GRADUATE THESIS PROPOSAL

EARTH SCIENCES 6300

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DEGREE PROGRAMME: MSc  SUPERVISOR(S): Dr. Rebecca Jamieson

TITLE OF PROPOSAL:
Did melting at UHP conditions trigger exhumation of the Western Gneiss Region?

KEY WORDS (up to 10):
Partial Melting, Ultra-High Pressure, Relative Timing, Exhumation, Fluid Source

FIELD(S) OF SPECIALIZATION:
Metamorphic Petrology, Geochronology, Stable Isotope Geochemistry, Tectonics

ESTIMATED COST OF PROPOSED RESEARCH:

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STUDENT'S SIGNATURE:  SUPERVISOR'S SIGNATURE:

DATE:
April 3rd, 2015
SUMMARY OF PROPOSED RESEARCH (in lay terms):

One of the most spectacular global scale geological phenomena is continental subduction – the process by which the leading edge of one continent collides with, and is driven beneath another. This process has transpired many times throughout the geological past, leading to mountain building events called orogenies. An example of this type of event can be seen today in the Himalayan-Tibetan system – the mountain chain formed as a result of the collision and subduction of the Indian sub-continent beneath Asia. In the aftermath of these collisions an even more intriguing process can occur: continental exhumation. This is the process by which a once subducted continent returns from the depths to the lower crust, and eventually the surface.

One of the world`s largest examples of exhumed continental crust is the Western Gneiss Region (WGR) of Norway. Between ca. 430-400 million years ago (Ma) the collision between the continents Baltica and Laurentia resulted in the subduction of western Norway to a depth of over 100 km beneath Greenland. By ca 385 Ma however, the subducted portion of Baltica had returned to lower crustal (~30 km) depths. The question of what triggered the exhumation of Baltica is the subject of considerable debate. One hypothesis is that at the peak of the ultra-high pressure (UHP) conditions, the subducted crust began to melt, weakening the crust enough to induce ductile flow. Although melting is known to have been widespread in the WGR as a result of decompression once the subducted crust had begun its return to the surface, it is debated whether melting also took place at peak pressure.

The goal of this research is to test the hypothesis of melting at peak pressure. This will be accomplished through several methods: 1. Detailed outcrop mapping in the Nordøyane UHP Domain, the region where pressure reached its highest, to look for evidence of partial melting at peak pressure in the relationship between preserved partial melt (leucosome) and UHP metamorphic rocks (eclogite). 2. U-Pb isotope dating of zircon to provide absolute constraints on the timing of partial melting and peak pressure 3. Stable isotope analysis of the mineral scapolite to trace the source of aqueous fluids (necessary for melting at peak pressure) in the lower crust. This will contribute to our understanding of the tectonic history of the WGR, as well as deepen our knowledge of (U)HP partial melting, crustal weakening processes, and the role of fluids in the lower crust.

TIMETABLE: (include work completed to date)

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**BUDGET:** (salaries not included; do not index for inflation)

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**EXPLANATION OF BUDGET:**

a) Field Work costs include air travel between Halifax and Trondheim, accommodations, meals, car rental and gas, ferry fees and sample shipping.

b) Laboratory expenses will cover 150 hours worth of user fees for the Dalhousie electron microprobe lab and 25 stable isotope analyses at the G.G. Hatch Stable Isotope Laboratory at the University of Ottawa and four days at the LA-ICP-MS Lab at the University of New Brunswick.

c) The allocated for equipment will be used to buy a GPS, portable UV lamp (for detecting scapolite in the field) and other necessary tools (hammers, chisels, notebooks etc.).

d) The budget for materials and supplies covers the cost of making 25 polished thin sections, 75 normal thin sections and 5 zircon grain mounts.

e) Travel costs plan for trips to Ottawa, Fredericton and one national/international conference.

f) The in other costs will cover the publication of two papers in relevant journals, such as the Journal of Metamorphic Geology.

**“IN-KIND” SUPPORT:**

Maps, air photos, and logistical support will be provided by the Norges Geologiske Undersøkelse (NGU). Some air travel will be subsidized using Aeroplan Miles provided by Cindy McKinley.
1. Statement of Problem

The mechanism behind the exhumation of deeply subducted Baltican continental crust in the Western Gneiss Region (WGR) of Norway at the end of the Caledonian Orogeny remains the subject of debate. One hypothesis suggests that partial melting at the peak of ultra-high pressure (UHP) metamorphic conditions, weakening the crust sufficiently to trigger its exhumation. It is widely accepted that decompression melting took place during exhumation of the WGR, although whether or not melting could have initiated at peak pressure (P) conditions is uncertain. Current pressure-temperature-time (PTt) paths calculated for the region do not show sufficiently high T at peak P for melting to begin, unless fluids were present to lower the solidus temperature sufficiently. In order to test this hypothesis, it is necessary to constrain both the time of partial melting in UHP rocks relative to peak metamorphic P conditions, as well as to trace possible sources of fluids. Investigating this hypothesis will advance our understanding of not only the tectonic history of the WGR, but continental subduction and exhumation mechanisms in general.

2. Background

2.1 Regional Geology of the Western Gneiss Region

Exposed in much of Norway, western Sweden, and northwestern Finland, the Scandanavian Caledonides form one part of the larger Caldeonian Orogen (Corfu et al. 2014 and references therein). This orogeny was the product of a number of collision and deformation events involving the Laurentian and Baltican cratons and a series of arcs and microcontinents, as a result of the Ordovician-Devonian closure of the Iapetus Ocean (Corfu et al. 2014). The closure of the Iapetus led to the stacking of allochthons eastward onto the Baltican margin, followed by continental collision and westward subduction of Baltic crust and parts of the allochthons beneath Laurentia, between ~430-400 Ma in a collisional phase known as the Scandian Orogeny (Hacker et al. 2010 and references therein).

Based on eclogite facies metamorphic ages ranging from ca. 415 Ma to ca. 400 Ma (Krogh et al. 2011, Butler et al. in press), the subducted crust is believed either to have spent an extended period of residence at mantle depths, or subducted very slowly, or been metamorphosed and exhumed in multiple pieces over this period of time. Baltican crust was subsequently exhumed to lower crustal depth and subjected to retrograde amphibolite/granulite facies metamorphism between ~ 400-385 Ma (Root et al. 2005, Hacker et al. 2010). Although currently dominated by amphibolite facies gneisses and retrogressed eclogite, the Proterozoic basement gneisses are thought to have been largely composed of dry granulites, which are locally preserved, at the time of subduction and were hydrated relatively late in the history of the orogen (Krabbendam et al. 2000, Butler et al. in press, Hacker et al. 2010).

The leading edge of the WGR was subducted to mantle depths of ~ 100 km and metamorphosed under ultra-high (UHP) pressure conditions (>2.5 GPa), recorded by the presence of coesite (high-P polymorph of SiO$_2$), coesite pseudomorphs, and microdiamonds (Dobrzhinetskaya et al. 1995, Root et al., 2005, Butler et al. 2013). Coesite (± microdiamond) bearing eclogites are found within three discrete UHP domains – Nordfjord-Stadlandet, Sorøyane, and Nordøyane, now separated at the surface by regions of coesite-free eclogite (Root et al. 2005, Butler et al. 2013). Whether the WGR was tectonically assembled before or during subduction, and whether or not it remained relatively coherent during subduction and exhumation (Butler et al. in press and references therein) are debated. The strong NE-SW P-T gradient and the eastward decrease in Caledonian deformation of the WGR are both indicative of subduction and exhumation as a coherent slab (Hacker et al. 2010, Butler et al. in press).

However deformation and localized internal thrusting within the Baltican basement (Terry and Robinson, 2003, Gee et al. 2013, Robinson et al. 2014) and the complex ‘mixed zone’ of interspersed HP/UHP eclogites on the north side of Nordfjord (Cuthbert et al. 2000) may indicate diachronous metamorphism, and/or exhumation and juxtaposition by a ‘plume-like’ exhumation in which weakened crust detaches from the slab and rises buoyantly up the subduction zone (Butler et al. in press).
A number of hypotheses have been developed to explain the mechanism behind the exhumation of subducted Baltican crust. Some, such as ‘eduction’ (where slab break-off triggers reverse transport of the subducted slab back up the subduction channel (Bottrill et al. 2014 and references therein)), or post-orogenic extension (where exhumation results from removal of the orogenic wedge through extension and erosion (Butler et al. in press)) favour the subduction and exhumation of the WGR as a coherent slab. Others, such as the hypothesis that partial melting at peak P triggered exhumation, are more compatible with a ‘plume-style’ exhumation. The uncertainty over the nature of the exhumation mechanism will not affect this study however, as the results will help to constrain the trigger mechanism of the process independent of the overall exhumation style.

2.2 Partial Melting at Peak Pressure Conditions

It has been hypothesized that partial melting of subducted crust at peak P conditions could have weakened it sufficiently to decouple the crust from its dense lithospheric root, triggering the process of exhumation (Labrousse et al. 2011, Ganzhorn et al. 2014). Although evidence for partial melting during decompression is widely preserved in the form of multiple generations of granitic leucosomes throughout the WGR, it is debated whether this process could have initiated at peak P (Butler et al. 2013). The peak pressure reached by the WGR, recorded in the Nordøyane domain, was 3.9 GPa (Doberzhinetskaya et al. 1995, Butler et al. in press – Figure 1a) but at this P it was not hot enough for dehydration melting (Figure 1b). This has led proponents of the UHP melting hypothesis to infer the presence of an aqueous fluid at depth, to lower the solidus sufficiently for melting to begin (Labrousse et al. 2011, Ganzhorn et al. 2014). Numerical modeling (Butler et al. in press) suggests that if the solidus is lowered by ~100 °C melting and weakening at could trigger plume-style exhumation.

Several lines of evidence have been used to support of the hypothesis of melting at peak P conditions. Partial melting experiments, using a WGR bulk compositional analogue and varying amounts of added water, produced melts that overlapped compositionally with natural leucosomes in the WGR (Labrousse et al. 2011). U-Pb zircon geochronology (Gordon et al., 2013) found some overlap between UHP metamorphic ages (ca. 425–400 Ma) and texturally magmatic zircon (ca. 410-400 Ma), interpreted by them as evidence for zircon growth from melt at the transition from eclogite facies to lower pressure conditions. Ganzhorn et al. (2014) also described the presence of polyphase inclusions in eclogite facies garnet, which they interpreted as evidence garnet growth from a melt at UHP conditions. However,
although these authors recognized the necessity of an aqueous fluid at depth to trigger melting at peak P, evidence of such a fluid has yet to be presented. Furthermore, the relative times of partial pelting and peak P have yet to be firmly constrained by geochronology.

2.3 The Nordøyane UHP Domain

This study will focus on the Nordøyane UHP domain (Figure 2). The northernmost of the UHP domains, it is exposed on a series of small islands (Nordøyane translates as ‘north islands’) and the immediately adjacent mainland coast. Rocks of the Nordøyane domain record higher peak metamorphic P conditions, at 3.9 GPA, than anywhere else in the WGR (Figure 1a). Combined with its excellent exposure of (relatively undeformed) UHP eclogites and multiple generations of associated leucosomes (Butler et al. 2013), this makes it the best choice for studying the time of melting relative to peak P conditions.

The islands are underlain by Baltican basement orthogneisses tectonically juxtaposed against, and locally infolded with, metasedimentary rocks of the allochthonous Sætra and Blåhø nappes (Terry & Robinson ca 2003; Steenkamp, 2012; Butler et al. 2013). In addition to thermobarometry, previous work in the area documented the presence of coesite in eclogite (Butler et al. 2013) and microdiamonds in pelitic gneiss (Dobrzhinetskaya et al 1995) as direct evidence of UHP metamorphism. U–Pb zircon geochronology (Krogh et al. 2011) constrains the timing of UHP metamorphism to ca. 415–410 Ma, broadly consistent with to slightly older than other UHP eclogites in the WGR, with the amphibolite facies overprint at ca. 395 Ma. Leucosomes and late stage pegmatites on the islands of Harøya and Finnøya locally contain the volatile-bearing silicate scapolite (Butler et al. 2013), suggesting the
interaction of carbon-(and possibly sulfur- and halogen-) bearing fluids with the melt. Scapolite provides a valuable monitor for fluids in the lower crust (Moecher et al. 1994), and may therefore prove vital to establishing the presence (or absence) of fluids at peak P conditions, as well as their origins.

3. Objectives

The overarching objective of this project is test the hypothesis that the onset of (fluid present) partial melting in the WGR coincided with peak P conditions, triggering the exhumation of subducted Baltican crust by weakening it sufficiently to induce ductile flow. This objective will be addressed by achieving the following short-term goals:

a. Determining the relative timing of partial UHP metamorphism and melting (through field and petrographic work)

b. Determining the absolute timing of melting through geochronology.

c. Determining whether scapolite is present in leucosomes throughout the migmatitic Baltican basement gneisses of the Nordøyane UHP domain.

d. If c. Is correct determining the source of scapolite-forming fluids.

4. Methods

4.1 Field Work

Mapping and sample collection are fundamental to addressing, at least in part, all of the above goals. The Nordøyane UHP domain has already been mapped at the regional scale (Terry and Robinson 2003, 2004), so mapping for this project will be at the outcrop scale, focusing in detail on a number of well-exposed areas of interest. Field work at known scapolite localities (Figure 2) will focus on the collection of scapolite and marble samples for stable isotope analysis, in order to determine the source of scapolite-forming fluids.

Detailed outcrop mapping to determine the relative timing of partial melting to UHP metamorphism, and whether scapolite is more broadly distributed throughout the Nordøyane domain, will be conducted in two well exposed localities (Figure 2). Addressing the former will involve working out the cross-cutting relationships between eclogite bodies and the multiple generations of leucosome in the migmatitic host gneisses. Mapping will focus on looking for evidence of melting within the eclogite bodies, as well as leucosomes which cross-cut the eclogites, or contain high-pressure minerals (such as garnet) which could indicate the coexistence of melt and eclogite at ultra-high pressure. Addressing the latter will involve searching for scapolite in the leucosomes in outcrops in Ulla Fyr (1) and the Flem Gabbro (2) using an ultra-violet (UV) lamp (scapolite has a distinctive red fluorescence under UV).

The three areas indicated on the map have been selected for their excellent exposure, abundant eclogite, and multiple generations of leucosomes, which have yet to be studied in depth. Furthermore, these are relatively low-strain areas where early cross-cutting may be preserved. Geochronology on both the eclogite facies metamorphism and the amphibolite facies overprint has been carried out on the Flem Gabbro, (Krogh et al. 2011), while rocks from the Harøya coesite locality (3) were the subject of thermobarometry carried out by Butler et al. (2013), providing a baseline for further work. Both eclogites and leucosomes from the mapped localities will be sampled for U-Pb zircon geochronology.

4.2 Sample Processing and Characterization

The rocks collected in the field will need to be processed, described, and characterized in the laboratory, in order to provide context to the results acquired by subsequent quantitative analysis. Numerous thin sections will be cut, and described petrographically. Particular attention will be paid to textural relationships in order to place scapolite, zircon, and other relevant minerals (such as garnet, and omphacite-clinopyroxene) in context. Thin sections with large quantities of scapolite/zircon will be analyzed further using optical cathodoluminescence (CL – available at Saint Mary’s University), back-scattered electron (BSE) imaging, and trace element mapping (using the electron microprobe (EMP) at Dalhousie University) to identify compositional zoning. Scapolite, and important facies-defining
minerals such as garnet and clinopyroxene, will be analyzed quantitatively by EMP. This will add compositional data in support of textural relationships, which will be used to calculate P-T conditions. Once zircon has been contextualized in thin section, whole rock samples will be crushed to obtain zircon separates for grain mounts. These will be imaged by BSE and CL, and analyzed by laser ablation inductively coupled mass spectrometry (LA ICP MS) for U-Pb and trace elements. If enough zircons of suitable size and shape are found in thin-section, laser ablation may be carried out in-situ, either instead of or in addition to dating of grain separates.

4.3 U-Pb Zircon Geochronology

As in all geochronology, both the chronometer and analytical technique will be selected based on the specific goals of the project. In this case, zircon was chosen as the target geochronometer because it has a closure temperature of greater than 900 °C (Lee et al. 1997) can form under high P-T conditions as a metamorphic reaction product or by crystallizing from melt, and can preserve multiple events through the growth of discrete, easily imaged texturally and compositionally distinct zones (Kylander-Clark et al. 2013, UNB Earth Sciences). Zircon also has the advantages that it tends to contain relatively minor amounts of common lead ($^{204}$Pb), which limits the uncertainty in the measured age, and can be dated by two separate U-Pb decay systems, providing a useful internal age check (Brownlow, 1996). LA-ICP-MS was chosen as the analytical technique because it provides a high level of spatial resolution, while maintaining high levels of accuracy and precision (Kylander-Clark et al. 2013). The laser ablation technique samples material from individual spots of ~20 μm in size for dating, so discrete zones of a grain can be dated separately, provided they are sufficiently large. Where this is not the case depth profiling can be used, to measure isotopic variations (and therefore age variations) as a function of ablation depth. Each laser pulse ablates a depth of ~ 0.06 μm and the technique can resolve isotopically distinct zones as little as 3 μm thick, with 2σ uncertainties for $^{207}$Pb/$^{206}$Pb ages as low as 0.2% (Kelly et al. 2014).

Linking the age of a given zircon to a specific event or set of conditions, such as crystallization at UHP, can be challenging. However, both the morphology and trace element geochemistry of a zircon can be used to interpret its history. Zircons crystallized from a melt tend to be prismatic with oscillatory zoning (Rubatto and Hermann, 2007, Kylander-Clark et al., 2013), while metamorphic zircons (Figure 3a) are generally homogenous or show ‘patchy’ zoning and, in the case of zircons formed by high-grade metamorphic reactions, ‘soccerball’ shapes (Butler, 2013, Krogh et al. 2011). Whether or not a zircon formed under (ultra) high pressure conditions can be determined based on its rare earth element (REE) pattern, which can be measured by LA-ICP-MS, using both standard ablation and depth profiling techniques (Kelly et al. 2014). The key elements of a high-pressure signal in eclogitic zircon are the lack of a negative Eu anomaly (indicating the absence of plagioclase) and a relatively low and flat HREE pattern (indicating that garnet was present), which in combination indicate crystallization at eclogite-facies conditions (Figure 3b, Rubatto, 2002, Rubatto and Hermann, 2007). While not diagnostic of UHP conditions, REE patterns in combination with other chemical and mineralogical data can be used to test the hypothesis of UHP crystallization.

These analyses will be carried out at the University of New Brunswick (UNB) using the Resonetics S-155-LR 193nm Excimer laser ablation system coupled to an Agilent 7700x quadrupole ICP-MS. Unfortunately, U-Pb isotopes, and REE geochemistry unfortunately cannot be measured at the same time on a single ablation pit with this instrument. However, a combination of targeted spot analysis and depth profiling for a large number of grains should provide a strong dataset for both purposes.
Figure 3: a – Cathodoluminescence image of a metamorphic ‘soccerball’ zircon modified from Butler (2013) showing a proterozoic core surrounded by a UHP metamorphic overgrowth (dates estimated for illustrative purposes). b – Simplified chondrite-normalized REE plot modified from Rubatto and Hermann (2007). The dark red line shows the expected pattern for the magmatic proterozoic core of the zircon in a, while the blue shows the trace element pattern expected for the overgrowth. The black boxes highlight the key points of difference – the magmatic core has a steep negative Eu anomaly, indicating that it crystallized while plagioclase was present, and a high, increasing HREE pattern, indicating crystallization in the absence of garnet. For the overgrowth, the opposite is true, with no negative Eu anomaly and a flat HREE pattern indicating crystallization at eclogite facies conditions (plagioclase absent, garnet present).

4.4 Stable Isotope Geochemistry

As a CO$_3$-, SO$_4$$^{2-}$-bearing mineral stable under a wide range of pressure and temperature conditions, scapolite is a valuable monitor of the composition and source of fluids circulating in the lower crust (Moecher et al. 1994). Isotope Ratio Mass Spectrometry (IRMS) is a commonly used technique in analyzing the stable isotope chemistry of inorganic solids, and C, S and O isotope systematic have a long history of being used to identify the source of fluids related to scapolite formation (Hoefs et al. 1981, Moecher et al. 1994, Yoshino and Satish-Kumar, 2001).

A number of possible sources of scapolite-forming fluids have been identified; these include fluids released from the marble-bearing metasediments of the Blåhø Nappe, fluids introduced from the mantle during subduction of Baltica, or from fluids (or scapolite crystals) already present in, and carried down with, the lower crust (Steenkamp, 2012, Moecher et al. 1994). Given the current known distribution of scapolite (Figure 2), the Blåhø Nappe metasediments are the most obvious source. However, if scapolite is found to be more widely distributed in leucosomes throughout the domain, or proves isotopically incompatible with marble other sources must be assessed. While individual isotope systems may not be able to distinguish among all these possibilities when used in combination ambiguity can be reduced or eliminated. For example, S ranges for the mantle (-1 to +4‰) and sediments (-40 to +40‰) overlap but can be resolved using C isotopes for those sources (-3 to -7 and -2 to +5 respectively (Hoefs et al. 1981)).

Stable isotope analyses will be carried out at the G.G. Hatch Stable Isotope Laboratory at the University of Ottawa using a Thermo-Finnigan GasBench coupled to a DeltaPlus XP IRMS. The specific analytical procedures for measuring C and S isotope ratios were discussed in detail in Révész and Landwehr (2002) and Grassineau et al. (2001), respectively. Analytical precision for C and O isotope ratios is ± 0.1 ‰, and ± 0.2 ‰ for S (G.G. Hatch Laboratories). A test batch of samples of marble (from Nordøyane) and scapolite (from Nordøyane, the Central Gneiss Belt in the Grenville Orogen and the Lake Harbour Group of the Trans-Hudson Orogen) were sent to the laboratory in
December 2014 to test the feasibility of the method. Combining precise analyses from multiple stable isotope systems will allow firm constraints to be placed on the source(s) of scapolite-forming fluids.

5. Significance

The proposed research will not only contribute to our understanding of the tectonic history of the WGR, but also deepen our knowledge of (U)HP partial melting, crustal weakening processes, and the role of fluids in the lower crust during subduction and exhumation. The data and results are expected to form the basis of two papers, which will be published in a relevant journal such as the Journal of Metamorphic Geology. One will cover the relative timing of partial melting relative to peak P, based on the results of outcrop scale mapping and geochronology. The other will focus on the stable isotope geochemistry of scapolite, and what (if any) role scapolite-forming fluids played in the melting and weakening of Baltic crust. To the extent that S is documented in fluids this research may constrain its origins in the lower crust.

6. References

University of New Brunswick Earth Sciences. [Cited Mar. 26th, 2015].