LITHOFLEX WORKSHOP

24-25 JUNE 2008

Research Centre Rotvoll – Trondheim – Norway

Lithoflex theoretical background: Part IV: Isostatic anomalies and basin evolution

Jörg Ebbing
Geological Survey of Norway
NTNU Trondheim

with help of:
Carla Braitenberg Christine Fichler, Laura Marello, Patrizia Mariani, Stephanie C. Werner, Susann Wienecke

StatoilHydro

NGU 150

Isostatic anomalies and basin evolution

1. **Local isostasy**
   - **Airy-Heiskanen**
   - **Pratt model**
2. **Regional isostasy (more in previous and next talk)**
3. **Basin evolution (McKenzie-rifting, cratonic basins)**
4. **Process oriented gravity modelling**
5. **Backstripping**

Isostasy is a term used in geology to refer to the state of gravitational equilibrium between the Earth's lithosphere and asthenosphere such that the tectonic plates "float" at an elevation which depends on their thickness and density. It is invoked to explain how different topographic heights can exist at the Earth's surface. When a certain area of lithosphere reaches the state of isostasy, it is said to be in *isostatic equilibrium*.

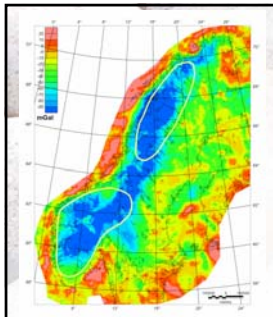
http://www.discoverourearth.org/student/topography/isostasy.html

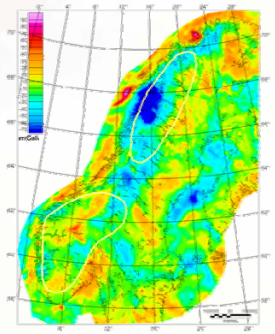
Isostasy is a term used in geology to refer to the state of gravitational equilibrium between the Earth's lithosphere and asthenosphere such that the tectonic plates "float" at an elevation which depends on their thickness and density. It is invoked to explain how different topographic heights can exist at the Earth's surface. When a certain area of lithosphere reaches the state of isostasy, it is said to be in *isostatic equilibrium*.

In general, the following types of isostatic concepts exists :

- Airy-Heiskanen isostasy
- Pratt isostasy
- Vening Meinesz isostasy

Isostatic anomalies represent in most cases Airy-Heiskanen compensation.





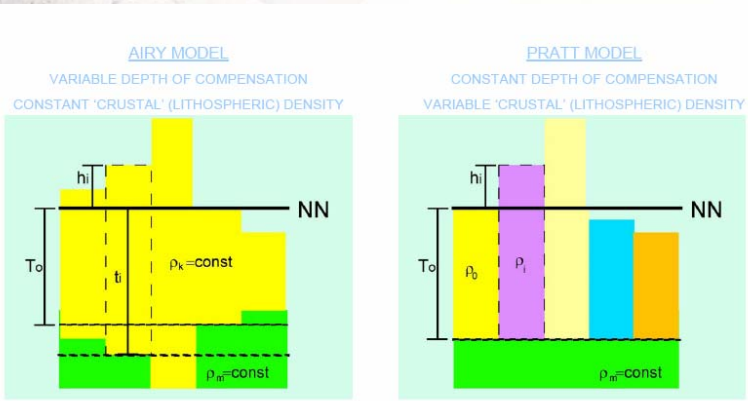
Isostatic anomalies

$g_{Iso} = g_{BA} - \Delta g_{Iso}$

$g_{BA} = g_{observed} - \Delta g_{topo} - \Delta g_{BA} - \gamma_0$

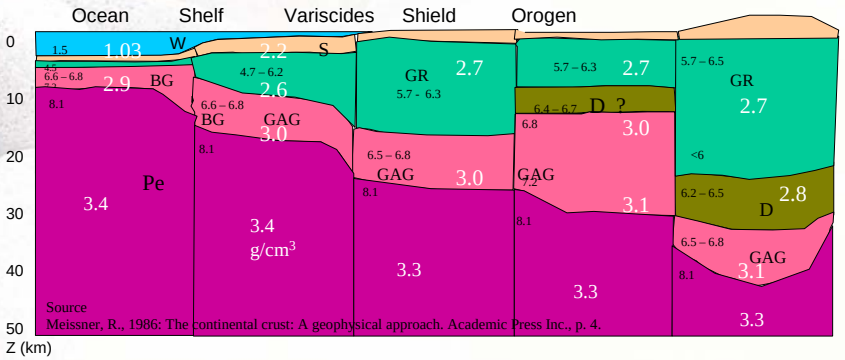
Δg_{Iso}=Isostatic reduction (Model)
γ_0=Earth Normal gravity field
Δg_{topo}=Topographic reduction
Δg_{BA} =Bouguer plate reduction

Concepts of local isostasy



TODAY, WE FEEL THAT THE ISOSTATIC MODEL IS A COMBINATION OF THE TWO THEORIES. EARTH'S RESPONSE TO LOADING DUE TO OROGENY, SEDIMENTATION, AND/OR GLACIATION INVOLVES A COMPLEX MASS-BALANCING INTERACTION BETWEEN THE RIGID LITHOSPHERE AND THE 'IMPRESSIONABLE' OR DEFORMABLE ASTHENOSPHERE.

Continental lithosphere densities



Source
Meissner, R., 1986: The continental crust: A geophysical approach. Academic Press Inc., p. 4.

Rock types:

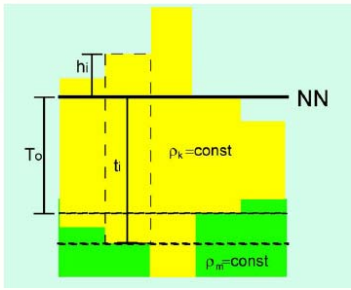
- BG = basaltic, gabbroic in oceanic crust
- GAG = amphibolitic & granulitic in continental crust
- PE = peridotitic, ultramafic
- D = Dioritic (?), possibly amphibolitic
- S = sediments
- GR = granitc gneissic upper crust
- W = water

P-wave velocities (km/s):
black numbers

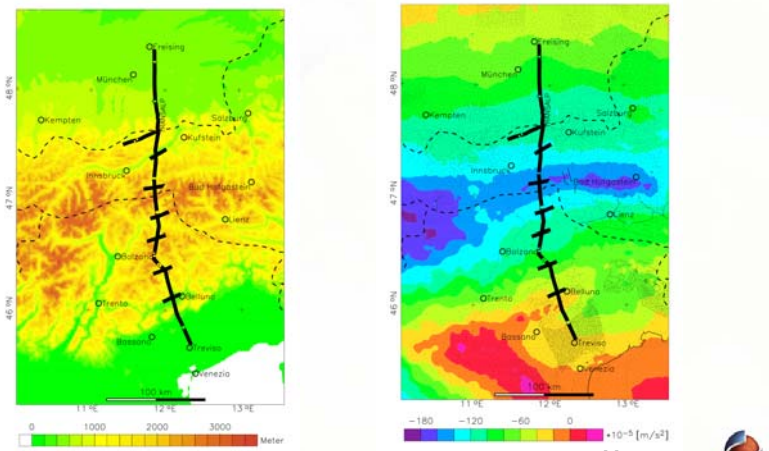
Densities (g/cm^3):
White numbers

Airy isostasy

- Collisional orogens
- Rift zones
- Non-volcanic margins (e.g. Iberia)

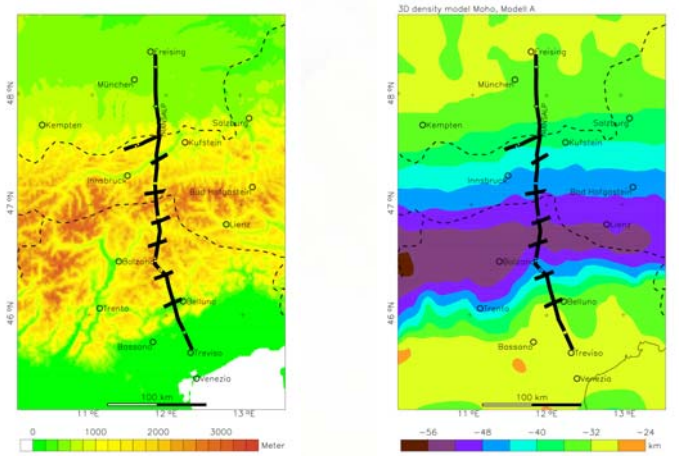


Eastern Alps:
Topography and Bouguer anomaly



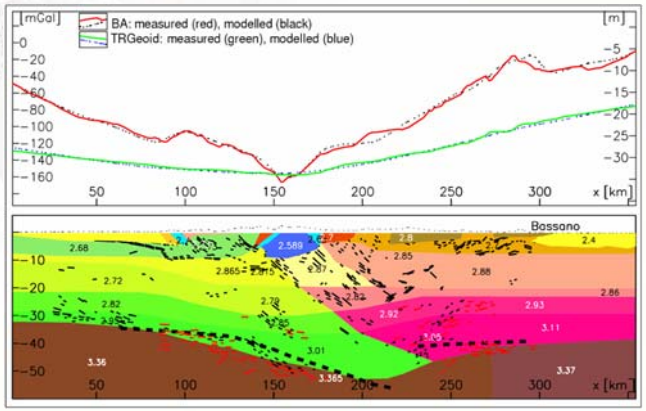
Ebbing 2002

Eastern Alps:
Topography and Moho



Ebbing 2002

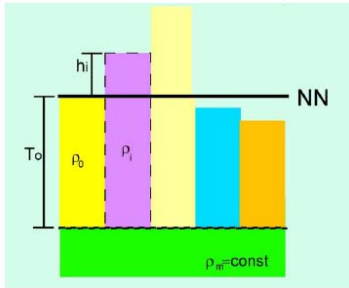
TRANSALP



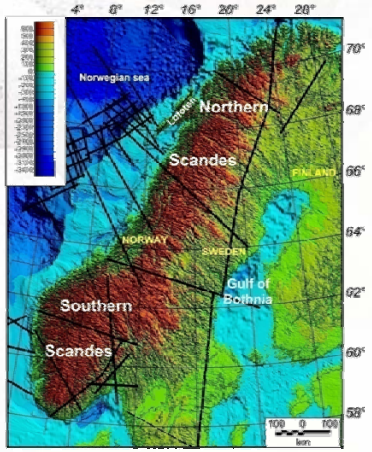
Ebbing et al. 2006

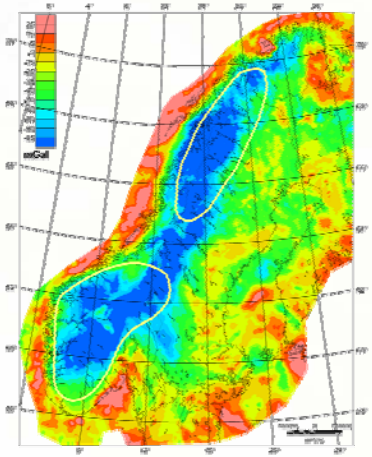
Pratt isostasy

- Fennoscandia
- Volcanic continental margins
  - mid-Norway



Topography and gravity

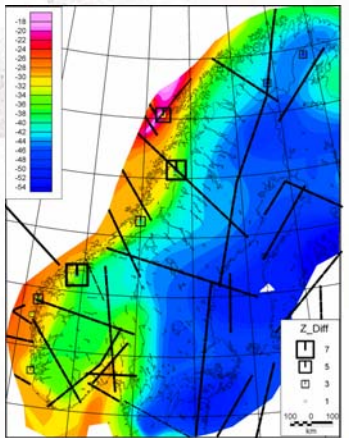


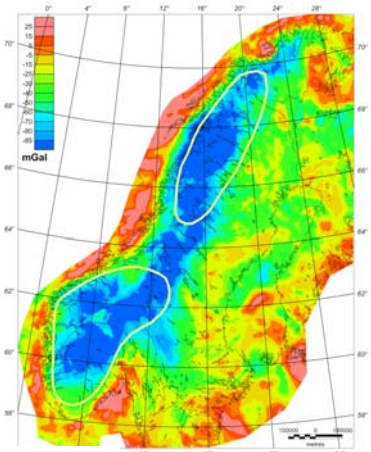


Topography/bathymetry compilation:
Dehls et al. 2000

Gravity map as compiled by:
Skilbrei et al. (2000), Korhonen et al. (2002)

Seismic and gravity studies



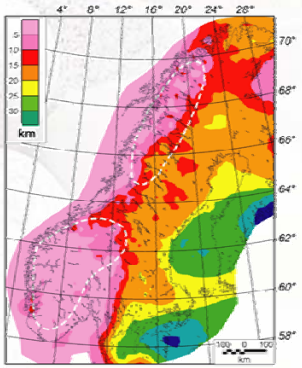


Deep seismic reflection and refraction experiments

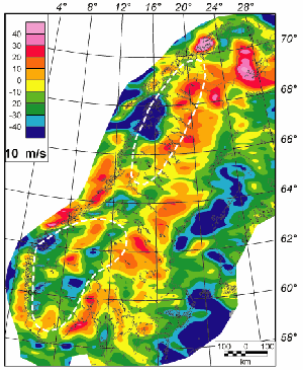
Seismic Moho depth after Kinck et al. 1993,
Mjelde et al. 2005, Olesen et al. 2002

Gravity map as compiled by:
Skilbrei et al. (2000), Korhonen et al. (2002)

Pratt isostasy and gravity residuals



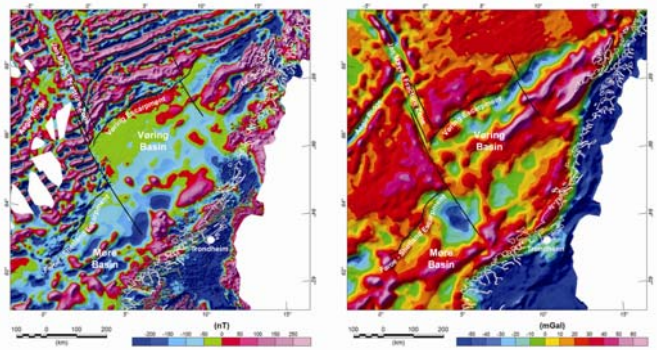
Isostatic high-density lower crust



Gravity residual of isostatic model

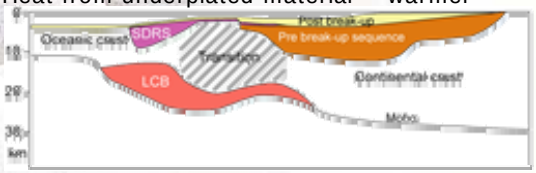
Ebbing, 2007

Mid-Norwegian margin

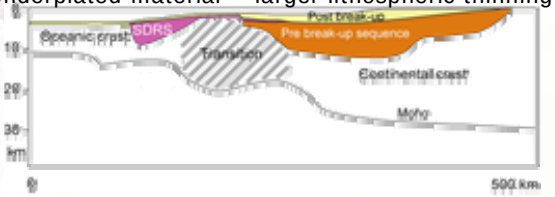


Ebbing et al. 2008

A) Heat from underplated material = warmer

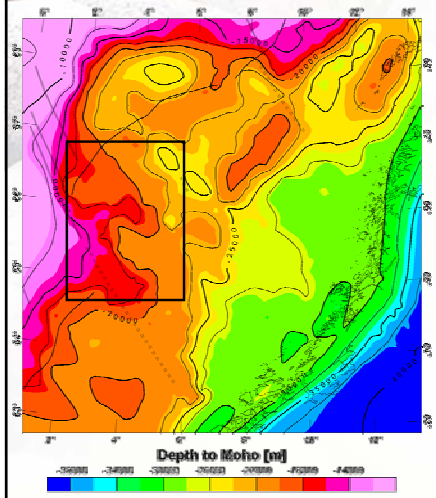


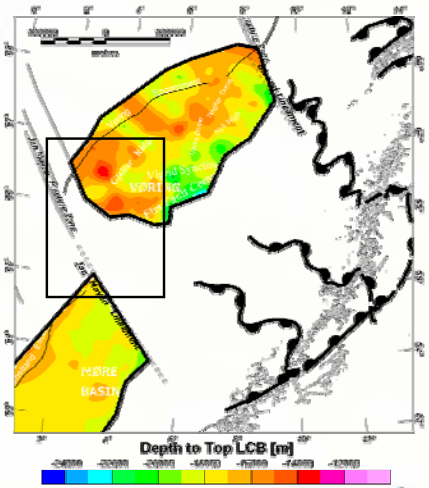
B) Underplated material = larger lithospheric thinning = warmer



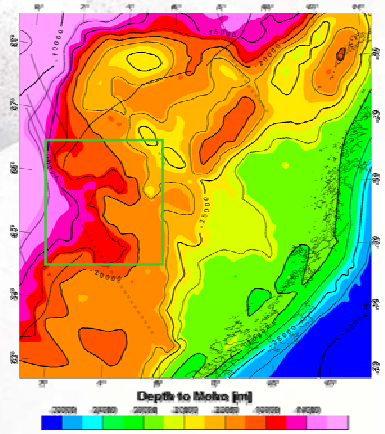
C) No underplated material = cooler

Origin and extend of LCB?

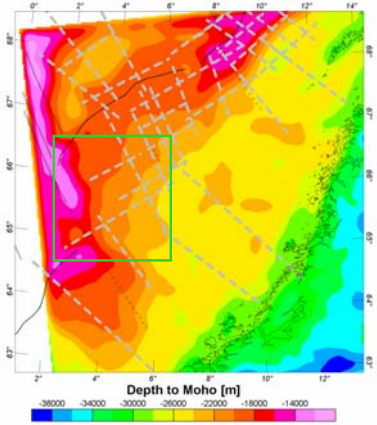




Isostatic state of the margin

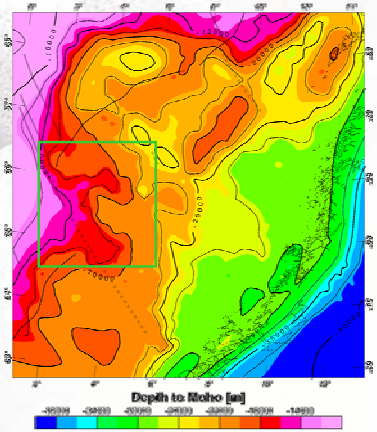


Seismic Moho

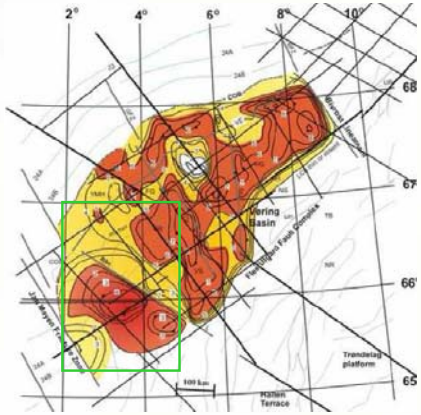


Isostatic Moho

Origin and extent of LCB?



Ebbing et al. , in press

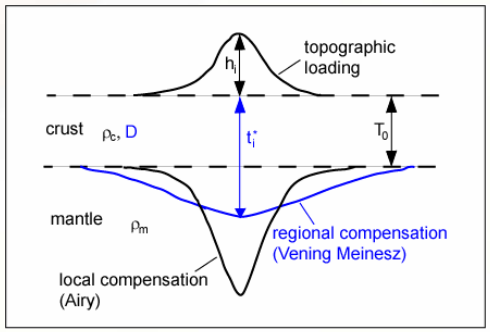


New interpretation: magmatic underplating (yellow) + eclogite (red)

Isostasy and flexural rigidity

Local Isostasy - model after Airy

$$t_i(x,y) = -T_0 - \frac{\rho_c}{\rho_m - \rho_c} h_i(x,y)$$



Regional Isostasy - model after Vening Meinesz

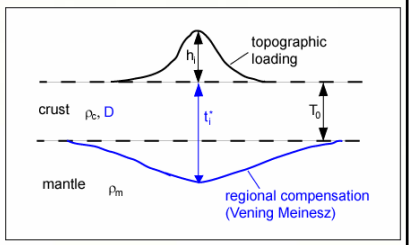
Isostasy and flexural rigidity
Vening Meinesz

Flexural models or models of a thin elastic plate use the transfer function

$$W(k) = -\frac{\rho_c}{\rho_m - \rho_c}\left(1 + \frac{16\pi^4 k^4 D}{(\rho_m - \rho_c)g}\right)^{-1} H(k)$$

and

$$t_i^*(x,y) = -T_0 - w_i(x,y)$$

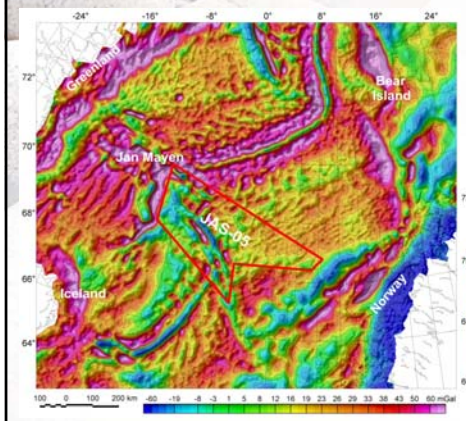


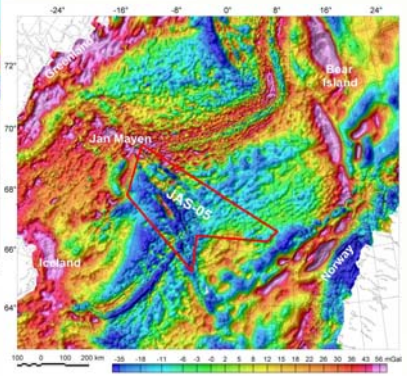
D = flexural rigidity of the lithospheric plate

H(k), W(k) = Fourier Transformation of topography and deflection

w(x,y) = Inverse Fourier Transformation of W(k)

Gravity field after regional isostatic correction





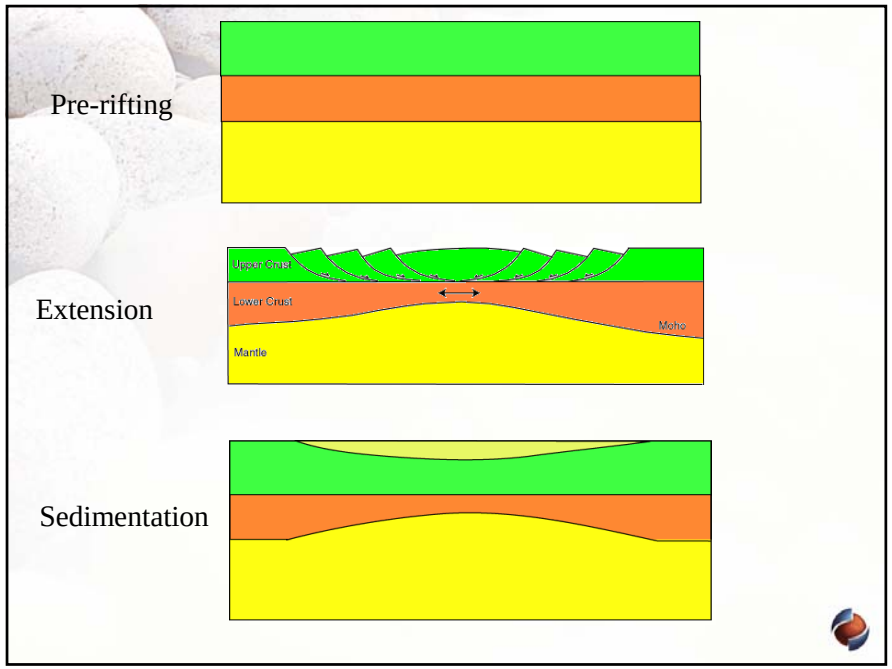
Olesen et al. 2007

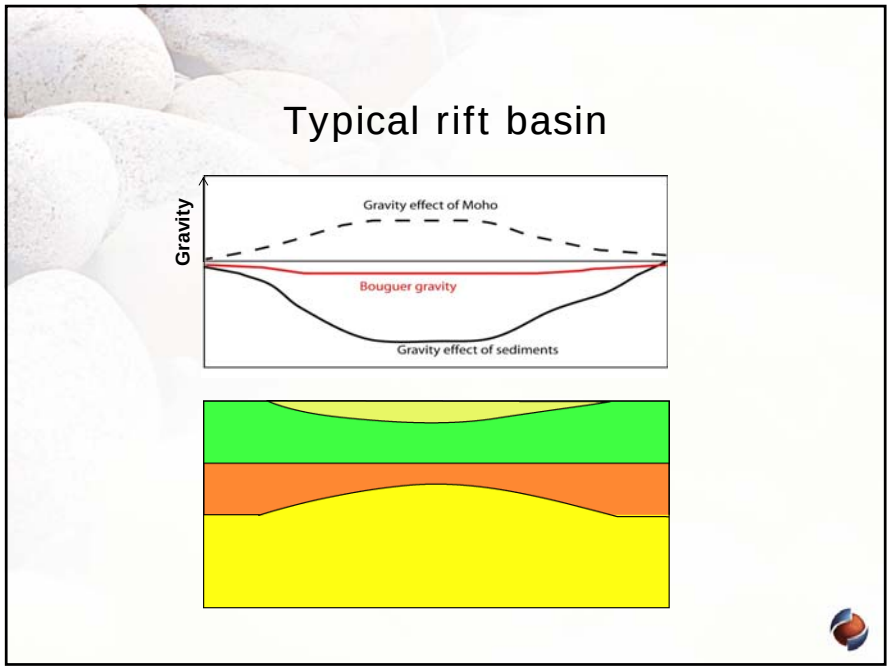
Isostasy and basin modelling

Simple rift basin
- McKenzie type ~Airy-Heiskanen isostasy

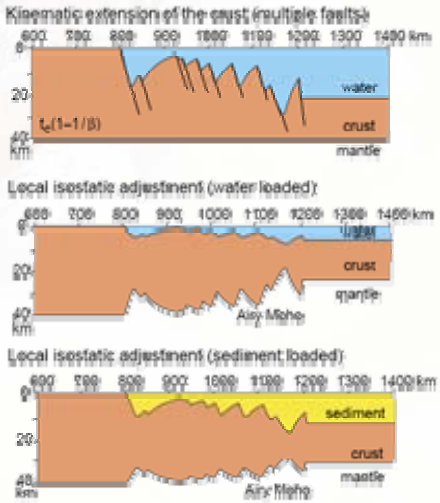
Extensional margins
- Vøring-Viking

Cratonic and intra-cratonic basins
- Barents Sea


Pre-rifting
Extension
Upper Crust
Lower Crust
Moho
Mantle
Sedimentation

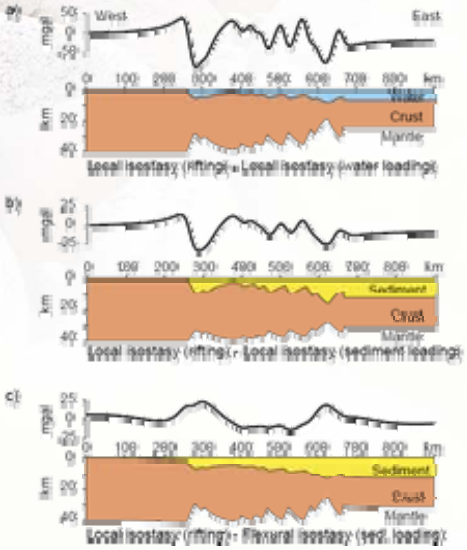

Typical rift basin
Gravity
Gravity effect of Moho
Bouguer gravity
Gravity effect of sediments

Isostatic response to loading and its gravity signal is depending on:
1) density (contrast)



Karner et al., 2005

Isostatic response to loading and its gravity signal is depending on:
1) density (contrast) and 2) strength of the lithosphere

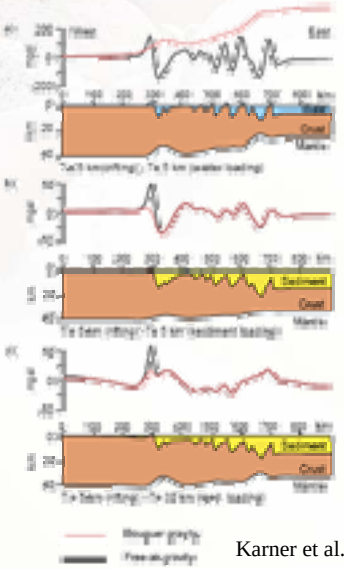


time-constant Te:
water loading

time-constant Te:
sediment loading

time-variable Te:
Sediment loading

Isostatic response to loading and its gravity signal is depending on:
1) density (contrast) and 2) strength of the lithosphere



time-constant Te:
water loading

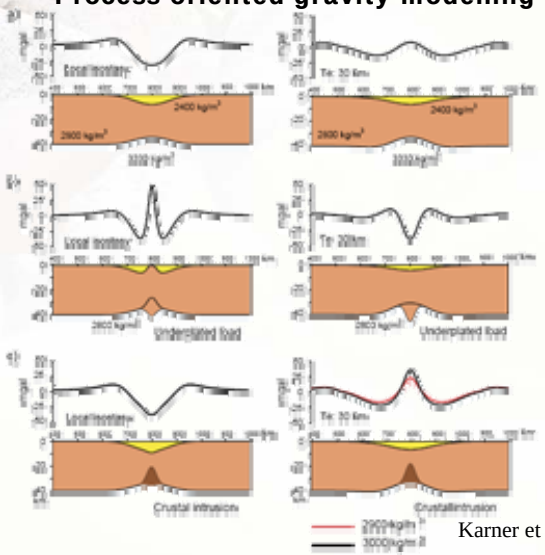
time-constant Te:
sediment loading

time-variable Te:
Sediment loading

Karner et al., 2005

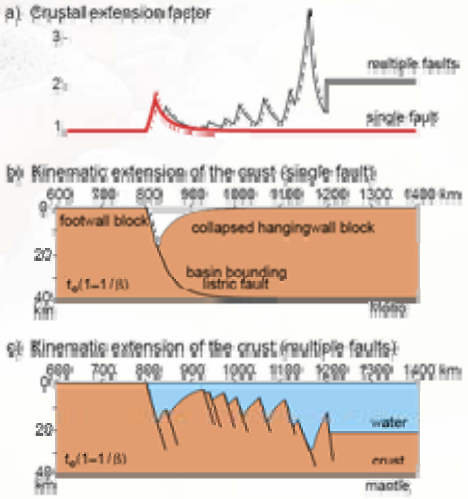
Isostatic response to loading and its gravity signal is depending on:
1) density (contrast) and 2) strength of the lithosphere. We can use this for:

Process oriented gravity modelling



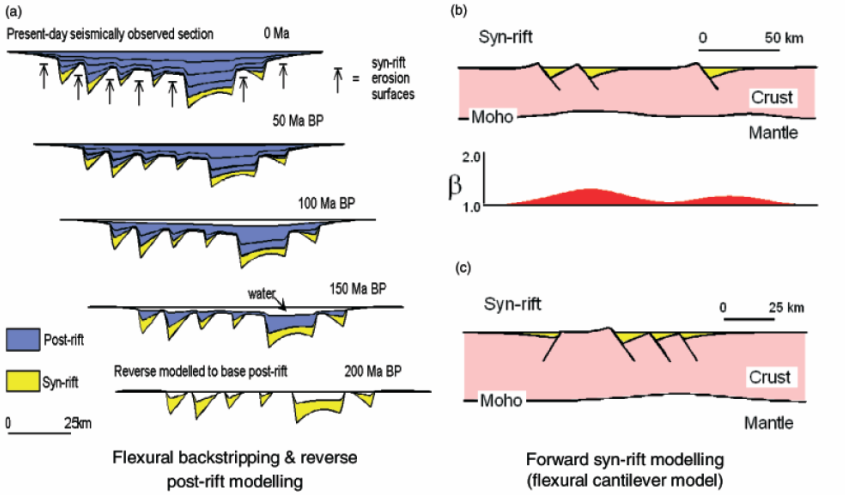
Karner et al., 2005

Crustal extension and isostatic response is connected to stretching factors



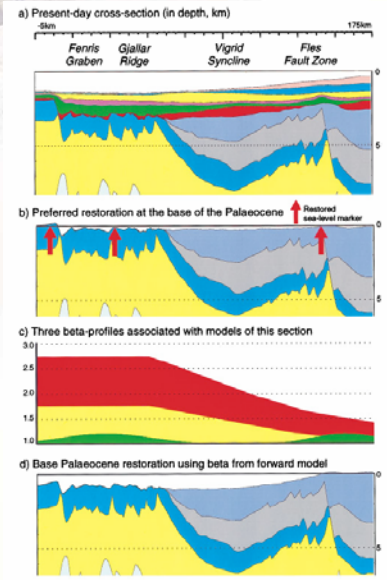
Karner et al., 2005

The Te distribution we apply to create the present-day gravity signal can be used and tested in backstripping



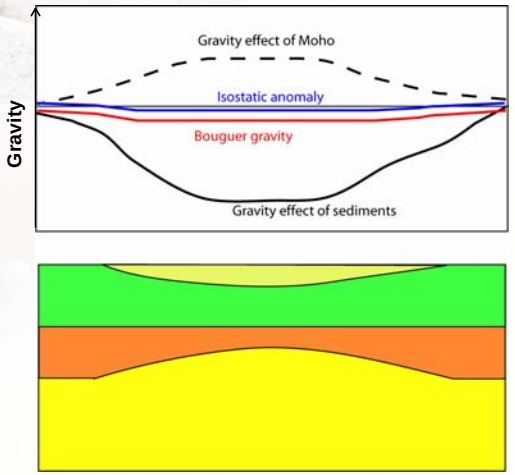
Kusznir et al. 2004

Basin modelling: backstripping

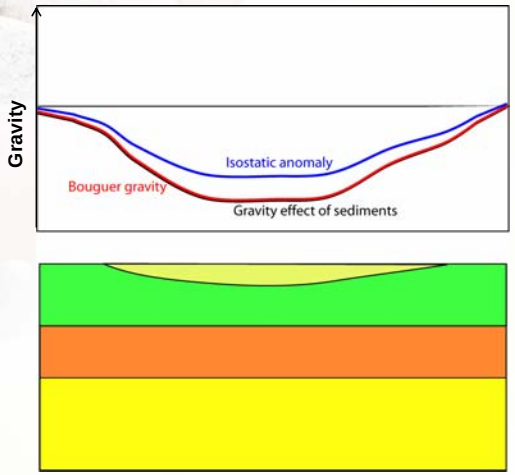


Roberts et al. 1997

Typical rift basin

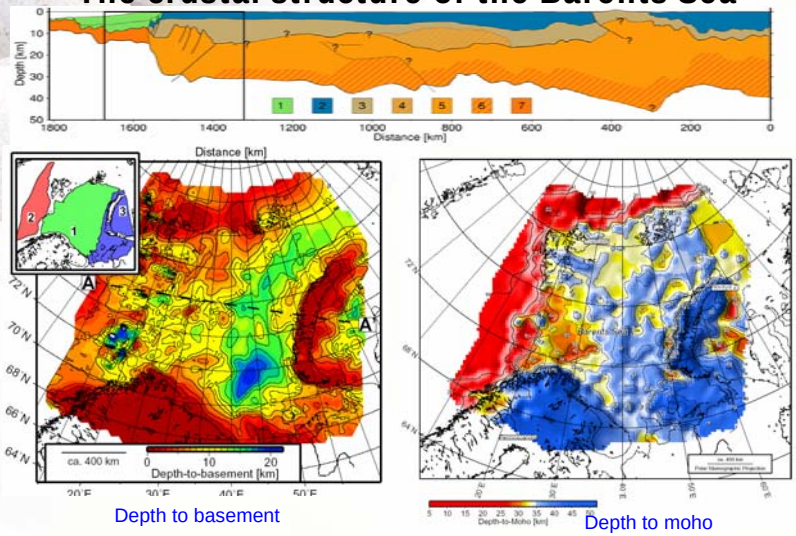


Non-typical rift basin, e.g. cratonic basin



….or after thermal post-rift subsidence

The crustal structure of the Barents Sea

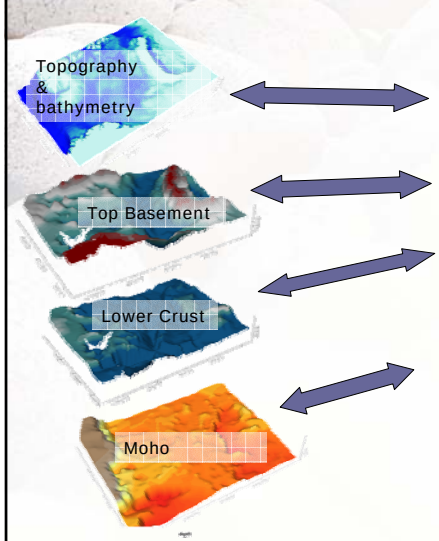


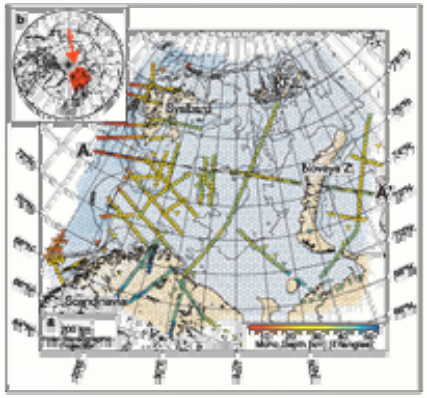
Depth to basement

Depth to moho

Bungum et al. 2005; Ritzmann et al. 2007

3D density modelling: model set up from Barents3D



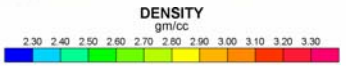


- UiO
- Norsar
- USGS

Ritzmann et al. 2007

Wienecke et al. 2007

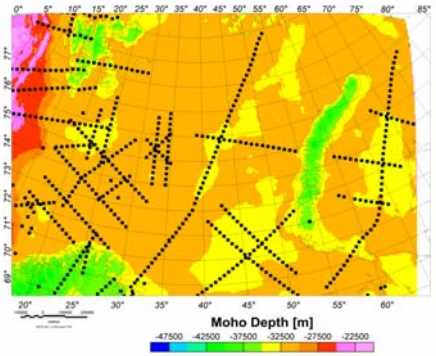
3D density modelling
Gravity effect of Barents50 - Profil



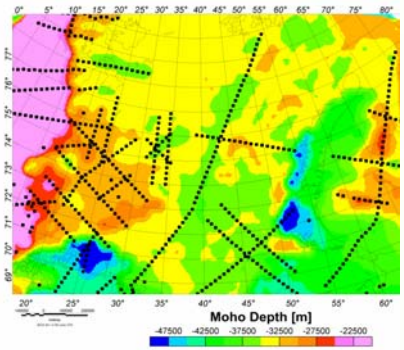
Possible error sources:

- **Geometry of Barents50**
- **Densities of Barents50**

Isostatic considerations
Isostatic vs. seismic Moho



Airy Moho
(incl. Sediment loading)



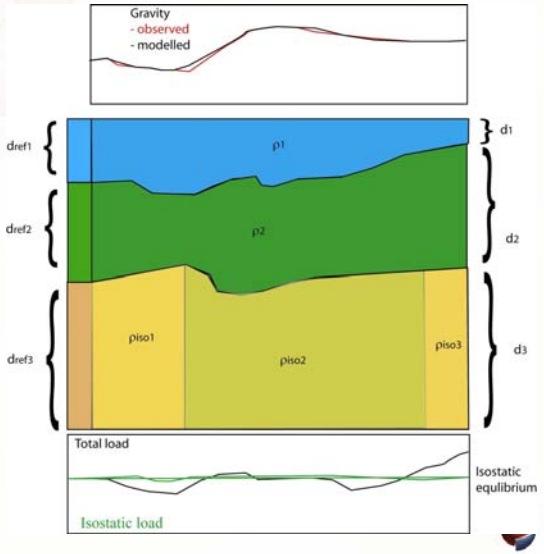
Seismic Moho

Ebbing et al. 2007

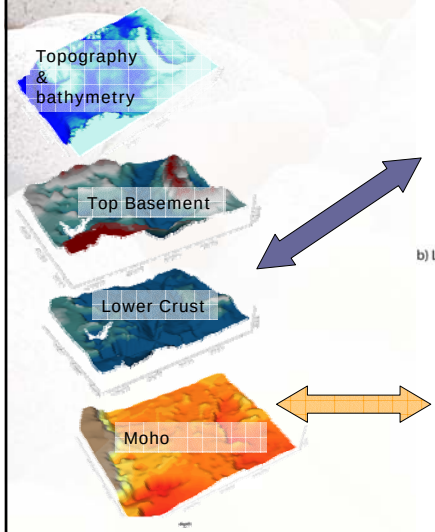
Isostatic density inversion

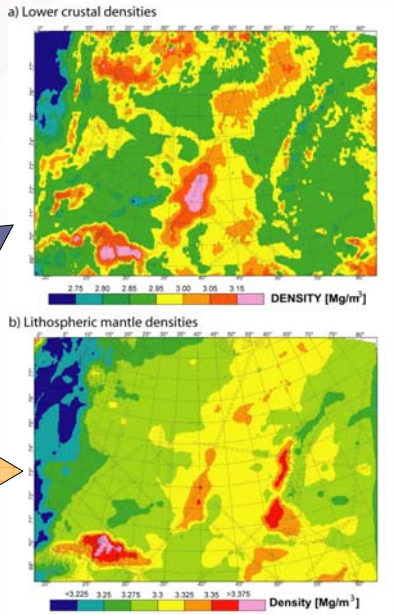
- Gravity
  - Regional trend/offset
- Isostasy
  - Moho is not compensating for loading by sediments & topography

=> Isostatic density inversion



3D density modelling:
Isostatic inverted lower crust & mantle densities

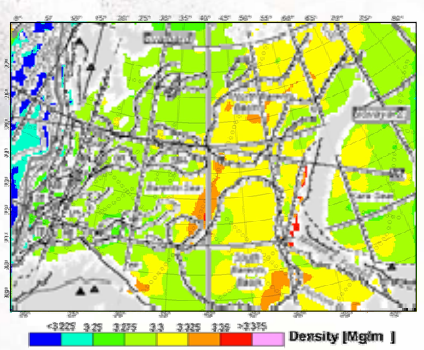




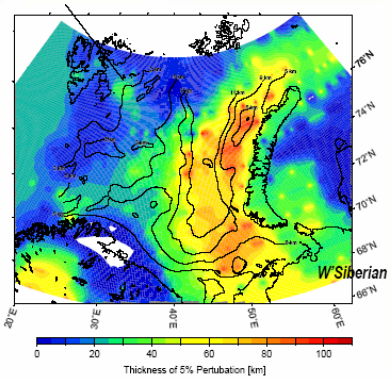
Wienecke et al. 2007

Ebbing et al. 2007

Isostasy vs. seismic tomography



Isostatic densities lithospheric mantle



Lithospheric mantle velocity perturbation (Faleide et al. 2006)

Summary

- isostatic concepts allow to model lithospheric structures
- isostatic modelling allows feedback on internal mass distribution and evolution
- concept oriented gravity modelling allows to evaluate different scenarios for basin development

- A careful selection of the isostatic concept (Airy-Heiskanen, Pratt, Vening Meinesz) has always to be made
- Flexural isostasy can also give information on crustal rheology *(not covered here)*

Literature 1/2

Allen, P.A. and Allen, J.R., 2005.Basin Analysis: Principles and Applications, 2. ed.,Blackwell Publishing, 549 pp.

Birch F. (1991). The velocity of compressional waves in rocks to 10 kbar. Part 2', J. Geophys. Res. 66, 2199-2224.

Braitenberg, C., Wienecke, S. and Wang, Y., 2006. Basement structures from Satellite Derived Gravity Field: the South China Sea Ridge. Journal of Geophysical Research-Solid Earth, 111, B05407.

Brocher, T. M. 2005 Empirical Relations between Elastic Wavespeeds and Density in the Earth's Crust Bulletin of the Seismological Society of America; December 2005; v. 95; no. 6; p. 2081-2092

Bungum, H., Ritzmann, O., Maercklin, N., Faleide, J., Mooney, W.D. & Detweiler, S.T. 2005: Three-Dimensional Model for the Crust and Upper Mantle in the Barents Sea Region. *EOS*, 86(16), doi: 10.1029/2005EO160003.

Carlson R.L. and Herrick C.N. (1990).Densities and porosities in the oceanic crust and their variations with depth and age, J. Geophys.Res., 95,9153-9170.

Carmichael, R,S. 1984. Handbook of physical properties of rocks. Volume I (1986), II (1982), III (1984).

Christensen, N. I., and W. D. Mooney (1995). Seismic velocity structure and composition of the continental crust: A global view, J. Geophys. Res. 100, 9761-9788.

Dehls, J.F., Olesen, O., Bungum, H., Hicks, E., Lindholm, C.D. & Riis, F. 2000: Neotectonic map, Norway and adjacent areas 1:3 mill. Norges geologiske undersøkelse, Trondheim, Norway.

Ebbing, J., 2002. 3D-Dichtemodellierung und isostatisches Verhalten der Lithosphäre in den Ostalpen (The 3D density structure and isostatic compensation of the lithosphere in the Eastern Alps). German *Ph.D thesis*, Freie Universität Berlin.

Ebbing, J., 2007: Isostatic density modelling explains the missing root of the Scandes. *Norwegian Journal of Geology*, 87, 13-20.

Ebbing, J., Braitenberg, C. and Götze, H.-J., 2006. The lithospheric density structure of the Eastern Alps. *Tectonophysics*, 414, 145-155.

Ebbing, J., Braitenberg, C. and Wienecke, S., 2007. Insights into the lithospheric structure and the tectonic setting of the Barents Sea region from isostatic considerations. *Geophysical Journal International*, 171 (3), 1390–1403.

Ebbing, J., Skilbrei, J.R. and Olesen, O. 2007. Insights into the magmatic architecture of the Oslo Graben by petrophysically constrained analysis of the gravity and magnetic field, *J. Geophys. Res.*, 112, B04404, doi:10.1029/2006JB004694.

Ebbing J., Olesen, O., Gernigon, L., Reynisson, R.F., og sokkelgeofysikk lag på NGU 2008: Tyngde og magnetiske data viser sporene av gamle strukturer på norsk sokkel. I: Geologi for samfunnet i 150 år –arven etter Kjerulf (T. Slagstad & R. Dahl, eds.), *Gråsteinen* 12, 89-98.

Ebbing, J., Gernigon, L., Pascal, C., Olesen, O. and Osmundsen, P.T., A discussion of structural and thermal control of magnetic anomalies on the mid-Norwegian margin. *Geophysical Prospecting, in press.*

Faleide, J.I., Ritzmann, O., C. Weidle, C. & A. Levshin, A. 2006: Geodynamical aspects of a new 3D geophysical model of the greater Barents Sea region – Linking sedimentary basins to the upper mantle structure. *Geophysical Research Abstracts*, 8, 08640.

Gardner, G. H. F., L. W. Gardner, and A. R. Gregory (1984). Formation velocity and density -The diagnostic basics for stratigraphic traps, Geophysics 39, 770-780.

Godfrey, N. J., B. C. Beaudoin, S. L. Klemperer, and the Mendocino Working Group USA(1997). Ophiolitic basement to the Great Valley forearc basin, California, from seismic and gravity data: Implications for crustal growth at the North American continental margin, Geol.Soc. Am. Bull. 109, 1536-1562.

Karner, G.D., Studinger, M., Bell. R.E., 2005. Gravity anomalies of sedimentary basins and their mechanical implications: Application to the Ross Sea [illegible] West Antarctica. Earth and Planetary Science Letters, 235(3-4), 577-596.

Literature 2/2

Kinck, J.J., Husebye, E.S. & Larsson, F.R. 1993: The Moho depth distribution in Fennoscandia and the regional tectonic evolution from Archean to Permian times. *Precambrian Research* 64, 23-51.

Korhonen, J.,V., Aaro, S., All, T., Elo, S., Haller, L.Å., Kääriäinen, J., Kulinich, A., Skilbrei, J.R., Solheim, D., Säävuori, H., Vaher, R., Zhdanova, L. & Koistinen, T. 2002a. Bouguer anomaly map of the Fennoscandian shield 1: 2 000 000. Geological Surveys of Finland, Norway and Sweden and Ministry of Natural Resources of Russian Federation.

Kusznir, N.J., Hunsdale, R. and Roberts, A.M., 2004. Timing of depth-dependent lithosphere stretching on the S.Lofoten riftedmargin offshoremid-Norway: pre-breakup or post-breakup?, Basin Research 16, 279–296.

Larsen, H.C., Saunders A.D., Clift P.C., and the Shipboard Scientific Party (1994). Proceeding of the Drilling Program Initial Report. Vol. 152, Ocean Drill. Program. College Station, Tex.

Ludwig W.J., Nafe J.E. and Drake C.L. (1970). Seismic refraction, in the Sea, A.E.Maxwell (Editor), Vol.4, Wiley-Interscience, New York, 52-84

Meissner, R., 1986: The continental crust: A geophysical approach. Academic Press Inc., p. 4

Mjelde, R., Raum, T., Breivik. A., Shimamura, H., Murai, Y., Takanami, T. & Faleide, J.I. 2005: Crustal structure of the Vøring margin, NE Atlantic: a review of geological implications based on recent OBS-data. In: Doré, A.G. & Vining, B.A. (eds.) Petroleum Geology: North-West Europe and Global Perspectives. Proceedings of the 6th Petroleum Geology Conference. Geological Society Special Publication, Geological Society, London, 803-813.

Mjelde, R., Faleide, J.I., Breivik, A.J., Raum, T., Lower crustal composition and crustal lineaments on the Vøring Margin, NE Atlantic: A review, *Tectonophysics* (2008), doi: 10.1016/j.tecto.2008.04.018.

Mussett, A. E., Khan, M.A., 2000. Looking into the earth. An introduction to Geological Geophysics. Cambridge University Press

Olesen, O., Lundin, E., Nordgulen, Ø., Osmundsen, P.T., Skilbrei, J.R., Smethurst, M.A., Solli, A., Bugge, T. & Fichler, C. 2002: Bridging the gap between the onshore and offshore geology in Nordland, northern Norway. *Norwegian Journal of Geology* 82, 243-262.

Olesen, O., Dehls, J.F., Ebbing, J., Kihle, O. & Lundin, E., 2007. Aeromagnetic mapping of deep-weathered fracture zones in the Oslo Region – a new tool for improved planning of tunnels. *Norwegian Journal of Geology*, 87, 253-267.

Ritzmann, O., Maercklin, N., Faleide, J.I., Bungum, Mooney, W.D. & Detweiler, S.T. 2007: A three-dimensional geophysical model of the crust in the Barents Sea region: model construction and basement characterization. *Geophys. J. Int.* 170, 417–435.

Roberts, A.M., Lundin, E. and Kusznir, N.J. 1997. Subsidence of the Vøring Basin and the influence of the Atlantic continental margin. *Journal of the Geological Society, London*, 154, 1997, 551–557,

Skilbrei, J.R., Kihle, O., Olesen, O., Gellein, J., Sindre, A., Solheim, D. & Nyland, B., 2000: Gravity anomaly map Norway and adjacent ocean areas, scale 1:3 Million, Geological Survey of Norway, Trondheim.

Sobolev, S. and Babeyko, A., 1994. Modeling of mineralogical composition, density and elastic wave velocities in anhydrous magmatic rocks. Surveys in Geophysics, 15: 515-544.

Tsikalas, F., 1992: *A study of seismic velocity, density and porosity in Barents Sea wells (N. Norway).* Master Thesis, Department of Geology, University of Oslo, Norway.

Wienecke, S., 2006. A new analytical solution for the calculation of flexural rigidity: significance and applications. PhD Thesis, Free University Berlin, Germany. http://www.diss.fu-berlin.de/2006/42/indexe.html.

Wienecke, S., Ebbing, J. & Gernigon, L. 2007: 3D density modelling, isostasy and elastic thickness calculation of the Barents Sea. NGU Report 2007.022, 56pp.