From mountains to basins: geochronological case studies from southwestern Norway, Western Australia and East Antarctica

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Authorship statement

Anna K. Ksienzyk is the first and principal author of all four manuscripts. The contributions of co-authors to each mansucript are specified below.

Manuscript I: Northampton Complex

Text and figures	Ksienzyk
Fieldwork and sampling	Ksienzyk, Jacobs
Data acquisition	Ksienzyk and Košler – laser ablation ICP-MS, detrital zircon Jacobs and Sircombe – SHRIMP, detrital zircon Ksienzyk, Jacobs and Whitehouse – SIMS, zircon rims Whitehouse – SIMS, monazite
Discussion and revisions of earlier versions of the manuscript	Ksienzyk, Jacobs, Boger, Košler, Sircombe, Whitehouse

Manuscript II: WAlahari

Text and figures	Ksienzyk
Fieldwork and sampling	Jacobs
Data acquisition	Jacobs and Sircombe
Discussion and revisions of earlier versions of the manuscript	Ksienzyk, Jacobs

Manuscript III: Fault dating

Text	Ksienzyk, Fossen Fossen has contributed approximately 20% of the text
Figures	Ksienzyk
Fieldwork and sampling	Ksienzyk
Data acquisition	Wemmer
Discussion and revisions of earlier versions of the manuscript	Ksienzyk, Wemmer, Jacobs, Fossen

Manuscript IV: Apatite fission track and (U-Th)/He analyses

Text	Ksienzyk
Figures	Ksienzyk, Kohlmann Kohlmann has contributed Figs. 5, 6 and 8
Fieldwork and sampling	Ksienzyk
Data acquisition	Ksienzyk – Apatite fission track analysis Ksienzyk, Dunkl – (U-Th)/He analysis Ksienzyk, Kohlmann – Thermal history modelling
Discussion and revisions of earlier versions of the manuscript	Ksienzyk, Dunkl, Jacobs, Kohlmann, Fossen

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Chapter 1

Introduction

Introduction

1 Orogen-rifted margin systems – four case studies

Continental margins are, from a geologist's point of view, one of the most exciting areas on the planet. A multitude of geological processes are acting on these boundaries between continents and oceans. The term 'continental margin' is used here in its widest possible sense to refer to the area 'where land meets sea'. A continental margin is the interface between areas affected predominantly by erosion (the continent) and areas of deposition (the ocean basin). It is the place that is first and most strongly affected by sea level changes. It is along their margins that continents collide to form orogens and become amalgamated into larger supercontinents; and more often than not, later rifting during continental breakup reactivates old suture zones, transferring an orogen into a rifted margin once again. Thus, many continental margins experience periodically a transition from rifted margin to orogen and back to rifted margin. Good examples of this are the Atlantic margins (Wilson, 1966).

In recent settings, geologic links across continental margins, e.g. from sedimentary source to sink or from one rifted margin to its conjugate partner, are easily identified. However, in ancient settings, these links are frequently broken. In such cases, geochronological methods are one of the tools that can help to re-establish broken links and unravel the tectonic history of a region. In the following four chapters, I present case studies from orogen-rifted margin systems in Western Australia, East Antarctica and southwestern Norway (Fig. 1), applying a variety of geochronological techniques such as U/Pb analyses of zircon and monazite, K/Ar analysis of illite and fission track and (U-Th)/He analyses of apatite. These methods cover a wide range of closure temperatures from 900 °C for zircon U/Pb dating (Cherniak and Watson, 2000) to 120-40 °C for apatite fission track and (U-Th)/He analyses (Reiners and Brandon, 2006). Each contribution utilises the technique that is most appropriate to the problem addressed and contributes a key piece to the geologic history of the respective study area. In Western Australia and East Antarctica, we trace sediments along their journey from their (orogenic) sources to their deposition in continental margin basins and their later incorporation into collisional orogens. In southwestern Norway, we follow the area's development from the Caledonian mountain belt to today's North Sea rift margin, with a special focus on the uplift history and the significance and timing of fault reactivation.

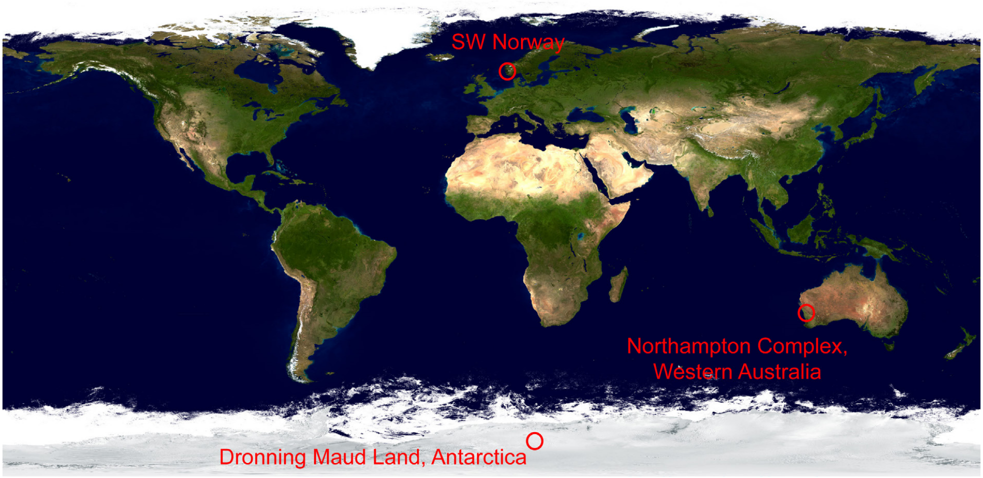

Fig. 1 Satellite image showing the locations of the study areas in southwestern Norway, Western Australia and East Antarctica.

2 Choice of field areas and methods

2.1 Detrital zircon U/Pb analyses from the Pinjarra Orogen (Western Australia) and the Maud Belt (East Antarctica)

Manuscripts I and II investigate a pair of continental margins in East Antarctica and Western Australia that were suggested to have been conjugate in the late Mesoproterozoic-Neoproterozoic (Fitzsimons, 2002, 2003a; Pisarevsky et al., 2003; Powell et al., 2001; Powell and Pisarevsky, 2002). Thick sequences of siliciclastic sediments were deposited along both margins in volcanic arc and back-arc settings and were deformed and metamorphosed during Grenville-age continent-continent collision (Bauer et al., 2003; Bisnath et al., 2006; Bruguier et al., 1999; Byrne, 1997; Jacobs, 2009; Jacobs et al., 2003a). If the margins were indeed a conjugate pair, then sedimentary sequences on either side might be expected to show the same provenance (Fitzsimons, 2002, 2003a). Alternatively, detrital material derived from one continent might be expected to be found on the other. In both the Maud Belt (East Antarctica) and the Pinjarra Orogen (Western Australia), the provenance of the metasedimentary rocks was so far insufficiently known to allow for a thorough comparative study.

The method of choice to establish the sedimentary provenance of a region is U/Pb analysis of detrital zircons. The U/Pb zircon system has a high closure temperature (ca. 900°C; Cherniak and Watson, 2000), thus dating magmatic and high-grade metamorphic events that 'fingerprint' potential source regions. Zircon is a very robust mineral that is neither easily destroyed during erosion nor affected by weathering or surface alteration. It has therefore the potential to carry age signals from the sedimentary source to the sink (e.g. Fedo et al., 2003).

In this study, we investigate the sedimentary provenance of both the Pinjarra Orogen and the Maud Belt by U/Pb analyses of detrital zircons. The Pinjarra Orogen is one of the least studied and understood orogens in Australia but it plays a key role in both Rodinia and Gondwana reconstructions. Not even the timing of orogenesis is universally agreed upon, with both a Mesoproterozoic and a Neoproterozoic age cited (e.g. Boger, 2011; Fitzsimons, 2003b). Exposure is poor, being restricted to three basement blocks within the Phanerozoic Perth Basin. The Northampton Complex is the largest exposed block of the Pinjarra Orogen. While it has been extensively investigated in the second half of the 19th and first half of the 20th centuries when lead and other metals were mined in the area (Blockley, 1971), it has received little attention in the last several decades, i.e. since the development of modern radiogenic dating methods (Bruguier et al., 1999). The detrital zircon analyses have been complimented in this case by U/Pb dating of metamorphic zircon rims and monazites in order to provide additional information on the metamorphic history of this region.

In the Maud Belt, on the other hand, the metamorphic history is well studied (e.g. Arndt et al., 1991; Bisnath et al., 2006; Jacobs et al., 2003a; Jacobs et al., 2003b), but previously published detrital zircon ages (Arndt et al., 1991; Harris, 1999) were sparse in number and insufficient to allow statistically sound comparisons with other regions.

While both contributions provide valuable knowledge about the geology of the Pinjarra Orogen and Maud Belt respectively, their implications for the palaeogeography of the supercontinent Rodinia (e.g. Li et al., 2008) transcend their regional significance. Comparing the detrital zircon age spectra from both regions with each other and with potential source regions from the Kalahari Craton and Western Australia-Mawson Continent provides a test for Rodinia models that place Kalahari adjacent to Western Australia (Fitzsimons, 2002, 2003a; Pisarevsky et al., 2003; Powell et al., 2001; Powell and Pisarevsky, 2002).

2.2 Apatite fission track and (U-Th)/He analyses and K/Ar illite dating of fault gouges in southwestern Norway

Manuscripts III and IV investigate the onshore tectonic history of southwestern Norway. The area is not a continental margin as such, since rifting in the North Sea was ultimately unsuccessful. However, the early stages of the transition from orogen to rift basin can be studied here without interference of later breakup-related structures. In the absence of a post-Devonian sedimentary record onshore, the tectonic history of the region is poorly understood and controversially discussed (e.g. Chalmers et al., 2010; Gabrielsen et al., 2010a, b; Lidmar-Bergström and Bonow, 2009; Nielsen et al., 2010a; Nielsen et al., 2010b; Nielsen et al., 2009a; Nielsen et al., 2009b). Generally, two end member models have been suggested: (1) Orogenic collapse and complete elimination of the Caledonian mountains with peneplanation during the Mesozoic and renewed tectonic uplift in the Cenozoic to account for the present-day high relief of interior southern Norway (e.g. reviews by Gabrielsen et al., 2010a; Lidmar-Bergström et al., 2000). (2) Incomplete orogenic collapse with a long-standing remnant of the Caledonian orogen that is slowly eroded to its present-day level – the isostasy-climate-erosion (ICE) hypothesis (Nielsen et al., 2009b). While the ICE hypothesis dismisses a tectonic cause for increased uplift rates in the Cenozoic, it suggests climate-driven increased erosion acting on an isostatically compensated mountain belt as an alternative cause for higher uplift rates. Increased sediment input of material derived from the Norwegian mainland into the North Sea basin is well documented for the Cenozoic and is equated to higher erosion rates onshore. The controversy about the cause and effect of uplift and erosion boils down to a chicken or egg problem: Did renewed tectonic uplift create a high topography which was then preferentially affected by erosion resulting in higher erosion rates? Or did climate changes cause faster erosion resulting in higher uplift rates? The controversy around the ICE hypothesis touches therefore two highly relevant topics: the interaction between tectonics and climate and the problem of persistent high-standing mountain belts.

In order to provide additional constraints on the post-Caledonian uplift history of southwestern Norway, we have chosen low-temperature thermochronological methods such as apatite fission track and (U-Th)/He analyses for their ability to date vertical movements in the upper crust (e.g. Reiners and Brandon, 2006). These methods were complimented by K/Ar illite dating of clay-bearing fault gouges from brittle structures assumed to be the youngest deformational features in onshore southwestern Norway. K/Ar dating of illite from clay gouges has emerged as a valuable tool to constrain the timing of brittle deformation in the upper crust in recent years (e.g. Zwingmann et al., 2010) and has now been successfully applied to late Palaeozoic to Mesozoic faults in southwestern Norway.

The combination of these three methods, all of which are recording upper crustal movement and deformation, provides improved estimates on uplift rates and fault activity in southwestern Norway during late Palaeozoic to early Cenozoic times.

3 Synopsis of research findings

The application of geochronological methods to investigate ancient orogen-rifted margin systems has produced interesting and valuable results in all three study areas. Contribution I and II, while focussing on different geographic areas, are connected by their contemporaneous nature and implications for Rodinia reconstructions. Contribution III and IV are companion papers, investigating the post-Caledonian history of southwestern Norway from slightly different angles.

3.1 Detrital zircon U/Pb analyses from the Pinjarra Orogen (Western Australia) and the Maud Belt (East Antarctica)

Comparative U/Pb zircon studies from the Northampton Complex and Maud Belt have provided valuable information on the sedimentary and metamorphic history of both regions, as well as testing a suggested Western Australia-Kalahari connection within Rodinia.

In the Northampton Complex, high-grade metamorphism was dated at 1090-1020 Ma by both metamorphic zircon rims and monazites. Detrital zircon cores show an age distribution that is consistent with derivation from the Albany-Fraser Orogen in southwestern Australia, with additional contributions from the Mawson Continent and possibly syn-sedimentary volcanism. A significant number of metamorphic rims also gave ages pre-dating metamorphism in the Northampton Complex and are interpreted as detrital. These rims can be correlated to the two-stage tectonic history of the Albany-Fraser Orogen and provide therefore a tighter constraint on the provenance of the sediments. The apparently conflicting provenance information recorded by the metamorphic rims and detrital cores respectively, suggests the possibility that all detrital zircons were derived from the Albany-Fraser Orogen, but some of them were remobilised from metasedimentary rocks that derived their zircon load from the Mawson Continent. In this case the detrital metamorphic rims record the primary provenance of the Northampton Complex sediments (the Albany-Fraser Orogen), while the detrital cores provide a mixed, primary and secondary provenance. The most important conclusion is, however, that all detrital zircons in the Northampton Complex could have been derived from within the combined Western Australia-Mawson Continent and no outside source is required to explain the age distribution.

Similar findings can be formulated for the Maud Belt. Here the sediments appear to be sourced primarily from within the Namaqua-Natal-Maud Belt, with minor contributions from the Kalahari Craton. Only a small number of detrital zircons ages could not be correlated with currently know sources in Kalahari but are inconclusive as to their alternative source. One sample is interpreted as a molasse deposit of the Maud Belt and was deposited during the Neoproterozoic. The detrital age spectrum is similar to that of the other two samples, with the addition of large amounts of Grenville-ages grains, suggesting that the molasse remobilised both syn-tectonic magmatic rocks of the Grenville-age Maud Belt and metasedimentary rocks similar to the other two samples analysed here. The timing of Grenville-age orogenesis is constrained by isotopic disturbance in the Mesoproterozoic sediments and a prominent peak in the detrital age distribution in the Neoproterozoic sediment at 1090-1060 Ma.

To summarise, while both areas experienced high-grade metamorphism at roughly the same time, no Australian fingerprint could be found in metasedimentary rocks of the Maud Belt and no indication of Kalahari-derived detritus was found in the Northampton Complex. A direct comparison between the zircon age spectra of both regions is even more decisive: samples from both regions show significantly different age distributions and the suggestion that they are part of the same sedimentary sequence should be abandoned. In light of the new geochronological data, a Western Australia-Kalahari connection within Rodinia appears unlikely.

3.2 Apatite fission track and (U-Th)/He analyses and K/Ar illite dating of fault gouges in southwestern Norway

The combination of low-temperature thermochronological methods with K/Ar illite dating of fault gouges proved successful in improving our understanding of the post-Caledonian development of southwestern Norway. Apatite fission track and (U-Th)/He data suggest relatively constant cooling rates of ca. 2 °C/Ma during Permian to early Jurassic times and slower cooling (< 1°C/Ma) since the middle Jurassic. The data are equally compatible with surface exposure during the mid-late Jurassic but require mild reheating to 40-65 °C during the Cretaceous or Palaeogene in this case. Both fission track and (U-Th)/He ages are offset across faults and fault-bound blocks yielded cooling histories that are distinctly different from their neighbours. Both these observations are consistent with fault activity throughout the Mesozoic. This is borne out by the K/Ar illite ages from fault gouges, which define three periods of fault activity in Carboniferous-Permian, late Triassic-early Jurassic and Cretaceous-earliest Palaeogene times respectively. Each of these periods coincides with tectonic or magmatic events previously described in southwestern Norway and appears thus to be of regional significance. The record provided by all three applied methods ends in the late Cretaceous to earliest Palaeogene. The youngest uplift history could therefore not be constrained. While we could not yet solve the questions of the ICE hypothesis vs. peneplanation and tectonic uplift, the present study provides solid grounds for future investigations that, by customised sampling strategies and careful sample selection might push the limits of low-temperature thermochronology just far enough to capture this elusive latest event.

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