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U-Pb geochronology of crustal evolution and orogeny

Contributions from Caledonide Spitsbergen and the Precambrian West Troms Basement Complex, North Norway

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"You have the key to mystery

Pick up the runes; unveil and see"

K. Grutle / Enslaved - *Axioma Ethica Odini (2010)*

Preface

This doctoral thesis was carried out at the Department of Geology, University of Tromsø from 2006 - 2011, financed by the University of Tromsø. I spent one academic year (autumn 2008 - spring 2009) at the Department of Earth and Atmospheric Sciences, University of Alberta. This visit was financed through a travel grant from the University of Tromsø, and laboratory work at the University of Alberta was financed by professor Larry Heaman. During the stay at the University of Alberta I enrolled in graduate courses, conducted U-Pb-laboratory work on mafic dykes and worked with the manuscripts of paper II and II.

Field and laboratory work presented in paper I was conducted in 2004 and 2005 as part of my master studies at the Department of Geoscience, University of Oslo. This project was led by professor Arild Andresen, UiO. Field and laboratory work in papers II, III and my contributions to paper IV from Troms was conducted from 2006 - 2011, as part of a project led by professor Steffen Bergh. ID-TIMS U-Pb-analyses were done at the University of Oslo during several stays there, and papers II and III also report some data analysed earlier by professor Fernando Corfu. ID-TIMS work at UiO was financed by professor Fernando Corfu, and the travelling costs were financed by the University of Tromsø. U-Pb SIMS analyses were carried out at Nordsim in Stockholm financed by the University of Tromsø and NFR Småforskmidler granted to associate professor Kåre Kullerud.

The thesis consists of three published papers, one manuscript and an introduction.

Front cover: Mountains close to Grunnfarnes on southwest Senja.

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Introduction

Scope of the thesis

The aim of the research presented in this thesis is to contribute geochronological and geological data on crustal evolution in two areas: the Albert I Land, northwest Spitsbergen and the West Troms Basement Complex, North Norway. The purpose of the study is firstly to contribute to the regional geological mapping of those areas by reconstructing the geological record from key locations in high detail. Secondly, those insights are placed into a wider context of crustal evolution through time and space. Only by obtaining a as complete as possible geological record of the continental crust can the global geological community reconstruct past tectonic movements and understand the associated geological processes. From the point of view of society, hard rock geoscience is a key to meeting the ever increasing human demand for resources .

The method applied in this thesis is structural geological field studies and U-Pb-geochronology of variably deformed igneous and metamorphosed crustal rocks. The two study areas differ in location and the ages of the rocks, but the geology is in many ways similar: Both regions have rocks with a multi-stage geological history characterised by several phases of magmatism, metamorphism, deformation and deposition of sediments, and occurring in an orogenic setting.

U-Pb-geochronology of rocks found in orogenic terranes

The components of continental crust are added from the mantle by magmatic processes or by subduction of oceanic crust, and reprocessed by deformation, metamorphism and magmatism, often as part of regional orogenic events (Rudnick and Gao, 2007). The finite result is a buoyant felsic crust that is extremely long-lived and makes up the bulk of continents. In earth science, a wide range of geological studies and techniques are applied in efforts to understand evolution of continental crust. One method that has become crucial for this purpose is dating of rock-forming and -modifying events by U-Pb-geochronology of accessory minerals, in particular zircon (e.g. review in Davis et al., 2003), represented by an ever increasing number of studies from around the world, in particular from Precambrian areas. The basis for this method is that some minerals (called geochronometres) incorporate minor amounts of U (usually up to a few hundred ppm in zircon in the ideal cases). Natural U has two principal radioactive isotopes, ^{235}U and ^{238}U, that decay to two different Pb isotopes (^{207}Pb and ^{206}Pb, respectively), and the age of the geochronometre is a function of the parent-daughter ratio, the decay constant and the initial Pb content (which is often negligible). The success of the U-Pb-method of dating is largely due to this paired decay system that provides an internal test on the results, which is the basis for the concordia plot (Tera and Wasserburg, 1972; Wetherill, 1956, 1963); if both the ^{207}Pb/^{235}U and ^{206}Pb/^{238}U-ages correspond, the analysis is *concordant*.

Zircon is the most commonly used geochronometre, with other important ones including titanite, monazite, baddeleyite and xenotime. Zircon is a very robust time capsule that readily survives metamorphism, cycles of magmatism and erosion and sedimentation, and still may retain the primary age. While this is the principal reason for its ability to yield robust ages, it also introduces some complications for the interpretation of the data: typically, samples of igneous or metamorphic rocks contain several generations of zircon and crystals that have been modified by metamorphism. The presence of multiple age populations within an analysis leads to discordant data, and this needs to be tackled with an appropriate analytical approach and careful interpretation of the result. Another property of zircon that commonly causes discordancy is its tendency to lose Pb, mainly at low temperatures, due the accumulation of radiation damage in the crystal structure which allows Pb to escape by diffusion or fluid transport. This can be handled by avoiding unfavourable crystals or parts of crystals, and careful interpretation. For these reasons, rather than obtaining an average result from randomly selected samples, successful application of U-Pb geochronology depends on isolating and analysing high-quality crystals that record the actual relevant events in a rocks history.

Today, three techniques are widely applied to U-Pb dating of zircon and other accessory minerals: isotope dilution thermal ionization mass spectrometry (ID-TIMS), secondary ionization mass spectrometre (SIMS) and laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS). ID-TIMS involves analysis of a dissolved sample mixed with a tracer (spike) of known isotopic composition, normally a mix of enriched ^{235}U and artificial ^{205}Pb. SIMS and LA-ICPMS are beam techniques that use an ion or laser beam to micro-sample a small part of a crystal which is subsequently analysed by a double-focusing mass spectrometre, and the results are then calibrated by concurrent analyses of a standard.

The present state of the ID-TIMS method of U-Pb-dating is the result of advances made in the past 30 - 40 years that have allowed increasingly small amounts of zircon to be analysed with increasingly better precision and accuracy (Krogh, 1973, 1982), see reviews in Davis et al. (2003), Kamo et al. (2011) and Parrish et al. (2003). An important step in the evolution of the technique was the development of Teflon laboratory equipment for acid distillation and high temperature decomposition of zircon, allowing a drastic reduction in contamination levels (Krogh, 1973). Synthesis of ^{205}Pb spike improved the ability to accurately measure the U-Pb isotopic ratios (Krogh and Davis, 1975; Parrish and Krogh, 1987). A method to improve the concordancy (the degree of correspondence between the calculated ^{207}Pb/^{235}U and ^{206}Pb/^{238}U-ages) of zircon by physically removing (abrading) the discordant parts was developed by Krogh (1982), and this represented a significant advance. Later, a chemical abrasion technique was developed with the same objective (Mattinson, 2005, 2011). With these refinements of the analytical procedures, the ID-TIMS method provided the most precise way of measuring U-Pb-ages, and with the great reduction in required sample size, fractions of individual zircons can be routinely analysed. Today, the two main objectives and challenges in practical applications are to remove discordant parts of the grains from the analyses, and being able to isolate multiple age populations within the same sample.

With the development of ion microprobes, or SIMS instruments (review in Ireland and Williams, 2003) came the ability to date individual spots within single grains. By "sputtering" the sample using a primary beam of oxygen ions, a small, near two-dimensional area usually around 20 µm across can be analysed, and in that way undesirable parts of zircon grains or mixed age domains can be avoided. Another advantage with SIMS is the ability to relatively rapidly analyse a large number of individual grains and domains within grains, increasing the statistical basis for interpretation of the data. However, as a consequence of the small sample volume, mass spectrometre counting statistics are much poorer and therefore the errors on the isotopic ratios are about one order of magnitude higher than ID-TIMS.

Essentially the ID-TIMS and SIMS techniques are complementary, each having their advantages and disadvantages. In that respect it is somewhat of a puzzle that so few studies have utilized both methods in order to resolve more completely the questions faced when dealing with complex orogenic rocks. Part of the reason for this is perhaps that each of the techniques' advantages and disadvantages are given disproportionally great significance by some. In this thesis both techniques are employed. Through the sound treatment of the data, with adequate caution given to each techniques' shortcomings, I suggest that a combined approach can be highly beneficial when dealing with complex orogenic rocks.

Appropriate interpretation of U-Pb data is obviously the key to success. A common situation in orogenic terranes is that the rock record is incomplete and complex, and this is reflected in the U-Pb-data as well. Knowledge about the geology of the samples, careful characterisation of the properties of zircon and any other geochronometres and common sense are all important virtues for interpretation of the data. Initial characterisation of properties of the geochronometre is normally done with an optical microscope, studying heavy mineral rock separates. It is usually also helpful to utilize SEM imaging, normally cathodoluminescence (CL) or back scattered electrons (BSE) images on polished grain mounts. SEM imaging is particularly powerful to study internal textures within the grains. In the most simple situations where a magmatic zircon population can be identified and yield concordant or collinear data points, the interpretation of the age of the rock is normally straightforward.

Successful identification of magmatic zircon is normally done using the external morphology and / or growth zoning. If more than one generation is present within the same grain, this will often be reflected as contrasting growth patterns. A multitude of other zircon textures and morphologies are also common, often restricted to particular rock types or geological environments and thus enabling interpretations of their origin with respect to the igneous and / or metamorphic history of the rocks. The empirical knowledge of the various textures and morphologies comes from a multitude of individual studies of different rock types (review in Corfu et al. (2003a). More complex cases where individual populations can not be easily identified, or where the origin of some population is unclear are not uncommon, especially in orogenic terranes. These can be some of the most interesting cases, since a lot of information about different stages in a rock's history can potentially be extracted.

More sophisticated linkage of geochronometres to specific metamorphic reactions is possible by using reaction textures or geochemical properties of the metamorphic minerals. For example, the principal constituents of titanite ($CaTiSiO_5$) are also major elements in most rocks, and the growth or breakdown of titanite can sometimes be linked directly to metamorphic textures or parageneses (Corfu and Stone, 1998; Verts et al., 1996) or isotope systematics (Amelin, 2009). Similar metamorphic textural relationships can sometimes also be observed involving zircon (Bingen et al., 2001; Heaman and LeCheminant, 1993) but since the principal constituents of zircon cannot always be linked with a metamorphic paragenesis, one often relies on zircon morphology and association with metamorphic mineral textures in order to identify metamorphic zircon populations (e.g. Davidson and Breemen (1988) and review in Corfu et al., 2003a). Also, an approach linking trace element patterns of zircon with metamorphic minerals is sometimes applied (e.g. Bingen et al., (2004) and review in Hoskin and Schaltegger, 2003).

One of the classical areas of Precambrian crust is the Lewisian Complex in northwest Scotland, and the understanding of the complex Neoarchaean and Palaeoproterozoic evolution here has been further advanced with the application of U-Pb dating on the various units (e.g. reviews in Park, 2005; Wheeler et al., 2010). An example of the application of U-Pb-dating to complex, multi-generation rocks is provided by the studies of Corfu et al. (1994), Whitehouse and Kemp (2010) and Love et al. (2004) on high-grade Neoarchaean granulite facies gneisses in the Scourie area in the Lewisian Complex. The data from equivalent high-grade gneisses, from Corfu et al. (1994) and Whitehouse and Kemp (2010), are shown in Fig. 1 and illustrate the complementary nature of the two techniques. First, the timing of the "Inverian" event at 2490 - 2480 Ma is well constrained in the ID-TIMS-data by dating of a pegmatite associated with rehydration of the granulite facies rocks and the lower intercept of zircons in the granulite samples. This event is also evident from the SIMS data, represented by single phase zircons, rims and some of the youngest cores in the felsic granulites sampled by Whitehouse and Kemp, but the SIMS data spread out along the concordia, making it difficult to choose an age for this phase. The youngest of these ages corresponds to the ID-TIMS data, and a rather unambiguous interpretation on the timing of the Inverian metamorphism can be made. The advantage that a large number of grains and individual domains of grains can be dated by SIMS is illustrated by the older, pre-Inverian zircons in these rocks. With a large number of analyses, the data presented by Whitehouse and Kemp show a near continuous record from 3.1 Ga to 2.5 Ga. The oldest parts of this record are interpreted as inheritance in the felsic granulites, but an unambiguous protolith age can not be determined. However, an age of c. 2.85 Ga is preferred as the protolith age by Whitehouse and Kemp based on the statistical abundance of zircons of this age, their CL-structures and evidence from Hf isotopes. This is consistent with, and adds detail to, the interpretation based on minimum ages and upper intercept lines in the granulite samples of Corfu et al (1994) that the protolith age and timing of an earlier metamorphic event was older than 2710 Ma. Whereas the details of the data and the interpretation in these samples may have some differences (see Corfu, 2007; Friend et al., 2007), the results presented by Corfu et al. (1994), Whitehouse and Kemp (2010) and Love et al. (2004) illustrate the complementary rather than conflicting nature of the two techniques.

Caledonian and Precambrian terranes in the North Atlantic region

Caledonian exotic terranes -Cordillera-type tectonics?

Exotic terranes are pieces of crust, oceanic or continental, that are tectonically transported or transposed from one tectonic plate to another during orogeny. The exotic terrane preserves a pre-orogenic history that is distinct from that of the tectonic plate it is currently part of. In order to identify a terrane as exotic, it is necessary to document that it has a distinct geological affinity, i.e. a distinct stratigraphic, tectonic, metamorphic or magmatic history.

Regarding the Caledonides of the North Atlantic north of the Arctic circle, recent studies have pointed out the exotic origin of many of the terranes in the upper and uppermost allochthons of the Caledonides of northern Norway and Sweden (Corfu et al., 2011, 2007; Kirkland et al., 2008, 2011) and Svalbard (Gee and Teben'kov, 2004). Important evidence for this is a preserved Neoproterozoic history in those terranes distinctly different from the northern parts of Baltica, and it appears that they originated near a common Neoproterozoic margin between eastern Laurentia, Baltic and Amazonia prior to the opening of the Iapetus Ocean (Kirkland et al., 2007, 2011). During the closing of Iapetus, a similar distribution of the terranes emplaced onto Baltica remained (Fig. 2), and the terranes eventually ended up in their current positions, probably by large-scale strike-slip translations (Gee and Teben'kov, 2004), i.e. Cordilleran-type tectonics (Fig 2, from Corfu et al. 2011). In detail the picture is complicated and to some degree uncertain, e.g. due to the lack of old sutures in most locations (Corfu et al., 2011) and also a rather complex and varied timing of events in the different areas (see for example compilation in paper I).

Neoarchaean - Palaeoproterozoic tectonic processes and continent reconstructions

The cores of the continents are made up of cratons that became stabilized in the Archaean and were subsequently involved in tectonic events that variably modified the Archaean crust. The current record of these Archaean cratons is found as c. 35 pieces distributed around the world (Bleeker, 2003). The outline of each craton is a result of cycles of collision, granitoid intrusion, extension, rifting and basin formation, and if several of these events can be correlated between various cratons, then it is possible to reconstruct former assemblages called "supercratons" (Bleeker, 2003). In particular, timing of large igneous provinces and associated episodes of continental breakup can be used for such analyses, whereby the most detailed record known is that of the Laurentian cratonic fragments (Ernst and Bleeker, 2010).

It is commonly considered that the Karelia and Superior cratons of Baltica and Laurentia were in the vicinity of each other or connected at the end of the Archaean (Mertanen and Korhonen 2011; and references therein). Various similar Palaeoproterozoic configurations have also been discussed in the literature (Buchan et al., 2000; Connelly et al., 2000; Park, 2005; Park et al., 2001; Pesonen et al., 2003). As an example, Fig. 3 shows a speculative model proposed by Park (2005): Following breakup of the Neoarchaean supercratons, oceanic arcs start to converge from c. 2.0 Ga, with eventual accretion of the cratons along sutures that follow the grain of the Palaeoproterozoic orogens. The model of Park finishes with a rather familiar configuration of the various Baltica and Laurentia cratons at the beginning of the Mesoproterozoic. Despite being a speculative model it illustrates well the need for, and opportunities represented by, detailed tectonostratigraphic research within these cratons and especially along their margins such as the Lewisian complex, parts of the North Atlantic and central Greenland cratons and, although not specifically considered by Park (2005), also the West Troms Basement Complex (WTBC).

The role of the West Troms Basement Complex

The question of a possible exotic origin of the Precambrian rocks in WTBC (and also Vesterålen and Lofoten) with regards to the geology of the Fennoscandian shield is sometimes raised (e.g. Koistinen et al., 2001). The reason is that these provinces occupy an interior position within the Caledonide orogen, far from shield rocks and bounded by faults (mainly extensional but some thrusts as well) against the Caledonian nappe stack in the east (Zwaan et al., 1998). They are usually not considered part of the Fennoscandian Shield (Hölttä et al., 2008; Koistinen et al., 2001), but instead assigned an uncertain tectonostratigraphic status (Koistinen et al., 2001). Whereas the interpretation of Svalbard's Albert I Land as an exotic Caledonian terrane with respect to Baltica is rather straightforward and accepted (paper I), the situation in WTBC is more complicated and unresolved. This is mainly due to the uncertainty regarding what role it played during Caledonian orogeny, with apparently only very minor (paper II, III and IV) effects on the Precambrian rocks and with no younger rocks present, in contrast to Lofoten which likely has Caledonian eclogites (Steltenpohl et al., 2003, 2011), and the metasedimentary Leknes group (Corfu, 2004b).

Regardless of whether the WTBC is an exotic Caledonian terrane or not, its position on the very edge of Baltica calls for considerations regarding its position within the various Neoarchaean and Palaeoproterozoic reconstruction efforts of the international Precambrian research community. Neoarchaean and Palaeoproterozoic areas, with many similar characteristics and ages but also notable differences, are present in the north Atlantic region as well as Fennoscandian craton: e.g. in the Lewisian complex (e.g. review by Park (2002), the Nagssugtoqidian orogen (Connelly and Mengel, 2000; Connelly et al., 2000), the hinterland of the east Greenland Caledonides (Thrane, 2004, 2002) and the Svecofennian or Lapland-Kola mobile belts within the Fennoscandian shield (e.g. reviews by Lahtinen et al. (2008); Hölttä et al. (2008).

Additional results: Svecofennian (1790-1775 Ma) metamorphic zircon and titanite U-Pb ages from metabasites in the WTBC

The Palaeoproterozoic (Statherian) tectonic evolution of the WTBC involved intrusion of bimodal plutons, NE-SW shortening followed by transpression, and greenschist, amphibolite or local granulite facies metamorphism (Bergh et al., 2010 and references therein).

In order to document the timing of metamorphism, several samples of metabasite dykes from Grøtfjord, Torsnes and Grunnfarnes (see Fig. 4i and paper III for locations) were investigated for geochronology, and two samples were dated by ID-TIMS at the Department of Earth and Atmospheric Sciences, University of Alberta. The ID-TIMS analytical protocol is described in Heaman et al. (2011). The procedure first involved thin section studies by electron microprobe (EMP) to determine the presence of any suitable geochronometres, i.e. baddeleyite or zircon. No baddeleyite was found in any of the samples, presumably because of their metamorphic nature. Instead zircon was present, ranging in size from sub-micron to 20-30 microns in thin section. Small quantities (< 500 grams) of sample were crushed with a hammer and then disc mill, and zircons were concentrated by Wilfley-table separation followed by incremental magnetic separation up to 1.8A using a Frantz magnetic separator. After magnetic separation only minor amounts of quartz and feldspar was present in the separates. In one case (pim07-32), heavy liquid floatation was done. Following this procedure, two samples (pim07-73 and pim07-32) yielded zircon with sufficient grain size and abundance for dating, and below follows a description of these samples and the results. In addition, sample k04-6 (representing the same dyke as pim07-32), was processed, and titanite analysed, at UiO.

Sample pim07-73 from Grøtfjorden, Kvaløya (sample locations in Fig. 4i) represents metabasite which intruded presumably Neoarchaean migmatitic felsic and mafic gneisses. The sample consists of plagioclase, hornblende and clinopyroxene with minor quartz, zircon and titanite. Subhedral, coarse-grained plagioclase and clinopyroxene presumably represent relict igneous phases, with metamorphic growth of hornblende defining the foliation. Zircon in the thin section are present as < 1µm to 20-30 µm round grains that occupy internal positions within metamorphic phases, typically hornblende (Fig. 4b), plagioclase or quartz. In some cases, trails of zircon can be observed within hornblende (Fig. 4b). Zircons found in the mineral separates are typically somewhat larger than those observed in thin section, commonly 50 - 70 µm in size. Otherwise they show the same sub-spherical morphology, and have a pink colour and clear interior. A group of pale titanite retrieved from the separates did not contain any U (Table 1), or was misidentified. Analysis of 4 multigrain fractions of zircon show a U content between 64 and 186 ppm (Table 1), and they form a collinear array on the concordia diagram (Fig. 4a), with one concordant analysis at 1791 ± 5 Ma. The discordia line trends towards c. 1.22 Ga, but since the three upper analyses plot very close together, a weighted average $^{207/206}$Pb-age is calculated for those at 1780 ± 5 Ma. To account for some non-recent Pb-loss, this can be taken as a minimum age. The concordant analysis seem to be slightly affected by the Pb-loss, and its concordia age can be taken as a maximum age of the zircon population.

Sample pim07-32 and k04-6 comes from a 20 metre wide mafic dyke in Grunnfarnes on Senja. The dyke is visible in the northwestern part in the map of Grunnfarnes in paper III. It cuts the Neoarchaean stromatic migmatite and is itself cut by a second generation of aplites. The dyke is almost completely recrystallized to amphibolite, with local garnet. Both samples have plagioclase, hornblende, garnet and ilmenite, and minor quartz, rutile and apatite. Biotite and zircon is observed in pim07-32, where ilmenite is intact and no titanite was discovered. In contrast, k04-6 contains no biotite, and ilmenite is in a decomposed state with coronas of titanite (Fig. 4g). This can also be observed in heavy mineral separates, where titanite commonly has black inclusions of ilmenite (Fig. 4h). One euhedral, U-rich tip was recovered from k04-6, and it does not plot near any of the other discordia lines in Fig. 4d and could be xenocrystic. Zircon from pim07-32 observed in EMP occurs as < 1 µm up to 30 µm round grains within quartz (Fig. 4e) and hornblende, and commonly associated with cracks and triple junctions. They have a similar morphology in the non-magnetic separates, reaching 70 µm in size and with a colour-less and clear appearance (Fig 4f). Three multigrain analyses of zircon are 4 - 8 % discordant and plot quite close to each other (Fig.

4d). A Pb-loss line that goes to 0 Ma can be fitted through the analyses, and assuming that recent Pb-loss is the cause of the discordance, a weighted average $^{207/206}$Pb-age of 1780 ± 6 Ma is calculated for the zircons. Titanite analyses from sample k04-6 plot with a wider range of discordant values, and a discordia line through 6 analyses of brown titanite with occasional ilmenite inclusions give an upper intercept age of 1762 ± 13 Ma, with a lower intercept of 440 ± 50 Ma. One analysis of clear, anhedral and flat titanite grains plot somewhat above this line, defining a trajectory towards 1715 ± 20 Ma with a lower intercept of c. 0 Ma. Incidentally, the five analyses defining this discordia have overlapping $^{207/206}$Pb-ages, a weighted average gives 1713 ± 2 Ma.

The age derived from the brown titanite in sample k04-6 of 1762 ± 13 Ma can be interpreted as the timing of the breakdown reaction of ilmenite to titanite described above, and is slightly younger than the zircon age in sample pim07-32. This discrepancy in ages could reflect that titanite formed after the zircons, alternatively the age calculation for titanite could be inaccurate due to the slight scatter of the data points around the discordia line. As an alternative, it is also possible that there is some mixing of two titanite generations, one coeval with the zircon age and the other one represented by the pale anhedral grains and a component of the brown titanite fractions that give the 1713 Ma $^{207/206}$Pb-age.

The morphology and textural position of zircons in samples pim07-73 and pim07-32 is consistent with a metamorphic origin (Corfu et al., 2003a) and they could possibly have formed from breakdown of igneous baddeleyite as described for mafic rocks by Davidson and Breemen (1988). Thus I interpret the ages of these zircons to date amphibolite facies metamorphism in the two locations in Grøtfjorden and Grunnfarnes between 1790 and 1775 Ma, possibly earlier in Grøtfjorden than in Grunnfarnes.

This postdates the bimodal intrusion stage in the WTBC by 10-30 Myr (c. 1800 Ma, Corfu et al. 2003a; Kullerud et al., 2006b; Myhre and Corfu, unpublished data). The timing is nearly coeval with metamorphic titanite at 1768 ± 4 documented in mafic dykes from Ringvassøya by Kullerud et al. (2006a), and data on granulite facies metamorphism in Sandøya (west of Ringvassøya) presented by Gjerløw (2008, unpublished MSc-thesis). Metamorphic titanite in the Ersfjord granite and syntectonic dykes in Kvaløya were formed between 1774 and 1750 Ma (Armitage and Bergh, 2005; Corfu et al., 2003b). These data also post-dates the main AMCG stage in Lofoten (Corfu, 2004a) and amphibolite and granulite facies metamorphism in Lofoten and Vesterålen (Corfu, 2007b)

Thus, it is clear that the Svecofennian bimodal intrusion stage in WTBC was followed by metamorphism up to at least amphibolite, locally granulite facies between 1790-1775 Ma, and eventually a late stage of deformation and continued metamorphism until c. 1750 Ma. The data indicate that there were some local variation in the timing of the amphibolite - granulite stage in the WTBC, but apparently no systematic variations in a southwest-northeast transect.

Considerations for future research

For the Caledonian exotic terranes in the North Atlantic region there is still a way to go before we reach an understanding nearly as complete as the equivalent North American Appalachian orogen (e.g. van Staal 2007). It remains a challenge to test the validity of the Cordilleran-style model that has been proposed, and document in more detail the geological history of various terranes.

For the WTBC, a more firm basis of structural, geochemical and geochronological mapping is necessary, because the WTBC is still in some aspects a geological *Terra incognita*. Internally within the WTBC there are still large areas, e.g. within the Senja shear belt and parts of Kvaløya, where the Neoarchaean and/or Palaeoproterozoic rocks are largely lacking documentation. For example, the Senja shear belt was proposed as the link between WTBC and the Fennoscandian shield (Zwaan, 1995), but this has yet to be tested and documented.

Another partially unresolved question is whether some of the metasupracrustal belts within WTBC represent sutures between Neoarchaean pieces of crust. A better structural understanding of the supracrustal belts, ideally with some qualitative strain estimations, reconstruction of the metamorphic history, and geochemical and petrogenetic isotope data would enable more concrete interpretations regarding this question. For example, to evaluate any differing geochemical affinities, a similar approach to Connelly and Thrane (2005); Duebendorfer et al., (2006) could be taken, using common Pb isotopic evidence to define different terranes.

We note finally, that the recent global effort towards improving Neoarchaean and Palaeoproterozoic palaeogeographical reconstructions, means that results from the WTBC are of international interest.

Presentation of papers

Paper I

Myhre, P.I., Corfu, F., Andresen, A., 2008. Caledonian anatexis of Grenvillian crust: a U/Pb study of Albert I Land, NW Svalbard. Norwegian Journal of Geology 89, 173-191.

The field work and analyses presented in this paper were carried out during my master studies at the University of Oslo and the paper was mainly written at the University of Tromsø. The aim of the paper is to document the metamorphic and plutonic evolution of the northwestern part of the Svalbard Caledonides in the so-called Albert I Land Terrane, and to better establish its place in the context of exotic terranes in Svalbard and the North Atlantic region. The U-Pb results document the presence of Grenvillian (968 ± 5 Ma) and Caledonian (422 ± 1 and 418 ± 1 Ma) granitoids. Caledonian prograde metamorphism within the Smeerenburgfjorden Complex was recorded by monazite growth preceding the granitoids by 8-10 Myr. Some evidence from migmatite samples suggest that the protolith sediments were deposited after c. 1070 Ma. This sequence of events led to the conclusion that Albert I Land terrane originated on the Laurentian margin along with many of the other Caledonian terranes found in Svalbard and northern Scandinavia. We propose a two-stage model for the metamorphic and plutonic evolution of Albert I Land Terrane: during the waning stages of the Grenvillian / Sveconorwegian orogeny (termed Rigolet phase), Albert I Land terrane records sedimentation followed by intrusion, volcanism and metamorphism at 980 - 930 Ma, similar to other terranes in Svalbard and northern Scandinavia and probably at a common margin with these between Baltica, Laurentia and Gondwana. This was followed, during the Caledonian orogeny, by another similar tectonic cycle ending with translation, likely in a strike-slip tectonic regime, to their current tectonic positions in Scandinavia and Svalbard.

Paper II

Myhre, P.I., Corfu, F., Bergh, S., 2011. Palaeoproterozoic (2.0-1.95 Ga) pre-orogenic supracrustal sequences in the West Troms Basement Complex, North Norway. Precambrian Research 186, 89-100.

The motivation for this paper were results from metagabbro dated by F. Corfu and detrital zircon studies which had been initiated earlier at UiT and which I then conducted at Nordsim in 2007, which showed that the two supracrustal belts that hosted the samples had a special origin. The aim of the paper was to document the geologic setting and geochronology, and place the supracrustal belts into their proper context of Palaeoproterozoic orogenies in the North Atlantic region. Essentially, the West Troms Basement Complex consists of Neoarchaean and Palaeoproterozoic gneisses and granites with supracrustal (greenstone) belts of varying Neoarchaean and Palaeoproterozoic ages. The Mjelde-Skorelvvatn belt is made up of deformed supracrustal rocks dominated by mafic metavolcanics including subvolcanic metagabbro with a crystallisation age dated by zircon at 1992 ± 2 Ma. Psammite from the base of the Torsnes belt of siliciclastic and overlaying metavolcanic mafic rocks has a maximum deposition age of 1970 ± 14 Ma, and the absence of younger zircon distinguishes it from most Svecofennian siliciclastic deposits in Fennoscandia. This lead to the conclusion that the Torsnes belt is also a distinct pre-orogenic basin but with differences in detail with respect to the Mjelde-Skorelvvatn belt. These data correlate with a period of pre-orogenic continental extension and basin formation that is documented in several locations in Fennoscandia and Laurentia, and the new results from WTBC constitute a small but important piece of information about the pre-orogenic relationship between the cratons of the North Atlantic region.

Paper III

Myhre, P.I., Corfu, F., Bergh, S.G., U-Pb geochronology along a Neoarchaean geotransect in West Troms Basement Complex, North Norway. Manuscript.

This paper reports U-Pb-data from 7 locations within the oldest gneisses in a geotransect from Ringvassøya via Kvaløya to Senja. Many of the samples were collected and initially analysed by F. Corfu, and I collected more samples and continued the analyses. These rocks have a long and complex history and this is reflected in the U-Pb-data. Through careful investigations of field relationships, characterisation of zircon and combining TIMS, CA-TIMS and SIMS analytical techniques, the paper presents a detailed account of the

Neoarchaean geological evolution of the WTBC. Essentially, including some published data, the cratonic evolution can be divided in three stages: the oldest rocks are found in the northeast, on Ringvassøya and Vannøya, and they record formation of a paired tonalite complex and greenstone belt from 2.92-2.80 Ga. This oldest complex is in contact with younger Neoarchean rocks along a high-grade shear zone. Although there is also some evidence of 2.83 Ga rocks in the geotransect to the southwest of the high-grade shear zone in Ringvassøya, the majority of those rocks record a two-stage (2.75-2.70 and 2.70-2.67 Ga) magmatic and migmatitic evolution. A swarm of mafic dykes documented in one location in Kvaløya concluded this event, possibly closely related with granitoid magmatism and migmatization of earlier rocks. Then, there is some evidence from zircons in two neosomes of a latest Neoarchaean high-grade event. The documented Neoarchean geotransect can probably be correlated with rocks in Vesterålen to the southwest, but a definitive correlation with the Fennoscandian shield rocks in the Norrbotten province cannot be confirmed or refuted. Instead, various correlative Neoarchaean - Palaeoproterozoic areas in the north Atlantic region as well as the Fennoscandian shield can be considered.

Paper IV

Bergh, S.G., Kullerud, K., Armitage, P.E.B., Zwaan, K.B., Corfu, F., Ravna, E.J.K., Myhre, P.I., 2010. Neoarchaean to Svecofennian tectono-magmatic evolution of the West Troms Basement Complex, North Norway. Norwegian Journal of Geology 90, 21-48.

This paper compiles the results from many years of geological investigations in the WTBC by many workers and institutions. The scope of the paper is to establish a tectonic framework for WTBC with special attention to high-strain mylonitic supracrustal belts that separate Neoarchaean gneisses, and discussing mechanisms for growth and stabilisation of the crust here. The synthesis builds on a large number of published, unpublished and preliminary radiometric ages. Many of these U-Pb-ages and the geology they are part of are presented and further elaborated in detail in papers II and III. The WTBC is made up of Neoarchaean gneisses with variable protoliths, Neoarchaean to Palaeoproterozoic supracrustal units and dyke swarms and Svecofennian bimodal plutons. The main conclusions are that the WTBC records Neoarchaean crustal contraction followed by Palaeoproterozoic rifting and basin formation. Following this, the Svecofennian event brought about NE-SW-directed contraction, initially expressed as low-angle thrusts, then as upright folds and as a late phase, sinistral strike-slip movement. A possible orogenic front in the SW can explain the NE-wards decreasing metamorphic grade.

References

Amelin, Y., 2009. Sm-Nd and U-Pb systematics of single titanite grains. Chemical Geology 261, 53-61.

Armitage, P.E.B., Bergh, S.G., 2005. Structural development of the Mjelde-Skorelvvatn Zone on Kvaløya, Troms: A metasupracrustal shear belt in the Precambrian West Troms Basement Complex, North Norway. Norwegian Journal of Geology 85, 117-132.

Bergh, S.G., Kullerud, K., Armitage, P.E.B., Zwaan, K.B., Corfu, F., Ravna, E.J.K., Myhre, P.I., 2010. Neoarchaean to Svecofennian tectono-magmatic evolution of the West Troms Basement Complex, North Norway. Norwegian Journal of Geology 90, 21-48.

Bingen, B., Austrheim, H., Whitehouse, M., 2001. Ilmenite as a Source for Zirconium during High-grade Metamorphism? Textural Evidence from the Caledonides of Western Norway and Implications for Zircon Geochronology. J. Petrology 42, 355-375.

Bingen, B., Austrheim, H., Whitehouse, M.J., Davis, W.J., 2004. Trace element signature and U–Pb geochronology of eclogite-facies zircon, Bergen Arcs, Caledonides of W Norway. Contrib Mineral Petrol 147, 671-683.

Bleeker, W., 2003. The late Archean record: a puzzle in ca. 35 pieces. Lithos 71, 99-134.

Buchan, K.L., Mertanen, S., Park, R.G., Pesonen, L.J., Elming, S.-Å., Abrahamsen, N., Bylund, G., 2000. Comparing the drift of Laurentia and Baltica in the Proterozoic: the importance of key palaeomagnetic poles. Tectonophysics 319, 167-198.

Connelly, J.N., Mengel, F.C., 2000. Evolution of Archean components in the Paleoproterozoic Nagssugtoqidian orogen, West Greenland. Geological Society of America Bulletin 112, 747-763.

Connelly, J.N., Thrane, K., 2005. Rapid determination of Pb isotopes to define Precambrian allochthonous domains: An example from West Greenland. Geology 33, 953-956.

Connelly, J.N., Van Gool, J.A.M., Mengel, F.C., 2000. Temporal evolution of a deeply eroded orogen: the Nagssugtoqidian Orogen, West Greenland. Canadian Journal of Earth Sciences 37, 1121-1142.

Corfu, F., 2004a. U-Pb Age, Setting and Tectonic Significance of the Anorthosite-Mangerite-Charnockite-Granite Suite, Lofoten-Vesterålen, Norway. Journal of Petrology 45, 1799-1819.

Corfu, F., 2004b. U-Pb geochronology of the Leknes Group: an exotic Early Caledonian metasedimentary assemblage stranded on Lofoten basement, northern Norway. Journal of the Geological Society 161, 619-627.

Corfu, F., 2007a. Comment to paper: Timing of magmatism and metamorphism in the Gruinard Bay area of the Lewisian gneiss complex: comparison with the Assynt Terrane and implications for terrane accretion by G.J. Love, P.D. Kinny and C.R.L. Friend (Contr Mineral Petrol (2004) 146:620–636). Contributions to Mineralogy and Petrology 153, 483-488.

Corfu, F., 2007b. Multistage metamorphic evolution and nature of the amphibolite-granulite facies transition in Lofoten-Vesterålen, Norway, revealed by U-Pb in accessory minerals. Chemical Geology 241, 108-128.

Corfu, F., Armitage, P.E.B., Kullerud, K., Bergh, S.G., 2003b. Preliminary U-Pb geochronology in the West Troms Basement Complex, North Norway:Archaean and Palaeoproterozoic events and younger overprints. Bulletin of the Geological Survey of Norway 441, 61-72.

Corfu, F., Gerber, M., Andersen, T., Torsvik, T., Ashwal, L., 2011. Age and significance of Grenvillian and Silurian orogenic events in the Finnmarkian Caledonides, northern Norway. Can. J. Earth Sci. 48, 419-440.

Corfu, F., Hanchar, J.M., Hoskin, P.W., Kinny, P., 2003a. Atlas of Zircon Textures. Reviews in Mineralogy and Geochemistry 53, 469-500.

Corfu, F., Heaman, L.M., Rogers, G., 1994. Polymetamorphic evolution of the Lewisian complex, NW Scotland, as recorded by U-Pb isotopic compositions of zircon, titanite and rutile. Contributions to Mineralogy and Petrology 117, 215-228.

Corfu, F., Roberts, R.J., Torsvik, T.H., Ashwal, L.D., Ramsay, D.M., 2007. Peri-Gondwanan elements in the Caledonian Nappes of Finnmark, Northern Norway: Implications for the paleogeographic framework of the Scandinavian Caledonides. American Journal of Science 307, 434-458.

Corfu, F., Stone, D., 1998. The significance of titanite and apatite U-Pb ages: constraints for the post-magmatic thermal-hydrothermal evolution of a batholithic complex, Berens River area, northwestern Superior Province, Canada. Geochimica et Cosmochimica Acta 62, 2979-2995.

Davidson, A., Breemen, O., 1988. Baddeleyite-zircon relationships in coronitic metagabbro, Grenville Province, Ontario: implications for geochronology. Contr. Mineral. and Petrol. 100, 291-299.

Davis, D.W., Krogh, T.E., Williams, I.S., 2003. Historical Development of Zircon Geochronology. Reviews in Mineralogy and Geochemistry 53, 145-181.

Duebendorfer, E.M., Chamberlain, K.R., Fry, B., 2006. Mojave-Yavapai boundary zone, southwestern United States: A rifting model for the formation of an isotopically mixed crustal boundary zone. Geology 34, 681-684.

Ernst, R., Bleeker, W., 2010. Large igneous provinces (LIPs), giant dyke swarms, and mantle plumes: significance for breakup events within Canada and adjacent regions from 2.5 Ga to the Present. Canadian Journal of Earth Sciences 47, 695-739.

Friend, C., Kinny, P., Love, G., 2007. Timing of magmatism and metamorphism in the Gruinard Bay area of the Lewisian Gneiss Complex: comparison with the Assynt Terrane and implications for terrane accretion—reply. Contributions to Mineralogy and Petrology 153, 489-492.

Gee, D.G., Teben'kov, A.M., 2004. Svalbard: a fragment of the Laurentian margin. Geological Society, London, Memoirs 30, 191 -206.

Gjerløw, E., 2008. Petrologi og alder av høymetamorfe mafiske bergarter i det vestlige gneiskomplekset i Troms. Unpublished MSc-thesis. University of Tromsø.

Heaman, L., Bohm, C.O., Machado, N., Krogh, T., Weber, W., Corkery, M., 2011. The Pikwitonei Granulite Domain, Manitoba: a giant Neoarchean high-grade terrane in the northwest Superior Province. Can. J. Earth Sci. 48, 205-245.

Heaman, L., LeCheminant, A., 1993. Paragenesis and U-Pb systematics of baddeleyite ($ZrO2$). Chemical Geology 110, 95-126.

Hoskin, P.W.O., Schaltegger, U., 2003. The Composition of Zircon and Igneous and Metamorphic Petrogenesis. Reviews in Mineralogy and Geochemistry 53, 27-62.

Hölttä, P., Balagansky, V., Garde, A.A., Mertanen, S., Peltonen, P., Slabunov, A., Sorjonen-

Ward, P., Whitehouse, M., 2008. Archean of Greenland and Fennoscandia. Episodes 31, 13-19.

Ireland, T.R., Williams, I., 2003. Considerations in Zircon Geochronology by SIMS. Reviews in Mineralogy and Geochemistry 53, 215-241.

Kamo, S.L., Corfu, F., Heaman, L.M., Moser, D.E., 2011. The Krogh revolution: advances in the measurement of time. Canadian Journal of Earth Sciences 48, 87-94.

Kirkland, C.L., Daly, J.S., Whitehouse, M.J., 2008. Basement-cover relationships of the Kalak Nappe Complex, Arctic Norwegian Caledonides and constraints on Neoproterozoic terrane assembly in the North Atlantic region. Precambrian Research 160, 245-276.

Kirkland, C., Stephen Daly, J., Whitehouse, M., 2007. Provenance and Terrane Evolution of the Kalak Nappe Complex, Norwegian Caledonides: Implications for Neoproterozoic Paleogeography and Tectonics. The Journal of Geology 115, 21-41.

Kirkland, C., Bingen, B., Whitehouse, M., Beyer, E., Griffin, W., 2011. Neoproterozoic palaeogeography in the North Atlantic Region: inferences from the Akkajaure and Seve Nappes of the Scandinavian Caledonides. Precambrian Research.

Koistinen, T., Stephens, M., Bogatchev, V., Nordgulen, Ø., Wennerström, M., Korhonen, J., 2001. Geological map of the Fennoscandian Shield.

Krogh, T., 1973. A low-contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations. Geochimica et Cosmochimica Acta 37, 485-494.

Krogh, T.E., 1982. Improved accuracy of U-Pb zircon ages by the creation of more concordant systems using an air abrasion technique. Geochimica et Cosmochimica Acta 46, 637-649.

Krogh, T., Davis, G., 1975. The production and preparation 205Pb for use as a tracer for isotope dilution analyses. Carnegie Inst Washington Yrbk 416-417.

Kullerud, K., Skjerlie, K.P., Corfu, F., de la Rosa, J.D., 2006a. The 2.40 Ga Ringvassøy mafic dykes, West Troms Basement Complex, Norway: The concluding act of early Palaeoproterozoic continental breakup. Precambrian Research 150, 183-200.

Kullerud, K., Corfu, F., Bergh, S.G., Davidsen, B., Ravna, E.K., 2006b. U-Pb constraints on the Archean and Early Proterozoic evolution of the West Troms Basement Complex, North Norway. Bulletin of Geological Society of Finland 1, 79.

Lahtinen, R., Garde, A., Melezhik, V., 2008. Paleoproterozoic evolution of Fennoscandia and Greenland. Episodes 31, 20-28.

Love, G., Kinny, P., Friend, C., 2004. Timing of magmatism and metamorphism in the Gruinard Bay area of the Lewisian Gneiss Complex: comparisons with the Assynt Terrane and implications for terrane accretion. Contributions to Mineralogy and Petrology 146, 620-636.

Mattinson, J.M., 2005. Zircon U-Pb chemical abrasion ("CA-TIMS") method: Combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages. Chemical Geology 220, 47-66.

Mattinson, J.M., 2011. Extending the Krogh legacy: development of the CA-TIMS method for zircon U-Pb geochronology. Can. J. Earth Sci. 48, 95-105.

Mertanen, S., Korhonen, F., 2011. Paleomagnetic constraints on an Archean-Paleoproterozoic Superior-Karelia connection: New evidence from Archean Karelia. Precambrian Research 186, 193-204.

Park, R.G., 2005. The Lewisian terrane model: a review. Scottish Journal of Geology 41, 105-118.

Park, R., 2002. The Lewisian Geology of Gairloch NW Scotland, Geological Society Memoir. The Geological Society, London.

Park, R.G., Tarney, J., Connelly, J.N., 2001. The Loch Maree Group: Palaeoproterozoic subduction-accretion complex in the Lewisian of NW Scotland. Precambrian Research 105, 205-226.

Parrish, R.R., Krogh, T.E., 1987. Synthesis and purification of 205Pb for U---Pb geochronology. Chemical Geology: Isotope Geoscience section 66, 103-110.

Parrish, R.R., Parrish, R.R., Noble, S.R., 2003. Zircon U-Th-Pb Geochronology by Isotope Dilution -- Thermal Ionization Mass Spectrometry (ID-TIMS). Reviews in Mineralogy and Geochemistry 53, 183-213.

Pesonen, L.J., Elming, S.-., Mertanen, S., Pisarevsky, S., D'Agrella-Filho, M.S., Meert, J.G., Schmidt, P.W., Abrahamsen, N., Bylund, G., 2003. Palaeomagnetic configuration of continents during the Proterozoic. Tectonophysics 375, 289-324.

Rudnick, R., Gao, S., 2007. Treatise on Geochemistry. Elsevier.

Steltenpohl, M., Hames, W., Andresen, A., Markl, G., 2003. New Caledonian eclogite province in Norway and potential Laurentian (Taconic) and Baltic links. Geology 31, 985-988.

Steltenpohl, M.G., Kassos, G., Andresen, A., Rehnstrom, E.F., Hames, W.E., 2011. Eclogitization and exhumation of Caledonian continental basement in Lofoten, North Norway. Geosphere 7, 202-218.

van Staal, C.R., 2007. Pre-Carboniferous tectonic evolution and metallogeny of the Canadian Appalachians, in: Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods:, Geological Association of Canada, Mineral Deposits Division, Special Publication no. 5. pp. 793-818.

Tera, F., Wasserburg, G., 1972. U-Th-Pb systematics in three Apollo 14 basalts and the problem of initial Pb in lunar rocks. Earth and Planetary Science Letters 14, 281-304.

Thrane, K., 2004. Palaeoproterozoic age of a basement gneiss complex in the Charcot Land tectonic window, East Greenland Caledonides. Geological Survey of Denmark and Greenland Bulletin 6, 57-66.

Thrane, K., 2002. Relationships between Archaean and Palaeoproterozoic crystalline basement complexes in the southern part of the East Greenland Caledonides: an ion microprobe study. Precambrian Research 113, 19-42.

Verts, L.A., Chamberlain, K.R., Frost, C.D., 1996. U-Pb sphene dating of metamorphism: the importance of sphene growth in the contact aureole of the Red Mountain pluton, Laramie Mountains, Wyoming. Contributions to Mineralogy and Petrology 125, 186-199.

Wetherill, G.W., 1956. Discordant uranium-lead ages. Transactions American Geophysical Union 37, 320.

Wetherill, G.W., 1963. Discordant Uranium-Lead Ages 2. Discordant Ages Resulting from Diffusion of Lead and Uranium. J. Geophys. Res. 68, PP. 2957-2965.

Wheeler, J., Park, R.G., Rollinson, H.R., Beach, A., 2010. The Lewisian Complex: insights into deep crustal evolution. Geological Society, London, Special Publications 335, 51-79.

Whitehouse, M.J., Kemp, A.I.S., 2010. On the difficulty of assigning crustal residence, magmatic protolith and metamorphic ages to Lewisian granulites: constraints from combined in situ U-Pb and Lu-Hf isotopes. Geological Society, London, Special Publications 335, 81-101.

Zwaan, K.B., 1995. Geology of the West Troms Basement Complex, northern Norway, with emphasis on the Senja Shear Belt: a preliminary account. NGU Bulletin 427, 33-36.

Zwaan, K.B., Fareth, E., Grogan, P.W., 1998. Bedrock map Tromsø. 1:250 000. Geological Survey of Norway.

Figures and table

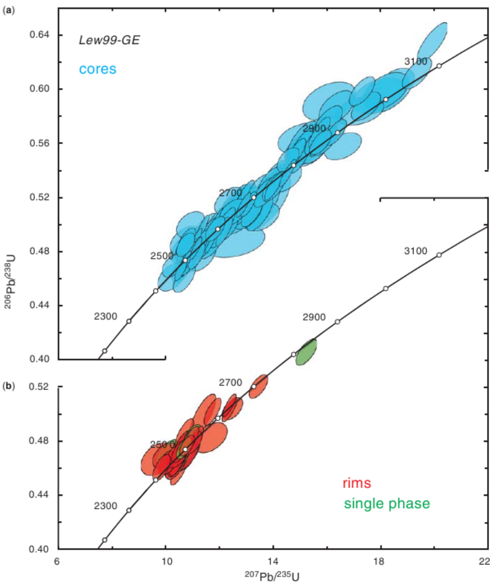


Fig. 7. Concordia diagrams showing ion microprobe data from sample Lew99-GE: (**a**) cores only; (**b**) rims and single phase grains. Colour coding follows that used in Figure 6. Error ellipses are plotted at 2σ.

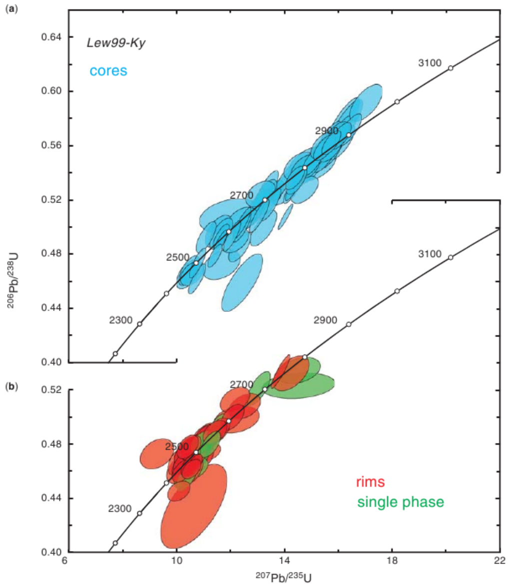


Fig. 4. Concordia diagrams showing ion microprobe data from sample Lew99-Ky: (**a**) cores only; (**b**) rims and single phase grains. Colour coding follows that used in Figure 3. Error ellipses are plotted at 2σ.

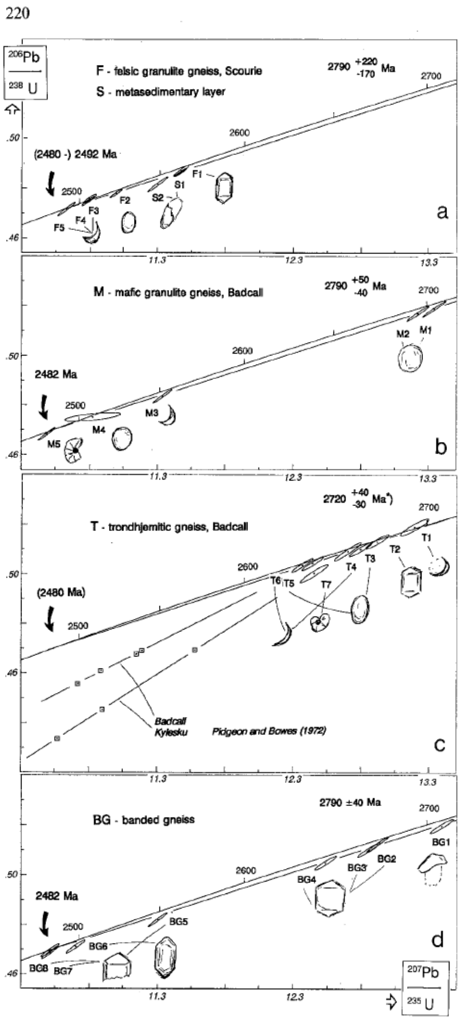


Fig. 3a–d Concordia diagrams showing U-Pb data and morphologies of zircon in high-grade gneisses at Scourie More and Badcall Bay and a banded biotite gneiss from Loch na Claise Feàrna; **c** also shows the zircon U-Pb data previously reported by Pidgeon and Bowes (1972)

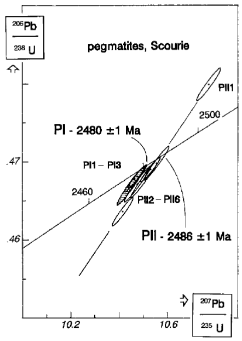


Fig. 2 Concordia diagram with U-Pb zircon data for two pegmatites from Scourie More. Error *ellipses* are drawn at the 95% confidence level

Fig. 1: Concordia diagrams from Whitehouse and Kemp (2010) (left-hand side) and Corfu et al. (1994) (right-hand side) from high-grade rocks from the Scourie area in the Lewisian Complex, northwest Scotland.

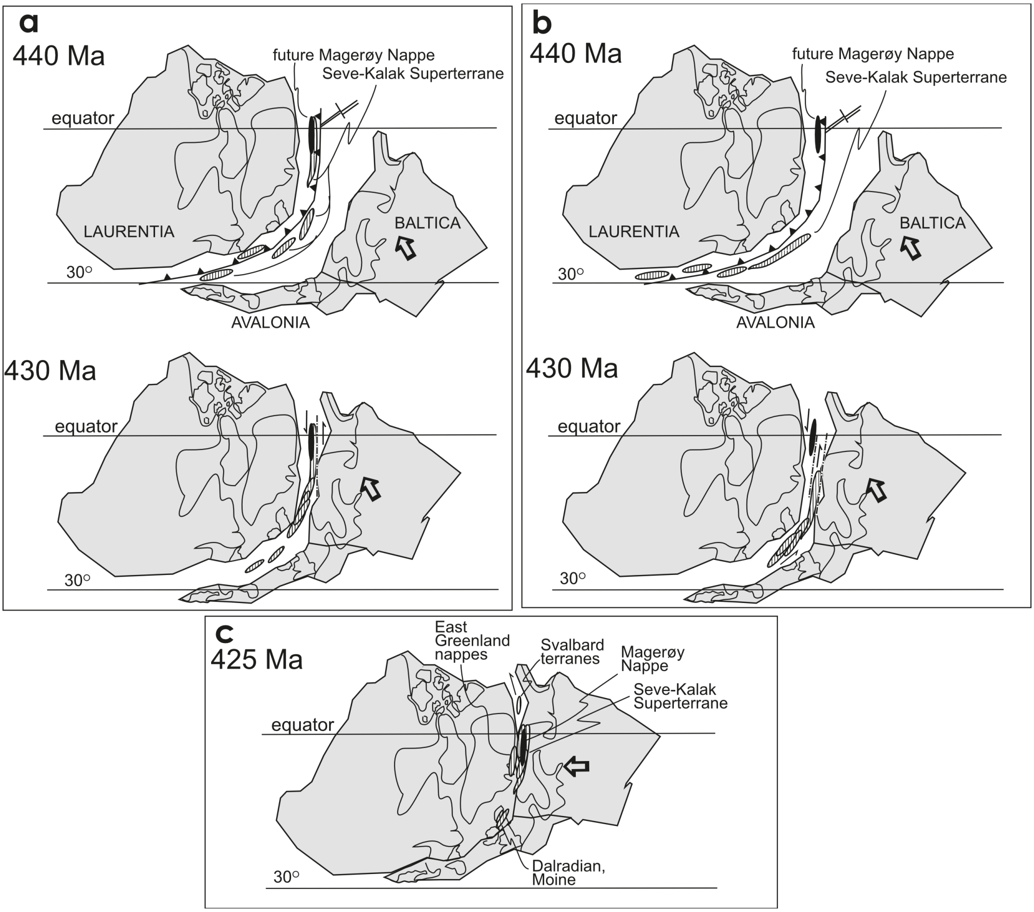
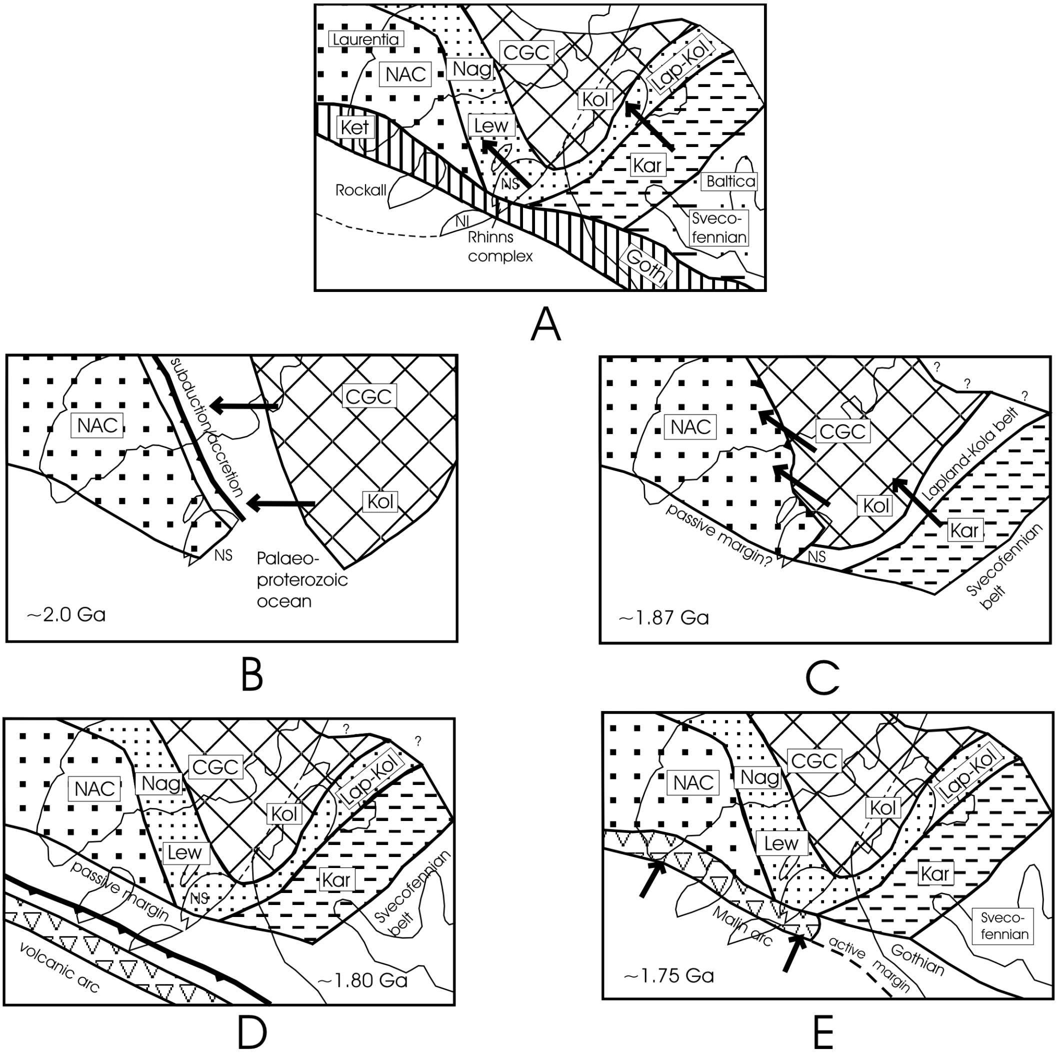


Fig. 2: A model for the situation between Laurentia and Baltica leading up to emplacement of the exotic Scandinavian Magerøya nappe and Seve-Kalak superterrane, and the exotic terranes in Svalbard. A strike-slip orogenic model (Cordilleran tectonics) allows for long translations of the terranes into their current positions in Svalbard and northern Scandinavia, and can explain the lack of a suture in the northern Scandinavian nappes. Figure is from Corfu et al 2011.



F . 4. Speculative plate tectonic setting of the Lewisian complex during the Palaeoproterozoic, based on the North Atlantic reconstruction of Buchan *et al.* (2000). CGC, central Greenland craton; Goth, Gothian belt; Kar, Karelia craton; Ket, Ketilidian belt; Kol, Kola craton; Lap-Kol, Lapland–Kola belt; Lew, Lewisian; NAC, North Atlantic craton; Nag, Nagssugtoqidian belt; NI, north Ireland; NS, north Scotland. (**A**) Distribution of cratons and orogenic belts during the Mesoproterozoic. (**B**) 2.0 Ga. Subduction and creation of a volcanic arc in oceanic crust between two continental plates (NAC and CGC/Kol) followed by accretion of oceanic/arc elements along the leading edge of the NAC. (**C**) 1.87 Ga. Collision of the two continents followed by underthrusting of the CGC/Kol craton beneath the NAC, causing the early Laxfordian deformation and metamorphism. At the same time, collision occurs in the Lapland/Kola belt to the SE caused by collision with the Karelia craton. Note the NW–SE movement direction. (**D**) 1.80 Ga. Development of a volcanic arc in oceanic crust SW of the amalgamated continent created in B. (**E**) 1.75 Ga. Collision between the 'Malin arc' and the continent, causing late Laxfordian deformation, metamorphism and granitic melt formation in the Lewisian complex.

Fig. 3: A model of a possible Palaeoproterozoic cratonic configurations in the North Atlantic region published by Park (2005).

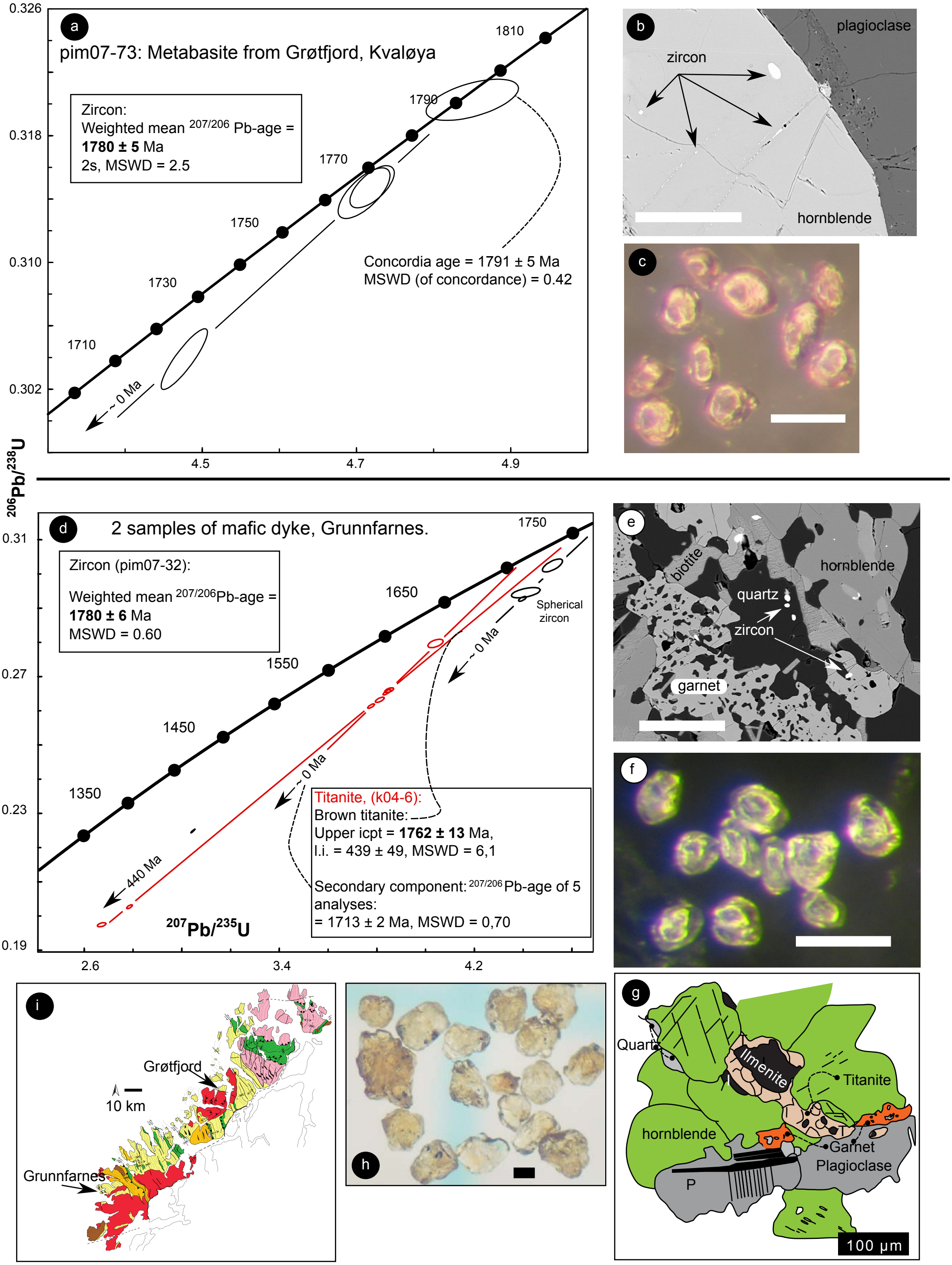


Fig. 4: U-Pb data and sample descriptions for metabasites from the Grøtfjorden and Grunnfarnes. Age calculations and error ellipses are 2 sigma. Scale bars are 100 micrometres. a): U-Pb-TIMS data from metabasite in Grøtfjorden (pim07-73). b): EMP backscattered electrons (BSE) image from sample pim07-32. c): picking scope photo of zircons from pim07-32. d): U-Pb TIMS data from mafic dyke in Grunnfarnes, Senja. e): EMP (BSE) image from sample pim07-32. f): picking scope photo of zircons from pim07-32. g): sketch of metamorphic assemblage from sample k04-6. h): brown titanite with local black inclusions of ilmenite. i): locations of samples (see paper III for legend and map description.

Table 1: U-Pb-TIMS-results

U-Pb Isotopic Ratios [f]

Sample	Wt.[2]	U	Th/U	Pbc[4]	$^{206}Pb^{5}$	$^{207}Pb^{6}$	2σ	$^{206}Pb^{6}$	2σ	rho	$^{207}Pb^{6}$	2σ	$^{207}Pb^{6}$	$^{206}Pb^{6}$	$^{207}Pb^{6}$	2σ	Disc.
mineral description[1]	[ug]	[ppm]	calc.	[pg]	^{204}Pb	^{235}U	[abs]	^{238}U	[abs]		^{206}Pb	[abs]	^{235}U	^{238}U	^{206}Pb	[abs]	[%]
PIM07-73: Metabasite from Grøtfjorden on Kvaløya UTM: [33N 636083 7746462][6]																	
A: pink, round na [10]	6.3	64	0.50	9.3	877	4.720	0.023	0.3148	0.0011	0.66	0.10873	0.00040	1765	1771	1778.2	6.8	0.9
H: pink, round, small na [10]	3.4	151	0.48	4.1	2421	4.476	0.025	0.3040	0.0016	0.88	0.10680	0.00028	1711	1727	1745.5	4.8	2.2
F: pink, round na [10]	2.9	133	0.60	7.3	1079	4.849	0.049	0.3203	0.0011	0.55	0.10980	0.00096	1791	1794	1796	16	0.3
G: pink, round, small na [10]	3.0	186	0.56	2.8	3920	4.713	0.027	0.3146	0.0013	0.70	0.10867	0.00046	1763	1770	1777.2	7.6	0.9
I:clear tit fragments na [5]	4.4	0	2.33	34	15												
pim07-32: Mafic dyke from Grunnfarnes on Senja. UTM: [33N 575675 7689041][6]																	
B: colorless round na [7]	<1	282	0.09	5.0	1029	4.397	0.021	0.29272	0.00092	0.70	0.10893	0.00036	1655	1712	1781.7	6.2	8.0
C: small colourless round na [8]	2.0	123	0.09	5.9	803	4.520	0.055	0.3025	0.0025	0.68	0.10839	0.00096	1704	1735	1773	16	4.4
E: small pinkish round na [7]	1.3	119	0.09	7.9	379	4.411	0.078	0.2945	0.0020	0.53	0.1086	0.0016	1664	1714	1777	27	7.2
K-04-6 Mafic dyke from Grunnfarnes on Senja UTM: [33N 57567x 768904x][7]																	
106/54 z eu tip [1]	1	4743	0.0	1.3	52180	3.0454	0.0068	0.22484	0.00044	0.96	0.09823	0.00006	1307	1419	1591	1	20
197/s.13 tit small cl anh na [6]	3	48	1.8	8.6	312	4.040	0.025	0.2797	0.0010	0.53	0.10478	0.00056	1590	1642	1710	10	8
197/s.7 tit fr br abr [5]	18	102	2.2	32	969	3.841	0.013	0.26542	0.00064	0.80	0.10497	0.00021	1517	1601	1714	4	13
184/s.18 tit [30]	120	65	2.4	243	548	3.851	0.014	0.26602	0.00056	0.60	0.10498	0.00032	1521	1603	1714	6	13
184/s.17 tit [30]	138	102	1.8	266	885	3.776	0.011	0.26136	0.00053	0.76	0.10479	0.00020	1497	1588	1711	4	14
197/s.5 tit fr br abr [1]	10	131	1.5	22	788	2.7852	0.0095	0.20272	0.00046	0.72	0.09965	0.00024	1190	1352	1618	4	29
197/s.10 tit br polycryst na [1]	12	73	1.4	30	380	2.671	0.014	0.19745	0.00049	0.48	0.09812	0.00046	1162	1321	1589	9	29
197/s.12 tit cl polycryst na [4]	24	2.7	1.2	62	23	1.14	0.32	0.1208	0.0046	0.01	0.068	0.020	735	770	873	>100.	17

[1] : eu = euhedral, an = anhedral, clr = clear, incl. = inclusion, a =air abrasion, na = not abraded, [1]= no. of grains, frgt = fragment, tit: titanite, br = brown

[2] : Weight is known to within 10 %.

[3] : Th/U is modelled based on measured $^{208/206}$ Pb-ratio and $^{207/206}$Pb-age.

[4] : Pbc = total common Pb in sample (initial + blank)

[5] : Corrected for fractionation.

[6] : Corrected for fractionation, blank, spike and initial Pb.

[7] : Approximate coordinates of sample location, [8] : Sample location from GPS with a few metres uncertainty

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