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Late Mesozoic to Early Cenozoic components of vertical separation across the Møre–Trøndelag Fault Complex, Norway

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Abstract

Low temperature apatite fission track (AFT) data from two horizontal transects across the Møre–Trøndelag Fault Complex (MTFC) and along the coast of the Fosen peninsula have defined a complicated series of structural blocks whose exhumation to temperatures cooler than the uppermost apatite Partial Annealing Zone (PAZ) occurred during a broad Mesozoic to Cenozoic time span. The ~100 million year cooling difference between the innermost and outermost blocks indicates they were subjected to very different exhumation pathways. Track length histograms and inverse model results also suggest that significant differences in thermal histories are present over very short horizontal distances. In conjunction with the offshore geological evidence, the AFT data and models strongly suggest that the innermost zones of the MTFC underwent between 2 and 4 km of structurally controlled net vertical rock column uplift/subsidence following latest Cretaceous time, and potentially much of the Tertiary as well. The up-to-the-east down-to-the-west relative offset at the Norwegian margin is interpreted in terms of a flexed, nearly broken lithospheric plate architectural model for late Mesozoic and Tertiary Scandes mountain building, whose driving force was likely dominanted by erosionally induced loading/unloading at the margin.

Keywords: Norway; Uplift; Apatite; Møre; Trøndelag; Fault; Fission track

1. Introduction

Fault zones of the Norwegian continental shelf, and their bearing on hydrocarbon systems, have been the focus of numerous studies (e.g. Doré and Gage, 1987;

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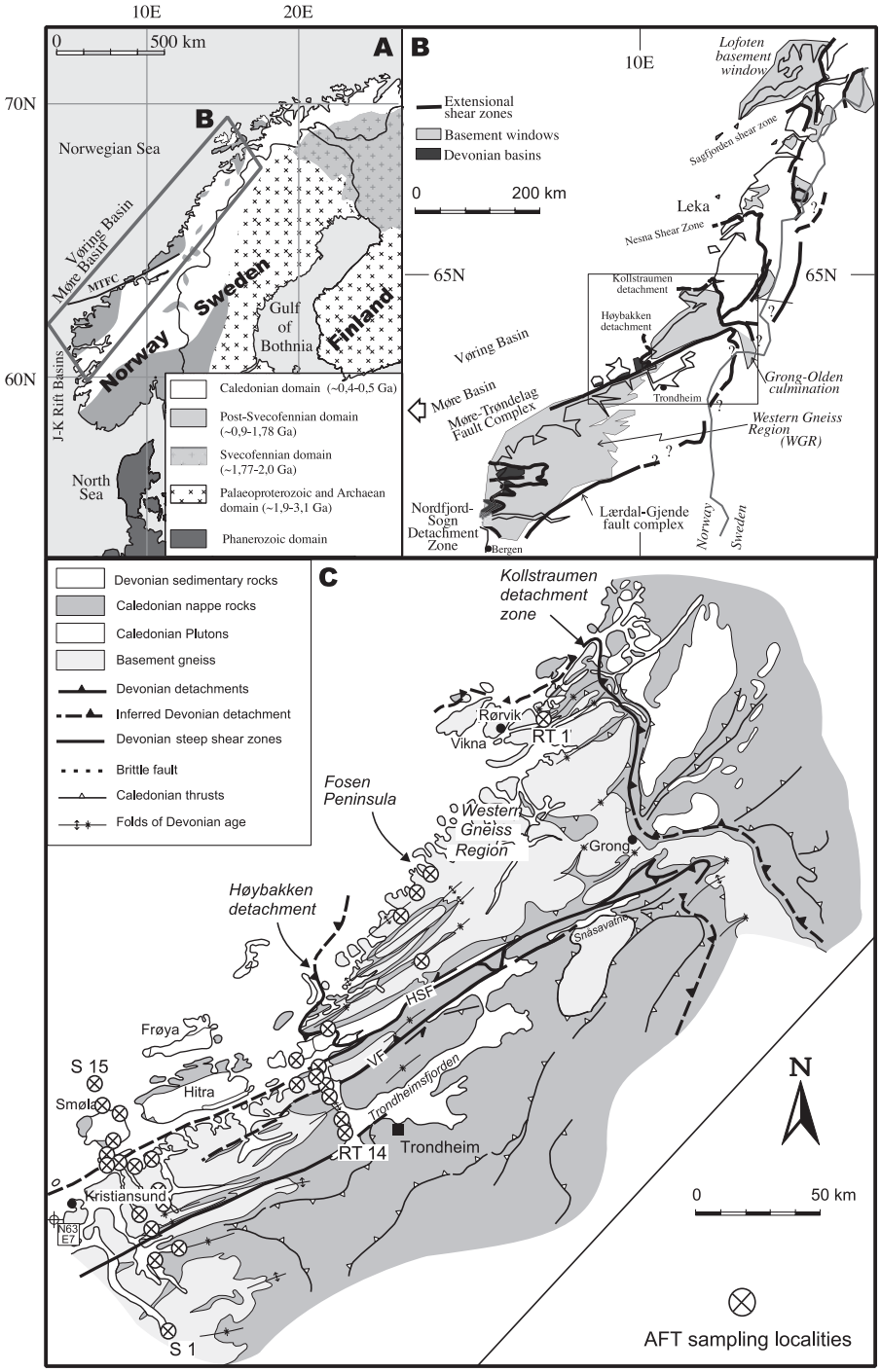


Fig. 1. Geotectonic maps. (A) Regional configuration of Scandinavia. (B) Major shear zones of Norway that were active during extensional denudation of the Scandian-phase Caledonides. (C) Simplified bedrock map of Central Norway, with fault strands of the Møre–Trøndelag Fault Complex (MTFC), and sites that have been sampled for the Apatite Fission Track (AFT) study. HSF—Hitra–Snåsa Fault; VF—Verran Fault; BL—Bæverdalen lineament; HSZ—Hardangerfjord Shear Zone; DF—Dalsfjord Fault; NSD—Nordfjord-Sogn Detachment; LGFS—Lærdal Gjende Fault System.

see Gabrielsen et al., 1999 for recent summary). In the near-shore regions, many of these faults can be traced onshore into what constitutes the basement substrate of the nearby sedimentary basins, permitting assessments of offshore–onshore structural linkages (e.g. Gabrielsen and Ramberg, 1979; Hospers and Ratore, 1984; Gabrielsen et al., 1999; Smethurst, 2000). Analysis of onshore basement faults can provide detailed kinematic and reactivation histories as well as information constraining depth and timing of faulting; such data are particularly important to better understand the controlling basement structures of the offshore domain.

The regional-scale Møre–Trøndelag Fault Complex (MTFC) of Central Norway is one of the most important onshore–offshore structures in the mid-Norway region. In the offshore region, it separates a well-defined Jurassic–Cretaceous basin system to the south from a more complex series of wider and deeper Cretaceous–Tertiary rift basins to the north (Fig. 1A). The MTFC has a long history of activity. While many of its kinematic records are consistent with strike–slip

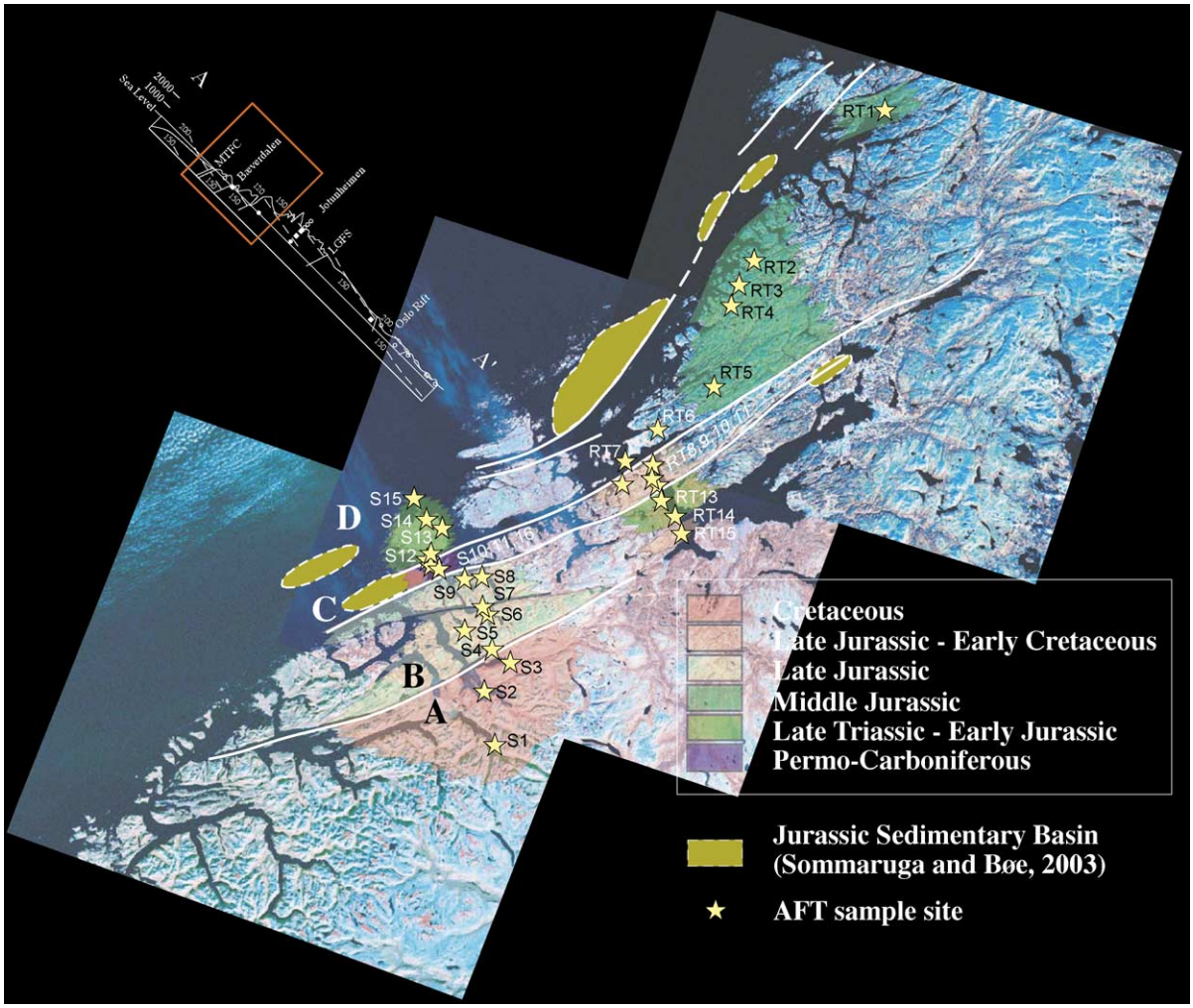


Fig. 2. Landsat 5 image utilizing bands 4, 5 and 7 showing the distribution of AFT samples, the AFT age domains (A—D) described in this paper, and the principal structures and features of the MTFC and surrounding regions. Upper left cross-section is modified from Rohrman et al. (1995) and shows the model presented in Fig. 5. The box in the cross-section illustrates the approximate area covered by Fig. 2.

faulting (admittedly of unknown scale), a significant vertical component has been reported (e.g. Bering, 1992; Watts, 2002). The timing of activity across the MTFC has been enigmatic, particularly with respect to its onshore segments. However, a better understanding of the fault system is important to the offshore industry because reactivation of older tectonic features like the fault strands of the MTFC (e.g. Grønlie et al., 1991, 1994; Braathen et al., 2000, 2002) may be linked with the formation of near-shore Jurassic basins (Fig. 2; Bøe, 1991; Sommaruga and Bøe, 2002).

In this contribution, we present new Apatite Fission Track (AFT) data from a transect across the northeastern onshore portion of the MTFC and compare these data to existing data from the southern portion of the fault complex (Redfield et al., 2004). Our analysis places temporal and (coarse) total offset constraints on the net vertical faulting component. These data resolve distinct footwall and hanging-wall domains, as well as internal fault blocks that were unroofed and/or buried at various times during the evolution of the MTFC.

2. Regional setting

The MTFC is a first-order structure in Norway, truncating the entire tectonostratigraphy of central Norway (Fig. 1). This tectonostratigraphy consists of autochthonous and parautochthonous Precambrian basement covered by lower Paleozoic platform deposits in the east, and in the west by four Caledonian allochthonous units (imbricate Baltic cover, stacked basement and cover, exotic rocks of ophiolitic and island arc affinity, and at top, suspect and exotic terranes; e.g. Bryhni and Sturt, 1985; Roberts, 1988). The Lærdal–Gjende fault complex, which runs northeast–southwest and continues offshore, also cross-cuts the Norwegian tectonistratigraphy (Fig. 1B). Between the Lærdal–Gjende structure and the MTFC, the E–W folded Nordfjord–Sogn Detachment Zone (Norton, 1986) wraps on- and offshore in a convoluted manner (e.g. Roberts, 1983), juxtaposing Devonian "Old Red Sandstone" rocks with rocks of the (Caledonian) western Norway ultrahigh pressure metamorphic domain. These features have been set into a common framework with the MTFC by (among others) Krabbendam and Dewey (1999), Fossen (2000), and Seranne (1992).

These and other regional shear zones found in northern mid-Norway have undergone a long and complex evolution (Torsvik et al., 1989; Andersen et al., 1999; Braathen et al., 2002; Osmundsen et al., 2003; Doré and Gage, 1987). They host varied structural elements such as thick, medium- and low-grade mylonitic zones, upon which are superimposed cataclasite, breccia and gouge. These fabrics are consistent with gradual unroofing through a series of tectonic events, spanning the period from the final stages of the Caledonian/Scandian orogeny until the present (e.g. Gabrielsen et al., 2002). Initially activated as major extensional structures that developed during Devonian denudation of the orogen (e.g. Andersen, 1998; Braathen et al., 2002), the regional shear zones juxtaposed lower crustal rocks with nappe units and sedimentary basins that never were buried below an upper crustal setting (Andersen and Jamtveit, 1990; Andersen, 1998; Braathen et al., in press).

3. Evolution of the Møre–Trøndelag Fault Complex

The Møre–Trøndelag Fault Complex (MTFC) is one of the most significant regional structures of mid-Norway. Offshore, the MTFC separates the northern deep Cretaceous Møre and Vøring Basins from the shallower Jurassic–Cretaceous–Tertiary basin systems to the south. Onshore, it cuts deep-seated parautochthonous and autochthonous basement and very likely influenced structural development from Caledonian times to the present. While dextral strike–slip, sinistral strike–slip, and vertical offsets have been proposed for the MTFC, a quantitative determination of its kinematic history is complicated by the lack of well-preserved stratigraphic markers. In particular, the net dip-slip component is poorly constrained.

The MTFC extends some 300+ km between its diffuse origin in central mid-Norway and its unmapped offshore terminus in the Norwegian Sea. Onshore, the MTFC can be traced from the Møre region (e.g. Gabrielsen et al., 1999; Oftedahl, 1975) northeastwards along the SE margin of the Western Gneiss Region (WGR), and across the Grong–Olden Culmi-

nation towards the Børgefjell Basement Window (Roberts, 1998). The zone consists of several marked, major fault strands (e.g. Hitra–Snåsa [HSF], Verran [VF], Fig. 1C), with a surrounding network of accommodation fault zones, all well represented on satellite images (e.g. Grønlie et al., 1991). The ENE–WSW to NE–SW trend of the MTFC affects a crustal panel from Trondheim in the south to Vikna and Leka in the north (Rindstad and Grønlie, 1986; Titus et al., 2002), but is best expressed along the segment made up of the major fault strands (Gabrielsen et al., 2002; Kyrkjebø et al., 2001) with associated Jurassic basins.

Faulting along the MTFC can be further constrained by sedimentation patterns. Jurassic sedimentary rocks are preserved in NE–SW striking basins in Beidstadfjorden (inner Trondheimsfjorden), in Edøyfjorden and around Griptarane near Kristiansund, and in Frohavet (Bøe, 1991; Sommaruga and Bøe, 2002; see Fig. 2). Typical of the three near-shore basins are their approximately NE–SW trending fault boundaries. Two basins are associated with the Verran Fault of the MTFC (Fig. 1C), whereas the basin-bounding fault in Frohavet can be traced northeastwards into Vikna (Figs. 1 and 2).

The MTFC clearly affects the distribution of onshore rock units (e.g. Braathen et al., 2002) as well as the position and geometry of offshore basins (e.g. Gabrielsen et al., 1999; Sommaruga and Bøe, 2002). In the vicinity of the MTFC, Devonian basins nonconformably overlie Caledonian nappe rocks. Both nappe rocks and basin rocks are separated from the underlying gneiss-cored culmination by regional extensional detachments (e.g. Braathen et al., 2002). The lowest structural level in the area comprises medium- and high-grade rocks of the Western Gneiss Region (e.g. Möller et al., 2002), unroofed during Devonian to Early Carboniferous time (Kendrick et al., 2004; Eide et al., 1999, 2003) by large-scale movements on opposing shear zones: the Høybakken (Seranne, 1992) and Kollstraumen detachments (Braathen et al., 2000; Nordgulen et al., 2002). The supradetachment basins, sourced from surrounding nappe rocks, were also receiving sedimentary input from the gneissic culminations being exhumed from lower crustal levels (Eide et al., 2003). This relationship suggests that even the most deeply seated rocks of the region were being actively eroded by this time. This tectonic scenario is supported by $^{40}Ar/^{39}Ar$ model ages from feldspar (Kendrick et al., 2004), interpreted to reflect Mid-Late Carboniferous, brittle fault activity along the upper part of the Høybakken Detachment.

The MTFC and its surrounding, regional damage zone have a long and complex evolution (Grønlie and Roberts, 1989; Grønlie and Torsvik, 1989; Grønlie et al., 1991, 1994; Watts, 2002). Many of the MTFC faults may have been reactivated and played various roles during shifting stress regimes (e.g. Gabrielsen et al., 1999). Documented events include Early to Middle Devonian sinistral ductile shear in fairly wide, steeply dipping zones of mylonites. White micas from these mylonites record Mid-Late Devonian growth ages, interpreted in terms of the unroofing history of the footwall section (Kendrick et al., 2004). The subsequent retrogression of mylonites marks a transition into a more brittle deformation regime, with deformation being concentrated within narrow fault strands aligned along fold limbs of the much wider and (now) tightly folded shear zone. The brittle fault strands have a long activation–reactivation history (e.g. Watts, 2002; Grønlie et al., 1991), including episodes of brittle, oblique-slip faulting in the Late Devonian, Permo-Triassic, and post Mid-Jurassic, also recorded by Permian pseudotachylyte formation (Watts, 2002). Normal faulting in Late Jurassic–Early Cretaceous time, Tertiary minor fracturing and faulting, and possible post-glacial reactivation carry the MTFC from the deep past into a geologically more recent period.

4. Thermochronometry

Throughout onshore Norway, post-Devonian stratigraphic markers are lacking. Consequently, low temperature thermochronology such as the AFT or Uranium Thorium Helium methods constitute the lone tool with which to identify structural offset at shallow levels (see Kohn et al., 1999; Redfield et al., 2004). Although the AFT data have limitations in resolution, the system is nonetheless a powerful method with which to identify different structural blocks and to compare cooling and exhumation histories. Gallagher et al. (1998) provided a thorough review of the fission track method and its application to geological problems. Referring the reader to their article for details, we note two considerations that are important to our use of AFT data.

First, an AFT age does not represent the passage of the sample below a single critical isotherm. Rather, a range of temperatures (PAZ) exists within which fission tracks are partially stable. Thus, relating a fission track age to a particular temperature is only plausible when it can be demonstrated that no significant annealing has occurred since the time that temperature was passed at the sample site—for example, if rapid cooling has taken place (Gallagher et al., 1998). All of the samples quoted in this and our previous study (Redfield et al., 2004) show ages, length histograms, and modeled ages indicating that cooling was slow, rather than rapid. Thus, we do not consider a fixed closure temperature to be valid for our AFT ages. Rather, we assume the ages reflect residence within a temperature zone that is a subset of the PAZ.

Second, many workers have demonstrated the sensitivity of AFT ages to changes in elevation, particularly where rapid exhumation enabled the preservation of a fossil PAZ (e.g. Fitzgerald and Gleadow, 1988). Potential pitfalls to a structurally-focussed AFT study include slow cooling within a PAZ, exposure to a lateral thermal gradient, differential sedimentary cover, or various combinations of these, that in certain cases could cause widely separated rocks of similar elevations within a homogeneous structural block to record very different AFT ages. We designed our sampling transect to minimize these problems.

5. Data and interpretation

We collected 29 samples along two transects perpendicular to the principle structural grain of the MTFC. The transects cross-cut three known fault and one topographically expressed lineament: the Verran and Hitra–Snåsa faults of the MTFC, the Høybakken detachment (Seranne, 1992), and the Bæverdalen lineament (Figs. 2 and 3). The Bæverdalen lineament runs south from Orkanger and Trondheimsfjord and, unlike the known faults of the MTFC, has been the subject of very little study.

All samples were collected within 100 m of sea level and away from zones of brittle and semi-brittle fault rocks where fluid circulation might have thermally affected fission track length and age data. Sample spacing was on the order of 5 to 10 km, and several samples were collected within each suspected structural block. Potential structures were identified by Landsat imagery, and sample locations were controlled with 1:50,000 scale topographic maps, and GPS/GIS technology. Laboratory work was completed at the Vrije University in Amsterdam, The Netherlands (see Table 1 caption for analytical details).

Along the southern transect, where age juxtaposition is greatest, the dataset can be divided into populations that fall into four spatially distinct groups (Figs. 2 and 3). Although the MTFC comprises complicated zones of fault lenses of widely varying scales, the relatively close spacing between AFT samples permits the definition of several structural domains. The southern inland domain (A) is consistent with the MTFC shoulder, or footwall block (samples S1–S2). A large southeastern fault block (B) between the MTFC and the Bæverdalen lineament has a Jurassic mean AFT age well defined by six tightly spaced samples (S4–S9). A narrow northwestern fault block (C) between the Verran and Hitra–Snåsa strands of the MTFC (S10, S11, S16) shows a mean Permian AFT age. This block may be tilted, or may represent several fault lenses. A northwestern domain (D), interpreted as the hanging-wall block, shows a Jurassic mean AFT age (S12–S15).

Along the northern transect, smaller but still statistically significant age juxtapositions are also observed across the MTFC strands (for example, RT8–RT11 and RT13–RT14). Track length histograms from all four groups are relatively broad, indicating prolonged residence time at apatite PAZ temperatures. However, the histogram shapes vary between innermost and outermost blocks (Fig. 3). Cooling paths estimated from best-fitting models also vary in shape between blocks: for example, in the southern transect, the two Group A samples show a convex path whose nick points lie within conventional PAZ temperatures, while paths from the other three groups tend to be concave.

Although it is not possible to unequivocally assign an absolute closure temperature to the AFT data, it is clear the ages were "set" at a temperature somewhere between ~60 and ~110 °C. Modeling of the track length data using the model of Laslett et al. (1987) with software by Ketcham et al. (2000) and various initial track length parameters suggests the AFT ages reflect temperatures on the order of ~80 to ~90 °C. Assuming a paleogeothermal gradient of 25 °C/km and a mean Paleo-Average Annual Surface Temperature (PAAST)

Table 1
Data and analytical procedures for ages presented in this paper

Name	Elevation (m)	Zone 32 North								1σ			P(X)	1σ			No. of tracks	Etch (s)	Block
		UTM East	UTM North	Latitude	Longitude	Grains	Ns	Ni	Nd	Age (pooled)	Age error	Chi^2		Length	Length error	Length S.D.			
S1	10	477610	6952090	62.7	8.56	20	224	392	13891	93.14	9.37	12.15	87.91	11.85	0.26	2.18	71	30	A
S2	10	474040	6971910	62.88	8.49	20	1278	1866	13891	111.94	6.79	28.63	7.20	12.69	0.18	1.82	102	30	A
S4	5	477619	6988271	63.02	8.56	20	202	355	13891	158.95	13.07	15.02	72.13	13.11	0.15	1.50	101	30	B
S5	10	466740	6994980	63.08	8.34	20	1188	1172	13891	164.99	10.51	30.05	5.12	13.47	0.13	1.38	101	30	B
S6	20	470950	7001220	63.14	8.42	20	1155	1286	13891	146.40	9.26	28.09	8.17	13.07	0.18	1.86	101	30	B
S7	5	471640	7004270	63.17	8.44	20	1922	1895	13891	165.09	9.64	27.91	8.52	12.89	0.14	1.42	103	30	B
S8	5	470200	7014120	63.25	8.41	20	1010	1007	13891	163.27	10.76	29.46	5.91	12.88	0.17	1.17	100	30	B
S9	5	463950	7013130	63.25	8.28	20	305	303	13891	163.86	15.49	14.05	78.08	13.21	0.15	1.49	99	30	B
S10	5	456280	7018330	63.29	8.13	20	1317	796	13891	267.17	17.67	21.58	30.57	12.79	0.15	1.56	101	30	C
S11	10	455000	7019500	63.3	8.1	21	2648	1423	13891	299.72	17.58	21.96	34.27	12.84	0.18	1.52	74	20	C
S12	5	454180	7022730	63.33	8.09	21	1424	1061	13891	217.56	13.77	17.01	65.23	13.00	0.14	1.43	103	20	D
S13	20	457610	7032350	63.42	8.15	18	1777	1396	13891	206.52	12.46	27.40	5.25	13.44	0.18	1.10	35	20	D
S14	5	451480	7037050	63.46	8.03	20	2148	1673	13891	208.28	12.19	17.76	53.85	13.40	0.13	1.37	100	20	D
S15	5	448710	7042540	63.51	7.97	13	2382	1678	13891	229.89	13.36	15.21	23.02	12.74	0.10	1.43	200	20	D
S16	5	453680	7020360	63.31	8.08	20	656	378	13891	279.95	22.62	21.35	31.78	12.80	0.15	1.57	100	20	C
RT01	5	623910	7191810	64.83	11.61	20	360	313	13230	177.67	16.08	11.96	91.74	12.82	0.18	1.87	109	30	D
RT02	20	570230	7130990	64.3	10.45	20	2252	1822	13230	190.74	10.81	23.87	20.12	13.01	0.11	1.43	156	30	D
RT03	10	569200	7126390	64.26	10.43	19	1530	1355	13230	174.47	10.49	11.50	88.79	13.36	0.10	1.05	101	30	D
RT04	35	567910	7120420	64.2	10.4	20	957	772	13230	191.29	12.92	18.94	46.07	13.18	0.15	1.55	100	30	D
RT05	10	560110	7092390	63.95	10.23	15	1374	1215	13230	175.17	10.96	14.08	44.38	13.29	0.14	1.39	100	30	D
RT06	20	540200	7071030	63.76	9.82	15	481	465	13230	160.01	12.85	14.84	38.92	12.16	0.19	2.07	118	30	D
RT07	5	525800	7057490	63.64	9.52	17	932	1023	13230	141.14	9.22	28.29	2.92	13.09	0.19	1.96	100	30	D
RT08	5	534190	7056750	63.64	9.69	21	360	399	13230	139.79	12.11	12.68	89.07	14.12	0.15	1.26	72	30	C
RT09	10	526920	7051020	63.59	9.54	22	287	310	13230	143.76	13.69	12.99	90.90	13.54	0.20	1.77	75	30	C
RT10	10	536580	7054050	63.61	9.74	22	1568	1719	13230	141.66	8.48	35.14	2.73	13.50	0.14	1.62	125	30	C
RT11	20	537500	7051110	63.59	9.76	21	465	548	13230	131.88	10.50	11.63	92.82	13.51	0.16	1.64	101	30	C
RT13	15	540390	7044180	63.52	9.81	19	514	447	13230	178.08	14.40	6.95	99.05	13.61	0.21	1.87	79	30	B
RT14	30	544070	7038510	63.47	9.88	24	957	772	13230	201.95	14.86	11.20	98.11	12.86	0.22	1.89	70	30	B
RT15	20	547670	7030490	63.4	9.95	23	1374	1215	13230	142.81	10.30	23.20	39.05	11.53	0.26	2.24	72	30	A
S transect									R transect										
Glass	CN5		Zeta			367.93			Glass	CN5				367.93					
rho d	896193.5484		Zeta S.D.			17.6			rho d	853546.3				17.6					
Nd	13891								Nd	13230									

All AFT data were measured at the Vrije Universiteit laboratory in Amsterdam. Samples were etched in 7% HNO_3 at 20 °C with the variable etching procedure described by Hendriks (2003). Etch times (s) are similar, indicative of similar apatite chemistry.

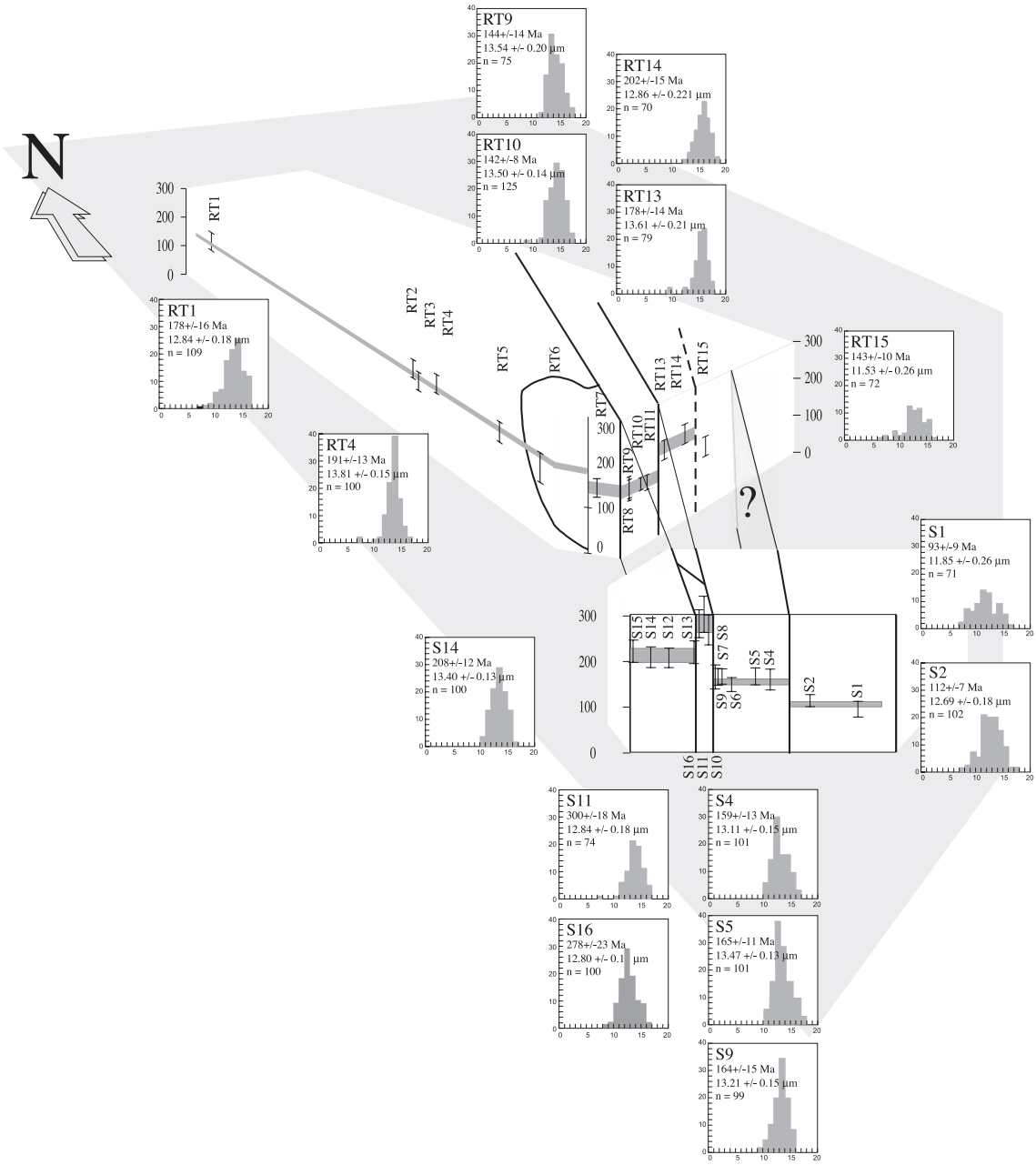


Fig. 3. Block diagram showing AFT data with respect to known and inferred structures and structural movements from the MTFC and the Fosen Peninsula in three-dimensional space. The age domains are shown schematically. Age and length data shown in histogram boxes are given at 1σ statistical confidence; however, age error bars on the block diagram are plotted at 2σ. The diagram illustrates the role played by the MTFC in separating southern and middle Norway. Post AFT closure movement across the Høybakken Detachment is suggested by age difference between R5 and R6 but is not resolvable at the 2σ confidence level.

of 10 °C, the AFT ages indicate residence at approximately 3 km, midway within a Partial Annealing Zone some 2–4 km deep. Following the date of AFT age retention, an estimated 3 km (plus or minus some 1 km) must have been stripped from above each sample site.

6. Discussion

We interpret the MTFC AFT data to reflect net vertical offset rather than differential sedimentary burial and subsequent erosion for the following reasons. (1) Neighboring sample ages may be grouped into statistically discrete blocks bounded by known structures or topographically impressive fracture lineaments. (2) Sample spacing was sufficiently close (commonly less than 10 km) that the former existence of large horizontal thermal gradients between blocks is geologically improbable. (3) The sample collection was designed to eliminate the AFT elevation function, and similar etch behavior between samples suggests the bulk chemistry of apatite varied insignificantly (see Table 1). Differences in AFT age or track shortening therefore do not reflect elevation or chemical differences. The data from the northern transect (RT series; Table 1) and the data reported by Redfield et al. (2004) thus tend to confirm the picture of the MTFC as a complicated structural zone. We thus reject an interpretation requiring rapidly changing horizontal gradients or extremely variable, now-vanished sedimentary cover sufficient to partially reset the AFT system in favor of one invoking net vertical structural offsets characterized by down-to-the-west relative movement between AFT-defined blocks (see Redfield et al., 2004).

Fig. 2 illustrates the analytical results of Table 1 within the structural framework of the MTFC. These data require large net components of vertical separation between the southern, inland Block A (Fig. 2) and Block D occurring some time after ~80 to ~100 Ma (Redfield et al., 2004). Examples include sample S16 (AFT age 280±23 at 1σ), from Edøy, located between the Verran and Hitra–Snåsa strands of the MTFC (Domain C), and sample S2 (AFT age 93±9 Ma) from near Sundalsøra (Domain A). Although the observed mean track lengths are very similar, the shapes of the track length histograms—reflecting the differences in distribution of track lengths, and thus the thermal history—between S2 and S16 vary significantly. These length differences translate into very different model cooling histories. For example, a similarly constrained Laslett et al. (1987) best-fit thermal history suggests S16 cooled to apatite PAZ temperatures at ~350 Ma, and remained within the PAZ until ~80 Ma. By comparison, the Laslett model for S2 suggests cooling began circa 150 Ma and exhumation from the PAZ did not occur until circa 40 Ma, implying structural uplift relative to the outboard samples and a corresponding increase in erosion and offshore sedimentation at that time (Fig. 4).

It is important to note that in our view these models do not represent the absolute cooling paths followed by each sample. Rather, we cite the models to show that, using nearly identical initial constraints, very different pathways are predicted across very short horizontal distances. Taken together, the models and AFT data produce a picture of structural disruption of the rock column. For example, Figs. 2 and 3 outline four blocks, A–D, separated by the Verran and Hitra–Snåsa faults and the Bæverdalen lineament. Within each block, ages are statistically similar at the 2σ confidence level (Table 1). The age juxtapositions across the named structures are also discrete. Track length populations within each block are similar as well, and discrete between the innermost Block A and its outboard neighbors B, C, and D (Table 1). Because sample S3 was uncountable, the offset between Blocks A and B is defined by samples S2 and S4. The Bæverdalen lineament lies between these samples, but fieldwork to the present has not revealed an exposed fault core; thus the fault(s) responsible for the AFT offset of Blocks A and B may also lie in neighboring lineaments.

Net components of vertical offset across the MTFC have previously been postulated (e.g. Grønlie and Torsvik, 1989; Grønlie and Roberts, 1989, 1990; Grønlie et al., 1991, 1994) but quantified only vaguely in magnitude and time. Here we show vertical offset across the vicinity of the Bæverdalen lineament must have occurred since ~100–110 Ma. Although offset cannot be constrained to be Tertiary on the basis of the AFT data alone, the offshore sedimentary record requires increased denudation of southern Norway during the Late Paleocene, the Eocene–Oligocene transition, the late Mid-Miocene, and the Plio-Pleistocene (e.g. Faleide et al., 2002) and the onshore

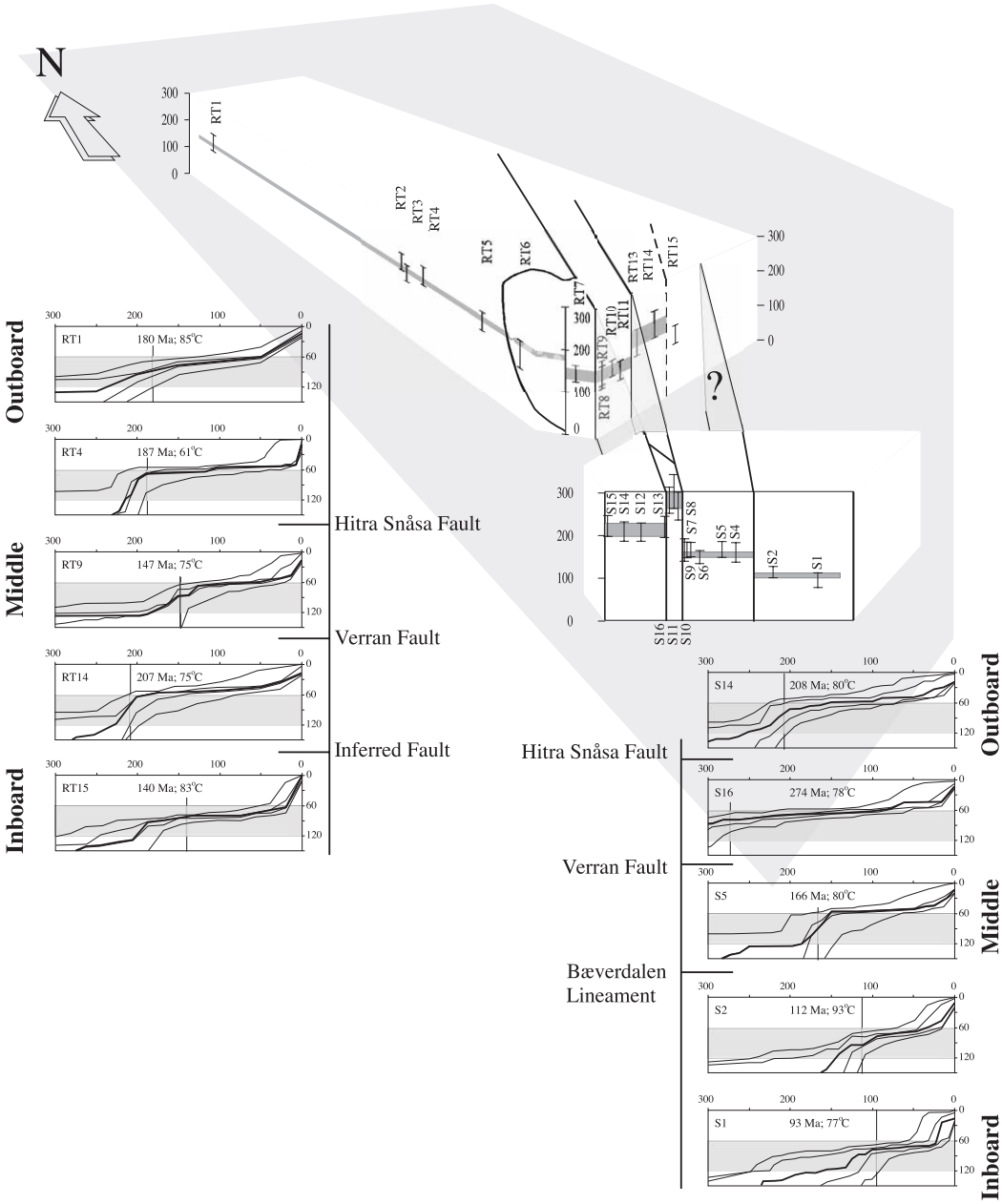


Fig. 4. Block diagram showing AFT model ages and model cooling paths with respect to known and inferred structures. The models incorporate the annealing equations of Laslett et al. (1987) using a Durango initial track length of 16.3 μm using the AFTsolve software of Ketcham et al. (2000). All models were subjected to minimal constraints. AFT modelling commonly creates "cooling artifacts," particularly when the path seeks to achieve surface temperatures as "present-day" is approached. However, the onset of cooling is less equivocal. These plots suggest cooling progressed from NW to SE, dislocation occurring across sharp structural boundaries.

geomorphic record holds tantalizing hints of Tertiary uplift (e.g. Lidmar-Bergstrom et al., 2000). Although AFT models are commonly subject to a late-cooling artifact and thus cannot be regarded as conclusive evidence, the influx of sediment into the offshore basins at these times is consistent with the mid-Tertiary

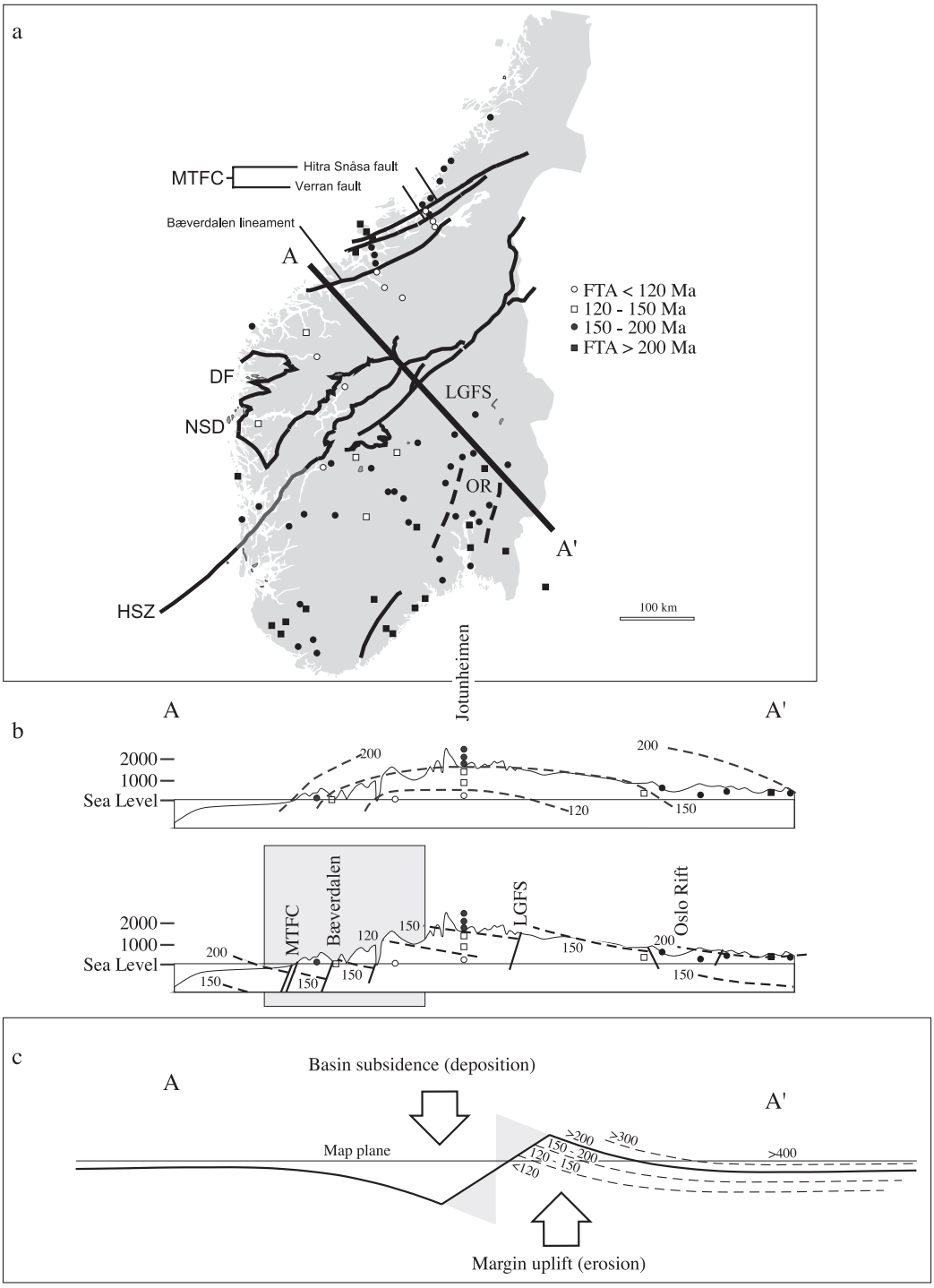
exhumation suggested by models S1, S2, and RT15 (Fig. 4). The magnitude of that exhumation may have been on the order of 2 km in Block A, and strongly suggests inboard rock-column uplift of Block A relative to the older outboard blocks. Although complicated models involving isotherms perturbed either by differential sedimentary cover or radical topography cannot be eliminated on the basis of the AFT data alone, they are geologically unreasonable within the confines of the MTFC. No onshore sedimentary cover is preserved that might point towards extensive Mesozoic burial sufficiently thick to partially anneal apatite fission tracks, and the planar, uplifted Paleic surfaces of southern Norway argue against a highly variable Mesozoic topography capable of disrupting cooling without recourse to structure.

Pascal and Gabrielsen (2001) suggested the MTFC acted as a mechanically very weak zone with a high potential for having influenced local and regional stress fields from the Paleozoic to today. The AFT data from the Fosen Peninsula are consistent with Jurassic exhumation from the apatite PAZ, followed by a long period of tectonic quiescence. Meanwhile their southern neighbors in Block A experienced kilometer-scale exhumation in the Cretaceous, lending support to the view that the MTFC represents a fundamental tectonic boundary dividing south and mid-Norway.

On the Fosen Peninsula, the Høybakken Detachment does not appear as a clear AFT-expressed boundary, although there is an indication of an age–distance gradient across it (Fig. 3; Table 1). This is interesting in view of the Devonian to Early Carboniferous unroofing of the region. The Høybakken Detachment and other regional shear zones were activated as major extensional structures that developed during Devonian denudation of the Scandian orogen (e.g. Andersen, 1998; Braathen et al., 2002). Denudation was rapid: within ~10 million years high-grade gneisses of the lower crust hosting bodies of eclogite (e.g. Terry et al., 2000) were juxtaposed with nappe units and sedimentary basins that were never buried below an upper crustal setting (Andersen and Jamtveit, 1990; Andersen, 1998; Braathen et al., in press). Furthermore, the uppermost section of the Devonian basins seems to have received some input from the gneissic domains of the footwall (Eide et al., 2003; Fonneland and Pedersen, 2003). Hence, parts of the footwall surfaced during the orogenic denudation, an event probably recorded by the AFT system of the time. Complementary metamorphic mineral parageneses present within the Devonian basins show that at least parts of the region were buried to greenschist facies conditions (Torsvik et al., 1989; Sturt and Braathen, 2001; Svensen et al., 2001), an episode suggested to be of Latest Devonian–Early Carboniferous age (Torsvik et al., 1986; Bøe et al., 1989; Eide et al., 1999). Consequently, the AFT system likely was partly or fully reset. Renewed unroofing brought the rocks back into an uppermost crustal setting, an event that may relate to regional Permian or Jurassic–Early Cretaceous extension (e.g. Torsvik et al., 1989; Eide et al., 1997; Andersen et al., 1999; Braathen, 1999; Gabrielsen et al., 1999). The AFT system resetting was clearly differentially throughout Fennoscandia: progressively older AFT ages are known in the east, whereas younger ages dominate coastal Norway (Rohrman et al., 1995; Hendriks and Andriessen, 2000, 2003; Hendriks, 2003; Cederbom et al., 2000, 2001a,b; Huigen and Andriessen, 2004; this study). Total resetting of the AFT system must have occurred under the Devonian basins, an event suggested to be of Early Carboniferous age in western Norway (Eide et al., 1999).

The AFT age data (Figs. 2 and 3) clarify the structural complexity within the MTFC: a general pattern of older coastal ages and younger inboard ages is readily discerned. Although the profiles cross only the north-westernmost flank of the southern Norwegian topographic Scandes high, the age pattern is in general harmony with that reported by Rohrman et al. (1995; Fig. 5a). However, Rohrman et al. (1995) described the architecture of the southern Scandes mountains as a dome, using AFT data to contour isochrons (see Fig. 5a,b). Our interpretation differs somewhat from that of Rohrman et al. (1995), as differential subsidence/uplift and the potentially significant post-Late Creteaceous, possibly Tertiary reactivation of the principal structures of Norway must be incorporated into architectural models of the southern Scandes.

Some previous causative models of Scandes uplift have invoked (1) glacial erosion and isostatic uplift (e.g. Dore, 1992; Riis and Fjeldskaar, 1992), (2) migrating phase boundaries (e.g. Riis and Fjeldskaar, 1992), (3) pre-subduction instability (e.g. Sales, 1992), (4) plate reorganization-derived intraplate stress (e.g. Jensen and Schmidt, 1992), (5) some form of mantle


a
MTFC
Hitra Snåsa fault
Verran fault
Bæverdalen lineament
A
DF
NSD
LGFS
OR
A'
HSZ
FTA < 120 Ma
120 - 150 Ma
150 - 200 Ma
FTA > 200 Ma
100 km
Jotunheimen
A
A'
b
2000
1000
Sea Level
200
120
150
MTFC
Bæverdalen
LGFS
Oslo Rift
c
Basin subsidence (deposition)
A
A'
Map plane
>200
>300
150 - 200
120 - 150
<120
>400
Margin uplift (erosion)

convection (e.g. Bannister et al., 1991), or (6) mantle diapirism (e.g. Rohrman et al., 1995). Many of these models consider the northern and southern Scandes uplift as "domal." In Fig. 5b, the difficulty reconciling a simple structural dome with the MTFC AFT data is illustrated. The A–A′ cross-section of Rohrman et al. (1995) (Fig. 5b, top) crosses the MTFC, whose late Mesozoic/potentially Cenozoic net-vertical component reactivation has been demonstrated (Redfield et al., 2004; this paper). Here we suggest the overall morphology of the southern Scandes mountains is less like a dome, and more similar to a flexed, thinned-on-its-margin, not-quite-broken lithospheric plate (see Gunn, 1943; Turcotte and Schubert, 1982) with a reactivated, uplifted core neighboring a down-faulted, retreating scarp. Fig. 5b and c illustrates this model. While in his original model, Gunn (1943) considered a compressional margin characterized by a fractured lithospheric plate, we—as did Stern and ten Brink (1989)—consider a margin once characterized by active extension. Unlike the flexural model proposed by Stern and ten Brink (1989) for the Transantarctic Mountains, no direct evidence exists that the Baltica margin should be considered broken, and estimates of the flexural rigidity T(e) of Fennoscandia range widely. Different values of T(e) have been suggested for Fennoscandia and the mid-Norwegian shelf (e.g. Reemst and Cloetingh, 2000; Poudjoum Djomani et al., 1999; Kusznir et al., 1991) and thus wide lateral variations in flexural rigidity probably exist. Nevertheless, whichever value (or values) are chosen, a flexural model clearly may be applied to the onshore–offshore mid-Norwegian margin (e.g. van Balen et al., 1998; Stuevold and Eldholm, 1996). In such a model, the MTFC might be considered to be (and have been) mechanically very weak (e.g. Pascal and Gabrielsen, 2001). Although it remains technically "unbroken," we suggest lithospheric extension and documented, deep-seated detachment faulting (e.g. Osmundsen et al., 2003) in the most compliant sectors of the mid-Norwegian margin have rendered the margin "effectively broken" and readily amenable to flexurally and structurally controlled rock column uplift and subsidence (Fig. 5b,c).

Following cessation of active extension in the Viking and Møre basins during the Cretaceous (e.g. Christiansson et al., 2000), onshore erosion and offshore deposition continued throughout the Pleistocene. The consequent mass redistribution may well have induced incremental creep and/or episodic normal reactivation along the strands of the MTFC and other margin-parallel onshore faults. Laterally distributed lithospheric density contrasts inherited from pre-Mesozoic times may have amplified erosionally induced tectonic instability as the locus of faulting stepped landwards and the original escarpment retreated, perhaps under an inherited structural control (see discussion in Gabrielsen et al., in press).

The model, schematically shown in Fig. 5b and c, incorporates the principle known structures of southern Norway, and predicts Cretaceous (and potentially Cenozoic) histories for many of these faults. It is also consistent with the rift margin postulate of Holtedahl (1953), whose recognition of the fundamental asymmetry of the Scandes mountains came well before offshore seismic exploration and well data revealed the structure of the Norwegian margin. It differs from flexural models presented by previous authors such as Stuevold and Eldholm (1996) and van Balen et al. (1998) principally in the conceptual degree to which a laterally variable T(e) and processes of margin modification (erosion, deposition, and scarp retreat) are conceptually integrated. Stuevold and Eldholm (1996) hypothesized a hot–cold asthenosphere boundary beneath the Caledonide–Baltic Shield transition combined with pre-Tertiary relief at the base of the lithosphere might induce small-scale convection and preferential volume expansion beneath the observed elongate uplift. Noting that flexural compensation for erosion at passive margins plays an important role in

Fig. 5. Map (a) and cross-sections (b) after Rohrman et al. (1995) showing AFT data (Rohrman et al., 1995; Redfield et al., 2004; this paper) and two structural interpretations. Map shows AFT data grouped by intervals presented in Rohrman et al. (1995). The top cross-section A–A′ (b) illustrates the interpretation of Rohrman et al. (1995). The lower A–A′ cross-section illustrates our interpretation incorporating the new AFT data from the MTFC. (The shaded square approximates the portion of the cross-section covered in Fig. 2). Cartoon (c) illustrates a conceptual model of a continuous thin lithospheric plate, modified from Gunn (1943). In applying such a model to the Scandes, we emphasize that flexural rigidity of Fennoscandia and its extended margin cannot be considered constant, nor can the lithospheric plate be considered completely broken. A dynamic balance is maintained between offshore deposition, onshore erosion, structural architecture, and consequent episodic isostatic adjustment.

rift flank uplift, van Balen et al. (1998) suggested major fault zones exerted a first-order control on the distribution of Norwegian margin uplift and subsidence, but placed more emphasis on "stress-induced amplification of the mantle-caused uplift." Because seismic S-wave tomographic studies indicate no significant regional-scale mantle perturbations below Scandinavia (see Becker and Boschi, 2002), we consider erosion to be the most likely driving mechanism. In such a model, the magnitude of uplift along the western Scandinavian margin would be largely controlled by the interplay between lateral variations in lithospheric flexural rigidity, erosional loading/unloading, offshore structuring, and fossil buoyancy forces seeking a new equilibrium.

7. Conclusions

This study has presented isotopic evidence for kilometer-scale net components of vertical offset and differential upheaval within and across the MTFC. Four domains around and within and around the MTFC that reveal significantly different unroofing histories may be identified by the AFT data. Domains characterized by wholly Permo-Carboniferous and wholly Late Cretaceous sea-level AFT ages exist within very close proximity, consistent with a long and complicated structural history. Net vertical offset on the kilometer scale across the Bæverdalen lineament or neighboring lineaments must have occurred since ~100 Ma, indicative of rock-column uplift of the innermost blocks relative to the outermost blocks. Forward modeling of the AFT age and track length data suggest the latest cooling event (e.g. exhumation from the apatite PAZ) may have partly occurred during Tertiary times in the inland areas (Domain A), a conclusion consistent with offshore Neogene sedimentation records. These data and conclusions require fault reactivation and rock column relative uplift at the innermost edge of the margin. The AFT data from the Fosen Peninsula are consistent with Jurassic exhumation from the apatite PAZ, followed by a long period of tectonic quiescence. Collectively, the two transects across the MTFC may be explained using a flexural model similar to those previously proposed, but modified to incorporate dynamically balanced forces, reactivated structures, and lateral variations in flexural rigidity between cratonic Fennoscandia and the thinned margin of the Norwegian Sea.

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