD contributes less than 20% of the total detrital input (Bareille *et al.* 1994) and it is largely quartz, suggesting an Antarctic contribution of glacial ice as the main IRD source (Labeyrie

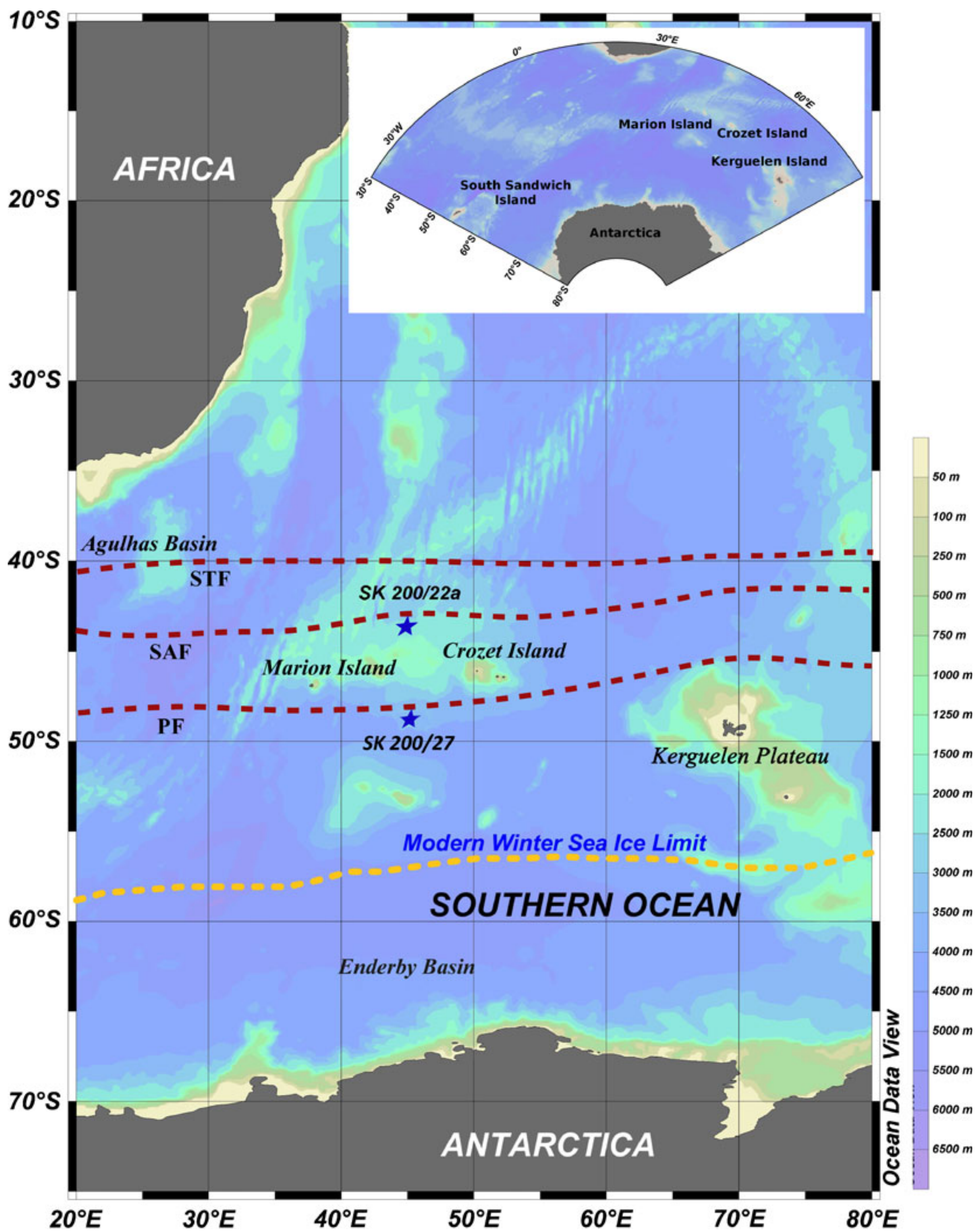

Figure 1. Study area showing location of the core site SK200/22a and SK200/27. Schematic position of important oceanographic fronts and winter sea ice in the Indian sector of the Southern Ocean are also shown.

et al. 1986). After calving from the main ice mass, icebergs drift westwards around the East Antarctic coast in the polar current. At locations where bathymetric highs and/or the wind patterns cause a northward component to the polar current, the icebergs drift north, and become entrained in the eastward flowing ACC (Williams *et al.* 2010).

In this study, we have examined the distribution, morphology, mineralogy and chemical compositions of IRD in late Quaternary sediment records from the Indian sector of the Southern Ocean. The main objective of the study is to report the provenance and the variability of IRD in response to climatic/oceanographic changes during the last glacial to interglacial period. The location of sediment cores also provides us an opportunity to determine the extent of changes in IRD records with respect to past changes in the Southern Ocean frontal regimes.

2. Materials and methods

Two sediment cores, SK200/22a (43°42′S/45°04′E) and SK200/27 (49°S/45°13′E), collected from the Indian sector of the Southern Ocean (figure 1) were examined for IRD distribution. The core SK200/22a is located in the sub-Antarctic Front (SAF) region collected at a depth of 2730 m, whereas the core SK200/27 is from the Polar Front (APF) region collected at a depth of 4389 m (Thamban *et al.* 2005). Main chronological controls were obtained by accelerator mass spectrometry (AMS) radiocarbon (^{14}C) dating of the planktonic foraminifers, *Globigerina bulloides* and/or *Neogloboquadrina pachyderma* (figure 2). While a chronological framework for core SK200/22a based on five AMS ^{14}C data was reported by Manoj *et al.* (2012), two additional dates were obtained subsequently (table 1). In the absence of calcitic foraminiferal tests below 80 cm in core SK200/27, further chronological constraints were obtained using AMS ^{14}C dating of the total organic carbon in the sediments (figure 2; table 1). All radiocarbon ages were calibrated to calendar ages using the Calib 6 program of Stuiver *et al.* (2005), and all dates cited in the text thus refer to calendar years (table 1). An age model was constructed based on the linear interpolation of the dated horizons. In the present study, we have focused on the distribution of IRD for the past ∼22,000 years (22 ka BP) incorporating the marine isotopic stages 1 (MIS 1) and MIS 2 (figure 2).

The coarse fraction (>125 μm) at every 2 cm interval of the core was separated and studied under a binocular microscope. The distribution of IRD grains was determined by counting 300–400 grains in >125 μm fraction (Baumann *et al.* 1995; Stoner *et al.* 1996; Nielsen *et al.* 2007). The IRD grains thus separated were cleaned by using an ultrasonicator to remove the contaminant particles from the surface of the grains. The IRD grains were mounted on a sample stub, Platinum coated (100 Å) for 30–60 s in a JEOL JFC-1600 Auto Fine

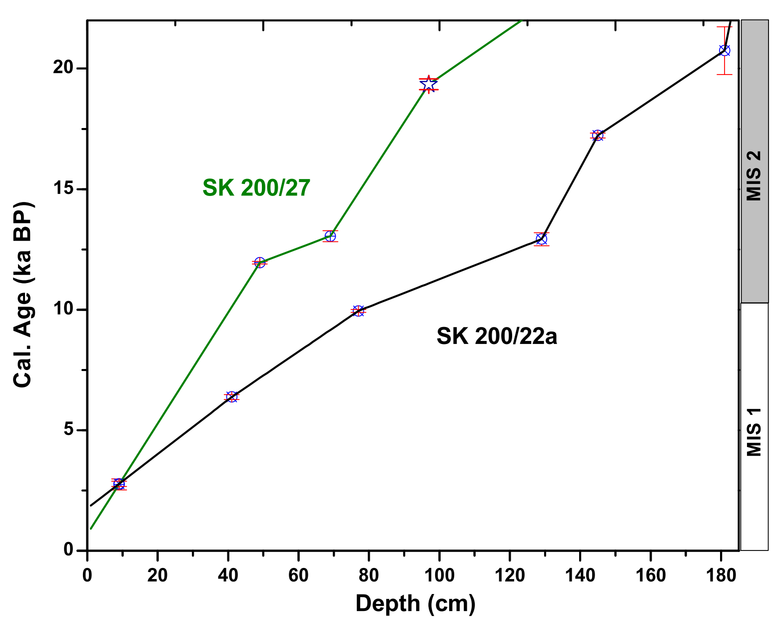

Figure 2. Age model for the cores SK200/22a and SK200/27. Radiocarbon control points are shown with error bars. The star sign at two intervals denotes that the ^{14}C measurements at these intervals were made on bulk organic carbon. The marine isotope stages (MIS) are given at the right axis.

Table 1. *AMS ^{14}C ages determined from cores SK200/22a and SK200/27 and calibrated calendar ages after Stuiver et al. (2005).*

Depth interval in the core (cm)	Lab code*	Radiocarbon age (years)	Error (±)	Calibrated age (years)	Remarks
SK 200/22a					
8–10	X8398 (a)	2635	36	2764 ± 16	
40–42	OS-87516 (b)	5590	35	6368 ± 37	
76–78	B7710A (a)	8822	46	9929 ± 151	
128–130	X8399 (a)	10943	70	12885 ± 98	
144–146	X8400 (a)	13881	68	17124 ± 200	Planktic foraminifers
180–182	B7711 (a)	17186	88	20636 ± 295	
196–198	OS-87526 (b)	32300	160	36635 ± 571	
SK 200/27					
8–10	X8401 (a)	2632	75	2713 ± 115	
48–50	X8402 (a)	10164	54	11817 ± 164	
68–70	X8403 (a)	11017	55	12924 ± 104	
96–98	OS-87596 (b)	16050	200	19212 ± 285	Organic carbon in bulk sediment
144–146	OS-87595 (b)	20200	310	24117 ± 438	

*Samples measured at (a) NSF-AMS Facility of the Arizona University and (b) NOSAMS facility at Woods Hole, USA.

Coater and examined under the Scanning Electron Microscope (SEM-JEOL 6360LV) for morphological characteristics. Representative IRD grains were also examined for major elements, using the OXFORD INCA 200 EDS system attached to the SEM. Mineralogy of the grains was determined by X-ray Diffraction (XRD) studies, using a Rigaku Ultima-4 model X-ray diffractometer.

3. Results and discussion

3.1 *Spatial and temporal variability in IRD records*

The average sedimentation rate at SK200/22a core site was 12.5 cm/1000 years and at SK200/27 core, it was 8 cm/1000 years. Accordingly, at core SK200/22a the IRD records were examined up to a depth of 183 cm, whereas in core SK200/27, the IRD were studied to a depth of 125 cm. IRD fractions consist of quartz and lithic grains. The lithic grains are sub-rounded to elongate vesicular rock fragments, dominated by volcaniclastic materials. Studies have shown that the spatial distribution of IRD in Southern Ocean depends on the proximity to glacial sources, directions of oceanic surface circulation, and surface-water temperature that controls the survival of rafted ice (Kanfoush *et al.* 2000). The IRD input at the core SK200/27 site was substantially higher than the SK200/22a core site. The IRD content in core SK200/22a consisted of equal proportion of quartz and lithic grains, whereas in core SK200/27, quartz grains dominated the lithic grains (figure 3).

The downcore distribution of IRD during the past 22 ka BP revealed that both the cores showed increased IRD input during the MIS 2 between 20 and 13 ka BP. IRD concentrations in core SK200/27 were twice that of core SK200/22a (figure 3). The LGM record of SK200/27 shows a substantial temporal offset with a peak IRD abundance preceding by nearly two millennia than at SK200/22a. Moreover, significant differences occur in their concentrations within MIS 2. In the core SK200/22a, the IRD constituted only a minor component of the total coarse fraction and peak high concentrations spread between 18 and 15 ka BP, immediately after the LGM (figure 3). In the core SK200/27, the peaks of high IRD spread between 22 and 15 ka BP and then decreased gradually to a minimum at 13 ka BP (figure 3). While this offset could be partly the result of chronological uncertainties in the lower portion of the core SK200/27, the increased IRD accumulation mainly indicate the equatorward migration of the APF and SAF in association with a strengthening of the ACC system that could have promoted wind induced shallow-water erosion around oceanic islands (Manoj *et al.* 2012). Irrespective of their position, both the cores SK200/22a and SK200/27 show similar concentration of lithic grains during the MIS2 which suggests a modulation of the ACC flow intensity and water masses like CDW and AABW. IRD concentrations occur in traces or absent during the Holocene in both the cores. It is evident that the core collected closer to the

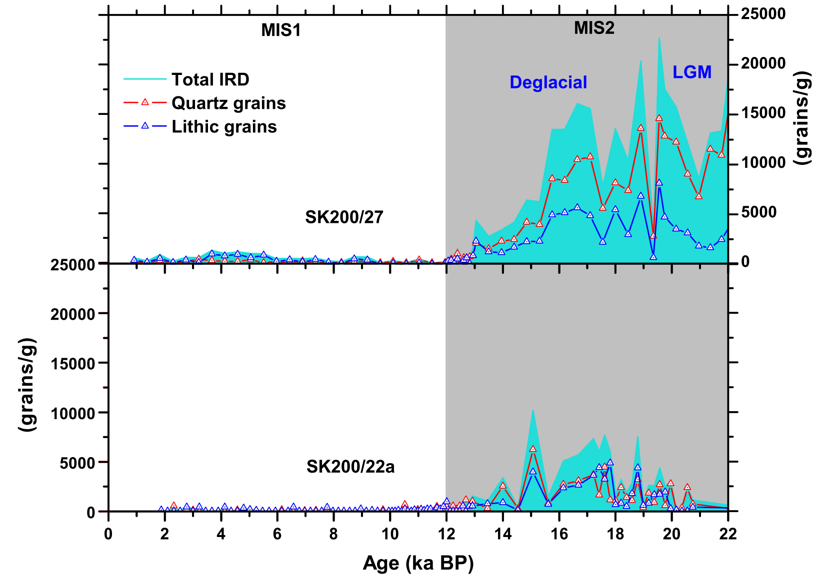

Figure 3. Down core profiles showing concentrations of total ice rafted debris (IRD) and its components (quartz and lithic grains) in the cores SK200/22a and SK200/27.

Antarctic continent (SK200/27) showed higher (of the order of two) quantity of IRD compared to the core collected north of it (SK200/22a).

3.2 *Morphological and compositional characteristics of the IRD*

Quartz is the dominant mineral in both the cores. Grain surfaces were characterized by conchoidal fractures, grooves and troughs (figure 4a–c). The EDS chemical analysis confirmed that silica is the dominant element. The SEM images show absence of sorting and step like features, which confirm the transport by ice sheets. In case of transport by ice, the grains are lifted by the calving ice and do not experience any rolling or saltation effect. Dominance of quartz in the IRD suggests that they may have derived from the Antarctic region (Labeyrie *et al.* 1986; Nielsen *et al.* 2007). A few garnet grains were observed along with quartz (figure 4e). The garnet grains appear fresh and are pale pink to dark red in colour, with high relief and high degree of angularity, suggesting glacial origin (Mahaney 2002). Presence of garnet also signifies the source from Precambrian metamorphic complexes (like gneiss and schist), typically found in the Antarctic continent. The presence of quartz and garnet mineral grains in the IRD record during the LGM at SK200/22a confirms that the Antarctic icebergs possibly reached up to 44°S.

Lithic fragments and quartz occur in equal proportions of IRD in SK200/22a and quartz forms the dominant IRD component in SK200/27 (figure 3). The lithic fragments are much larger (up to 5–10 mm) in size than the quartz grains (up to 2–4 mm), with very irregular edges and surfaces. Vesicular features and voids are characteristic of many fragments and, a few of them are characteristic of volcanic glass. The SEM-EDS study confirmed that the majority of lithic grains are similar to those found in basaltic-lava (figure 5a–d). Since voids are formed by the expansion of bubbles of gas/steam during the solidification of the basaltic rock, these lithic materials are most probably the fragments of extrusive basalt. The EDS composition of these grains shows the elemental oxides in the order of $SiO_2 > Al_2O_3 > FeO > CaO > Na_2O > MgO > K_2O > MnO$. The chemical composition of IRD grains studied here are similar to those in the South Atlantic by Nielsen *et al.* (2007). Besides, a few lithic grains revealed typical texture and composition similar to that of volcanic glass (figure 5d–e). XRD analysis revealed that plagioclase feldspars are dominant minerals in lithic grains (figure 6). Almost all major peaks corresponding the plagioclase feldspars and other minor amount of quartz and olivine are also identified. The 100% peak of plagioclase feldspar is shown with the 'd' spacing of 3.20 Å. Additionally, well defined peaks of plagioclase feldspars are shown at 3.75 (80%), 3.35 (60%), 3.22 (80%), 3.17 (90%), 3.12 (70%) and 2.64 Å (60%) 'd' spacings. The morphology, mineralogy and chemical composition of the lithic grains in the cores thus confirm to their origin from extrusive basaltic rocks.

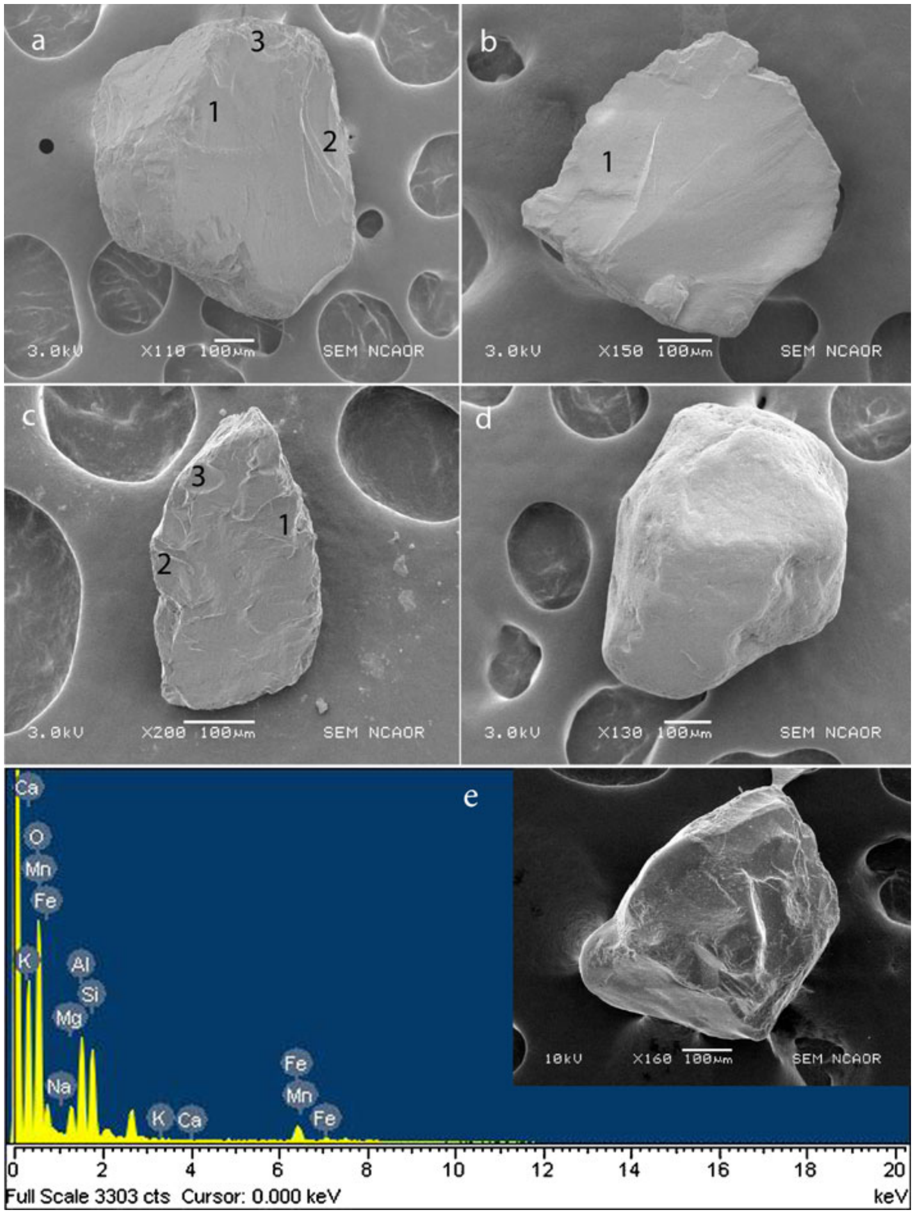

Figure 4. SEM images of the typical quartz grains with surface glacial features in panels (**a**–**d**) showing conchoidal fracture (1), step-like (2) and trough like features (3), and typical garnet grains with chemical composition using EDS (**e**).

3.3 *Provenance and controlling factors of the IRD in the Indian sector of Southern Ocean*

Modern iceberg distribution in Southern Ocean shows that the northern limit of iceberg occurrence is associated with a surface water temperature around 4°C (Becquey and Gersonde 2002). The core SK200/27 is located at 49°S, just south of the APF, where any changes in past sea surface temperature will significantly alter the iceberg production and preservation. On the other hand, the core SK200/22a is located at 44°S and is within the SAF, with very limited Antarctic iceberg supply at modern times. The low or near absence of IRD content in the entire Holocene interval in both the cores suggests that the present interglacial conditions are not favourable for ice rafting and IRD transportation to the core sites. The increase in IRD during LGM at the core sites could be attributed to the increased production of icebergs, increased survival of icebergs and sea ice, as well as reduced dilution by biogenic material. During the last glaciation when global sea level was ~120 m lower than the present, ice shelves surrounding Antarctica were reported to be more extensive as grounding lines advanced seaward over the continental shelf (Denton and Hughes 1983; Bindschadler *et al.* 1998). During periods of such glaciations, the APF was reported to have migrated northward by more than 5° of latitude

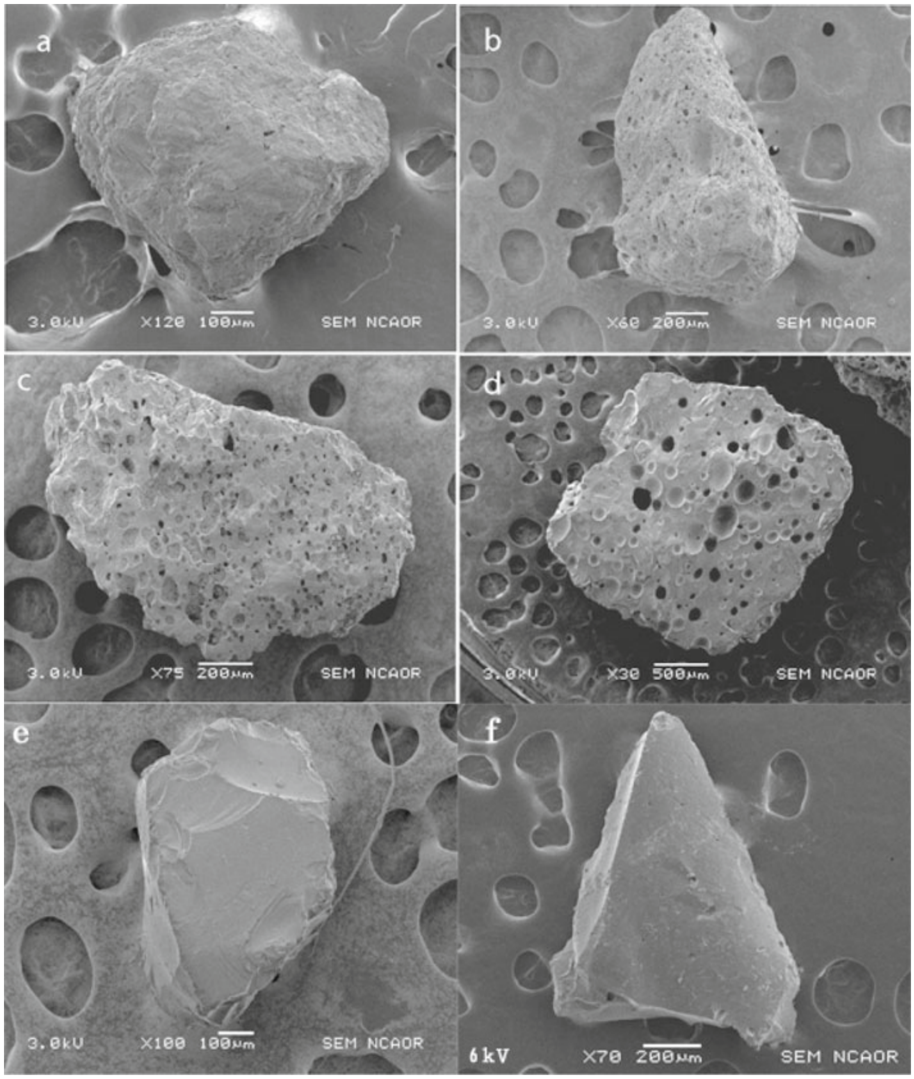

Figure 5. SEM images of the lithic grains showing irregular surfaces, edges and vesicular textures of extrusive basalt (**a**–**d**); volcanic glass fragments (**e**–**f**).

with an associated equatorward migration of winter sea ice limit (Crosta *et al.* 1998; Brathauer and Abelmann 1999). Increased ice-rafting during glacial stages is also supported by the oxygen isotope anomalies reported in a sediment core from the Indian sector of the Southern Ocean (44°S) by Labeyrie *et al.* (1986).

In the foregoing discussion we have suggested that the quartz grains were transported by the icebergs detached from Antarctica, whereas the lithic fragments and tephra by the sea ice. Following the ice drift during the falling sea level and melting of the sea ice during the early deglacial warming, the IRD deposition would have increased at the core sites. Studies in the Southern Ocean have shown that the quartz and other non-ash lithics are sourced from Antarctica by calving of icebergs (Bareille *et al.* 1994; Kanfoush *et al.* 2002). Accordingly, it was proposed that the discrete layers of Antarctic-derived IRD indicate instability of Antarctic ice sheets that led to increased production of icebergs (Bareille *et al.* 1994; Kanfoush *et al.* 2002). A majority of icebergs originate from ice shelves such as those found in the Weddell Sea, where debris-rich basal ice can be produced by melting and freezing at the base of these ice shelves (Hulbe 1997). Most of the coarse detrital material originating from Antarctica could have been transported to the Southeast Indian sector mainly by icebergs from the eastern Antarctic region (Ross Sea to Enderby Land) along with a variable amount of icebergs from the western Antarctic (Bareille *et al.* 1994). Icebergs probably travelled away from the continental margin via the ACC as observed today in the Indian sector of the Southern Ocean (Williams *et al.* 2010). It is therefore, suggested that quartz grains which constitute 55–65% of the IRD material are exclusively

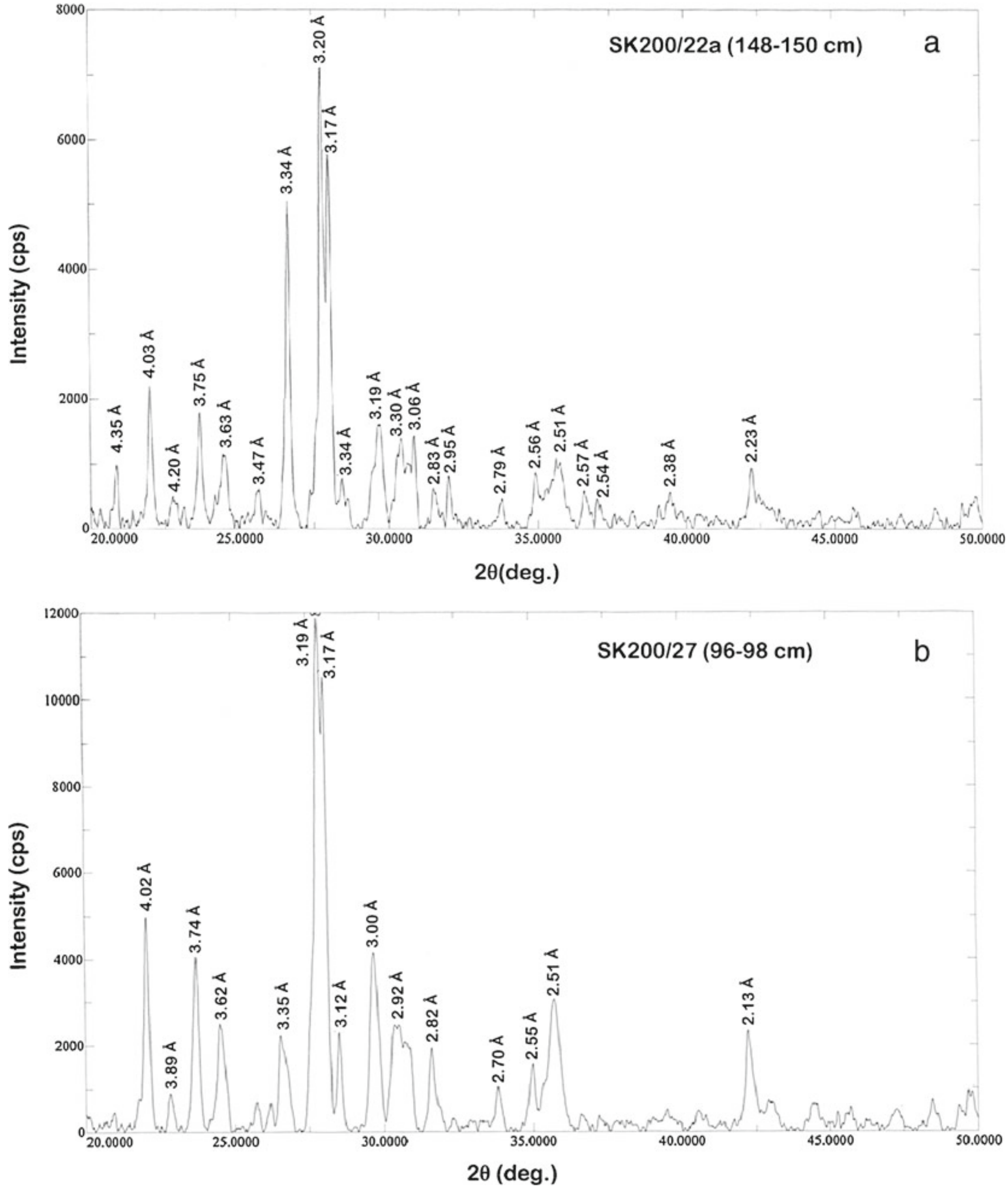

Figure 6. The X-ray diffractograms of the lithic (basaltic) grains selected from MIS 2 intervals in cores SK200/22a and SK200/27.

supplied from the Antarctic continent and icebergs played a key role in their transport from Antarctic continent to the Southern Ocean.

The lithic fragments form an important constituent of IRD in core SK200/22a (around 50%) than in core SK200/27 (30–40%) (figure 3). The morphological and compositional characteristics of the lithic grains confirm a basaltic lava origin. Although there are volcanoes in West Antarctica, there are no known volcanoes in East Antarctica, specifically in the Indian Ocean sector of Antarctica. However, there are several island chains in the Southern Ocean that are of volcanic origin. Therefore, the lithic fragments in the cores appear to have a different source than the mainland Antarctica. The entire oceanographic processes in this region are influenced by ACC, including the movements of sea-ice and icebergs. A stronger wind-forcing of the ACC during glacial times may have enhanced the transport capacity of ACC (Pudsey and Howe 1998). Therefore, the possible sources of lithic material in IRD at the core site could be from the weathered volcanic islands, located in the vicinity of the core sites or from the immediate South Atlantic region and transported by the ACC.

The Indian sector of Southern Ocean is characterized by the presence of several volcanic islands such as Kergulen, Crozet, Marion and Prince

Edward Islands (Bareille *et al.* 1994; Diekmann 2007; Nielsen *et al.* 2007). Moreover, the area between the South Atlantic and Indian sector of the Southern Ocean represents an IRD province with high abundance of volcaniclastic glass shards and rock fragments, derived from the South Sandwich and other nearby islands (Connoly and Ewing 1965; Smith *et al.* 1983). Figure 7 shows the plot between SiO_2 and the Na_2O+K_2O of the lithic grains from core SK200/22a and rocks from Marion and South Sandwich Islands (Le Masurier and Thomson 1990; Mahoney *et al.* 1992). The geochemical characteristics of lithic grain studies here are broadly in agreement with that of rocks from Marion and South Sandwich Islands. Most of the samples from Marion and South Sandwich Islands are subalkalic, basaltic-andesitic to andesitic, and tholeiitic in composition (Wilson 1989; Nielsen *et al.* 2007). The presence of both quartz and lithic grains thus confirms a dual provenance for the IRD material in the Southern Ocean, as proposed by earlier researchers (Bareille *et al.* 1994; Kanfoush *et al.* 2000; Diekmann *et al.* 2004; Thamban *et al.* 2005; Diekmann 2007). The quartz grains appear to have derived from the metamorphic complexes of Antarctica and the lithic fragments were derived from the Southern Ocean volcanogenic islands. Such a source possibility underlines the crucial role played by the ACC in transporting the terrigenous material to the core sites.

Manoj *et al.* (2012) have shown that the IRD represents only a minor component of the terrigenous influx to the Indian sector of the Southern Ocean and the total terrigenous input to this region is controlled by several oceanographic and climatic factors. The concentrations of IRD in the core SK200/27 is nearly two times that in core SK200/22a during the MIS 2 (figure 3). Such a distinct spatial variability suggests a latitudinal control in the IRD distribution with significant decrease towards north. The near absence of IRD during the Holocene suggests that the ice sheet accumulation during interglacials was largely limited to elevated regions of Antarctica. The IRD content decreased dramatically after the termination I with values approaching near zero. During the LGM, glacier and sea-ice extent in the Southern Ocean seems to have significantly extended and the subsequent early deglacial warming lead to ice rafting, depositing the IRD to the sea floor. Sea ice could be a dominant delivery mechanism of tephra/ash to the study region from volcanic islands. The IRD and $\delta^{18}O$ records during MIS 2 at SK200/22a revealed that the changes in ice-sheet dynamics and intensity of the ACC strongly controlled the IRD deposition and, sea-surface temperature had only a secondary influence during the late Quaternary (Manoj *et al.* 2012). A comparison between IRD records of SK 200/22a and SK200/27 with available Antarctic ice core temperature records (Blunier and Brook 2001; EPICA Community Members 2006) suggests that the major ice rafting events in the Indian sector of the Southern Ocean peaked towards the end of LGM as well as the onset of deglacial warming.

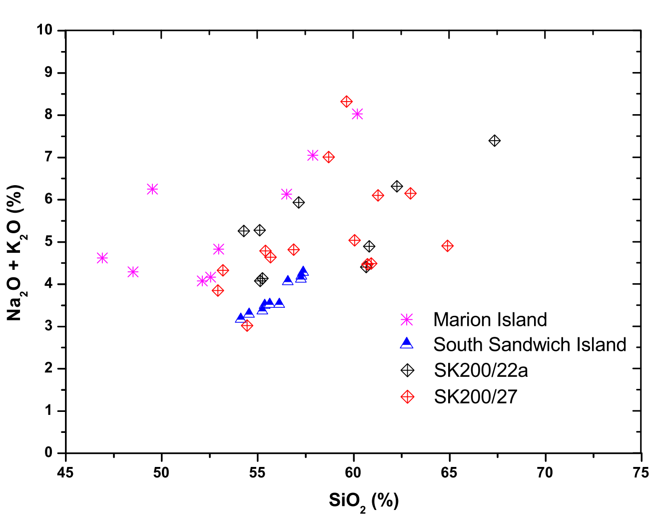

Figure 7. A plot between SiO_2 and Na_2O+K_2O of the lithic grains (studied here) and fine-grained vesicular basalt from Marion and South Sandwich Islands (Le Masurier and Thomson 1990; Mahoney *et al.* 1992).

4. Conclusions

IRD records of the cores SK 200/22a and SK200/27 provided insight on the ice rafting and sediment source in Indian sector of the Southern Ocean during the past 22 ka BP. The IRD input was substantially high during LGM and early deglacial warming at core SK200/27 (49°S), but it remained low during LGM and increased during the early deglacial warming at SK200/22a (44°S). The IRD concentrations decreased substantially since then and were nearly absent in both cores during the Holocene. The high IRD flux in core SK200/27 could be due to increased iceberg production and a northward migration of APF during glacial period. Increased quartz grains along with garnet suggest a dominant Antarctic contribution for the IRD at SK200/27. Equal proportions of quartz and lithic material in core SK200/22a suggest an additional IRD source from the volcanic islands in this region. The chemical composition of lithic grains is comparable with the lithic fragments originated from the Marion and South Sandwich Islands. The IRD record at the core sites shows that the delivery of

IRD to the core sites is controlled by past changes in ocean circulation and sea surface temperature.

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