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Proposed drill site near the Ross-Amundsen ice divide, West Antarctica


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Synopsis
This document summarizes conditions near the Ross-Amundsen ice divide, and discusses candidate drill sites in context of the science objectives outlined in the lead proposal for the project. We identify a preferred site for the Western Divide Core (WDC).

To summarize:
• A suite of short (~100m) ice cores extracted during ITASE traverses in central West Antarctica all show very well preserved records of seasonal chemistry and recent global-scale volcanic eruptions (Dixon et al., In press).
• Sites near the divide with thick ice and moderate accumulation are most likely to satisfy the science requirements (Morse et al., 2002);
• We make use of available geochemical and geophysical data and ice-flow models to identify a preferred drill site that is 24 km southwest of the present-day ice divide. Radar-detected internal stratigraphy upstream from the site is smoothly varying. The combination of thick ice (3465m) and moderate accumulation (21.5 cm/yr ice equivalent) at the site should produce a core with stratigraphy that can be resolved annually back to ~44ka BP. Age at 96% depth (3325m) is expected to be ~112ka BP.
• Co-ordinates for the site are S79.4676, W112.0859, but sites within a kilometer of this location will likely have equivalent characteristics.
Introduction

The planned deep ice core near the divide between the Ross and Amundsen Seas will allow investigation of past climate, ice dynamics, and cryobiology of West Antarctica. The drill-camp will be constructed during the 2005/2006 Antarctic field season. This document reiterates the science objectives and requirements, summarizes what is known about the region, and discusses several specific sites.

Figure 1: Location map with 50m surface elevation contours shows the western divide region of central West Antarctica covered by airborne geophysical surveys during 1994-96. Also shown are Byrd, the ITASE 00-1 core site, Morse sites A, B and E, and our preferred Western Divide core site - WDC.

Science objectives and requirements

Core site criteria necessary to achieve the science objectives, outlined in the lead proposal for the project [http://www.dri.edu/People/kendrick/], require a location in West Antarctica where the combined histories of ice dynamics and accumulation will produce a high-resolution climate record that can be used to help interpret histories of both regional and global climate for at least 80k years. Hence site requirements include:

1. internal stratigraphy that can be interpreted back at least 80k years. This requires a location with relatively smooth bed topography, and minimal horizontal flow of ice;
2. ice deposited during the last deglaciation (~10 to 18ka BP) should not be brittle;
3. a stratigraphic record that can be resolved annually (requiring layers >1cm thick) for at least 40k years;
4. gas-age ice-age difference should be less than 500 years.

Although logistical requirements are secondary to science objectives, other things being equal, a site where logistics are minimized is preferred. Criterion (1) requires a location near the Ross-Amundsen ice divide (Fig. 1). Criteria (2), (3) & (4) require combinations of relatively thick ice and moderate accumulation.

Recent Studies

1. Airborne geophysical surveys
Using results from high-resolution, grid-based airborne surveys conducted during 1994-96, Morse et al., (2002) discussed conditions expected at seven potential core sites in the region of the divide. They showed that sites with thick ice and moderate accumulation, such as sites B and E (Fig. 1), are most likely to satisfy the above requirements. More at http://www.ig.utexas.edu/research/projects/waiscores/index.html

2. US International Trans-Antarctic Scientific Expeditions (ITASE)
Comprehensive glaciological data collected during traverses and from shallow (~100m) cores over a large region of West Antarctica (Fig. 2), have revealed information about spatial and temporal patterns of near-surface chemistry and accumulation (Arcone et al., In press; Dixon et al., In press; Kaspari et al., In press) and deep internal stratigraphy (Welch and Jacobel, 2003; Jacobel and Welch, In press). More at: http://www.ume.maine.edu/USITASE/

![Figure 2: Map of routes and ice cores collected during recent U.S. ITASE traverses. Core 00-1 is of special interest because of its proximity to sites B and E.](image)

All of the ITASE cores in central West Antarctica show very well preserved, seasonal records of chemistry (Dixon et al., In press; Kaspari et al., In press). Further, results suggest that the likelihood of significant wind scouring at any of the potential sites is low, because the annual layering is preserved between each of several volcanic events identified from core site to core site (Dixon et al., In press). Of particular interest are
measurements from ITASE 00-1, a 105m core extracted from near the divide (Figs. 1&2). The core, which extends back to 1655 AD, contains well-preserved, seasonal chemistry (Fig. 3a), and a record of global-scale volcanic eruptions (Fig. 3b). Mean accumulation over the past 345 years is 24.8cm/yr (ice equivalent).

**Figure 3:** Ion concentrations (ppb) measured in 00-1 core. The upper time series (1950-2000) shows well-preserved seasonal peaks that were used to derive the time scale. Distinct volcanic horizons [Tambora (1815), Krakatau (1883), Agung (1963) and Pinatubo (1991)] can be identified in the lower time series (1655-2000).
3. Ground-based geophysical measurements
Detailed ground-based radar (at several frequencies) and surface strain measurements in
the vicinity of sites B and E were carried out during the 2002-03 and 2003-04 field
seasons (Fig. 4). Internal layers detected by high frequency (200MHz and 7MHZ) radar
were used to extrapolate the depth-age relationship and accumulation rate from core 00-1
to candidate sites. Deeper internal layers and the bed, detected by low frequency (1MHz
and 5MHZ) radar (Fig. 5) were traced from the dated Byrd core (Hammer et al., 1994;
Blunier and Brook, 2001) and used to derive depth-age relationships at candidate core
sites (Fig. 6). The depth of the oldest traceable layer (“old faithful”) corresponds to an
acidity event measured in the Byrd core that is attributed to “excessive volcanism” 17.5ka
BP (Hammer et al., 1994).

![Figure 4: Ground-based measurements carried out during 2002-04 include radar profiles at 1.0, 1.5, 5, 7
and 200MHz, and repeat GPS surveys of 102 survey poles (Conway et al., 2003; 2004).](image)

Apart from the bed, continuous, coherent reflections from layers deeper than “old
faithful” have not been detected by any of the airborne or ground-based surveys that have
been carried out in the region. Although stratigraphic disturbances near the bed likely
cause an “echo-free zone” at depth (Robin, 1983), power and sensitivity limitations of
existing radar systems also limit detection of deep reflectors, especially in warm ice
(Bogorodsky et al., 1985; Winebrenner et al, 2003).
**Candidate sites**

We make use of available geochemical and geophysical data and ice-flow models to examine characteristics of potential core sites that are most likely to satisfy the scientific goals of the project. Ice cores are often drilled near ice divides in order to minimize stratigraphic disturbance caused by horizontal shearing of ice (e.g., Waddington et al., 2001; Jacobson and Waddington, 2004). Ice flow models can be used to estimate depth profiles of age and layer thickness.

![Figure 5: 1 MHz radar profile along-flow line L1 (15:1 aspect ratio). The upper 300 m of the ice sheet are not resolved by our system at this frequency. Present-day divide is located about 10 km east of the bedrock high. The strong reflecting layer at about 2,200 m ("old faithful", which was deposited 17.5 ka BP) is observed over much of West Antarctica (Welch and Jacobel, 2003).](image)

Here we use a 1-D model (Waddington et al., 2005) to investigate past possible combinations of ice dynamics, basal melting and surface accumulation that could have produced the observed radar-derived depth-age relationship from 17.5 ka BP to present. Prior to 17.5 ka BP, we derive a depth-age relationship by prescribing reasonable histories of ice dynamics, melting and accumulation. The advantage of this simplified approach is that it allows investigation of transients in ice-sheet thickness, accumulation rate, and ice-divide position. A disadvantage is that the model is 1-D. To reduce the limitations of this
approach, we start with the accumulation history derived from the 1-D model in a fully coupled, 2-D flowband model (Price et al., 2004). The mismatch between observed and modeled internal stratigraphy along a flowband is used to identify locations where 1-D assumptions are not adequate, which helps guide site selection. Currently, neither model accounts for the effects of ice-fabric evolution on the vertical-velocity profile.

At an ice divide that is frozen to the bed, vertical velocity at mid-depths is lower than on the flanks (Raymond, 1983). As a result, in steady state, internal stratigraphy is arched upward (known as a “Raymond bump”) at the divide; hence other things being equal, ice extracted from a divide site will be older than ice at the same depth on the flank. This is advantageous for retrieving old ice, but the older stratigraphy is compressed, making it more difficult to achieve annual resolution in older ice at a divide.

Below we discuss characteristics of several potential core sites:

1. Sites far to the north and east of the divide are preferred for extracting a high-resolution Holocene climate record for West Antarctica (Steig et al., 2003). Good candidate sites for extending ENSO records, or examining the regional patterns of response to millennial-scale climate changes would be ITASE sites 01-1 and 01-3 (Fig. 2). However complications arising from flow far from the divide over a rough bed are likely to hamper interpretation of older ice. Further, even if the stratigraphy in the upper 90% of the ice sheet was not disrupted by ice flow, model results for conditions expected at one such site typical of the region east of the divide (ice thickness 2000m, accumulation rate of 30-40cm/yr) indicate that the age of ice 200m above the bed would be at most 40ka BP (unpublished model calculation by Tom Neumann). Thus, while such sites would provide excellent Holocene and possibly last-glacial-maximum records, they would not allow us to test key hypotheses concerning D-O events, which is a major goal of the US ice core research community.

2. Although the summit of the central dome along the ridge (site A - Fig. 1) might be a potential core site, the dome is located over what appears to be the center of a large caldera, and the internal stratigraphy has been disturbed by flow across the sides of the caldera (Morse et al., 2002). In addition, ice thickness is only ~2900m, which limits the maximum age and the resolution of the stratigraphic record (Morse et al., 2002).

3. Site B at the divide has characteristics that are attractive for extracting an ice core (Morse et al., 2002). We have not found unequivocal evidence for a Raymond bump around (Raymond, 1983) beneath the present-day Ross-Amundsen divide; the apparent lack of this distinctive signature suggests that either the divide has moved and/or the bed is sliding (Pettit et al., 2003). Acknowledging that the divide may have moved around and complicated the geochemical stratigraphy, we think that locations up to ten ice thicknesses from the present-day divide are a good compromise between being far enough away to minimize the possibility that the divide has migrated through that site, and yet close enough to minimize stratigraphic disturbances caused by horizontal shearing of the ice.

4. Differences in accumulation and ice dynamics between sites on- and off-divide to the southwest are such that the stratigraphic record off the divide (such as E) should be longer and higher resolution than on the divide. However radar profiles
along the flowline between the divide and site E show an isolated bedrock bump near the divide and the internal stratigraphy downstream from the bump is undulating. The mismatch between modeled (using our 2-D flowband model) and observed radar-detected stratigraphy suggests that the undulating stratigraphy is likely caused by the spatial pattern of accumulation. It is likely that the bedrock bump contributes to the observed pattern of accumulation by perturbing the surface topography.

5. The bedrock bump is much smaller 7km to the northwest along the divide, and radar-detected stratigraphy along the flowline off the divide is more smoothly varying (Fig. 6). Given this simpler stratigraphy upstream, we prefer a site that is about 7km to the northwest of site E and 24km southwest of the divide (Fig. 1). The internal layers start to trend upward just downstream from the site, a likely response to the higher bed topography and lower accumulation rate that exists farther downstream. Figure 7 shows depth profiles of age and layer thickness for the site. Model calculations constrained by surface temperature (-30°C), surface accumulation (21.5 cm/yr) and ice thickness (3465m) indicate the bed will be melting if the geothermal flux exceeds 70mW/m²; melting of 0.5mm/yr is expected if Q_{geo} ~ 75mW/m².

Figure 6: Section of 1-MHz radar profile along flowline southwest of the divide. The upper 300m of the ice sheet are not resolved by our system at this frequency. Also shown are manual picks of the bed reflection; it is indistinct from 20.7 to 23.6km. “Old Faithful” (the 17.5ka layer) is clearly visible about 2480m below the surface. Coordinates of the preferred site (denoted by the vertical line at km 24) are S79.4676, W112.0859.
Summary of characteristics of the preferred site

Results from high-frequency radar suggest that the well-preserved, seasonal record of chemistry observed at ITASE core 00-1 should extend over the region. Radar-detected internal stratigraphy upstream from WDC is smoothly varying. The combination of thick ice (3465m) and moderate accumulation (21.5 cm/yr ice equivalent) should produce a core with stratigraphy that can be resolved annually back to ~44ka BP. Age at 96% depth (3325m) is expected to be ~112ka BP. The brittle ice zone is expected between 1.8ka BP (400m) to 8.4ka BP (1600m).

Site coordinates are S79.4676, W112.0859, but locations within a kilometer of this site are likely to have equivalent characteristics. Expected characteristics for the proposed core are:

<table>
<thead>
<tr>
<th>Basal melt (mm/yr)</th>
<th>Thickness (ice-equiv.)</th>
<th>Age at 90% depth</th>
<th>Age at 96% depth</th>
<th>Age of 1cm thick layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3465m</td>
<td>57ka (3120m)</td>
<td>144ka (3325m)</td>
<td>42ka</td>
</tr>
<tr>
<td>0.5</td>
<td>3465m</td>
<td>54ka (3120m)</td>
<td>112ka (3325m)</td>
<td>44ka</td>
</tr>
</tbody>
</table>

Figure 7: Depth profiles of age and layer-thickness for our preferred WDC site, 24km southwest of the present-day divide. Ice-equivalent thickness is 3465m, and surface accumulation is 21.5 cm/yr. Depth-age tie points (denoted by circles) come from radar layers traced from the dated Byrd ice core. Prior to 17.5ka BP (dashed lines), the time scale is estimated by prescribing histories of ice thickness and accumulation.

Logistical considerations

The site is about 180km from Byrd; we did not detect any evidence of crevasses during our radar traverses between Byrd and the divide region. During the 2002-03 and 2003-04 field seasons, weather near the site was generally much better than on, and northeast of the divide; weather was less cloudy and less stormy than reports from Siple Dome during those periods. However climate inferred from two years (Sept 2001 to October 2003) of forecasts by the Antarctic Mesoscale Prediction System suggest that the divide region is generally colder, wetter and cloudier than either Byrd or Siple Dome (unpublished presentation by Andy Monaghan and David Bromwich). It is likely that weather varies seasonally; results from ITASE cores indicate that El Nino-years are particularly snowy (Kaspari et al., In press).
References