

U-Pb geochronology and evolution of Caledonian Nappes in northern Norway

Terrane identifications, correlations and provenance of metasedimentary
cover sequences and nappes in the Scandinavian Caledonides

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Landegode Island as seen from Keiserverden

“We are like a judge confronted by a defendant who declines to answer, and we must determine the truth from the circumstantial evidence.”

-Alfred Wegener, *The Origin of Continents and Oceans*

To Gifty, Papa Yaw and Kukua

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Preface

The research for this doctoral thesis was financed by NORECO and the University of Oslo, and was carried out at the Department of Geosciences, University of Oslo for 3 and a half years, starting July 2011 and ending April 2015. Courses required for the PhD were taken at the University of Oslo. Field work was conducted in the summers during the period and was led by Professor Arild Andresen. Some of the results from the field work and laboratory work during my master studies are incorporated into Papers #I and #II of this thesis.

All LA-ICP-MS analyses of detrital zircons presented in this thesis were conducted at the Department of Geosciences, University of Oslo by me, except for one sample presented in Paper #IV which was analysed by Steve Braun in the Department of Earth and Environmental sciences, Vanderbilt University, USA. ID-TIMS analyses presented in Papers #I and #II was conducted by Lars Eivind Augland (a co-author) at the Department of Geosciences, University of Oslo. SHRIMP analyses presented in Paper #II were conducted by Lars E. Augland at the Centre for Isotopic Research at VSEGEI, St. Petersburg, Russia by Lars E. Augland.

This thesis consists of an introduction, three published papers and two manuscripts in preparation. The thesis provides new geochronological data on several metasedimentary packages within various nappes in northern Norway, and combining them with pre-existing data in an attempt to better understand the systematic of the northern Norwegian Caledonides. The introduction states the objectives of the study and provides a geological background for the Norwegian Caledonides, as well as an elementary review of the principles of geochronology as applied in this thesis. The contributions are presented after the introduction in chronological order of development. Cross references in the introduction to the papers are given with the paper numbers, #1 to #5.

Acknowledgements

First of all, I wish to thank my main supervisor, Arild Andresen, for his support, help, advice, and patience in correcting the many mistakes I made along the way. Countless discussions in the field and his office have been of cardinal importance and have shaped the development of this thesis. This work could not have been completed without him. NORECO is thanked for providing the funding for this research. Arild was also instrumental in securing financing from NORECO for this work.

Tom Andersen was the second supervisor on this thesis and introduced me to the LA-ICPMS. His patience in reviewing my data has contributed greatly to the quality of this work.

I also wish to thank Siri Simonsen for her invaluable assistance during LA-ICPMS analysis and her help in preparing zircon mounts. Gunborg Bye Fjeld is thanked for teaching me the mineral separation procedures in the laboratory. Berit Løken Berg is thanked for her help in SEM imaging. Help from Magnus Kristoffersen in sample preparation is greatly appreciated. Thank you to Lars Eivind Augland and Deta Gasser for insightful discussions on the geology of the Bodø area. A big thank you goes to Mark Steltenpohl for stimulating discussions on the geology of both the Bodø and Ofoten areas.

Many thanks are due to my parents and siblings for all your diverse support and encouragement.

Special thanks go to my dear wife Gifty for her never-ending support and encouragement.

And to God, who makes all things beautiful in His time.

Introduction

Scope of the thesis

The lithological, structural features, tectonomagmatic and metamorphic features of some thrust sheets in the Scandinavian Caledonides are incompatible with current interpretations of their tectonostratigraphic positions and origins.

The aim of the research presented in this thesis is to contribute geological data on the evolution of such terranes in parts of northern Norway. The purpose of the study has been to contribute to the regional geologic understanding of those areas by reconstructing the geological record from key locations. The insights into their origins and geologic histories are placed in a wider context of the evolution of the Caledonian mountain chain as a whole. Central to this, has been the determination of the origin of (potential) exotic terranes present in the Scandinavian Caledonides prior to the Scandian continent-continent collision between Laurentia and Baltica in the Late Silurian to Early Devonian.

Discoveries made during the course of the research have required that the focus of the work was broadened beyond what was originally envisaged. This has brought up new ideas on the understanding of crustal interactions during orogenesis.

The principal methods applied in this thesis are structural field studies and U-Pb geochronology. Literature reviews and re-evaluation of already available data have also provided informational foundations for the conclusions presented.

Study area and Specific aims of the thesis

The selection of study areas was based on known occurrences of rock units whose genesis and tectonic development are poorly studied/explained, or seemingly incompatible with current models.

- ❖ Most maps and publications dealing with the geology of the Bodø-Sulitjelma area have postulated the presence of a major basement culmination, the “Heggmovatn basement dome” between Bodø and Fauske. Granitic gneisses and orthogneisses which dominate the region west of Bodø have also been considered to be comparable with basement rocks exposed in the Tysfjord, Rishaugfjell and Glomfjord culminations. However, the rocks of the Heggmovatn dome have several features that are significantly different from other Baltic basement windows occurring elsewhere in the northern Scandinavian Caledonides. Field mapping during my master studies indicated that the granitic gneisses west of Bodø were allochthonous units. The first aim was to test the allochthonous nature of these rocks and contrast them to the rocks of the Heggmovatn dome. Paper #I, *The Heggmovatn supracrustals, North Norway—A late Mesoproterozoic to early Neoproterozoic (1050–930 Ma) terrane of Laurentian origin in the Scandinavian Caledonides*, characterizes the Heggmo terrane as part of the Uppermost Allochthon closely linked to the Meso- to Neoproterozoic rock complexes in the central-southern segment of the East Greenland Caledonides. Paper #II, *The Bratten–Landegode gneiss complex: a fragment of Laurentian continental crust in the Uppermost Allochthon of the Scandinavian Caledonides* characterizes the granitic rocks west of Bodø, lithologically and geochronologically and deciphers their geologic history and evolution. It is shown that the Bodø-Landegode gneiss complex is an Early Neoproterozoic terrane of continental basement origin from the same palaeogeographic segment in the East Greenland Caledonides as the Heggmo terrane.
- ❖ The Dividal Group is an autochthonous succession of Late Neoproterozoic to Cambrian terrigenous sediments deposited along the western margin (present day coordinates) of Baltica. Most previous workers have considered the sediments of the Dividal Group to be derived from the Fennoscandian Shield further east and thus diagnostic of Baltica. The second topic of this thesis is to document the detrital zircon signature of the Baltic shield by

sampling and analysing the Dividal Group and use it as baseline to which the detrital zircon population of sediments in the Norwegian Sea may be compared. Paper #III, A Timanian foreland basin setting for the late Neoproterozoic–Early Palaeozoic cover sequences (Dividal Group) of north-eastern Baltica, demonstrates based on LA-ICP-MS U–Pb and Hf-isotope data that the autochthonous cover sequence above the Fennoscandia Shield in northernmost Scandinavia is not derived from an easterly Archaean and Palaeoproterozoic source within Baltica as commonly thought. Detrital zircon age populations in the Dividal Group are dominated by Mesoproterozoic zircons with relatively few Palaeoproterozoic and Archaean zircons. A significant population of Ediacaran zircons (ca. 570–560 Ma), indicates a Timanian source area for most of the lower Cambrian Dividal Group sediments. It is argued that the Dividal Group sediments were deposited in a foreland basin south and southwest of the Timanian Orogen. This, in turn, is important in any discussion about the origin of suspect/exotic terranes within the Caledonides and other orogens surrounding the Arctic Ocean. This paper highlights the importance of the role of exhumation and erosion of the Neoproterozoic Timanian Orogen as an important source area for clastic sediments.

- ❖ Paper #IV does not present any new data but rather explores the possibility of the Kalak Nappe Complex originating from a fragment of the Timanide orogen, based on a review of already published data (including data from Paper #III).
- ❖ Basement and cover units in the Northern Scandinavian Caledonides are preserved in three orogenic settings: Baltic foreland, external Rombak window and internal Lofoten-Vesterålen (LVT) terrane. Westward-increasing degrees of Caledonian metamorphism and deformation have left structurally isolated metasedimentary lenses with obscured contacts within LVT plutonic rocks, leaving debatable their significance for possible pre-Caledonian microcontinental sutures, the Caledonian A-type subduction zone boundary,

and the Iapetan suture with Baltica. The third objective of this thesis was to use U-Pb LA-ICPMS dating of detrital zircons from structurally dismembered and isolated metasedimentary packages within LVT basement granite to explore their provenance. However, because detrital zircon-age data was lacking from less strongly Caledonized cover sequences in the foreland, leaving little with which to compare, compelling the investigation to move eastward into the external parts of the orogen. Paper #V, *Tectonostratigraphic Correlations and Provenance of Metasedimentary Cover Sequences and Caledonian Nappes in the Northern Scandinavian Caledonides: Insights from U-Pb Detrital Zircon Analysis*, presents U-Pb data on detrital zircons from metasedimentary cover sequences and Caledonian allochthons from 3 different transects in Northern Norway (Sulitjelma-Bodø, Tornetrask-Lofoten, and Skibotn-Tromsø) and explores their provenance, as well as correlations between them.

The Caledonian orogen: anatomy of a mountain chain.

The rocks of the Caledonian – Appalachian orogen are exposed today, on opposite sides of the North Atlantic Ocean. They are present on the eastern margin of North America and in the British Isles, Northeast Greenland, western Scandinavia and the Svalbard archipelago.

The Caledonides of western Scandinavia and Northeast Greenland have been recognized to have been part of a collisional orogen of Alpine-Himalayan dimensions (Dewey, 1969). The convergence between Baltica and Laurentia begun in the Early Ordovician (Cocks and Torsvik, 2006) resulting in the narrowing of the Iapetus Ocean (Harland and Gayler, 1972). Development of intra-oceanic and arc-continent subduction systems occurred during the Ordovician resulting in the accretion of Iapetan magmatic arcs onto the Laurentian margin by the Late Ordovician. This east-dipping subduction polarity shifted to a west-dipping polarity after the Late Ordovician accretion (van Staal, 1998, 2009; Yoshinobu et al., 2002). After this, arc magmatism was initiated on the Laurentian East Greenland margin and persisted to ca. 424 Ma (Kalsbeek et al., 2008; Rehnström,

2010; Augland et al., 2012). The Scandian phase of the orogeny is defined by the continent-continent collision of Baltica and Laurentia (East Greenland) (Torsvik et al., 1996), which commenced in the Silurian and continued into the Middle Devonian (Gee and Sturt, 1985; Tucker et al., 2004; Gee et al., 2008). The Scandian collision resulted in the subduction of Baltica to great depths (e.g. Root et al., 2004), and its subsequent exhumation to mid and upper crustal levels on both Baltica and Northeast Greenland (Andersen et al., 1991; Hacker, 2007; Augland et al., 2011). Late orogenic extension led to the formation of large Devonian collapse basins (Seguret et al., 1989; Chauvet et al., 1992; Tucker et al., 2004) well exposed in SW Norway.

Scandinavia

The oblique Silurian-Devonian convergence and collision between Baltica and Laurentia modified the margin of Baltica and loaded it with a stack of nappes (Torsvik et al., 1996; Dewey and Strachan, 2003). The Caledonian fold and thrust belt in Scandinavia extend for more than 1500 km along the length of Norway. The Norwegian Caledonides comprise an Archean to Paleoproterozoic autochthonous/parautochthonous basement with a Neoproterozoic to Early Palaeozoic sedimentary cover sequence derived in part from the Baltic shield and the Timanides (Føyn, 1967; Kumpulainen and Nystuen 1985; Nystuen et al. 2008 Paper #III, this thesis), and a series of overlying Caledonian thrust sheets comprising Mesoproterozoic, Neoproterozoic and Cambro-Silurian metasediments as well as several intrusive units of variable age intruded into these sequences (Gee and Sturt, 1985).

The rocks of the (par)autochthonous basement forms the foreland of the orogen and are well exposed in southwestern Norway. They also outcrop further in the hinterland from the foreland in a series of antiformal windows within the Caledonian nappes and comprise a wide variety of rocks. The basement rocks present in southern Scandinavia today are generally deformed and metamorphosed and were formed largely as a result of two orogenic/magmatic episodes; the Gothian (1700 – 1500Ma) and the Sveconorwegian (1130 – 900Ma). They occur in a large area in

southern Norway and the adjacent part of southern Sweden west of the Transscandinavian Igneous Belt (TIB) (Andersen, 2005). In northern Scandinavia, the basement is composed of gradually younger units from the northeast to the southwest. The northeastern part of the Baltic Shield is composed of a Late Archean Domain (3.1–2.6 Ga) and an early Svecofennian supracrustal sequence (2.6–2.1 Ga) (Skår, 2002). Rocks of the Transscandinavian Igneous Belt are composed of alkali-calcic, mafic to acid rocks with I- and A-type characteristics intrude the Svecofennian domain (Skår, 2002).

The traditional view of the Scandinavian Caledonides subdivides the thrust sheets into four major tectonic units; the Lower, Middle, Upper and Uppermost Allochthons. The Upper and Uppermost Allochthons are considered to be exotic with respect to Baltica (Roberts and Gee, 1985). The Lower and Middle Allochthons are generally considered to be derived from shelf and continental rise sediments of the western margin of Baltica) in the Neoproterozoic and associated crystalline basement (Gee and Sturt, 1985; Roberts and Gee, 1985; Andreasson, 1994; Grenne et al., 1999; Roberts, 2003). The Lower Allochthon is composed of low grade sedimentary successions with minor Precambrian crust while the Middle Allochthon contains siliciclastics and carbonate sediments of Neoproterozoic age overlain by tillites and sandstones (Nystuen et al., 2008). The upper parts of the Middle Allochthon have a similar stratigraphy to the lower part; composed of thick Neoproterozoic siliciclastic and carbonate sediments overlain by tillites and sandstones (Nystuen et al., 2008). However, the upper part of the Middle Allochthon (Sarv nappes) is heavily intruded by ca. 600Ma mafic dykes swarms (Gee, 2005). The Lower and Middle Allochthons are metamorphosed under greenschist facies conditions and locally strongly imbricated (Roberts and Gee, 1985; Bjørklund, 1987).

The Upper Allochthon is thought to represent outboard, magmatic arc, ophiolitic and marginal basin deposits derived from locations within or peripheral to, the Iapetus Ocean (Stephens and Gee, 1989; Pedersen et al., 1991). The tectonostratigraphic units of the Upper Allochthon include the

Køli Nappe (Gee, 1978), the Narvik nappe complex (Steltenpohl and Andresen, 1991; Andresen and Steltenpohl, 1994), the Ofoten nappe complex, and a lower nappe known as the Seve Nappe which overlies the Särvi Nappe of the Middle Allochthon.

Tectonic units making up the Uppermost Allochthon are interpreted to be truly exotic with respect to Baltica, originating along Laurentia's eastern margin (Stephens and Gee, 1985; Roberts et al., 2007; Paper #I, #II, this thesis). It is almost entirely confined to north – central Norway in the counties of Troms, Nordland and part of Nord-Trøndelag covering six degrees of latitude over a strike length of more than 700km (Roberts et al., 2007). South of the Tysfjord window, the Uppermost Allochthon is dominated by the Rödöfjället Nappe Complex, the Beiarn Nappe Complex, the Helgeland Nappe Complex (Ramberg, 1967; Barnes et al., 2007) and the Heggmo terrane (Paper #I, #II, this thesis). In the Ofoten and Troms area north of the Tysfjord culmination, the Uppermost Allochthon is composed of the Evenes and Bogen nappes (Ofoten Nappe Complex) and the Niingen nappe complex, and the Nakkedal and Tromsø nappes, respectively (Zwaan et al., 1998; Corfu et al. 2003; Steltenpohl et al., 2003; Ravna and Roux, 2006).

Geochronology: theoretical foundations

A central part of this thesis is U-Pb geochronology by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). Specific analytical details employed in the thesis are not discussed here. Rather, the general theory, the geochronometers used (U-Pb and Lu-Hf) and its applicability is discussed. The ID-TIMS and SIMS methods are only briefly mentioned as data from these methods were gathered by Lars E. Augland.

Atomic Structure

The basic components of an atom are a small, positively charged nucleus and a surrounding cloud of negatively charged electrons. The nucleus is about 10^{-12} cm in diameter, and contains a number of elementary particles called nucleons. The chemical properties of an atom reflect its electronic

structure. The number of electrons in a neutral atom is equal to the number of positively charged units in the atomic nucleus. The atomic mass is controlled by the number of elementary particles in the atomic nucleus. Only the protons and neutrons which are mostly responsible for the mass and charge of the nucleus are relevant for this introduction. Neutrons have no charge, and are equal or higher in number than protons (with the exception being hydrogen). The number of protons defines the chemical behaviour of an atom. A nuclide is uniquely defined by its number of protons (Z) and neutrons (N). The number of nucleons (A) equals the sum: $A=N+Z$. This is also known as the Mass number.

A nuclide of element X can be denoted: A_ZX

Isotopes

A single chemical element may consist of several atomic species, which have the same nuclear charge, but different nuclear mass due to differences in the number of neutrons present. Isotopes are atoms of the same element with the same atomic number but different mass numbers. When the N/Z ratio in an isotope gets too high, it becomes unstable and decays to a daughter isotope (of another element). The decay of unstable isotopes to stable isotopes is the basis of geochronology. Isotopes are best displayed in the chart of nuclides of (N) on the x-axis versus (Z) on the y-axis. Isotopes of one element are displayed on one row (Fig. 1). Vertical rows contain different elements but with the same number of neutrons and are called isotones, whereas isotopes of

different elements with the same mass number (A) are called isobars.

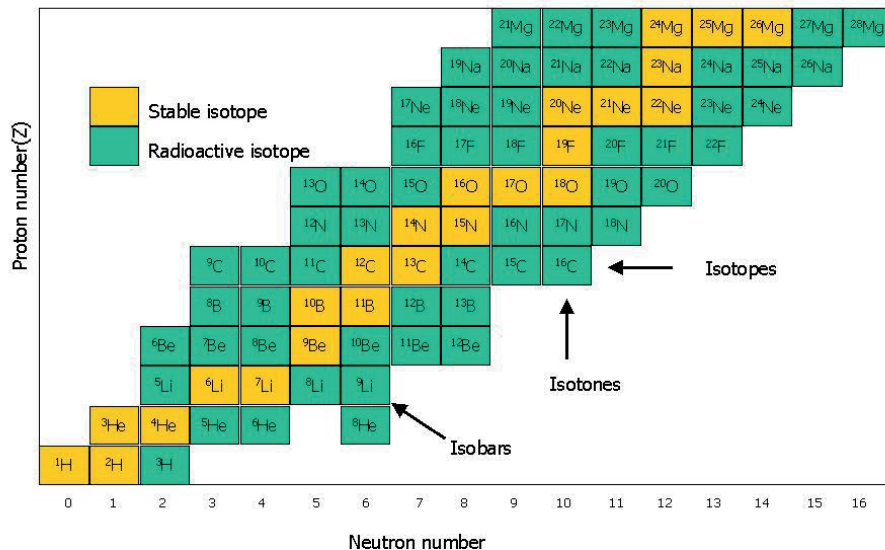


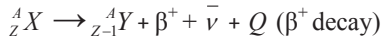
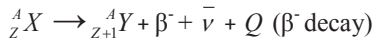
Fig. 1 Chart of nuclides (Source: <http://www.ims.uaf.edu/isotopes/class-images/isotope-table.jpg>)

Radioactive decay and decay mechanisms

Unstable isotopes decay via intermediate unstable product isotopes to stable daughter isotopes.

The rates of decay are independent of external conditions and are constant over time. It is expressed in terms of the half-life ($t_{1/2}$), which is the time elapsed until half of the parent isotope has decayed. Radioactive decay occurs through a number of mechanisms:

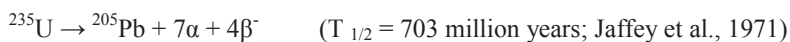
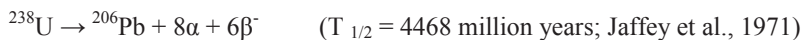
- Alpha (α) decay: the parent isotope emits a particle with two protons and two neutrons (a He nucleus). i.e. ${}^A_ZX \rightarrow {}^{A-4}_{Z-2}Y + \alpha + Q$
- Beta (β) decay: the parent isotope emits an electron (β^- decay) or positron (β^+ decay), and an electron antineutrino ($\bar{\nu}$). In this mechanism, a neutron converts to a proton or vice versa, changing the charge of the nucleus but retaining the same number of nucleons.



- Gamma (γ) decay: the nucleus changes from a higher energy state to a lower energy state through the emission of a high energy photon. The number of nucleons does not change in this process, so the parent and daughter atoms are the same chemical element. This often accompanies other decay mechanisms to balance the energy level.
- Electron capture: the capture of an electron (usually from the K- or L- electron shells), resulting in the conversion of a proton into a neutron and the simultaneous emission of an electron neutrino.
- Spontaneous fission: a rare form of decay occurring in the heaviest nuclei (e.g. ${}^{238}\text{U}$) in which the nucleus splits into two uneven lighter daughter nuclei, which are often still unstable. Excess, free neutrons are produced and the product nuclides are β^- active.

U-Pb isotope systematics

The uranium-lead system is especially useful for dating minerals and rocks with ages of 5 to 5000 m.y. The U-Pb decay system relies on the presence of two isotopic clocks with identical chemical characteristics but different rates of decay. U forms three isotopes: ${}^{234}\text{U}$, ${}^{235}\text{U}$ and ${}^{238}\text{U}$. ${}^{234}\text{U}$ is an intermediate product of the ${}^{238}\text{U}$ decay series. ${}^{235}\text{U}$ and ${}^{238}\text{U}$ decay to two different Pb isotopes (${}^{205}\text{Pb}$ and ${}^{206}\text{Pb}$ respectively) via α - and β - decay mechanisms according to the equations given below:



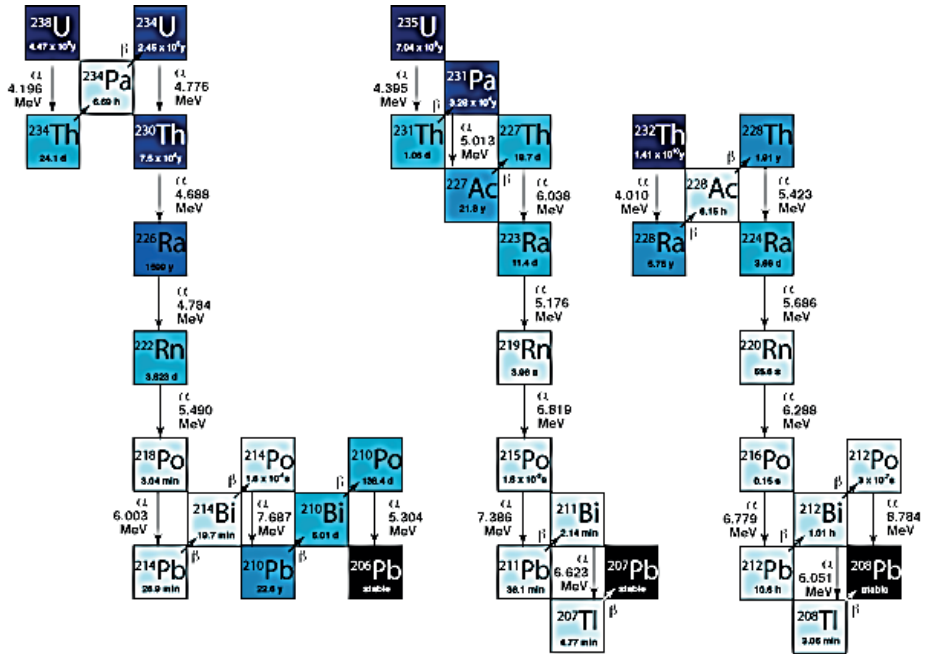


Fig. 2 Decay chain of ^{238}U to ^{206}Pb , ^{235}U to ^{207}Pb and ^{232}Th to ^{208}Pb

The age of the geochronometer is a function of the parent-daughter ratio, the decay constant and the initial Pb content. The success of the application of this system to dating rocks is that the paired decay system provides an “internal test” on the results provided that ^{235}U and ^{238}U have not fractionated in the mineral being analysed (Davis et al., 2003; Faure and Mensing, 2005). This paired decay chain forms the basis for the concordia plot (Wetherill, 1956, 1963; Tera and Wasserburg, 1972). For a mineral to give a meaningful U-Pb age, the following conditions must be satisfied:

- U was incorporated into the mineral’s structure during crystallization
- Correct values are used for the mineral’s initial Pb composition (preferably no initial Pb)
- The mineral is able to retain U, Pb and intermediate daughters
- Closed isotopic systems (no gain or loss of U or Pb)

It is a further advantage if the mineral has a structure that is not compatible with the incorporation of Pb during crystallization. This provides a high U/Pb ratio which is less sensitive to the initial Pb composition which cannot be measured directly in a mineral containing radiogenic Pb.

However, minerals (rocks) are often disturbed and exhibit isotopically open systems. In addition, minerals and rocks can consist of more than one generation, in which case their U/Pb ratios have no immediate geological meaning, representing mixed age and requiring careful interpretation.

The Concordia plot

Treating the $^{238}\text{U} \rightarrow ^{206}\text{Pb}$ and $^{235}\text{U} \rightarrow ^{207}\text{Pb}$ decay systems independently results in the construction of separate age equations, assuming secular equilibrium at the time of system closure.

These isochron equations are:

$$^{206}\text{Pb}/^{238}\text{U} = (e^{\lambda t} - 1) \dots\dots\dots \text{Eqn (1)}$$

$$^{207}\text{Pb}/^{235}\text{U} = (e^{\lambda t} - 1) \dots\dots\dots \text{Eqn (2)}$$

Wetherill (1956) introduced the concordia diagram, which plots $^{206}\text{Pb}/^{238}\text{U}$ versus $^{207}\text{Pb}/^{235}\text{U}$ from the same analyses. The parametric concordia curve can then be drawn as the set of solutions to equations (1) and (2) for equal values of t (Fig. 1), which is nonlinear because ^{238}U and ^{235}U have different half-lives leading to a much faster production of ^{207}Pb than ^{206}Pb . In other words, points on the concordia curve are where $^{207}\text{Pb}/^{235}\text{U}$ and $^{206}\text{Pb}/^{238}\text{U}$ both correspond to the same date. If both the $^{207}\text{Pb}/^{235}\text{U}$ and $^{206}\text{Pb}/^{238}\text{U}$ ages correspond, the analysis is said to be concordant. All samples that remained a closed system since the time of formation fall on the concordia curve whereas those that do not are called discordant and have experienced some form of open-system behaviour. If Pb loss occurred, the points plot along a line below the concordia. If U loss occurred, the points would plot along a line above the concordia. The line that results from discordant

samples is called discordia line. The upper discordia intercept may represent the age of formation of the mineral. The lower intercept may represent the date of Pb loss, if this loss occurred in a single stage, and not continuously. Intermediate daughter product disequilibrium and (the presence of) initial Pb, as well as partial recrystallization also result in discordance.

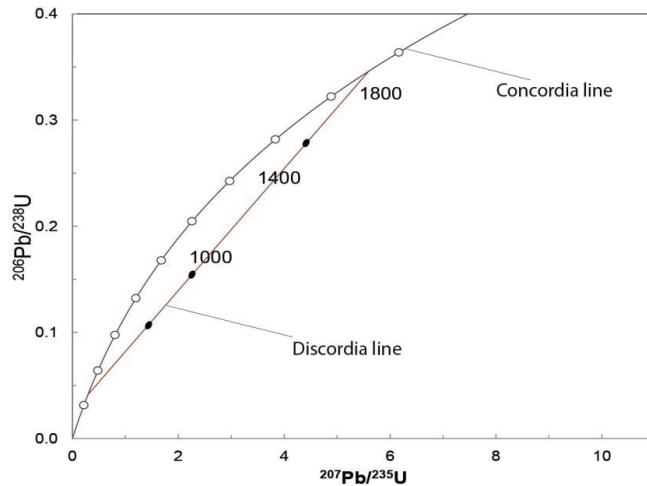


Fig. 2 Classical concordia diagram showing concordia curve and discordant points which define a discordia line

Zircon

Zircon (ZrSiO_4) is the most commonly used geochronometer, with other useful ones including titanite, rutile, monazite, baddeleyite and xenotime. However, only zircon is discussed here as it is the only geochronometer utilized in this thesis. U^{4+} can replace Zr^{4+} in zircon due to their similar ionic radii ($r \text{Zr}^{4+} = 0.80 \text{ \AA}$; $r \text{U}^{4+} = 0.97 \text{ \AA}$), but Pb^{2+} is excluded from the structure during crystallization due to its higher ionic radius ($r \text{Pb}^{2+} = 1.18\text{-}1.29 \text{ \AA}$, $r \text{Pb}^{4+} = 0.78\text{-}0.94 \text{ \AA}$ [$r \text{Pb}^{4+}$ is an extremely rare state]) and low charge (Faure and Mensing, 2005). Zircon is a common accessory mineral in felsic magmatic rocks and is locally found in mafic intrusives (e.g. Paper #II, this thesis), making it very useful for dating igneous events (e.g. Papers #I and #II, this thesis). It is a very robust mineral that may survive cycles of metamorphism, magmatism, erosion and sedimentation and still retain its primary age. Zircon has a high closure temperature for Pb

diffusion ($> 900\text{ }^{\circ}\text{C}$; Cherniak and Watson, 2001) and may also grow during metamorphism.

However, even when there has been metamorphic overgrowth, it may still preserve a record of its protolith and, therefore, allow for the dating of its crystallization age as well as the metamorphic event. Its high chemical stability at surface geological conditions and its hardness also allow it to survive sedimentary cycles and can thus be used to constrain depositional ages and sediment provenance.

Mass Spectrometry

The mass spectrometer is an instrument that can separate and measure the masses and relative concentrations of ions/isotopes when they move through a magnetic field. It consists of three major parts: an ion source, a mass analyser, and an ion collector (Faure and Mesning, 2005). It is closed to the environment and operated under high vacuum. There are three principal techniques applied in the U-Pb dating of zircon and other geochronometers; isotope dilution thermal ionization mass spectrometry (ID-TIMS), secondary ionization mass spectrometry (SIMS) and laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS).

ID-TIMS and SIMS

ID-TIMS produces high precision data, but requires relatively large zircon grains (in general grains more than $50\text{ }\mu\text{m}$ in diameter) and the grain is destroyed. In the ID-TIMS technique the U/Pb ratio is determined by mixing in a spike of known composition. A spike (tracer) is a solution containing a known concentration of an element strongly enriched (artificially or naturally) in one of the isotopes. As the abundance and isotopic composition of the spike is well known, the measurement of isotopic ratios provides a way to determine the abundance of the element(s) in the unknown sample. The synthesis of spike ^{205}Pb (Krogh and Davis, 1975; Parrish and Krogh, 1987) has allowed for a greater accuracy in measuring U-Pb isotopic ratios. A method to improve the concordance of zircon by physically abrading the discordant parts was developed by Krogh (1982)

while a chemical abrasion technique been developed by Mattinson (2005, 2011) has greatly refined the analytical procedure.

SIMS instruments have the ability to date individual spots within a single grain due to the smaller size of the area that is sputtered (typical spot is 25 μm wide and less than 1 micron deep), and the rest of the sample is preserved. The sample is sputtered by a primary beam of oxygen ions. The size of the sputtered area allows for the undesirable parts of the zircon grain to be avoided. Because it can analyse a large number of grains (or domains within grains) relatively rapidly, it increases the statistical basis for interpretation of the resulting data. However, the errors on the isotopic ratios produced by SIMS are about one order of magnitude higher than that of ID-TIMS. This is because the small sample volume results in poorer mass spectrometer counting statistics.

LA-ICP-MS

In an inductively coupled plasma mass spectrometer, the sample is introduced as an aerosol (from a solution) or by ablation of a solid sample by laser, to a plasma torch with flowing Ar gas. The sample and Ar gas are seeded with energetic electrons ionizing the Ar gas and the sample. The resulting plasma is then transported into the mass spectrometer by flowing Ar gas. Ions are accelerated in a high potential electric field and subsequently separated on mass-to-charge ratios in a magnetic sector (Montaser et al., 1997).

LA-ICPMS provides a fast and affordable way to generate a huge amount of U–Pb isotopic data, which is ideal for characterizing complex detrital zircon populations (Fedo et al., 2003). Detrital zircon studies have been utilized in a number of ways. They have proven useful in paleogeographic reconstructions, identifying tectonically induced drainage pattern switches, placing time constraints on uplift, and identifying pulses of magmatism (e.g., Rainbird et al., 1992; Bruguier et al., 1997; Ireland et al., 1998; Stewart et al., 2001; Dickinson and Gehrels, 2003) leading to improved tectonic models of orogenic belts. Correlation of sedimentary strata in

palaeogeographic reconstructions has also employed detrital zircon analysis (e.g. Murphy et al., 2004; Paper #V, this thesis). Detrital zircon analysis can constrain the maximum depositional ages for sedimentary strata in the absence of dateable volcanics/intrusives and fossils (e.g. Robb et al., 1990; Papers #I, #V, this thesis). LA-ICPMS drills 50 to 15 microns wide, and 10-50 micron deep holes in the zircons; it uses less material than ID-TIMS, but considerably more than SIMS analyses. The precision is comparable to that of SIMS. The main difficulty lies in the calibration of U-Pb ratios. There can also be problems with the impurity of Ar (interferences from Hg limit the ability to correct for common Pb).

Detrital zircon age data

Despite the successes of detrital zircon analysis, there are still several challenges in utilizing the method. There is currently no consensus on the best way to interpret detrital zircon spectra in terms of the significance of peak heights (when plotted on probability density function diagrams), differences in the relative abundances of peaks between samples in stratigraphic succession, or what statistics can be applied to spectra (Gehrels, 2011). Furthermore, several recent studies on modern sediments highlight the impact that biased provenance sampling, especially with low sampling resolution, and grain-size sorting during sediment transport can have on depositional age interpretations (Moecher and Samson, 2006; Hietpas et al., 2011).

Most U-Pb detrital data are presented as an accumulated probability density plot (Fig. 2) defined by the expression for an average of n of Gaussian probability scores, each defined by a mean value (i.e. age) μ and an uncertainty σ , as:

$$f(t) = \frac{1}{n} \sum_{i=1}^n \frac{1}{\sigma_i \sqrt{2\pi}} e^{-\frac{(t-\mu_i)^2}{2\sigma_i^2}}$$

This diagram combines information on the distribution of points and the analytical quality. It is superb for data presentation but can be potentially dangerous as a tool for interpretation, when n is (too) small.

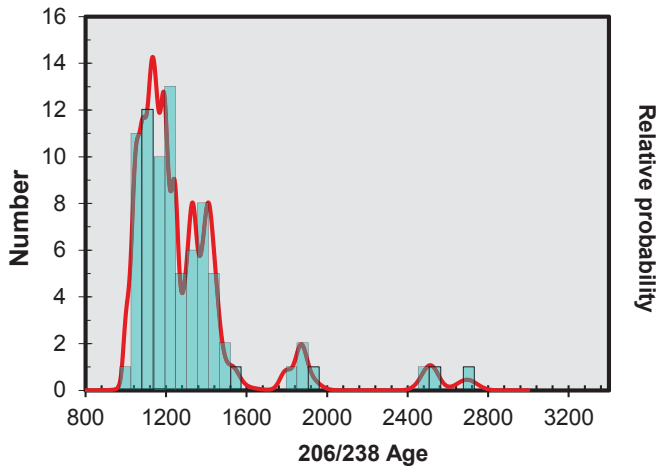


Fig. 2 Typical probability density plot and histogram showing detrital zircon age populations in a sample (data from Gullesfjord quartzite presented in Paper #5).

The robustness of the interpretations made from detrital data depends to a large extent, on the number of zircon grains analyzed. Theoretical considerations suggest that the sample will be quantitatively representative only when n is unreasonably large ($\gg 100$). The number of analyses required for a given level of confidence is given by Dodson et al. (1988) as:

$$P = (1 - f)^n$$

P = the probability that a given population might have been missed

n = the total number of analyzed grains

f = the frequency of the missed population

This equation assesses the probability of missing a provenance component comprising a certain proportion of that component within the total sample, and the number of grains analyzed. The typical case is a provenance component comprising 1 in 20 in the total sample. Using the expression in Dodson et al. (1988), at least 59 randomly selected grains need to be measured to reduce the probability of missing this component to 5%. Vermeesch (2004) argues that 119 grains should be analyzed per sample for a provenance study, although this could increase to > 300 if Vermeesch's principles are strictly applied. In practice, the number of zircons to be analyzed depends on what you need to know and how complex the sample is. Between 60-100 analyzed grains per sample appears to be in common use.

General Conclusions

Field and geochronological data (U-Pb ID-TIMS, SHRIMP, and LA-ICPMS) on granitoids and their metasedimentary host rocks reported for rocks of the Bodø and Ofoten regions of north-central Norway in this thesis helps to document the distribution of Baltican versus Laurentian crust and allows for tectonostratigraphic correlations to be made across the E-W-trending Tysfjord orogenic culmination. In the Bodø region, large areas previously interpreted as pre-Caledonian (ca. 1.8 Ga) Baltic basement domes (Heggmovatn and Landegode domes) are in fact Caledonian thrust sheets belonging to the exotic (Laurentian) Uppermost Allochthon.

The Bratten-Landegode gneiss complex and Heggmo units have straightforward age correlations to Mesoproterozoic to Neoproterozoic rock complexes from Laurentian complexes now exposed in southern East Greenland and in other parts of the North Atlantic realm. Laurentian Grenville-continental crust preserved in the Uppermost Allochthon of the Bodø region, therefore, record tectonic events that had taken place on the northeastern Laurentian continent prior to its Caledonian continent-continent collision with Baltica. In Ofoten, ~150 km north of Bodø, the basal units of the Uppermost Allochthon comprise a thick sequence of platformal marbles (Evenes

Group) that overlie a fragmented ophiolite complex dated at ca. 474 Ma. Suites of multiple phases of felsic intrusions occur within the overlying Bogen and Niingen nappes and the underlying Narvik nappe (Upper Allochthon) but are absent in the Evenes Group. A suite of ca. 470 Ma granites (Snaufjell granite) intrudes the Bogen Group and implies correlation to parts of the Uppermost Allochthon in the Helgeland nappe far to the south of Bodø; lithologically correlative units, however, occur directly south of Tysfjord in the Engeløy synform, which likely forms the southern counterpart of the Ofoten synform. Pre-Scandian relics within the Lofoten-Vesterålen region also imply that slivers of Uppermost Allochthon exist far to the west of areas previously mapped as Baltic basement. Although Tonian-aged plutonic rocks that so characterize the Uppermost Allochthon south of Tysfjord have not been identified in the Ofoten area, U-Pb detrital zircon age populations in quartzites from Lofoten-Vesterålen (Leknes and Gullsfjord), and the Evenes, Bogen, and Niingen groups indicate that they too could have Laurentian origins. Provenance studies are used extensively to understand pathways for clastic sediments from their source area(s) to their present position as reservoir units in sedimentary basins (sinks). Examples of this are represented by the post-Caledonian hydrocarbon-producing basins surrounding the North Atlantic.

A prerequisite for successful provenance studies is sufficient knowledge about the geology of likely source areas, which in the “North Atlantic case” are the pre-Devonian rocks in East Greenland and Scandinavia, possibly also Svalbard and Great Britain. The recognition of Laurentian continental crust in the Scandinavian Caledonides presented in this thesis, and the presence of an eclogite terrane in the East Greenland Caledonides (Liverpool Land) of Baltican affinity (Augland et al., 2011) makes the previous subdivision of Scandinavian (3) and East Greenland (2) into 5 diagnostically different source areas (Morton et al., 2005; Morton and Chenery, 2009) problematic.

The story of the Scandinavian Caledonides has mostly been about the interactions between Baltica and Laurentia, often excluding other (micro) continental masses. The recognition of a Timanian signature in the Dividal Group and the possibility that the well-studied Kalak Nappe Complex is a fragment of the Timanian orogen makes it apparent that other crustal blocks have also influenced the current configuration of the Scandinavian Caledonides.

The Mesoproterozoic “problem”

Most of the nappes (from northern Norway) sampled and analysed in this study contain a significant population of Mesoproterozoic zircons with a broad spread of ages ranging between ca. 0.9 and 1.6 Ga, which is not easily explained since Grenvillian-Sveconorwegian aged crystalline rocks are uncommon except in the southernmost part of the Fennoscandian shield. Zhang et al. (2015) report an abundance of Mesoproterozoic aged zircons grains from the Fugleberget Formation (Vadsø Group), Grønneset and Gamassfjellet Formations (Tanafjorden Group) from the Varanger Peninsula in northernmost Norway with palaeocurrent data indicating derivation of the sediments from the south, although no crystalline rocks of Grenvillian/Sveconorwegian age are found north of Trondheim, except in the allochthonous Bratten-Landegode Gneiss Complex and the Heggmo Terrane of Nordland (Paper #I, #II, this thesis) which are interpreted to be exotic with respect to Baltica, and are likely of Laurentian origin. Zhang et al. (2015) argue that Mesoproterozoic aged zircons may be derived from a distal southerly source, for example the 1.65–1.50 Ga rapakivi granite suites in southern Finland, SW Russia and Estonia, or the Sveconorwegian orogen (Bingen et al., 2008). This is plausible given that the autochthonous successions of Varanger-Tanafjord Region would have extended much farther south prior to their subsequent erosion and denudation in Phanerozoic time (Larson and Tullborg, 1998; Huigen and Andriessen, 2004; Murrell and Andriessen, 2004). Samples from the Stappogiedde Formations of the Vestertana Group also on the Varanger Peninsula reported by Zhang et al. (2015) also yield a similar Mesoproterozoic detrital zircon age spectrum in addition to a major peak at 554 Ma with

palaeocurrent data indicating derivation from the northeast (Banks et al., 1971). This suggests that the Tonian-Cryogenian metasedimentary rocks which characterise the pre-Timanian succession in the region (e.g., Lorenz et al., 2004; Roberts et al., 2008) may carry an abundance of recycled Mesoproterozoic zircons. This gives a very strong indication that the Ediacaran and Mesoproterozoic zircons were recycled mainly from the growing Timanian orogen to the north-east (Paper # III, this thesis; Zhang et al., 2015) and further suggests the presence of an unidentified crustal block located north of Baltica containing Mesoproterozoic aged complexes involved in the Timanian orogeny (Paper #III, this thesis), although these complexes are as yet unknown.

Gee et al. (2015) also report similar detrital zircon spectra of Mesoproterozoic zircons with a prominent Sveconorwegian peak in rocks of the Lower and Middle Allochthons across the Silver Road (Silvervägen) profile through the Scandinavian Caledonides, located in Sweden along the Arctic Circle at 66–67°N, which are closely comparable to those obtained from similar tectonostratigraphic levels in the central Scandes, 400 km to the south at ca. 63–64°N.

Gee et al. (2015) interpret the persistence of this detrital zircon distribution in the Lower and Middle Allochthons along the length of the orogen to indicate that the entire, ca. 1800 km length of the Baltoscandian margin was underlain by latest Paleoproterozoic to Mesoproterozoic crust influenced by the Sveconorwegian Orogeny (Nystuen et al., 2008). It is further argued that most of this attenuated basement was “lost” during Scandian collisional orogeny and the underthrusting of Laurentia by Baltica. Kuznetsov et al. (2012) favour a vast river system that may once have extended across the central Fennoscandian Shield, transporting zircon from Mesoproterozoic terranes in southern Norway and Sweden to the north, although this interpretation is disputed by Lorenz et al. (2012, 2013) on the basis of the presence of dominating Grenville-Sveconorwegian signatures on the Barents Shelf as far north as Svalbard (78–80°N).

Considerations for future research

Further isotopic studies and geochemical investigations on the various igneous rocks of the Bratten-Landegode gneiss complex and the Heggmo terrane would be useful as a further test of the derivation of these units from NE Greenland. Similar data would be required from the Neoproterozoic rocks of NE Greenland for comparison. A detailed structural and metamorphic study of the nappes along the Sulitjelma-Bodø transect, especially the contact relations between them would provide insights on the timing and emplacement geometries of these units onto Baltica. Isotopic studies of other plutons in northern Norway would also aid in the recognition of other Laurentian continental crustal pieces in the Caledonides.

The extent of the influence of Timanian exhumation and erosion in the Scandinavian Caledonides is unknown. Also unknown is the timing of change in tectonic setting from rift- to foreland-settings of the Dividal Group. One way to determine this timing is to study the vertical and lateral variations in the detrital record in the Digermul peninsula where thick successions of the Dividal Group are present. Such a study is in progress.

Isotopic and geochemical studies of the Seiland Igneous Province and similarly aged Timanian rocks would serve as a good test of the Kalak Nappe Complex being derived from the Timanide orogen. A comparison of the Lu-Hf isotopic signatures of the diagnostic ca 570 Ma detrital zircons in the Dividal Group and those from other known sediments sourced from the Timanide orogen would also be a further test on the link between the Timanides and the Dividal Group.

The data presented in Paper #5 of this thesis highlights the discrepancies between the use of detrital zircons and chemostratigraphy, in determining depositional ages and correlating rock units in the Fauske and Ofoten areas. A systematic detrital zircon study along the rock successions in these areas is needed to establish the reliability of C, O, and Sr isotopes vs detrital zircons in medium to high grade metasediments.

List of Papers

Paper I

Agyei-Dwarko, Nana Yaw; Augland, Lars Eivind & Andresen, Arild (2012). The Heggmovatn supracrustals, North Norway-A late Mesoproterozoic to early Neoproterozoic (1050-930 Ma) terrane of Laurentian origin in the Scandinavian Caledonides. *Precambrian Research*. **212-213**, 245- 262. doi:10.1016/j.precamres.2012.06.008

Paper II

Augland, Lars Eivind; Andresen, Arild; Corfu, Fernando; Agyei-Dwarko, Nana Yaw & Larionov, Alexander (2014). The Bratten-Landegode gneiss complex - a fragment of Laurentian continental crust in the Uppermost Allochthon of the Scandinavian Caledonides. *Geological Society Special Publication*. **390**, 633- 654.doi: 10.1144/SP390.1

Paper III

Andresen, Arild; Agyei-Dwarko, Nana Yaw; Kristoffersen, Magnus & Hanken, Nils-Martin (2014). A Timanian foreland basin setting for the late Neoproterozoic - Early Paleozoic cover sequences (Dividal Group) of north-eastern Baltica. *Geological Society Special Publication*. **390**, 157- 175 doi: 10.1144/SP390.29

Paper IV

Andresen, Arild & Agyei-Dwarko, Nana Yaw. Detrital zircon age data support a Timanian origin for the Kalak Nappe Complex, northern Scandinavian Caledonides (In preparation)

Paper V

Agyei-Dwarko, Nana Yaw; Andresen, Arild; Steltenpohl, Mark & Gasser, Deta.
Tectonostratigraphic Correlations and Provenance of Metasedimentary Cover Sequences and Caledonian Nappes in the Northern Scandinavian Caledonides: Insights from U-Pb Detrital Zircon Analysis (In preparation)

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