A Glacial Geologic History of Tucker Glacier, Antarctica

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ABSTRACT

Antarctica's contribution to sea-level change is a highly debated topic in glacial geology. Ice at the Last Glacial Maximum (LGM) reached out to the continental shelf in the Ross Sea embayment. Since the LGM, ice has retreated south ~1300 km to its present position. Tucker Glacier, which drains from East Antarctica through the Transantarctic Mountains (TAM) into the northwestern Ross Sea, is located just north of the proposed LGM grounding line. This project will use glacial landform mapping and till analysis including: grain size, lithology, roundness and shape to identify past changes in the extent and thickness of Tucker Glacier. In turn the extent and thickness of Tucker Glacier will constrain thickness and grounding line position of the Ross Sea ice sheet during the LGM. Ice at Tucker Glacier reached a minimum of ~244 m a.s.l. in the past. This elevation may indicate LGM ice thickness but without precise dates this project cannot state an exact age of the erratic. Future work will include utilizing cosmogenic isotope analysis to date the deposits discussed in this paper.

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INTRODUCTION

Retreat of ice from the Ross Sea Embayment in Antarctica has contributed to sea-level rise over the last 20,000 years, but the amount and timing of its contribution is not well known (Hall et al., 2013). One approach to characterizing this contribution is to study glacial geologic deposits at outlet glaciers flowing into the Ross Sea. This project uses glacial deposits specifically erratics and till, to identify what the extent and thickness of Tucker Glacier (figure 1) was during the last glacial maximum (LGM) and what this can tell us about timing of retreat. There are two possibilities for the extent and thickness of ice in the Ross Sea during the LGM. Denton and Hughes (2002) use a numerical model to show ice to be about 400 meters above sea-level (m a.s.l.) in the Ross Sea adjacent to Tucker Glacier at the LGM (figure 2). Glacial damming would have caused Tucker Glacier to deposit glacial erratics and moraines at or near 400 m a.s.l. (figure 3).The other possibility is presented by Bentley (1999); using a numerical model he shows that ice adjacent to Tucker Glacier was mostly ice shelf (figure 4). Ice shelf would not have dammed Tucker Glacier to the extent that Denton and Hughes' (2002) reconstruction shows.

The overall project has the potential of determining the rate at which Tucker Glacier thinned and retreated. It will also constrain when the grounding line retreated from its LGM position in the Ross Sea. These will both, in turn, indicate past timing of Antarctic contributions to sea-level rise as well as provide information about future contributions. The work done in this paper will provide data to constrain the volume of LGM ice from Antarctica that has contributed to sea-level and will improve understanding of Antarctic contributions to sea-level rise since the LGM. In doing so it will answer two questions, the first is what was the extent and thickness of

Tucker Glacier during the LGM? The second is what can glacial till tell us about the relative age, transport, and provenance of deposits at the confluence of Tucker and Whitehall Glaciers?

First this paper provides background information about glacial deposition and retreat since the LGM in the Ross Sea. The methods included in this study are broken into three different categories. The first were completed in preparation for entering the field, and included using ArcGIS (Geographic Information Systems) to create base maps for use in the field. Next are the field methods which included collecting elevation, GPS and weathering observations about glacial landforms and deposits which were used to create glacial geologic maps. Also performed in the field was the collection glacial till samples. Back in the lab at Pacific Lutheran University (PLU) the till was dry sieved and clast axis measurements, lithology observations and roundness observations of >30 mm clasts were made. There is extensive weathering of clasts at higher elevations, and less weathering of material closer to the ice margin. These results indicate a minimum ice elevation in the past as well transport methods of material deposited at ice free areas.

BACKGROUND

Glaciers 101

A glacier is a flowing body of ice that is formed on land due to the compaction of snow over many years (Ritter et al., 2006). There are two zones on a glacier, the accumulation zone and the ablation zone. The accumulation zone is generally located at higher elevations and is where mass is gained. The ablation zone is located at lower elevations and is where most of the mass loss occurs (NSDIC, 2015). The equilibrium line altitude (ELA) is the line between the accumulation zone and the ablation zone (Bennett and Glasser, 2009). An ice sheet is a continental-sized glacier that expands more than 50,000 square km (NSIDC, 2015). As an ice sheet flows into the ocean there are two zones that are worth noting. The first is grounded ice, which is where the ice sheet is thick enough that it is resting on the sea floor (figure 5). At the second zone there is a change in thickness of ice, this is called an ice shelf. An ice shelf is ice floating on the water due to the difference in density. The boundary between these two zones is the grounding line, which is the ice sheets last contact with the bedrock (figure 5).

Glacial Deposits

Moraines

As glaciers ablate, rocks are deposited at the terminus and along the edges of the ice. When the glacier is in equilibrium for a long period of time, the debris transported both supraglacially and englacially is deposited in linear features. These linear features are called moraines (figure 6). Common types of moraines are terminal, found where the terminus used to be, and lateral which form along the flanks of the glacier (Bennett and Glasser, 2009). Terminal moraines indicate the furthest extent a glacier reached down valley and how this fluctuated through time (Bennett and Glasser, 2009). Lateral moraines can indicate past ELAs. Both types of moraines can be ice cored. An ice cored moraine is an ice-marginal landform containing a piece of glacier ice underneath the sediment. Ice-cored moraines indicate a younger transitional landform as the ice must first melt before the final deposit is stable (Lukas, 2014).

Erratics

Another type of glacial deposit that can inform us about the extent and thickness of a glacier in the past are erratics. Erratics can range in size from pebbles to large boulders and are left behind by a glacier as it retreats (figure 7). These rocks are transported relatively long distance, and therefore are of a different rock type from the local bedrock (figure 7). Erratics can indicate vertical extent of an ice sheet (Bennett and Glasser, 2009), and how it changed through time. For erratics to provide precise information about past vertical extent of glaciers they must be deposited on flat ground with no possibility of movement from changes in the surface they are deposited on. If they roll down slope then an exact elevation of deposition would not be possible to collect. Thus the data would have to be used as a minimum thickness of past glacier extent rather than a maximum.

Till

Glacial till is unsorted sediment deposited directly by glacier ice. It is usually pebble to boulder (16mm to 256 mm) sized clasts within a fine matrix (Hubbard and Glasser, 2005). Glacial till can be used to inform us about the basal conditions of a glacier, where material has been transported from, and how far that material travelled within the glacier (Bennett and Glasser, 2009). To come to these conclusions there are a few common analyses that first need to be done. To understand the transport method and distance transported it is important to look at the clast shape and roundness (Benn and Ballantyne, 1994). Clasts that have been actively transported within the glacier are more rounded whereas passive transport results in more angular clasts (Benn and Ballantyne, 1994). The lithology of the pebbles will inform us about where the material was transported from. Size fraction analysis will show the basal conditions as well as the transport methods (Hubbard and Glasser, 2005).

Field Area

Antarctica

Antarctica is 12,272,800 square km, about 1.4 times larger than the United States and less than a percent of the continent is ice-free (British Antarctic Survey, 2015). There are two ice sheets in Antarctica, the West Antarctic Ice Sheet (WAIS) and the East Antarctic Ice Sheet (EAIS; figure 8). These two ice sheets are separated by the TAM (Bennett and Glasser, 2009).

The WAIS contains three major ice drainages, the Amundsen Sea Embayment, the Ross Sea Embayment and the Weddell Sea Embayment (Holt et al., 2006; figure 8).The mean ice thickness in the WAIS is about 1048 m and the mean for the EAIS is 2146 m (Lythe et al., 2001; figure 9). Due to the vast amount of ice in Antarctica, the continent plays a huge role in the climate of the southern hemisphere (Hall et al., 2013). Using field-based reconstructions Bentley (1999) puts ice volume equivalent to sea-level change during the LGM between 7.6-13.1 m. This paper focuses primarily on Tucker Glacier, which flows from the EAIS into the northwestern Ross Sea (figure 8).

Ross Sea

The Ross Sea spans from 150 and 165˚east and 77 and 86˚ south. There are two sources of ice flowing into the Ross Sea Embayment which drains nearly one-quarter of the ice in East and West Antarctica (Hall et al., 2013). The first is from the ice streams that flow out of WAIS (figure 4). This ice terminates in the Ross Ice Shelf along the Siple Coast (figure 10). The second source of ice is from the EAIS, flowing through the TAM (figure 4) and terminating either at the Ross Ice Shelf (farther south) or directly into the Ross Sea (Bentley, 1999; figure 8). This ice creates the Ross Ice Shelf which is 400 meters thick and about the size of France (The Last Ocean, 2015).

Tucker Glacier

Field work performed in Antarctica focused on one glacier located in the northwestern Ross Sea. Tucker Glacier, which flows between the Admiralty Mountains and the Victory Mountains (figure 1). Tucker Glacier flows into the Ross Sea north of Coulman Island (figure 11) which is just north of the LGM grounding line proposed by Anderson et al., (2002). The glacier is about 145 km long and ~13 km wide near the Ross Sea. This area was first explored in the 1957-58 field season by the New Zealand Geological Survey Antarctic Expedition (NZGSAE; USGS, 2015). The NZGSAE team noted in their report that the rock types in the ice-free areas at the Tucker Glacier are granodiorite at some of the outcrops and volcanic mafics at others (Harrington et al., 1963; 1968). They also reported seeing glacial erratics up to 400 m a.s.l., and a moraine complex along the south side of Tucker Glacier.

Whitehall Glacier is a smaller tributary glacier that flows into Tucker Glacier about 20 km from the terminus. It flows south to north between the Daniell Peninsula and the Victory Mountains (USGS, 2015; figure 1). The field sites are located at the confluence of Whitehall and Tucker Glaciers. There is one site on the west side of the Whitehall, for this study it is named Skua Basin. On the east side of Whitehall Glacier there is a second ice free area, named Shark Fin for the purposes of this study. At Shark Fin the rocks are mainly volcanic (pumice and andesite) and metasedimentary. On the west side, at Skua Basin the rocks are mainly metasedimentary and intrusive (granites and granodiorites).

Ice Sheet and Sea-Level Rise

The ice is about 4 km thick in parts of the WAIS but 2 km of this is below sea-level (Fretwell et al., 2013; figure 9). Since this portion of the ice sheet is below sea-level it is more susceptible to rapid deglaciation if sea-level continues to rise (Stone et al., 2003). Fretwell et al., 2013 shows two different potential sea-level contributions from the WAIS. The first is on the order of 4.3 m, this number is for all of the WAIS. The second estimate is 3.4 m, and is only based on ice grounded below sea-level (Fretwell et al., 2013). Thus if the sea-level rises there will be more contribution from WAIS than from EAIS. There have been rapid sea-level rise events in the past that may have involved Antarctic ice (Anderson et al., 2002), but the amount and timing is still up for debate.

Glacial History

Ice Damming

Researchers also map glacial deposits to determine past positions of the glacier margin (figure 6). A sequence of deposits can signify the nature of retreat from a maximum elevation to its present position. For example, a series of lateral moraines could indicate the magnitude of a series of ice thinning events. As glaciers flowed out of the TAM during the LGM into the Ross Sea they were dammed by thicker LGM Ross Sea ice (figure 3; Denton et al, 1989b). This damming would have caused the glaciers to begin to thicken at the toe with less thickening farther up-glacier (Bentley, 1999; Hall et al., 2013). Once glaciers were able to flow freely, after LGM ice retreated in the Ross Sea, they began to thin at the toe. This thinning likely then propagated up the glacier length (figure 3). While the glaciers thinned they would leave behind erratics and moraines (Bentley, 1999; figures 6 and 7). These deposits can provide information about the thickness of glaciers and Ross Sea Ice at the LGM.

Last Glacial Maximum in the Ross Sea

Denton et al. (1989b) created two reconstructions of ice extent and thickness in the Ross Sea for the LGM, a minimum and a maximum. Based on the minimum reconstruction, the grounding-line was retreated from its LGM position between 100 to 200 km to the Siple Coast and 700 km in the western Ross Sea (figure 10). The maximum reconstruction indicates the grounding line has retreated ~500 km to the Siple Coast and 1000 km in the western Ross Sea (figure 10; Bentley, 1999). This maximum reconstruction puts the grounding in the Ross Sea at the continental shelf during the LGM (Bentley, 1999; Conway, 1999; Hall et al., 2013).

Anderson et al. (2004) found the Ross Sea LGM ice at the Hatherton/Darwin glaciers to be about 800 m thicker than present day (figure 10). The thickness of glaciers during the LGM increases steadily the further south in the TAM (figure 10). At the lower reaches of Beardmore Glacier the thickness could have been as much as 1250 m (Denton et al., 1989a). At Terra Nova Bay (figure 10) ice reached a thickness of 400 m (Hall et al., 2013). Adjacent to Tucker Glacier Denton and Hughes (2002) believe that Ross Sea Ice reached elevations similar to Terra Nova Bay at about 400 m of elevation during the LGM (figure 2). Bentley (1999) provides a reconstruction showing that the ice adjacent to the Tucker outlet during the LGM was only ice shelf (figure 4) which would cause minimal thickening if at all of Tucker Glacier. Ice shelf thickness above sea-level can vary greatly with a maximum of between 100-150 m a.s.l. (NSDIC, 2015).

Radiocarbon Dating to Track Retreat

Throughout the Ross Sea, radiocarbon dating is used to track the retreat of the grounding line. Radiocarbon dating is a process in which the concentrations of ^{12}C, ^{13}C, and ^{14}C are measured (Bradley, 1999). Dates give an age of the death of the organism, because at this point the replacement of ^{14}C stops (Bradley, 1999). Radiocarbon dating in Antarctica is done on blue-green algae, carbonate material, mollusk shell fragments, penguin and seal bones, penguin guano and egg shell fragments from penguins (Bentley, 1999; Hall et al., 2004). These samples can be found in glacially dammed lakes and on raised beaches. The raised beaches are formed as the coast becomes ice free. It is not yet proven whether the formation of these beaches is from the final retreat of grounded ice or the loss of the ice shelf (Bentley, 1999). As the glacier deposits rocks and sediments along the coast the ocean reworks them into raised beaches. There is also isostatic rebound that occurs as the glacier retreats causing the beach to raise (Hall et al., 2004).

Retreat Ages of Grounded Ice

Ice in the Ross Sea was at or near its LGM grounding line between 27,820 to 12,880 years B.P. (Conway et al., 1999). Similarly Denton et al. (1989b) found a minimum age for deglaciation to be 13,000 yr BP. There is also evidence in lacustrine deposits implying thick ice in the western Ross Sea until 8300 yr BP (Bentley, 1999). Ice in the Ross Sea appears to be retreating in a swinging gate fashion (Conway et al., 1999). The hinge of the gate is on the northeastern side of the Ross Sea and it is closing inwards towards the continent (figure 11). As seen by the dotted lines in figure 11, there is a lot of information missing regarding how ice has retreated in the Ross Sea. There have not been many studies onshore in West Antarctica to constrain the history of its retreat (Stone et al., 2003; figure 10 and 11). There are radiocarbon dates from the Scott Coast (figure 11) about 480 km south of Tucker Glacier, indicating that grounded ice had retreated past this area as recently as 6600 ^{14}C years B.P. (Hall et al., 2004). Outlet glaciers in the TAM were close to or had reached their current thickness by 6000-5200 yr BP (Bentley, 1999).

The extent and thickness of Ross Sea ice is still unknown today as is highlighted by figure 11 with the dotted lines as well as the numerous reconstructions of this area at the LGM (Bentley, 1999; Denton and Hughes, 2002). With this work at Tucker Glacier as well as more studies of ice free areas in the Northwestern Ross Sea, the grounding line at the LGM will be constrained along the coast. The overall project will provide data about the full extent of Ross Sea ice at the LGM ice and the subsequent timing of retreat. However, in this paper, using the methods outlined below will provide a thickness of Tucker Glacier in the past, which will, in turn, provide information about the thickness of ice in the Ross Sea Using this data, estimations of sea-level contribution from Antarctica will also be made.

METHODS

GIS Work

Glacial landform mapping

The images used for preliminary landform mapping come from four different satellites. Three of these satellites are run by Digital Globe: Worldview-1, Worldview-2 and Quickbird-2. The fourth satellite is run by Geoeye and is geoeye-1. Worldview-1 is the only one of these satellites that cannot produce color images as well as panchromatic ones. They have a minimum resolution of 0.5-2.4 m. The multiple band images (color) have the lowest resolution for all sensors.

These images are used both to do preliminary glacial deposit identification (figure 12) and to create base maps for the use in field. On the preliminary glacial deposit maps, lines and polygons were created using ArcGIS to show possible moraines and areas with possible glacial drift (figure 12). Moraines were identified by searching for linear features on ice-free slopes (figure 12). The glacial drift was identified by zooming in on ice-free areas and looking for glacial erratics, which were a different color than the bedrock. Also noted on these maps are areas of patterned ground (figure 12 and 13). Patterned ground is not favorable for collecting samples as the rocks may move due to freeze-thaw processes; this movement causes the deposit to no longer represent a past glacier position.

Field Work

Glacial Geologic Mapping

One goal of this project is to map glacial deposits from LGM ice and their subsequent retreat positions. All the observations and data collection was done as part of a field team. At Tucker Glacier, these deposits include ice cored moraine sequences, and glacial drift or erratics.

Once these landforms were identified we made observations to understand how these deposits are connected to past glacier configurations. One issue that could arise is if the glacier extended laterally during the LGM to a position that is not parallel to current glacier margins, moraine sequences and striations would not be in the orientation we would expect. In the field, we used base maps to note the location and orientation of these deposits and landforms. We then collected the elevation and location of these features as well as the height of moraines and their proximity to the ice margin. Weathering observations of cobbles and larger sized material were made which includes: discoloration due to staining, smoothness of the surface, and competency of the rock. Observations were also made about the condition of the bedrock in areas in which it was present. The clast size, angularity and sorting as well as rock type is important for identifying transport by glacier.

Till Sampling

Till was collected from two different ice free areas. They were selected during the initial mapping work done before entering the field. Skua Basin and Shark Fin were selected based on their location at the confluence of Tucker and Whitehall Glaciers. Based on the location of the two sites, thicker Tucker ice, had the potential of being picked up from Skua Basin and deposited at Shark Fin. These two sites also had potential of providing different elevation transects that would hold deposits from ice as it retreated.

We used the following criteria to select the sample sites. First the area should be representative of a unique or different surface than previous sample locations as well as representative of the area around it. Each sample site should show a change in glacier thickness. The site should be as flat as possible and away from signs of recent snow cover which include moss, salt accumulations, or saturated soil in the drainage of a snow field. We also looked for areas that are between embedded boulders and large cobbles to be able to capture changes with depth of the soil. Much of the ground is patterned so finding a sample location within a polygon is ideal to get the most representative sample, and is preferable because the outside of the polygon contains mostly larger clasts as the fines have fallen into the crack during freeze thaw.

Once the sampling sites were located the first step was to lay out the ruler for scale then take a photograph of the undisturbed sampling pit. The next step was to take the slope of the surface. We took the GPS elevation and location for mapping purposes as well as for comparison to other drift features. We also used a barometric altimeter for a precise elevation of the sample. Once the information was collected about the sampling area we dug a pit as deep as possible noting if moisture was reached as well as the reason we stopped digging. Often this was because we could not maintain the pit walls or because the bottom of the pit was compact diamicton. We then took a photograph of the pit for description with a scale card in the pit**.** If any cobbles from the pit were left out of the sample bag due to size, we measured the b-axis. We took about 3 liters of till at each sampling site.

Lab Work

Till Sample Analysis

Before any analysis was done, I separated the >30 mm sized clasts from the rest of the material. Then the smaller clasts were dry sieved using seven sieves with screens ranging from 4 mm to 62.5 µm (Bromley et al., 2010). Each sample was mechanically sieved for fifteen minutes. After the sample was sieved, each size fraction was weighed. Then using Excel I calculated a weight percent for each size fraction.

The >30 mm clasts were used to classify the provenance, transport methods, distance travelled, and relative age. Observations were made about lithology to determine the provenance of the material. Using Powers, (1953) roundness scale I determined the degree of roundness of each clast, which will provide information about transport method (figure 14). Following this clast a-b-c axis measurements were taken to identify the shape of the clasts. The a-axis is the longest and the c-axis is the shortest. This will provide information about the transport method as well as the distance travelled (Bennett and Hubbard, 2005). The relative age can be determined based on the weight percent of each size fraction as well as observations of the >30 mm size fraction.

RESULTS

After data collection using the methods outlined above, analysis of the information was next. First descriptions of the field areas are provided to show the observations about lithology and extent of weathering at the ice free areas. Following these observations, the results will highlight trends in the data that will be used to discuss the transport methods, relative age, and provenance of the deposits on Shark Fin and Skua Basin.

Till Sample Site Descriptions

Shark Fin

There are five till sample sites at Shark Fin (SFS; figure 16). The highest elevation site, 290 m a.s.l., was located near an ice-cored moraine deposited by a small local glacier. SFS-02 was collected below a metasedimentary bedrock ridge at 151 m a.s.l. (figure 16). This bedrock ridge is covered by a lava flow. SFS-03 was collected at 88 m a.s.l. near the base of an andesite cliff. This pit was dug outside of the rock fall so the data would not be skewed. Site SFS-04, 61 m a.s.l., was located among large granite erratics, greater than a meter in size. The last sample, SFS-05, was collected from the crest of an ice-cored moraine at the margin of Whitehall Glacier (figure 1). It was only 2 m a.s.l.

The deepest pit dug at Shark Fin was 28 cm deep and was located at SFS-05, 2 m a.s.l. and the shallowest pit was 10 cm deep and located at site SFS-04, 61 m a.s.l. (table 1). The pit with the deepest moisture level was SFS-01, 290 m a.s.l. Moisture reached 15 cm deep (table 1). Each of the sites contained larger clasts that were not collected that displayed signs of weathering. Many of the boulder-sized clasts were discolored due to iron staining (figure 16). They also had rough surfaces from the weaker minerals weathering away. Some of the boulders were cavernously weathered (figure 16). The slope of the surface for each of the sampling sites is less than 10°. Much of the surface at Shark Fin is inflationary soil, meaning that the top layer consists of gravel sized clasts and the lower layer is all fine silty sediment. For more information about each till sample site see Appendix A, sub heading Shark Fin.

Skua Basin

Skua Basin is located on the western side of Whitehall Glacier (figure 1). There were four samples collected from this area (table 1). The highest sample was collected from a dense pumice till at 193 m a.s.l. (figure 17). This pumice is located on this upper bench of Skua Basin only, it was most densely populated near sample SBS-09 but reached all the way too SBS-10 (figure 17). From here we moved towards Tucker Glacier and collected the next sample at the edge of the bench (figure 18), 183 m a.s.l. SBS-10, was collected from an area containing granite boulders spaced less than a meter apart. SBS-11 was collected from the base of this bench at 58 m a.s.l. The final sample, SBS-12, was collected from the crest of the ice-cored marginal moraine at 3 m a.s.l. (figure 17 and 18).

The deepest pit was dug at SBS-11 which also had the shallowest depth to moisture of any of the sample sites (table 1). Moisture was reached at 0 cm. The shallowest pit was dug to 8.5 cm at SBS-10 (table 1). The surface slope for all the sites was 5° or less. Ice was never reached in the ice-cored moraine. Collapsing walls prevented us from digging deep enough to reach the ice. Boulders located near sample SBS-10 were heavily discolored due to iron staining and many of them were cavernously weathered (figure 16). The boulders located near SBS-11 are deeply embedded and show less signs of weathering i.e. less surface staining (figure 19). For more information about each till sample site at Skua Basin see Appendix A.

Glacial Landform Mapping

The primary rock type at Shark Fin is metasedimentary overlain by volcanic flows. The glacial deposits identified at Shark Fin include granite erratics, large deposits of granite boulders, patterned ground and moraines (figure 20). There was two large boulder deposits identified both densely clustered (figure 6). These two granite boulder deposits were located at 83 m a.s.l and 64 m a.s.l. The higher of the two deposits contained boulders that exhibited more weathering i.e. staining and rough surface. The highest granite erratic observed at Shark Fin was at 244 m a.s.l. (table 2). There were other sporadically located granite boulders at Shark Fin, many of which were located in a basin beneath an andesite head wall (figure 20). The moraines identified at Shark Fin, are ice-cored modern moraines meaning they are still at the margins of the current glacier position (figure 20). These were located both at the edge of the Whitehall as well as tributary glaciers (small glaciers that feed into the Whitehall or stop short). There was also extensive patterned ground, a para-glacial feature caused by freeze thaw (figure 13).

The primary rock type at Skua Basin is granite and granodiorite, as well as some metasedimentary outcrops. At Skua Basin the glacial deposits include ice-cored marginal moraines which are located at the edge of Tucker Glacier, as well as the margins of local tributary glaciers (figure 18). Also identified at Skua Basin, was extensive pumice till. This till was most densely clustered in the area indicated on the map in figure 18, but extended all the way to the edge of the bench where sample SBS-10 was collected from (figure 19). There was also extensive patterned ground at this ice free area (figure 13).

Till Results

Lithology

The >30 mm sized fraction was used for a number of tests. One of these was to identify the lithology of the clasts. At Shark Fin a majority of the material was locally derived i.e. metasedimentary and volcanic. At SFS-05 the lowest till sample site on Shark Fin there was one piece of erratic material or granite identified in the >30 mm size fraction. In the SFS-04 sample there were some small pieces of granite identified in the 4 mm and 2 mm size fractions. There were no other pieces of granite identified in any of the other samples.

At Skua Basin, the primary rock types identified in the till samples were granite and metasedimentary rocks. These are both the local bedrock in this area. There was pumice till sampled (figure 21). This sample contained all three rock types: granite, metasedimentary and volcanic rocks. This pumice till extended from the location of SBS-09, slowly decreasing in concentration the closer to SBS-10 (figure 17).There were no pieces of pumice identified in SBS-10 however. SBS-11 and SBS-12 both had granodiorite, granite and metasedimentary clasts.

Grain Size

At Shark Fin, each of the five sites we see relatively the same amount of >30 mm size fraction in each sample. This size fraction makes up no more than 20% of the total weight percent at each site (figure 22). There are two major trends in the grain size distribution for the five till sample sites on Shark Fin. First when looking at the >30, 4 and 2 mm grain sizes in figure 22 we see an increase in the weight percent with a decrease in elevation. Meaning there is more of the larger size fraction at the lower elevations. In sample SFS-05, collected from the modern moraine, the 4 mm size fraction makes up almost 50% of the total sample. The second trend is the notable decrease in the 1 mm to <0.063 mm size fractions with a decrease in elevation (figure 22, table 1). This meaning that there is more fine grained material at the higher sample sites compared to the lower sites. At SFS-01 all the material <1 mm in size makes up about 45% of the sample whereas at SFS-05 the <1 mm sized material only makes up about 20% of the sample (figure 22).

At Skua Basin there is a decrease in the larger sized material from SBS-09 to SBS-11 then we see an increase again at the modern moraine, SBS-12 (figure 23). Samples SBS-09 and SBS-12 have similar distributions of grain sizes. There is more >30 mm sized material in the SBS-09 sample but more 4 mm sized material in the SBS-12 sample (figure 23). SBS-11 has the greatest amount of the 0.50 mm size fraction, which is classified as sand (Hubbard and Glasser, 2005). There is a slight increase in the amount of >30 mm size fraction from SBS-10 to SBS-12. More than 70% of the till sample from SBS-09, the highest till sample collected at Skua Basin, is greater than or equal to 2 mm in size. This is a much larger percent compared to the highest till sample at Shark Fin (figure 22 and 23).

Roundness

The roundness of the material is helpful in determining both the transport method as well as distance traveled within the glacier. At Shark Fin there was no rounded or well-rounded material identified in any of the five samples (figure 24). There is an overall increase in the amount of sub-rounded material from the highest sample site to the lowest. There is also a relative decrease in the percentage of sub-angular material from SFS-01 to SFS-05, although there is an increase at SFS-03. There is also an increase in the amount of angular material atSFS-

03. It makes up about 45% of the total sample. There is only very angular material in four of the samples. SFS-03 does not contain any (figure24).

At Skua Basin there are no well-rounded clasts but there are rounded clasts at SBS-09 and SBS-12, the highest and lowest sites (figure 25 and table 1). Sample site SBS-09 contains the only very angular material identified in any of the till samples at Skua Basin. SBS-10 has the most sub-angular material out of the four samples (figure 25). There is not much change in the amount of sub-rounded material at the four sites. The sub-rounded clasts range from 20% at SBS-10 to 30% at SBS-12 (figure 25). SBS-12 provides the best representation of the sample site as there were 44 clasts that were >30 mm or greater. The rest had less than 30 clasts.

Shape

Shape of clasts is used to determine the transport method as well as the distance traveled. The top point on the ternary diagram is representative of spherical or block shaped material, i.e. all three of the axes are the same length (figure 26). The bottom two points on the ternary diagram are representative of slabs on the left and rods on the right. The axes measurements that would indicate slab material are a=b; c=0 and for rods a > 0; b=c=0 (Benn and Ballantyne, 1993). For most of the samples collected from Shark Fin and Skua Basin the clasts cluster in the center of the ternary diagram and not near one of these points (figures 27-35). The two highest samples SFS-01 and SBS-09 are both clustered closer to the top of the ternary diagram (figure27 and 32). Several of the samples are clustered to the block vs slab axis.

DISCUSSION

From current ice flow patterns of Tucker Glacier as well as the data in the results section it can be concluded that material was transported from the granite/granodiorite cliffs of Skua Basin and deposited on Shark Fin (figure 36). These granite erratic deposits range in elevation from 244 m a.s.l. to the current ice margin at 2 m a.s.l. (table 2). These elevations indicate that at some time in the past Tucker Glacier ice reached a minimum elevation of 244 m a.s.l. Analysis of glacial till from Shark Fin and Skua Basin reveals a decrease in relative age with elevation. This is evident in the grain size distribution as well as the lithology of the material at each sample site. Further analysis of the till shows that material was primarily passively transported, meaning it was carried supraglacially. Shape analysis of the till at both Shark Fin and Skua Basin also suggest primarily supraglacial material. With this data there is no way to conclude if these deposits are from LGM ice or earlier in history. However if these deposits are from the LGM they would indicate an estimated sea-level contribution between 9-11 m. If the highest observed granite boulder is not an LGM deposit and the dense boulder deposits are this would indicate a much smaller Antarctic contribution to sea-level.

Glacial Deposits

The glacial deposits that provide the most information at Shark Fin are erratics. These erratics indicate past ice thickness of Tucker Glacier. The highest observed granite erratic at Shark Fin was 244 m a.s.l. which indicates Tucker Glacier ice reached a minimum elevation of 244 m a.s.l. Even though this elevation is based on the highest observed granite, there might be erratics that were deposited higher that were not observed or are not yet visible. There are also small local glaciers near this erratic that could have transported the boulder down slope from its original position at the time of deposition. This boulder was also located on a steep scree slope. As this is an unstable surface there is a likelihood that the boulder would shift or slide down slope. A more reliable source of past ice elevations are the dense granite benches at 83 m and 64 m a.s.l. (table 2). The dense clustering of these boulders could also indicate a past ice margin. There is evidence of similar boulder deposits at the current ice margin. These deposits contain large granite boulders. The boulders are densely clustered, and exhibit less weathering then the boulder deposits at higher elevations.

Relative Age of Deposits

The grain size distribution in the till samples show an increase in 2 mm and larger grain sizes at lower elevations both at Shark Fin and Skua Basin (figure 22 and 23) which indicates less weathering of the material has occurred. SFS-05 was the only sample that contained any granite in the >30 mm size fraction. SFS-03 and SFS-04 were both collected in areas containing densely clustered granite boulders. There were small fragments of granite in the SFS-04 4 mm size fraction, but no other granite was identified in any of the samples. The lack of granite material in till samples SFS-03 and SFS-04 is shows the increase in weathering at higher elevations. The greater extent of weathering is also seen in the granite boulder deposits at higher elevations which can be compared to the deposits located at the ice margins with less weathering. Material that has been exposed to the environments for longer will exhibit more weathering (Bromley et al., 2010).Tucker Glacier ice free areas contain older material at higher elevations. This is evident from the weathering patterns identified at Shark Fin and Skua Basin. These findings are consistent with Bromley et al., 2010 and Denton et al., 1989a which show older deposits at higher elevations along Reedy Glacier and Beardmore Glacier respectively.

There is some potential error as well as subjective analysis associated with dating using weathering observations of boulders. Some of the error comes from the possible reworking of material which indicates older material is present in areas where new material should be (Bromley et al., 2010). The subjective analysis is an issue while making observations about weathering extent. By using till analysis to identify weathering patterns subjective analysis is less of an issue.

Transport Methods

Tucker Glacier transports the material falling off the cliff onto the ice at the margin near Skua Basin and is then transported ~9 km to Shark Fin (figure 36). Roundness and shape data collected for SFS-01 to SFS-05 indicate that the material being deposited on Shark Fin is sub-rounded to very angular (figures 24 and 25). The lack of rounded and well-rounded material indicates that this material was passively transported (Benn and Ballantyne, 1994). Actively transported material would be modified by the glacier (Bennett and Glasser, 2009). This there would be faceted clasts present and the material would not be as angular. There are some rounded clasts present at Skua Basin. They were identified in the highest and lowest till samples SBS-09 and SBS-12 (figure 25). The rounded clasts from SBS-12 were transported from up Tucker Glacier, and indicate a more active transport. Passive transportation is not the only explanation for angular clasts at these sample sites. Rock fall also plays a role in the roundness and shape of the material at sample sites SFS-03, SBS-09 and SBS-11. The rock fall has the largest impact on roundness at SFS-03 as the sample was collected in a basin at the base of an andesite cliff.

All of the samples from Tucker Glacier are clustered in the center of the diagram, and often closer to the block vs slab axis (figures 27-35). When compared to shape ternary diagrams in the literature, the till samples from Tucker Glacier most closely resembled that of scree and supraglacial material (e.g. Benn and Ballantyne, 1993; Benn and Ballantyne, 1994; Bennett et al., 1998). The ternary diagrams that are indicative of till show the clasts being clustered in the upper part of the triangle (blocky) and against the block vs. rod axis (figure 32). The shape data also indicates passively transported material, actively transported material tend to cluster in the upper part of the ternary diagram (Benn and Ballantyne, 1994).

The analyses of clasts for shape and roundness data include some subjective analysis. This is mostly the case for the roundness data. Since there are no measurements taken, the analysis is strictly comparing the clasts to a generalized roundness table the data is dependent on the person conducting the analysis. The data for the shape data is not as helpful as it could be. Several of the samples contained less than 20 rocks to be analyzed. This does not provide an accurate representation of the sample site and it is hard to interpret the data.

Thicker Tucker Ice

The data in this paper indicates that ice was thicker at Tucker Glacier at some point in the past. However there is not substantial or precise enough data to definitively say these deposits are LGM in age. Depending on the age of this material, there are different potential sea-level contributions that can be inferred.

A reconstruction done by Denton and Hughes (2002) shows ice in the Ross Sea adjacent to Tucker Glacier to be about 400 m a.s.l. If this reconstruction is accurate ice damming would cause Tucker Glacier to be 400 m thicker during the LGM than its current elevation. The highest observed granite erratic at Shark Fin is 244 m a.s.l. This is significantly lower than we would expect to see deposits if Ross Sea ice had been 400 m thicker during the LGM. Bentley (1999) uses a reconstruction from Denton et al., (1989b) to determine volume of ice at the LGM. The Denton et al., (1989b) reconstruction puts ice adjacent to Tucker Glacier as ice shelf. The thickness of ice shelf can vary but for this study we are assuming the ice shelf adjacent to Tucker Glacier was 150 m a.s.l. This would have caused Tucker Glacier to thicken about 150 m a.s.l. which is lower than the highest erratic indicates.

Based on both reconstructions (Bentley, 1999; Denton and Hughes, 2002) a relative sea-level contribution can be determined based on the data from this study. This sea-level contribution estimation is for if the highest granite erratic deposit is from the LGM. Bentley, 1999 concludes from his study that since the LGM Antarctica has contributed somewhere between 7.6-13.1 m of sea-level rise. The Denton and Hughes, 2002 reconstruction speculates that since the LGM Antarctica has lost ~14 m of volume equivalent to sea-level. The potential thickness of Tucker Glacier would indicate ice in the Ross Sea reached about ~250 m a.s.l. From these two reconstructions and the data presented in this paper we can estimate that Antarctica had the potential of contributing about 9-11 m of sea-level rise since the LGM.

This is only an accurate estimation of sea-level contribution if the deposits discussed above are LGM in age. If the highest observed granite erratic is not LGM in age then this would indicate a much smaller Antarctic contribution to sea-level rise. More likely LGM deposits are the clustered granite on benches at elevations of 83 m and 64 m a.s.l. These deposits are more likely to be LGM in age. The densely concentrated material is representative of a glacier that was in equilibrium for an extended period of time. Glaciers were at their LGM position from about 30,000 to 13,000 years ago (Conway et al., 1999). This work leaves some questions unanswered, for example, when exactly were these erratics deposited?

Future Work

This project cannot determine these deposits are LGM in age. The overall project can and the next step is to perform cosmogenic isotope analysis on samples of granite erratics and bedrock at Shark Fin, Skua Basin, and two other ice free areas not discussed above. This analysis will be done primarily on erratic samples and will provide dates for when these rocks were uncovered by ice. Another dating technique will be implemented for the bedrock samples. By using a radiocarbon dating method we will be able to determine if the bedrock was covered by ice in the last 50,000 years.

There are a few pieces of analysis that should be added to this paper. First is the sieving and analysis of a third till sample set from Walsh Spur another ice free area at the confluence of Tucker and Whitehall Glaciers. These deposits appear to be much older than those observed at Shark Fin and Skua Basin. The material here was extensively weathered and the location of the material indicates a huge Tucker Glacier or larger tributary glaciers deposited the material sometime in the past. The second part of analysis that needs to be completed is the 3D modelling of current glacial thickness at Tucker Glacier. This analysis can be used to determine the current change in glacial volume at Tucker Glacier.

CONCLUSIONS

To conclude, my data indicates Tucker Glacier was thicker at some point in the past. At this point in time Tucker Glacier deposited granite erratics from Skua Basin on to Shark Fin (figure 1). The highest observed granite erratic was at 244 m a.s.l. This material was passively transported and primarily supraglacial in origin (Benn and Ballantyne, 1994; Bennett et al., 1998). The boulder deposits as well as till at both Skua Basin and Shark Fin exhibit extensive weathering at higher elevations, showing a decrease in the extent of weathering at lower elevations. This indicates younger material at lower elevations (Bromley et al., 2010).

The question now is if these deposits are LGM in age. This project cannot answer that question. Using the data presented above however, and by making the assumption the deposits are LGM in age an estimation of sea-level contribution from Antarctica can be made. This was done using reconstructions from Bentley, (1999) and Denton and Hughes, (2002). The estimated sea-level contribution from Antarctica after the LGM is 9-11 m. If this highest deposit is not LGM in age, this would indicate a much smaller sea-level rise contribution from Antarctica. Future work will determine the exact age of deposits.

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BIBLIOGRAPHY

Anderson, J. B., S. S., Shipp, A. L., Lowe, J. S., Wellner, and A. B., Mosola, (2002). The Antarctic Ice Sheet during the Last Glacial Maximum and its subsequent retreat history: a review. *Quaternary Science Reviews*, *21*, 49-70.

Anderson, B. M., R. C., Hindmarsh, and W. J., Lawson, (2004), A modelling study of the response of Hatherton Glacier to Ross Ice Sheet grounding line retreat. *Global and Planetary Change*, *42*, 143-153.

Benn, D. I., and C. K., Ballantyne, (1993), The Description and Representation of Particle Shape, *Earth Surface Processes and Landforms, 18*, 665-672.

Benn, D. I., and C. K., Ballantyne, (1994), Reconstructing the transport history of glacigenic sediments: a new approach based on the co-variance of clast form indices, *Sedimentary Geology, 91*, 215-227.

Bennett, M., and N. F. Glasser, *Glacial Geology: Ice Sheets and Landforms*. Chichester: Wiley, 2009.

Bennett, M. R., and M. J., Hambrey, and D. Huddart, (1998), Modification of Clast Shape in High-Artcic Glacial Environments, *Journal of Sedimentary Research, 67,* 550-559.

Bentley, M. J. (1999), Volume of Antarctic ice at the Last Glacial Maximum, and its impact on global sea level change, *Quaternary Science Reviews,18,* 1569-1595.

Bradley, R. S., "3.2.1 Radiocarbon Dating." *Paleoclimatology: Reconstructing Climates of the Quaternary*. Second ed. San Diego, CA: Academic, 1999. 50-72.

British Antarctic Survey, Antarctic Factsheet Geographical Statistics [Internet]. United Kingdom, May 2005. c2015 [cited 2015 Mar 16] Available from: http://www.antarctica.ac.uk/about_antarctica/teacher_resources/resources/factsheets/factsheet_geostats_print.pdf

Bromley, G. R., Hall, B. L., Stone, J. O., Conway, H., & Todd, C. E. (2010). Late Cenozoic deposits at Reedy glacier, Transantarctic mountains: implications for former thickness of the west antarctic ice sheet. *Quaternary Science Reviews*, *29*, 384-398.

Conway, H., Hall, B. L., Denton, G. H., Gades, A. M., & Waddington, E. D. (1999). Past and future grounding-line retreat of the West Antarctic ice sheet. *Science*, *286*, 280-283.

Denton, G. H., J. G., Bockheim, S. C., Wilson, J. E., Leide, and B. G., Andersen, (1989a), Late Quaternary ice-surface fluctuations of Beardmore Glacier, Transantarctic Mountains. *Quaternary Research*, *31*, 183-209.

Denton, G. H., J. G., Bockheim, S. C., Wilson, and M. Stuiver, (1989b), Late Wisconsin and early Holocene glacial history, inner Ross embayment, Antarctica, *Quaternary Research*, *31*, 151-182.

Denton, G. H., and T. J., Hughes, (2002), Reconstructing the Antarctic ice sheet at the Last Glacial Maximum, *Quaternary Science Reviews*, *21*, 193-202.

Fretwell, P., H. D., Pritchard, D. G., Vaughan, J. L., Bamber, N. E., Barrand, R. Bell, and M. J. Siegert, (2013), Bedmap2: improved ice bed, surface and thickness datasets for Antarctica, *The Cryosphere, 7*, 375-393.

Hall, B. L., C., Baroni, and G. H., Denton (2004), Holocene relative sea-level history of the Southern Victoria Land Coast, Antarctica. *Global and Planetary Change* 42.1. 241-263.

Hall, B. L., G. H., Denton, J. O., Stone, and H., Conway, (2013), History of the grounded ice sheet in the Ross Sea sector of Antarctica during the Last Glacial Maximum and the last termination, *Geological Society, London, Special Publications*, *381*, 167-181.

Harrington, H.J., B.L., Wood, I.C., McKellar, and G.J., Lensen, (1963), The Geology of Cape Hallett Tucker Glacier District, in Adie, R.J., ed., Antarctic Geology: Proceedings of the First International Symposium on Antarctic Geology, Amsterdam: North Holland Publishing Company.

Harrington, H.J., B.L., Wood, I.C., McKellar, and G.J., Lensen, (1968), Topography and Geology of the Cape Hallett District, Victoria Land, Antarctica: New Zealand Geological Survey Bulletin 80. Wellington: New Zealand Geological Survey.

Holt, J. W., D. D. Blankenship, D. L. Morse, D. A., Young, M. E. Peters, S. D. Kempf, T. G. Richter, D. G. Vaughan, and H. F. J. Corr (2006), New boundary conditions for the West Antarctic Ice Sheet: Subglacial topography of the Thwaites and Smith glacier catchments, Geophys. Res. Lett., 33, L09502, doi:10.1029/2005GL025561.

Hubbard, B., and N. F., Glasser, (2005), *Field Techniques in Glaciology and Glacial Geomorphology*, John Wiley & Sons.

Liu, H., K. C., Jezek, B., Li, and Zhao, Z. (2001), RADARSAT Antarctic Mapping Project Digital elevation model.

Lukas, S. (2014), In *Encyclopedia of Snow, Ice and Glaciers*, Springer, Netherlands.

Lythe, M. B. and D. G., Vaughan, (2001), BEDMAP: A new ice thickness and Subglacial topographic model of Antarctica, *Journal of Geophysical Research: Solid Earth (1978 -2012)* 106.B6 11335-11351.

NSIDC (National Snow and Ice Data Center), All About Glaciers [Internet]. Boulder (CO):

NSDIC; c2015[cited 2015 Jan 18]. Available from: http://nsidc.org/cryosphere/glaciers

Ritter, D.F., R.C., Kochel, and J.R., Miller (2006), *Process Geomorphology*, 4th ed.,Waveland Press, Inc., Long Grove, Illinois.

Stone, J. O., G. A., Balco, D. E., Sugden, M. W., Caffee, L. C., Sass, S. G., Cowdery, and C., Siddoway (2003), Holocene deglaciation of Marie Byrd Land, west Antarctica, *Science, 299*, 99-102.

The Last Ocean [Internet]. Christchurch [NZ]; c2004-2015 [cited 2015 Mar 16] Available From: http://www.lastocean.org/Ross-Sea/Last-Ocean-New-Zealand-__I.103

USGS (United States Geologic Society), Geographic Names Information System [Internet]. Reston (VA) [modified 2015 Mar 18; cited 2015 Mar 18]. Available from: http://geonames.usgs.gov/.

APPENDICES

Appendix A

Shark Fin

14-TUG-01-SFS

This pit was dug near an ice cored moraine above the highest observed granite erratic (Table 2). This is the highest elevation sampling site on the Shark Fin ice free area. The surface in this area consists of compacted diamicton overlying silty soil. The gravel at the surface is between .5 and 3 cm. There are also assorted cobbles ranging from 5 cm to 10 cm. There are not many clasts larger than 26 cm in this sampling location and the ones that are present have poor integrity from heavy weathering and are deeply embedded. The lithology consists of primarily of volcanic rock e.g. pumice andesite and basalt with sporadic metasedimentary rocks. The material is mostly rounded with some angular to sub-angular clasts. The moisture depth at this soil pit is at 15 cm deep. Possible sources for this moisture in the soil could be the ice cored moraine or the local glacier.

14-TUG-02-SFS

This surface is a prime example of inflationary soil. The top ~2 cm of material is much coarser containing clasts ranging from about ~.5 cm-5 cm. Beneath this layer is a fine silty-sand. The clasts in and around this pit are dominated by metasedimentary and volcanic rock. Above this pit there is a bedrock ridge. The ridge is metasedimentary rock covered by a lava flow. The larger clasts are heavily weathered basalt and andesite and the smaller clasts are pumice and metasedimentary rocks. The moist soil is located at 11 cm deep and can be attributed to seasonal melt from a snow field located above the sampling site. There is a large polygon crack near this site that is approximately 10 cm deep.

14-TUG-03-SFS

This pit is located below a large andesite cliff. We dug it outside of the rock fall perimeter as to not skew the lithology. The moisture level in this pit is at 4 cm. It is most likely due to seasonal melt from a snow field located on the slope above the sampling site. There are ~1-2 m sized granite boulders that are embedded as well as >25 cm andesite and metasedimentary clasts on top of the surface. This larger material is heavily weathered, the granite showing staining and rough surfaces and the andesite is of poor integrity. The material <8 cm is predominantly volcanic and metasedimentary rocks.

14-TUG-04-SFS

This sample was taken from a bench containing a dense grouping of granite boulders. These boulders range in the amount of weathering. Some of the boulders are fresher and exhibit only small amounts of staining. Others show large amounts of weathering both discolorations from iron staining as well as cavernous wreathing. There are also cobble sized clasts of metasedimentary and volcanic material. The surface clasts are primarily andesite and metasedimentary material with some coarse gravel sized pieces of granite. Below this pavement is a fine silty-sand. The large clasts here range from being deeply embedded and to sitting on top of the pavement. The moisture level in this pit is 1 cm and could be due to melt from a snowfield.

14-TUG-05-SFS

This is the lowest elevation sample on the Shark Fin outcrop. It is located on an ice-cored moraine at the margin of Whitehall Glacier. The pit was dug on the crest of the moraine. It reached 28 cm and no ice was reached because the pit walls kept collapsing. The proximal side of the moraine was dug into and ice was reached at approximately 10 cm. The moraine is 2m wide and about 3m tall on the distal side and about 10 m high on the proximal side. The clasts are metasedimentary, and granite. The material is much less compacted compared to the other sampling sites on Shark Fin. The rocks on the moraine are smoother than the more weathered rocks at higher elevations on Shark Fin. There were two cobbles not collected due to their size, one was 12.5 cm and the other was 10 cm.

Skua Basin

14-TUG-09-SBS

This sample is the highest till sample collected in the Skua Basin area. It was collected from a dense of pumice till only located in this area on Skua Basin. Along with the pumice in this area there are weathered granite boulders showing discoloration from iron staining and rough surfaces. Some of the granite is cavernously weathered and others exhibit surface weathering from pieces flaking off. The granite boulders are about a meter apart from each other. The material at the surface is sub-angular to rounded. The metasedimentary rocks are sparse here. There are two cobbles not collected that were angular, their b-axis were both 8 cm. This pit was dug to 17 cm where it became too difficult to continue due to larger cobbles. Moisture was reached at 6.5 cm and is most likely caused by seasonal snow melt. Some of the boulders are embedded and some are sitting on top of the pavement. There is a granite ridge near here which could be the source of the larger boulders that are not embedded.

14-TUG-10-SBS

This sample was collected from the same bench as the pumice till closer to Tucker Glacier. The site was selected because its proximity an area with granite boulders spaced less than a meter apart. Here the boulders are again both cavernously weathered, stained from iron and rough surfaces. The pieces of metasedimentary rock present are about softball sized and are angular to sub-angular. There are very few small pieces of pumice throughout the sampling site no more than 2 cm in size. The pit was dug to 8.5 cm and moisture was reached at 2 cm. There was one 8 cm cobble that was not collected with the sample. The material is compacted and that is the reason that digging was stopped. This area is most likely covered by snow seasonally based on observations of snow fields around it. Again the granite boulders are both embedded and resting on top of the till.

14-TUG-11-SBS

This sample was taken on the next bench down from sample 10, below a granite ridge. The sampled surface contained small weathered pieces of granite and metasedimentary rock as well as grus. The cobble and boulder sized material is spaced sparsely. The large granite boulders are deeply embedded and do not appear too heavily weathered i.e. not much surface staining. The ones that are exhibit surface weathering due to flaking. This till is not as compact as any of the other sampling sites at Skua Basin. The soil is moist at less than a cm of depth. There are small snow fields above this sampling site that could be the cause of the wet soil. The soil was wet enough to perform a cast test which indicated some clay content. The pit was dug to 29 cm and there are three cobbles that did not make the sample bag. The b-axis measurements are 8, 9, and 9 cm.

14-TUG-12-SBS

Sample 12 was taken from the modern moraine at Skua Basin. The sample was taken from the crest of the ice cored moraine and was chosen based on the absence of boulder sized material. The material is loosely compacted and contained silty material as well as gravel to cobble sized clasts. The boulders on the moraine are angular and lack staining as well as significant weathering of minerals to produce rough surfaces. The material is mostly granite and metasedimentary material. There was no moisture reached on the crest of the moraine. The distal side of the moraine was dug into to locate ice. Moisture is present within the till but due to collapsing walls a precise depth was not obtained. This moraine is thought to be ice cored based on the morphology and proximity to the ice margin as well its similar traits to the ice cored moraine at the Shark Fin ice margin.

TABLES

Table 1: Till sample site descriptions.

Shark Fin				
	Depth	Depth to Moisture	Elevation (GPS)	Surface Slope
14-TUG-01-SFS	25 cm	15 cm	290 m	8°
14-TUG-02-SFS	18 cm	11 cm	151 m	8°
14-TUG-03-SFS	16 cm	4 cm	88 m	0°
14-TUG-04-SFS	10 cm	1 cm	61 m	3°
14-TUG-05-SFS	28 cm	-	2 m	8°
Skua Basin				
	Depth	Depth to Moisture	Elevation (GPS)	Surface Slope
14-TUG-09-SBS	17 cm	6.5 cm	193 m	2°
14-TUG-10-SBS	8.5 cm	2 cm	183 m	3°
14-TUG-11-SBS	29 cm	0 cm	58 m	5°
14-TUG-12-SBS	19 cm	-	3 m	5°

Table 2: Granite erratics at Shark Fin. The weathering is categorized by high, moderate and low. High means the boulder is very rough and stained. Moderate means the boulder is either very rough or very stained with minimal other weathering. Low means the boulder exhibits some weathering but it is not extensive.

Granite Erratics at Shark Fin		
Notes	**Elevations**	**Weathering**
Highest observed boulder	244 m	high
Highest boulder in andesite basin	189 m	high
Erratic	179 m	moderate
Dense boulder deposit 1	63 m	moderate to high
Dense boulder deposit 2	56 m	low to moderate
Ice marginal deposits	3 m	low
Boulders on ice cored moraine	2 m	low

FIGURES

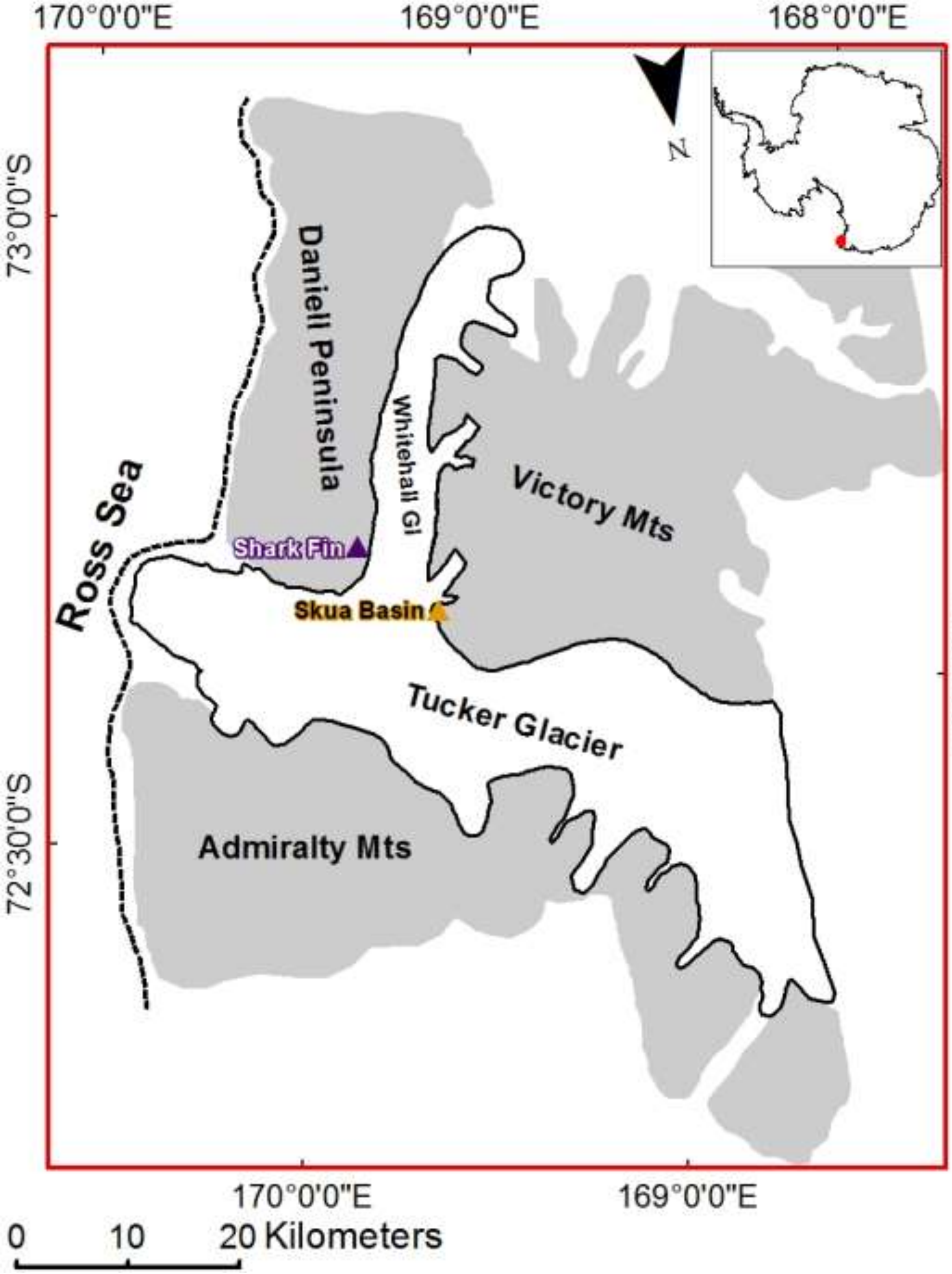

Figure 1: Map of Tucker and Whitehall Glaciers. Note the size difference between Tucker and Whitehall Glaciers. Also shown on this map are the locations of the till sample sites.

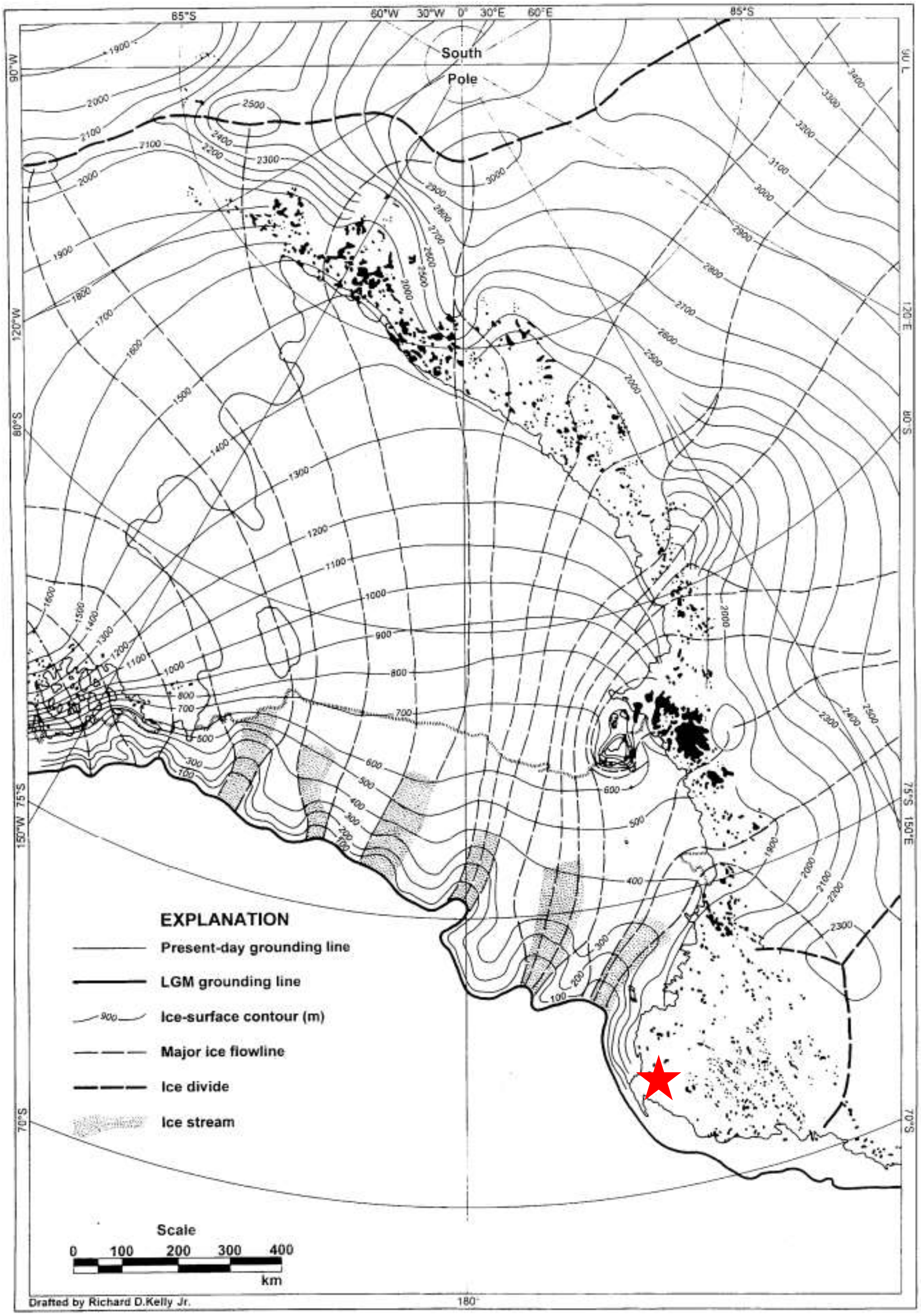

Figure 2: Ice elevation reconstructions from the LGM by Denton and Hughes (2002). The contour adjacent to Tucker, Mariner and Aviator Glaciers is 400 m. The red star is indicating Tucker Glacier. Denton and Hughes (2002).

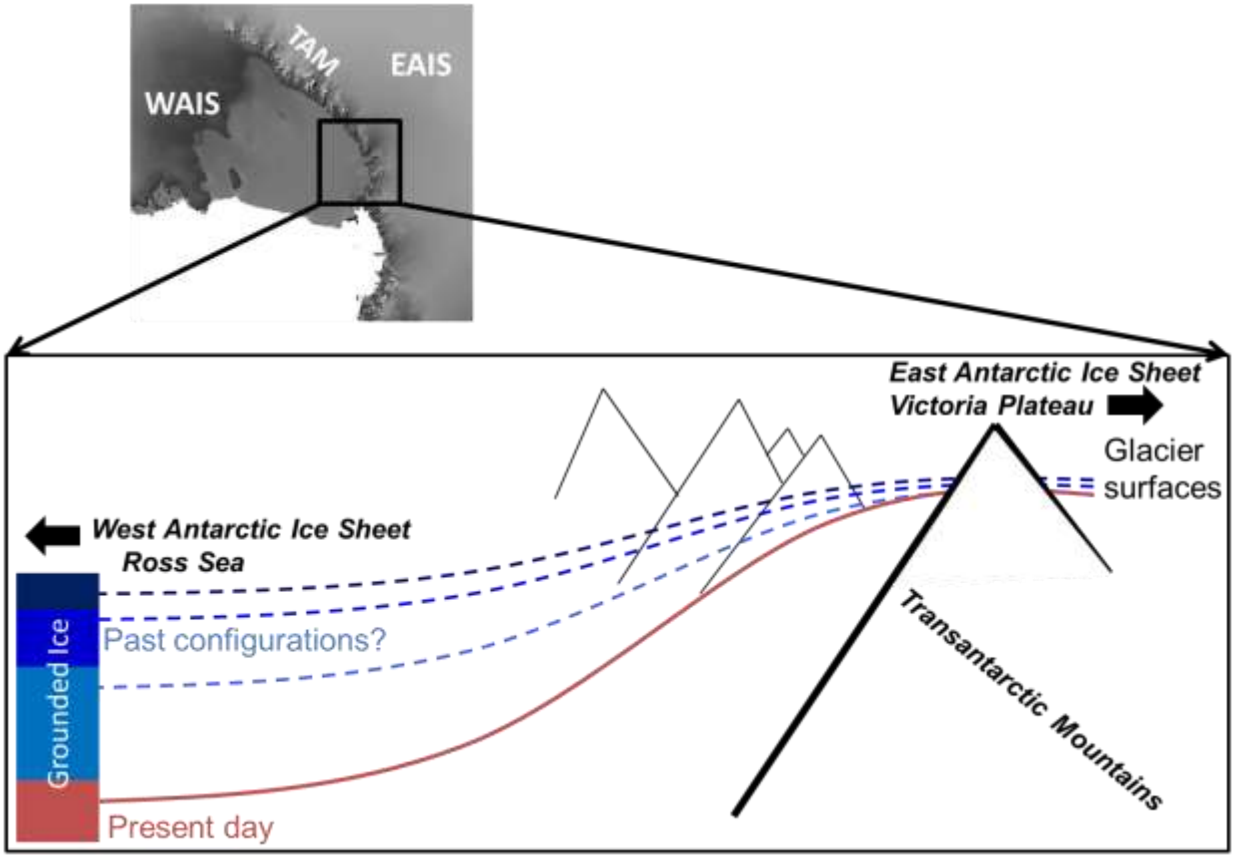

Figure 3: Damming of TAM ice due to thicker Ross Sea ice**.** The blue dotted lines are indicating elevations of TAM glaciers due to thicker Ross Sea ice. As grounded ice retreats the ice flowing out of the TAM will begin to thin as it is no longer dammed, to current thickness (red line). The rectangle on the left is showing a decrease in Ross Ice thickness and subsequent thinning of the outlet glaciers. Modified from Claire Todd by Isaac Moening-Swanson

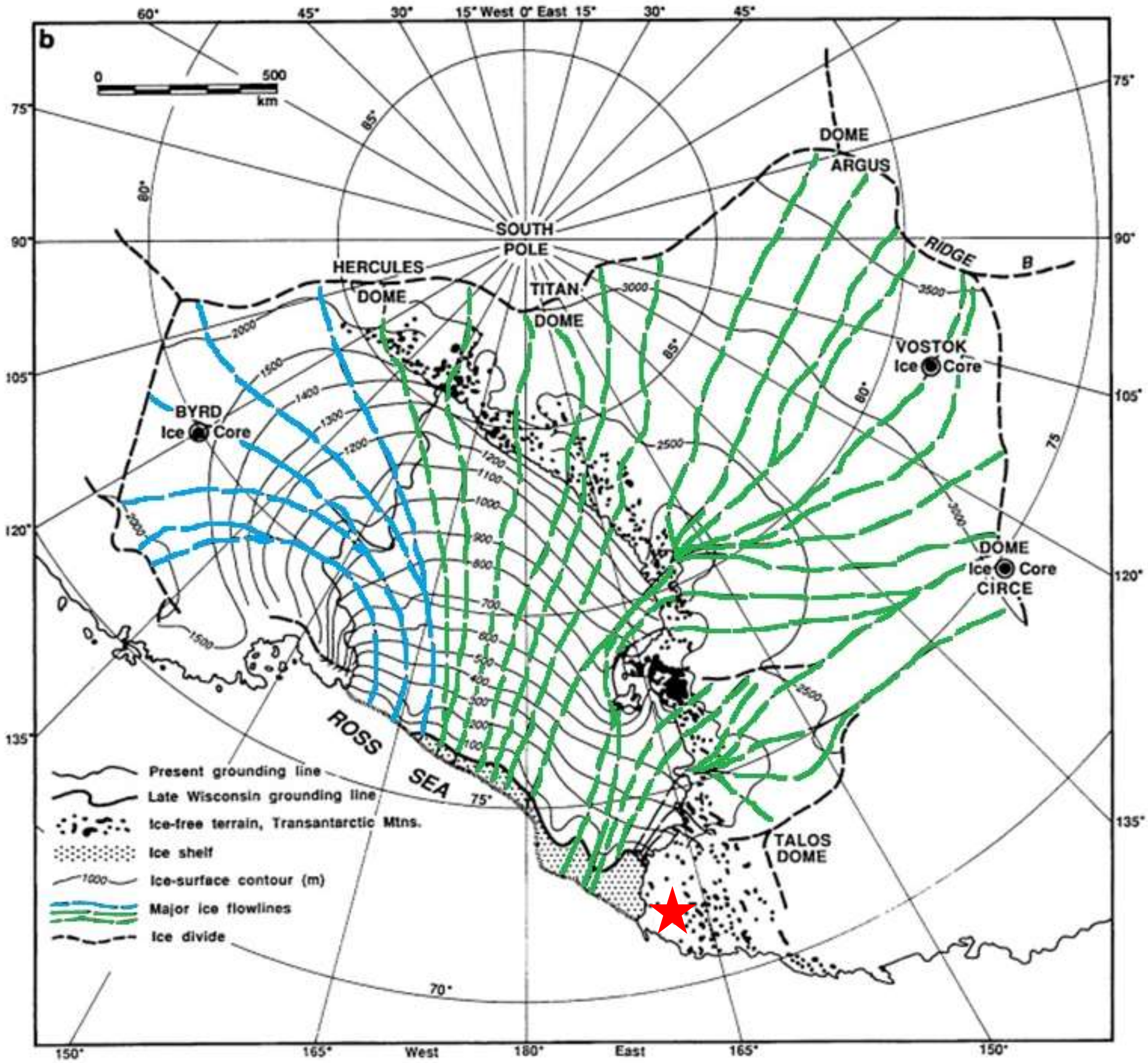

Figure 4: Ice thickness reconstruction from the LGM done by Bentley (1999). This reconstruction indicates ice adjacent to Tucker Glacier as ice shelf, potential elevation 100-150 m a.s.l. The red star is indicating Tucker Glacier. The blue lines are showing ice flow from WAIS and the green lines are from EAIS. Modified from Bentley (1999).

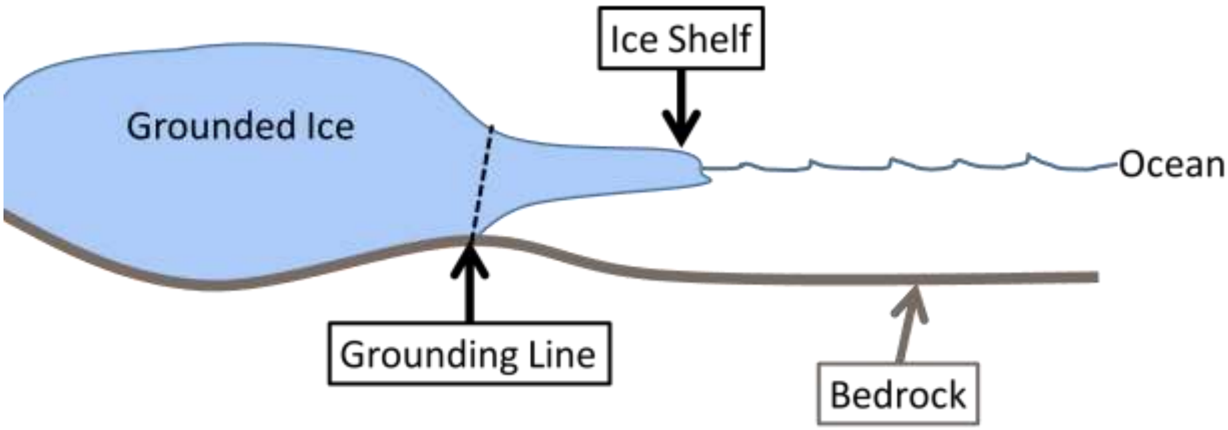

Figure 5: This is a diagram of an ice sheet**.** Note the boundary between the grounded ice and ice shelf, is the grounding line.

Figure 6: Ice marginal moraine at the edge of Whitehall Glacier. The red line is indicating the crest of the moraine. Photo credit: Claire Todd

Figure 7: Granite erratics at Shark Fin**.** The light colored rocks are the erratics the darker material is volcanic and metasedimentary rocks. Note the dense clustering of erratics in this image. Photo credit: Claire Todd

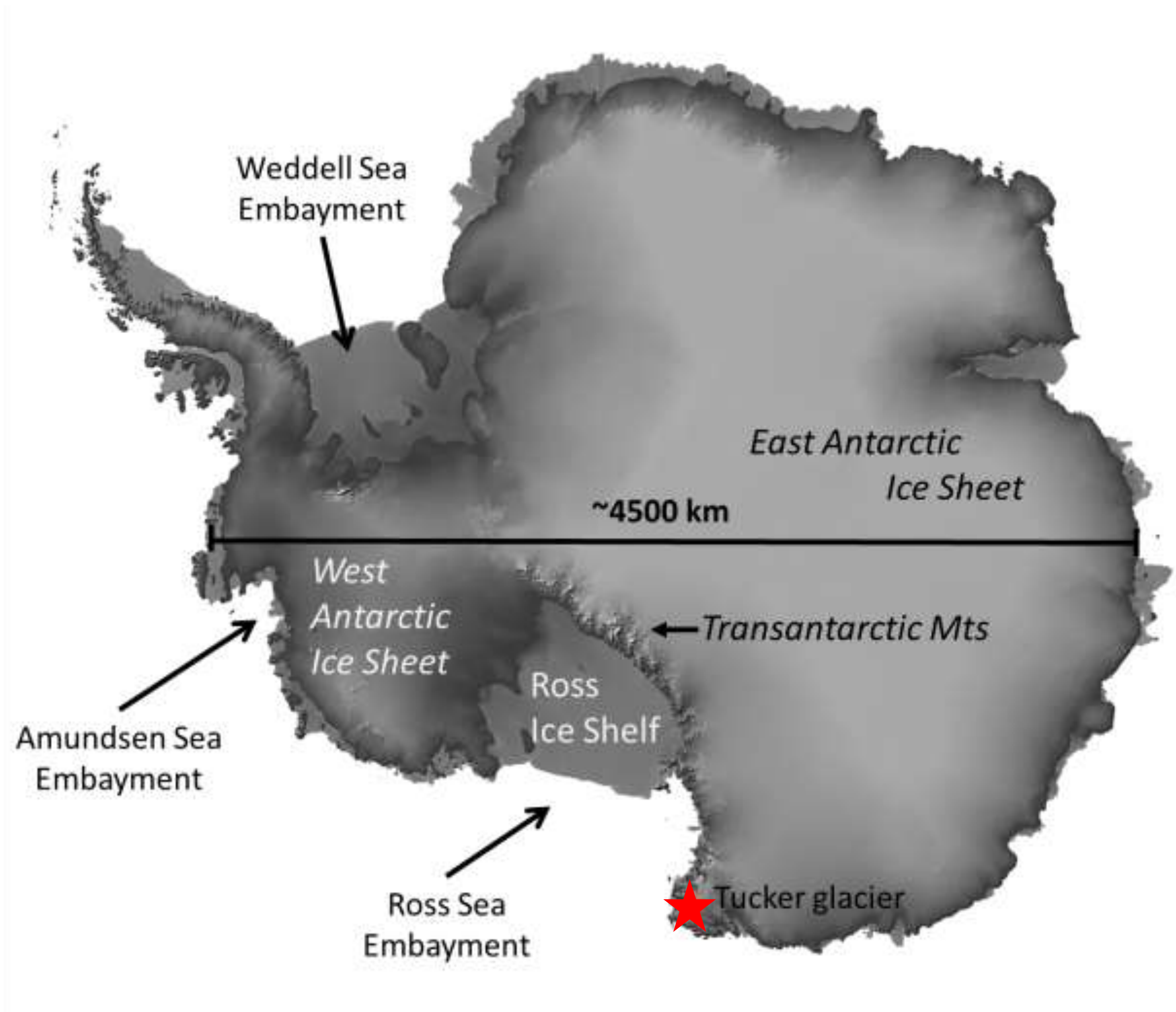

Figure 8: Radarsat Antartic Mapping Project Digital Elevation Map (RAMP-DEM). Labeled on this map are the two ice sheets, the major embayment's, Ross Ice Shelf and Tucker Glacier. The red star on the lower part of the map is pointing to Tucker. The RAMP-DEM is from Liu et al., 2001.

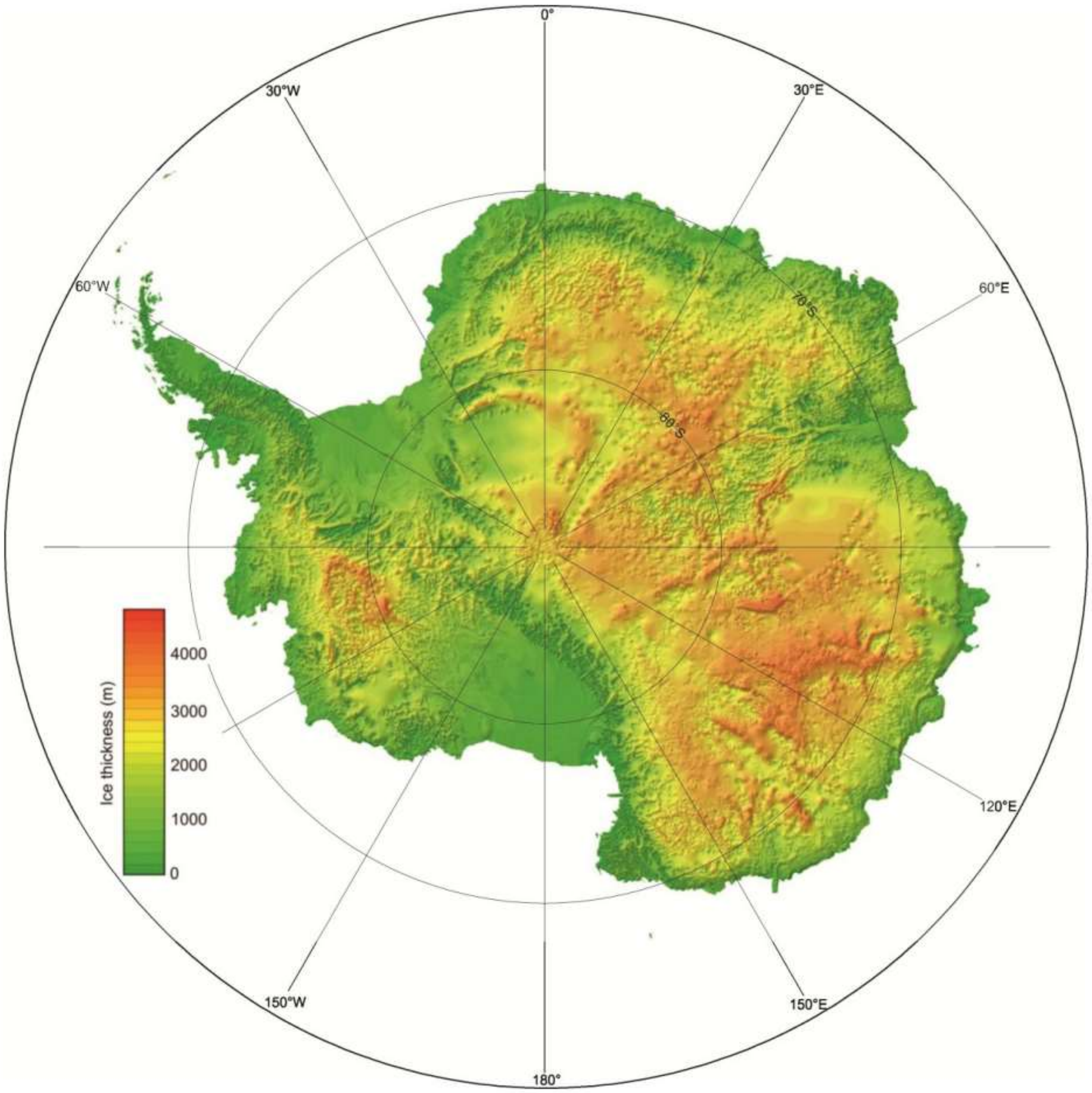

Figure 9: BEDMAP2 image showing ice thickness in Antarctica. (Fretwell et al., 2013)

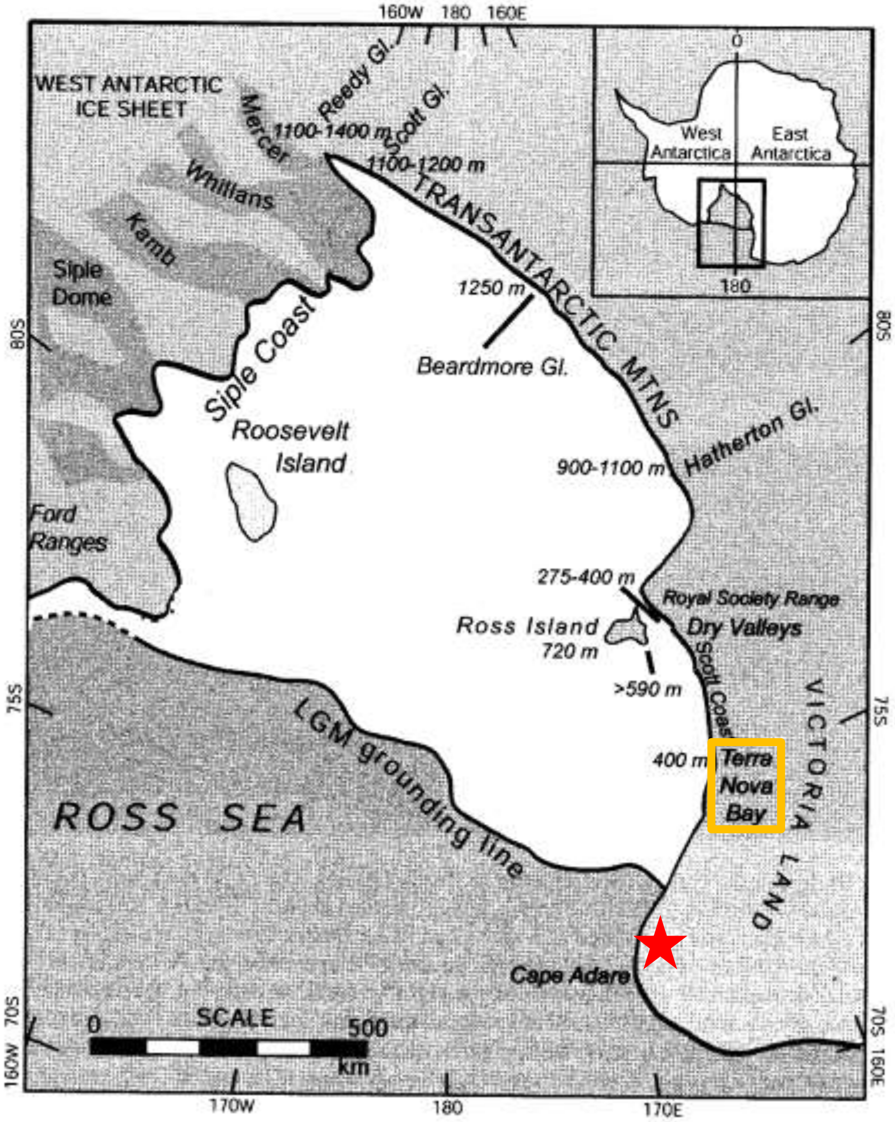

Figure 10: Ice surface elevations of glaciers at the LGM as determined from glacial geologic data. The red star on the lower part of the map is pointing to Tucker Glacier. The orange box is highlighting Terra Nova Bay which is about 350 km from Tucker Glacier (Hall et al., 2013)

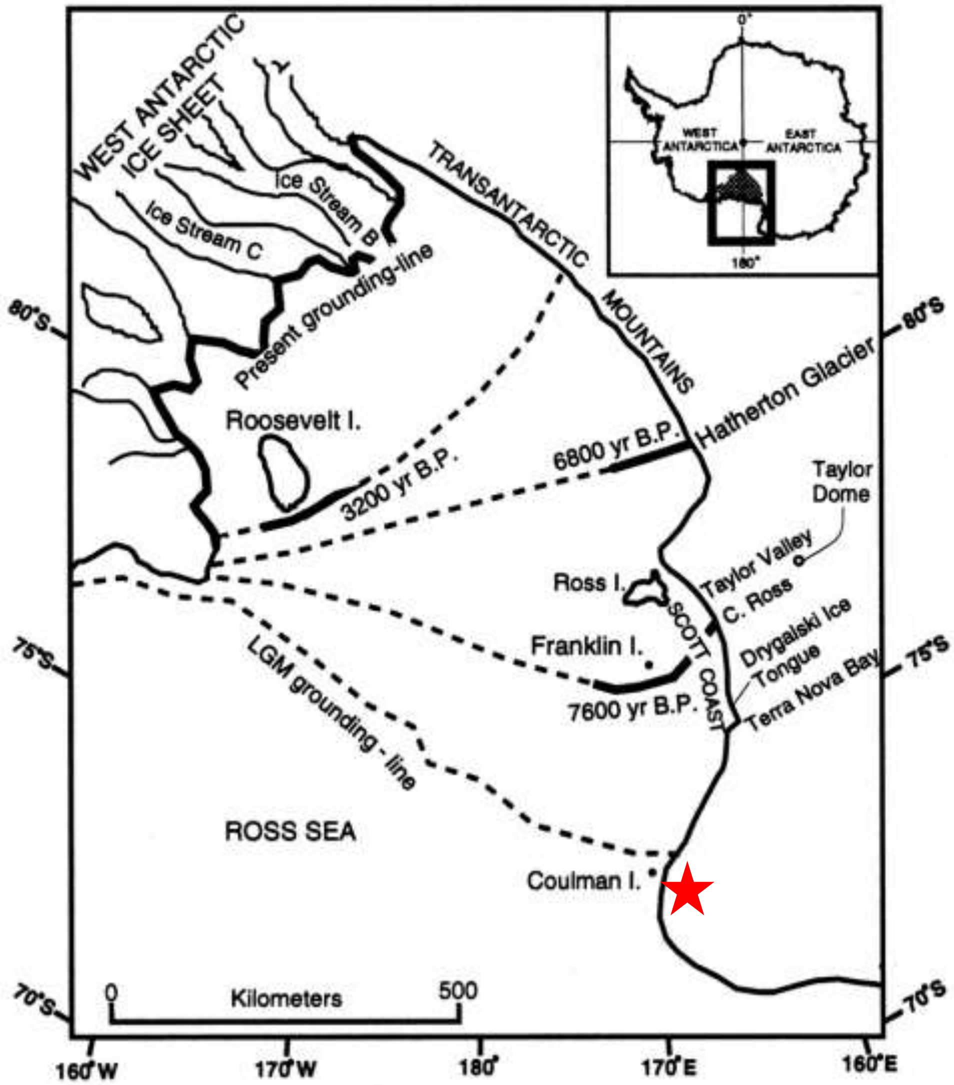

Figure 11: Swinging gate retreat hypothesis. The dotted lines in this show the potential shape of the grounding line and the solid lines are showing areas where we know grounded ice was. The hinge of the gate is located on the east side of Ross Sea. The star on the lower part of the map is pointing to Tucker. (Conway et al., 1999)

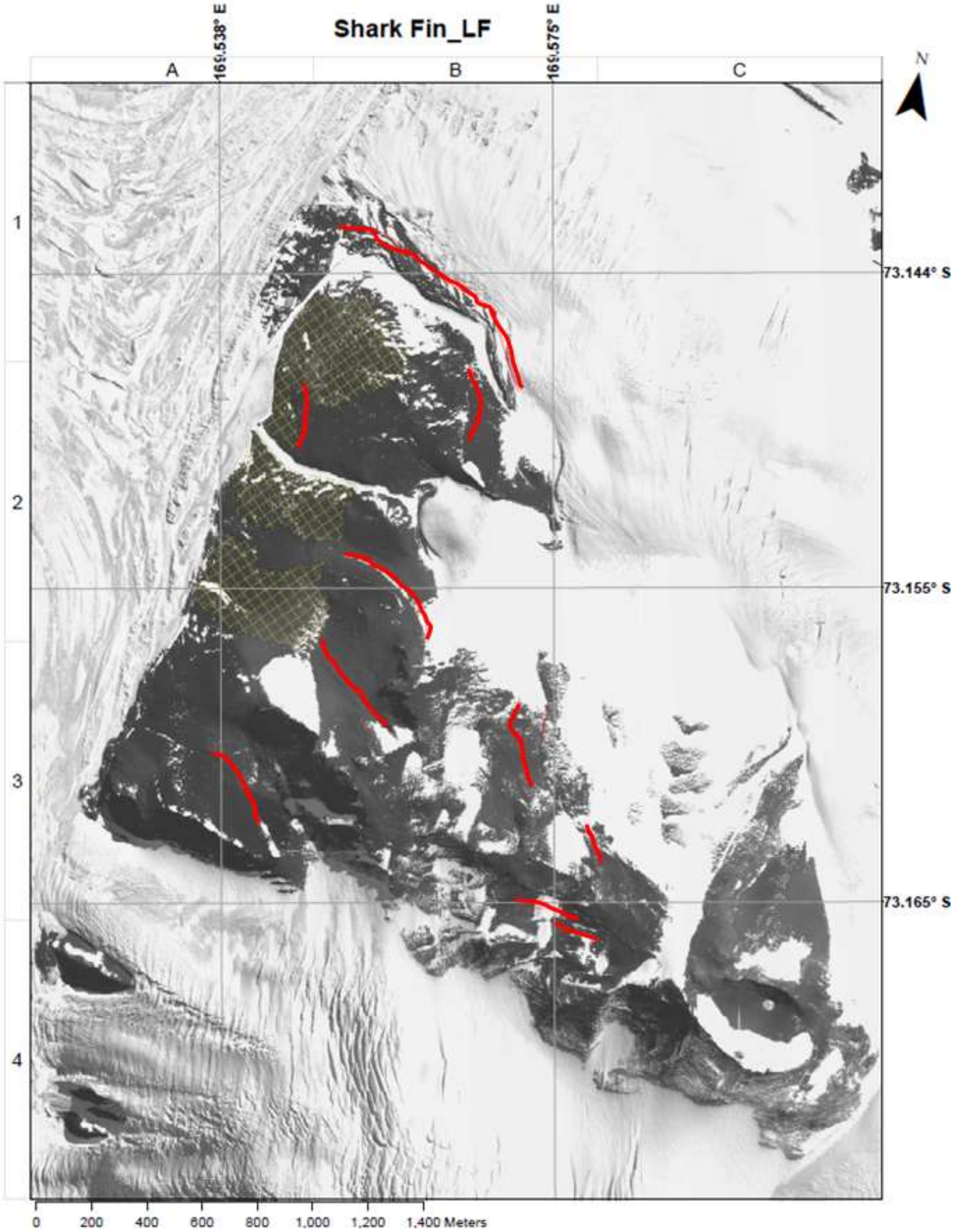

Figure 12: Potential glacial deposits at the Shark Fin outcrop near the confluence of Tucker and Whitehall Glaciers. The red lines are showing potential moraines and the yellow hatch marks are showing areas of patterned ground. The satellite imagery is from a World View satellite and provided by The Polar Geospatial Center.

Figure 13: Patterned ground. The red lines are highlighting the cracks seen in the first image that are formed as freeze thaw occurs. Photo credit: Claire Todd

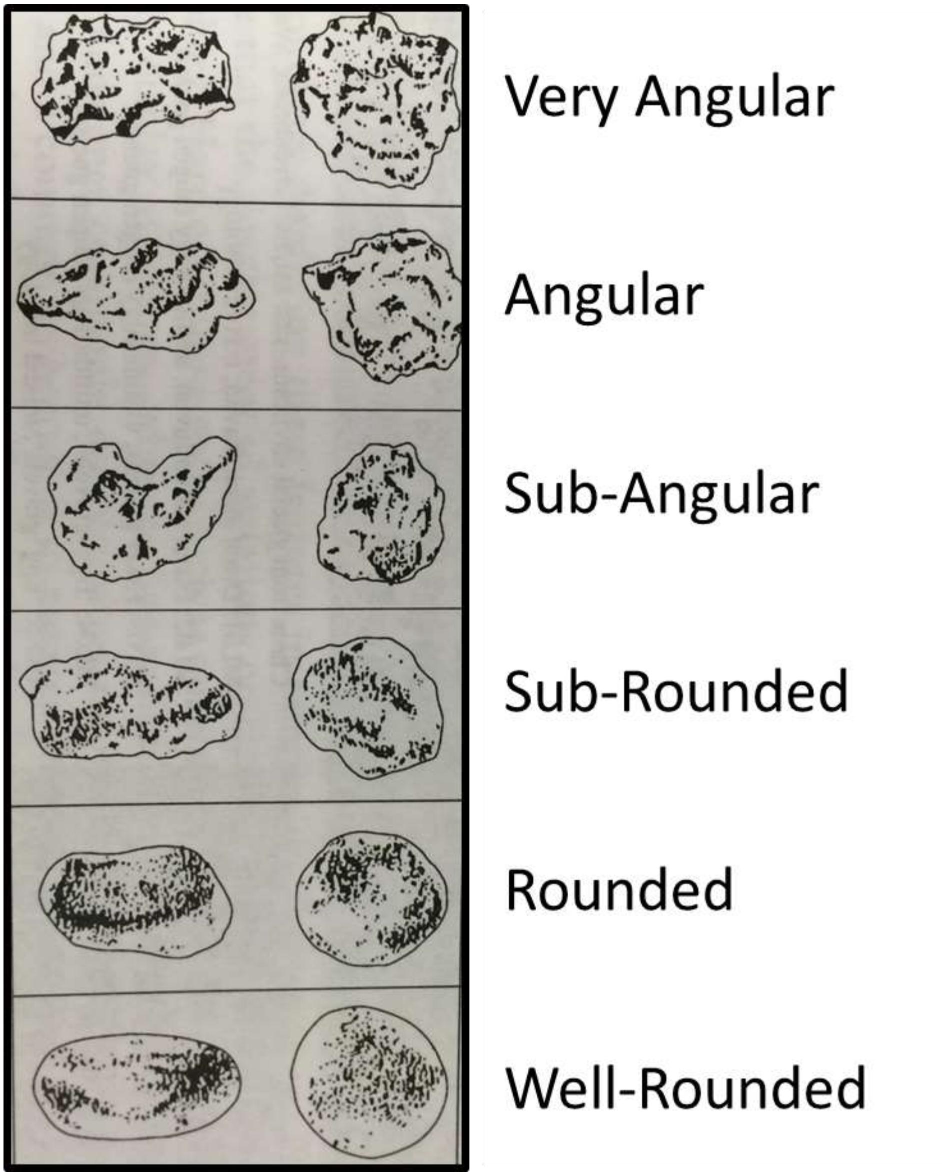

Figure 14: Powers, (1953) roundness scale**.** This diagram is showing the degree of roundness from very angular to well-rounded. This was used to determine the roundness of clasts >30 mm. Modified from Powers, (1953).

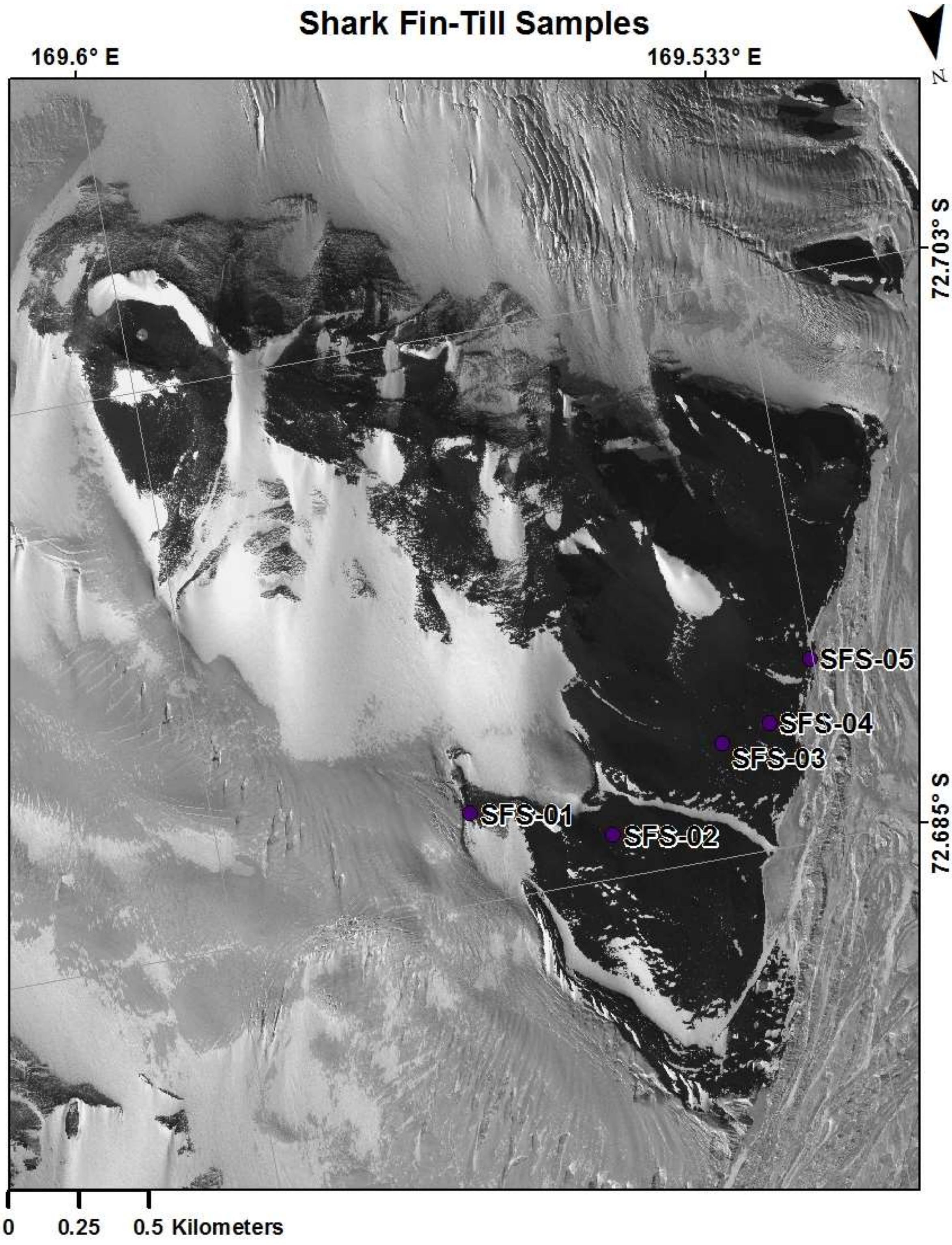

Figure 15: Shark Fin till sample locations. Site-01 is the highest sample location on Shark Fin and Site-05 is the lowest located on the marginal moraine.

Figure 16: Cavernously weathered boulder with iron staining and rough surface. Dr. Brent Goehring is used for scale. Photo credit: Claire Todd

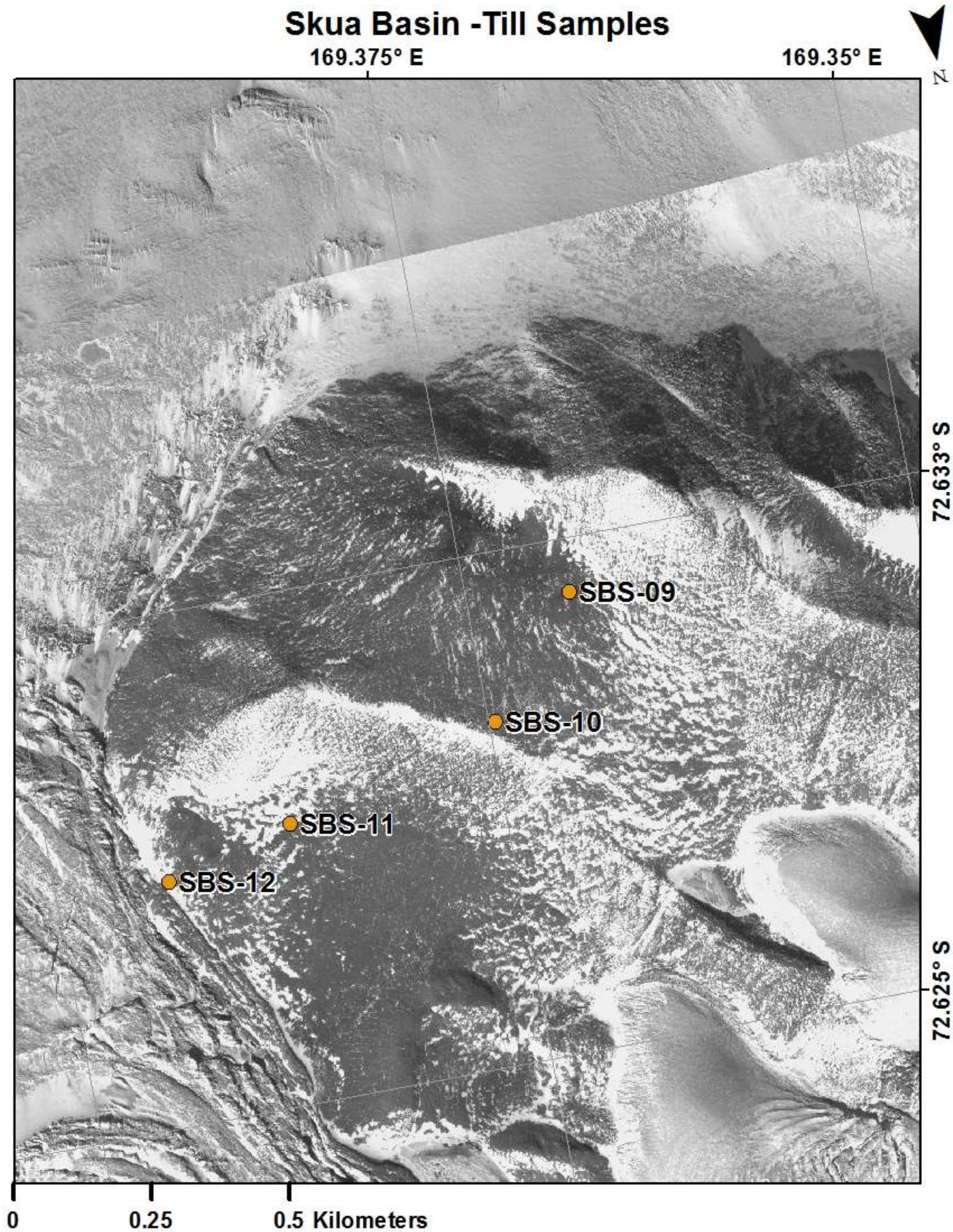

Figure 17: Skua Basin till sample locations. SBS-09 is the highest sample site at Skua Basin, and SBS-12 is the lowest, located on the marginal moraine.

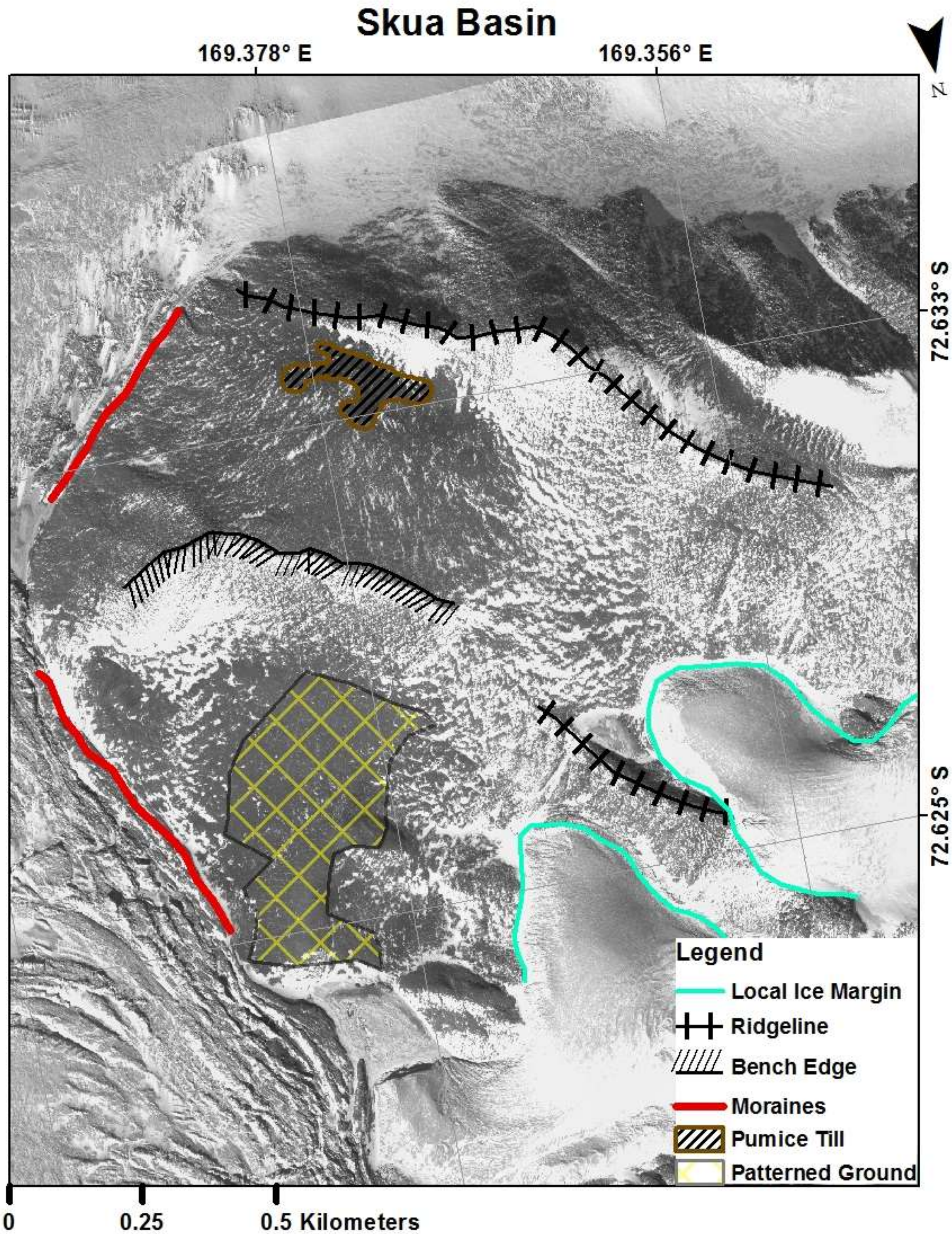

Figure 18: Glacial landform map of Skua Basin**.** This map is showing the different landforms identified at Skua Basin, the legend indicates the different symbols.

Figure 19: Fresher looking boulder at SBS-11, less discoloration from iron staining and smoother surface.

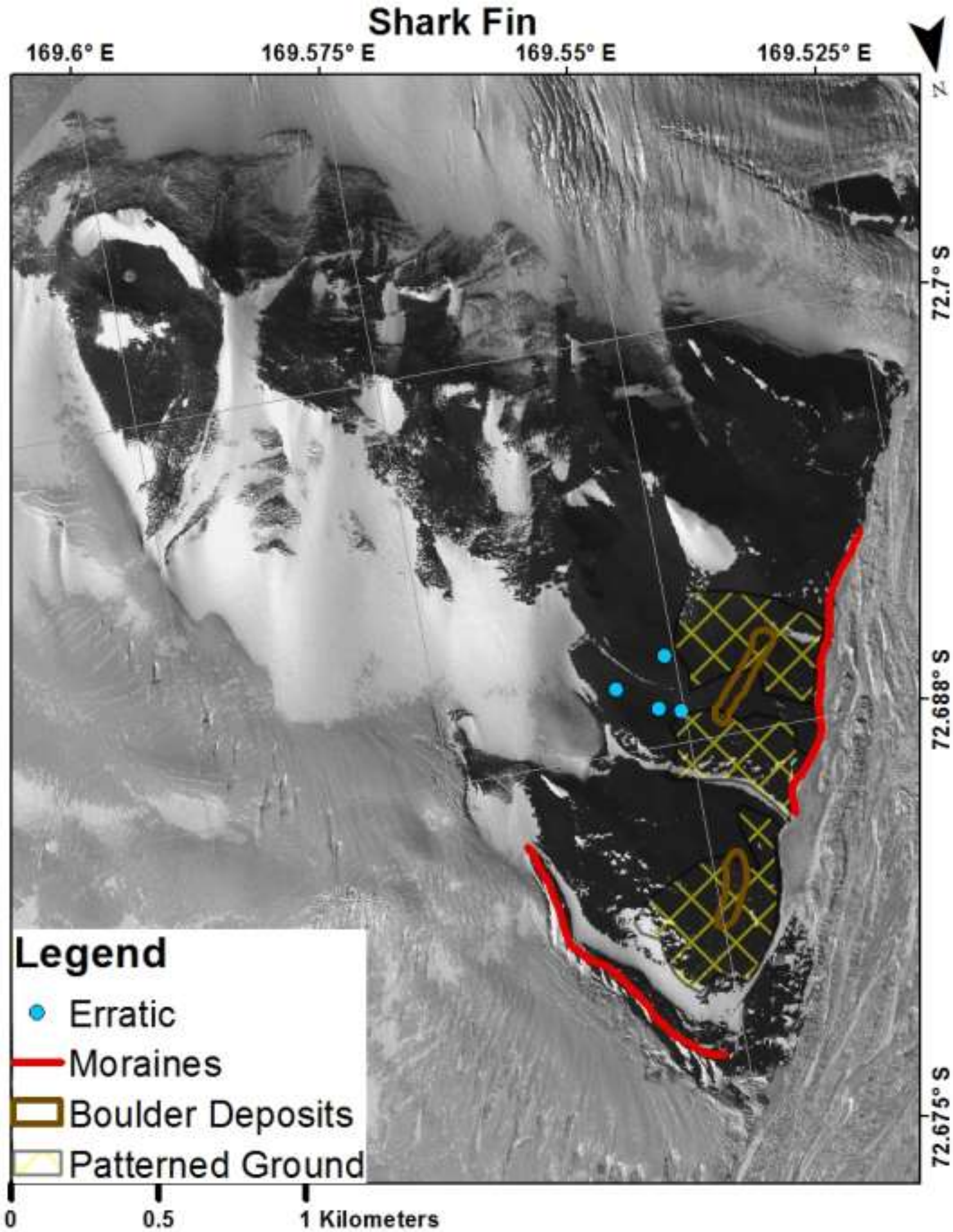

Figure 20: Glacial deposits at Shark Fin. The brown shapes are densely clustered granite boulder deposits, the blue dots are also granite boulders but not found in densely clustered areas.

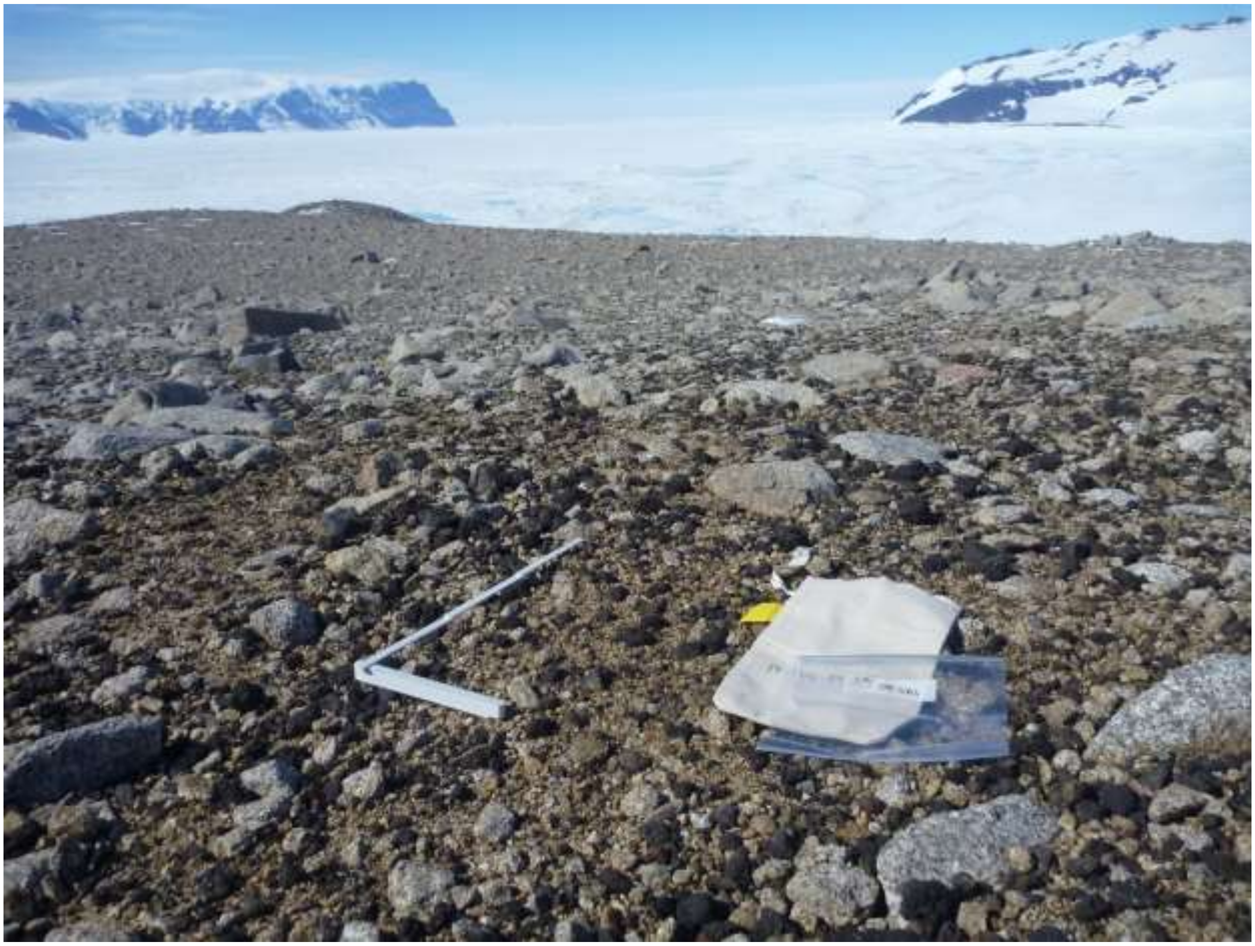

Figure 21: Pumice till at sample site SBS-09**.**

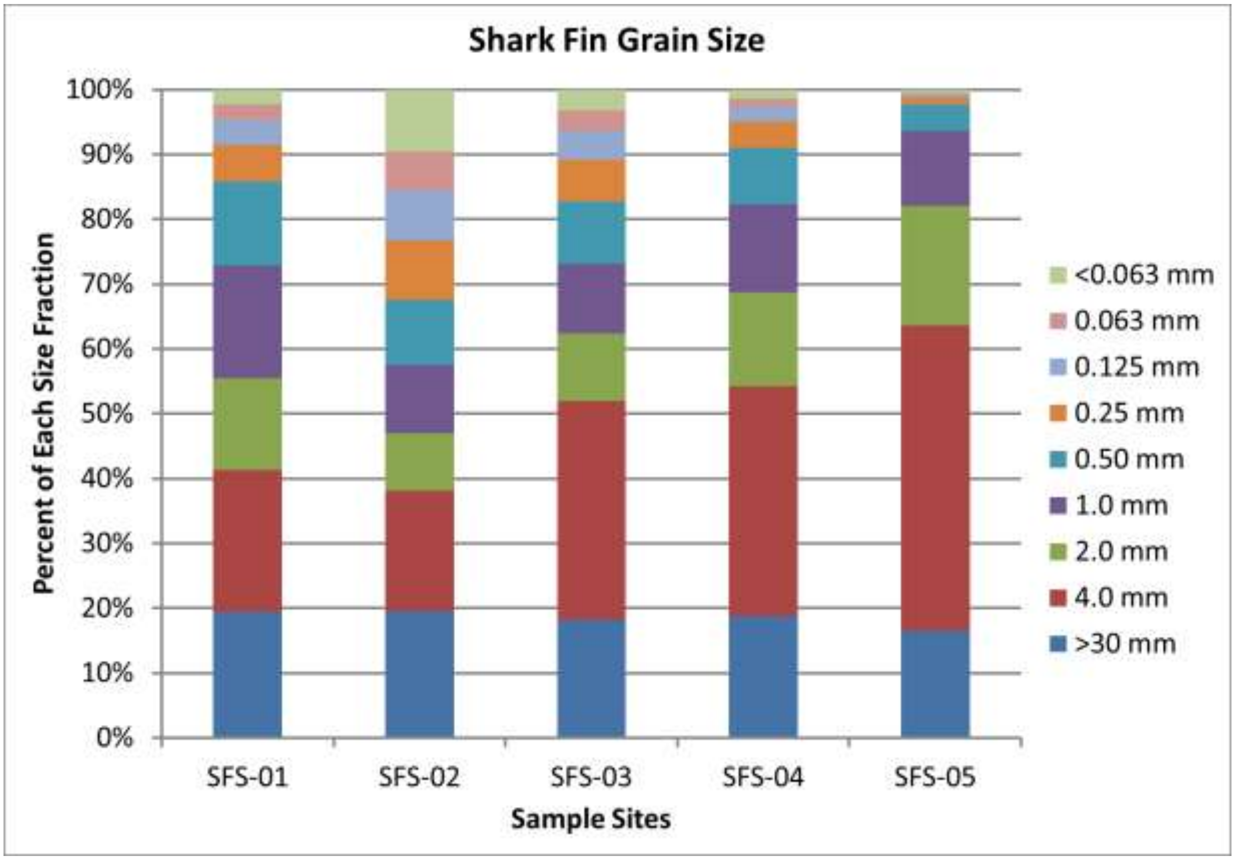

Figure 22: Grain size distribution at Shark Fin**.** This graph is comparing the grain size distribution at the five till sample sites on Shark Fin. SFS-01 is the highest elevation sample site and SFS-05 is the lowest.

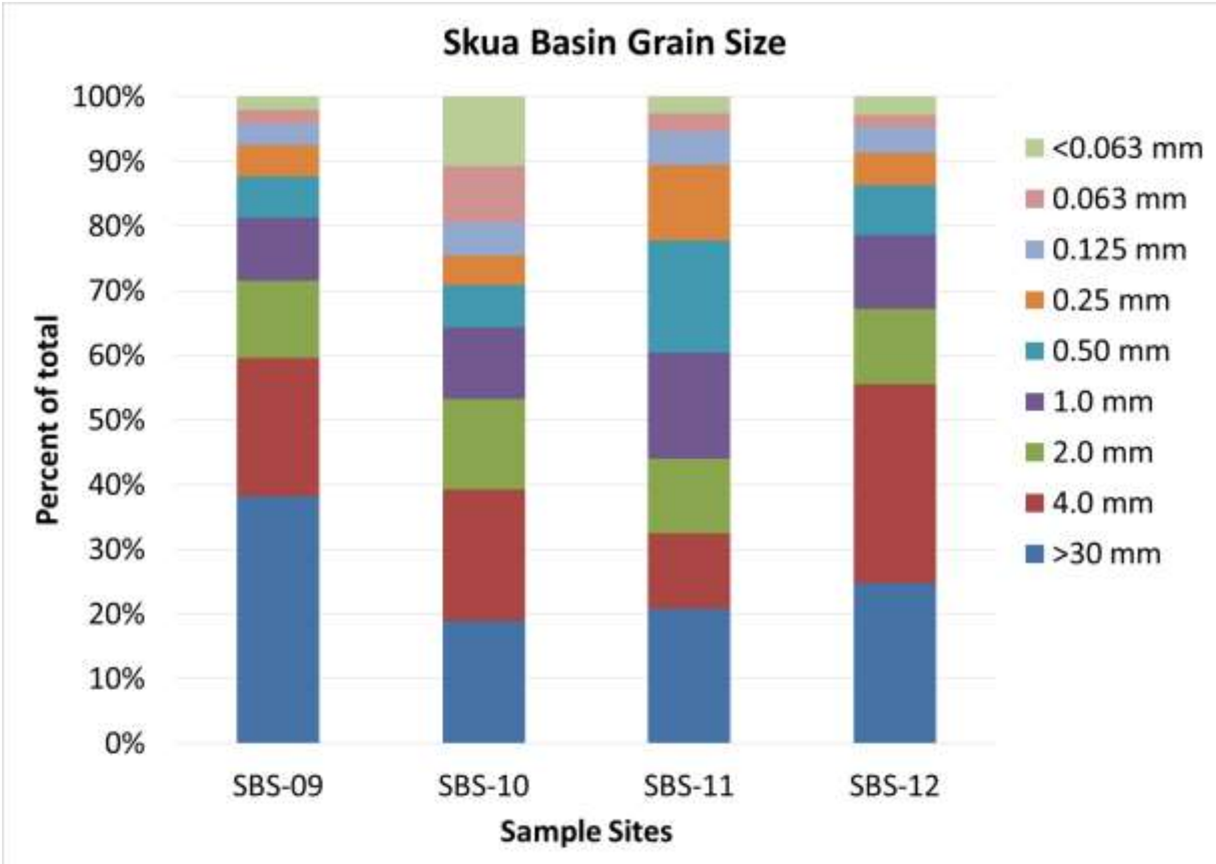

Figure 23: Grain size distribution at Skua Basin**.** This graph is comparing the grain size distribution at the four till sample sites on Skua Basin. SBS-09 is the highest elevation sample site and SFS-12 is the lowest. All four sample sites indicate different glacial environments. SBS-11 and SBS-12 are the most closely related and show the relationship with change in elevation.

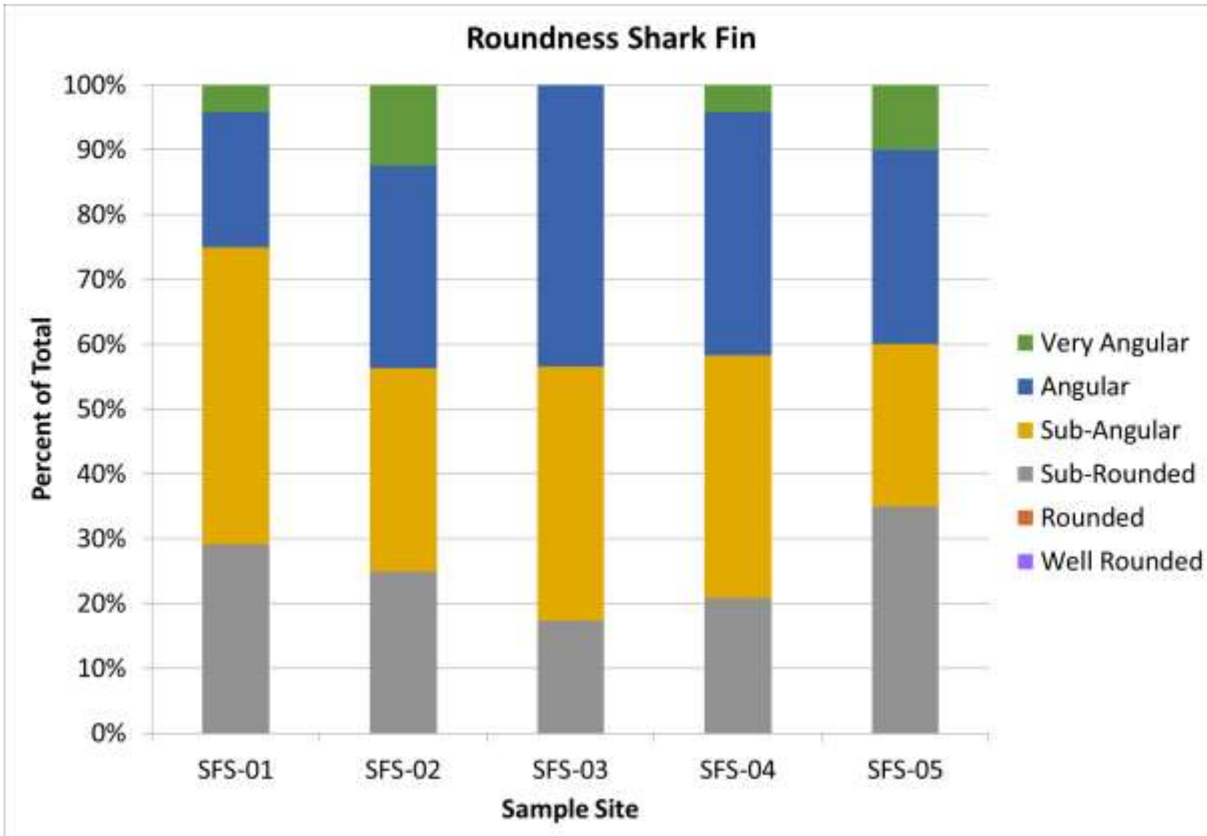

Figure 24: Roundness at Shark Fin**.** This graph is showing the different degrees of roundness in each of the samples from Shark Fin. There is a large spike in angular material at SFS-03, which is most likely due to the location of the sample.

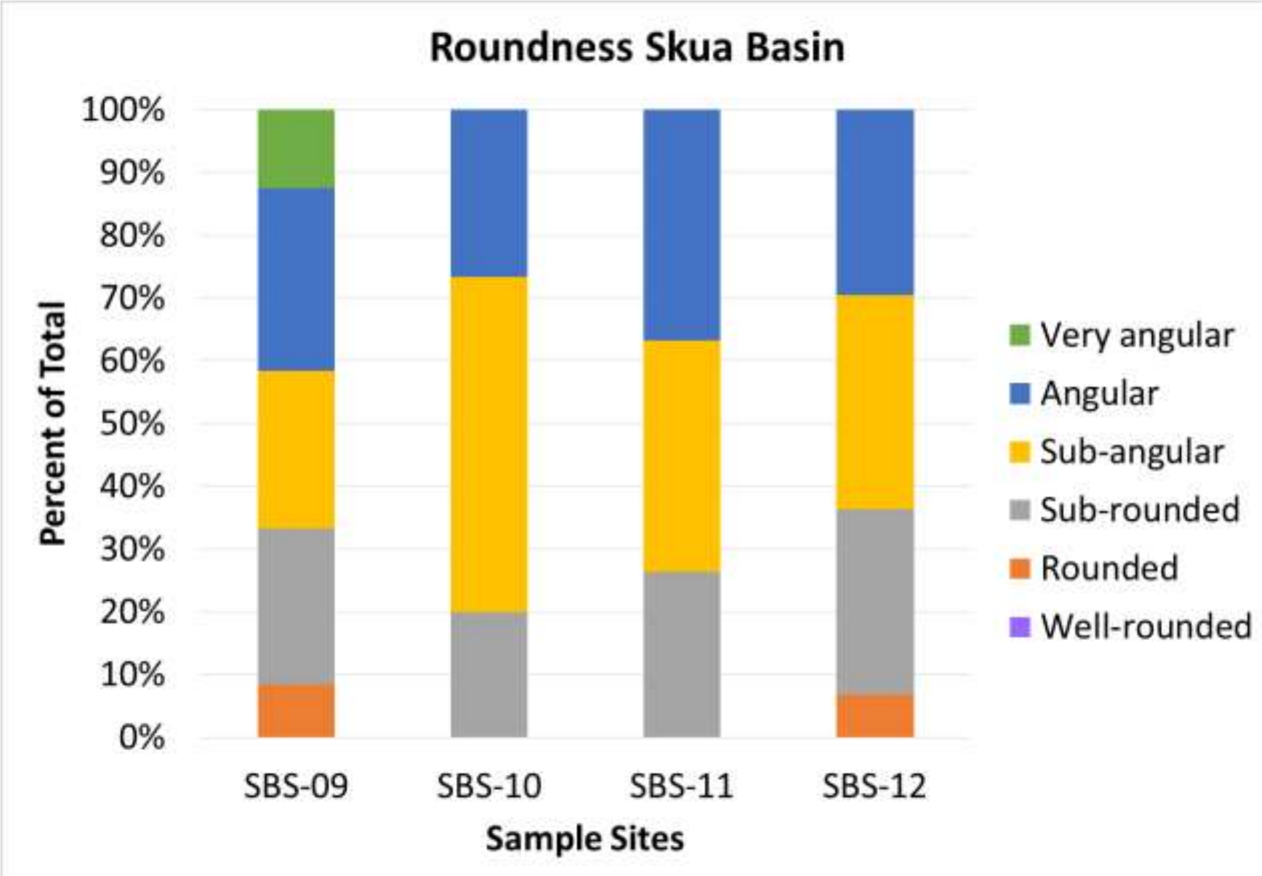

Figure 25: Roundness at Skua Basin**.** This graph is showing the different degrees of roundness in each of the samples from Skua Basin. There is rounded material identified at both SBS-09 and SBS-12, the highest and lowest sites.

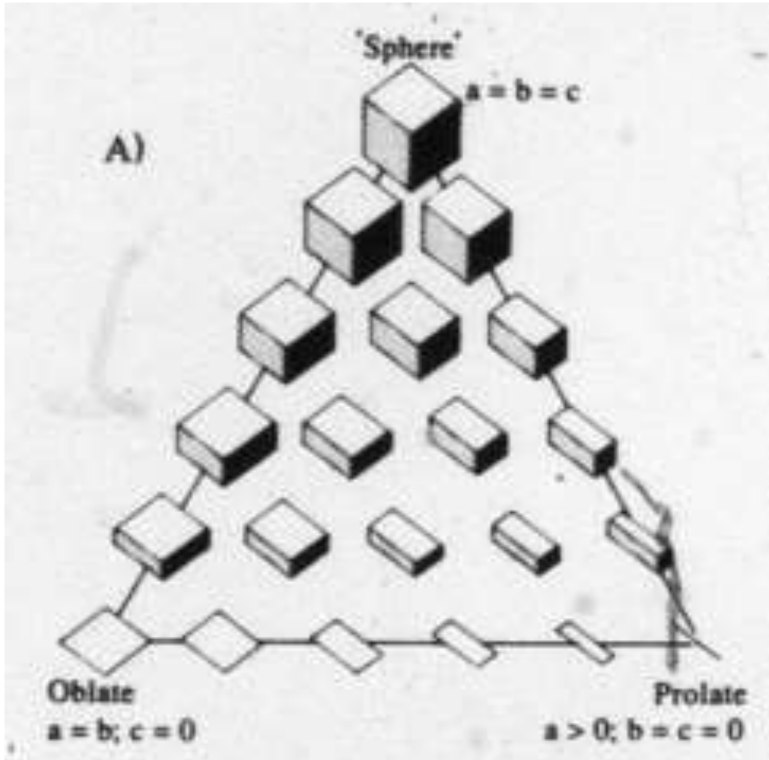

Figure 26: Shape ternary diagram**.** The different categories, including sphere or block, oblate or slab, and prolate or rod, also indicated are the clast axes measurements that would place a rock at one of these points.

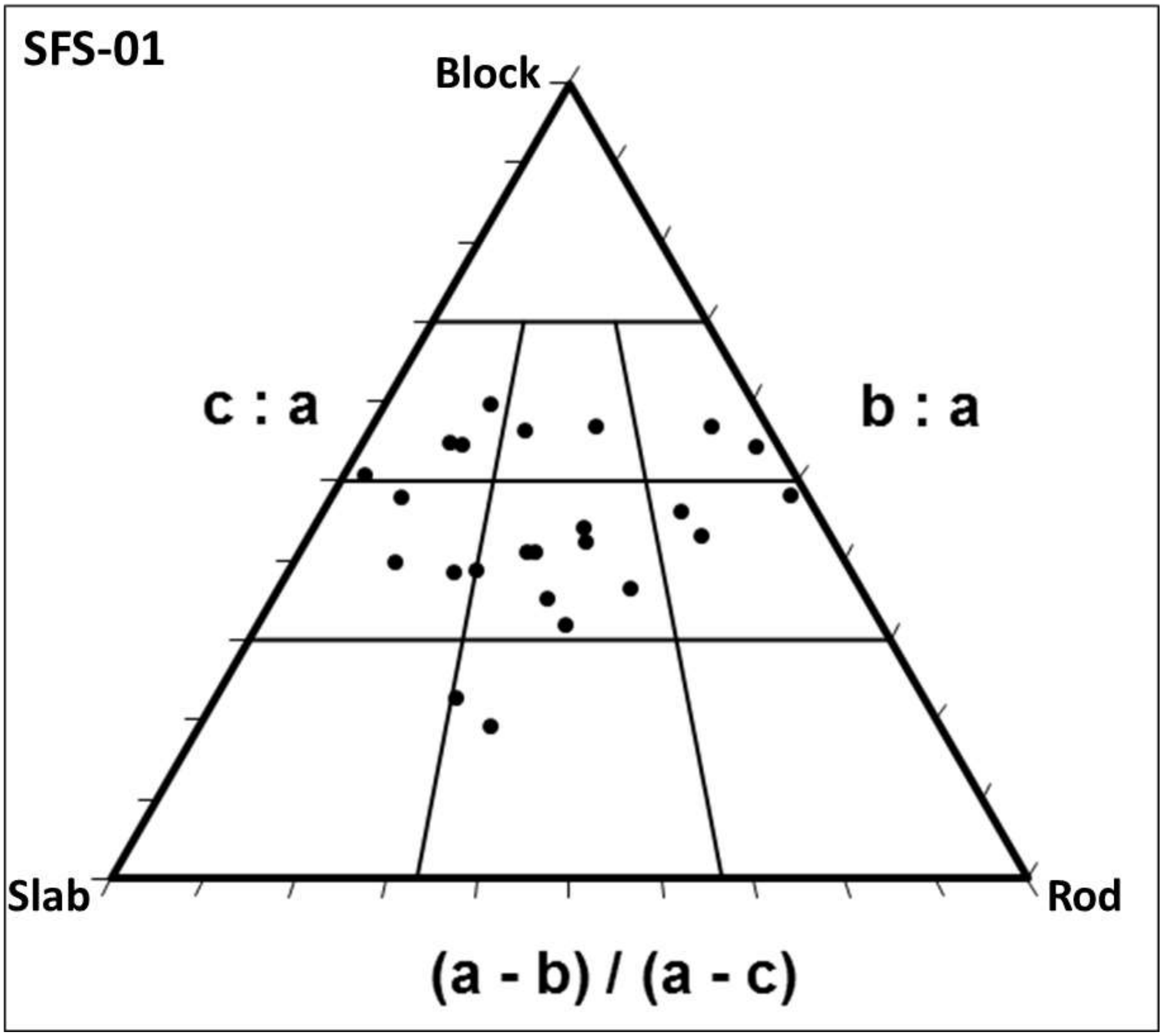

Figure 27: SFS-01 ternary shape diagram. This diagram is showing a supraglacial deposit containing some altered material.

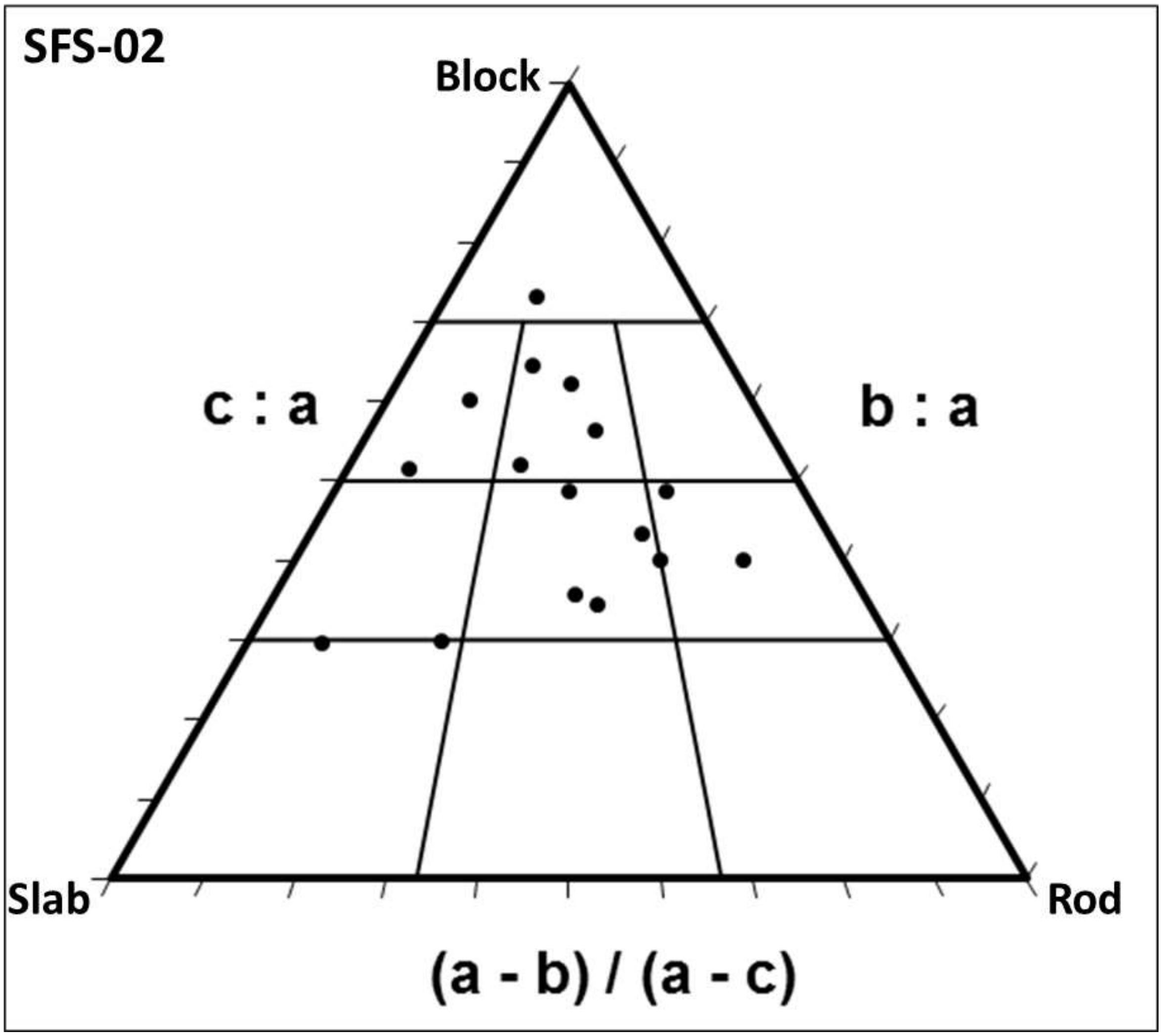

Figure 28: SFS-02 ternary shape diagram. There are not enough data on this graph to determine a representative deposit.

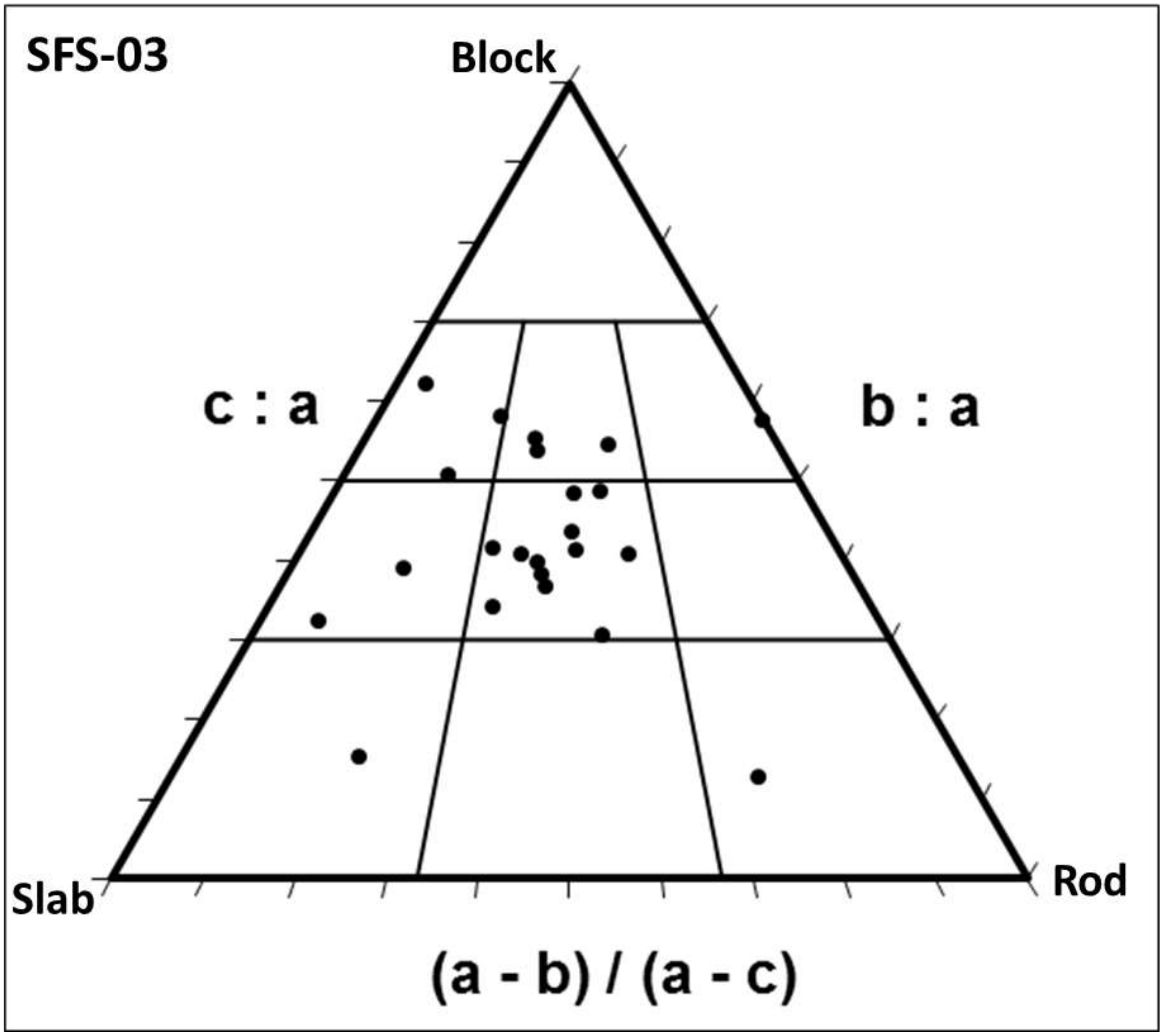

Figure 29: SFS-03 ternary shape diagram. The clustering of this material represents either scree or supraglacial material.

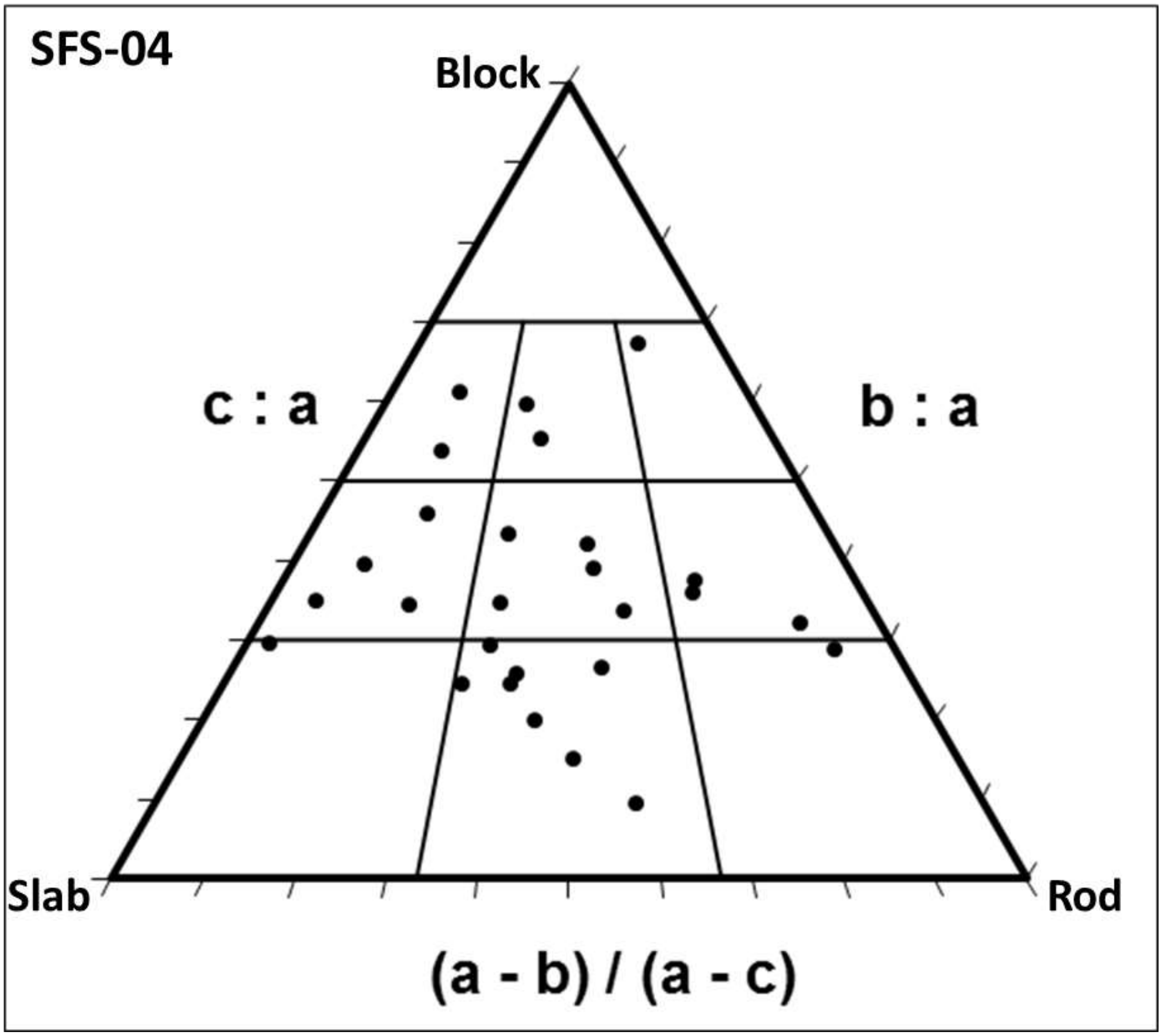

Figure 30: SFS-04 ternary shape diagram. The data points on this ternary diagram most closely represent a supraglacial deposit.

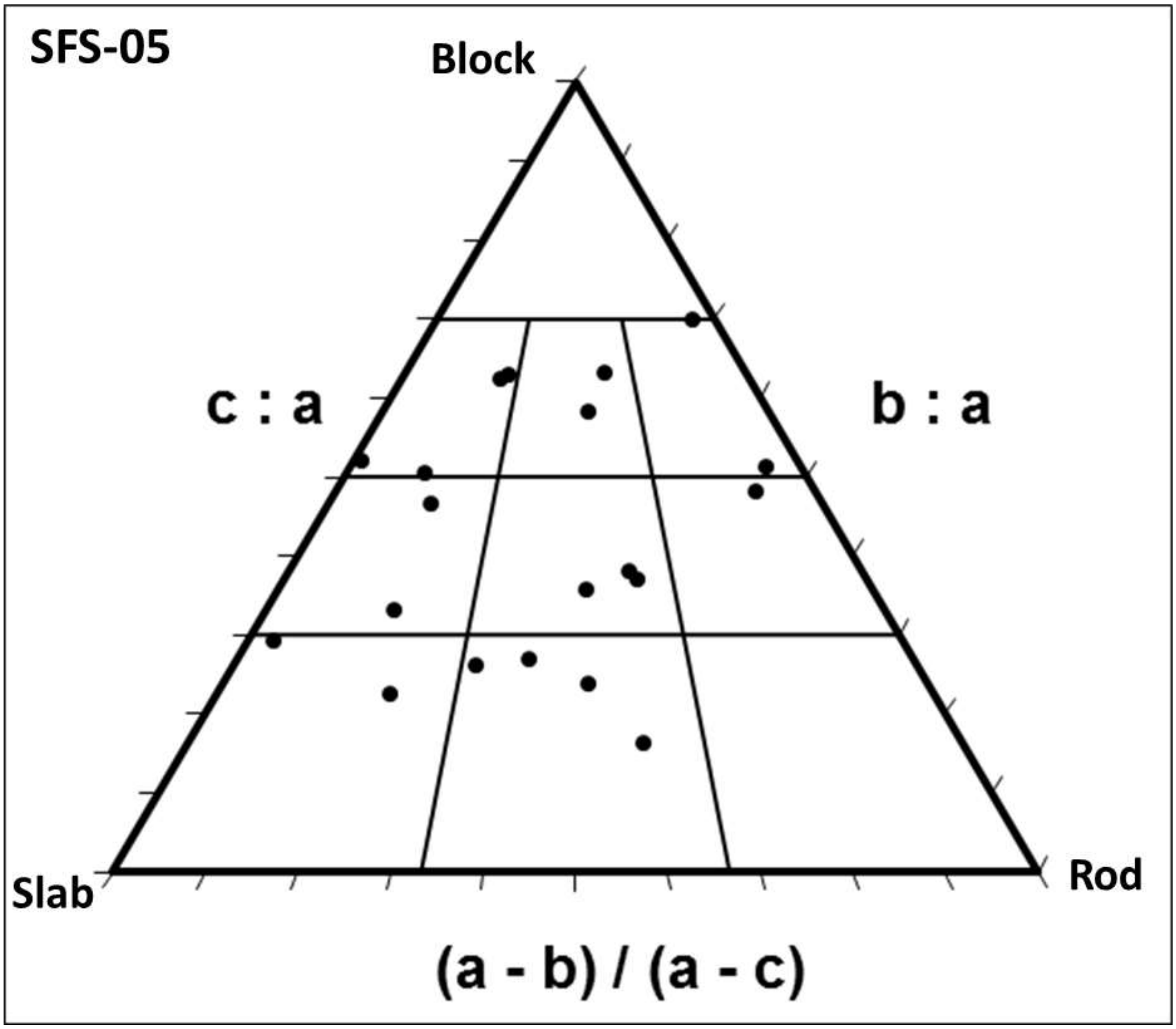

Figure 31: SFS-05 ternary shape diagram. There are not quite enough data points on this graph to determine a representation of the data.

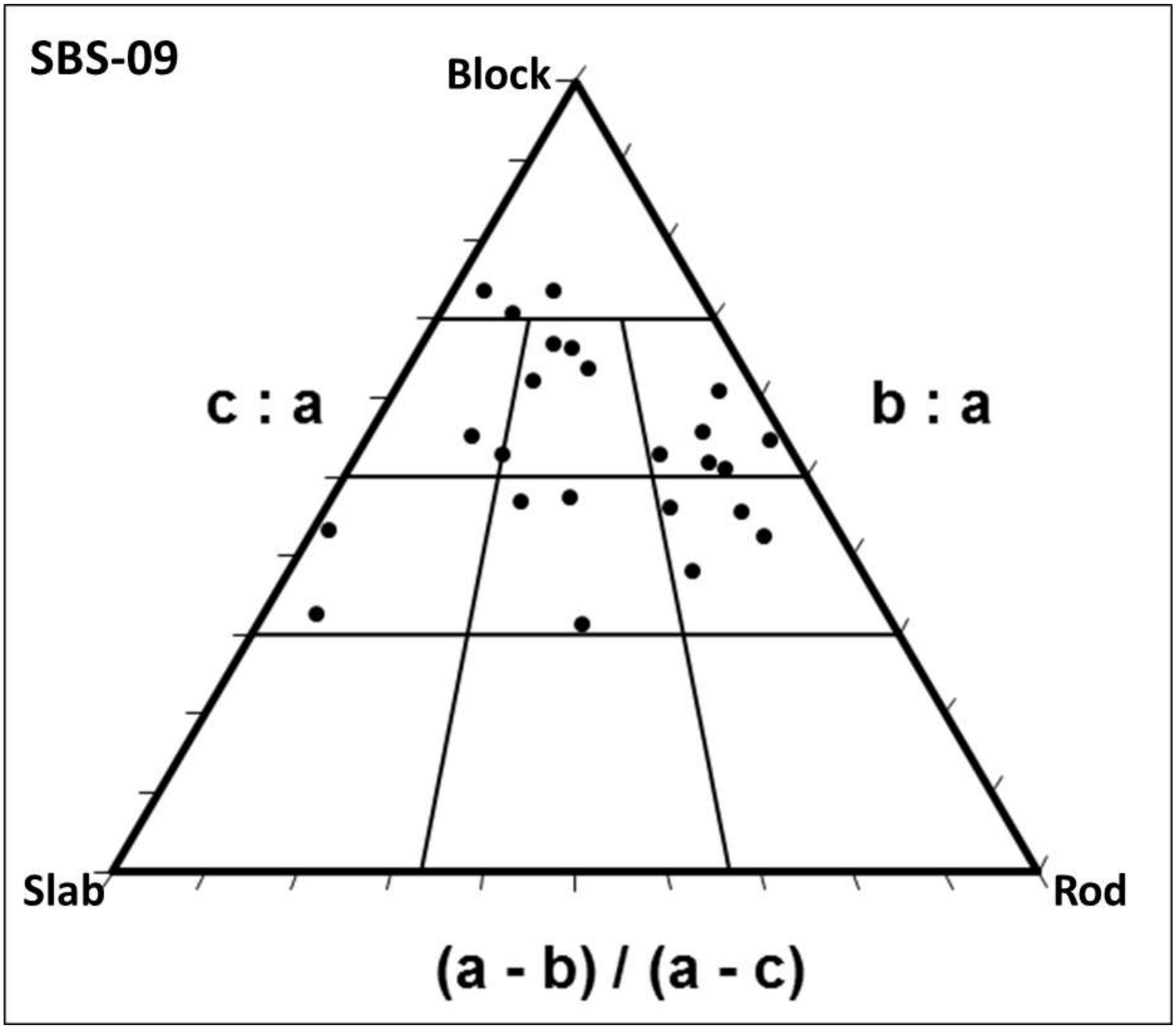

Figure 32: SBS-09 ternary shape diagram. This sample is most representative of a till sample.

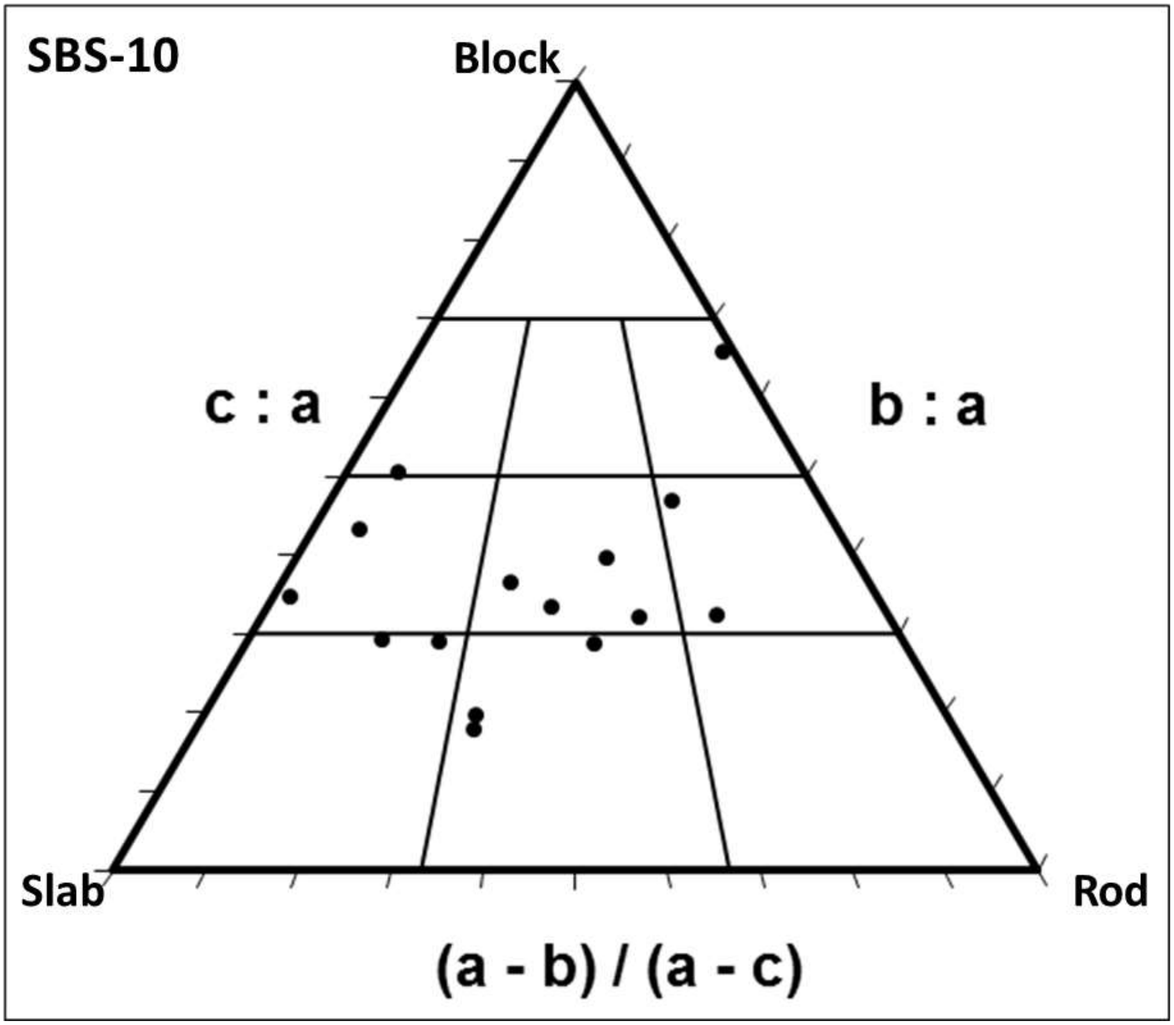

Figure 33: SBS-10 ternary shape diagram. There are not enough data points on this diagram to definitively describe the environment it represents.

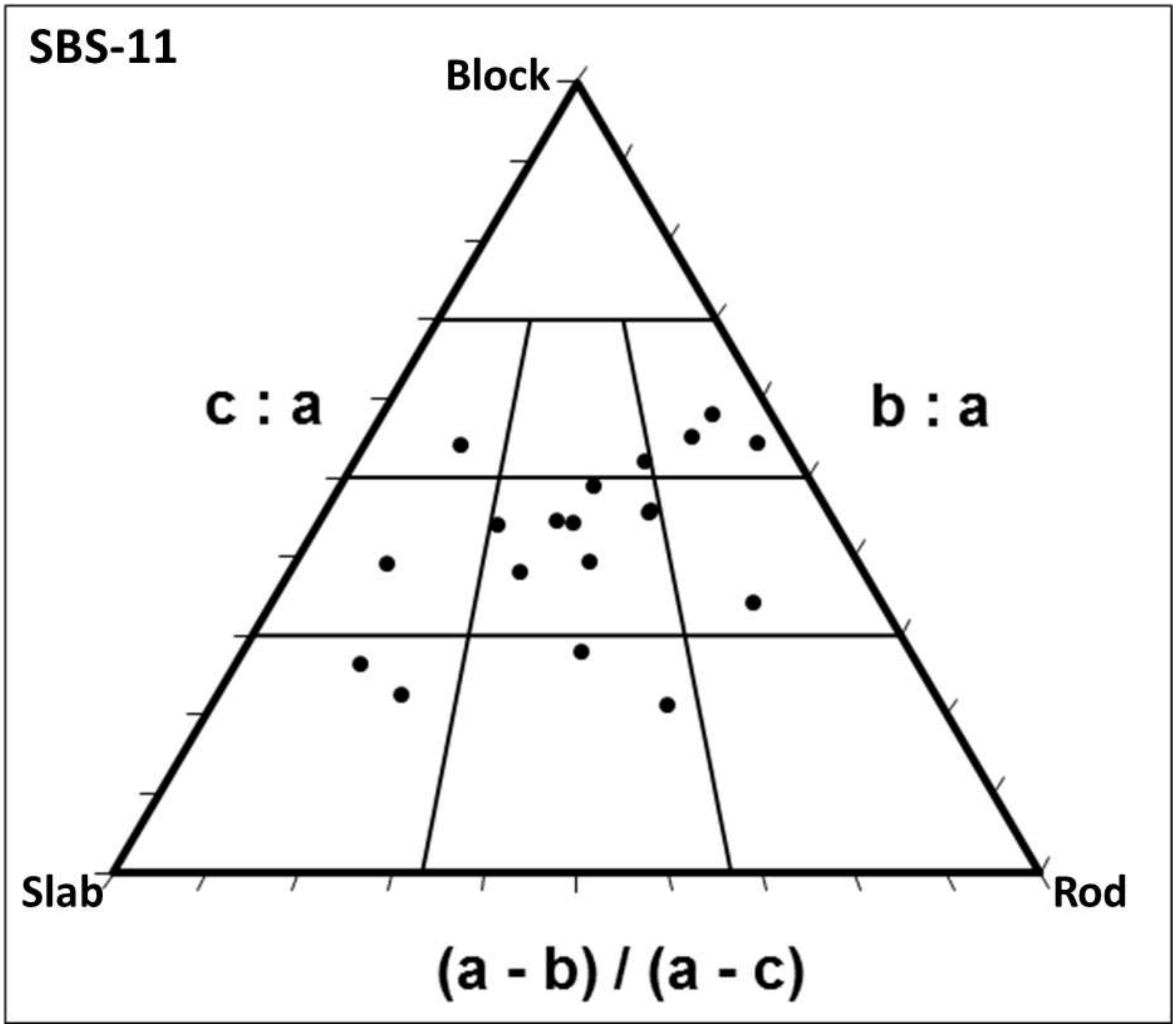

Figure 34: SBS-11 ternary shape diagram. The clustering here is indicative of scree or supraglacial material.

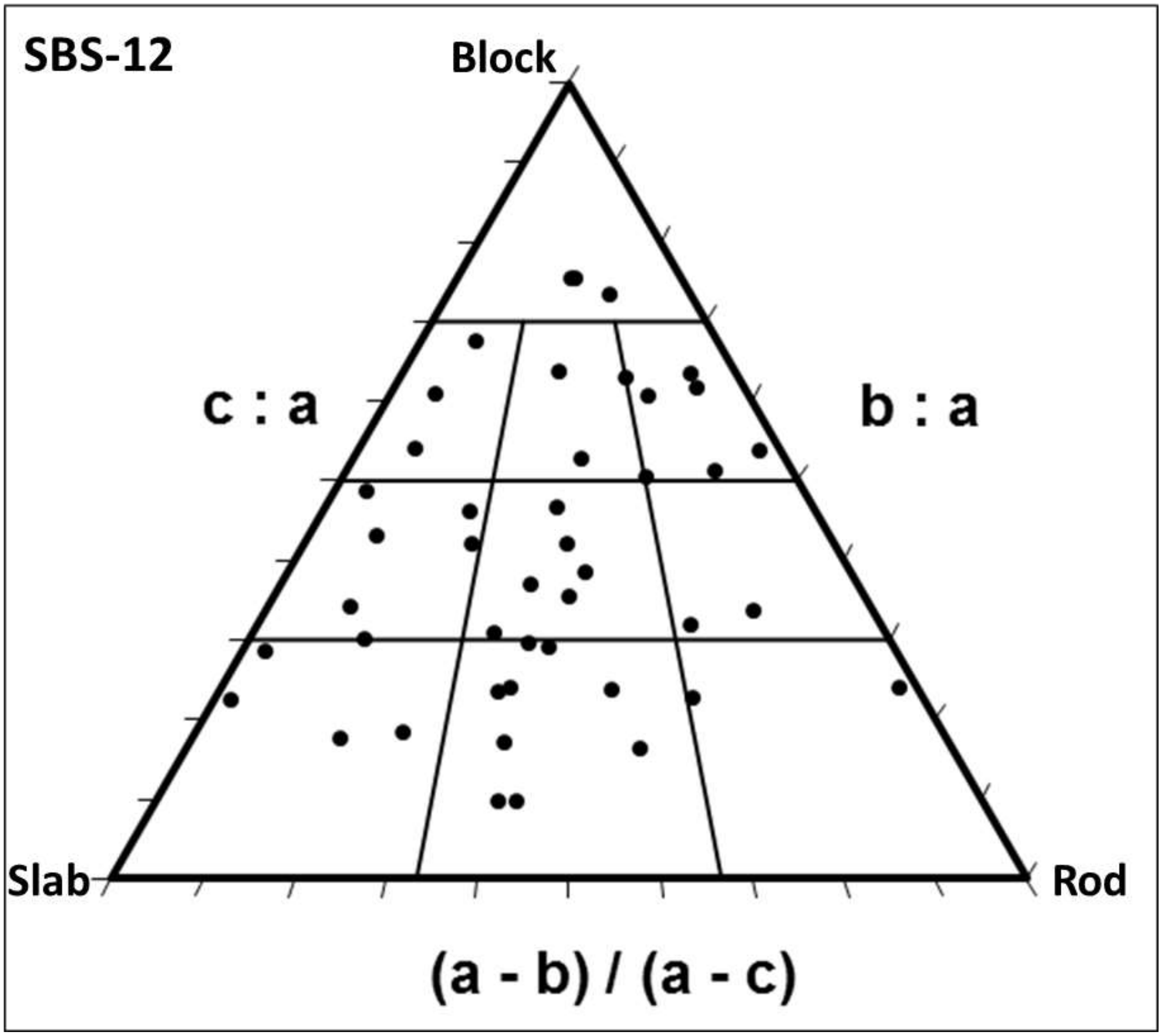

Figure 35: SBS-12 ternary shape diagram**.** This clustering of the dots is indicative of a supraglacial deposit.

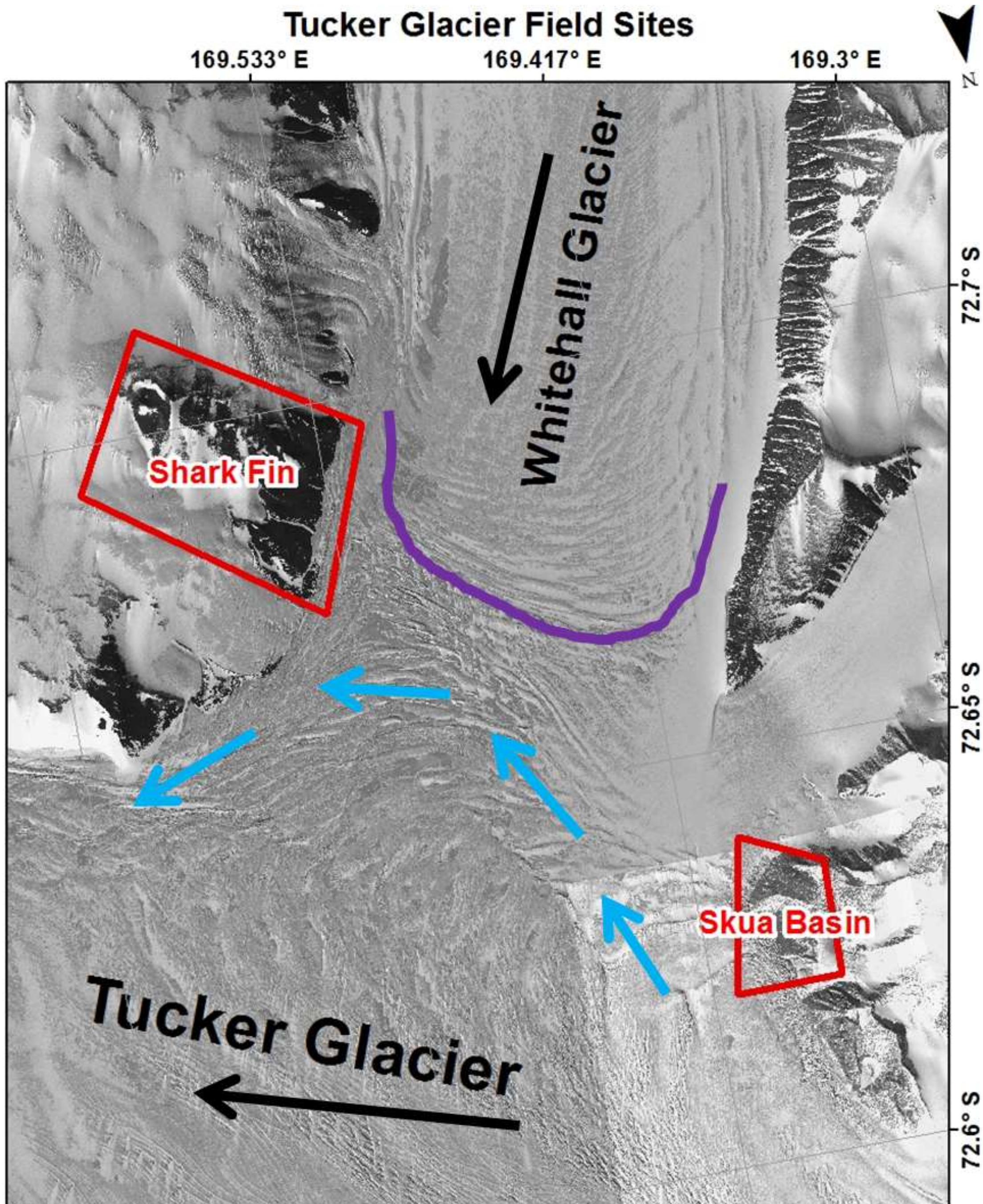

Figure 36: Flow directions for Tucker and Whitehall Glaciers. The blue arrows are showing flow of Tucker Glacier as well as transport path of material from Skua Basin to Shark Fin. The black arrows are indicating flow direction. The purple is representative of the Whitehall boundary and the red boxes are field sites.