PROVENANCE STUDY OF REEDY GLACIER AND WEST ANTARCTIC ICE STREAM TILLS

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ABSTRACT

Katie L. Kramer

Provenance Study of Reedy Glacier and West Antarctic Ice Stream Tills

In January 2007, 26 samples of till from 6 different moraines along the Reedy Glacier, East Antarctica were collected with the goal of differentiating between these samples and till collected from the base of the Whillans, Kamb, and Bindschadler Ice Streams of West Antarctica. The ability to differentiate between East and West Antarctic ice will allow us to constrain ice flow into the central Ross Sea during the Last Glacial Maximum (LGM), which has implications for more accurate reconstructions of the Ross Ice Sheet and its behavior.

Moraines sampled from the head of Reedy Glacier give insight to the geology beneath the EAIS, and may be representative of what the glacier is eroding from its bed. Samples along the trunk of the glacier capture representative rock types eroded along the length of Reedy Glacier. At each moraine 3 replicate sub-sites were selected for collection to represent the diversity of material within each moraine. Comparisons are based on the composition of pebbles, particle size distributions, and sand petrography. Analysis of the pebble fraction shows that each sub-site contains similar rock types, however, the concentration of each rock type varies as much as 25-35%. Similar variation is also seen within the sub-site sand fraction. Both the pebble and sand fraction reflect the mapped bedrock geology. The dominant pebble types are coarse-grained felsic and intermediate igneous rocks, as well as quartzite. Similarly felsic igneous grains, quartzite, quartz, and feldspar characterize the sand fraction. Particle size analysis shows that

Reedy Glacier till averages 85% sand. The subglacial West Antarctic samples contain approximately 30% sand, and equal amounts of silt and clay, approximately 35% each.

An observation of the sand fraction from beneath the West Antarctic Ice Streams shows composition similar to tills from Reedy Glacier. However, tills from the base of the West Antarctic Ice Streams contain up to 75% polymict grains, and in contrast, these grains are absent in the tills from Reedy Glacier. These sand-sized polymict grains dominate material from the base of Whillans and Bindschadler Ice Streams, whereas material from the base of Kamb Ice Stream contains grains of felsic igneous, quartz, feldspar, and few to no polymict grains. In addition to the polymict grains, the sand fraction in the ice stream cores contains trace fragments of sedimentary, and volcanic rocks, both of which are absent from the Reedy Glacier sand fraction. However, polymict grains are believed to represent a process occurring beneath the ice sheet, rather than indicate provenance. It is difficult to differentiate between the two tills, as both contain high concentrations of felsic-intermediate igneous lithics, quartz, and feldspar. The central Ross Sea contains sediment similar in rock type and mineralogy as seen within sediments from both Reedy Glacier, and the base of the ice streams of West Antarctica.

Kathy Licht, PhD

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INTRODUCTION

Two vast, dynamic ice sheets cover Antarctica. The East Antarctic Ice Sheet (EAIS) is a land based ice sheet that is relatively stable (Figure 1) (Anderson, 1999). In contrast, the West Antarctic Ice Sheet (WAIS) (Figure 1) is a marine base ice sheet, which may be unstable as sea level rises due to increasing atmospheric and ocean temperature (e.g., Hollin, 1962; Alley and Whillans, 1991; MacAyeal, 1992; Alley and Bindschadler, 2001). Ice shelves play an important role in buttressing upstream ice, and the disintegration of these ice shelves is prevalent in West Antarctica. The recent 2002 collapse of a section of the Larsen B Ice Shelf along the Antarctic Peninsula has been followed by a two to six-fold increase in the centerline velocities of four glaciers flowing into the ice shelf (Scambos et al., 2004). These observations of the smaller Larsen B Ice Shelf give us insight into the potential future of the WAIS. Antarctic ice sheets are the largest fresh water repository on Earth and play an important role in controlling global temperature and sea level (Anderson, 1999).

This research seeks to better constrain the relative input of East Antarctic ice verses West Antarctic ice to the Ross Sea during the Last Glacial Maximum (LGM). Presently two models are often cited, one reconstruction of the Ross Ice Sheet portrays the WAIS as the dominant contributor of ice, with western Ross Sea ice being derived from East Antarctica, and central and eastern Ross Sea ice being derived from West Antarctica (Figure 2) (Stuiver et al., 1981; Shipp et al., 1999). This hypothesis is supported by the distribution of glacial troughs, interpreted to be extensions of modern ice stream channels, and other topographic basal ice features such as mega scale glacial lineations located on the Ross Sea floor (Shipp et al., 1999; Mosola and Anderson, 2006).

Other LGM reconstructions show a relatively equal contribution of ice, with as much as half of the ice delivered to the Ross Ice Sheet flowing from East Antarctica (Denton and Hughes, 2000; Licht et al., 2005) (Figure 2). These models are supported by provenance studies of till collected from across the Ross Sea, which suggests that the mixing zone of sediments being transported through the Transantarctic Mountains (TAM) occurs in the central Ross Sea near 180° (Licht et al., 2005; Farmer et al., 2006).

Currently the WAIS contains numerous ice streams that have the ability to move ice several hundred kilometers per year (Bindschadler et al., 2001; Whillans et al., 2001). The presence or absence of ice streams greatly effects reconstructions of ice flow dynamics of the LGM Ross Ice Sheet; West Antarctic Ice Streams flow rapidly by dynamic constraints related to basal sediment and water conditions (Hughes, 1977; (Bindschadler et al., 2001; Whillans et al., 2001). Slow East Antarctic ice flow off the plateau is accelerated due to constriction produced by flow through valleys of the TAM. Some reconstructions of the Ross Ice Sheet use the presence of paleo-ice streams on the Ross Sea continental shelf to provide evidence for the WAIS dominated LGM Ross Sea ice sheet (Stuiver et al., 1981; Shipp et al., 1999), while the extension and persistence of West Antarctic ice streams could produce a much larger flux of ice in the Ross Ice Sheet. Establishing the relative contribution of East Antarctic Ice and West Antarctic Ice will allow us to better constrain ice flow into the Ross Sea during the LGM, which has implications for more accurate reconstructions of the Ross Ice Sheet and its behavior. Constraining ice flow will also allow us to create better models for ice sheet retreat and possible collapse.

This research compares samples collected from outlet glaciers transporting material through the Transantarctic Mountains, specifically Reedy Glacier, to sediment samples from beneath WAIS ice streams, both of which transport sediment to the Ross Sea. Furthermore, I will compare both of these sample suites with samples of till from the central Ross Sea to determine the provenance of this sediment. Reedy Glacier is the southern-most major East Antarctic outlet glacier located within the Ross Sea drainage, and comparing these samples to West Antarctic ice stream samples may provide constraints on the boundary between East and West Antarctic ice. In addition to sediment provenance in the central Ross Sea, this study also examines the geology of Reedy Glacier, a region that is mostly unknown as it is covered by ice, and also seeks to provide insight to the processes of glacial transport.

Previous studies have found distinct compositional differences in sand fractions of till collected from outlet glaciers within the TAM and material from beneath West Antarctica (Lederer, 2003; Licht et al., 2005). Distinct isotopic and zircon signatures are also evident between East Antarctic and West Antarctic till (Farmer et al., 2006; Palmer, 2008). However, no samples south of Beardmore Glacier were analyzed in those studies. If sediments from Reedy Glacier and West Antarctic Ice Streams are distinct, then comparing these two distinct terranes to sediment cores from the central Ross Sea can be used to place tighter constraints on the LGM contributions of West Antarctic and East Antarctic ice to the Ross Ice Sheet.

PHYSICAL SETTING

The Ross Sea is a 45,000 square kilometer embayment between the landmasses of East Antarctica and West Antarctica, bounded on the west by the TAM and on the east by Marie Byrd Land (Figure 1). Currently much of the Ross Sea is covered by the Ross Ice Shelf, which is a floating extension of grounded ice bordering the embayment (Figure 1). Seaward of the Ross Ice Shelf, the continental shelf has an average depth of approximately 500 meters and displays a reverse gradient typical of coastal regions weighted down by large ice caps (Anderson, 1999). The continental shelf slopes toward the continent due mostly to glacial erosion of the inner continental shelf combined with depression from glacial isostasy (Anderson, 1999; Shipp et al., 1999). The stability of the WAIS is compromised by the landward sloping deep continental shelf, as the buoyant force of water maybe able to unseat the ice sheet and persists to work down slope eventually leading to the breakup of the WAIS (Hollin, 1962).

East Antarctica is a craton comprising most of the Antarctic continent land area. It is nearly completely covered by the EAIS with the only rock outcroppings occurring within the TAM and around the craton perimeter. West Antarctica is an archipelago of islands nearly entirely covered by the WAIS. Rock exposures in West Antarctica are generally confined to the Marie Byrd Land (Figure 1).

Geology

Geologically, Antarctica is broken into two basic components: the Precambrian craton of East Antarctica, and the much younger terranes of West Antarctica, which are primarily Mesozoic and Cenozoic in age. The East Antarctic craton has likely been fairly tectonically and structurally stable since the breakup of Gondwanaland beginning in the late Jurassic (Tingey, 1991). Generally, the rocks comprising most of East Antarctica are much older than West Antarctic rocks, however, our knowledge of Antarctic bedrock geology is limited due to the nearly complete ice sheet coverage. The TAM are exposed in areas and provide the only direct knowledge of bedrock. The ancestral TAM, which divides East Antarctica from West Antarctica, began forming during the Beardmore Orogeny, 633-620 Ma (Stump, 1995). Subsequent active plate margin processes along the length of the TAM during the Cambro-Ordovician Ross Orogeny produced deformation of existing rocks and large-scale magmatism, represented by the Granite Harbor Intrusive Complex, which outcrops within Reedy and Scott Glaciers (Stump, 1995; Myrow et al., 2002; Goodge et al., 2004).

The bedrock geology of the Reedy Glacier region is generally composed of granitic batholiths associated with the Ross Orogeny (termed the "Queen Maud-Wisconsin Range Batholith (Stump, 1995)), which extends almost 600 km from the Wisconsin Range to Scott Glacier (Figure 3) (Stump, 1995). Much of this batholith is composed of medium- to coarse-grained, biotite hornblende granodiorite and quartz monzonite (Stump, 1995). The Wyatt Formation is composed of silicic porphyry, which outcrops at Metavolcanic Mountain (Figure 3) near the head of Reedy Glacier (Stump, 1995). The Wyatt Formation is mid-Cambrian in age, and is thought to represent the remnants of a silicic volcanic complex that was intruded by hypabyssal magmas (Stump et al., 1986). An "unknown metamorphic rock" composes Strickland Nunatak, located at the head of Reedy Glacier (Davis and Blankenship, 2006).

The age of the Queen Maud- Wisconsin Range Batholith is poorly constrained. Faure et al. (1968) initially found an age of 613 ± 22 Ma through Rb/Sr whole rock dating of the rapakivi phase (also known as the Zanuck Granite) of the Granite Harbor Intrusive Complex. This age was then revised by Faure et al. (1979) to 496 ± 23 Ma using Rb/Sr whole rock dating. Granite from the head of the Scott Glacier (Mount Wilbur) has produced an age of 479 ± 14 Ma through K/Ar biotite dating (Minshew, 1965). Scatterings of K/Ar ages are consistent with cooling ages elsewhere in the TAM (Stump, 1995).

Following the uplift of the Ross Orogeny, basement rocks were eroded to form the Kukri Peneplain, upon which glacial, shallow marine and alluvial plain sediments of the Beacon Supergroup were deposited from the Permian to Triassic (Studinger et al., 2006). Then Jurassic-aged Ferrar Dolerite sills intruded basement rocks and Beacon Supergroup Strata (Stump, 1995; Murtaugh, 1969; Borg, 1983). Beacon group rocks outcrop within a few kilometers of Mims Spur, one of the study sites (Figure 3).

In contrast, West Antarctica is largely characterized by the approximately 3000 kilometer long Cenozoic West Antarctic rift system, with bedrock composed primarily of alkaline basalts (LeMasurier, 1990), ranging in age from about 30 Ma to present (Behrendt et al., 1996). Episodic rifting, including the formation of the rift basin beneath the Ross Sea, has been associated with West Antarctica crustal extension since the late Mesozoic, when most of the extension took place (Behrendt et al., 1994). Late Mesozoic rifting was possible simultaneously with the rifting of New Zealand or earlier (Behrendt et al., 1994; Wilson, 1992). In addition, Cooper and Behrendt (1991) have proposed more recent stages of rifting characterized by downfaulting beneath the Ross Sea continental shelf, and associated bimodal alkalic volcanism throughout the area.

Subglacial West Antarctic rocks are primarily interbedded volcanic and sedimentary strata, as shown by magnetic and seismic studies (Jankowski and Drewry, 1981; Bentley, 1997). Behrendt et al. (1994) characterized the volcanic rocks as Cenozoic flood basalts that originated from a mantle plume (associated with rifting). Overlying the basalts are Oligocene or younger glacial-marine sediment, which may be as thick as 600 meters, approximately the upper 20 meters corresponds to Plio-Pleistocene tills (Rooney et al., 1991; Tulaczyk et al., 1998; Studinger et al., 2001). A large component of the sediments have likely been transported from the slopes of the flanking TAM and Marie Byrd Land into the rift basin.

As important as it is to understand Antarctica's geologic history, it is vital to understand Antarctica's glacial history. Understanding the influence of ice streams on the WAIS is critical in the debate over LGM reconstruction of the Ross Ice Sheet and the current stability of the WAIS, as ice streams have the ability to move ice several hundred kilometers per year (e.g., Bindschadler et al., 2001; Whillans et al., 2001). During the LGM the presence or absence and location of ice streams could greatly affect how and where sediment was deposited on the continent shelf, as well as the retreat of ice from the LGM grounding line. The debate over the relative contribution of West Antarctic ice versus East Antarctic ice in the Central Ross Sea during the LGM is centered on the extension and influence of West Antarctic ice streams on the behavior of the WAIS (Stuiver et al., 1981; Shipp et al., 1999; Licht et al., 2005).

PREVIOUS RESEARCH

Currently, two models are used to explain the configuration of the LGM Ross Ice Sheet. One model predicts a dominantly WAIS-derived expansion (i.e., Hughes, 1977; Stuiver et al., 1981; Balshaw, 1980; Anderson et al., 1992; Domack et al., 1999; Shipp et al., 1999). The second model yields a more balanced contribution from both EAIS and WAIS ice, with the ice masses meeting in the Central Ross Sea (Licht and Fastook, 1998; Licht, 1999; Denton and Hughes, 2002; Licht et al., 2005; Farmer et al., 2006; Palmer, 2008).

Balshaw (1980) analyzed the clay fraction of Ross Sea till retrieved via cores from the submarine troughs that were deposited during the LGM ice advance. The objective of Balshaw's (1980) study was to use LGM-aged till in the Ross Sea to characterize the clay fraction of till beneath the WAIS. The study used the expanded WAIS model as the proposed style of LGM ice advance on to the Ross Sea continental shelf. Balshaw (1980) found that significant variations existed in the smectite concentrations across the Ross Sea, with the highest concentrations occurring in the eastern Ross Sea troughs and lower concentrations occurring in the western and central Ross Sea troughs.

Seismic profiles (Hughes, 1977) coupled with the clay mineral composition in the till led Balshaw (1980) to propose LGM paleoflow lines consistent with those of Stuiver et al. (1981). Based on the Hughes (1977) flow lines, Balshaw (1981) suggested that low smectite concentrations in the western Ross Sea were derived from Mercer (formerly A), Whillans (formerly B), and Kamb (formerly C) Ice Streams (Figure 1) and high smectite concentrations in the central and eastern Ross Sea were derived from Bindschadler (formerly D), MacAyeal (formerly E), and Echelmeyer (formerly F) Ice Streams (Figure 1). Balshaw (1980) had no samples from beneath the WAIS, and was therefore unable to directly correlate Ross Sea till with West Antarctic till.

Similar to the smectite variability across the Ross Sea, Anderson et al. (1992) noted significant east-west variability in the pebble, coarse sand, and heavy mineral compositions. They reported that the western and central Ross Sea sand fraction is dominantly composed of rounded quartz and schist, with small quantities of gneiss, granite, and diabase. The eastern Ross Sea sand fraction is similar to the western Ross Sea sand, but in addition contains diamicton fragments, litharenites, and volcanic glass. Anderson et al. (1992) linked the pebble-sized fraction from the western Ross Sea with source rocks, determined to be dominantly Beacon Group sandstone, biotite schists and gneisses, and Ferrar Group dolerite. Based on the pebble lithology, Anderson et al. (1992) determined the source this sediment to be the Darwin Glacier in Victoria Land, as well as the McMurdo Volcanic Province.

The highest magnetic susceptibility values reported in the Ross Sea till occur in the western Ross Sea adjacent to McMurdo Volcanic Group rocks of northern Victoria Land (Licht, 1995; Licht et al., 1999). Diamictons in the Drygalski trough contain a median magnetic susceptibility value nearly two orders of magnitude greater than diamictons east of Drygalski trough. The magnetic susceptibility variations reported by Licht et al. (1999) reflect the compositional variability in the till reported by Anderson et al. (1992) and Balshaw (1981) across the Ross Sea; however, no direct link was established between the magnetic susceptibility and sand petrography trends in the till.

Submarine landforms have also been used for paleoice-flow reconstructions. Shipp et al. (1999) identified mega scale glacial lineations in the central and western Ross Sea features that indicate a northeast paleoice-flow direction. Similarly, in the south central Ross Sea, “drumlinized” topography indicates a northeast paleoice-flow direction. Lineations in the central Ross Sea fit reasonably well with either the WAIS dominated reconstruction or the EAIS- WAIS balanced reconstruction.

Until the study by Tulaczyk et al. (1998), previous provenance investigations supplied little evidence directly correlating the Ross Sea till with a source, because few till samples from the source areas were available. Tulaczyk et al. (1998) examined till retrieved from beneath the Whillans and Kamb Ice Streams and found the sediment to be extremely poorly sorted diamicton with sparse pebbles, which they interpreted to represent a widespread subglacial till. The sand fraction averages 59 ± 5% quartz, 27 ± 3.5% feldspar, and 16 ± 3.5% lithic fragments. The clay fraction contains 60% illite, 20% smectite, 10% kaolinite, 10% chlorite, and little evidence of comminution.

Licht et al. (2005) specifically investigated the sand fraction of LGM tills from across the Ross Embayment, as well as till from lateral moraines of outlet glaciers within the TAM, and beneath the Whillans and Kamb Ice Streams. Similar to Tulaczyk et al., (1998), Licht et al. (2005) found that samples from the base of West Antarctic Ice Streams contained felsic intrusive igneous and detrital sedimentary lithic fragments, as well as plagioclase grains, and abundant quartz. In contrast, the majority of the samples from East Antarctic till contained mafic intrusive and detrital sedimentary lithic fragments, and less abundant quartz. The distinctive composition from both source areas was then linked to specific cores of LGM age till from across the Ross Sea. Samples from the central Ross Sea were found to be compositionally similar to the till within the TAM with a West Antarctic component, suggesting that West Antarctic Ice Streams did not expand during the LGM and dominate the continental shelf as suggested by Stuiver et al. (1981).

Farmer et al. (2006) analyzed major elements, trace elements, and Nd, Sm, and Pb isotopic compositions in the < 63 μm sediment fraction of the same tills in Licht et al., 2005. Tills from the central Ross Sea were most likely related to ice emanating from the central TAM and possibly West Antarctica, based on similar isotopic and chemical compositions. This suggests that the ice flowed from the central TAM north across the central Ross Embayment to the continental shelf margin, further supporting the EAIS-WAIS balanced ice flow hypothesis of Licht et al. (2005) (Figure 2).

METHODS

Sample Acquisition

Samples of lateral moraines along Reedy Glacier provide material being eroded from the TAM, transported by the glacier and potentially deposited on the continental shelf. Moraines from the head of the glacier provide material from beneath the EAIS, as this material may be representative of bedrock beneath the ice sheet (Whillans and Cassidy, 1983). Sampling in this manner captures representative rock types along the length of Reedy Glacier, specifically intrusive igneous rocks, volcanic rocks, and metamorphic rocks. To maximize collection of material produced by glacial erosion rather than rock fall, samples were collected from moraines closest to actively flowing ice, as opposed to inner ridges which are more likely to be dominated by material being eroded off nearby outcrops.

In January 2007, 12 samples of till from 4 different moraines along the Reedy Glacier, Antarctica, were collected (Figure 4; Table 1). Sample sites were chosen based on topographic maps showing mapped moraines, and an aerial photograph of the sample sites confirmed if till was present. At each moraine 3 replicate sub-sites were selected for collection. Sub-site samples were collected to represent the diversity of material within each moraine. After laying out a rope into a 1 meter by 1 meter square, approximately 100 pebbles (material 4-32 mm in size) were collected within the boundary. After removing wind deflated sediments from the surface, an approximately 3 liter of till was collected in a Zip-lock® bag. Approximately ten to fifteen clasts (10-40 cm)were also collected at each site to characterize the diversity of material within each site. Additionaly, five bulk till samples were collected from two lateral moraines on Reedy

Glacier (sites CH and QH) (Figure 4) by Dr. Brenda Hall and Gordon Bromley of The University of Maine. To constrain West Antarctic till composition, thirteen till samples from previously collected cores at base of Whillans Ice Stream, and 4 samples from previously collected cores at the base of Kamb Ice Stream, have been acquired for this study from Hermann Engelhardt of the California Institute of Technology (Figure 4; Table 1).

Sample Processing and Data Analysis

Multiple methods have been employed to provide the data necessary for this research. These methods include compositional analysis of pebble and finer fraction, including point counting of grain mounts of the 500-2000 μm fraction, as well as particle size distributions. Pebbles have been classified through hand sample examination, and thin section analysis when necessary (for pebbles containing interesting mineralogy or textures). Pebble analysis was only utilized on samples collected from Reedy Glacier, as till cores collected from the base of Whillans Ice Stream and Kamb Ice Stream do not contain a significant amount of pebbles.

Point Counting Methodology

The Indiana point counting method (Suttner, 1974) was modified for the analysis of thirty-four grain mount thin sections containing the 500-2000 μm sand fraction of each till sample. The Indiana method counts rock fragments and individual minerals. A rock-fragment is considered to be a grain consisting of two or more minerals or mineral phases (Table 2). The Indiana point counting method was chosen over the Gazzi-Dickinson

Method (Dickinson, 1970) because it accounts for both lithology and mineralogy. By categorizing lithic fragments and individual mineral grains, more categories become available for describing each till sample.

To prepare grain mounts, an approximately 3 g representative sub-sample of the 500-2000 μm sand fraction was taken from each till sample. The goal was to obtain approximately 300 grains, which were then placed into a flat-bottomed ice cube tray. A 91 mL Buehler Epo-thin resin/11 mL Buehler Epo-thin hardener mixture was combined to produce the resin compound, was poured over the sand grains and allowed to harden for twenty-four hours. The "pucks" containing the sand grains were removed from the ice cube trays and prepared for mounting on a standard thin section slide. The bottom-side of each resin puck was polished using 600 and 1000 grit silicon carbide polishing compound to obtain a flat polished surface that exposed the maximum area of the interiors of the sand grains. Once exposed and polished, the puck was attached to a standard thin section slide using a 3/8-gram resin to 1/8-gram hardener ratio of Epo-thin® low-viscosity epoxy. The samples were allowed to set for twenty-four hours. After the epoxy was fully set, the excess sample pucks were removed then ground using a Buehler® Petrothin and polished with 1000 grit silicon carbide polishing compound to a thickness of approximately 30μm.

Point counts were made using a Leitz® Laborlux 11 POL S petrographic microscope fitted with a Leitz® Wetzlar point counting stage. Transects were made across the thin section under 40x magnification. Every grain in each slide was counted, with the goal of making at least 300 counts for each sample. However, because of the low sand concentrations in the till, several of the thin sections did not contain three hundred appropriately sized grains. Point counts were replicated three times per slide to ensure consistent identification of grains. The average of the three counts was used for comparison purposes.

Particle Size Analysis

Approximately two grams of material were separated from the bulk till sample for particle size analysis. Material greater than 1000 μm was removed by dry sieving and weighed. The remaining material was cooked on low heat for 15 minutes and on high heat for 75 minutes, while being purged of organic matter by adding five mL of 35% H_2O_2 every 30 minutes. Following the last treatment of 35% H_2O_2, 8 mL of 25-g/mL magnesium chloride was added to the sample. The sample was then wet sieved through a 125 μm sieve. The fraction less than 125 μm was saved, while the larger material was examined under a Leica MZ95 stereoscope and any remaining organic matter was removed from the sample. The 125-1000 μm sample was recombined with the less than 125 μm in a 600 mL beaker, topped off with deionized water, and allowed to settle for twenty-four hours. After twenty-four hours, the remaining water was siphoned off and the sediment centrifuged in a 50 mL centrifuge tube for twenty minutes at 8000 rpm. After centrifuging, 20 mL of 25-g/mL sodium metaphosphate dispersant was added. The samples were split using an ELE sample splitter into 1/4 or 1/8 splits depending on amount of clays present, and analyzed on the Malvern Mastersizer 2000 Laser Particle Size Analyzer in the IUPUI Sediment Analysis Laboratory. Each sample was measured on the “Malvern” three times and averaged to reduce any discrepancies.

RESULTS

East Antarctica- Reedy Glacier Pebble Data

On average the pebble fraction contained lithologies similar to mapped bedrock geology (Figure 5; Table 3). Samples from Strickland Nunatak (SN) are characterized almost entirely by quartzite within the pebble fraction, with < 5% of other metamorphic rocks (such as marble) (Figure 5). There is a < 2% difference in composition between sub-sites (Table 3). Samples from Metavolcanic Mountain (MM) are characterized almost entirely by intermediate and felsic igneous pebbles, with approximately 8% quartzite pebbles present at one subsite. MM has substantial compositional variety (greater than 22%) between sub-sites (Table 3), as was visually observed in the field. Mims Spur (MS) has the greatest compositional variety of all sites on Reedy Glacier. MS is characterized by 47.9 ± 14.5% coarse-grained intermediate igneous pebbles, 18.6 ± 9.7% mafic igneous pebbles, 22.7 ± 9.3% fine-grained intermediate igneous pebbles, and minor amounts of quartzite and schist pebbles. Quonset Glacier (QG) is characterized by equal amounts of felsic igneous and intermediate igneous pebbles (44.3 ± 18.6%, and 41.8 ± 14.3% respectively), as well as 12.5 ± 8.6% gneiss and schist pebbles, and trace amounts of quartzite pebbles.

East Antarctica- Reedy Glacier Sand Petrography

Each site from Reedy Glacier contains lithic fragments and individual mineral grains that are similar in composition to the mapped geology of the area (Figure 5; Table 4). Overall the coarse sand fraction from Reedy Glacier tills contains mostly felsic lithic fragments (39.4 ± 23.1%), quartzite lithic fragments (17.5 ± 29.4%), and quartz grains

(16.1 ± 8.1%) (Table 4). Lesser amounts of plagioclase feldspar grains (9.2 ± 9.0%), potassium feldspar (8.3 ± 6.6%), biotite (4.4 ± 4.9%), and other metamorphic lithic fragments (4.4 ± 5.9%) are also present within the till. The non-quartzite metamorphic lithic fragments are typically foliated lithic grains. The Reedy Glacier till also contains trace amounts (< 1%) of intermediate igneous lithic fragments, muscovite, and chlorite.

Spatial variability in the sand composition exists between sites from different moraines along Reedy Glacier (Table 4). Till from Strickland Nunatak contains the greatest amount of quartzite lithic fragments (88.8 ± 2.8%). Metavolcanic Mountain and Mims Spur are the only other sites with quartzite lithic fragments present in the coarse sand fraction, and contain 9.3 ± 3.5% and 24.1 ± 3.4% respectively. No quartzite lithic fragments were found within the coarse sand fraction at Quartz Hills, Caloplaca Hills, or Quonset Glacier, however schist fragments are found within these sites.

Spatial variability in the sand composition also exists between sub-sites on each moraine, with the greatest standard deviation being 13.8% occurring within the felsic igneous lithic fragments of Quartz Hills, however the average standard deviation between sub-sites was less than 5% (Table 4) (Appendix C).

Petrographic analysis of the sand fraction from Reedy Glacier reveals many fewer intermediate igneous lithic fragments as compared to the pebble data from each site. This could be attributed to the relative mineral abundance in rocks. For example, if amphibole makes up < 5% of intermediate igneous pebbles, the chances of finding a sand fragment with amphibole is smaller than 5%. Grains containing quartz and plagioclase feldspar could be classified as either felsic or intermediate without the presence of pyroxenes or amphiboles.

Strickland Nunatak (SN)

The coarse sand fraction of the till samples collected from Strickland Nunatak is dominantly (88.8 ± 2.8%) composed of metamorphic lithic fragments, specifically quartzite lithic fragments, with the remainder being composed of quartz grains (11.1 ± 2.6%) (Figure 5; Table 4).

Metavolcanic Mountain (MM)

The coarse sand fraction of the till samples collected from Metavolcanic Mountain is dominated by felsic igneous lithic fragments (65.4 ± 12.1%), and approximately 10% of both quartz and potassium feldspar grains (Figure 5; Table 4).

Mims Spur (MS)

The coarse sand fraction of the till samples collected from Mims Spur is dominated by felsic igneous lithic fragments (39.0 ± 8.8%) and metamorphic (quartzite) lithic fragments (24.1 ± 3.4%) (Figure 5; Table 4). This site contains the highest percentage of biotite within all of the Reedy Glacier sites (12.0 ± 5.5%). Other sites on Reedy Glacier contain, except CH, less than 5% biotite.

Caloplaca Hills (CH)

The coarse sand fraction of the till samples collected from Caloplaca Hills is dominated by felsic igneous lithic fragments (49.1%), quartz grains (15.2%), and plagioclase feldspar (12.2%) (Table 4). This site only contains 3.0% quartzite lithic fragments, and has > 10% biotite.

Quartz Hills (QH)

The coarse sand fraction of the till samples collected from Quartz Hills is very similar to the samples collected from Caloplaca Hills. The samples are dominated by felsic igneous lithic fragments (41.4 ± 13.8%), quartz (19.5 ± 5.7%), and plagioclase feldspar (18.2 ± 5.1%) (Table 4). Quartz Hills contains almost double the amount of potassium feldspar grains (15.5%) as compared to Caloplaca Hills (8.7%), and the till from Quartz Hills contains the greatest percentage of potassium feldspar for all of the sites on Reedy Glacier. This implies that variability in composition exists within the Granite Harbor Intrusive Complex.

Quonset Glacier (QG)

The coarse sand fraction of the till samples collected from Quonset Glacier contain the highest percentage of quartz grains (29.5 ± 0.5%) throughout Reedy Glacier (Figure 5; Table 4). The coarse sand fraction from this site also contains 36.2 ± 1.6% felsic igneous lithic fragments, and 19.5 ± 2.0% plagioclase feldspar grains. Although metamorphic pebbles were identified, no metamorphic lithic fragments were observed in the coarse sand fraction.

East Antarctica- Reedy Glacier Particle Size Analysis

The particle size data (0.5-2mm) collected from Reedy Glacier tills shows similar results among sample sites (Figure 6) (Table 5). Samples are dominated by medium to coarse sand (89.6 ± 7.8%), with much smaller amounts of silt and clay (8.2 ± 6.3%, and 2.1 ± 1.8% respectively) (Table 6). Sites SN, MM, and MS contain very similar particle size distributions, although these sites are all mapped as different bedrock types (Figure 3), although SN has up to 21% silt and clay, which possibly indicates that this is unlikely to be derived from the local breakdown of quartzite, suggesting some upstream contribution. Sites CH, QH, MS, and QG are all mapped as Granite Harbor Intrusive

Complex (Figure 3), and contain similar particle size distribution, containing more fine sand size grains than SN, and MM.

West Antarctic Ice Stream Sand Petrography

Whillans Ice Stream (WIS 1)

A two-meter long sediment core was taken beneath Whillans Ice Stream, and sub-samples for petrographic analysis were taken at a 0.1 to 0.2-meter interval. Samples from Whillans Ice Stream contains high concentrations of polymict grains (73.6 ± 4.6%), approximatly 12% quartz, and < 10% each of quartzite lithic fragments, felsic igneous lithic fragments, and plagioclase feldspar (Table 4). Trace amounts (< 1%) of biotite, opaque, mafic igneous lithic fragments, and metamorphic lithic fragments (typically foliated grains) are present within the Whillans Ice Stream core (Figure 8). One mafic igneous lithic fragment was found within this core in the 150-160 cm interval; this is the only mafic igneous lithic fragment found from West Antarctica in this study.

Kamb Ice Stream (KIS 1)

A two-meter long sediment core was also taken beneath Kamb Ice Stream, and four intervals were analyzed petrographically. The coarse sand fraction of two samples nearest the ice-bed interface show great variability with respect to depth (Figure 9). The samples from the lower intervals (SAL 1771, SAL 1772, and SAL 1773) of this core contain few polymict grains (1.0 ± 0.6%), and much greater amounts of quartzite lithic fragments (approximately 30%), felsic igneous lithic fragments (approximately 25%), and quartz (approximately 30%), as compared to the Whillans Ice Stream core samples (Table 4). The Kamb Ice Stream samples also contain < 5% potassium feldspar, intermediate igneous lithic fragments, plagioclase, and < 1% iron ore grains. However, the upper sample from Kamb Ice Stream, SAL 1774, contains higher percentages of polymict grains (Table 4). This sample contains 27.9% polymict grains, but also contains a similar proportion of fragments as the samples below it. One extrusive volcanic grain was found within the sand fraction from the lower-most portion of the Kamb Ice Stream core (SAL 1771), this is the only extrusive grain found in this study.

West Antarctica Ice Stream- Particle Size Analysis

Particle size distribution data were collected from core samples taken from the base of three West Antarctic Ice Streams (Figure 4) (Table 6). Because of the small amount of sample available, some samples (WIS 4, KIS 2, KIS 4, and BIS 1) only had particle size analysis performed, and did not have point counts performed on the material. Particle size data collected from Whillans Ice Stream 1 (WIS 1) show non-systematic variation with respect to depth (Figure 7, Figure 8). WIS 1 contains greatest variability with respect to depth in the sand size fraction (37.2 ± 11.1%), and slight variability in the silt and clay fraction, 32.4 ± 5.7%, and 30.3 ± 5.9% respectively (Table 5). WIS 4 has little variability with depth for all size fractions: sand (28.4 ± 3.5%), silt (36.9 ± 1.6%), and clay (34.5 ± 1.2%) (Table 5).

Particle size data collected from Kamb Ice Stream 1 (KIS 1) has an interesting distribution with respect to depth (Figure 7, Figure 9). The uppermost sample, SAL 1774, contains 19.4% sand, 52.9% silt, and 27.5% clay, whereas the three samples below this sample contain on average 81.7 ± 2.9% sand, 14.8 ± 1.9% silt, and 3.4 ± 1.1% clay (Figure 7) (Table 5). This distribution is not seen within the other cores from this ice stream. KIS 2 contains similar amounts of sand and silt, and approximately 20% clay, whereas KIS 4 contains similar amounts of silt and clay with variable amounts of sand (25 ± 7%). Particle size data collected from Bindschadler Ice Stream (BIS 1) has slight variability with depth, 25.1 ± 5.5% sand, 41.7 ± 2.5% silt, and 33.1 ± 3.4% clay.

DISCUSSION

Reedy Glacier Till

Reedy Glacier flows through the Queen Maud batholith that contains intermediate to felsic igneous rocks and the majority of the till samples are reflective of the mapped bedrock geology. Analysis of the coarse sand fraction revealed that mineral fragments are more abundant in the till samples in the lower half of the glacier, whereas lithic fragments are more abundant in the till samples near the head of the glacier. This may reflect either bedrock texture, bedrock type, or the erosional processes occurring within the glacier as it moves down-slope. The till sample compositions are discussed in a south to north (i.e. down glacier) order by sampling location.

Strickland Nunatak (SN)

Petrography of the sand fraction shows that Strickland Nunatak till is completely dominated by quartzite lithics and quartz (Table 4). The pebble fraction confirms this, as it is composed of almost 100% quartzite fragments. Phyllite and marble are also present (< 5%) in the pebble fraction. However, the high concentration of a single rock type indicates that this till is locally derived. These components of the till are likely derived from the bedrock geology of Strickland Nunatak, as it is mapped as unidentified metamorphic rocks (Davis and Blankenship, 2006). The particle size distribution of this site shows more finer material than most downstream sites (Figure 6).

Metavolcanic Mountain (MM)

Felsic-intermediate igneous lithic fragments dominate the Metavolcanic Mountain pebbles and coarse sand fraction of till. The high concentration of felsic-intermediate igneous material at this site is interesting as the majority of outcrop is mapped as Wyatt

Formation, a silicic porphyry, with a small outcrop of Granite Harbor Intrusive Complex. Thus the till samples collected must have been derived from the Granite Harbor Intrusive Complex rocks. No porphyritic lithic fragments are seen within the sand fraction, nor are any porphyritic rock types seen in the pebble fraction. This site also contains metamorphic grains (7.7 ± 4.2%) that are quartzite in composition, which may be associated with the erosion and transport of material near Strickland Nunatak.

Mims Spur (MS)

Mims Spur contains the highest percentage of mafic igneous material in the pebble fraction within all Reedy Glacier sites (18.6 ± 9.7%). This higher concentration of mafic igneous pebbles may be derived from the Ferrar Dolerite of the Beacon Supergroup that outcrops within kilometers of this site. However, no mafic igneous lithic fragments are found in the coarse sand fraction, and no other characteristic signatures from the Beacon (i.e. clastic lithic fragments, as characterized by Licht et al., 2005) are found in the pebble or coarse sand fraction.

Caloplaca Hills (CH)

The till samples collected from Caloplaca Hills are representative of material being eroded from Granite Harbor Intrusive Complex-type rocks (dominated by felsic igneous lithic fragments, quartz, and feldspar). The small (3.0%) percentage of metamorphic lithic fragments are probably derived from subglacial metamorphic outcrops similar in composition to Strickland Nunatak.

Quartz Hills (QH)

Quartz Hills till samples are very similar in composition to the till collected from Caloplaca Hills, and are representative of material being eroded from Granite Harbor

Intrusive Complex-type rocks. However, two distinct differences are noted between this site and Caloplaca Hills. CH contains a much lower concentration of metamorphic lithics (0.7%), and also higher concentration of potassium feldspar grains (15.5% as compared to 8.7% at Caloplaca Hills). The till from Quartz Hills contains the greatest percentage of potassium feldspar for all of the sites on Reedy Glacier. This implies that variability in composition exists within the Granite Harbor Intrusive Complex. The high concentration of potassium feldspar at this site may also indicate that the till is very immature, and this site has a more "local" signature as it contains so few metamorphic lithic grains.

Quonset Glacier (QG)

The till collected from Quonset Glacier is representative of the mapped bedrock, Granite Harbor Intrusive Complex, containing felsic-intermediate igneous lithic fragments, quartz, and feldspar. No metamorphic lithic fragments are present within the coarse sand fraction; however, the pebble fraction is composed of approximately 1.4% quartzite. This site does have the highest concentration of quartz grains in the coarse sand fraction (30%) throughout the entire Reedy Glacier region.

Textural and Compositional Maturity

Analysis of the grain size distribution for samples from Reedy Glacier and the West Antarctic Ice Streams revealed the textural maturity of the samples (Figure 7). Till from Reedy Glacier contained > 70% (on average 90%) sand, indicating that the samples were texturally immature (Figure 6). Whereas, till from the ice streams contained mostly silt and clay (on average 40% and 30% respectively), indicating that the samples were more texturally mature (Figure 7). This more even distribution is also seen in the till from the central Ross Sea (Licht et al., 2005; Palmer, 2008), which implies greater transport distance.

These results are consistent with Tulaczyk et al. (1998), who compared Whillans Ice Stream till with till from Mackay Glacier and Taylor Glacier in East Antarctica. Particle size analysis results from this study also showed that West Antarctic till generally contains finer material than East Antarctic tills. West Antarctic samples are of a finer particle-size than East Antarctic samples largely because they are a secondary deposit (Studinger et al., 2001) and have been reworked subglacially. Rooney et al. (1991) suggested that West Antarctic tills are probably derived from preexisting Tertiary glacimarine sediments of the Ross Sequence. Hence, unlike East Antarctic till, West Antarctic till is a secondary deposit and was not originally deposited by subglacial processes (Tulaczyk et al., 1998).

It is also possible that the coarse grained nature of Reedy Glacier till is reflective of the original bedrock grain size. Dreimanis and Vagners (1971) found that till deposited subglacially matures with transport distance, causing matrix modes to grow. A majority of the pebbles and clasts collected are coarse grained, and some are pegmatitic. The weathering, and subsequent glacial transport and crushing of coarse grained material would yield coarser till, as compared to till that is produced by the erosion and crushing of finer grained rock types.

West Antarctic Ice Stream Basal Material

The observed composition of the coarse sand fraction from West Antarctic till is consistent with Tulaczyk et al. (1998) and Licht et al. (2005), who noted that the West

Antarctic till sand (60 – 2000 μm) fraction contains quartz, feldspar, and moderate concentrations of lithic fragments, but no rift-associated volcanic fragments.

Extrusive volcanic fragments were expected in the basal material, because the WAIS overlies a rift valley, however, only one volcanic grain was found within the coarse sand fraction of both two-meter cores, consistent with the findings of Licht et al. (2005). The absence of extrusive lithic fragments supports data showing that the basin is filled with hundreds of meters of sediments (Rooney et al., 1991). Tulaczyk et al. (1998) proposed that the till is likely a relict glacial deposit formed under a previous glacial regime, and offers a suggestion that the subglacial sediment may have been generated in the past by sediment released from melting debris laden basal ice during a time when West Antarctica became ice-free.

It is likely that during ice-free conditions prior to WAIS development during the Oligocene, the TAM and/or Marie Byrd Land rocks shed sediment into the West Antarctic rift basin. The presence of felsic igneous lithic fragments, and metamorphic lithic fragments (specifically quartzite) from beneath both ice streams suggests the possibility of derivation from the Reedy Glacier area, specifically felsic-intermediate igneous fragments from the Granite Harbor Intrusive Complex, and quartzite from the unidentified metamorphic rocks at the head of Reedy Glacier (Strickland Nunatak, Figure 3). The TAM is a plausible source for material in the West Antarctic basin, and is a closer source material as compared to Marie Byrd Land (Figure 11). A topographic high also exists between Whillans Ice Stream and Kamb Ice Stream (Figure 11), possibly preventing widespread deposition of material from Marie Byrd Land.

The preservation of massive quantities of polymict grains beneath Whillans Ice Stream, and the upper portion of Kamb Ice Stream remains unresolved. The upper portion of the Kamb Ice Stream core contains a third more polymict grains than the lower portions of the core. The change in polymict abundance may be attributed to the shut down of Kamb Ice Stream approximately 200 years ago due to stream piracy (Whillans et al., 2001), however it is unknown at this time if polymict grains can be attributed to streaming ice flow. However, we do see high concentrations of polymict grains throughout the Whillans Ice Stream core, which is an actively flowing ice stream (Whillans et al., 2001).

Polymict Grains

The discovery of polymict grains beneath the WAIS opens a new realm of questions about the processes occurring beneath streaming ice. These polymict grains are generally composed of a grain of quartz surrounded by a matrix of silt-clay material (Figure 10). Approximately 80% of the grains analyzed in this study have a "core-grain," whereas, some of the grains examined (approximately 20%) are just silt-clay matrix material. Petrographically, the polymict grains do not appear to have accreted or "rolled" textures. These grains are not likely a product of lab preparation, as various methods were utilized to disaggregate the cores, with the final product containing similar concentrations of polymict grains. Remarkably, the grains are only semi-lithified, but survive various sieving, and freeze-drying processes.

Two different populations of polymict grains are distinguishable from the WAIS material. Polymict grains from the base of Whillans and Kamb Ice Streams are generally rounded (Figure 10A-E); however, polymict grains from the base of Bindshadler Ice Stream are more angular and rod shaped. Unfortunately this study was limited by the amount of material available from Bindshadler Ice Stream, and further investigation of material from this site of was not possible.

Anandakrishnan and Winberry (2003) estimated the thickness of the subglacial sedimentary layer beneath two sites on Kamb Ice Stream, which revealed varying thickness of sediment at the base of the ice stream. Estimates for one location (STC2) were 0 ± 50 meters of sediment, and the other location (STC6) had 180 ± 50 meters of sediment at the base of the ice stream (Anandakrishnan and Winberry, 2003). The difference in sediment thickness was attributed to the speed of ice, where fast-flowing ice accumulated more sediment beneath it (Anandakrishnan and Winberry, 2003). The findings of Anandakrishnan and Winberry (2003) are supported by Studinger et al. (2001), who also found thick subglacial sediment beneath West Antarctica. Studinger et al. (2001) used areogeophysical data to estimate the distribution of sediment beneath the WAIS, and found that significant accelerated ice flow occurs exclusively in regions covered by subglacial sediment.

Joughin and others (2004) estimated the melt rates at the bottom of the West Antarctic ice streams, and found that Whillans and Bindshadler Ice Streams were melting in excess of 15 m a^{-1}, while Kamb Ice Stream was neither freezing nor melting with an estimated rate of 0 m a^{-1}. This data supports the theory that when melting ceases to occur at the base of the ice sheet, streaming ice no longer occurs (Alley et al., 1994). It is also interesting to note that this research found fewer (< 30%) polymict grains beneath Kamb Ice Stream, an in-active ice stream.

The known presence of basal sediment (Anandakrishnan and Winberry, 2003; Studinger et al., 2001) coupled with basal melt (Joughin et al., 2004) suggests that polymict grains may be a product of the two. Hicock and Dreimanis (1992) describe changes in till rheology in relation to pore water content. As the pore water content increases, ductile shear is promoted and unlithified till may form spherical clasts. It is possible that this is the mechanism by which these polymict grains begin to form. Hicock and Dreimanis (1992) also suggest that as pore water content decreases the shapes of the clasts may morph to more deformed lens shapes. Pore water content may influence the shape of the polymict grains, thus creating the two distinct populations seen within this research. Material from the Whillans Ice Stream cores reflect high pore water conditions at the base of the ice stream, whereas Bindschadler and Kamb Ice Stream cores reflect less water present at the bed.

Central Ross Sea Core Material

Material collected from the central Ross Sea contains sand with compositional similarities to EAIS and WAIS samples, suggesting input from both East and West Antarctic sources (Licht et al., 2005; Farmer et al, 2006). Petrographically it is difficult to differentiate between the Reedy Glacier and WAIS samples, thus making it difficult to differentiate ice input to the central Ross Sea (Figure 12). The central Ross Sea contains sediment similar in rock type and mineralogy as seen within sediments from both Reedy Glacier, and the base of the ice streams of West Antarctica (Figure 12). Similar lithologies include igneous felsic-intermediate grains, and quartzite grains, with few/no mafic grains.

This data suggests that we are unable to delineate input from the southern TAM versus material from the base of the WAIS to the central Ross Sea (Figure 12). It is possible that material has previously been eroded from the southern TAM and deposited in the WAIS basin (Figure 11), which would produce similar “fingerprints” in both areas, indicating that the mixing line at 180° in the central Ross Sea, as suggested by Licht et al., 1999, represents the maximum extent of the LGM WAIS in the Ross Sea. Further research, specifically dating of zircons from both areas, may provide a better “fingerprint” for these areas, as similar ages would indicate that material from the Southern TAM is being deposited in the WAIS basin. If this hypothesis was true, it would support the model proposed by Licht and Fastook (1998) and Denton and Hughes (2002) (Figure 2). Their models show that LGM ice advanced onto the Ross Sea continental shelf, receiving a more equal contribution from the EAIS and WAIS than had been previously suggested (e.g. Stuiver et al., 1981). If dating of zircons from both areas provided different ages, it would suggest that material beneath the WAIS is being derived from a different source, such as Marie Byrd Land, or even an unknown outcrop beneath the ice sheet (Figure 11).

The discovery of similar till compositions beneath the WAIS and the southern TAM presents the question; how large of an area possesses a single compositional “fingerprint?” This study has focused on one outlet glacier in the TAM, which is eroding a batholith of unknown size. It is possible that the Granite Harbor Intrusive Complex extends much further southeast but is covered by ice. The Wisconsin Range (Figure 3) is also composed of Granite Harbor-type rocks (Faure et al., 1968). It is possible that an extremely large area is being eroded and filling the WAIS basin with material, thus making a distinct “fingerprint” difficult to obtain based solely on lithology and mineralogy.

Comparisons of the percent quartz, feldspar (both plagioclase and potassium), and mafic igneous lithic fragments within the coarse sand fraction revealed distinct groups between sample locations (Figure 13). The distribution of these groups gives possible insight to the provenance of material in the central Ross Sea. Samples from Reedy Glacier plot near 50% feldspar, 50% quartz, with no mafic igneous lithic fragments, whereas, samples from beneath the West Antarctic Ice Streams contain higher concentrations of quartz (80-90%), with little mafic igneous lithic fragments (Figure 13). Material from the central Ross Sea plots between these two groups, with some mafic igneous lithic input (Figure 13). While this comparison does not show a mixing of only material from Reedy Glacier and from the base of the WAIS in the central Ross Sea, it does suggest that the central Ross Sea is receiving input from both EAIS and WAIS sources, as suggested by Licht et al., 2005, and Farmer et al, 2006.

The abundance of polymict grains is unlikely to be related to the provenance of till. For comparative purposes these grains were removed from data comparing Reedy Glacier, WAIS basal material, and the central Ross Sea material (Figure 12). The abundance of polymict grains (with as much as 92.3% in the 100-102 cm interval of SAL 282) in the central Ross Sea creates additional questions about the processes occurring at the time this interval was deposited. Do polymict grains represent a modern process occurring at the base of the ice sheet? The question remains unanswered at this time, however further research must be conducted as they may hold clues to ice sheet processes.

CONCLUSIONS

This study has found that the composition of Reedy Glacier till is reflective of the mapped bedrock geology, and that the till is relatively immature based on the dominance of coarse sand, and little silt and clay fraction within the till, coupled with the high concentration of lithic fragments. This particle size distribution may also attributed to the original grain size of the bedrock, as it is very coarse grained. The discovery of quartzite at Strickland Nunatak provides a clearer description of the area's geology (mapped as unknown metamorphic rocks by Davis and Blankenship, 2006).

This study also showed the variability of till composition within Reedy Glacier. Presumably the composition of till in this region should be very similar, as it is mostly being eroded from the Granite Harbor Intrusive Complex. However, substantial amounts of quartzite pebbles and lithic fragments, and mafic igneous pebbles are also present within the till. Also, characterizing multiple subsites on each moraine proved high resolution data regarding the variability within a single moraine. Some subsites exhibited little variability in till composition, such as the subsites of Strickland Nunatak, and Quonset Glacier (< 2% variability between subsites), whereas other showed much higher variability, such as Quartz Hills (± 13.8% variability in the concentration of felsic igneous lithic fragments).

Analysis of till from Reedy Glacier and material from the base of the WAIS revealed similar compositions, even though the WAIS overlies (and has presumably eroded) a rift basin. The discovery of similar material from both sources creates new questions about processes occurring beneath the ice sheet. These data suggest that sediment fill in the West Antarctic basin beneath the Whillans and Kamb Ice Streams was eroded from the southern TAM. Further work is needed to determine the age distribution of zircons in the tills to prove if they are in fact related. The mixing line of East Antarctic and West Antarctic ice at 180° in the central Ross Sea, as suggested by Licht et al., 2005, probably represents the maximum extent of the LGM WAIS in the Ross Sea.

The discovery of polymict grains beneath the WAIS provides additional information about the processes occurring beneath ice streams. The presence of polymict grains in the Whillans Ice Stream core, and the absence of these same grains in the lower portions of Kamb Ice Stream core may indicate a relationship between pore water and the formation of polymict grains. Further work is needed to determine the processes occurring to form polymict grains, as well as to investigate basal conditions of former (not actively flowing) ice streams.

Table 1: Site Locations and Descriptions.

Site Name	Latitude	Longitude	Elevation (mamsl)	Mapped Bedrock*
Reedy Glacier Samples				
Strickland Nunatak (SN)	86° 29.18' S	124° 43.10' W	2106	Unknown Metamorphic
Metavolcanic Mountain (MM)	86° 13.63' S	126° 54.99' W	1760	Wyatt Formation/Granite Harbor Intrusive Complex
Mims Spur (MS)	86° 00.103' S	125° 18.356' W	2213	Granite Harbor Intrusive Complex
Caloplaca Hills (CH)	86° 07' S	131° 00' W	1571	Granite Harbor Intrusive Complex
Quartz Hills (QH)	85° 56' S	132° 50' W	1660	Granite Harbor Intrusive Complex
Quonset Glacier (QG)	85° 24.72' S	126° 9.08' W	1201	Granite Harbor Intrusive Complex
West Antarctic Ice Stream Samples				
Whillans Ice Stream 1 (WIS 1)	83° 27' S	137° 46' W	334	
Whillans Ice Stream 3 (WIS 3)	83° 28' S	138° 14' W	334	
Whillans Ice Stream 4 (WIS 4)	83° 27' S	137° 46' W	334	
Kamb Ice Stream 1 (KIS 1)	82° 26' S	135° 57' W	527	
Kamb Ice Stream 2 (KIS 2)	82° 24' S	135° 44' W	527	
Kamb Ice Stream 4 (KIS 4)	82° 40' S	135° 49' W	527	
Bindschadler Ice Stream (BIS 1)	81° 4' S	140° 0.3' W	493	

* Data from Davis and Blankenship (2005)

Table 2: Point count classification scheme.

Category	Lithic- Fragment Classification Criteria
Sedimentary Lithic Fragments	
Silt/Sandstone	Grains with distinct boundaries Possibly contain some matrix Sand- and/or silt-sized components
Mudstone	Contain silt and clay-sized particles Difficult to determine exact composition
Claystone	No discernable grain boundaries
Polymict	Lithic fragment consists of unspecified clast surrounded by fine-grained matrix May or may not be lithified
Intrusive Igneous Fragments	Large crystals and obvious boundaries
Felsic	Quartz + K-spar ± plagioclase, biotite, hornblende, muscovite
Intermediate	± Quartz + > 50% plagioclase + minor K-spar ± hornblende, biotite, clinopyroxene
Mafic	> 50% plagioclase + orth/clinopyroxene ± olivine, iron oxide
Extrusive Igneous Fragments	± Large crystals with matrix of smaller elongate angular crystals
Basalt ± Andesite ± Rhyolite	Multiple zoned and/or twinned plagioclase ± fibrous glass ± opaque minerals ± volcanic glass ± clinopyroxene
Metamorphic Fragments	
Quartzite	Intergrowth of quartz crystals
Marble	Twinned calcite
Schist	Grains exhibit fabric

Table 3: Reedy Glacier Pebble Count Percentage Data.

Site		Coarse Grained Felsic	Coarse Grained Intermediate	Fine Grained Felsic	Fine Grained Intermediate	Fine Grained Mafic	Gneiss	Schist	Phyllite	Quartzite	Marble
Strickland Nunatak A		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	98.1	1.9
Strickland Nunatak B		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
Strickland Nunatak C		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
	Average	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	99.4	0.6
	Standard Dev.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.1
Metavolcanic Mountain A		0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Metavolcanic Mountain B		43.6	48.5	0.0	0.0	0.0	0.0	0.0	0.0	7.9	0.0
Metavolcanic Mountain C		17.5	82.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Average	20.4	77.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6	0.0
	Standard Dev.	21.9	26.2	0.0	0.0	0.0	0.0	0.0	0.0	4.6	0.0
Mims Spur A		0.0	44.1	0.0	28.8	23.7	0.0	3.4	0.0	0.0	0.0
Mims Spur B		2.7	35.6	5.5	27.4	24.7	0.0	4.1	0.0	0.0	0.0
Mims Spur C		12.0	63.9	0.0	12.0	7.4	0.0	2.8	0.0	1.9	0.0
	Average	4.9	47.9	1.8	22.7	18.6	0.0	3.4	0.0	0.6	0.0
	Standard Dev.	6.3	14.5	3.2	9.3	9.7	0.0	0.7	0.0	1.1	0.0
Quonset Glacier A		36.7	54.4	0.0	0.0	0.0	7.6	1.3	0.0	0.0	0.0
Quonset Glacier B		65.5	26.4	0.0	0.0	0.0	1.8	4.5	0.0	1.8	0.0
Quonset Glacier C		30.6	44.7	0.0	0.0	0.0	8.2	14.1	0.0	2.4	0.0
	Average	44.3	41.8	0.0	0.0	0.0	5.9	6.6	0.0	1.4	0.0
	Standard Dev.	18.6	14.3	0.0	0.0	0.0	3.5	6.7	0.0	1.2	0.0

Table 4: Percentage data from point counts made on each thin section.

Location	Depth (cm)	Sample ID	Counted by		qtz	pyrox	kspar	plag	biot	chlor	opq	other/ unk.	poly	silt/s.s.	mudst	extr	maf	int	fel	meta	n =
West Antarctic Samples																					
Whillans Ice Stream	10-20	SAL 1755	KLK		11.9	0.0	0.0	3.1	0.0	0.0	0.3	0.0	68.3	0.0	0.0	0.0	0.0	0.0	7.8	8.6	360
89-1-4	30-40	SAL 1754	KLK		13.4	0.0	0.0	2.5	0.0	0.0	0.0	0.0	72.8	0.0	0.0	0.0	0.0	0.0	3.3	8.0	276
	40-50	SAL 1753	KLK		12.3	0.0	0.0	3.0	0.0	0.0	0.3	0.0	72.0	0.0	0.0	0.0	0.0	0.0	7.3	5.3	400
	80-90	SAL 1752	KLK		11.5	0.0	0.0	1.6	0.0	0.0	0.3	0.0	65.9	0.0	0.0	0.0	0.0	0.0	4.9	15.7	364
	110-120	SAL 1751	KLK		13.1	0.0	0.0	1.4	0.2	0.0	0.0	0.0	76.0	0.0	0.0	0.0	0.0	0.0	4.5	4.8	420
	130-140	SAL 1750	KLK		8.4	0.0	0.0	1.7	0.3	0.0	0.6	0.0	79.2	0.0	0.0	0.0	0.0	0.0	3.5	6.4	346
	140-150	SAL 1747	KLK		12.4	0.0	0.0	1.7	0.6	0.0	0.0	0.0	72.1	0.0	0.0	0.0	0.0	0.0	3.4	9.8	348
	150-160	SAL 1745	KLK		11.2	0.0	0.0	2.0	0.0	0.0	0.0	0.0	74.8	0.0	0.0	0.0	0.3	0.0	3.9	7.8	357
	160-170	SAL 1744	KLK		15.5	0.0	0.0	1.0	0.0	0.0	0.0	0.0	73.4	0.0	0.0	0.0	0.0	0.0	2.8	7.2	387
	180-190	SAL 1743	KLK		12.0	0.0	0.0	1.1	0.0	0.0	0.4	0.0	81.3	0.0	0.0	0.0	0.0	0.0	2.2	3.0	267
				Average	12.2	0.0	0.0	1.9	0.1	0.0	0.2	0.0	73.6	0.0	0.0	0.0	0.0	0.0	4.4	7.6	
				STNDEV	1.8	0.0	0.0	0.7	0.2	0.0	0.2	0.0	4.6	0.0	0.0	0.0	0.1	0.0	1.8	3.5	
Kamb Ice Stream	30-40	SAL 1774	KLK		26.8	0.0	3.8	0.6	0.0	0.0	0.0	0.0	27.9	0.0	0.0	0.0	0.0	0.5	18.2	22.2	308
96-3-1	40-50	SAL 1773	KLK		30.3	0.0	5.1	2.4	2.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	2.7	23.1	34.0	294
	140-150	SAL 1772	KLK		29.2	0.0	4.8	1.3	2.2	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	2.6	28.2	30.1	312
	180-190	SAL 1771	KLK		30.0	0.0	4.0	2.2	2.2	0.0	0.0	0.0	1.4	0.0	0.0	0.1	0.0	4.0	25.6	30.7	277
				Average	29.0	0.0	4.4	1.6	1.6	0.0	0.0	0.0	7.8	0.0	0.0	0.0	0.0	2.4	23.8	29.3	
				STNDEV	1.6	0.0	0.6	0.8	1.1	0.0	0.0	0.0	13.5	0.0	0.0	0.1	0.0	1.4	4.2	5.0	
Reedy Glacier Samples																					
Quartz Hills		SAL 1628	KLK		19.1	0.0	6.4	19.9	2.8	0.8	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	48.6	1.2	251
Quartz Hills		SAL 1629	KLK		11.9	0.0	10.3	18.4	2.2	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	55.7	1.1	185
Quartz Hills		SAL 1630	KLK		25.3	0.0	20.9	23.2	4.7	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.0	0.3	383
Quartz Hills		SAL 1631	KLK		21.7	0.0	24.5	11.1	2.9	1.3	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	37.3	0.3	314
				Average	19.5	0.0	15.5	18.2	3.1	1.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	41.4	0.7	
				STNDEV	5.7	0.0	8.6	5.1	1.1	0.4	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	13.8	0.5	
Caloplaca Hills		SAL 1632	KLK		15.2	0.0	8.7	12.2	10.4	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	49.1	3.0	230
Metavolcanic Mountain A		SAL 1643	KLK		9.1	0.0	7.5	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8	73.6	6.7	254
Metavolcanic Mountain B		SAL 1644	KLK		7.4	0.0	13.3	0.0	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	63.3	13.3	392
Metavolcanic Mountain C		SAL 1645	KLK		5.6	0.0	10.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	75.7	8.0	288
				Average	7.3	0.0	10.3	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	70.9	9.3	
				STNDEV	1.8	0.0	2.9	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	6.7	3.5	
Mims Spur A		SAL 1646	KLK		13.4	0.0	6.9	4.9	15.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8	29.7	27.6	246
Mims Spur B		SAL 1647	KLK		9.3	0.0	5.7	4.8	15.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	40.1	23.8	227
Mims Spur C		SAL 1648	KLK		14.7	0.0	6.1	3.5	5.6	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	47.2	20.8	231
				Average	12.5	0.0	6.2	4.4	12.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	39.0	24.1	
				STNDEV	2.9	0.0	0.6	0.8	5.5	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	8.8	3.4	
Strickland Nunatak A		SAL 1658	KLK		8.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	91.6	334
Strickland Nunatak B		SAL 1659	KLK		11.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	88.7	284
Strickland Nunatak C		SAL 1660	KLK		13.6	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	86.1	287
				Average	11.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	88.8	
				STNDEV	2.6	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8	
Quonset Glacier A		SAL 1684	KLK		29.8	0.0	9.1	17.4	6.1	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8	34.4	0.0	363
Quonset Glacier B		SAL 1685	KLK		29.0	0.0	4.6	21.3	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.9	37.6	0.0	348
Quonset Glacier C		SAL 1686	KLK		29.6	0.0	6.6	19.8	4.9	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	36.5	0.0	348
				Average	29.5	0.0	6.8	19.5	4.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.1	36.2	0.0	
				STNDEV	0.4	0.0	2.3	2.0	1.8	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	1.6	0.0	
RISP Samples																					
RISP 78-8	42 - 44	SAL 219	KLK		45.9	0.0	0.0	0.5	0.0	0.0	0.0	0.0	6.5	0.5	13.7	8.2	0.5	0.0	19.1	1.1	183
RISP 78-14	82 - 84	SAL 223	KLK		52.6	0.0	0.4	0.7	0.0	0.0	0.0	0.0	7.5	0.3	11.2	1.7	0.0	0.0	17.3	1.8	146
RISP 78-44	99-101	SAL 222	KLK		57.9	0.0	0.7	1.4	0.0	0.0	0.0	0.0	1.4	0.0	10.7	1.4	0.0	0.0	13.6	2.9	140
				Average	52.1	0.0	0.4	0.9	0.0	0.0	0.0	0.0	5.1	0.3	11.9	3.8	0.2	0.0	16.7	1.9	
				STNDEV	6.0	0.0	0.4	0.5	0.0	0.0	0.0	0.0	3.3	0.3	1.6	3.8	0.3	0.0	2.8	0.9	

Table 4 continued: Percentage data from point counts made on each thin section.

Location	Depth (cm)	Sample ID	Counted by		qtz	pyrox	kspar	plag	biot	chlor	opq	other/ unk.	poly	silt/s.s.	mudst	extr	maf	int	fel	meta	n =
Central Ross Sea Samples																					
NBP94-07-39	100-102	SAL 282	EFP		2.8	0.0	0.7	0.7	0.0	0.0	1.4	0.7	92.3	0.7	0.0	0.0	0.0	0.0	0.0	0.7	142
NBP95-01-11	48-50	SAL 537	EFP		17.3	1.3	7.2	6.5	0.0	0.0	1.3	1.0	30.1	3.6	1.0	0.3	0.3	10.1	7.8	12.1	405
NBP95-01-11	100-120	SAL 538	EFP		18.6	0.2	4.7	12.1	0.0	0.0	0.4	0.9	32.2	2.0	0.7	1.6	0.7	6.7	11.2	8.0	374
NBP95-01-17	48-50	SAL 540	EFP		25.0	0.8	3.3	4.9	0.0	0.0	0.8	0.3	23.4	1.1	1.4	0.5	0.0	4.9	19.0	13.1	375
NBP95-01-17	100-102	SAL 543	EFP		14.7	0.0	6.4	4.4	0.7	0.0	0.7	0.5	30.1	2.7	0.5	0.5	0.5	6.1	17.6	13.7	324
NBP95-01-17	153-155	SAL 534	EFP		20.7	0.3	5.2	5.8	0.3	0.0	0.3	0.3	22.4	5.5	0.3	0.0	1.2	5.0	20.7	11.1	320
ELT32-21	54-58	SAL 1640	EFP		15.2	0.1	4.8	5.4	0.0	0.0	0.3	0.6	33.0	6.1	1.2	0.3	1.7	4.3	9.5	17	1090
ELT32-21	104-108	SAL 1641	EFP		14.2	0.1	3.3	2.6	0.0	0.0	0.0	0.0	50.7	3.7	2.2	0.4	2.2	2.5	5.6	12	957
ELT32-21	154-160	SAL 1642	EFP		2.1	0.0	1.1	0.6	0.0	0.0	0.2	0.2	87.4	1.3	0.2	0.0	0.2	0.6	1.6	5	1238
				Average	14.5	0.3	4.1	4.8	0.1	0.0	0.6	0.5	44.6	3.0	0.8	0.4	0.8	4.5	10.3	10.2	
				STNDEV	7.6	0.5	2.2	3.5	0.3	0.0	0.5	0.3	26.9	1.9	0.7	0.5	0.8	3.1	7.5	5.0	
Western Ross Sea Samples																					
NBP94-01-02	50-52	SAL 372	EFP		13.5	0.3	8.3	4.0	0.0	0.0	2.0	1.3	37.3	1.0	0.7	10.0	1.7	4.0	5.6	10.2	303
NBP94-01-02	111-116	SAL 1633	EFP		1.7	0.2	0.6	0.1	0.0	0.0	0.3	0.0	90.9	0.8	0.2	1.2	0.9	0.7	0.9	1.6	903
NBP94-01-02	150-152	SAL 374	EFP		19.2	0.0	5.3	7.3	0.7	0.0	5.3	1.3	9.3	2.0	2.6	11.3	9.3	4.6	7.9	13.6	151
ELT32-13	49-51	SAL 406	EFP		42.0	1.0	16.0	17.0	1.0	0.0	9.0	1.0	83.0	18.0	3.0	76.0	8.0	16.0	46.0	24.0	268
ELT32-13	100-102	SAL 407	EFP		46.0	0.0	9.0	24.0	1.0	0.0	10.0	1.3	47.0	6.0	1.0	23.0	4.0	3.0	26.0	17.0	212
ELT32-13	149-151	SAL 408	EFP		21.0	0.0	6.0	9.0	0.0	0.0	3.0	0.0	15.0	7.0	1.0	21.0	4.0	8.0	17.0	13.0	121
ELT32-20	64-69	SAL 1638	EFP		5.8	0.4	2.4	2.4	0.0	0.0	0.0	0.2	61.0	1.8	0.6	0.2	7.2	3.6	5.2	8.9	497
ELT32-20	132-134	SAL 1639	EFP		0.0	0.0	0.6	0.3	0.0	0.0	0.1	0.1	96.7	0.3	0.0	0.2	0.5	0.5	0.3	0.4	1188
ELT27-14	47-50	SAL 1634	EFP		9.4	0.6	3.1	2.0	0.0	0.0	0.0	0.6	65.3	1.1	0.3	0.3	2.0	2.8	3.7	8.5	352
ELT27-14	63-66	SAL 1635	EFP		10.3	0.2	1.4	4.2	0.0	0.0	0.3	0.0	65.5	0.3	0.5	1.6	3.1	1.6	2.6	8.2	621
ELT27-14	105-109	SAL 1636	EFP		18.9	0.6	1.7	0.9	0.0	0.0	0.3	0.3	55.9	1.7	1.4	0.0	4.9	0.0	5.4	8.0	349
ELT27-14	164-170	SAL 1637	EFP		9.9	0.0	3.3	1.7	0.0	0.0	0.3	0.2	67.1	0.3	0.2	0.7	2.1	1.2	5.3	7.7	605
				Average	16.5	0.3	4.8	6.1	0.2	0.0	2.6	0.5	57.8	3.4	1.0	12.1	4.0	3.8	10.5	10.1	
				STNDEV	14.5	0.3	4.5	7.4	0.4	0.0	3.6	0.5	27.3	5.1	1.0	21.8	2.9	4.4	13.3	6.4	
Eastern Ross Sea Samples																					
NBP9407-63	112-114	SAL 142	JRL		75.3	0.0	1.3	3.9	0.4	0.0	0.9	3.0	0.0	0.0	0.9	2.6	0.0	0.0	7.4	0.0	231
NBP9902-04	10-12	SAL 138	JRL		69.0	0.0	1.2	1.2	0.0	0.0	0.6	5.4	0.0	0.0	3.0	3.7	0.0	0.6	10.4	0.0	164
NBP9902-04	97-99	SAL 169	JRL		64.1	0.5	2.0	1.5	0.0	0.0	1.5	3.5	0.0	0.0	4.6	1.5	0.0	0.0	9.7	2.0	195
NBP9902-05	105-107	SAL 177	JRL		78.8	0.0	5.6	7.1	0.6	0.0	0.6	0.0	0.0	0.3	0.6	0.0	0.0	0.0	6.2	0.3	354
NBP9902-08	103-105	SAL 178	JRL		65.6	0.0	1.6	3.6	0.0	0.0	0.3	1.0	0.0	1.0	3.3	0.7	0.0	0.0	16.0	3.9	305
NBP9902-17	104-106	SAL 141	JRL		76.0	0.0	0.5	0.0	0.0	0.0	0.5	0.5	0.0	2.0	6.6	0.0	0.0	0.0	6.1	1.5	196
				Average	71.5	0.1	2.0	2.9	0.2	0.0	0.7	2.2	0.0	0.6	3.2	1.4	0.0	0.1	9.3	1.3	
				STNDEV	6.1	0.2	1.8	2.5	0.3	0.0	0.4	2.1	0.0	0.8	2.3	1.5	0.0	0.2	3.7	1.5	

Note: Point count data for the 500 - 2000 micron sand-fraction of each West Antarctic, East Antarctic, RISP, and Ross Sea sample analyzed. Mineral and lithic fragment percentages have been rounded to the nearest tenth of a percent, therefore the percentages do not always sum to exactly 100 % for each sample. SAL numbers correspond to sample numbers assigned in the IUPUI Sediment Analysis Laboratory. In order to demostrate reproducibity and calculate error, several samples have been counted multiple times. Where this is the case, the average petrographic composition of till from an entire area (i.e. West Antarctica) has been calculated using the average values from the sample replicates. Note qtz=quartz, pyrox=pyroxene, k-spar=potassium feldspar, plag=palgioclase, biot=biotite, chlor=chlorite, opq=opaques, unk=unknown, silt=siltstone, s.s.=sandstone, mud st=mud stone, clay=st=claystone, extr=extrusive volcanic, maf=mafic intrusive, int=intermediate intrusive, fel=felsic intrusive, and meta=metamorphic, n=number of point counts for the thin section. KLK=Kate Kramer, EFP=Emerson Palmer, and JRL=Jason Lederer.

Table 5: Particle Size Data from Reedy Glacier Samples.

Sample Number	**1628**	**1629**	**1630**	**1631**	**1632**	**1643**	**1644**	**1645**	**1646**	**1647**	**1648**	**1658**	**1659**	**1660**	**1684**	**1685**	**1686**
Location	QH	QH	QH	QH	CH	MM-A	MM-B	MM-C	MS-A	MS-B	MS-C	SN-A	SN-B	SN-C	QG-A	QG-B	QG-C
v. fine	12.6	10.7	12.6	8.1	15.8	0.1	0.2	2.0	3.7	5.6	7.1	2.9	4.8	2.5	6.6	6.1	5.0
fine	22.4	15.2	21.7	15.9	23.0	0.0	1.8	7.8	8.2	6.9	12.7	5.5	7.6	2.8	14.2	11.8	9.9
medium	27.6	15.6	22.9	20.4	21.6	1.8	12.4	17.0	10.2	14.1	17.5	9.7	13.4	6.0	18.8	19.5	20.6
coarse	17.1	12.1	11.5	13.5	7.2	9.9	20.7	17.2	9.2	18.1	14.3	10.1	16.5	12.2	14.0	17.0	24.2
v. coarse	4.6	34.7	21.5	34.1	0.0	87.3	63.8	52.3	66.7	43.8	38.5	58.1	36.7	67.7	40.5	31.2	34.8
Total % Sand	**84.4**	**88.3**	**90.4**	**92.0**	**67.6**	**99.1**	**98.9**	**96.3**	**98.0**	**88.6**	**90.1**	**86.2**	**79.0**	**91.3**	**94.1**	**85.5**	**94.6**
v. fine	1.6	1.2	0.6	0.9	4.6	0.2	0.2	0.8	0.2	1.3	1.3	2.0	3.5	1.4	0.7	2.0	0.6
fine	2.6	1.8	1.3	1.2	6.0	0.2	0.2	0.5	0.3	1.8	1.6	2.2	4.1	1.8	0.9	2.5	0.9
medium	3.8	2.7	2.4	1.6	7.0	0.2	0.1	0.3	0.5	2.7	1.9	2.0	3.1	1.6	1.2	2.9	1.4
coarse	6.3	5.0	4.9	3.0	9.1	0.1	0.1	0.5	1.0	4.0	3.0	1.8	2.7	1.7	2.2	3.6	2.4
Total % Silt	**14.2**	**10.6**	**9.3**	**6.7**	**26.8**	**0.6**	**0.7**	**2.2**	**1.9**	**9.8**	**7.8**	**7.9**	**13.4**	**6.5**	**5.0**	**11.0**	**5.3**
fine	0.0	0.0	0.0	0.1	0.5	0.0	0.0	0.1	0.0	0.1	0.2	0.9	0.9	0.2	0.0	0.4	0.0
medium	0.5	0.4	0.0	0.5	2.2	0.1	0.2	0.5	0.0	0.6	0.9	2.5	3.2	1.0	0.4	1.6	0.4
coarse	0.9	0.7	0.4	0.7	3.0	0.1	0.3	0.8	0.1	0.9	1.1	2.4	3.5	1.1	0.5	1.5	0.4
Total % Clay	**1.4**	**1.2**	**0.4**	**1.3**	**5.7**	**0.2**	**0.4**	**1.4**	**0.1**	**1.7**	**2.1**	**5.9**	**7.6**	**2.3**	**0.9**	**3.5**	**0.9**

Particle size data is averaged over 3-4 replicates. Data is normalized to include the 1-2mm fraction.

Table 6: Particle Size Data from West Antarctic Samples.

Sample Number	1755	1754	1753	1752	1751	1750	1749	1748	1747	1746	1745	1744	1743	1767	1766	1765
Location	WIS 1	WIS 1	WIS 1	WIS 1	WIS 1	WIS 1	WIS 1	WIS 1	WIS 1	WIS 1	WIS 1	WIS 1	WIS 1	KIS 2	KIS 2	KIS 2
Depth (cm)	15	35	45	85	115	135	138	140	145	150	155	165	185	35	115	145
v. fine	7.9	4.9	5.5	6.3	6.2	7.6	8.6	7.1	7.6	6.4	10.3	7.8	3.6	9.4	6.1	8.4
fine	6.8	6.8	4.3	5.2	4.2	7.6	7.4	7.4	5.8	6.2	10.9	4.5	4.3	11.4	7.4	8.8
medium	4.9	8.9	5.1	8.7	4.6	8.9	6.9	8.7	4.5	7.9	10.9	2.4	6.3	13.0	8.5	9.7
coarse	5.4	32.2	21.0	29.3	23.3	16.9	7.3	11.4	5.8	9.1	11.3	6.0	37.1	11.1	8.5	15.5
Total % Sand	25.1	52.8	35.9	49.6	38.3	41.0	30.2	34.6	23.7	29.5	43.4	20.7	51.3	44.8	30.5	42.4
Total % Silt	35.9	25.7	34.1	27.6	32.7	34.4	35.0	35.4	40.6	35.7	41.3	41.6	23.5	35.2	40.3	36.6
Total % Clay	39.1	21.5	30.0	22.8	29.0	24.6	34.9	30.0	35.7	34.8	15.3	37.7	25.2	19.9	29.2	21.0

Sample Number	1769	1768	1774	1773	1772	1771	1780	1779	1778	1777	1776	1775	1783	1782	1781
Location	KIS 4	KIS 4	KIS 1	KIS 1	KIS 1	KIS 1	BIS 1	BIS 1	BIS 1	BIS 1	BIS 1	BIS 1	WIS 4	WIS 4	WIS 4
Depth (cm)	45	145	35	45	145	185	15	20	35	45	115	185	35	115	185
v. fine	5.3	6.8	3.4	12.3	5.5	8.6	7.8	5.3	4.2	2.4	2.1	4.5	9.5	6.5	7.4
fine	3.7	7.3	2.2	19.7	6.1	12.1	7.0	3.0	1.9	1.2	1.6	3.9	7.4	5.8	5.7
medium	2.3	7.0	3.1	23.0	11.1	18.3	7.3	3.8	2.9	3.5	3.1	4.0	5.4	5.7	4.7
coarse	9.2	9.3	10.7	28.2	55.6	44.7	12.8	14.1	9.8	15.4	15.5	13.6	9.9	9.9	6.0
Total % Sand	20.5	30.4	19.5	83.1	78.4	83.8	34.9	26.2	18.8	22.5	22.3	26.0	32.1	27.9	23.8
Total % Silt	40.4	36.7	53.0	14.4	17.0	13.2	38.5	40.4	46.1	41.8	42.3	41.4	36.3	36.9	39.3
Total % Clay	39.1	32.8	27.5	2.6	4.6	3.1	26.6	33.4	35.1	35.7	35.4	32.5	31.6	35.2	36.9

Particle size data is averaged over 3-4 replicates. Data is normalized to include the 1-2mm fraction.

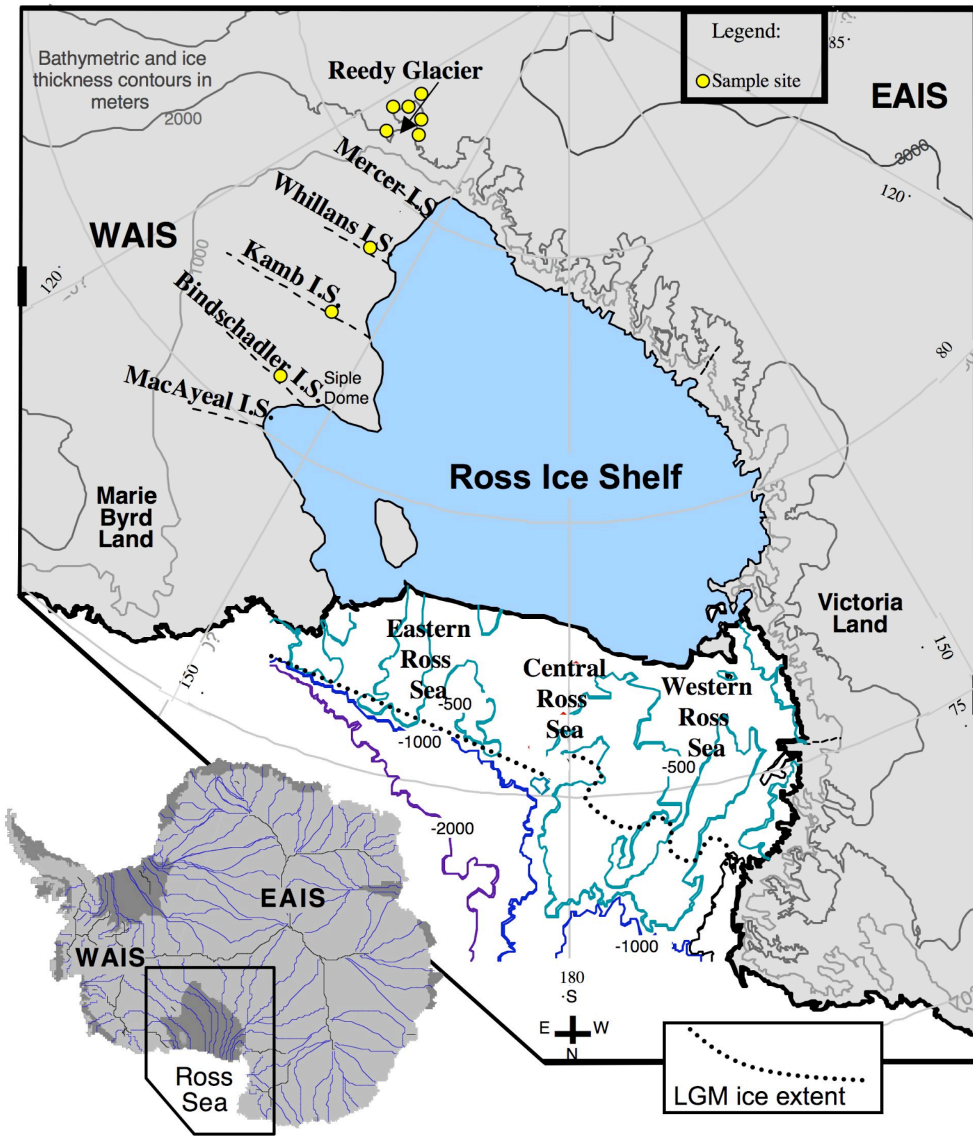


Figure 1: (A) Antarctic map showing modern ice flow paths. EAIS= East Antarctic Ice Sheet, WAIS= West Antarctic Ice Sheet.
(B) Topography and bathymetry of the Ross Embayment (contours in m). Yellow dots show sample locations described in this study (I.S. = Ice Stream).

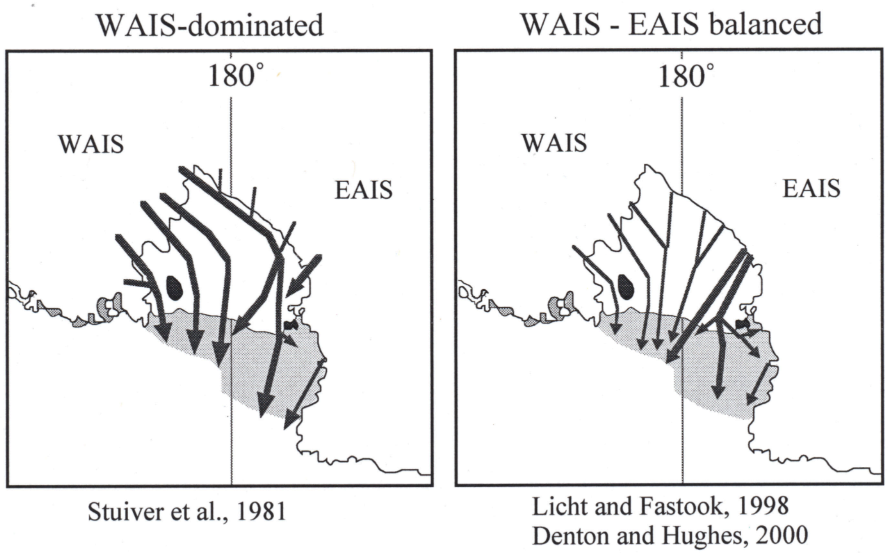


Figure 2: Diagram of ice flow hypotheses during the LGM (Licht et al., 2005).

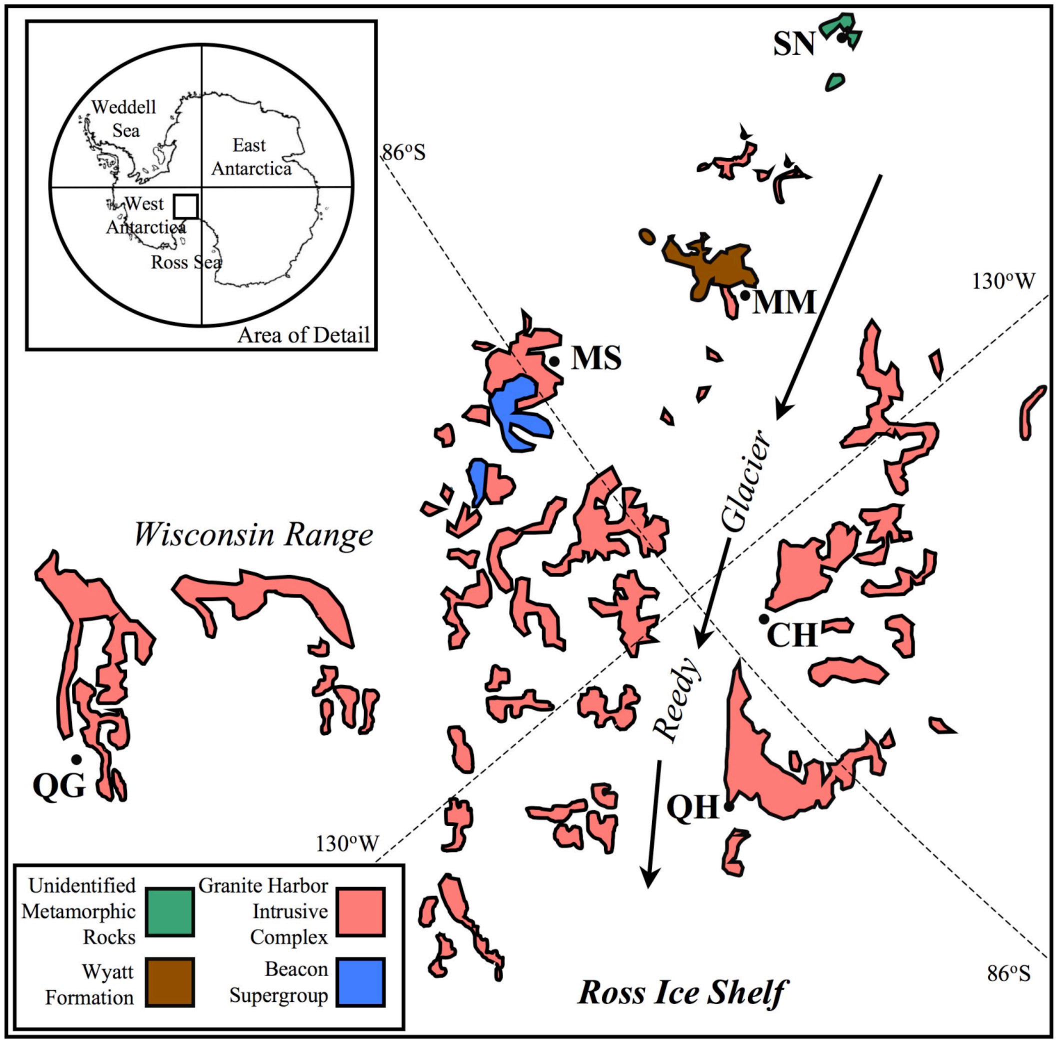


Figure 3: Geologic Map of exposed bedrock Reedy Glacier with sample locations marked (modified from Davis and Blankenship, 2006).

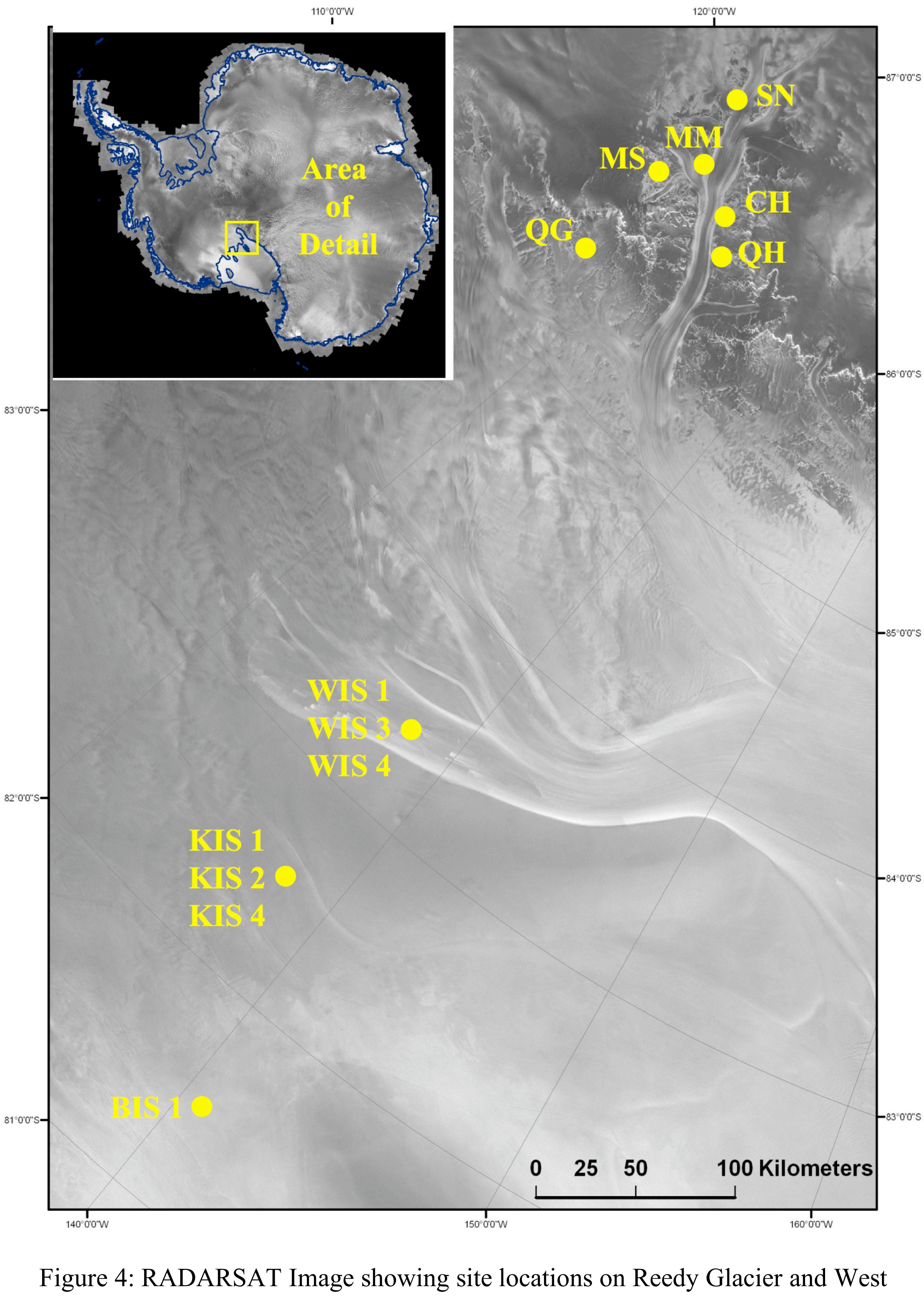


Figure 4: RADARSAT Image showing site locations on Reedy Glacier and West Antarctic Ice Streams. Refer to Table 1 for abbreviations.

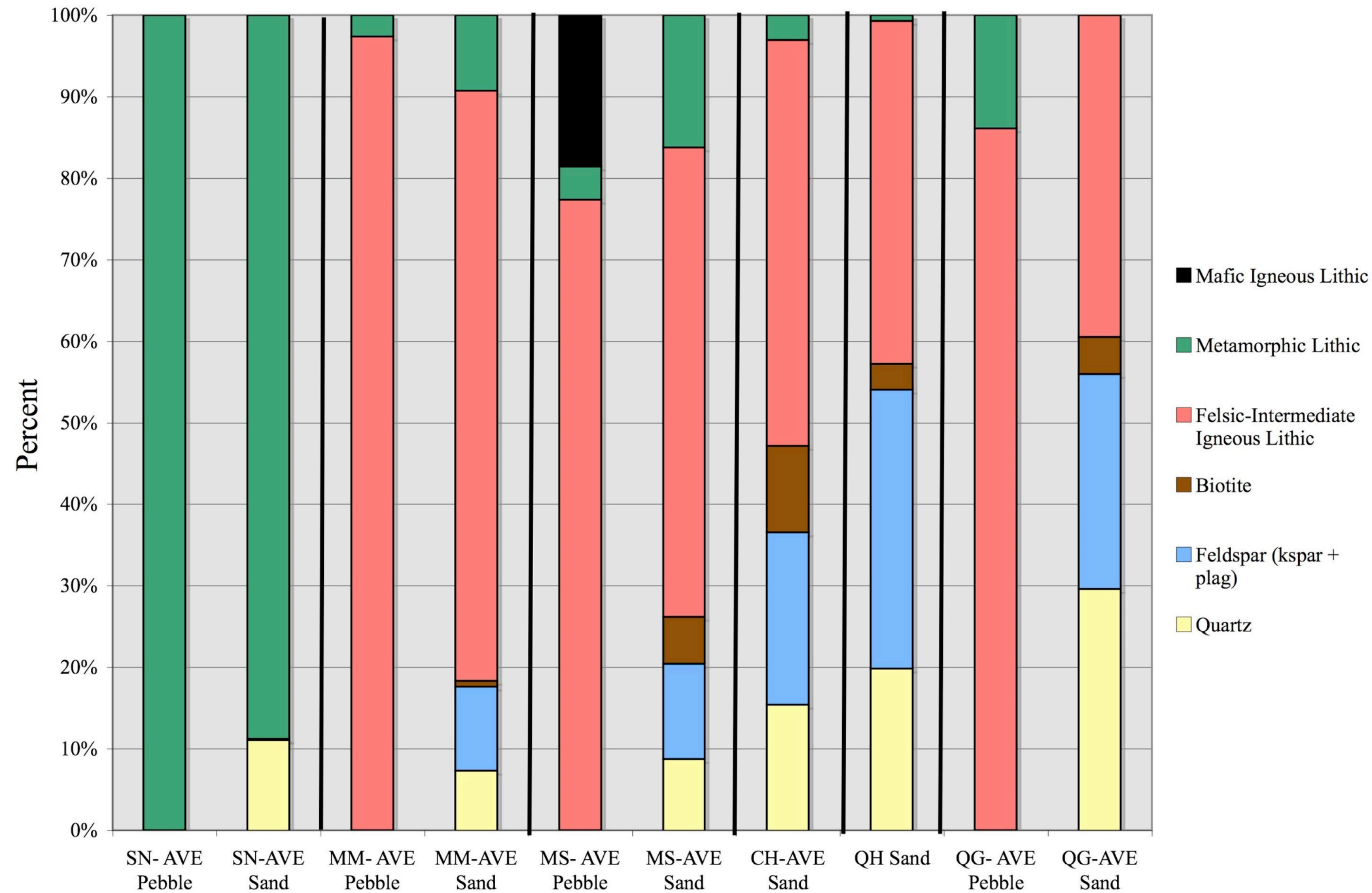


Figure 5: Pebble and sand fraction data from Reedy Glacier sites (average of all 3 subsites, with the exception of CH, which has 4 subsites,and QH, which has one sample).

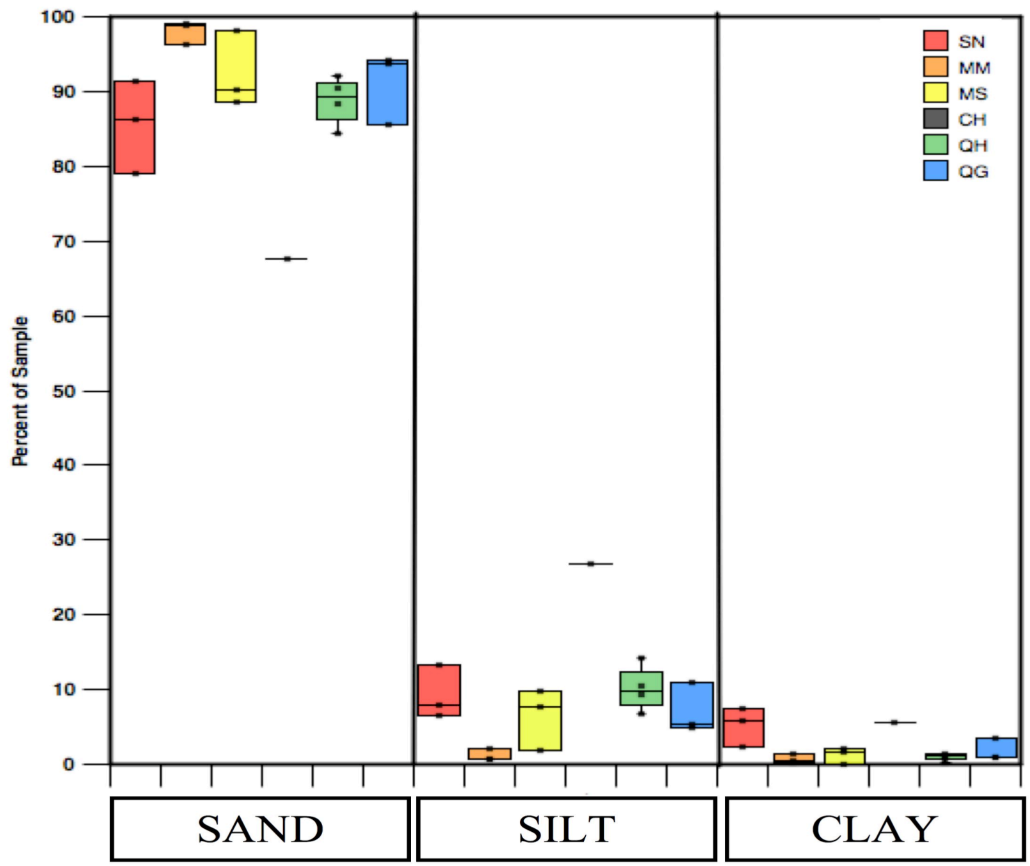


Figure 6: Box and whisker plot of Reedy Glacier particle size data by site location. See Table 1 for site abbreviations. Box encloses 95% of data.

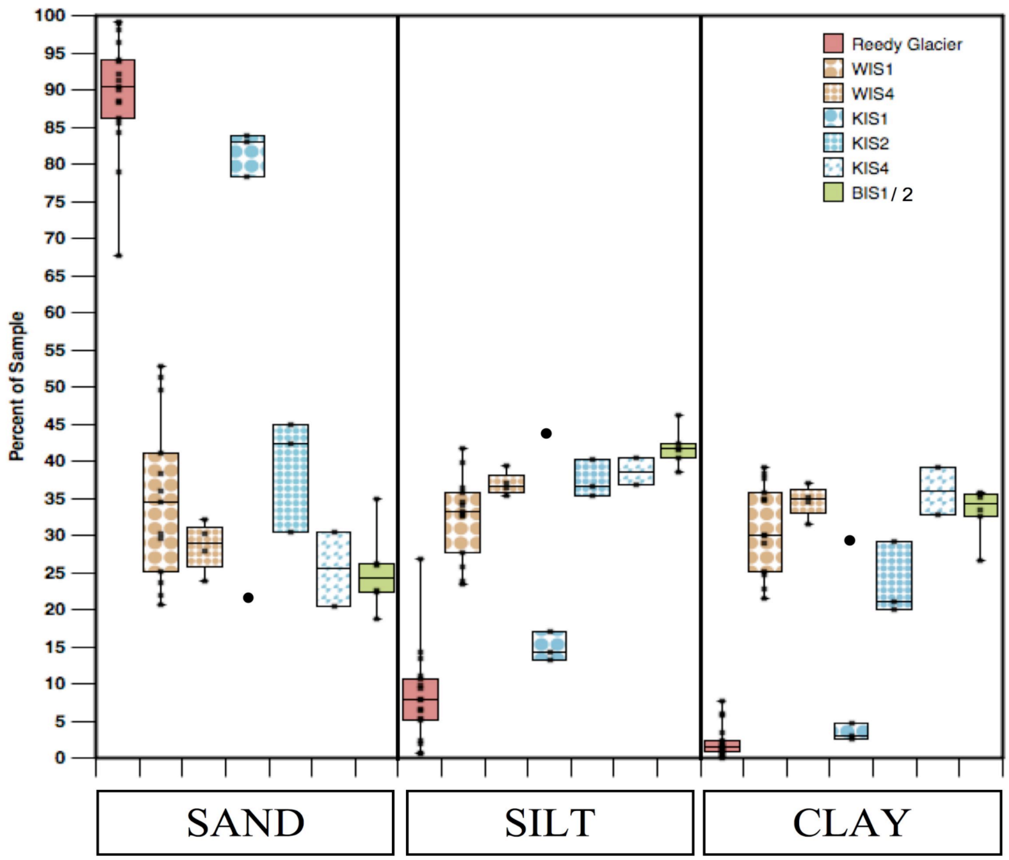


Figure 7: Box and whisker plots of all particle size data. See Table 1 for site abbreviations. Box encloses 95% of data.

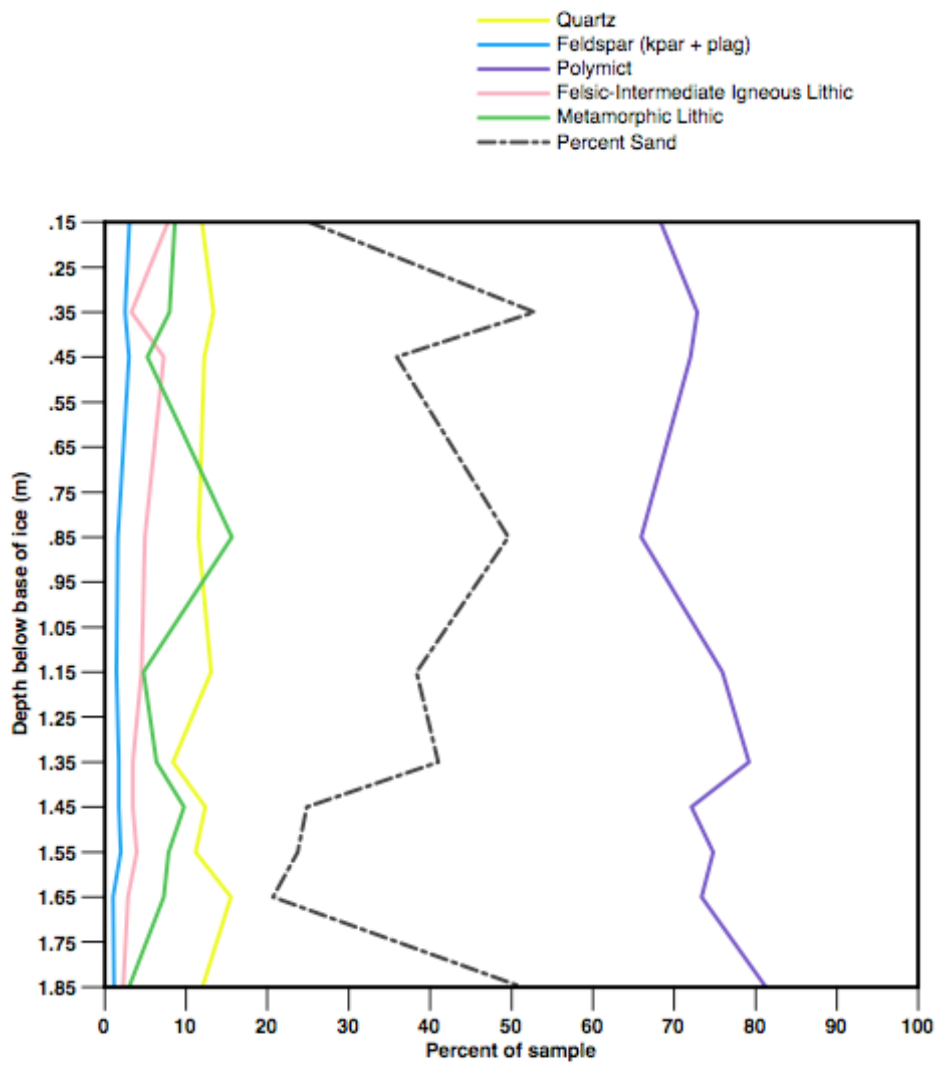


Figure 8: Petrography versus depth comparison of WIS 1 samples.

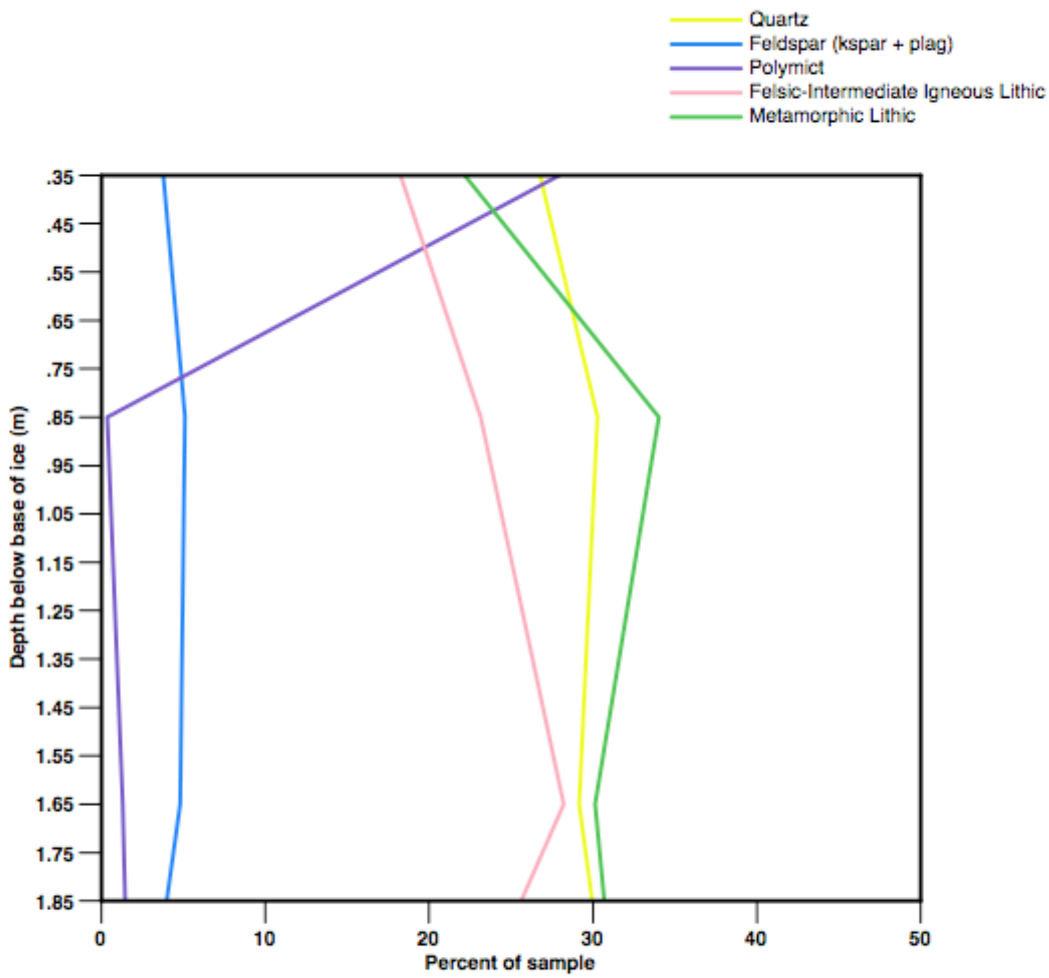


Figure 9: Petrography verses depth comparison of KIS 1 samples.

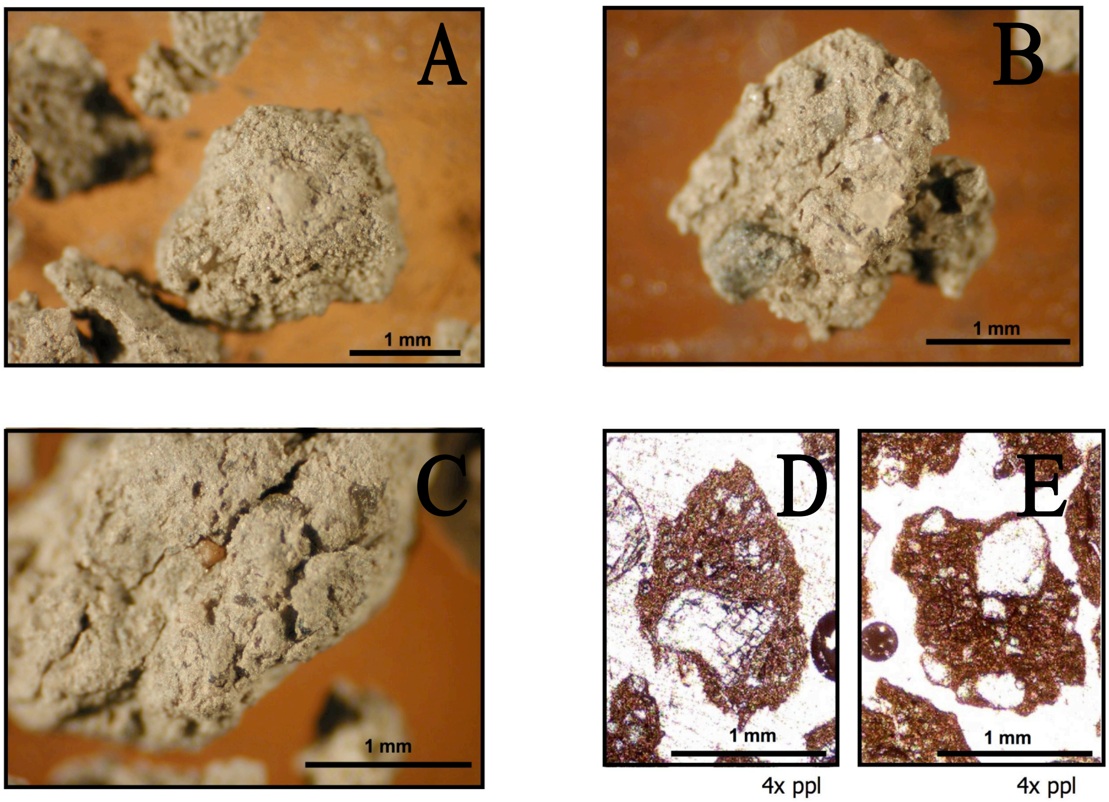


Figure 10: Polymict grain photographs. A = SAL 1745 (WIS 1), B = SAL 1752 (WIS 1), C = SAL 1774 (KIS 1), D = SAL 1749 (WIS 1), and E = SAL 1755 (WIS 1).

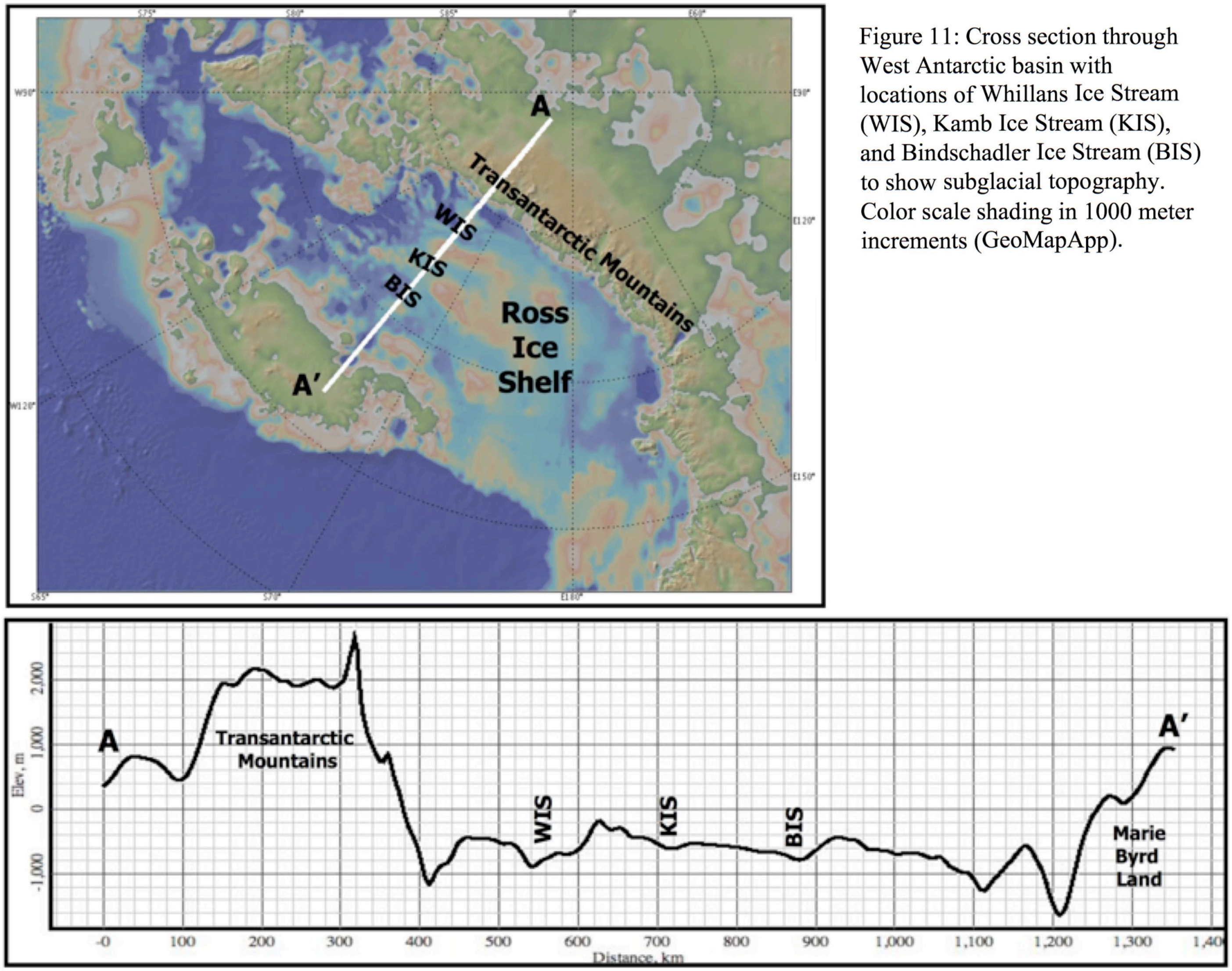


Figure 11: Cross section through West Antarctic basin with locations of Whillans Ice Stream (WIS), Kamb Ice Stream (KIS), and Bindschadler Ice Stream (BIS) to show subglacial topography. Color scale shading in 1000 meter increments (GeoMapApp).

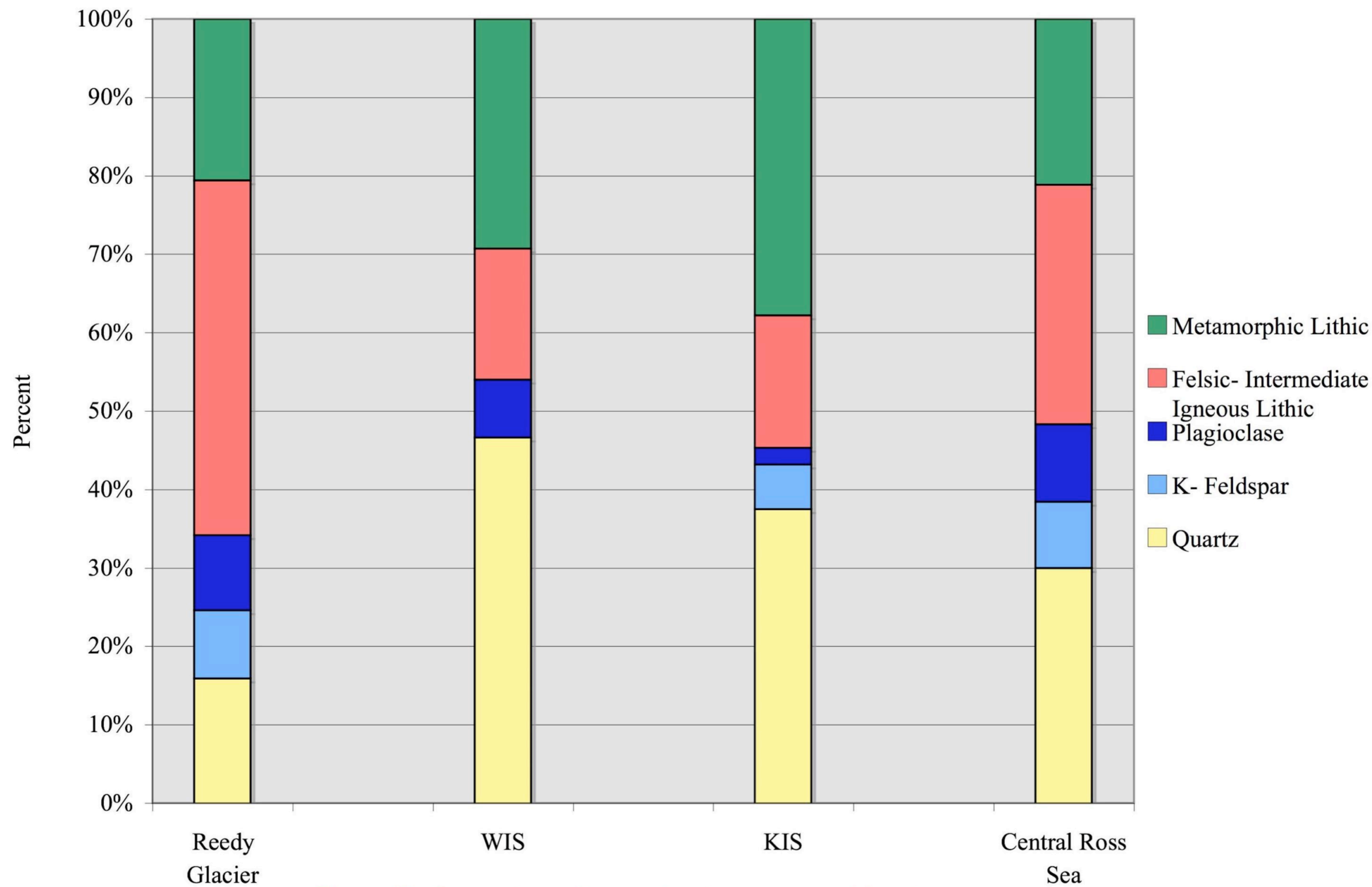


Figure 12: Comparison of non-polymict coarse sand fraction.
Average of entire data set, normalized without polymict.
WIS = Whillans Ice Stream, KIS = Kamb Ice Stream.

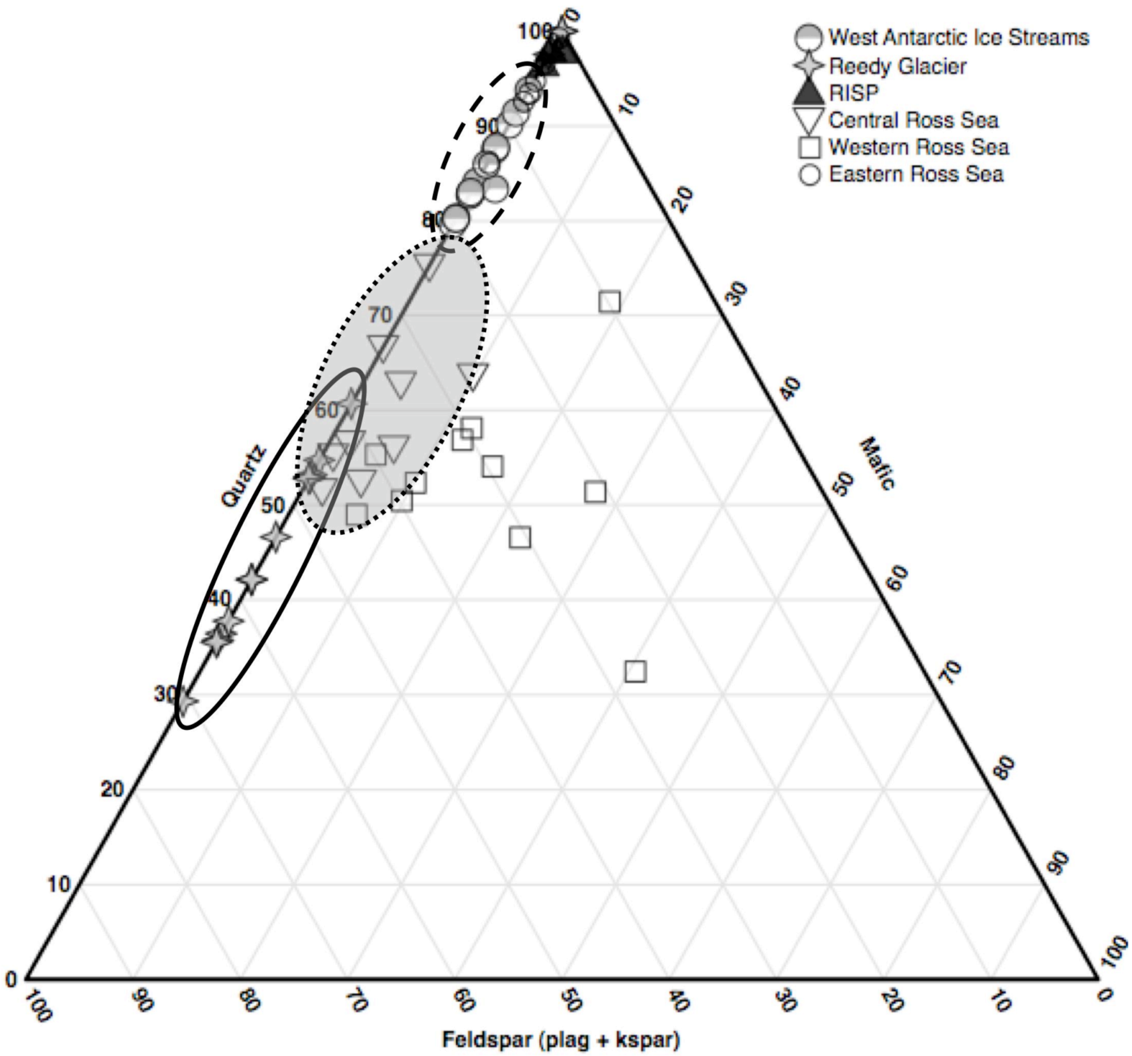
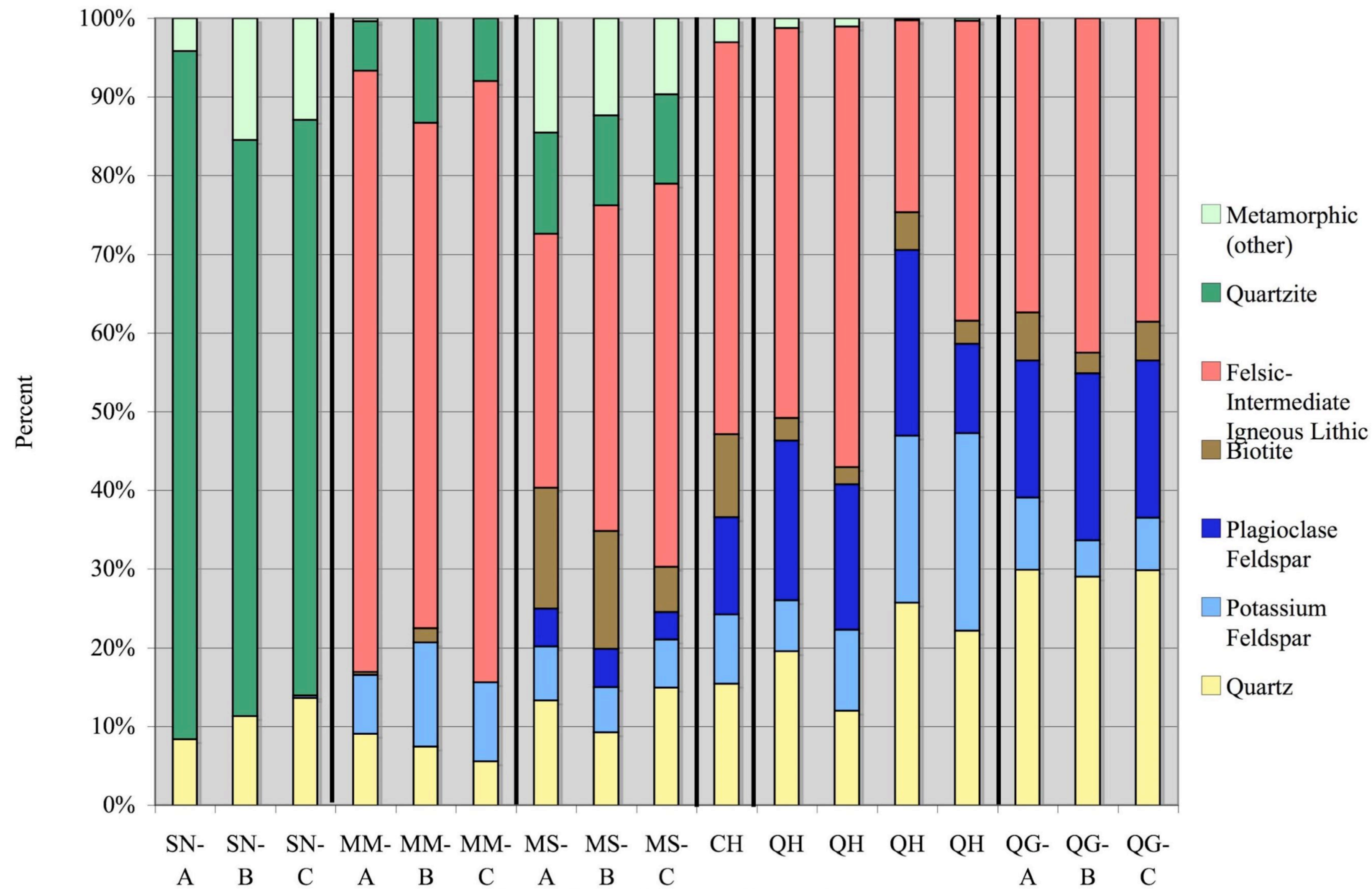


Figure 13: Quartz Feldspar Mafic Igneous Fragment (QFM) Ternary plots for the 500-2000 μm sand fraction of all till samples analyzed in this study. The shaded area highlights positions of Central Ross Sea samples, the dashed circle highlights positions of West Antarctic Ice Stream samples, and the solid circle highlights Reedy Glacier samples.



Appendix A: Point count data for Reedy Glacier subsites.
See Table 1 for site abbreviations.

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CURRICULUM VITAE

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EDUCATION

- **Masters of Science in Geology** - 2008 Indiana University, Indianapolis, IN
- **Bachelors of Science in Geology** - 2006 University of Wisconsin, Oshkosh, WI

AWARDS AND GRANTS

- **IUPUI** School of Science Graduate Student Council Travel Grant (2008)
  Financial assistance provided for travel to American Quaternary Association meeting to present research - $600.00
- **North Central Geologic Society of America** New Harmony Student Award (2008) Award presented for best graduate student oral presentation at annual meeting - $200.00
- **IUPUI** Graduate Student Organization Educational Enhancement Grant (2006)
  Financial assistance provided for travel to Antarctica to collect glacial till samples for thesis research - $500.00

TEACHING EXPIERIENCE

- **Environmental Geology Laboratory, IUPUI** (Fall 2007, Spring 2008): Lectured and administered laboratory exercises covering the basic components of environmental geology to non-geology majors.
- **Physical Geology Laboratory, IUPUI** (Spring 2008): Lectured and administered laboratory exercises covering the basic components of physical geology to both non-geology and geology majors.
- **Assistant Administrator, Camp Invention- Oshkosh, WI** (Summer 2007): Assisted Camp Administrator with daily activities at summer camp for children grades 1-5. Unique camp encourages students to be creative and think like inventors, while educating through scientific discovery.
- **Mineralogy Laboratory Teacher's Assistant, UW-O** (Fall 2004, Fall 2005): Assisted with Mineralogy laboratory preparation, laboratory exercises, and evaluated student's assignments and examinations.

MENTORING EXPIERIENCE

- **Fall 2006 - present** - Assisted Dr. Kathy Licht in the supervision and instruction of students in the IUPUI sediment analysis laboratory where they carried out independent and class-related laboratory work.
- **Fall 2002 - Spring 2006** - Worked with local middle school students introducing them to topics in geology as a member of the UW-O Geology Club- explained multitude of topics, and answered questions about earth science.

FIELD EXPERIENCE

<u>Field Equipment</u>

- **Antarctica**: collected glacial till from lateral moraines of alpine glaciers (January 2007); sampled moraine material from various outlet glaciers within the southern Transantarctic Mountains for ongoing research regarding sediment provenance and sediment transport in Antarctica. Assisted in logistics coordinating for sample locations. Gained experience working in a polar climate.

- **Larsen, WI**: well water sampling and analysis – Larsen, WI (Spring 2006); used water pump and filter to obtain well water samples for Arsenic and nitrate analysis. Samples were acidified in the field.
- **Wasatch Mountains, UT**: geologic field camp – Wasatch Mountains, UT (Summer 2005); advanced geologic mapping course, used Brunton compass to determine strike and dip of strata, measured geologic sections using a Jacobs Staff, and created geologic maps and cross sections based on field notes.

LABORATORY EXPERIENCE

- **Laboratory Equipment**: Coulter LS230 Grain Size Analyzer, Malvern Mastersizer 2000 Laser Particle Size Analyzer with Hydro 2000 MU, Thin section and sample polishing equipment, transmitted and reflected light polarizing microscopes, VirTis bench top freeze drier, Siemens D500 X-ray diffractometer, Graphite Furnace Atomic Absorption Spectrometer, Hach DR/2000 Spectrophotometer.
- **Analysis of Till from Antarctica**: Fall 2006-present - freeze dried 166 till samples - separated the 125-2000 μm from 48 till samples, prepared thin-sections, and preformed *petrographic analysis* on mineral and rock fragments via point counting. Bulk sample analyzed for *particle size* and clay mineral composition.
- **Analysis of well water samples, Larsen, WI**: Spring 2006- compared contaminant levels of arsenic and nitrate to well construction and geologic data. Used GIS to map high contaminant levels on a neighborhood scale. Presented results to Town Board Meeting.

<u>Computer Skills/Software</u>

Microsoft Word, Excel, PowerPoint, Front Page, ArcView, Arc Map, Mastersizer 2000, Photoshop, Illustrator, Sigma Plot. Familiar with Macintosh and PC platforms.

ABSTRACTS

- Licht, K. J., Palmer, E. F., Kramer, K. L., and Swope, R. J., 2008. The Polymict Puzzle: Potential Predictor of Past Ice Streaming? American Quaternary Association Biennial Meeting, University Park, PA.
- Kramer, K. L., Licht, K. J., 2008. A Comparative Study of Reedy Glacier and West Antarctic Ice Streams to Determine Provenance of Central Ross Sea Last Glacial Maximum Till. North-Central GSA 42nd Annual Meeting, Evansville, IN.
- Licht, K. J., Kramer, K. L., 2007. A Provenance Study of Reedy Glacier, Antarctica. Indiana University Department of Geological Sciences Research Days, Bloomington, IN.
- Kramer, K. L., Muldoon, M., 2006. Assessing the Effects of Well Construction and Geology on Groundwater Quality in Larsen, Wisconsin. University of Wisconsin – Oshkosh Celebration of Scholarship, Oshkosh, WI.