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3D lithospheric-scale structural model of the Norwegian continental margin (the Vøring and Møre basins)

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Helmholtz Centre Potsdam,
GFZ German Research Centre for Geosciences
Section 4.4: Basin Analysis

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Overview

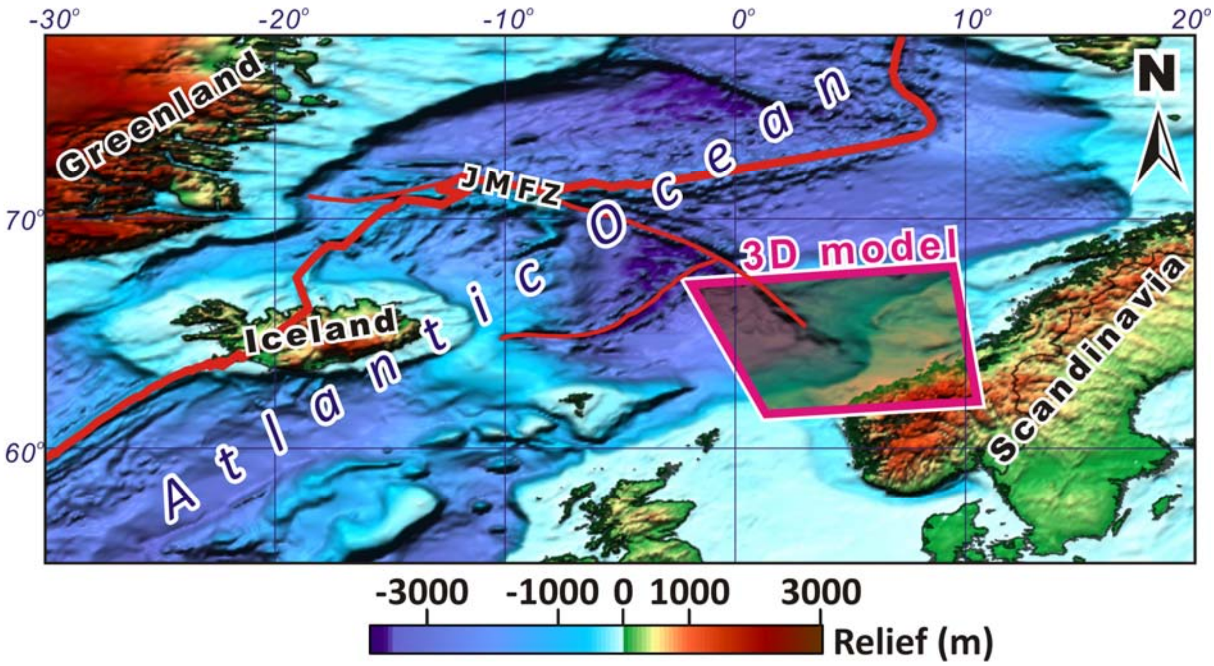

Figure 1. 3D lithospheric-scale structural model of the Norwegian continental margin (the Vøring and Møre basins) within the Northern Atlantic (plate boundaries and position of the Jan Mayen Fracture Zone (JMFZ) are from Müller et al., 1997; the bathymetry is taken from IOC, IHO, and BODC, 2003). Magenta rectangle corresponds to the 3D lithospheric-scale structural model.

The Norwegian continental margin is the passive margin which is situated within the eastern part of the North Atalntic region (Fig. 1). In our particular case, the study area covers the Vøring and Møre basins of this continental margin. Tectonically, the Vøring and Møre basins are located between two domains with different tectonic settings, the exposed Fennoscandian Caledonides in the south-east within the continent and the Paleogene oceanic crust of the northern Atlantic Ocean in the north-west (Fig. 1, 2). This part of the Norwegian continental margin is subdivided into several tectonic sub-units (Fig. 2). The major sub-units are the Trøndelag Platform with a thick pre-Cretaceous succession, the Cretaceous Vøring and Møre basins, which are separated from

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the oceanic crustal domain by the Vøring and Møre marginal highs (Blystad et al., 1995; Fig. 2). The present-day structure of the study area is the result of several tectonic events which occurred within this segment of the continental margin after the Caledonian Orogeny (Blystad et al. 1995). One of the major tectonic events is the late Palaeocene-early Eocene continental breakup the North Atlantic Ocean. The pre- and post-breakup sedimentary strata of the margin are very thick reaching more than 17 km within the Vøring and Møre basins.

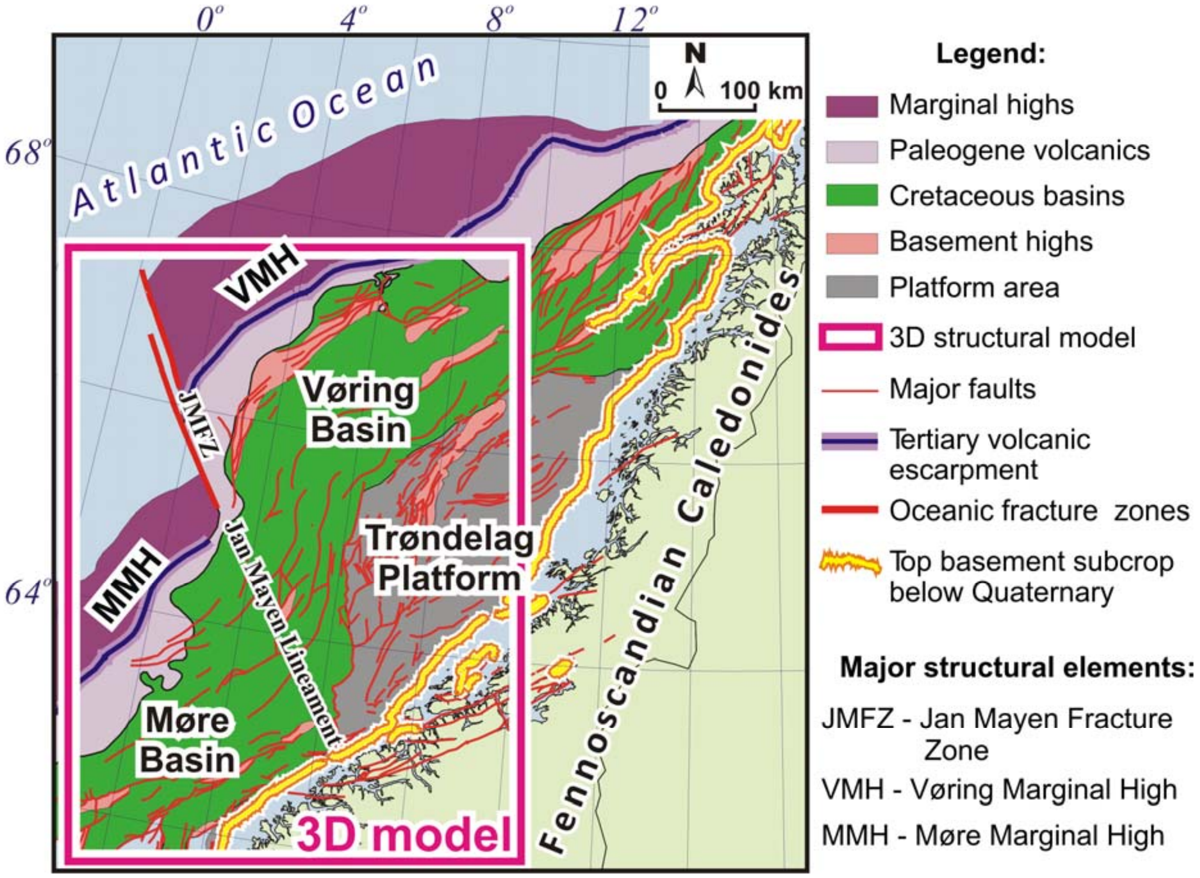

Figure 2. Structural setting at the Norwegian continental margin (after Blystadt et al., 1995) with the location of the 3D structural model (see magenta rectangle). Abbreviation: JMFZ - the Jan Mayen Fracture Zone.

The sedimentary succession of the Norwegian continental margin (the Vøring and Møre basins) is well studied as a result of extensive hydrocarbon

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exploration within the study area (e.g. Blystad et al., 1995; Brekke, 2000; Skogseid et al., 2000). The deep crustal structure of the margin and adjacent areas is know from several deep refraction seismic lines (Mjelde et al., 1997, 2001, 2002, 2003, 2005, 2009; Raum, 2000; Raum et al., 2002, 2006). Based on these results, a 3D structural model of the study area has been constructed, integrating the present-day knowledge about the structure of the Norwegian continental margin at the lithospheric scale. The initial 3D structural model of the Norwegian continental margin (Scheck-Wenderoth et al., 2007) has been validated by 3D thermal modelling (Scheck-Wenderoth and Maystrenko, 2008) and 3D gravity modelling (Maystrenko and Scheck-Wenderoth, 2009).

Data sources

The topography (Fig. 3) and the bathymetry (Fig. 4) within the area covered by 3D structural model have been extracted from the GEBCO Digital Atlas (IOC, IHO and BODC, 2003). Thicknesses of sediments at the Norwegian continental margin have been derived from five maps of the major Cretaceous-Cenozoic unconformities in two-way travel time (Brekke, 2000). The area covered by these five maps is outlined by the blue dotted lines in Figure 5. The thicknesses of the layers between these major unconformities were calculated as the difference between the structural time maps. The obtained thickness maps have been depth-converted, using respective interval velocities (Scheck-Wenderoth et al., 2007). The obtained thickness maps (Figs. 7-9, 11-13) were crosschecked with available deep well data (NPD, 2007).

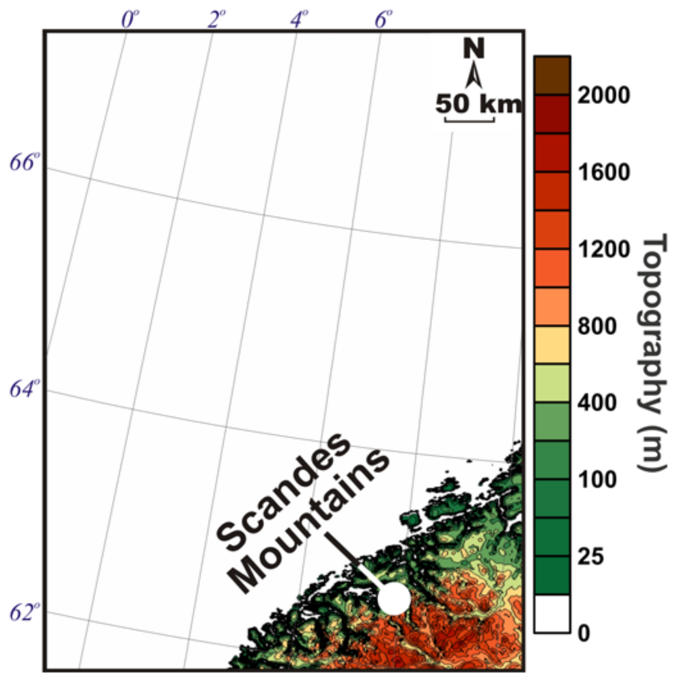

Figure 3. Topography (IOC, IHO, and BODC, 2003) within south-western Norway (Scandes Mountains; data file: *0_Topography.dat*). Black lines in the right lower corner correspond to Norwegian coast line.

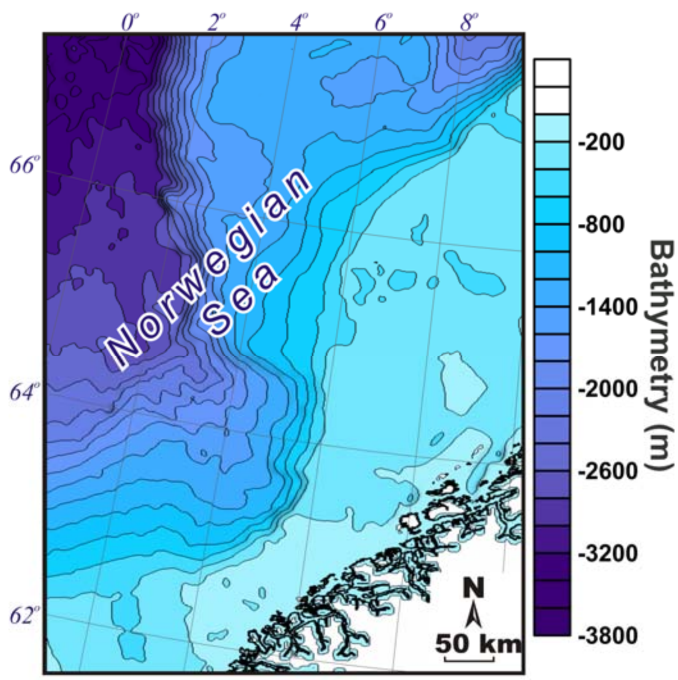

Figure 4. Bathymetry (IOC, IHO, and BODC, 2003) within the area covered by the 3D structural model (layer 1: sea water; data file: *1_Bathymetry.dat*). Black lines in the right lower corner correspond to Norwegian coast line.

The structure of the continental crystalline crust (Figs. 14, 16 and 18) has been derived from published results based on the interpretation of long-offset seismic refraction profiles (orange lines in Fig. 5; Mjelde et al., 1997, 2001, 2002, 2003, 2005, 2009; Raum, 2000;

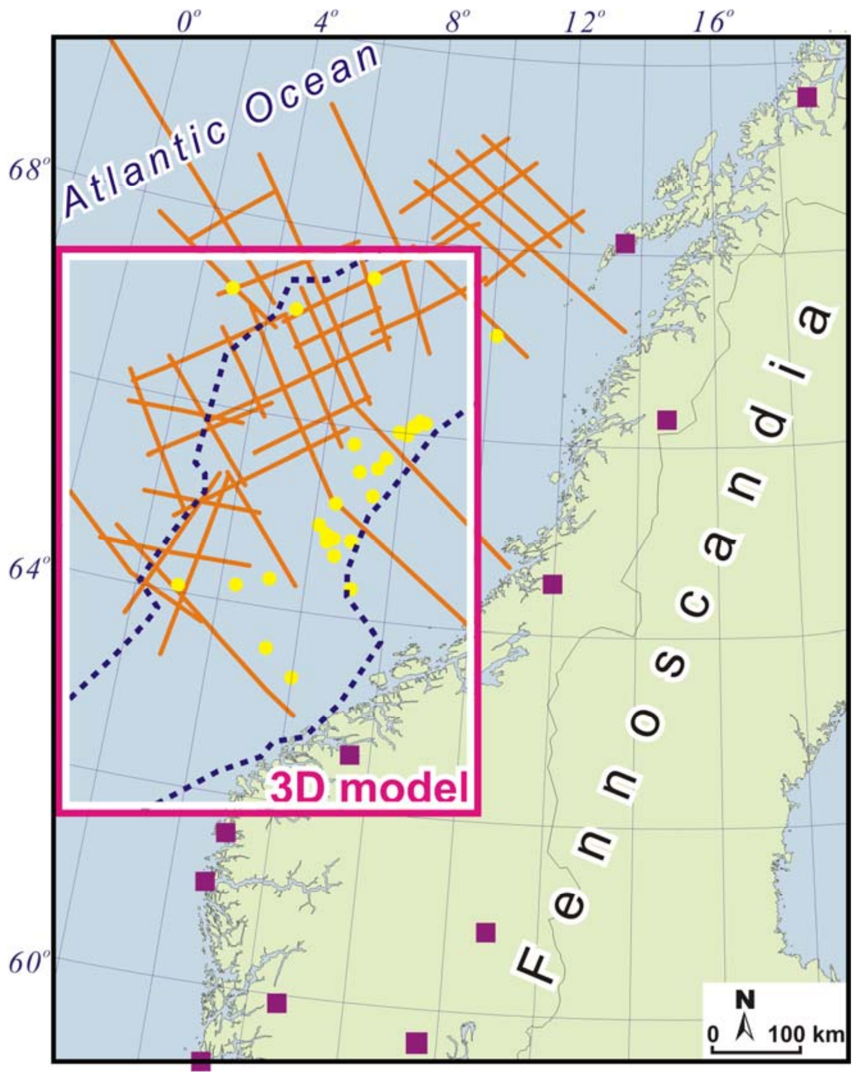

Figure 5. Data coverage of the 3D model area (Scheck-Wenderoth et al., 2007; Maystrenko and Scheck-Wenderoth, 2009). Yellow circles correspond to well data (NPD, 2007); blue dotted lines outline the area covered by published maps of sedimentary interfaces (Brekke, 2000); dark orange lines are deep refraction profiles (Mjelde et al. 1997, 2001, 2002, 2003, 2005, 2009; Raum et al. 2000, 2002, 2006); and lilac squares are depth to Moho from inversion of teleseismic receiver functions (Ottemöller and Midzi, 2003).

Raum et al., 2002, 2006). The Moho topography has also been extracted from this database. The configuration of the high-density zones within the continental crystalline crust (Fig. 16) and the high-density bodies within the lower continental crystalline crust (Fig. 18) below the Vøring and Møre basins were partially obtained from the deep seismic refraction profiles (Mjelde et al., 2009) and partially derived from 3D gravity modelling (Maystrenko and Scheck-Wenderoth, 2009). In addition, data from the inversion of teleseismic receiver functions (Ottemöller and Midzi, 2003; lilac squares in Fig. 5) have been used to define the depth of the Moho below the continent where deep seismic refraction profiles are not available. The final Moho used for the 3D model is shown in Figure 20.

The oceanic crystalline crust beneath the Cenozoic sediments has been subdivided into three layers according to the deep refraction seismic lines (Mjelde et al., 2005; Raum et al., 2006). The upper oceanic layer 2AB (Fig. 10) is interpreted to represent flood basalts and diabase dikes, the middle layer 3A (Fig. 15) is assumed to consist mainly of a mixture of sheeted dykes and gabbroic intrusions and the lowermost oceanic crustal layer 3B (Fig. 17) includes gabbros and ultramafic rocks.

The depth to the base of the lithosphere beneath the oceanic crustal domain has been calculated according to relations between the age of the oceanic lithosphere and Love and Rayleigh wave phase velocity (Zhang and Lay, 1999). The age of the oceanic lithosphere is according to Müller et al. (2008). Beneath the continent, depth to lithosphere-asthenosphere boundary has been derived according to global heat flow studies and seismologic data (Artemieva et al., 2006). However, there are no direct data defining the depth to the base of the lithosphere beneath the continental margin itself (the Vøring and Møre basins).

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In order to fill this gap, Scheck-Wenderoth and Maystrenko (2008) have applied interpolation between the oceanic part and continent. The resulting depth to the lithosphere-asthenosphere boundary is shown in Figure 21. It has to be mentioned that the base of the lithosphere has not been corrected according to new results, obtained using combined 3D thermal and 3D gravity modelling (Maystrenko and Scheck-Wenderoth, 2009)

In order to construct the 3D structural model of the Norwegian continental margin, all mentioned datasets were compiled and gridded separately for each layer. The gridded data were merged into the 3D structural model and, therefore, all obtained thickness maps and structural depth maps are spatially consistent in 3D.

Description of the 3D structural model

The 3D structural model covers the Vøring and Møre basins. In addition, a part of the exposed Fennoscandian Caledonides in the south-east and an oceanic crustal domain are covered by the model. The constructed 3D model (Fig. 6) is 490 km wide and 660 km long with a horizontal grid spacing of 2500 m, and a vertical resolution corresponding to the number of integrated layers. The latest version of the lithospheric-scale 3D structural model includes 14 layers (Figs. 4, 7-19): (1) sea water; (2) upper Neogene (post-middle Miocene) sediments; (3) middle-upper Paleogene-lower Neogene (pre-middle Miocene) sediments; (4) lower Paleogene (Paleocene) sediments; (5) oceanic layer 2AB (basalts); (6) Upper Cretaceous (post-Cenomanian) sediments; (7) Lower Cretaceous (pre-Cenomanian) sediments; (8) pre-Cretaceous sediments; (9) the continental crystalline crust; (10) the oceanic layer 3A; (11) the high-density zones within the continental crystalline crust; (12) the oceanic layer 3B; (13) the high-density

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bodies within the lower continental crystalline crust; (14) the lithospheric mantle. The thicknesses of the layers correspond to apparent thicknesses.

The grid of each layer consists of 196 cells in W-E direction and 265 cells in S-N direction. The grid limits are the following: X_{min} is -222590 and X_{max} is 267410; Y_{min} is 6892200 and Y_{max} is 7552200. The vertical datum of the 3D model refers to the mean sea level. Model coordinates are based on the UTM 33 (Northern Hemisphere) system using the WGS 84 datum.

The data format is ASCII and contains three columns (X, Y and Z), where X and Y are coordinates; Z is thickness of the layer or structural depth (base of the layer). For example:

	X	Y	Z
Thickness:	-222590	6892200	171.354888916
Structural depth:	-222590	6892200	-23572.600051498

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Data files from the 3D structural model of the Norwegian continental margin are in the sequence of the layers from top to bottom of the model:

Thicknesses data (thickness values of 0.1000000014901 or close to 0.1 correspond to zero values, i.e. absence of sediments)

1_thickness_sea_water.dat

2_thickness_post_mid_Miocene.dat

3_thickness_pre_mid_Miocene.dat

4_thickness_Paleocene.dat

5_thickness_oceanic_layer_2AB.dat

6_thickness_post_Cenomanian.dat

7_thickness_pre_Cenomanian.dat

8_thickness_pre_Cretaceous.dat

9_thickness_continental_crystalline_crust.dat

10_thickness_oceanic_layer_3A.dat

11_thickness_high_density_zones.dat

12_thickness_oceanic_layer_3B.dat

13_thickness_high_density_bodies.dat

14_thickness_lithospheric_mantle.dat

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Structural depth data

1_Bathymetry.dat

2_base_post_mid_Miocene.dat

3_base_pre_mid_Miocene.dat

4_base_Paleocene.dat

5_base_oceanic_layer_2AB.dat

6_base_post_Cenomanian.dat

7_base_pre_Cenomanian.dat

8_base_pre_Cretaceous.dat

9_base_continental_crystalline_crust.dat

10_base_oceanic_layer_3A.dat

11_base_high_density_zones.dat

12_base_oceanic_layer_3B.dat

13_base_high_density_bodies_Moho.dat

14_base_lithosphere.dat

In addition, topography can be found in the following file: *0_Topography.dat*.

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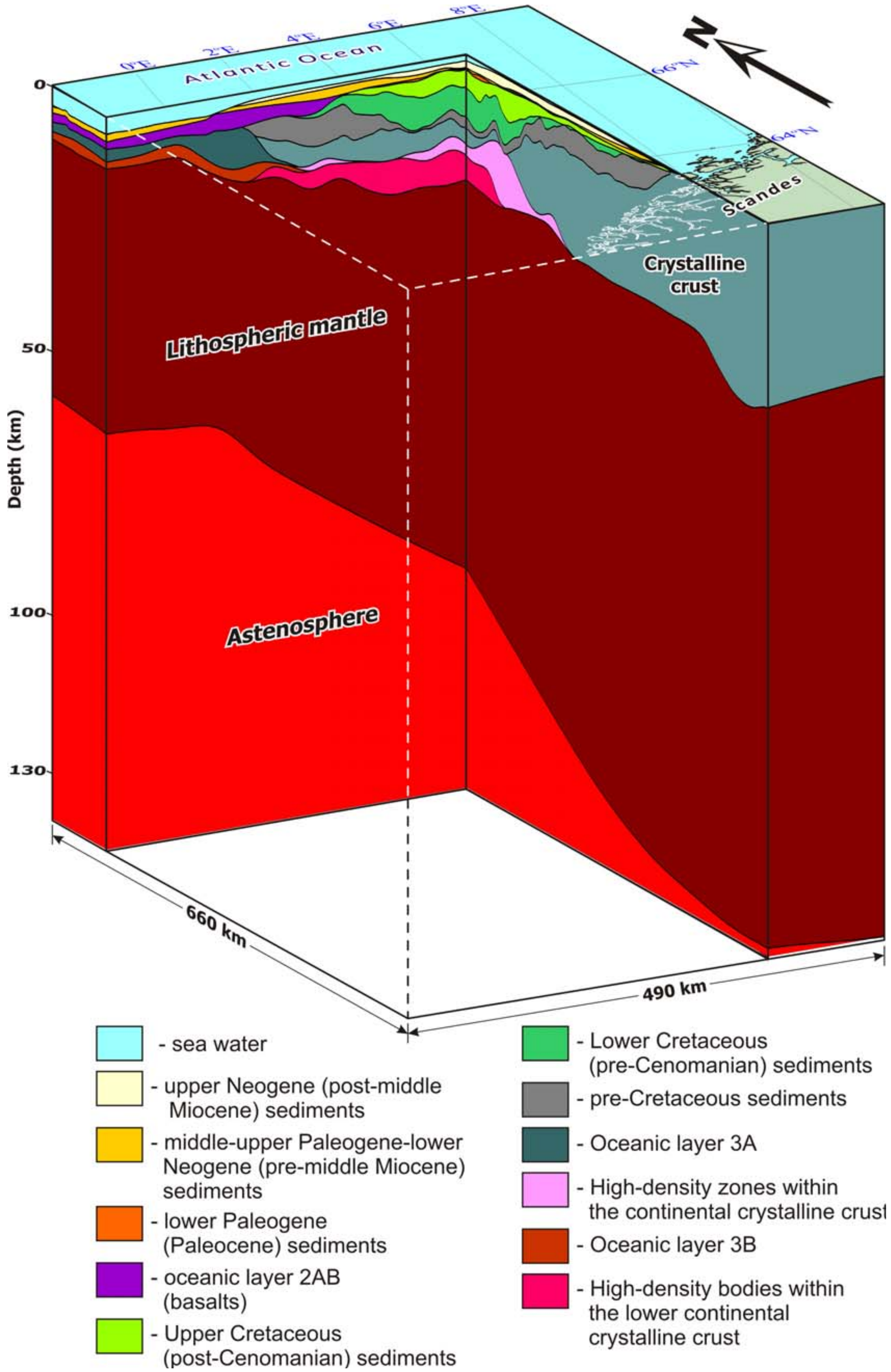

Figure 6. 3D lithosphere-scale model of the Norwegian continental margin (the Vøring and Møre basins) showing the internal geometry of the study area. Vertical exaggeration is 5 times.

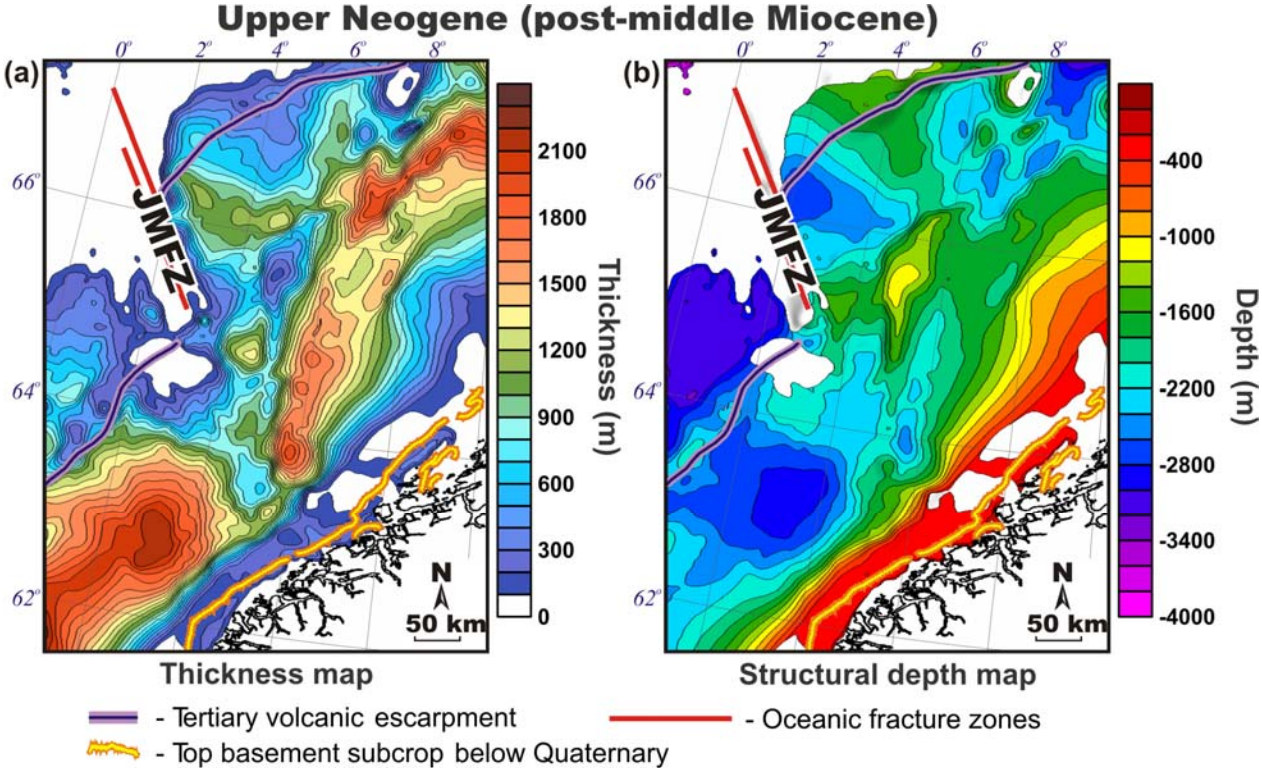

Figure 7. Layer 2 - upper part of the Neogene (post-middle Miocene sediments): (a) thickness map (data file: *2_thickness_post_mid_Miocene.dat*) and (b) structural depth map of the base (data file: *2_base_post_mid_Miocene.dat*). Black lines in the right lower corner correspond to the Norwegian coast line. Abbreviation: JMFZ - Jan Mayen fracture zone.

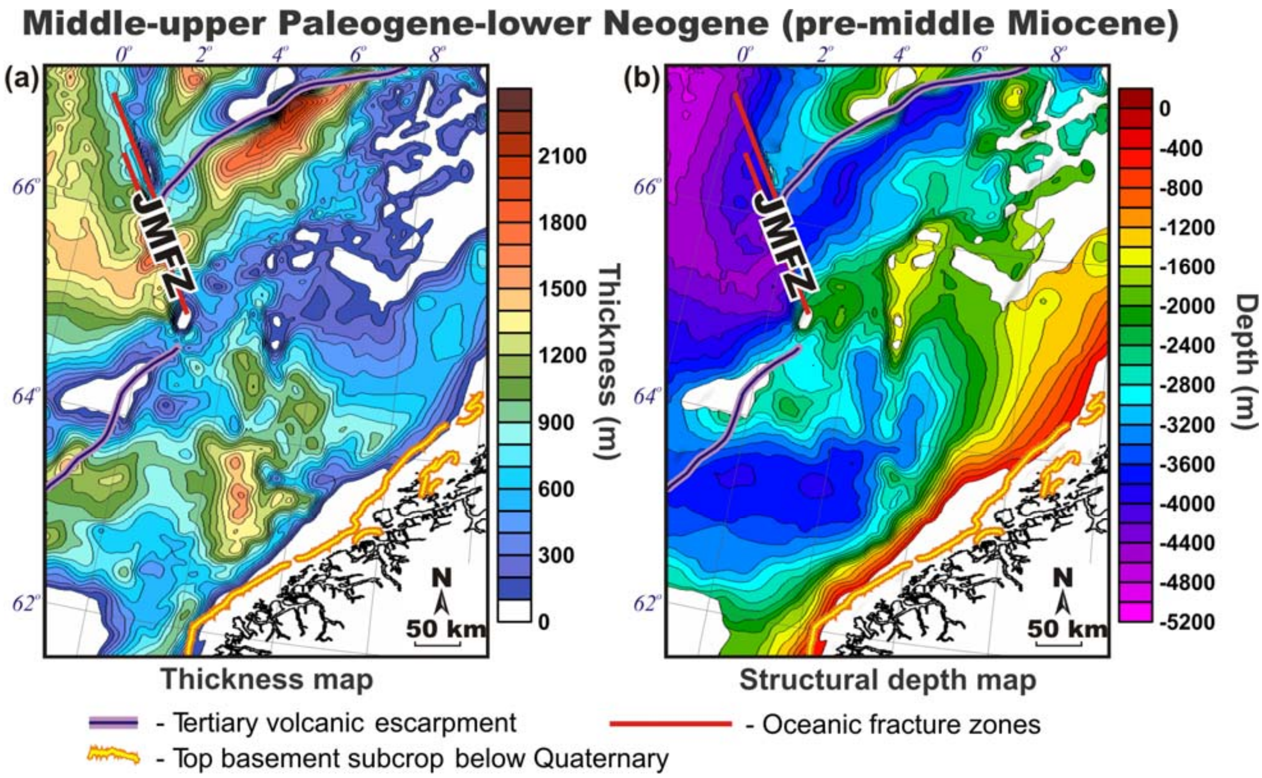

Figure 8. Layer 3 - middle-upper part of the Paleogene-lower part of the Neogene (pre-middle Miocene sediments): (a) thickness map (data file: *3_thickness_pre_mid_Miocene.dat*) and (b) structural depth map of the base (data file: *3_base_pre_mid_Miocene.dat*). Black lines in the right lower corner correspond to the Norwegian coast line. Abbreviation: JMFZ - Jan Mayen fracture zone.

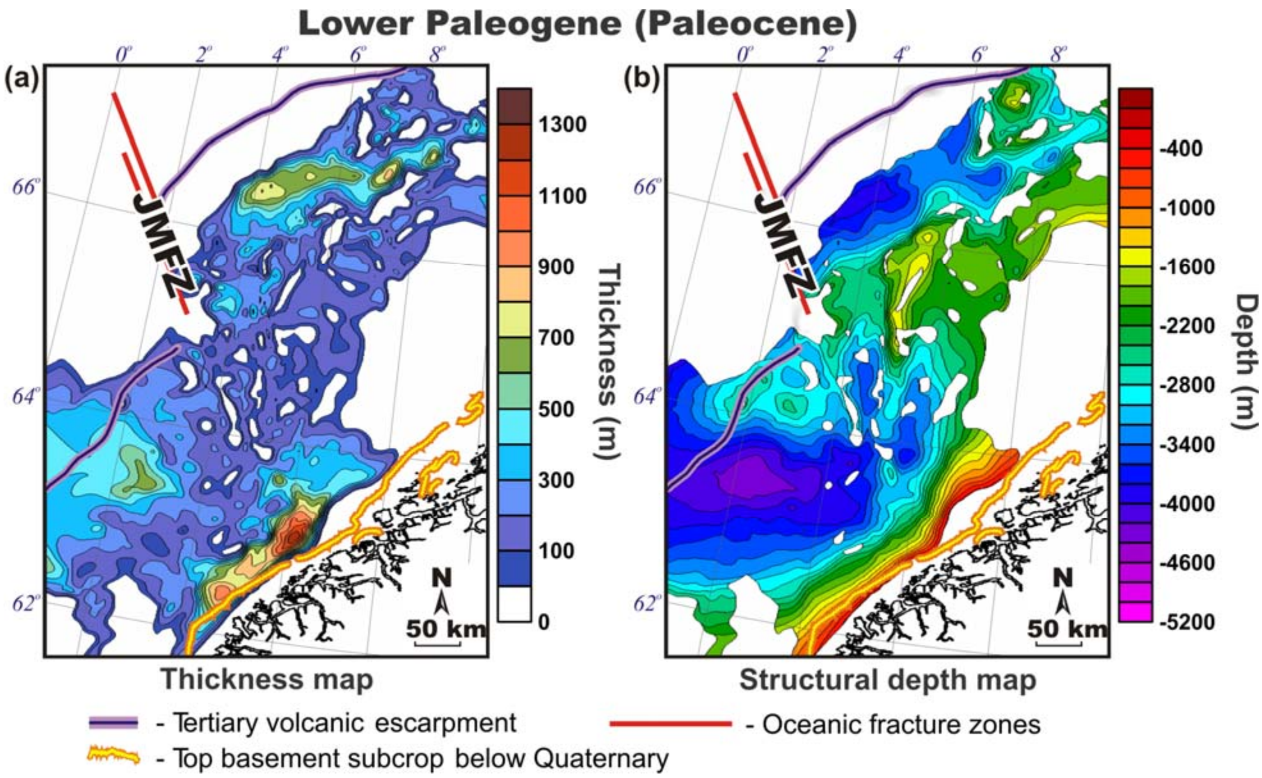

Figure 9. Layer 4 - lower part of the Paleogene (Paleocene sediments): (a) thickness map (data file: *4_thickness_Paleocene.dat*) and (b) structural depth map of the base (data file: *4_base_Paleocene.dat*). Black lines in the right lower corner correspond to the Norwegian coast line. Abbreviation: JMFZ - Jan Mayen fracture zone.

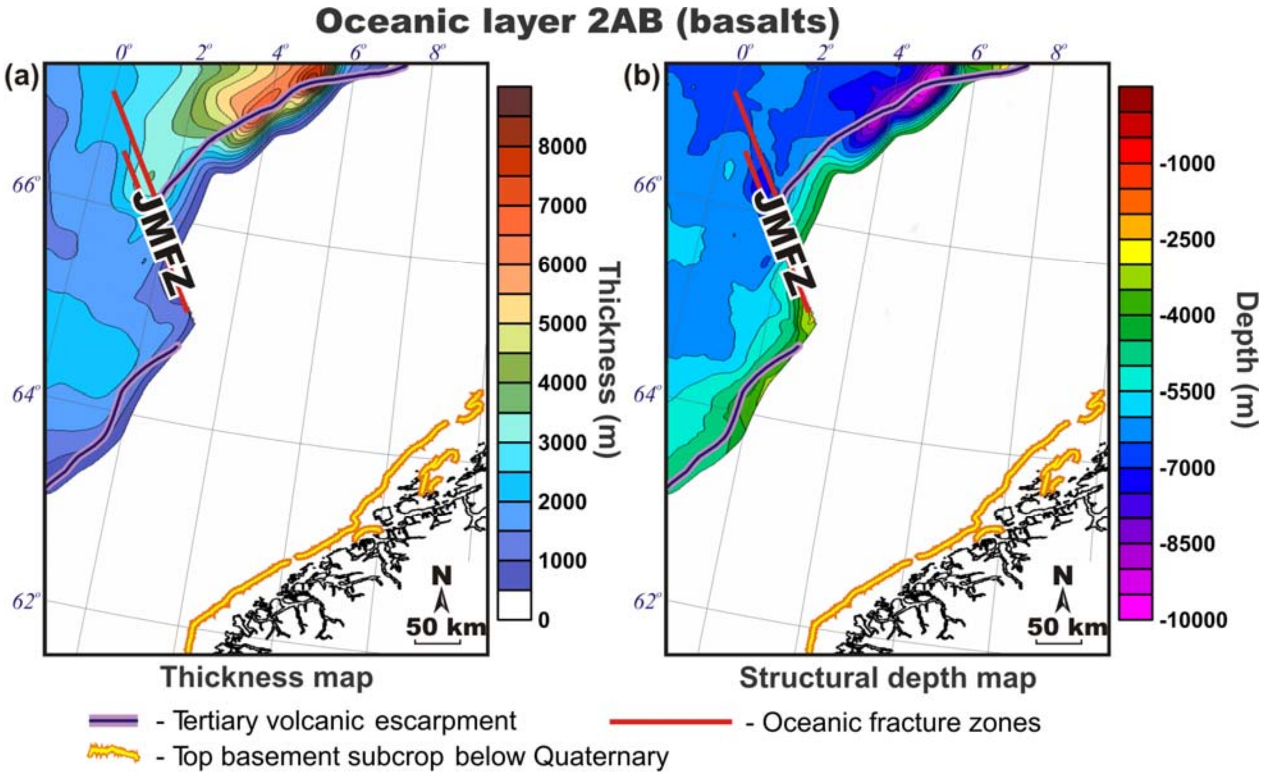

Figure 10. Layer 5 - the oceanic layer 2AB (basalts): (a) thickness map (data file: *5_thickness_oceanic_layer_2AB.dat*) and (b) structural depth map of the base (data file: *5_base_oceanic_layer_2AB.dat*). Black lines in the right lower corner correspond to the Norwegian coast line. Abbreviation: JMFZ - Jan Mayen fracture zone.

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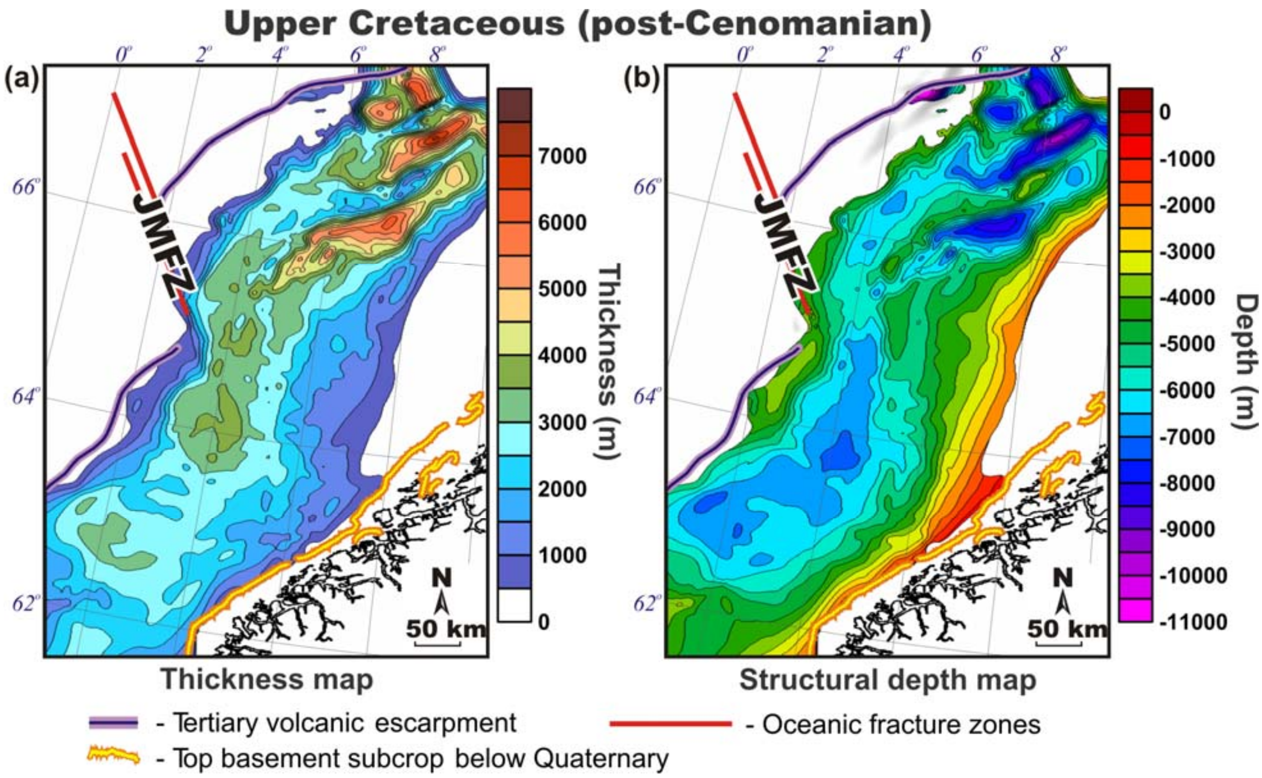

Figure 11. Layer 6 - the Upper Cretaceous (post-Cenomanian sediments): (a) thickness map (data file: *6_thickness_post_Cenomanian.dat*) and (b) structural depth map of the base (data file: *6_base_post_Cenomanian.dat*). Black lines in the right lower corner correspond to the Norwegian coast line. Abbreviation: JMFZ - Jan Mayen fracture zone.

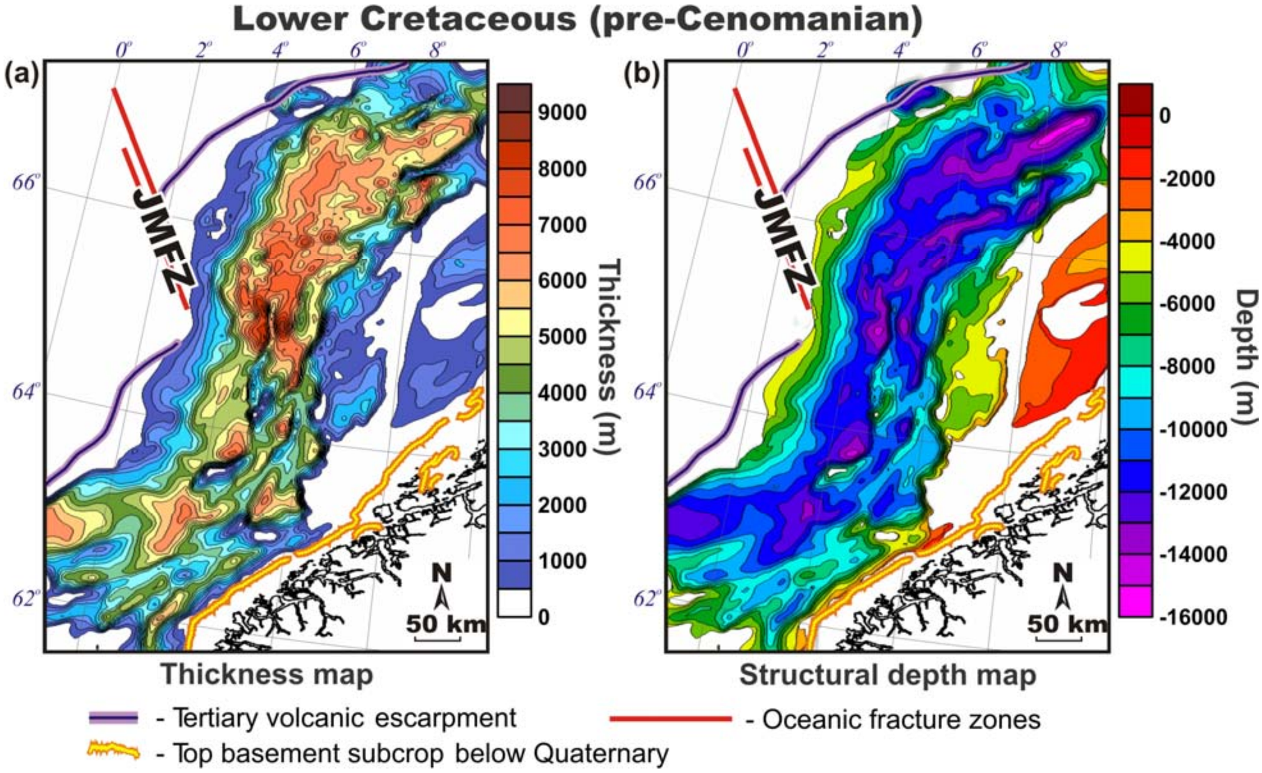

Figure 12. Layer 7 - of the Lower Cretaceous (pre-Cenomanian sediments): (a) thickness map (data file: *7_thickness_pre_Cenomanian.dat*) and (b) structural depth map of the base (data file: *7_base_pre_Cenomanian.dat*). Black lines in the right lower corner correspond to the Norwegian coast line. Abbreviation: JMFZ - Jan Mayen fracture zone.

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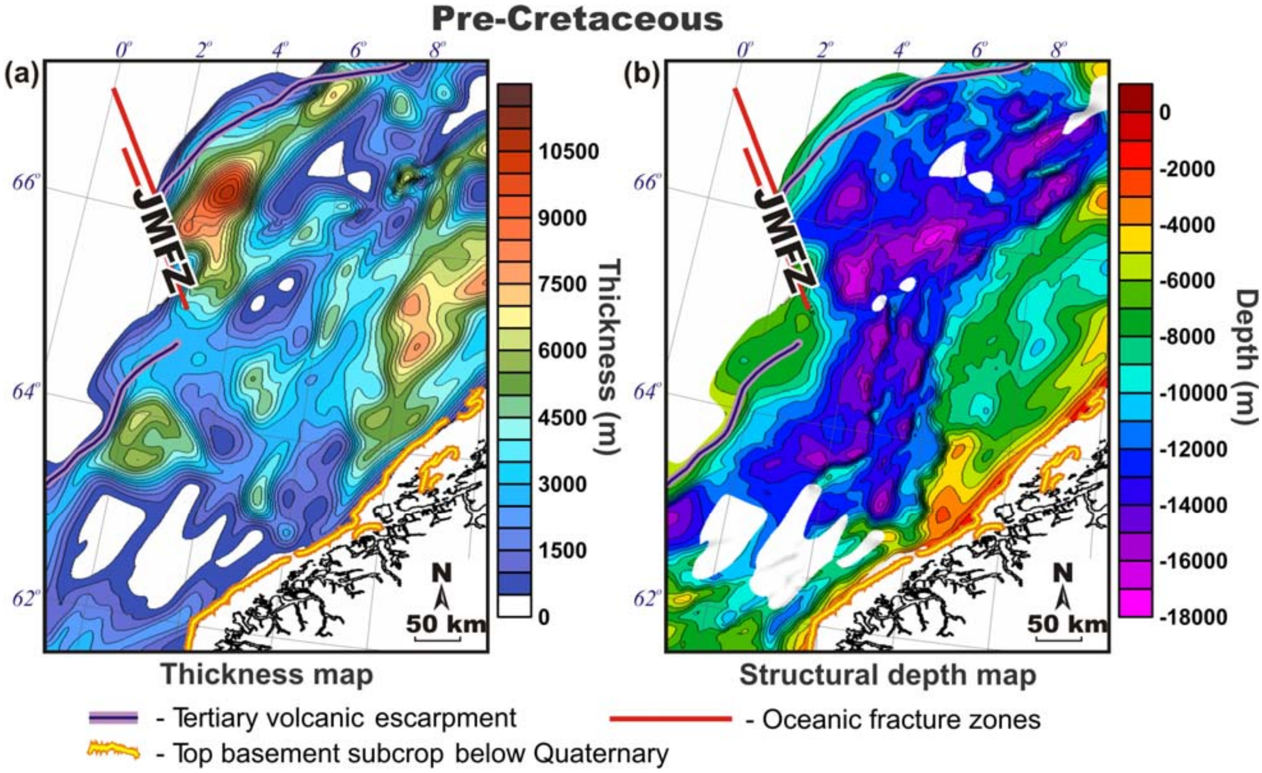

Figure 13. Layer 8 - pre-Cretaceous sediments: (a) thickness map (data file: *8_thickness_pre_Cretaceous.dat*) and (b) structural depth map of the base (data file: *8_base_pre_Cretaceous.dat*). Black lines in the right lower corner correspond to the Norwegian coast line. Abbreviation: JMFZ - Jan Mayen fracture zone.

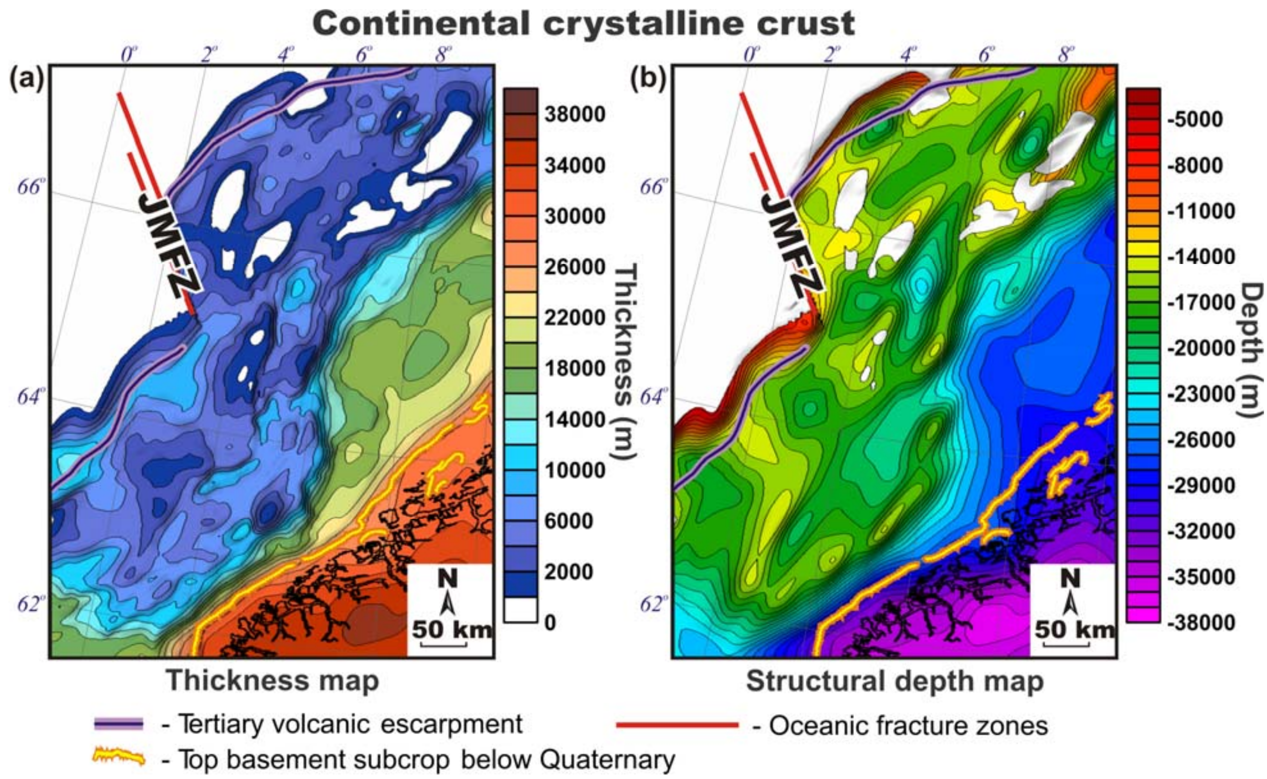

Figure 14. Layer 9 - the continental crystalline crust: (a) thickness map (data file: *9_thickness_continental_crystalline_crust.dat*) and (b) structural depth map of the base (data file: *9_base_continental_crystalline_crust.dat*). Black lines in the right lower corner correspond to the Norwegian coast line. Abbreviation: JMFZ - Jan Mayen fracture zone.

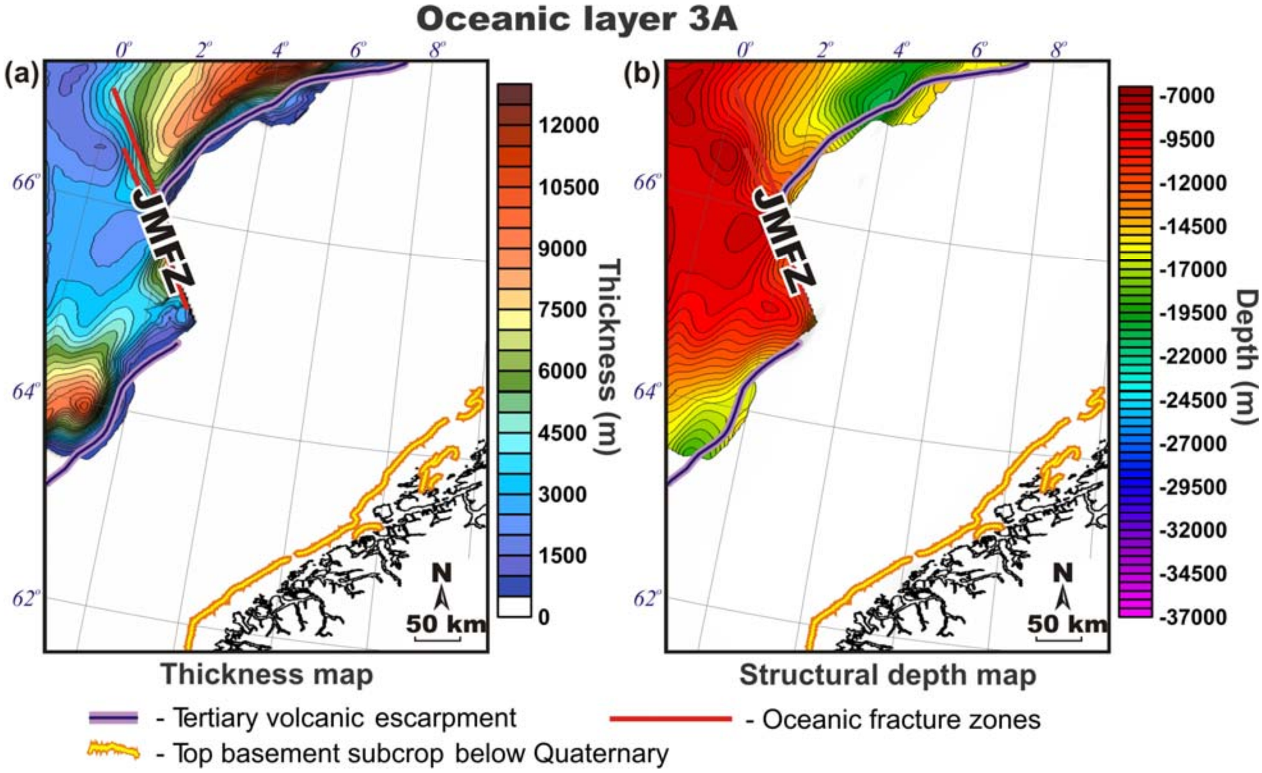

Figure 15. Layer 10 - the oceanic layer 3A: (a) thickness map (data file: *10_thickness_oceanic_layer_3A.dat*) and (b) structural depth map of the base (data file: *10_base_oceanic_layer_3A.dat*). Black lines in the right lower corner correspond to the Norwegian coast line. Abbreviation: JMFZ - Jan Mayen fracture zone.

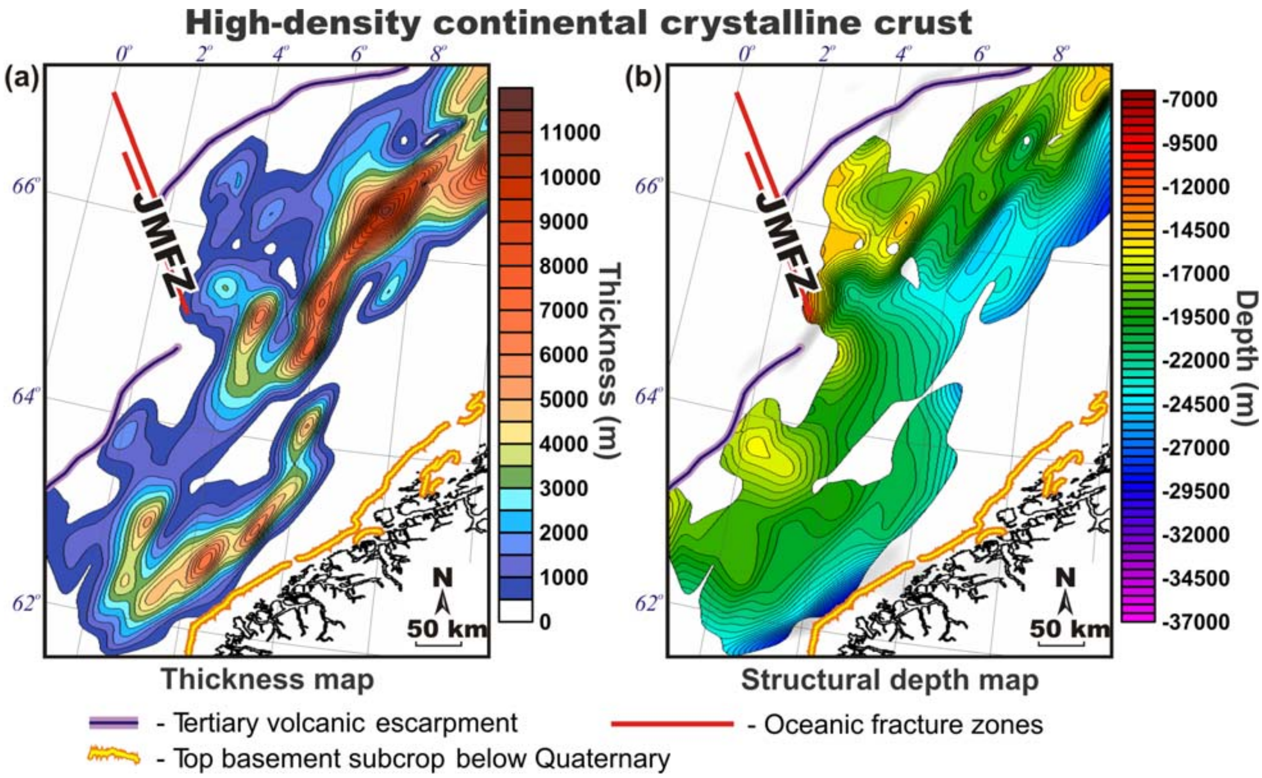

Figure 16. Layer 11 – the high-density zones within the continental crystalline crust: (a) thickness map (data file: *11_thickness_high_density_zones.dat*) and (b) structural depth map of the base (data file: *11_base_high_density_zones.dat*). Black lines in the right lower corner correspond to the Norwegian coast line. Abbreviation: JMFZ - Jan Mayen fracture zone.

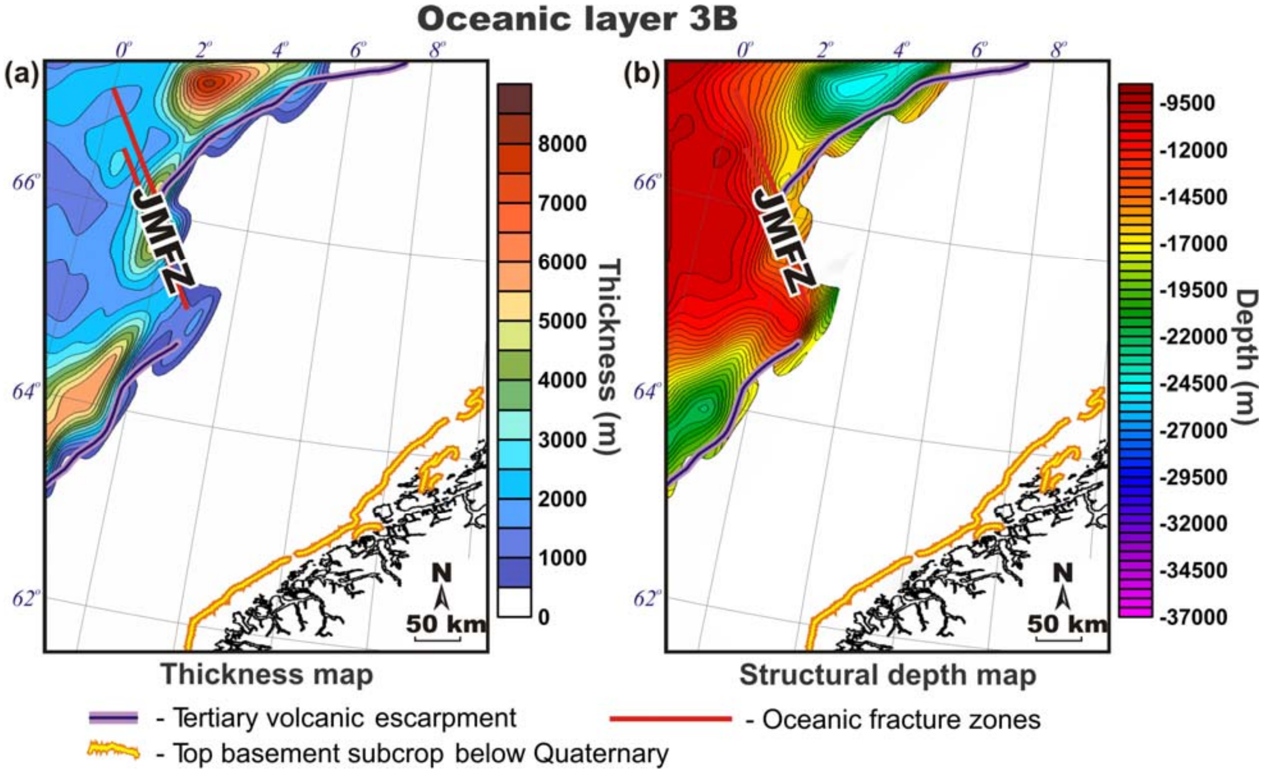

Figure 17. Layer 12 - the oceanic layer 3B: (a) thickness map (data file: *12_thickness_oceanic_layer_3B.dat*) and (b) structural depth map of the base (data file: *12_base_oceanic_layer_3B.dat*). Black lines in the right lower corner correspond to the Norwegian coast line. Abbreviation: JMFZ - Jan Mayen fracture zone.

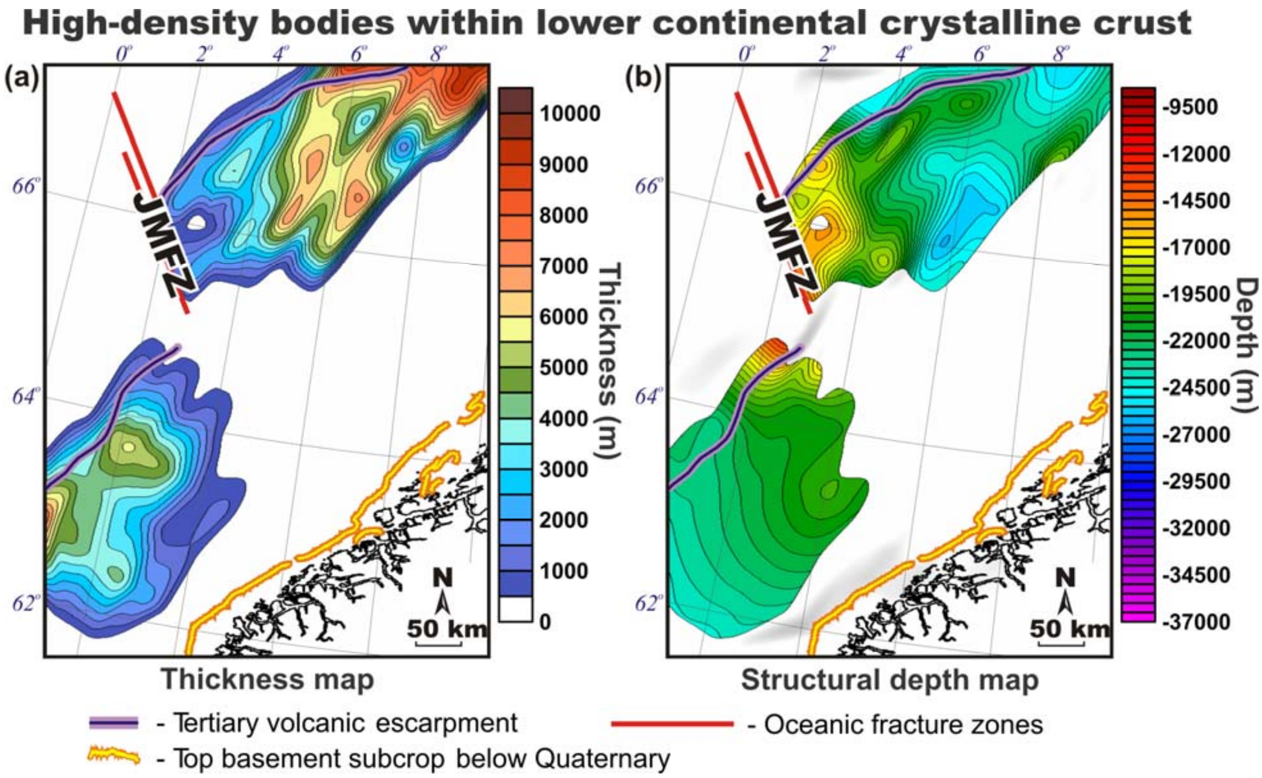

Figure 18. Layer 13 - the high-density bodies within the lower continental crystalline crust: (a) thickness map (data file: *13_thickness_high_density_bodies.dat*) and (b) structural depth map of the base (data file: *13_base_high_density_bodies_Moho.dat*). Black lines in the right lower corner correspond to the Norwegian coast line. Abbreviation: JMFZ - Jan Mayen fracture zone.

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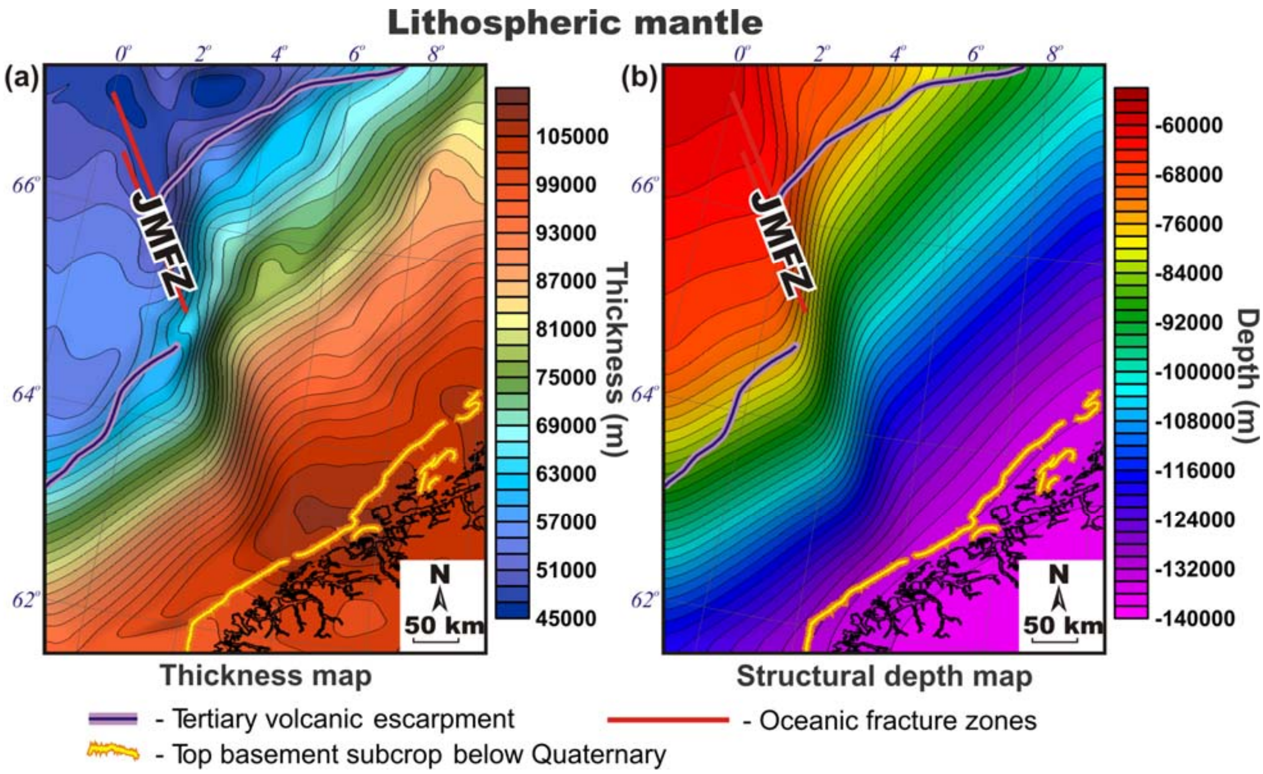

Figure 19. Layer 14 - the lithospheric mantle: (a) thickness map (data file: *14_thickness_lithospheric_mantle.dat*) and (b) structural depth map of the base (data file: *14_base_lithosphere.dat*). Black lines in the right lower corner correspond to the Norwegian coast line. Abbreviation: JMFZ - Jan Mayen fracture zone.

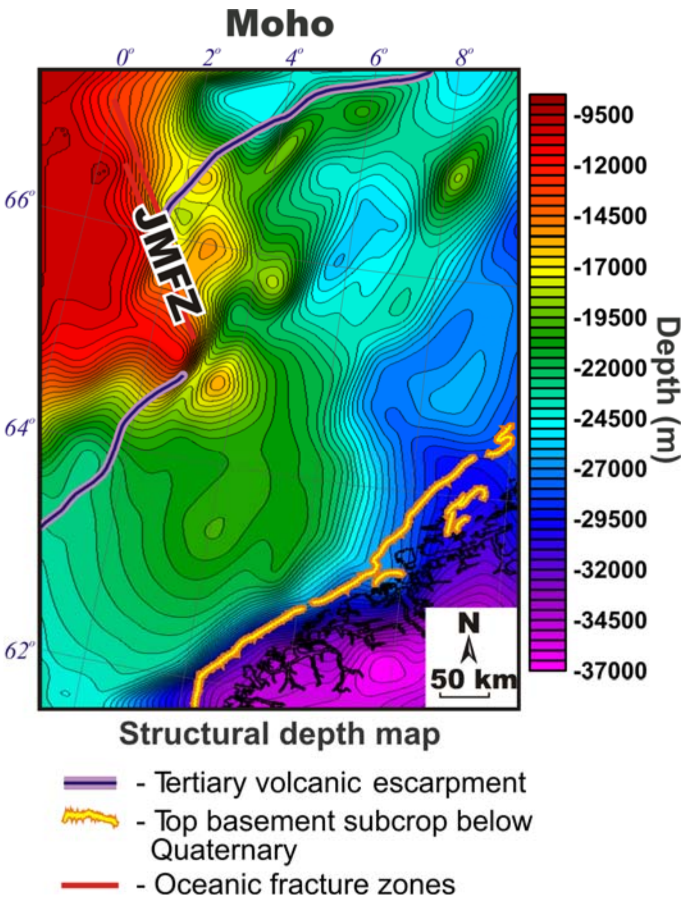

Figure 20. Depth to Moho within the study area (data file: *13_base_high_density_bodies_Moho.dat*), based on data from Ottemöller and Midzi (2003), Raum et al. (2006) and Maystrenko and Scheck-Wenderoth (2009). Black lines in the right lower corner correspond to the Norwegian coast line. Abbreviation: JMFZ - Jan Mayen fracture zone.

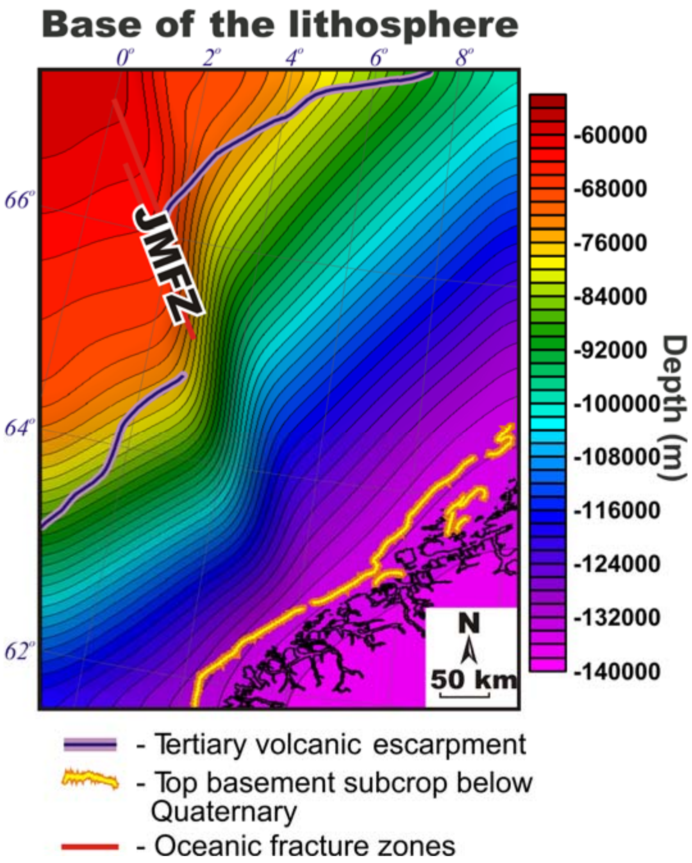

Figure 21. Depth to lithosphere-asthenosphere boundary (the same as in Fig. 19b; data file: *14_base_lithosphere.dat*), based on seismology data (after Zhang and Lay, 1999). Black lines in the right lower corner correspond to Norwegian coast line. Abbreviation: JMFZ - Jan Mayen fracture zone.

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