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Interactive comment on "Trace elements and cathodoluminescence of detrital quartz in Arctic marine sediments – a new ice-rafted debris provenance proxy" *by* A. Müller and J. Knies

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Reply to discussion: Müller and Knies CPD 9, 4145-4189: "Trace element and cathodoluminescence . . . .ice-rafted debris provenance proxy"

Reviewer #2

Reviewer comment: "In the Introduction the authors refer to the review paper of Hemming (2004, focusing on Heinrich layers in the North Atlantic!) for outlining the importance of IRD provenance studies. This statement is followed by a brief listing of other proxies mainly applied to central Arctic Ocean sediments. However, as this manuscript focuses on the western Svalbard margin, a bit more detailed review of the large number of studies (e.g., Elverhoi et al. 1995, Andersen et al. 1996, Hebbeln et al. 1994, papers by Jens Bischof and by the Tromso group and others) dealing with IRD provenance from exactly this region definitely would improve the paper. It would be especially good to know, which proxies (lithology, mineralogy, clay minerals, but also those referred to in the above mentioned listing: Nd isotopes etc.) have been successfully applied and where we still have major gaps in tracking IRD provenance. Also sediment trap studies from the region have been used to link sea ice transported material to sea ice advection from eastern Svalbard by the East Spitsbergen Current (Berner & Wefer 1994, Hebbeln 2000)."

Reply: Yes, we agree and have added new references and re-structured the introduction completely. The new version of the introduction chapter is shown below: 1 Introduction Provenance studies of ice-rafted debris (IRD) in the North Atlantic – Barents Sea are a remarkable tool for providing insights into the dynamics of large ice-sheets and the timing and duration of their disintegration (e.g. Hemming, 2004 for a review). Prominent IRD layers in the North Atlantic – the sedimentological expression of ice-sheet surging during a Heinrich event - and their origins illustrate the complexity of ice-sheet – ocean interactions in the Northern Hemisphere during the last glacial period (e.g. Kolla et al., 1979; Grousset et al., 1993; Bond et al., 1997, 2001; Farmer et al., 2003; Peck et al., 2007; Andrews et al., 2009; Verplanck et al., 2009). Identifying the provenance of such IRD layers in the Arctic is, however, not straightforward because of the abundance of IRD from both sea ice and glacial rafting (Stein 2008, for review). For instance, the provenance of IRD-rich sediments along the Spitsbergen continental margin has been constrained by various approaches including bulk/clay mineralogy (Elverhøi et al., 1995; Andersen et al., 1996; Vogt et al., 2001; Forwick et al., 2010), petrography of dropstones (>500 μm) (Bischof, 1994; Hebbeln et al., 1994, 1998), iron grain chemical fingerprinting (Darby et al., 2002) and stable isotope geochemistry (Sr, Nd) (Tütken et al., 2002). The results of all studies have demonstrated their potential to provide insights into both the changing sea ice drift patterns in the Arctic Ocean and the complex Eurasian ice-sheet history during the Quaternary. The application of these provenance proxies is particularly relevant for identifying large scale geological provinces and thus circum-North Atlantic/Arctic ice sheet dynamics and sea ice patterns. However, they are limited to pin point the exact bedrock formation onshore and consequently delineating material derived through glacial erosion, transport, and deposition from individual ice stream (ice sheet) dynamics over time.

In the present study, we focus on detrital quartz grains in the >500 μm fraction of marine sediments offshore of Spitsbergen considered to be IRD derived from melting icebergs and sea ice (cf. Elverhøi et al., 1995; Hebbeln et al., 1998). Potential source rocks for specific bedrock formations are constrained by introducing a new analytical approach combining structural studies of quartz grains by optical microscopy, scanning electron microscope backscattered electron imaging (SEM-BSE), scanning electron microscope cathodoluminescence imaging (SEM-CL) with chemical analyses of quartz grains by laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS). Quartz is a mineral preferred for provenance studies due to its resistance to weathering and common presence in rocks and soils. The structural analysis of detrital quartz grains in sedimentary rocks by means of optical microscopy and SEM-CL has a long history in provenance evaluation in sedimentology (e.g. Seyedolali et al., 1997; Götze and Zimmerle, 2000 and references therein). Recent developments of micro beam techniques, such as LA-ICP-MS and secondary ion mass spectrometry enable the chemical characterisation of quartz grains down to $\sim$100 μm in size. Chemical analyses have shown that the trace element signature of quartz is controlled by the physicochemical conditions of quartz formation (e.g. Götze, 2009 and references therein) and, thus, represents a geochemical fingerprint of the quartz origin. However, the chemical characterisation of quartz grains by these analytical techniques has not been applied for provenance studies so far.

Up to now, we have studied 9 core-top (0-1 cm) samples randomly distributed along the western and southern coast of Spitsbergen (Fig. 1) and compared the quartz properties in the >500 μm fraction with 18 onshore samples from potential source areas in central, west, south and southeast Spitsbergen. Our results show that various bedrock provinces in the study area are identifiable in the quartz grains offshore of Spitsbergen. Long-distance transport by sea ice is the dominant transport mechanism for the quartz grains. In addition, quartz grains released from melting icebergs/sea ice, originating from either central or southeastern Spitsbergen, are clearly recognized. Considering the complicated glacial dynamics of former Barents Sea ice sheets as recently outlined by Dowdeswell et al. (2010), this new approach applied to Arctic continental margin sediments will help to define the sources of IRD and thus spatial/temporal changes in ice-flow drainage patterns better.

Reviewer comment: "Although I trust in their conclusion that most of the IRD comes from eastern Svalbard (as also other studies have shown before, see above), I am a bit skeptical regarding the reasoning. With their method the authors identify typical populations of the quartz types A-E related to specific onshore source areas. At the end they link these populations to those populations found in the sea floor samples. However, after uptake by sea ice and icebergs and after transport, the final deposition of the IRD will largely take place as individual grains. So, I wonder how the "artificial" population made up by these individual grains coming from a variety of icebergs/sea ice deposition events can be compared to populations being derived from a discrete rock sample? Maybe that works out, but to be convinced I would like to see some statistics."

Reply: First part of the reviewer comment: Our paper is structured in that way that we first classified the IRD quartz grains >500 μm found in offshore samples into five groups on the base of mineral micro inclusions, CL intensity, intra-granular structures visualized by SEM-CL imaging and trace element content. The classification was developed by means of the observed, most significant features of the investigated offshore grains and, thus, the classification application is restricted to the offshore sample area of this study. The distinguishing features were chosen in that way that each offshore grain could assigned to one group only. We did not use properties of quartz of onshore

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samples for the classification. In the second step onshore quartz, where possible, was assigned to one of the grain type groups defined by the offshore samples. However, a number of onshore samples contain quartz grains with features which were not observed in offshore grains. For these grains a classification was not necessary because they could immediately be excluded as the source of offshore grains.

To make the establishment of our classification more clearly we added explaining sentences at the beginning of the chapters 5.1 and 5.2.

Second part of the comment: Almost all offshore regions sampled contain grains of the "artificial" groups A and B and these groups represent the major quartz-grain populations in the >500 μm size fraction. The onshore samples which were collected from possible provenance regions in the catchment areas of rivers and surging glaciers relative close to the offshore samples contain often (about 60% of the samples) A type grains. However, none of the onshore samples contain type B grains except the samples from the Late Triassic De Geerdalen Formation at Egdeøya. These B type grains are rather specific (compared to the almost featureless A type grains) being polycrystalline and polyphase quartz grains intergrown with K-feldspar, mica (biotite and/or muscovite), chlorite, and calcite and containing micro inclusions of apatite, pyrite, Fe oxides, calcite, dolomite, barite, rutile, zircon, and monazite. The grains originate (originally) from low-grade metamorphic quartzites which do not occur on Spitsbergen today. The remains of sericite and Fe-oxides/hydroxides on the grain surfaces indicate that they are detrital grains from eroded sandstones (secondary origin). The rocks of the De Geerdalen Formation cover more than 50% of the surface of Egdeøya and Barentsøya and almost 100% of the island Hopen which corresponds to more than 3000 km2 (Fig. 1). (We added the previous sentence to the manuscript to underline the enormous extension of this stratigraphic unit.) Thus, the identified source rocks are not just locally outcropping rocks. The area of the inner Storfjord, Barentsøya and Egdeøya are the major iceberg-producing areas in southern Spitsbergen (Dowdeswell and Dowdeswell, 1997) and the icebergs and sea ice formed there are transported by the East Spitsbergen Current (ESC) from Storfjord westward around southern Spitsbergen continuing northward along the continental shelf, passing Forlandsund and Prins Karls Forland. Occasionally westerly winds blow drift ice coming with the ESC in the inner parts of the fjords along the western coast, namely Hornsund, Van Mijenfjord, Isfjord and Kongsfjord (Umbreit, 2009), implying that even the sample sites 1258 and 1265 might be affected by ESC drift ice. The grain-type distribution statistics in form of pie charts shown in Figure 5 illustrate impressively that the source of type B grains is with very high possibility the sandstones of the De Geerdalen Formation. However, our study represents a pilot study and in the frame of this study we were able to sample only a certain amount of onshore samples. We tried to cover all major sequences in the possible catchment areas which contain quartz grains >500 μm.

Reviewer comment: "If the high amount of Type D quartz in sample 1265 is indicative for a local source, where is the considerable amount of type B quartz in this sample coming from as it is not found in the surrounding onshore samples?"

Reply: Type D grains which represent the major grain population in the sample 1265 from the inner Isfjord are interpreted to originate from sandstones of the Kapp Toscana and Adventdalen Group. These units are in the catchment area of the tidewater glaciers of the Tempelfjord and - in historical times - Sassendal and are the major source of drift ice in inner Isfjord (cf. Forwick and Vorren, 2009). The second, minor source of drift ice in the Isfjord is the area of Storfjord from where ice is transported by the ESC around southern Spitsbergen and blown by common westerly winds into the inner parts of the Isfjord (Umbreit, 2009). Thus, type B grains in sample 1265, forming the minor population, are interpreted as IRD originating from the Triassic De Geerdalen Formation at Edgeøya, Barentsøya and inner Storfjord. We added the last two sentences to the manuscript.

Reviewer comment: "The type E grains in sea floor sample 1244 are linked to the only onshore sample containing this type of grains: DH7A-1. However, according to Fig. 5 this sample is located close to the Isfjord, where this group of samples has been used

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to explain the high contribution of type D sediments to the Isfjord sample 1265 (see above). Maybe this is a matter of clear presentation in the figure. But as it is presented now, it is somewhat confusing."

Reply: Type E grains are rather specific comprising fine-grained arkose fragments (2 to 3 mm) containing predominantly detrital rounded quartz grains and some K-feldspar grains cemented by non-luminescent authigenic quartz. In the onshore samples this grain type was found only in the sandstone sample DH7A-1 of the Early Cretaceous Adventdalen Group from southern Isfjord. Exposures of the Adventdalen Group extend from north Adventdalen, south Isfjord, to Argadhdalen at the western coast of Storfjord (Fig. 1). The location of sample 1244 is relatively close to surging glaciers north and south of Argadhdalen whose catchment areas are partially in the Adventdalen sandstones. We changed the manuscript accordingly for clarification.

Reviewer comment: "Sample 1246 from the southern Storfjord that is right in the proposed main IRD transport path, contains quite some Type C grains that are not common in the proposed source area on Edgeoya. A comment on this observation would be great."

Reply: In chapter 5.1, where the type C grains are described we wrote "Coatings of sericite and Fe-oxides/hydroxides at the grain surfaces (see black arrow in Figure 4) indicate that type C grains represent detrital grains from eroded sandstones (secondary origin) similar to type A and B grains." Further on in the discussion chapter 6 we wrote: "However, it appears that types A, B and C grains are regionally and genetically connected." ...and "Thus, the most likely regional sources of the IRD for type A, B, and C are the east coast of Edgeøya and Barentsøya and the inner Storfjord (Fig. 5)." We think, that this findings and explanations express clearly that type C grains belong to the assemblage of A and B type grains which originate from Egdeøya.

Reviewer comment: Finally, the entire region has been glaciated several times with the last glaciation being just 20 ka ago. Glacial erosion and transport probably have distributed quartz grains from various source regions to all around the north-eastern Barents Sea. And, of course, also these glacigenic sediments can be picked up by icefloes and icebergs probably delivering a quite variable quartz signal to the western Svalbard margin. In which way would such a "reworked source" signal interfere with the conclusions drawn in the manuscript?

Reply: This is exactly the beauty of this new approach! By studying a LGM-deglaciation-Holocene record from the western Svalbard margin (or any other margin where we have control on the sources for the detrital quartz), we identify first the exact bedrock formation that sourced the detrital quartz grains in the marine record during a specific time interval. Second, we then reconstruct the controlling processes for erosion/transport of detrital quartz for each (crucial) time interval. For instance, during the LGM we identify the sources for reconstructing the ice sheet (ice stream) dynamics. For the deglaciation, we monitor the timing of break-up and retreat/re-advance. And for the Holocene, we reconstruct the ice floe drift pattern (from where the ice-rafted debris was originally deposited to the final depocenter, as exemplified by the present study). Once this pilot study on surface sediments is introduced, we will apply it to records with well-constrained age models from the western Svalbard margin and potentially the northern Barents Sea margin (Yermak Plateau) where changes in paleo ice-stream dynamics can be reconstructed over time.

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