

## Final report VISTA 2015

### Uplift, burial and fault reactivation across the Norwegian margin: a Viking Graben – Utsira High – Haugesund – Hardangervidda thermochronological transect

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Project number: 6262

We would like to point out that as per an agreement with the University of Bergen, Anna Ksienzyk has been hired for teaching duties at the University of Bergen in spring 2014 and spring 2015, and the official end date of the VISTA project has been moved to 28.02.2016.

Presentation of the project:

#### **1. ½ A4 page with a popular presentation of the project (to be written by the scholar)**

Much of Norway's economic wealth lies offshore in the form of oil and gas deposits stored in the sediments of the North Sea and North Atlantic. Another important source of income, tourism, capitalizes on the spectacular landscape of western Norway's mountains and fjords. These two very different natural resources formed side by side by the same geological processes that have been shaping Norway for a very long time. The story starts about 420 million years ago, when Norway collided with Greenland and North America, pushing up the Caledonian mountain range, which was similar in size to the Himalayas. When Norway and Greenland/North America started moving away from each other, the mountain range broke apart along large fracture zones (faults). Weathering and erosion added their destructive forces to help wear down the mountains, and the erosional products, sand and clay, were deposited in topographic lows (sedimentary basins). Eventually, the continents pulled apart far enough, that a new ocean, the North Atlantic, could open between them. The details of this development from a high mountain range to a new ocean are not yet fully understood. Our research project helps to provide a timeline of geological events, by measuring the age of rocks and by estimating when certain rocks came to the earth's surface or when they were buried again under sediments. We have focused on two areas: the Utsira High in the northern North Sea and a transect from Haugesund to the Hardangervidda. The Utsira High is especially interesting because it is also the location of the latest large oil discoveries of the Johan Sverdrup and Edward Grieg fields. Our data show that the Utsira High was a topographic high from late Carboniferous/Permian to Jurassic/Cretaceous times. During these ca. 150 million years, the rocks experienced deep weathering and erosion, acting as a sediment source for the surrounding sedimentary basins.

In the late Carboniferous/Permian, when the Utsira High first reached the earth's surface, most rocks of onshore western Norway were still located deep in the earth's crust. The coastal areas experienced rapid uplift and erosion during the Permian and Triassic when rifting between Norway and Greenland/North America created the sedimentary basins of the North Sea. Rocks of the inland were the last to reach the surface, with significant uplift and erosion of the inland during the Mesozoic and Cenozoic. The large faults that formed during the destruction of the Caledonian mountains played an important role during this later history. Dating of minerals that grow during fault movements shows that many faults were reactivated during North Sea rifting and possibly again when the North Atlantic opened. These faults allow large blocks of rock to move vertically against each other, changing the topography and creating potential for erosion. Some of these faults still seem to control the landscape of western Norway today.

**2. Have there been any changes in the objective/goals during the project period? Did you achieve what was promised in the project description? (to be written by the scholar)**

The main research goals and objectives have not changed and most of the analyses suggested in the project description have been completed:

- Altogether, 52 samples have been analysed by the fission track method (suggested were 60) from both offshore and onshore samples.
- The number of (U-Th)/He analyses was doubled from ca. 15 suggested in the project description to 30 that were actually analysed, including seven samples from the Utsira High. For several samples both apatite and zircon (U-Th)/He ages were measured.
- Time-temperature modelling based on fission track and (U-Th)/He analyses has been performed for all offshore samples and representative onshore samples.
- The K-Ar dating method was used to date illite-bearing fine fractions of 27 fault gouge samples from 23 different faults (suggested were 10-20), including one fault in a drill core from the Utsira High.
- Instead of U-Pb dating zircons by laser ablation ICP-MS, we have chosen to primarily utilize the more precise but also more time-intensive SIMS method at the Nordsim laboratory. As a consequence, fewer samples than originally suggested were dated, altogether 8 (5 by SIMS and 3 by ICP-MS) as compared to the suggested ca. 15 samples.
- A comprehensive model of the tectono-thermal history of the Norwegian margin-North Sea rift system is under development.

**Publications:**

There have been significant delays in the publication schedule. Three to five possible publications were originally suggested. Considering the small number of U-Pb data, these will be integrated into the other publications rather than published as a separate paper. The K-Ar fault dating, on the other hand, yielded more than enough data for a stand-alone publication. The results have been presented at several conferences and manuscripts are in different stages of preparation: Papers on both the results from the fault dating and the thermochronology of the Utsira High are relatively advanced and will be submitted early this year, while manuscripts on the onshore thermochronology

and a synthesis of all the results are still in their early stages and will hopefully be submitted later this year. We will keep VISTA updated on the status of these publications.

### 3. Publications (scholar)

Fossen, H., Khani, H.F., Faleide, J.I., **Ksienzyk, A.K.**, Dunlap, W.J., in press. Post-Caledonian extension in the West Norway – northern North Sea region: the role of structural inheritance. Geological Society of London, Special Publications.

Jacobs, J., Thomas, R. J., **Ksienzyk, A. K.**, Dunkl, I., 2015. Tracking the Oman Ophiolite to the surface – new fission track and (U-Th)/He data from the Aswad and Khor Fakkan blocks, United Arab Emirates. *Tectonophysics*, 644-645, 68-80.

Johannessen, K. C., Kohlmann, F., **Ksienzyk, A. K.**, Dunkl, I., Jacobs, J., 2013. Tectonic evolution of the SW Norwegian passive margin based on low-temperature thermochronology from the innermost Hardangerfjord area. *Norwegian Journal of Geology* 93, 243-260.

**Ksienzyk, A. K.**, 2012: From mountains to basins: geochronological case studies from southwestern Norway, Western Australia and East Antarctica. Ph. D. Thesis, University of Bergen, 162 pp.

**Ksienzyk, A. K.**, Dunkl, I., Jacobs, J., Fossen, H., Kohlmann, F., 2014. From orogen to passive margin: constraints from fission track and (U-Th)/He analyses on Mesozoic uplift and fault reactivation in SW Norway. Geological Society of London, Special Publications 390, 679-702.

**Ksienzyk, A. K.**, Jacobs, J., 2015. Western Australia-Kalahari (WAlahari) connection in Rodinia: not supported by U/Pb detrital zircon data from the Maud Belt (East Antarctica) and the Northampton Complex (Western Australia). *Precambrian Research* 259, 207-221.

**Ksienzyk, A. K.**, Jacobs, J., Boger, S. D., Košler, J., Sircombe, K. N., Whitehouse, M. J., 2012: U-Pb ages of metamorphic monazite and detrital zircon from the Northampton Complex: evidence of two orogenic cycles in Western Australia. *Precambrian Research* 198-199, 37-50.

Sirevaag, H., Jacobs, J., **Ksienzyk, A.K.**, Rocchi, S., Paoli, G., Jørgensen, H., Košler, J., in press. From Gondwana to Europe: the journey of Elba Island (Italy) as recorded by U-Pb detrital zircon ages of Paleozoic metasedimentary rocks. *Gondwana Research*.

Publications in prep.

**Ksienzyk, A. K.**, Wemmer, K., Jacobs, J., Fossen, H., Schomberg, A.C., Süssenberger, A., Lünsdorf, N.K., in prep.: Dating post-Caledonian brittle deformation in southwestern Norway: K-Ar analyses of illite from fault gouges. Soon to be submitted to the *Norwegian Journal of Geology*.

**Ksienzyk, A.K.**, Jacobs, J., Fossen, H., Dunkl, I., Wemmer, K., in prep. The basement of the Utsira High: U-Pb, K-Ar, fission track and (U-Th)-He thermochronology.

**Ksienzyk, A.K.**, Woznitza, T., Hermansen, C., Jacobs, J., Fossen, H., Wemmer, K., Dunkl, I., in prep. Reactivation of the Hardangerfjord and Stavanger shear zones: evidence from low-T thermochronology.

Paoli, G., Sirevaag, H., Stokke, H.H., Rocchi, S., **Ksienzyk, A.K.**, Jacobs, J., Košler, J., submitted. Basement provenance revealed by U-Pb detrital zircon ages: a tale of African and European heritage in Tuscany, Italy.

Rønnevik, C., **Ksienzyk, A. K.**, Fossen, H., Jacobs, J., in prep. Thermal evolution and exhumation history of the northern Colorado Plateau (Uncompahgre Plateau, La Sal Mountains), based on apatite fission track and (U-Th)/He thermochronology and zircon U/Pb SIMS dating.

Conference presentations (Oct. 2012 – Jan. 2016):

Fossen, H., **Ksienzyk, A. K.**, Dunlap, W. J., Jacobs, J., Kohlmann, F., 2013. Insights into the post-Caledonian tectonic history of W Norway using geochronology and thermochronology – recent results. NGF Vinterkonferansen 2013, 8.-10. Jan. 2013, Oslo.

Hermansen, C., Woznitza, T., **Ksienzyk, A. K. (presenting author)**, Jacobs, J., Dunkl, I., Wemmer, K., Fossen, H., 2015. New apatite fission track and (U-Th)/He ages from the Rogaland area: Mesozoic reactivation of brittle structures. NGF Vinterkonferansen 2015, 12.-14. Jan. 2015, Stavanger.

Jacobs, J., Bauer, F., **Ksienzyk, A.K.**, Sirevaag, H., 2015. The East Africa – Dronning Maud Land Orogen – Passive Margin System. XII International Symposium on Antarctic Earth Sciences, 13.-17. July 2015, Goa, India.

Johannessen, K. C., Jacobs, J., Kohlmann, F., **Ksienzyk, A. K.**, Dunkl, I., 2013. The Eidfjord area revised: new thermochronological constraints on the exhumation history of central southern Norway. NGF Vinterkonferansen 2013, 8.-10. Jan. 2013, Oslo.

Kohlmann, F., **Ksienzyk, A. K.**, Fossen, H., Jacobs, J., 2013. Exhumation history along the Hardangerfjord Shear Zone – new insights from combined (U-Th)/He and fission track analysis. NGF Vinterkonferansen 2013, 8.-10. Jan. 2013, Oslo.

Kohlmann, F., **Ksienzyk, A. K.**, Jacobs, J., Fossen, H., 2012. Constraining the exhumation history of the Norwegian North Sea rift margin through low-temperature thermochronological data from the Hardangerfjord area, SW-Norway. Onshore – Offshore relationships on the North Atlantic Margin, 17.-18. Oct. 2012, Trondheim.

**Ksienzyk, A. K.**, Jacobs, J., Fossen, H., Dunkl, I., Košler, J., 2013. The basement of the Utsira High: U/Pb, (U-Th)/He and fission track thermochronology. NGF Vinterkonferansen 2013, 8.-10. Jan. 2013, Oslo.

**Ksienzyk, A. K.**, Kohlmann, F., Dunkl, I., Wemmer, K., Jacobs, J., Fossen, H., 2012. Late Caledonian orogenic collapse and Permian-Mesozoic rifting: dating onshore faults in SW Norway with low-temperature thermochronological methods. Onshore – Offshore relationships on the North Atlantic Margin, 17.-18. Oct. 2012, Trondheim.

**Ksienzyk, A. K.**, Wemmer, K., Jacobs, J., Fossen, H., Rotevatn, A., 2015. Dating fault activity in SW Norway: K/Ar analyses of illite from fault gouges. NGF Vinterkonferansen 2015, 12.-14. Jan. 2015, Stavanger.

**Ksienzyk, A.K.**, Jacobs, J. (presenting author), 2015. Western Australia-Kalahari (WAlahari) connection in Rodinia: not supported by U/Pb detrital zircon data from the Maud Belt (East Antarctica) and the Northampton Complex (Western Australia). XII International Symposium on Antarctic Earth Sciences, 13.-17. July 2015, Goa, India.

**Ksienzyk, A.K.**, Jacobs, J., Fossen, H., Dunkl, I., Wemmer, K., 2016. Uplift and faulting of the Utsira High basement: evidence from low-T thermochronology. 32<sup>nd</sup> Nordic Geological Winter Meeting, 13.-15. Jan. 2016, Helsinki, Finland.

**Ksienzyk, A.K.**, Kohlmann, F., Jacobs, J., Fossen, H., Dunkl, I., Wemmer, K., 2013. The effect of North Sea and North Atlantic rifting on onshore SW Norway: evidence from low-temperature thermochronology. 3P Arctic 2013, 15.-18. Oct. 2013, Stavanger.

Rønnevik, C., **Ksienzyk, A. K. (presenting author)**, Fossen, H., Jacobs, J., Dunkl, I., Bea, F., 2014. Thermochronology of the Uncompahgre Plateau and La Sal Mountains: new apatite fission track, (U-Th)/He and zircon U/Pb data. 14<sup>th</sup> International Conference on Thermochronology, 8.-14. Sept. 2014, Chamonix-Mont Blanc.

Rotevatn, A., **Ksienzyk, A. K.**, Sømme, T., Wemmer, K., Fossen, H., Jacobs, J., 2013. Timing of brittle deformation associated with the Nordfjord-Sogn Detachment Zone: preliminary results from K/Ar illite dating. NGF Vinterkonferansen 2013, 8.-10. Jan. 2013, Oslo.

Sirevaag, H., Jacobs, J., **Ksienzyk, A. K.**, Dunkl, I., 2015. Review of the low-temperature thermochronological data from the Dronning Maud Land Mountains, East Antarctica. NGF Vinterkonferansen 2015, 12.-14. Jan. 2015, Stavanger.

Sirevaag, H., Jacobs, J., **Ksienzyk, A. K.**, Dunkl, I., 2014. Thermochronological data from the Dronning Maud Land Mountains, East Antarctica – a review. 14<sup>th</sup> International Conference on Thermochronology, 8.-14. Sept. 2014, Chamonix-Mont Blanc.

Sirevaag, H., Jacobs, J. (presenting author), **Ksienzyk, A.K.**, Dunkl, I., 2015. Recent development of the low-temperature thermal history of the Dronning Maud Land Mountains – evidence from (U-Th)/He dating. XII International Symposium on Antarctic Earth Sciences, 13.-17. July 2015, Goa, India.

#### **4. Reflections on continuation of the project (to be written by the project director)**

This project has great potential for continuation. Although West Norway is now relatively well covered by apatite fission track and (U-Th)/He data, as well as K-Ar fault gauge data, the thermal histories of the various basement highs are only poorly studied so far. We were for example not able to get access to borehole samples from the northern Utsira High, because of restrictions imposed by oil companies. The present study could very well be extended to cover a larger part of the Utsira High, especially the northern part, and could be expanded to other basement highs, particularly the Shetland Platform and the Frøya High. It would also be very useful to use the results of this project and its continuation in restoration of transects across the North Sea rift in order to better understand its evolution. Overall, the long-term thermal histories of the basement highs of the North Sea appear under-investigated.