New Insights into Gardar Rifting:

Geological Mapping of Tuttutooq, SW Greenland

Rory Changleng, Lot Koopmans, Lucy Mathieson, Alasdair Murphy, Rob Webster

31/12/19

Contents

Preface

We are a group of five undergraduate Geologists from the University of St Andrews who undertook a six-week geological mapping expedition to the island of Tuttutooq, south-west Greenland, during the summer of 2019. Our focus was on ancient igneous intrusions representing the guts of a continental rift system. Their unique nature presented the perfect opportunity to study the processes that give rise to unique, and often economically crucial, geology. We arrived on our uninhabited island by boat and were greeted on the first few mornings by a thick carpet of frost. By the time we left, all the snow had melted, the temperatures were in double digits and Greenland was experiencing one of its warmest summers on record. Each morning we woke up to the sound of songbirds and crashing icebergs and were treated to unspoiled views across endless fjords. Although there were challenges, each member of the team had the time of their lives and fell completely in love with our bonnie wee isle. We are excited to see the scientific outcomes of this expedition continue to grow and to see where the geological and logistical skills we have learned will lead us. It goes without saying, how immensely grateful we are to those who supported this expedition and allowed us to study world class geology in a place as magical as Greenland; we hope that as you read on, you will be able to share at least a little of our experience.

Rory Changleng - Expedition Leader

Team Members

Rory Changleng

Age: 21

Nationality: Scottish (British)

Degree: MGeol

Favourite Mineral: Sodalite – it exhibits tenebrescence meaning it changes colour when exposed sunlight.

Favourite Field Snack: Mint Imperials

Rory is fascinated by the natural world around him and developed his passion for geology through exploring the natural landscapes of Scotland. Although he enjoys all aspects of Earth Science, petrogenesis has become his primary focus. From the Swiss Alps to the Barberton Greenstone Belt of South Africa, he has been fortunate enough to examine much of the world's best geology through both university and self-directed field trips. His love of exploration and our natural world shows in his other passions, namely white-water kayaking, mountain biking, hiking and photography. He is especially grateful for this opportunity to undertake a geological expedition to south-west Greenland as it has developed his self-confidence and geological skillset immeasurably, both of which he looks forward to using in the adventures to come.

Lot Koopmans

Age: 20

Nationality: Dutch (The Netherlands)

Degree: BSc Geology

Favourite Mineral: Plagioclase

Favourite Field Snack: Biscoff Wraps

Lot finds peace in the great outdoors, seeking out areas untouched by man. Be it through hiking, skiing, or surfing on the open waters, he feels incredibly lucky to combine this with his passion of science through geology. His geological interests lie in igneous and structural geology, and loves tackling large questions that remain unanswered. Lot enjoyed the daily showers in the frigid lake, and became an expert in tin-can culinary skills during his time in Greenland.

Lucy Mathieson

Age: 21

Nationality: Scottish (British)

Degree: MGeol

Favourite mineral: Tugtupite

Favourite Field Snack: Jelly babies

Lucy's interests lie with igneous petrology and physics, but she loves mapping and structural geology, too. Although never happier than when doing fieldwork, she is very much looking forward to learning and utilising geochemical techniques in the lab as part of her Research Placement and Masters dissertation. Aside from her studies, Lucy is a keen baker and loves to bake treats for her friends and family (as a group we can vouch for this!). She also plays the French Horn and enjoy walks along the Fife coastal path. Lucy has no doubts when she says that Greenland was the best experience of her life and believes the benefits gained from the expedition are boundless. She will never forget her time there and is sure to carry the acquired skills and expertise to her next ventures.

Alasdair Murphy

Age: 22

Nationality: Scottish (British)

Degree: MGeol

Favourite mineral: Labradorite

Favourite Field Snack: Mushy peas!

Driven by a love for the outdoors (and mushy peas), Alasdair is most at home sliding down a rock face in the name of science or fun. Currently, he achieves this through igneous petrology, geochemistry, climbing and white-water kayaking. Armed with bad jokes and an equally suspect music taste, he made sure island life wasn't taken too seriously. Until now his exploration has remained UK based, but, using Greenland as a springboard, he is already planning how he can take his passion for outdoor sports and geology elsewhere in the world.

Rob Webster

Age: 21

Nationality: English (British)

Degree: MGeol

Favourite mineral: Aegerine

Favourite Field Snack: Custard Creams

Rob is driven to wonder by all things rock related and loves a chemical formula to help understand a system to the most intricate level. Constantly putting random things in his pocket as a child, he turned his interest towards collecting only rocks. Nowadays, this manifests itself as igneous petrology and an untameable thirst for knowledge. He is a firm believer that wearing rugged gear in the cold outdoors is the best way to conduct fieldwork but that this is best followed up by moving indoors to train judo, to calm and discipline the mind. Greenland left an immeasurable impression on him.

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Alasdair – ajm46@st-andrews.ac.uk

Rob – rw99@st-andrews.ac.uk

Introduction and Geological Motivation

Introduction to Gardar Geology

The geology of South-West Greenland is intimately linked to the life cycle of the Columbia supercontinent. Its formation, ~1800 Ma (million years ago), gave rise to granite and gneiss which currently forms basement rocks; its breakup, ~1300 – 1100 Ma, is expressed in sedimentary sequences and a series of magmatic intrusions. In SW Greenland, this break up period is known as the Gardar and its area of influence is named similarly.

Magmatic bodies in the Gardar take the form of dykes, giant dykes, and central complexes, although there are some other minor components such as diatremes. The present-day exposure of these bodies is excellent and represents a depth of 3-5km relative to the ancient surface; what we see is thought to be analogous to the roots of the modern day East African Rift (EAR). Chemically they can be designated to a scarce family of rocks, known as the alkaline suite, but within this they represent some of the most primitive and evolved rocks known to man. This rich diversity presents the perfect opportunity to study the mechanisms and processes occurring within igneous systems.

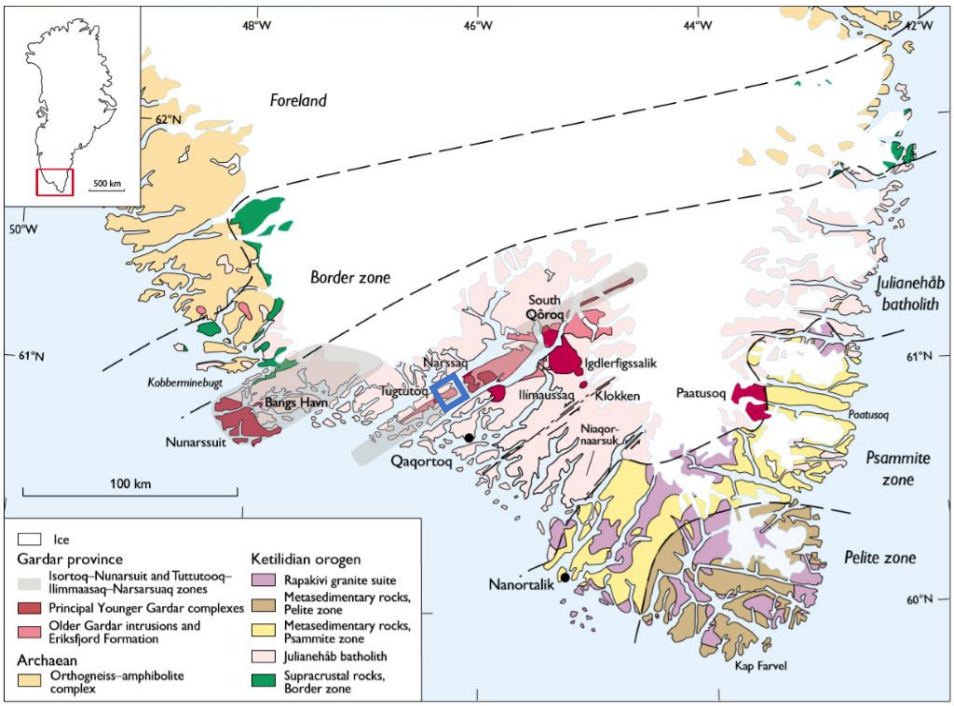


Figure 1. Generalised geological map of Southern Greenland. The eastern side of Tuttotooq island is indicated by the blue box. Adapted from Upton 2013.

Much research has already been carried out within the Gardar province, with widely applicable outcomes. The direct analogies to the EAR aids our understanding of the volcanic systems that have massive potential to sustain life yet can be so devastating. Alkaline rocks can act as concentrators of critical metals that are crucial for modern technology. Not only does the Gardar contain deposits of such elements but the systems leading to their concentration can be readily studied and applied elsewhere. However, despite this work, many discoveries and breakthroughs are still to be made concerning alkaline igneous systems and the Gardar is the perfect place to do this.

For further discussion of the Gardar province, refer to Prof. Brian Upton's excellent 2013 memoir.

Figure 2. A view towards the Ilímaussaq (top) and Motzfeldt complexes (bottom). Both host critical metal resources and Ilímaussaq in particular has one of the world's largest inventories of rare earth elements. Note the scale, these mountains are between 1300-1500m in height.

Tuttutooq in a Geological Context

The island of Tuttutooq (previously Tugtutôq) lies within the Gardar province, to the west of Narsaq township. Original mapping by Prof. Brian Upton, he revealed the presence of two giant dyke complexes (the Older & Younger Giant Dyke Complexes, henceforth OGDC & YGDC), a central complex (the Tugtutôq central Complex), expressions of the Late Gardar main dyke swarm and ultramafic lamprophyre (UML) bodies. Since then, some subsequent research has focused on the island but, despite its diverse geology, this has been limited (cf. Mingard 1990, Upton 2006).

As a team we were drawn to the island due to its diversity but also because of some specific features: the YGDC has several 'pods' where it develops layering or evolves from basaltic to syenitic; the UML's deviate both spatially and geometrically from their equivalents near Narsaq; zones within the central complex represent different magmas from the same source. UML's are representative of the most primitive mantle melts, evolution of magmas such as

the YGDC lead to bodies such as the Ilímaussaq complex and layering is dependent on magma chamber dynamics. Thus, the island would allow for the investigation of the bigger picture of magmatism – from beginning to end.

Aims

After distilling our motivations for going to Tuttutooq we arrived at the following aims:

1. To create a detailed 1:5,000 scale geological map of Eastern Tuttutooq, with particular focus on ultramafic lamprophyres, the late dyke swarm, part of the central complex, the evolved Assorutit pod of the YGDC, and the layered basins at Sissarlutoq & Marrait within the YGDC.

2. To undertake a systematic sampling campaign to allow for further work to be carried out. Particular focus on transects across the YGDC, within the evolved pods and layered basins, will allow for geochemical and magnetic analysis to enhance understanding about dyke emplacement, magmatic evolution and magma chamber dynamics.

3. To gain experience in organising a multi-week expedition to a challenging Arctic environment.

Expedition Notebook

January - May, **Planning and Preparation**: Over these months we organised everything we'd need for the expedition: equipment, food, shipping our equipment & food, funding, in-country logistics, basemaps etc.

27th-31st May, Travel: Travelling to Tuttutooq from Edinburgh via Copenhagen, Kangerlussuaq, Narsarsuaq and Narsaq. Transport methods included airplane and boat. We collected our shipment from a warehouse in Narsaq before heading to Tuttutooq where a day was spent moving boxes on the island and setting up camp.

Figure 3. Loading the boat with our gear and food.

1st June-19th June, **Independent mapping**: Days began at around 07:30/08:00 when we enjoyed many bowls of porridge before setting off at 09:30 and returning at around 18:00. We ate dinner at around 20:00 after bathing in the lake and making our lunches for the next day. Everybody was usually tucked up in their tents by 22:00 when we looked over our maps and work from that day. Towards the end of this time we started collecting samples.

Figure 4. Celebrating Lucy's 21st birthday with mac n' cheese and surprise Irn-Bru

20th June-24th June, Time in Narsaq: A short break in Narsaq allowed us to start organising the samples we had already collected and to experience life in Greenland. It gave the opportunity to visit the geological sweetshop of the Kvanefjeld mine tailings. We were also able to meet with the local manager of Greenland Minerals how are looking to develop the mine.

Figure 5. Left: Hiking to the Kvanefjeld mine tailings. Right: fortunately, we only met the friendlier locals

25th June-6th July, Last field push: This stretch of the trip was used to finish up our geological maps and begin rock sampling. A day was spent dissembling the camp and making sure we left no litter or rubbish on the island. Two boat trips were required to return all of our samples from the island.

Figure 6. Working hard or posing for the camera?

7th July-12th July, Final days: A couple of days were set aside as a bad weather buffer to make sure we could return to the UK. Fortunately, these weren't needed so the time was spend in Narsaq packing our rock shipment and revisiting Kvanefjeld to collect samples for the department. We were also able to aid a team from the USGS who were conducting work in the area too. We said goodbye to the friends we had made and travelled back to Narsarsuaq. Here, we hiked to the Narsarsuaq glacier which was a fantastic experience. After that, Lot and Rory flew home to prepare for research in South Africa. Rob, Alasdair and Lucy stayed in Narsarsuaq to conduct further work with Kris, a PhD student from University of St Andrew's. The time spent on Tuttutooq meant everybody was better prepared for the work in South Africa and as Kris' field assistants in Igaliku.

Problems encountered

Although the expedition was a resounding success, it was not without its setbacks. Our first plight became apparent upon realising that the small peninsula our boat driver had found as a suitable landing point was tidal. Fortunately, we realised sooner rather than later but with 28 boxes to move and Greenland's large tidal range, by the time our last box had been moved we were wading through knee deep water from the Labrador Sea. Then, the heavy boxes had to be carried through a treacherous boulder field that traced around the bay. Had we been dropped off on the opposite side of the bay, this task could have been avoided and would have saved a day of work. The camp was a further 2km from this point and we took turns ferrying boxes of food and equipment.

We had heard stories of the flies on the island but hadn't quite expected what we were presented with. Once night temperatures rose to roughly freezing the black flies and mosquitoes started to make daily tasks that little bit trickier. By the end of our time we still hadn't found an optimal solution that maximised amount of rock seen and minimised the number of flies eaten but we were able to eat in relative comfort.

Due to topography and a recurring knee problem we had to abandon our aims regarding the Tugtutôq Central Complex and switched up the mapping areas to include a section where the main dyke swarm could be studied in more detail. Our only other injury was a twisted ankle, which luckily occurred just before our break in Narsaq, allowing for a short period of rest before mapping was continued.

If anything, the setbacks taught us resilience and the successes far outweighed any drawbacks.

Figure 7. Left: rescuing our boxes from a tidal island. Right: on the fly solutions for eating in peace. Bottom: we got on well as a team…mostly.

Scientific Research and Maps

After an initial reshuffling of mapping areas, our areas of study were as displayed in figure 8 (see figure 1 for regional context). Although this didn't allow for study of the central complex, we were able to spend time looking at the Younger Giant Dyke Complex, Older Giant Dyke Complex, late Gardar main dyke swarm and ultramafic lamprophyres. Our time on the island provided new insights into each of these.

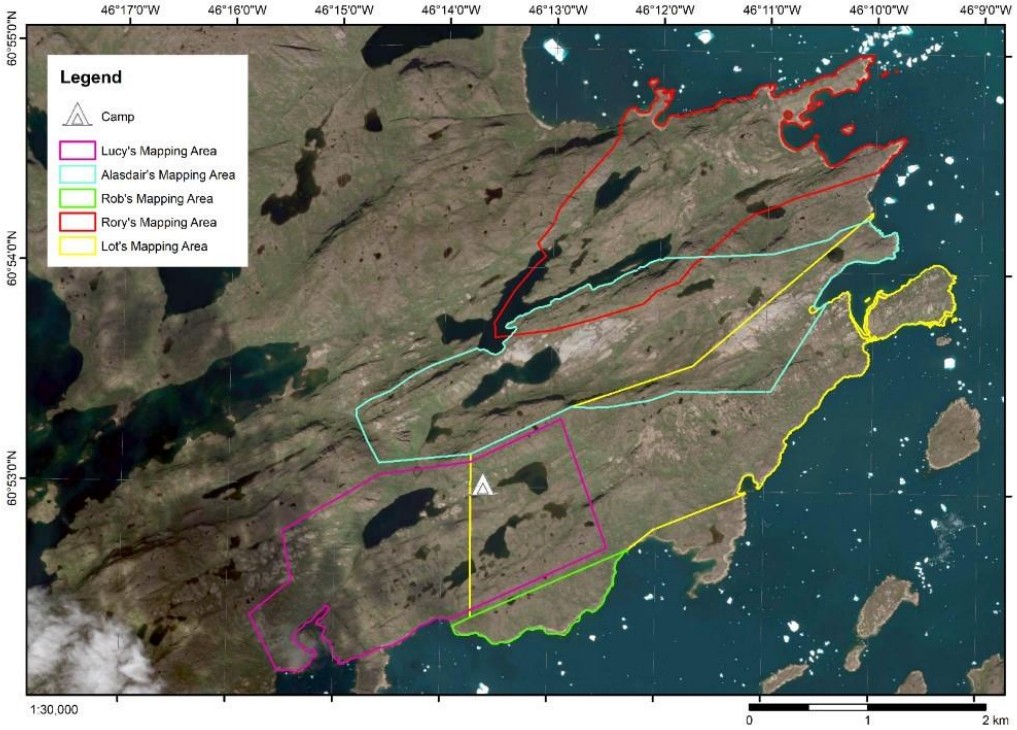


Figure 8. Satellite image of eastern Tuttutooq, with each members' mapping area outlined.

The primary goal of mapping sections of key interest on Tuttutooq was completed by the production of a selection of maps ranging from 1:1000 to 1:5000 scale. Our final combined maps are presented at the bottom of this section and individual maps can be found in appendix 3. We could wax lyrical about the geology of Tuttutooq, it was all we had hoped for and more. But, in the interest of keeping this report brief, we have provided only a summary of our main findings below. If more information is sought, we can make individual mapping reports available and are more than happy to answer any questions.

- Mapping the evolved pods in the northern limb of the YGDC led to the identification of gradational contacts within them, indicating that these likely formed through *in-situ* fractionation processes. Geochemical work is planned to investigate this and their relation to the wider Gardar further. Investigation of rock magnetics will also be undertaken to give further insights into the dyke emplacement mechanisms.
- New features were found within the layered synformal structures at Marrait (SW YGDC). These will be used to develop an understanding of the origin of these structures within the giant dykes. A definite interpretation of the nature of these structures eludes scientists to date, and our work has the potential to shed new light on the subject.

- Mapping of the tidal island Sissarlutooq (SE YGDC) presented evidence of a multi-step intrusion history of the YGDC, suggesting its emplacement is not as simple as was previously thought. Furthermore, detailed study of the layered basins provides further insight into layering processes, supporting findings identified at Marrait.
- The two ultramafic lamprophyres within our mapped areas were of distinct ages not previously described in the Gardar. This finding enables their study to provide insight into mantle processes under the province, which can enhance our understanding of the relationship between the mantle and rare hyperevolved magmatism.
- Detailed mapping of a selected section within the granitic basement complements our understanding of the later dyke swarms present throughout the Gardar province. Focussing on the physical relationships and mineralogical changes within the area, new insights into how these dykes interact with the host rock are identified, which enhances our understanding of how melts evolve through their movement in the crust.

Over 300 samples were collected during our expedition, which will be used to further understand the mechanisms at play in the formation of the igneous province. A primary focus will be put on geochemistry and anisotropy of magnetic susceptibility to build upon and test our findings so far. We're really excited to continue working with these rocks - keep an eye out for further publications.

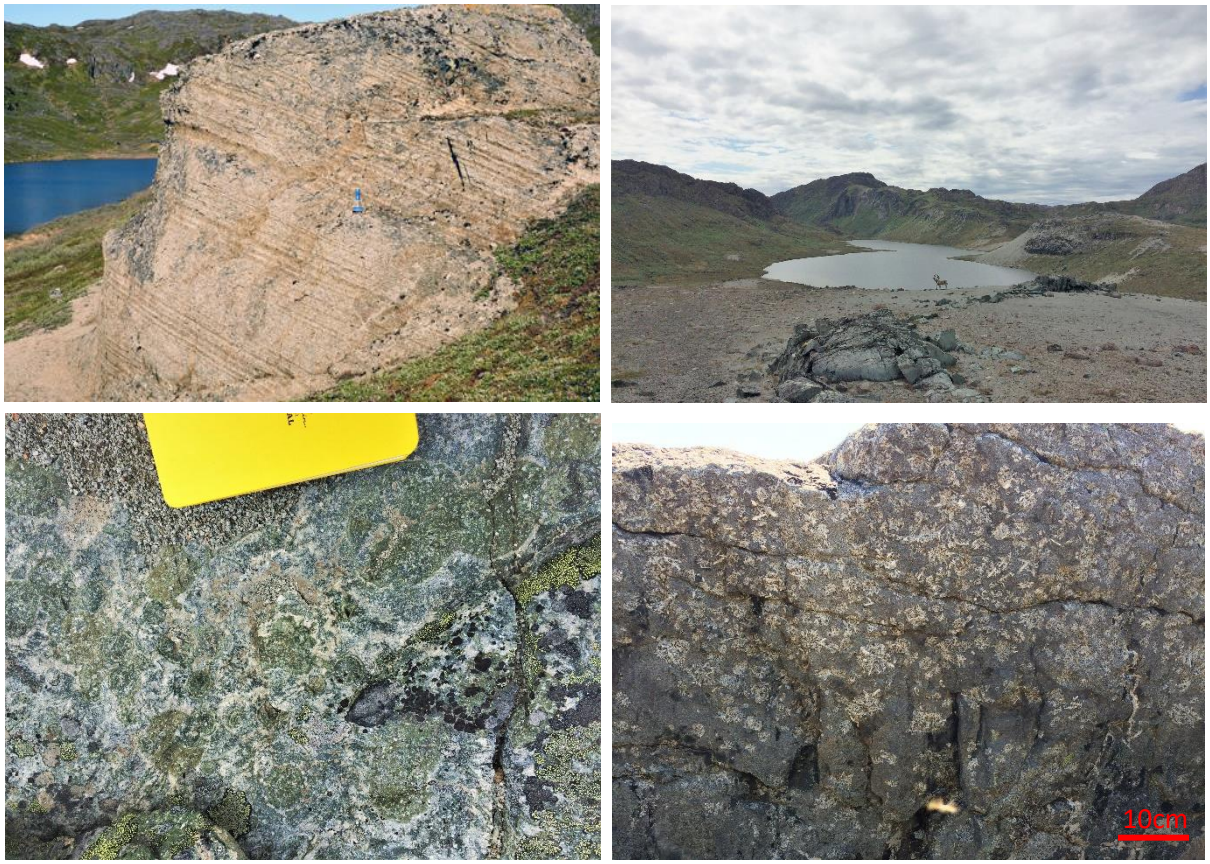


Figure 9. Some of the many rocks we studied. Top left: a layered section of the YGDC. Top right: a dyke cutting through the OGDC. Bottom left: spot the lichen amongst the devitrification textures. Bottom right: glomeroporphyritic dolerite of the YGDC (and a mosquito).

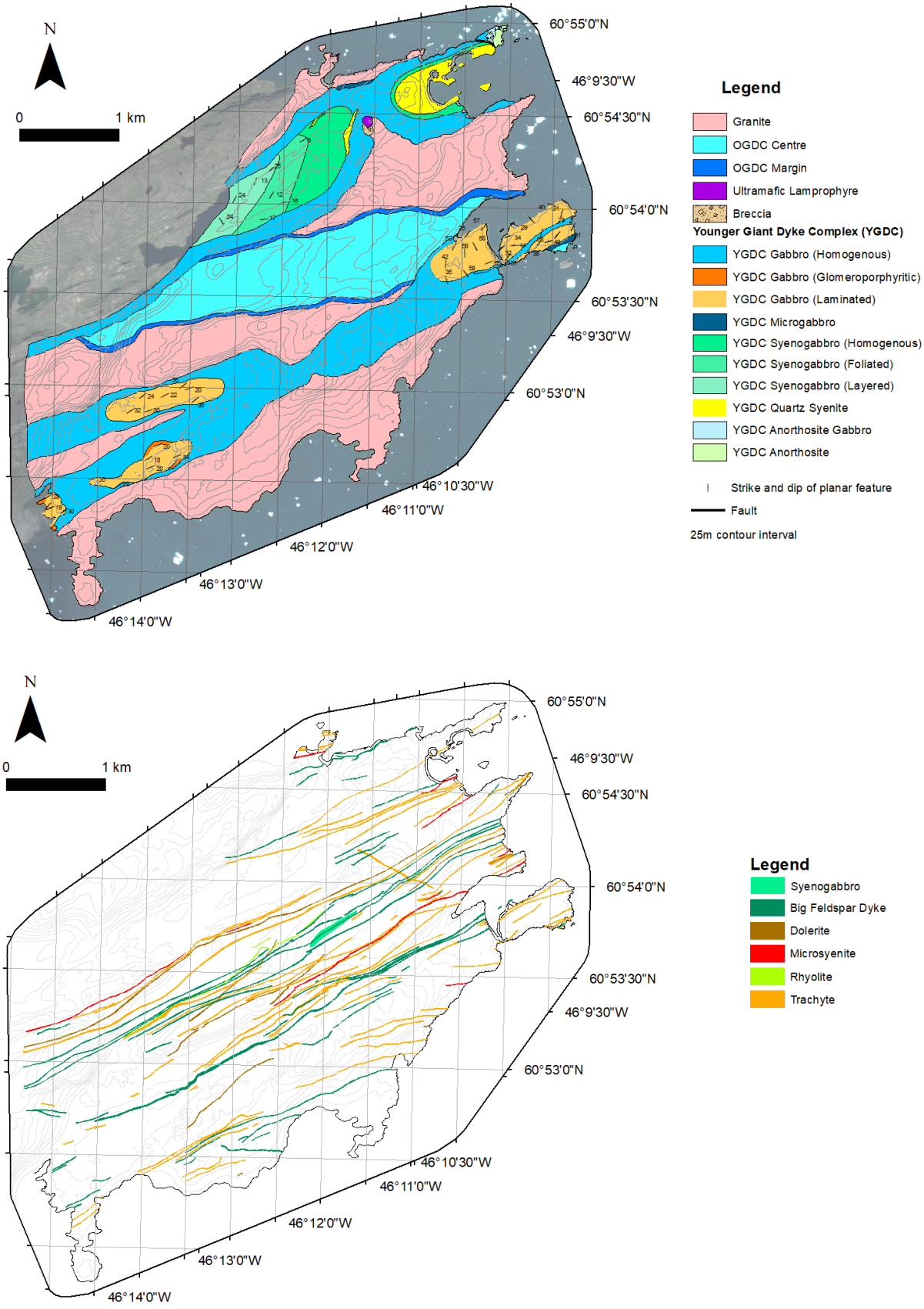


Figure 10: The culmination of our field mapping. Top: basement and giant dyke geology. Bottom: dykes within the mapped area.

Outreach

Our work in Greenland did not grind to a halt upon our return to the UK and has stretched much further than just undergraduate projects. We have contributed to the geology department at the University of St Andrew's by providing teaching samples which will be used to teach 3rd year students the processes involved in igneous fractionation. They will get to see and analyse these first-hand and the samples from Tuttutooq can be used for years to come. Moreover, our samples from Kvanefjeld mine may also be used to illustrate the enigmatic nature of alkaline igneous rocks with their weird and wonderful minerals; including those which fluoresce, such as sodalite. Some of these samples, such as the Lujavrites, may be used in the 5th year Advanced Petrogenesis module.

We presented at a seminar for the Mining Institute of Scotland and spoke of our time there and what we achieved. Students and staff from the University attended. In this coming January, two members of the group will attend the Volcanic and Magmatic Studies Group (VMSG) Conference in Plymouth to present posters on their work so far as well as the mapped area of Tuttutooq. We will also present our work during an evening lecture at the Edinburgh Geological Society in due course and are arranging to give talks in our old schools.

Acknowledgements

This expedition would not have been possible were it not for the help of several people and our sponsors – we are immensely grateful to you all.

Firstly, we would like to thank the academic staff at the University of St Andrews for helping us pursue our love for geology. In particular, Professor Adrian Finch and Dr Will McCarthy's supervision made every step of the whole process substantially smoother and without them this project would never have started. We'd also like to extend our thanks to Professor Brian Upton at the University of Edinburgh who was readily available to meet with us and discuss our ideas and plans.

If it were not for the financial support from the following bodies, we would never have been able to leave Scotland. We cannot quite describe how grateful we are. But going beyond this, thank you also for supporting those who have gone before us. Funding from the MIST and IOM^3 allowed a group of St Andrews students to visit Southern Greenland in 2018, the advice, help and inspiration they provided us was priceless. We have also loved finding out what other teams receiving support have been doing, both past and present; it is incredibly motivating and we are excited to be involved.

In-kind sponsorship made our work safer, warmer, and more enjoyable. It's hard to exaggerate how much of a difference having warm clothes and tasty filling food makes to morale and productivity.

Finally, to all those we met in Greenland; qujanaq, mange tak and thank you. We felt welcome from the beginning and cannot wait to return.

Appendix 1: Summary of Expenses

Category	Item	Cost	Total
Transport			£7550
	Flights	£5800	
	Boats Transfers	£1700	
	Taxis	£50	
Accommodation			£1400
	Copenhagen	£400	
	Greenland	£1000	
Food			£1550
	In Country	£250	
	For Shipment	£1300	
Shipping	Pallet Shipment		£900
Equipment			£800
	Geological Equipment	£600	
	Camping Equipment	£200	
Miscellaneous	Insect Repellent, Medical Supplies, Charging equipment		£1700
		Total	**£13,900**

Appendix 2: References

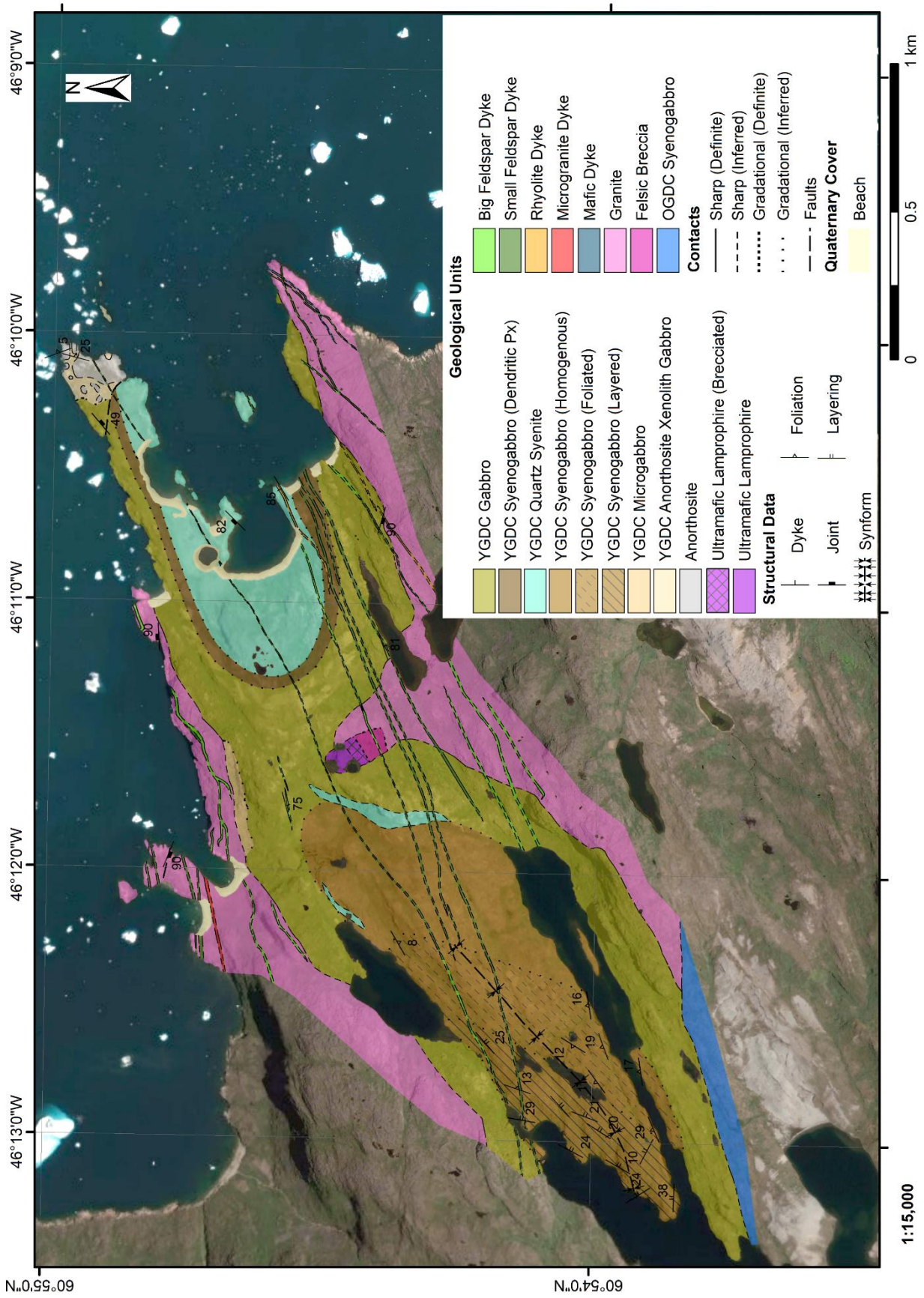
Mingard, S.C. (1990) Crystallisation processes in giant dykes of the Tugtutoq rift, South Greenland. Unpublished PhD thesis, University of Edinburgh, UK

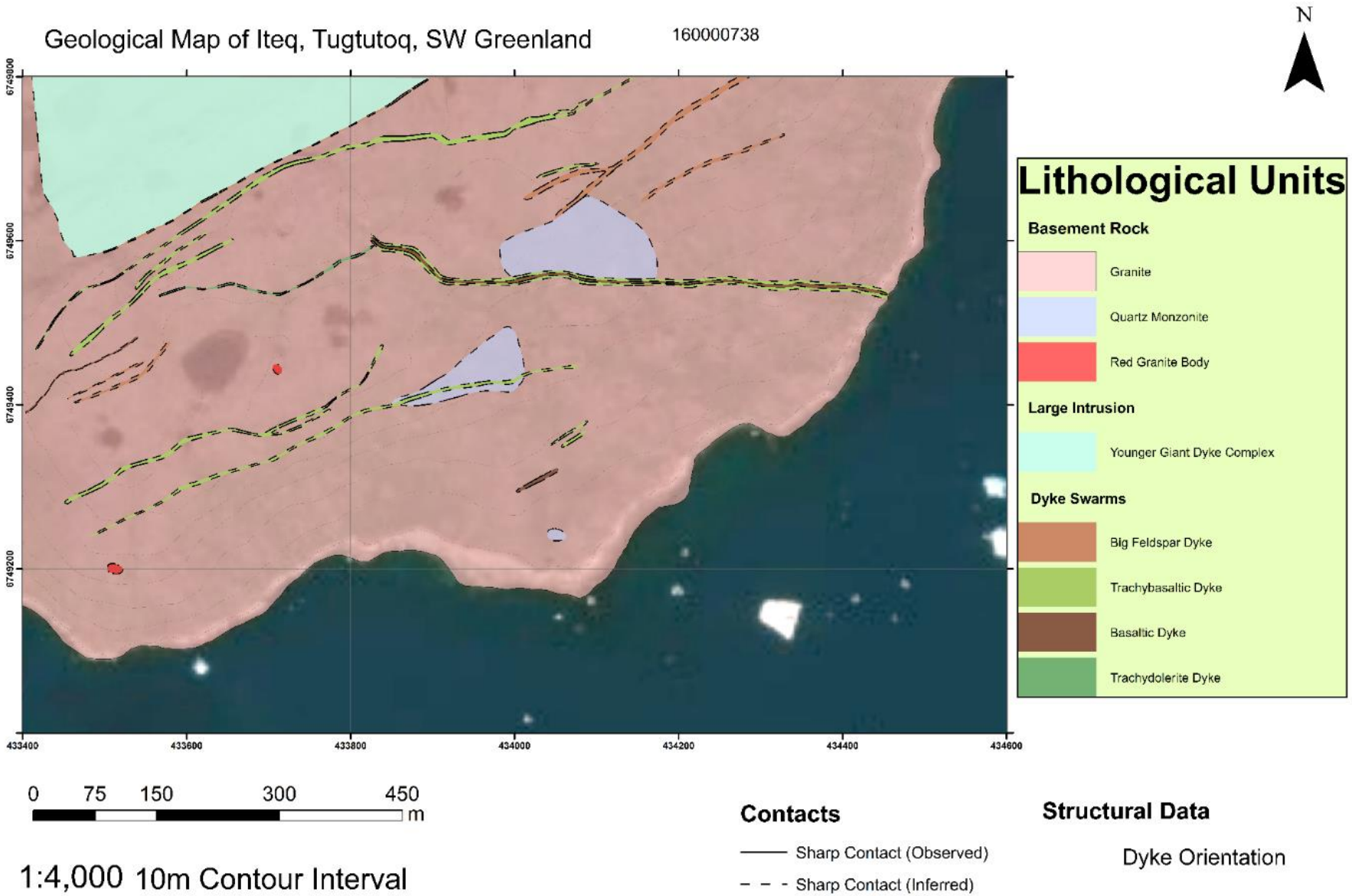
Upton B. G. J. (2013) Tectono-magmatic evolution of the younger Gardar southern rift, South Greenland. Geological Survey of Denmark and Greenland Bulletin 29 124 pp.

Upton, B. G. J., Craven, J. A. and Kirstein, L. A. (2006) 'Crystallisation of mela-aillikites of the Narsaq region, Gardar alkaline province, south Greenland and relationships to other aillikitic-carbonatitic associations in the province', *Lithos*, 92(1–2), pp. 300–319. doi: 10.1016/j.lithos.2006.03.046

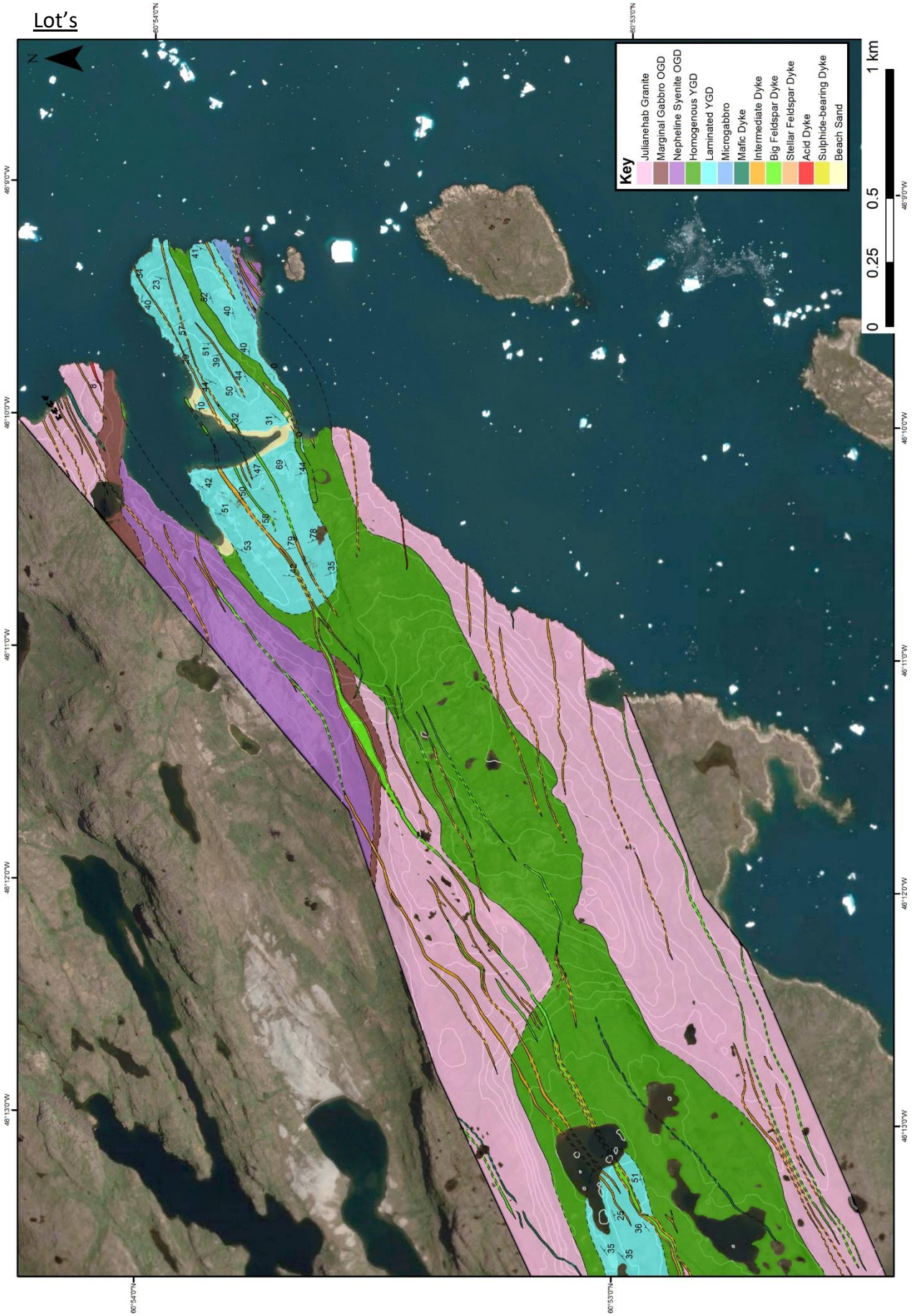
Appendix 3: Individual Maps

Rory's

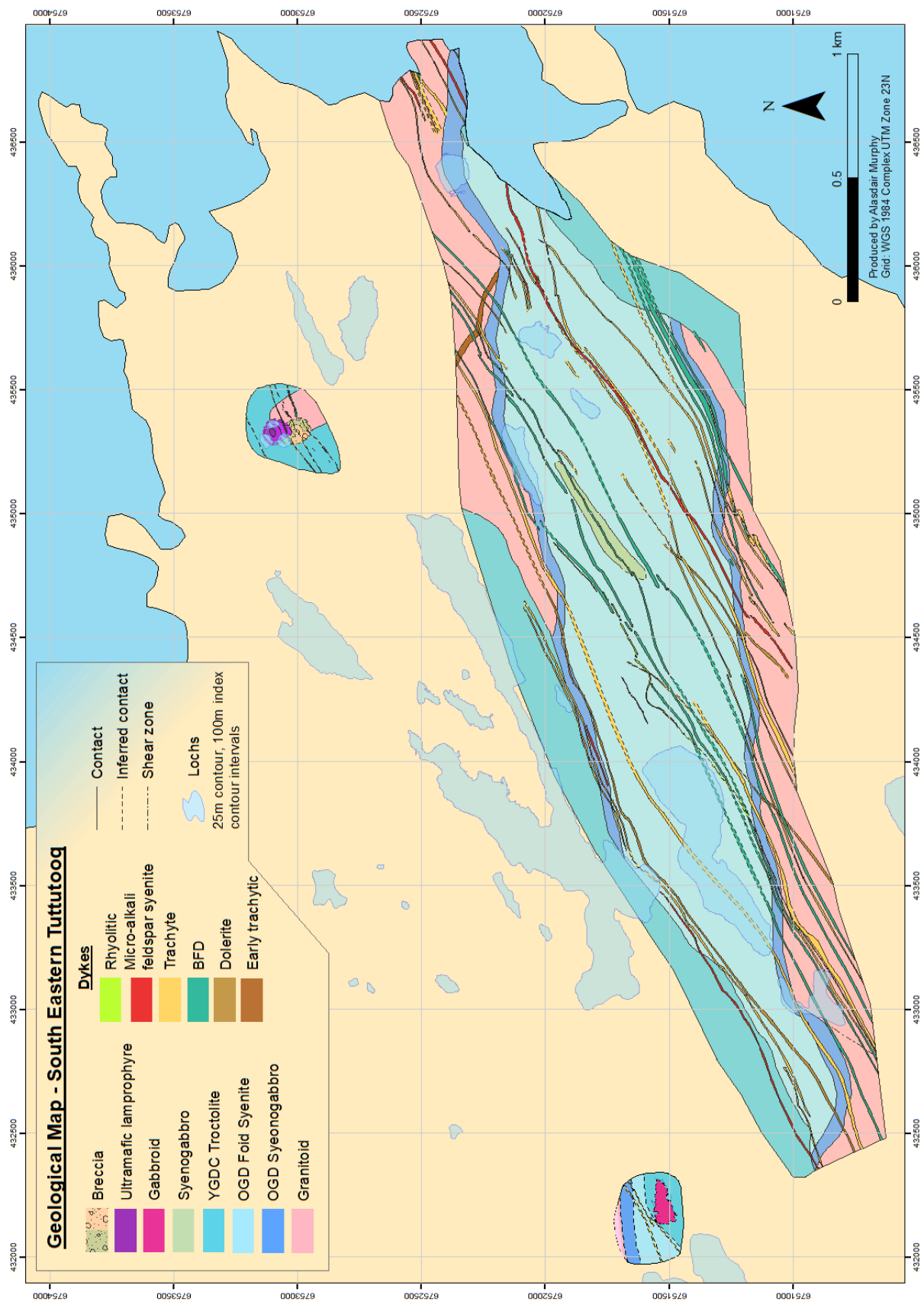



Geological Map of Iteq, Tugtutoq, SW Greenland
160000738
N
Rob's
6749800
6749600
6749400
6749200
433400
433600
433800
434000
434200
434400
434600
Lithological Units
Basement Rock
Granite
Quartz Monzonite
Red Granite Body
Large Intrusion
Younger Giant Dyke Complex
Dyke Swarms
Big Feldspar Dyke
Trachybasaltic Dyke
Basaltic Dyke
Trachydolerite Dyke
0 75 150 300 450
m
1:4,000 10m Contour Interval
Coordinate System - UTM WPS 1984
Contacts
Sharp Contact (Observed)
Sharp Contact (Inferred)
Structural Data
Dyke Orientation

Lot's


Key
Julianehab Granite
Marginal Gabbro OGD
Nepheline Syenite OGD
Homogenous YGD
Laminated YGD
Microgabbro
Mafic Dyke
Intermediate Dyke
Big Feldspar Dyke
Stellar Feldspar Dyke
Acid Dyke
Sulphide-bearing Dyke
Beach Sand
0
0.25
0.5
1 km
N
60°54'0"N
60°53'0"N
46°9'0"W
46°10'0"W
46°11'0"W
46°12'0"W
46°13'0"W

Alasdair's


Geological Map - South Eastern Tuttutoog
Breccia
Ultramafic lamprophyre
Gabbroid
Syenogabbro
YGDC Troctolite
OGD Fold Syenite
OGD Syeonogabbro
Granitoid
Dykes
Rhyolitic
Micro-alkali feldspar syenite
Trachyte
BFD
Dolerite
Early trachytic
Contact
Inferred contact
Shear zone
Lochs
25m contour, 100m index contour intervals
N
0
0.5
1 km
Produced by Alasdair Murphy
Grid: WGS 1984 Complex UTM Zone 23N

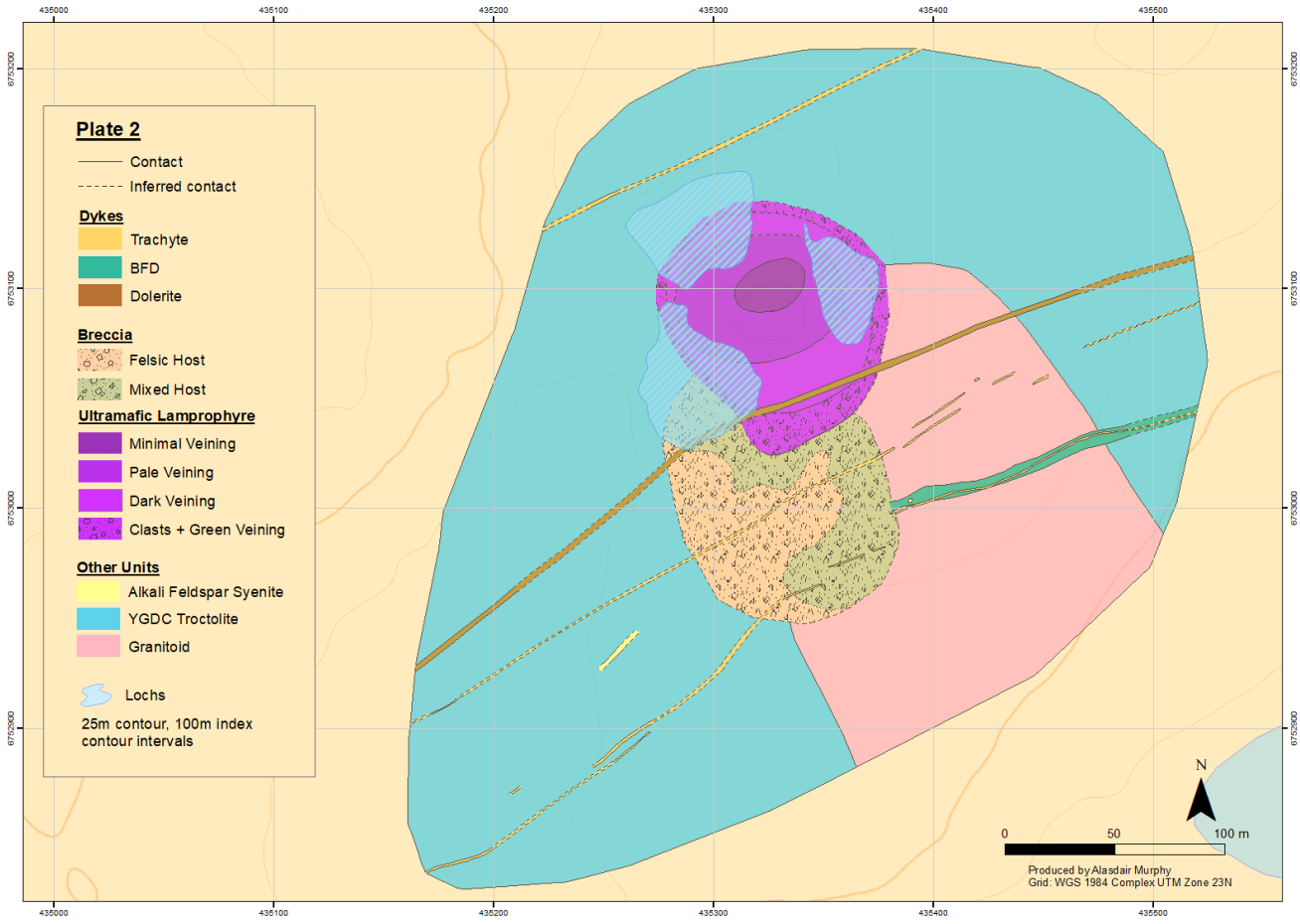


Plate 2
Contact
Inferred contact
Dykes
Trachyte
BFD
Dolerite
Breccia
Felsic Host
Mixed Host
Ultramafic Lamprophyre
Minimal Veining
Pale Veining
Dark Veining
Clasts + Green Veining
Other Units
Alkali Feldspar Syenite
YGDC Troctolite
Granitoid
Lochs
25m contour, 100m index contour intervals
435000
435100
435200
435300
435400
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6753200
6753100
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6752900
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Produced by Alasdair Murphy
Grid: WGS 1984 Complex UTM Zone 23N

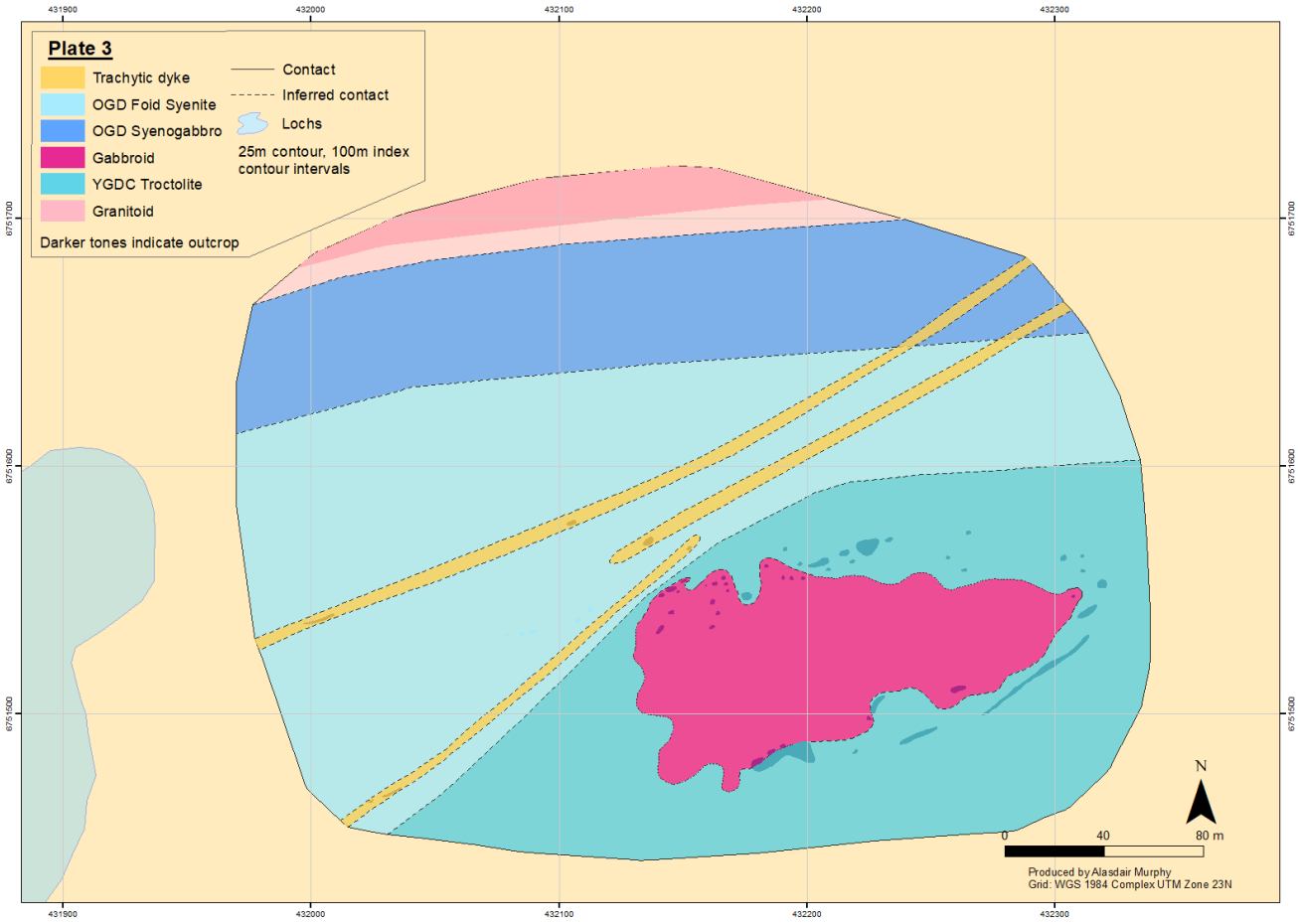
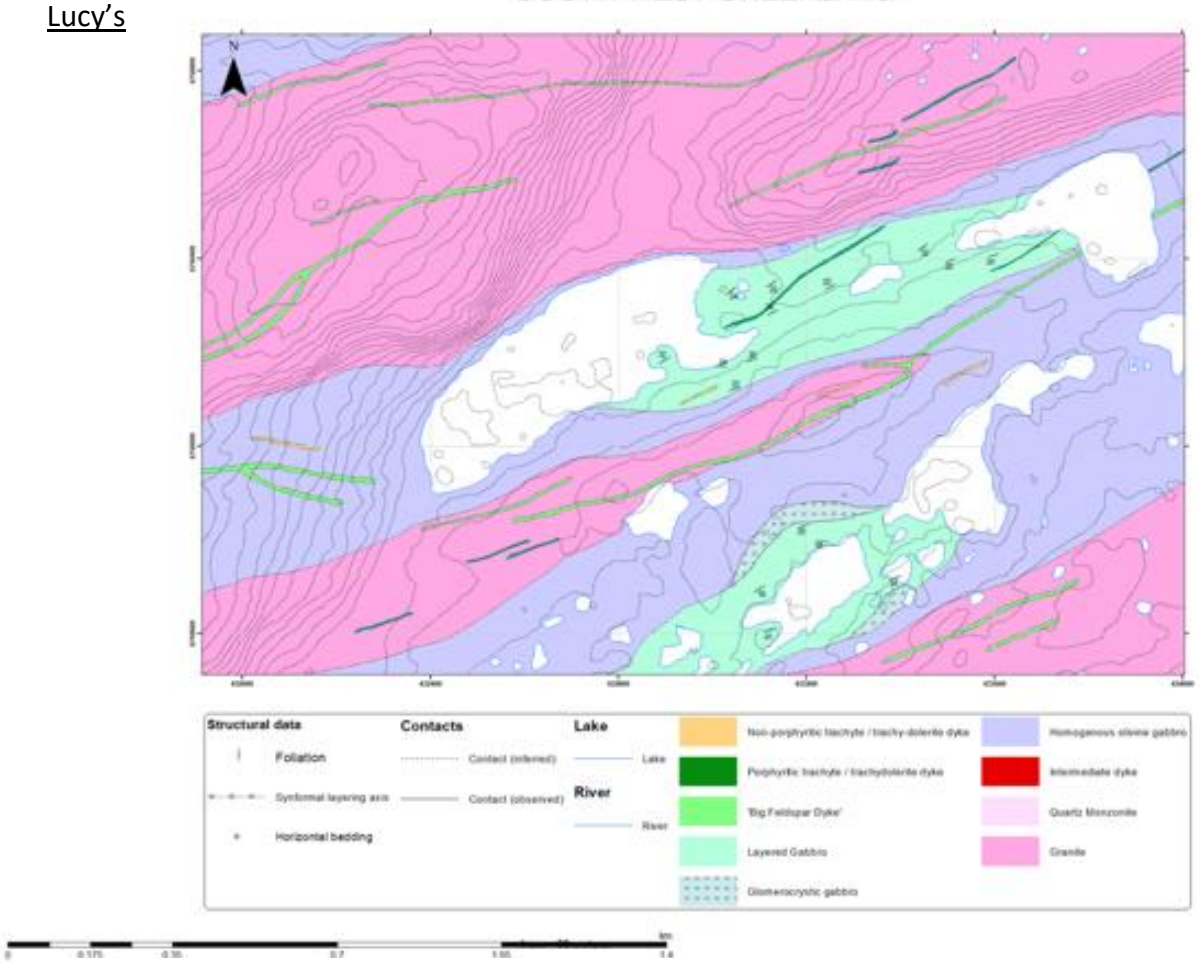


Plate 3
Trachytic dyke
OGD Foid Syenite
OGD Syenogabbro
Gabbroid
YGDC Troctolite
Granitoid
Darker tones indicate outcrop
Contact
Inferred contact
Lochs
25m contour, 100m index contour intervals
431900
432000
432100
432200
432300
6751700
6751600
6751500
N
0
40
80 m
Produced by Alasdair Murphy
Grid: WGS 1984 Complex UTM Zone 23N

GEOLOGICAL MAP OF SYNFORMALLY LAYERED POD AT MARRAIT, TUGTUTOQ, SOUTH WEST GREENLAND

Lucy's



GEOLOGICAL MAP OF SYNFORMALLY LAYERED POD AT MARRAIT, TUGTUTOQ, SOUTH WEST GREENLAND