Geologic constraints on the existence and distribution of West Antarctic subglacial volcanism

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[1] Strong and abundant magnetic anomalies imaged beneath the West Antarctic Ice Sheet by aerogeophysical surveys have been interpreted as evidence of widespread Late Cenozoic basaltic volcanism, perhaps even a large igneous province. Petrological and geochemical composition of subglacial sediment samples from West Antarctica supports crustal provenance and does not provide positive evidence for the existence of the proposed mafic Late Cenozoic large igneous province. The only two identified basaltic pebbles, out of a total of >500 examined pebbles, are of Mesozoic to Cambrian age. We conjecture that the subglacial large igneous province does not exist or is blanketed by an at least Miocene age sedimentary drape.
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1. Introduction

[2] Geophysical studies suggest that subglacial volcanic activity and geothermal phenomena may help control the position and the rate of motion of at least some West Antarctic ice streams [*Blankenship et al.*, 1993, 2001; see also *Maule et al.*, 2005]. In fact, subglacial geology introduces significant uncertainty into predictions of future contribution of the West Antarctic Ice Sheet (WAIS) to global sea level changes [*Anandakrishnan et al.*, 1998; *Bell et al.*, 1998; *Studinger et al.*, 2001; *Vaughan and Spouge*, 2002].

[3] Late Cenozoic volcanic activity in West Antarctica is manifested in volcanic centers outcropping along the rift flanks of the West Antarctic Rift System (WARS). This stage of volcanic activity started around 30 Ma extending in some areas to the present [*LeMasurier and Thomson*, 1990]. Holocene volcanic activity is reported from Marie Byrd Land (MBL) and the McMurdo Province (Mt. Erebus and other volcanoes in Northern Victoria Land, NVL) [*LeMasurier and Thomson*, 1990]. Interpretations of geomagnetic anomalies suggest that late Cenozoic volcanic activity extends beneath the WAIS [*Behrendt et al.*, 1994, 1996, 1998, 2004, 2002, 2006; *Blankenship et al.*, 1993]. Shallow source magnetic anomalies beneath the interior of the WAIS show similarities to magnetic anomalies in the western Ross Sea, which are interpreted as submarine volcanoes of the McMurdo province [*Behrendt et al.*, 1996]. Based on the extent of these magnetic anomalies it was concluded that 43% of the surveyed area is underlain by basalts and it was proposed that this high subglacial abundance of basalts is representative for ~1.2 million km^2 of the rift area beneath the WAIS and Ross Ice Shelf [*Behrendt et al.*, 1994, 2006]. The inferred total volume of the basalts was estimated to be about one million cubic kilometers, sufficient to qualify as a large flood basalt province [*Behrendt et al.*, 1994] or in the more recent terminology as a large igneous province (J. C. Behrendt, personal communication, 2006).

[4] If these hypothesized subglacial basalts are of late Cenozoic age geothermal heat associated with their emplacement and cooling could play a crucial role in basal melt water production. For instance, the geothermal flux estimate in the vicinity of a (potential) recently active subglacial volcano (Mt. Casertz) on the southern rift flank exceeds typical continental heat fluxes [*Sclater et al.*, 1980]($\sim$30 to 40 mWm^{-2}) by three orders of magnitude [*Blankenship et al.*, 1993]. Therefore if individual active subglacial volcanic centers, or recently active, subglacial volcanism exists beneath the WAIS, heat supplied by subglacial eruptions and/or enhanced geothermal activity could melt enough ice to help lubricate the ice base and sustain or even accelerate West Antarctic ice streams [*Blankenship et al.*, 1993, 2001].

[5] While aero-geophysical data put constraints on the distribution and thickness of potential subglacial volcanic rocks, analyses of samples have to constrain their composition and age. Here we present the first petrological and geochemical characterization of subglacial and basal sediments recovered from boreholes drilled to the base of the WAIS. Our data provides new constraints on the extent and distribution of subglacial volcanism beneath the WAIS and illustrates its potential significance for the stability of the WAIS.

2. Samples

[6] Over the last half a century, samples of subglacial sediment (till) and basal debris was obtained from several locations across the WAIS (Figure 1) [*Bindschadler et al.*, 1987; *Engelhardt et al.*, 1990; *Gow et al.*, 1979; *Kamb*,

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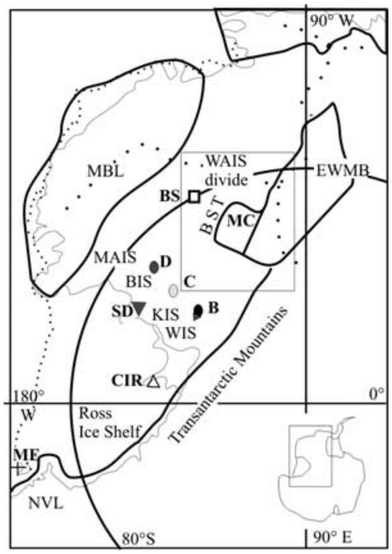

Figure 1. Map of the WARS showing sediment sample locations (UpB and Unicorn (B), UpC (C), UpD (D), Siple Dome (SD) and Byrd Station (BS)) and location of selected rock outcrops on both rift flanks (Marie Byrd Land, MBL; Transantarctic Mountains, TAM; Ellsworth Whitmore Mountains Block (EWMB), Mt Erebus (ME) a currently active volcano and Mt Casertz (MC) a potential subglacial volcano. Dotted line indicates the ice divide of the WAIS. Thin dotted line outlines the ice sheet and shows the approximate grounding line location.

2001; *Vogel*, 2004; *Vogel et al.*, 2005]. Sediment underlying the Siple Coast ice streams was generally characterized as subglacial till, that has formed largely by recycling of underlying Tertiary glacio-marine sediment [*Tulaczyk et al.*, 1998]. Peak abundance of late Miocene age diatoms in WIS sediment [*Scherer et al.*, 1998] indicates deposition of this inferred sedimentary unit prior to the onset of West Antarctic glaciation (~5 Ma) [*Zachos et al.*, 2001].

3. Geological Constraints

[7] Mineral identification in thin sections of the sand fraction from sub-ice stream sediments (UpB, new UpB, UpC and UpD; ~60% quartz, ~40% feldspar and <10% lithics) indicates a provenance from upper crustal rocks in a transitional crust or basement uplift setting [*Dickinson and Valloni*, 1980], similar to rocks outcropping along the Transantarctic Mountains (TAM) (Figure 2a). In all samples across the Ross Ice Streams and CIR the lithic fraction consists generally of quartz-rich meta-sedimentary fragments and granitoids, providing no positive evidence for derivation of these sediments from the hypothesized late Cenozoic alkalic flood basalt province [*Behrendt et al.*, 1994]. This is consistent with geochemical analysis of the clay and silt fraction of this sediment. The chondrite-normalized REE patterns of the mud size fraction show negative Eu anomalies (Figure 2b). This is indicative of provenance from an upper crustal source rather than a mafic mantle derived volcanic source [*Taylor and McClennan*, 1985, 1995]. In contrast to Cenozoic mafic rocks from Marie Byrd Land [*Hart et al.*, 1997] and Northern Victoria Land [*Rocchi et al.*, 2002] (Ti-Al ratios of 0.22 ± 0.05; 2σ), major element analyses of the mud fraction (XRF) yield low Ti-Al ratios (0.04 ± 0.01; 2σ), which are more consistent with those of granitoids from the TAM (0.03 ± 0.01; 2σ) (S. G. Borg, unpublished data, personal communication, 2004). Also TDM ages (Time of Depleted Mantle) [*Depaolo et al.*, 1991] and the Sr, Nd isotopic composition of our mud and sand samples (1.0 to 1.5 Ga) are much older than TDM ages calculated for late Cenozoic volcanics from MBL and the McMurdo Province using published data (0.25 Ga ± 0.08; 2σ [*Hart et al.*, 1997] and 0.34 Ga ± 0.16; 2σ [*Rocchi et al.*, 2002] respectively).

[8] Overall our results show a general lack of evidence for widespread exposure of mafic material in the vicinity of the Siple Coast ice streams. The only evidence for the subglacial exposure and erosion of mafic material was found in debris melted out of the Byrd ice core [*Gow et al.*, 1979]. The only two basaltic pebbles, out of a total of more than 500 pebbles, derived from West Antarctic subglacial sediment were found in the Byrd ice core and are of Mesozoic and Cambrian but not of late Cenozoic age (Pebble Lit-1408 dating to 83.22 ± 0.09 Ma and pebble DT-1408 to 511 ± 5 Ma, 523 ± 3 Ma) (Figure 3). The debris derived from different sediment-laden basal ice layers in the

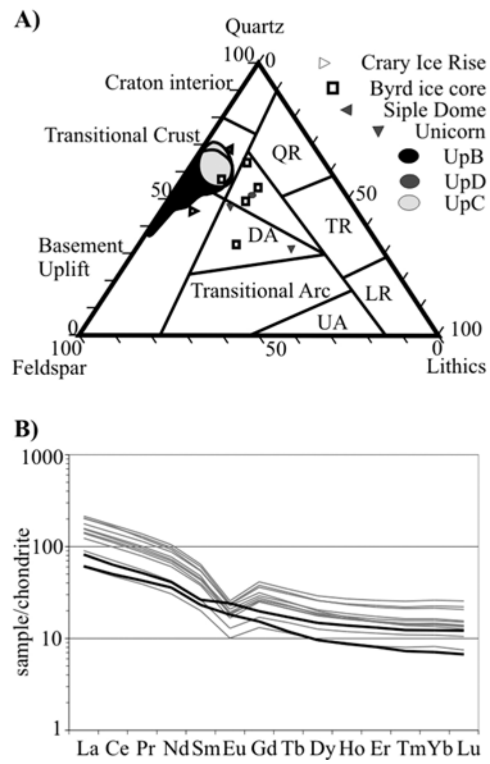

Figure 2. Petrological and geochemical characterization of subglacial sediment from West Antarctica. (a) Ternary diagram showing mineralogical composition of sand fraction (125 to 250 μm) plotted on a template indicating general tectonic provenance after *Dickinson and Valloni* [1980]. (b) Chondrite-normalized rare earth element patterns sediment mud fraction (<38 μm) and two basaltic pebbles, Lit1408 and Dt1408 (thick line), from the Byrd ice core [*Vogel*, 2004]. (UA - Undissected Arc, LR – Lithic Recycled, TR - Transitional Recycled, DA - Dissected Arc, QR - Quartzose Recycled).

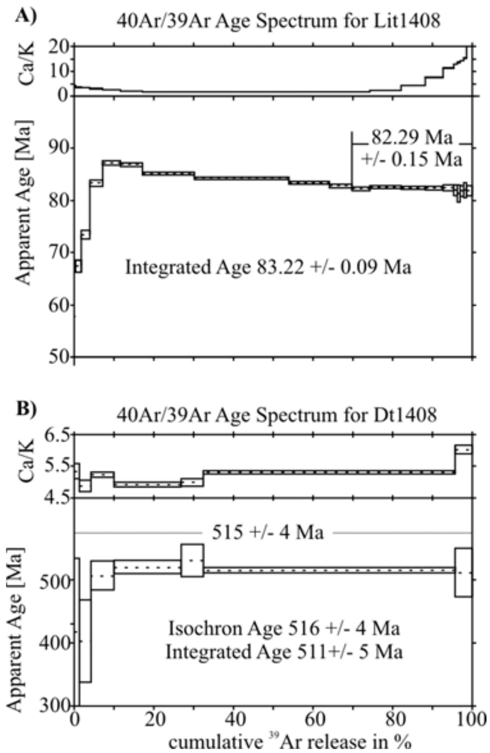

Figure 3. The $^{40}Ar/^{39}$ AR age spectra for basaltic pebbles (a) Lit 1408 and (b) DT1408.

Byrd ice core has generally higher (18% ± 6%) lithic concentration (Figure 2a). Approximately, 50% of the lithic fraction shows similarities to highly altered mafic volcanic groundmass (fine-grained, clay-rich ground mass with small altered phenocrysts), clearly indicating the presence and erosion of however Mesozoic to Cambrian age mafic volcanic rocks in direct contact with the ice sheet.

4. Discussion

[9] Our results show that subglacially exposed mafic volcanics are currently eroded at the base of the WAIS. However, the age of these rocks is Mesozoic to Cambrian, in contrast to the late Cenozoic age inferred for these subglacial volcanics through comparison to the mafic volcanic centers exposed on the flanks of the West Antarctic rift [*Behrendt et al.*, 1994, 2006]. Moreover, mafic rocks were found at just one (Byrd Station) out of five sampling locations across West Antarctica (Figure 1), suggesting that direct exposure of mafic volcanics to subglacial erosion is also spatially limited. *Behrendt et al.* [1995] had proposed that the volcanic edifices themselves may have been readily and relatively quickly removed by glacial erosion during the early part of the West Antarctic glaciation. However, if Late Cenozoic mafic volcanics are supposed to be responsible for the numerous magnetic anomalies observed in aerogeophysical data, it is reasonable to expect that the volcanic rocks associated with the eruptive event/s that formed, the possibly eroded, volcanic edifices should still be present. Continued glacial erosion of these mafic rock bodies should therefore continue to yield significant amounts of mafic debris. The eroded mafic material would mix with other sediment sources, like the underlying sedimentary basin fill [*Scherer*, 1991; *Tulaczyk et al.*, 1998]. Dependent on the distance of the source to the sample location [*Clark*, 1987; *Klassen*, 1999] mafic material would form a major, minor or trace constituent of the till found beneath the WAIS ice streams downstream of the original source. It is generally thought that fast ice streaming should be associated with long-distance debris transport [*Alley et al.*, 1989; *Clark*, 1987]. Yet no detectable mafic component is found in any of the retrieved ice stream samples.

[10] We estimate that through the combination of our analytical methods we would be able to ascertain the presence of mafic material as a major or minor constituent of the sediment. This even if its concentration would be as low as a few percent of the dry weight fraction. Our interpretation is that our observation significantly limits the potential exposure of mafic volcanic rocks in the vicinity upstream of our ice stream locations. This may be in accordance with [*Behrendt et al.*, 2004], who reported that ‘‘half of all the high-topographic sources’’ are connected to the Sinuous ridge. The Sinuous Ridge is located at a distance of ~150 to 200 km from the Byrd ice core location and at a distance of ~600 km from the ice stream locations. This relationship may provide a measure for the interpretation and significance of our findings. Our results should at least be representative for an area of at least 100 to 200 km upstream of our sample locations [see also *Alley et al.*, 1989; *Clark*, 1987]. This corresponds to about 20 to 40% of the ~500 km distance from our ice stream sample locations to the ice divide. While no mafic material was found in our ice stream samples numerous magnetic anomalies are found within 100 to 200 km upstream of our ice stream locations and the mafic material found in the Byrd ice core was of Mesozoic to Cambrian and not late Cenozoic age.

[11] There are several potential explanations for the discrepancy between our results and the proposed age and distribution of the inferred late Cenozoic large igneous province [*Behrendt et al.*, 1994, 2006]:

[12] 1. The large igneous province (alias subglacial flood basalt province [*Behrendt et al.*, 1994, 2006]) does not exist and that the proposed subglacial volcanic activity was/is limited to individual subglacial volcanic centers [*Behrendt et al.*, 2006; *Blankenship et al.*, 1993].

[13] 2. Majority of the large igneous province consists of subvolcanic intrusions which have not (yet?) have protruded through the sedimentary basin fill and are therefore protected from erosion.

[14] 3. Other (non-mafic and/or non-late Cenozoic) highly magnetic (0.05 to 0.15 (0.3) SI [*Behrendt et al.*, 1994, 2002, 2006]) rocks may produce the observed magnetic anomalies.

[15] It is possible that a combination of these explanations is responsible for the lack of mafic material in the ice stream sediment. In our opinion, the preponderance of available evidence favours the explanations 1 and 3. Susceptibility measurements on some granitic and dioritic rocks and pebbles extracted from our subglacial sediment samples (A. M. Grunow et al., Magnetic properties of pebbles from beneath the West Antarctic Ice Sheet, U.S. Polar Rock Repository, 2004, available at http://www-bprc.mps.ohio-state.edu/emuwebusprr/pages/usprr/Query.php), are within the range used by [*Behrendt et al.*, 1994, 2002, 2006].

Ferraccioli et al. [2002] also reported magnetic anomalies with a similar wavelength from Marie Byrd Land. These anomalies however are associated with the Devonian to Carboniferous Ford Granodiorite plutons and a high-grade metamorphic complex in the Alexandra Mountains.

[16] In addition it is possible that mafic volcanic rocks older than Late Cenozoic make up a (potentially significant) portion of the WARS horst and graben structure and are responsible for the abundant magnetic anomalies. Such old mafic volcanic activity may have been related to the Mesozoic break up of Gondwana Land, and/or may even be older. The ages obtained by us for the only two basaltic pebbles recovered from the sediments are Mesozoic and Cambrian and clearly support this possibility. Such old mafic bodies may have subsided during the rifting process and become buried beneath a marine sedimentary basin fill, limiting their current subglacial exposure and subsequent glacial erosion of such material.

5. Conclusions

[17] Mafic volcanic debris represent neither a major nor minor constituent of subglacial sediments recovered from beneath Ross ice streams but are present in the sediment-bearing, lowermost section of the Byrd ice core. This finding suggests that subglacial exposure and erosion of mafic, subglacially or sub aerially erupted, volcanics in the vicinity of WAIS ice streams is limited or non-existent. Subglacial exposure of mafic volcanics may therefore be limited to the interior of the WAIS. The new data does not exclude the existence of individual late Cenozoic subglacial volcanic centers. The data however does indicate that at least a portion of the magnetic anomalies consist of either non eruptive volcanic intrusions or of older volcanic rocks or other high magnetic rocks, which are buried under at least Miocene age [*Scherer*, 1991; *Tulaczyk et al.*, 1998] West Antarctic rift sediment. Dates obtained on two basaltic pebbles demonstrate that mafic volcanics of however Mesozoic to Cambrian age exist beneath the WAIS.

[18] While these findings may reduce the overall extent of the inferred late Cenozoic subglacial volcanism it does not reduce the significance and importance individual subglacial volcanic centers may have for the overall stability of the WAIS. For example the estimated heat flux from only one subglacial volcanic center, Mt. Casertz [*Blankenship et al.*, 1993], could produce enough basal melt water to offset the basal energy balance of and relubricate the currently dormant KIS [*Vogel and Tulaczyk*, 2006]. It is therefore of outmost importance to further study the distribution and extent of individual subglacial volcanic centers and to determine the nature and age of magnetic anomalies in West Antarctica by recovering samples from these rock formations.

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