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Normal faulting and block tilting in Lofoten and Vesterålen constrained by Apatite Fission Track data

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ABSTRACT

Mesozoic and possibly younger normal faulting and block tilting in the Lofoten–Vesterålen archipelago can be constrained by Apatite Fission Track data. Previous studies have documented the polyphase structural evolution of the archipelago, based on field data and onshore–offshore correlations. Our new AFT data document vertical movements on a more regional scale, with kilometer-scale offset on some faults. Below Sortlandsundet, the Hadselfjord Fault Zone forms the eastern limit of the Sortlandsundet half-graben and our data reveal latest Cretaceous and younger half-dome shaped uplift of the footwall. East of the Western Lofoten Border Fault, on Vestvågøya, southeastward tilting is indicated both by the pattern of AFT ages, ranging from 81 +/− 7 Ma to in the NW to 167 +/− 16 Ma in the SE, and tilted paleosurfaces. AFT ages immediately east of Sortlandsundet (72 +/− 5 Ma) and on Vestvågøya (81 +/− 7 Ma) are among the youngest ones found on the Norwegian mainland.

The present-day landscape of the Lofoten–Vesterålen archipelago does not represent a re-exposed and glacially modified Mesozoic landscape. Although most of our data indicate cooling to below ~60 °C took place during the Mesozoic, the youngest footwall ages are hard to explain without alluding to Cenozoic normal faulting. A Cenozoic structural control on the landscape can thus be inferred for Lofoten and Vesterålen.

1. Introduction

Post-rift flank uplifts on the Norwegian North Atlantic margin have until recently been regarded as broad, domal features unaffected by faults (e.g. Rohrman et al., 1995). More recent work (Hendriks and Andriessen, 2002; Hendriks, 2003) has indicated that uplift of the margin in Northern Norway was asymmetric and that the role of faults probably was greater than previously thought. The marked topographic and drainage-pattern asymmetry observed there has been reported as characteristic of regions undergoing active normal faulting (e.g. Leeder and Jackson, 1993). Apatite Fission Track (AFT) studies by Redfield et al. (2004, 2005a,b) provided direct evidence that post-rift uplift of Mid-Norway was aided by normal faulting with kilometer-scale vertical offsets in the Møre–Trøndelag Fault Complex (MTFC). Like the MTFC, the Lofoten and Vesterålen Archipelago (LVA, Fig. 1) is known for a very dynamic history of vertical movements and is therefore an obvious target for further investigations on the role of faulting during and after rifting in the North Atlantic. Fault-control has also been demonstrated to play a critical role in the landscape development of Northernmost Norway (Osmundsen et al., 2009), and could be important in shaping the LVA as well (Bergh et al., 2008; Osmundsen et al., 2010).

Many of the brittle structures (Fig. 2, inset) exposed in the LVA have been studied in the field by Wilson et al. (2006) and by Bergh et al. (2007). Both of these studies described onshore fault populations, compared these to offshore structures, and invoked seismic sections to constrain timing of the onshore structures. Here, we use AFT data to document vertical offset across specific faults. AFT data can also constrain folding, amounts of denudation, and fault block tilt. However, the spatial resolution of the AFT method is lower than that of Wilson et al. (2006) and Bergh et al. (2007): only structures with major vertical offset will be resolved by our dataset. Assuming temperature can be constrained with an uncertainty in the order of 10–15 °C by the AFT inverse thermal history models, this corresponds to 400–600 m uncertainty for a geothermal gradient of 25 °C/km. Furthermore, the uncertainty on the geothermal gradient itself limits how accurate absolute vertical movements can be constrained. The history of vertical movements presented here is therefore of a more regional character compared to the studies of Wilson et al. (2006) and Bergh et al. (2007). We are, however, able to demonstrate statistically significant AFT age-jumps (i.e. ages that do not overlap when taking into account 2σ errors) across some of the most important structures.

2. Geological setting

The LVA constitutes the only basement high exposed above sea level on the northern Norwegian margin. It is built up of high-grade poly-metamorphic Precambrian rocks (Griffin et al., 1978). Rocks of

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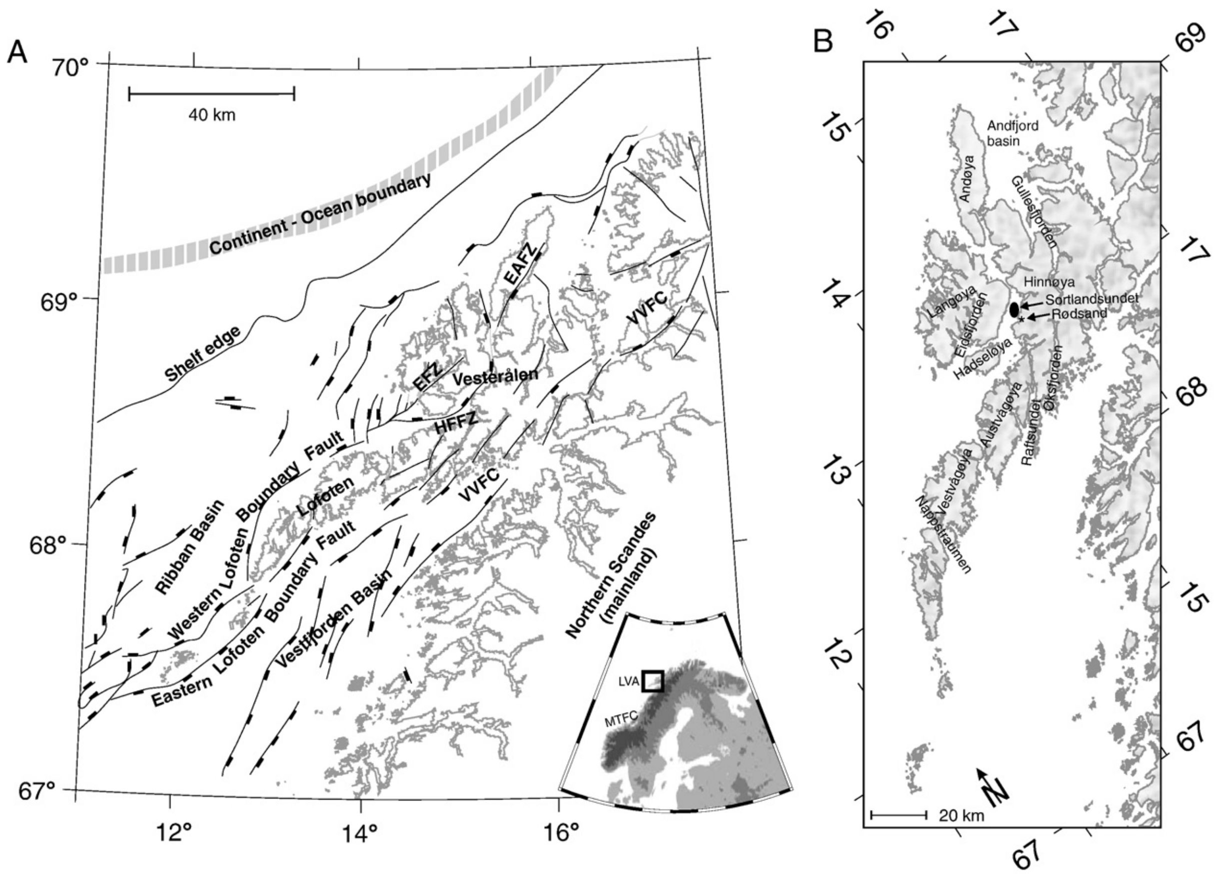

Fig. 1. Location map for (A) the Northern Norwegian Atlantic margin (after Olesen et al., 1997, 2002) and (B) the Lofoten and Vesterålen archipelago. LVA, Lofoten–Vesterålen Archipelago. MTFC, Møre–Trøndelag Fault Complex. LTZ, Lenvik Transfer Zone. EAFZ, Eastern Andøya Fault Zone. VVFC, Vestfjorden–Vanna Fault Complex. SVF, Storvatnet fault. EFZ, Eidsfjord Fault Zone. HFFZ, Hadselfjord Fault Zone. HFZ, Hamarøya Fault Zone. IBR, Intrabasin Ridge. WLBF, Western Lofoten Boundary Fault. ELBF, Eastern Lofoten Boundary Fault. MTZ, Mosken Transfer Zone. Black ellipse in (B) indicates the location of the Sortlandsundet sedimentary basin (see text).

the Caledonian orogen are under-represented in Lofoten, being limited to the Leknes Group (Tveten, 1978). Caledonian nappes extending from the Norwegian mainland are also present on the easternmost part of Hinnøya (Gustavson, 1974). Caledonian deformation of the Precambrian rocks appears to be limited. Based on K/Ar and $^{40}Ar/^{39}Ar$ ages for basement rocks and regional reconstructions of uplift and subsidence all of the rocks exposed at the surface today are thought to have cooled below ~200 °C by the late Paleozoic (Løseth and Tveten, 1996; Steltenpohl et al., 2004).

The LVA is located immediately adjacent to the shelf edge (Fig. 1A) and the continent–ocean boundary (Brekke, 2000). Studies of seismic refraction data and gravimetric data have indicated that the Lofoten ridge is situated above an anomalously shallow Moho, a so-called anti-root (Mjelde et al., 1993). Tsikalas et al. (2005) explain this shallow Moho by the development of a core complex at middle to lower crustal levels during late/post-Caledonian orogenic extension. The evolution of the offshore basement structures has been heavily debated (Olesen et al., 1997, 2002; Tsikalas et al., 2001, 2005), but new data may provide clarity: some of the previously proposed 'transfer zones' that have been interpreted to segment the offshore — and possibly onshore — domain are not evident in more recent seismic lines and aeromagnetic datasets (Olesen et al., 2007).

Offshore, the Vestfjorden and Ribban Basins form half-grabens, to the southeast and northwest of the Lofoten Ridge respectively. The half-grabens are largely filled with Cretaceous sediments (Brekke, 2000). Border faults separate these sequences from the crystalline basement highs that constitute the LVA (Bergh et al., 2007). Onshore, only a few pockets of Mesozoic sedimentary rocks have survived. On Andøya, a fault-bounded sedimentary section with a total thickness of more than 500 m is the onshore part of the Andfjord basin. It consists of two major fining-upwards sequences, of Middle Jurassic and Early Cretaceous age respectively (Dalland, 1980). The only other Mesozoic sediments found onshore in the region are boulders derived from the Sortlandsundet basin, a Late Jurassic basin identified recently in the sound between Hinnøya and Langøya (Davidsen et al., 2001).

Strong geomorphologic contrasts are found throughout Lofoten and Vesterålen. The southern end of the Lofoten ridge is characterized by jagged mountain peaks and deep fjords. Hinnøya also displays 'alpine' topography. However, elsewhere in the archipelago (for example on Andøya where smaller ridges are separated by wide flats and mires) the landscape is much more subdued. In the field, the flats and mires are characterized by a maximum 10 m thick layer of peat (which is actively produced) on top of either the Mesozoic sedimentary succession or directly on top of deeply weathered basement rocks. Peulvast (1986) pointed out the importance of structural control of the landscape by faults and lithological contacts, and this concept has recently been advanced and expanded upon (Osmundsen et al., 2009, 2010). Glacial erosion has modified the landscape extensively, but seemingly pre-glacial features such as up to 25 m thick successions of deeply weathered basement rocks are preserved in some areas (Peulvast, 1986).

3. Apatite Fission Track results

Hendriks (2003) investigated segmentation and differential uplift within the LVA based on AFT and Apatite (U–Th)/He data, with a strong emphasis on the Lofoten ridge. Few data had been obtained from Hinnøya and Langøya and consequently Mesozoic and