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# An unstable stable continental region: Fennoscandian Seismotectonics

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# An unstable stable continental region:

# Fennoscandian Seismotectonics

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ICTP

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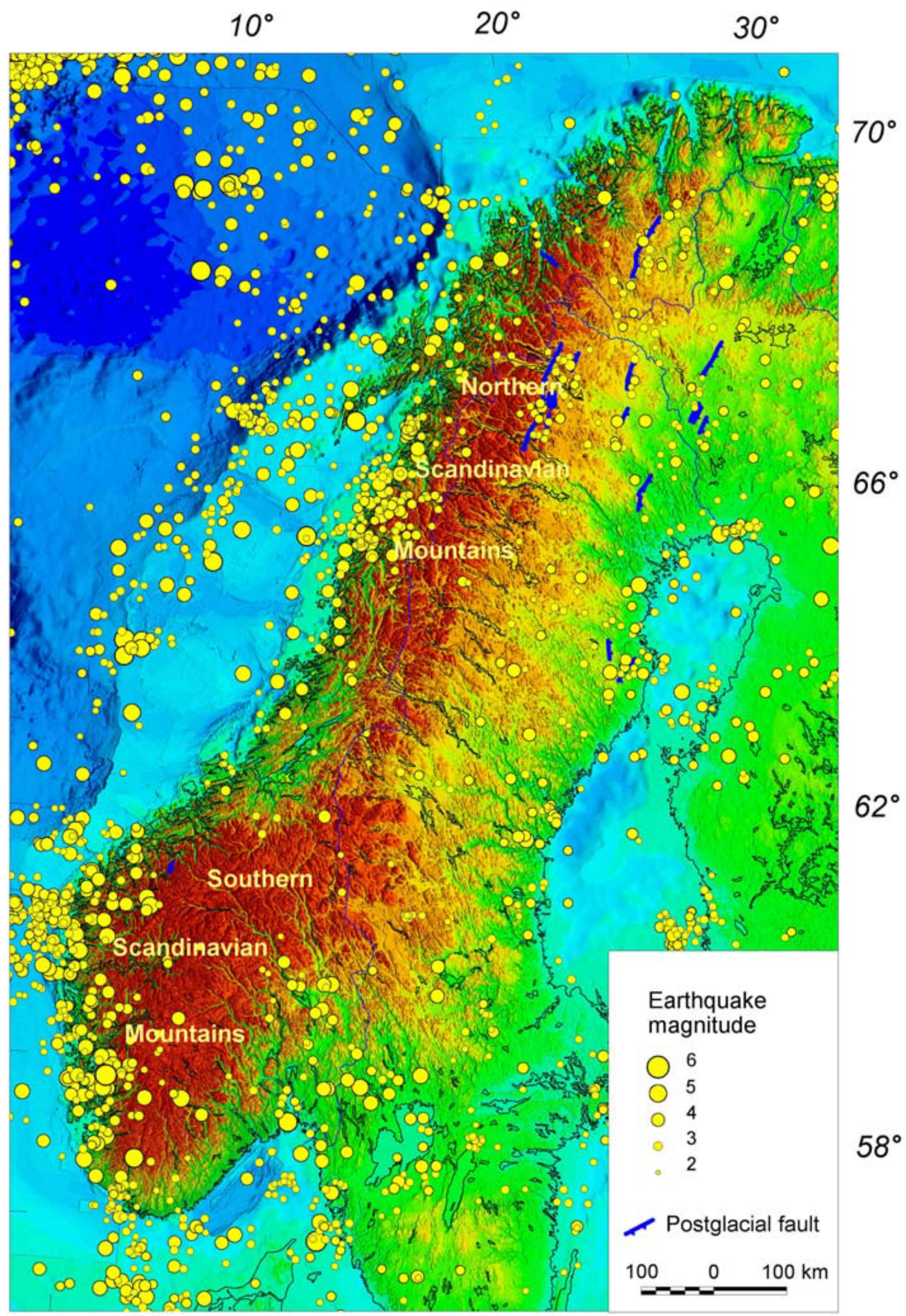
# Fennoscandia: ”An unstable stable continental region”

- Seismotectonics
  - Frame of reference and historical basis
- Intraplate seismotectonics
  - Principle characteristics
  - Stable continentinal regions
  - Neotectonics
- Fennoscandian seismotectonics
  - Postglacial and present-day seismicity, neotectonics
  - Earthquake distributions and energy release
  - Earthquake generation mechanisms
  - Case histories; examples
- Conclusions

# Fennoscandian seismicity

- Earthquakes during the period 1758-2007, with postglacial faults (blue), topography and bathymetry.
- Size of earthquake symbols are proportional to magnitude.
- Earthquakes are largely confined to the coastal regions, to the continental margin, to the Viking Graben and to the Oslo Rift zone.



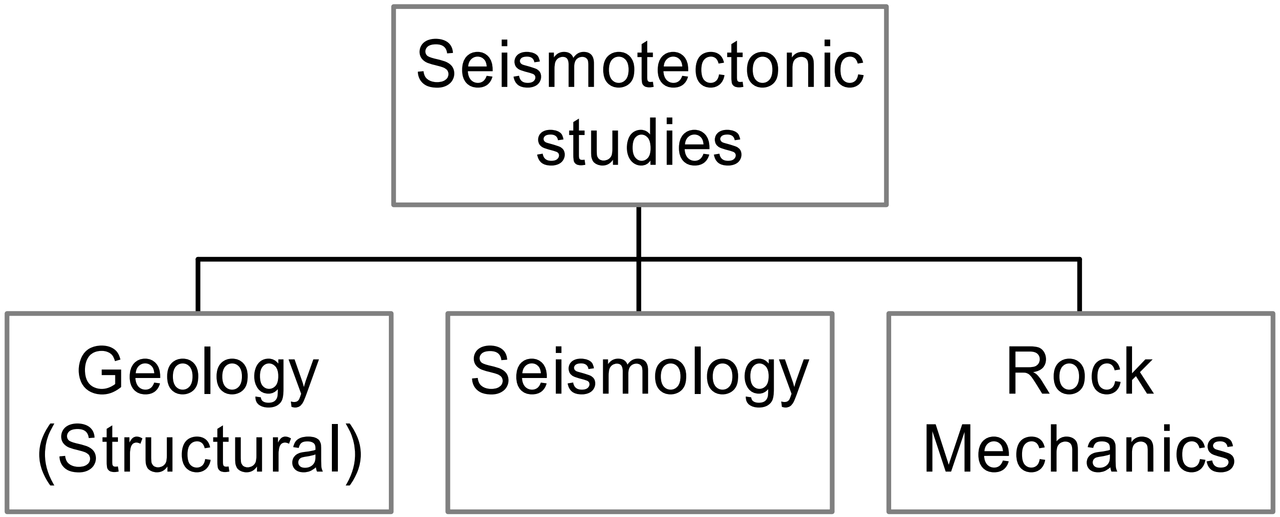

From Olesen et al. (2008)

# Suggested definitions of seismotectonics

- The study of earthquakes as a tectonic component (Scholz, 1990)
- The relationship between earthquake occurrence and tectonic processes (Lay and Wallace,1992)
- The study of active faulting and its relationships to plate motions and lithospheric properties (Lay and Wallace, 1992)
- The ‘added value’ in our understanding of crustal deformation and lithospheric dynamics as provided through studies of earthquakes
- ”Explaining why earthquakes occur”

# Seismotectonics

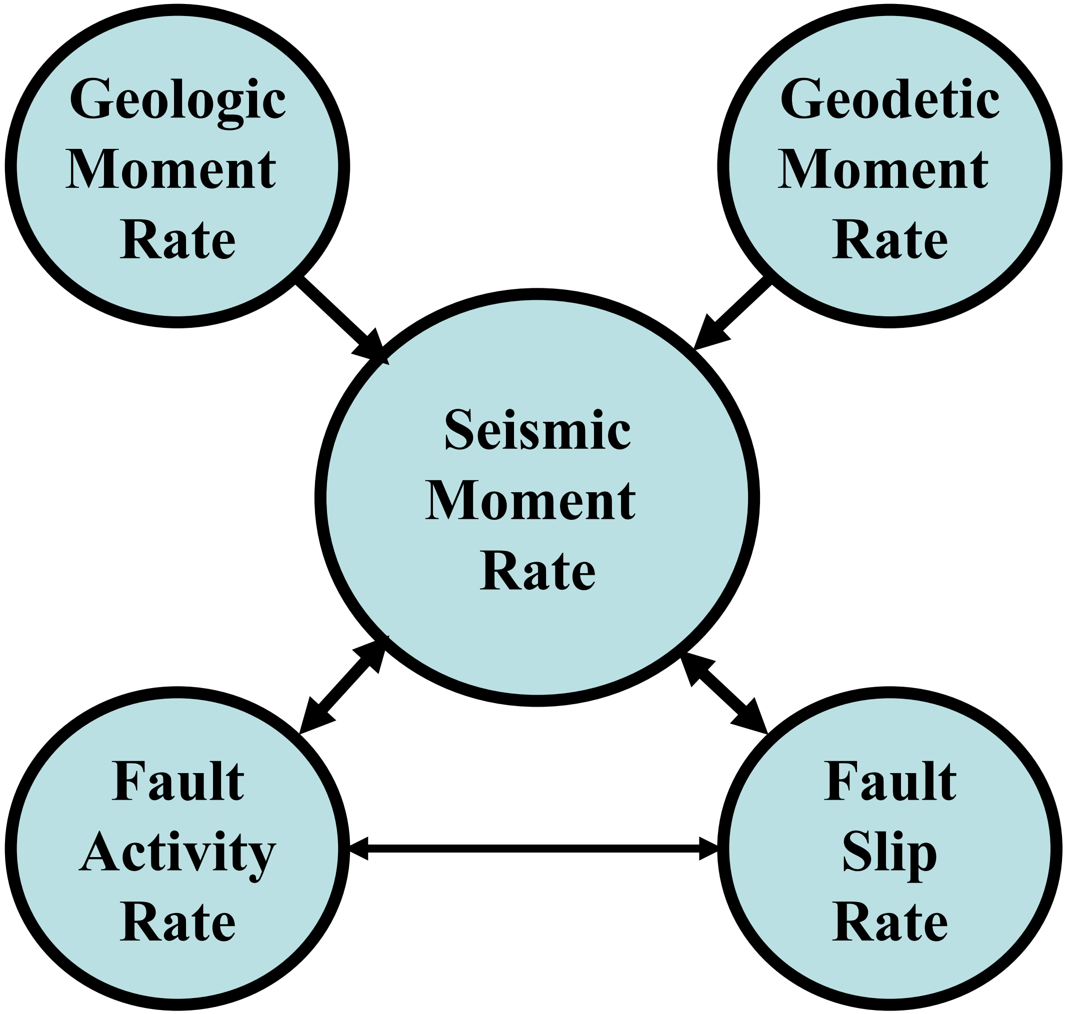
Multidisciplinarity:



# The Earthquake Energy Budget

Modelling earthquake activities on faults:

- Slip rates available:
  - Convert slip rates to moment rates
  - Convert moment rates to earthquake occurrence rates
- Slip rates not available:
  - Estimate activity rates from other information such as historical seismicity of the region surrounding the fault



# The geologic significance of earthquakes
## Historical Frame of Reference

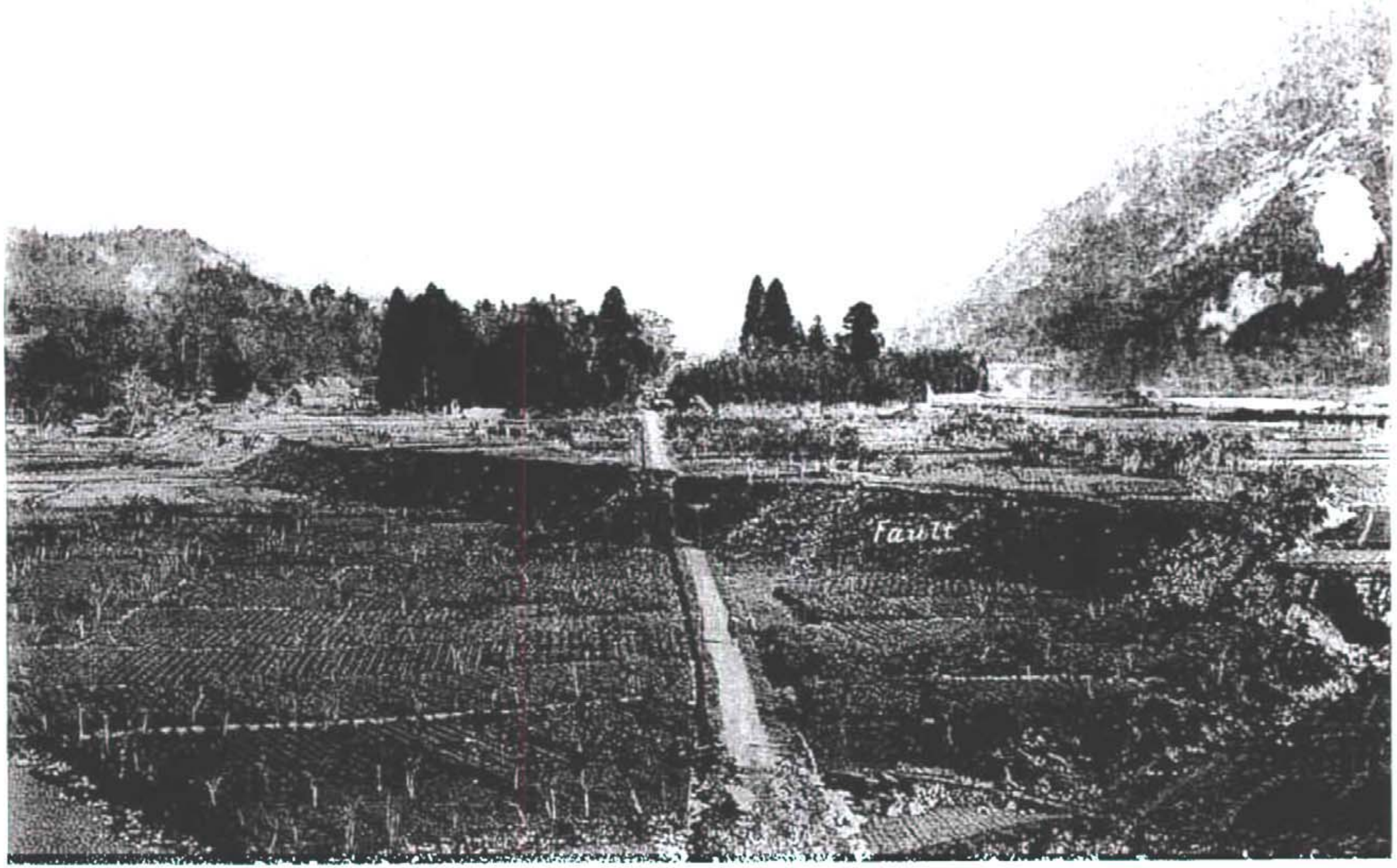
- Robert Hooke (1635-1703)
  - Developed the idea that earthquakes represent an elastic reaction to geologic phenomena
    - Discourse of Earthquakes (1668)
- James Hutton (1926-1797)
  - Founder of modern Geology
    - Theory of the Earth (1875)
- Charles Lyell (1797-1875)
  - Founder of modern Geology
  - Considered earthquakes to be an important agent in earth dynamism
  - Aware of both faulting and elevation changes
    - Principles of Geology (1830 ++)
    - Gradualism (uniformitarianism)
    - Influencing strongly Charles Darwin (1809-1882)

# Are Earthquakes and Faults connected?

## Important case studies

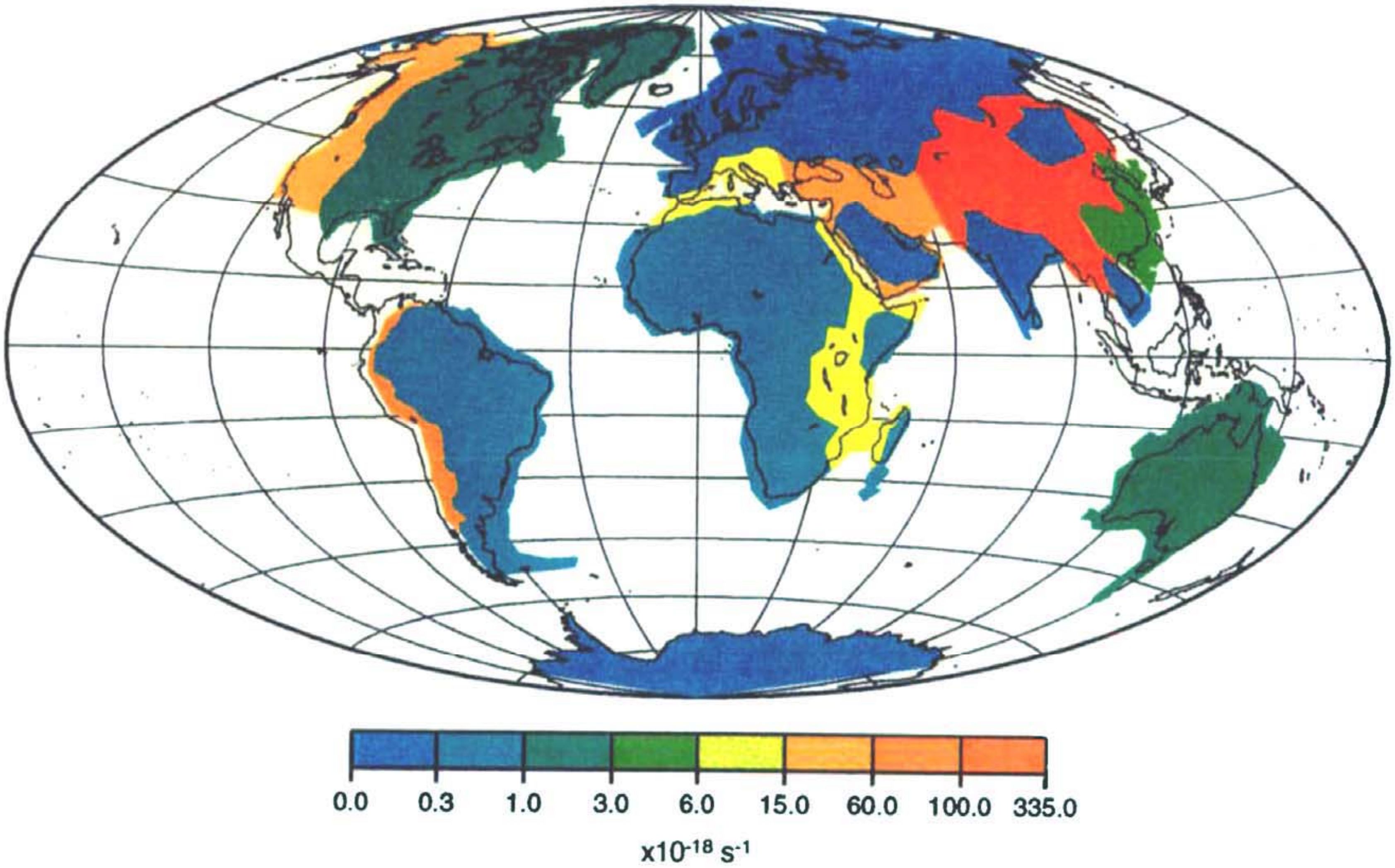
- California
  - 1872 Owens Valley earthquake
    - Gilbert (1884)
  - 1906 San Francisco earthquake:
    - Reid (1910, elastic rebound theory)
- New Zealand
  - 1888 South Island earthquake
    - McKay (1890)
- Japan
  - 1891 Nobi earthquake
    - Koto (1893)

# Famous 1893 photograph of the 1891 Nobi earthquake, establishing link between faults and earthquakes




From Scholz (2002)

# Strain rates in intraplate regions (Sykes)




From Scholz (2002)

# Approaches to Intraplate seismicity

- Typical rates of deformation
  - Active plate margins: ~$10^{-6}$ $yr^{-1}$
  - Norwegian margin: ~$10^{-9}$ $yr^{-1}$
  - Other stable continental regions: up to $10^{-13}$ $yr^{-1}$
- Structural geology
  - Combined dynamic and kinematic viewpoints
  - Recent movements in younger strata
  - Geophysical innvestigations, paleoseismology
  - Understanding fault growth
- Inferences from earthquakes
  - Individual earthquakes (source parameters, stress drop, mode of faulting, etc.)
  - Ensemble assessments (spatio-temporal characteristics, moment rates, etc.)
  - Stress drop, stress fields and energy; kinematics and dynamics
- Ergodicity principle
  - Learning and inferring from other similar regions
  - Appreciating similarities and differences

# Two ways to learn from earthquakes

## Single event studies

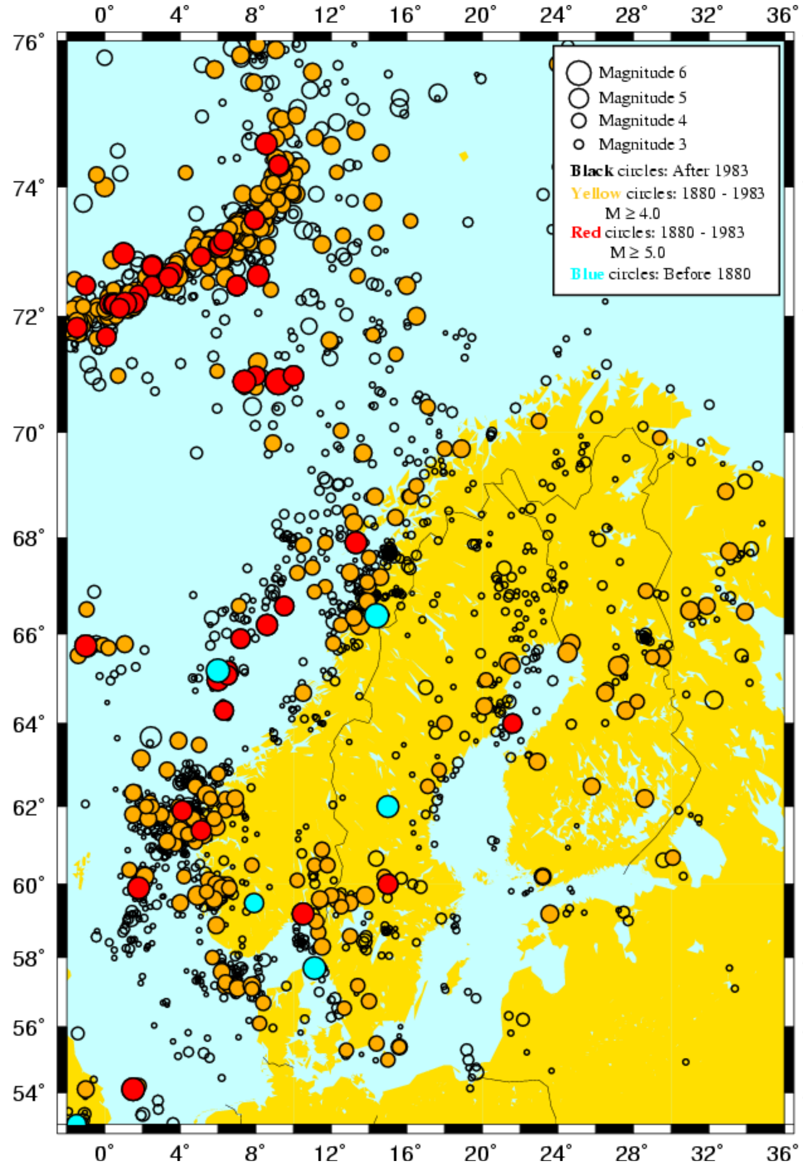
- Location and depth
- Magnitude, energy release, moment tensor
- Faulting  mechanism (mode of faulting)
- Fault length, width and displacement
- Stress drop
- Source time functions
- Rupture characteristics
- Source complexity
- Permanent crustal effects
- etc. ...

## Ensemble studies

- Spatio-temporal development
- Inferred stresses and driving forces
- Moment rates, energy budgets, coupling factors
- Inter-plate movements and plate motions (size and orientation)
- Crustal deformation, strain rates
- Lithospheric dynamics
- Occurrence and recurrence statistics, earthquake ‘prediction’
- Social and economic implications
- etc …

# Fennoscandian seismicity since 1880

- Highest seismicity in NW Europe, highest offshore
- Magnitude 5.8, 1819, Rana
  Magnitude 5.4, 1904, Oslofjord
- Broadly confined to coastal regions
- Follows the passive continental margin along mid-Norway
- Confined as well to (failed) rift zones (North Sea and Oslo Graben)
- Stability but also randomness
- Significant time variations over ~10-20 years
- Last 'quiet' period: 1989 to present (none above M 4.5)




From Fjeldskaar et al. (2000)

# Neotectonic research in Norway

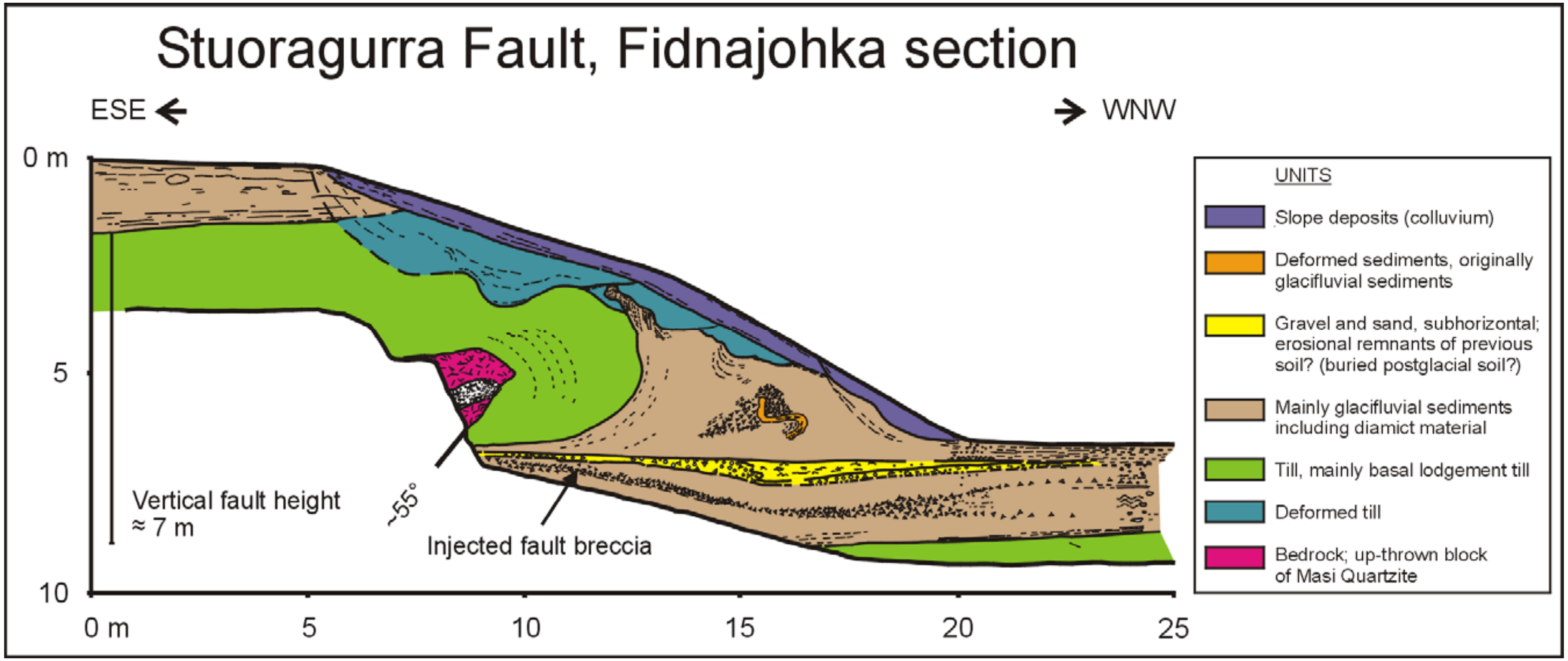
- Research goals
  - Spatio-temporal characterization of crustal deformations
  - Processes causing crustal deformations
  - Geohazard implications
- Approaches
  - Reassessment and classification of neotectonic observations
  - Reassessment and contouring of present rates of uplift
  - Studies of postglacial faulting and other similar phenomena
  - Search for new neotectonic indicators, onshore and offshore
  - Understanding present level and character of crustal movements
- Results
  - Most earlier claims for neotectonic phenomena discarded
  - Stuoragurra (Masi) fault: One major earthquake (M7+)
  - Norwegian margin: Most likely hidden thrust faults
  - Present seismicity very small as compared to present uplift
  - Many simultaneous sources of stress (regional to local)

# Stuoragurra (Masi) postglacial fault, Finnmark (8-9 kybp)

Photo: Odleiv Olesen (NGU)

# Stuoragurra Postglacial Fault (Masi, Finnmark)

- Trench oriented normal to the fault, vertical fault height 7 m
- Folded Quaternary sequence consisting of basal till and glaciofluvial sediments above and in front of the up-thrown hangingwall block of the fault.
- The fault breccia that has been injected into the glaciofluvial sediments most likely as a mixture of rock fragments and high-pressure groundwater.




From Dehls et al. (2000)

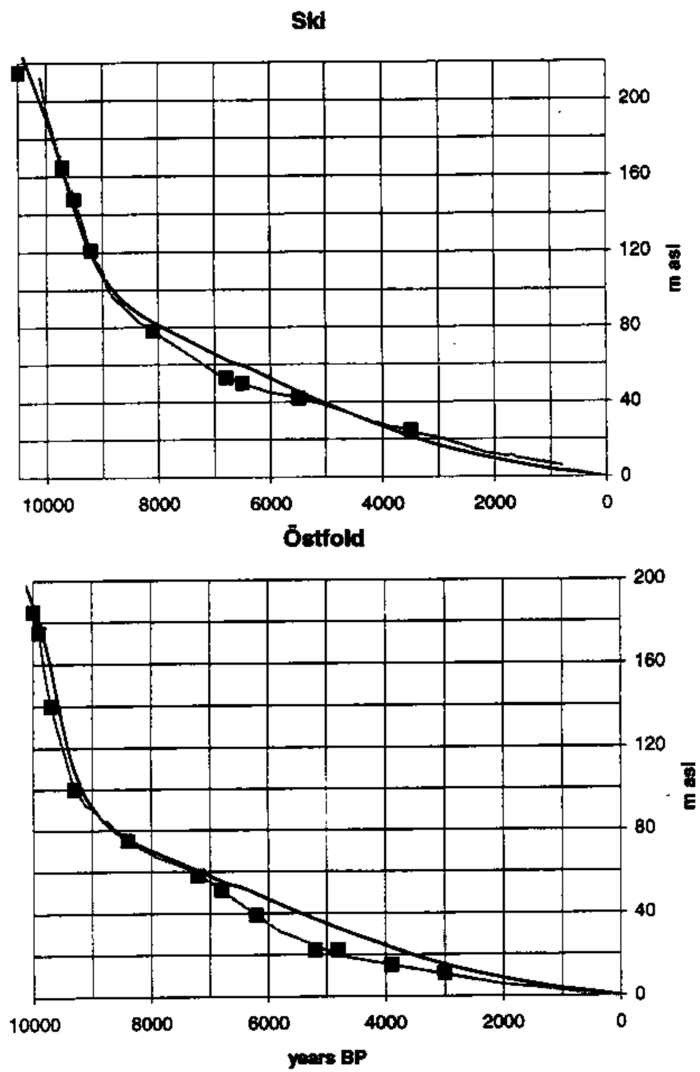
# Large postglacial earthquakes, northern Fennoscandia

- Pärve and Landsjärv faults have been extensively studied earlier (by SKB)
- The Stuoragurra has been extensively studied recently (NGU):
  - Most likely there was one large earthquake (M~7.7)
  - The fault zone is weakly seismically active at present,
  - albeit under a completely different stress field

| Fault | Length (km) | Displace -ment (m) | Magni-tude |
|---|---|---|---|
| Pärve | 165 | 13 | 8.1 |
| Stuoragurra (Masi) | 80 | 7 | 7.7 |
| Laino-Suijavaara | 55 | 30 | 8.0 |
| Suasselka | 48 | 5 | 7.4 |
| Landsjärv | 50 | 55 | 7.9 |

# Shore Level Displacement Curves (Påsse)

- Development in seismicity may grossly have followed the shore level displacement curves
- Outstanding problems:
  - For how long does the effect (with respect to the Mohr failure criterion) of the removal of the ice cap last?
  - Irregular release of remnant stresses to be expected
  - Only a small part of the energy involved in the uplift is taken our seismically
  - Interaction with tectonics essential but still poorly known
  - Long return periods creates 'catalog inhomogeneities'

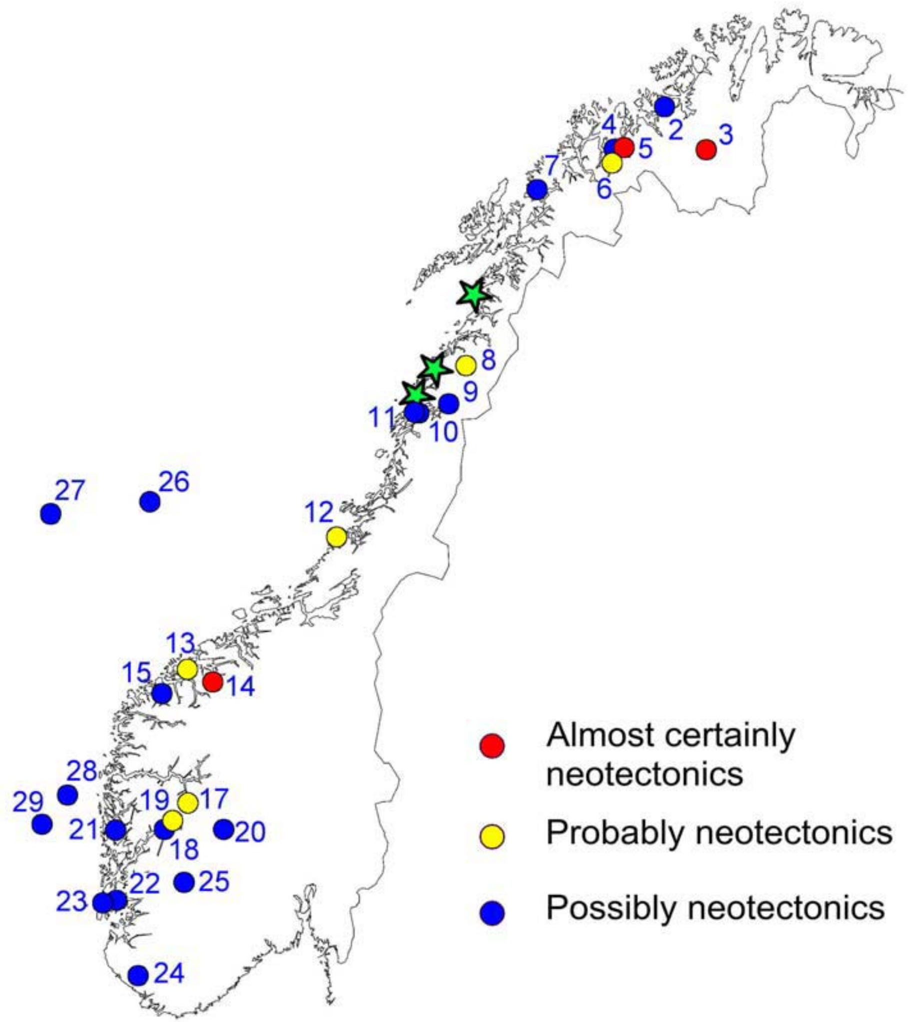



From Påsse (1997; 2001)

# Neotectonic claims and observations in Norway

- Locations of neotectonic claims that have been classified A, B and C (reports with grades D and E are not shown).
- Green stars denote shallow earthquake swarms (mostly normal faulting).
- See also

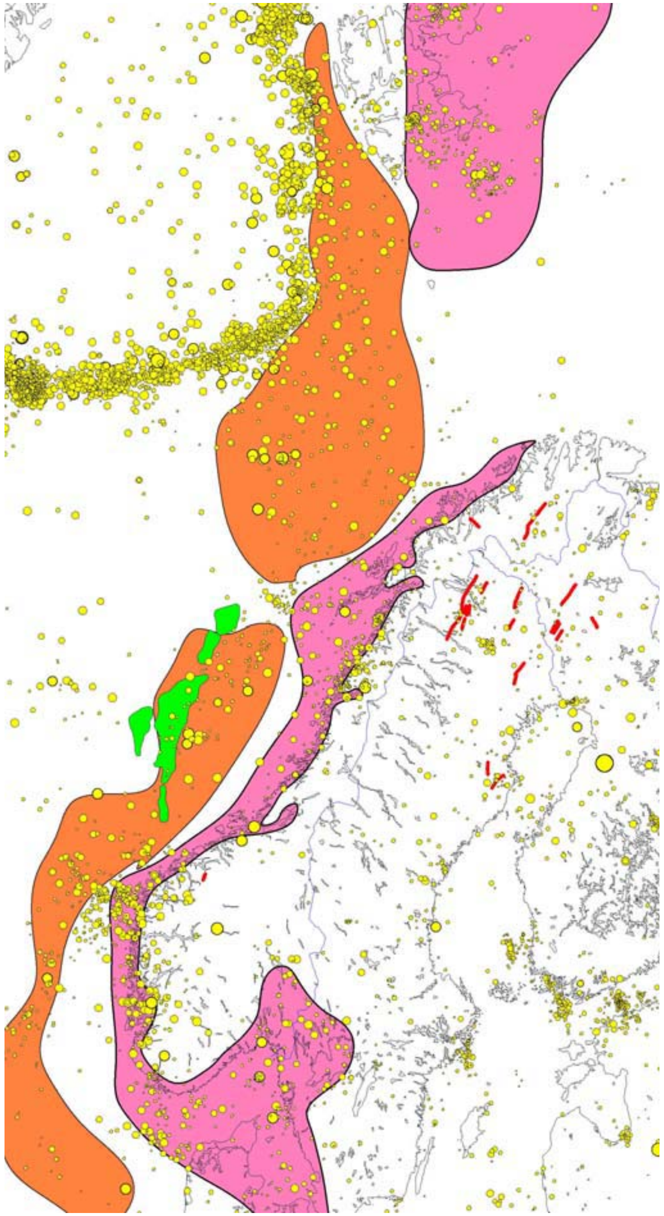
  Dehls et al. (2000);
  Olesen et al. (2000)




From Olesen et al. (2008)

# Fennoscandian seismotectonics

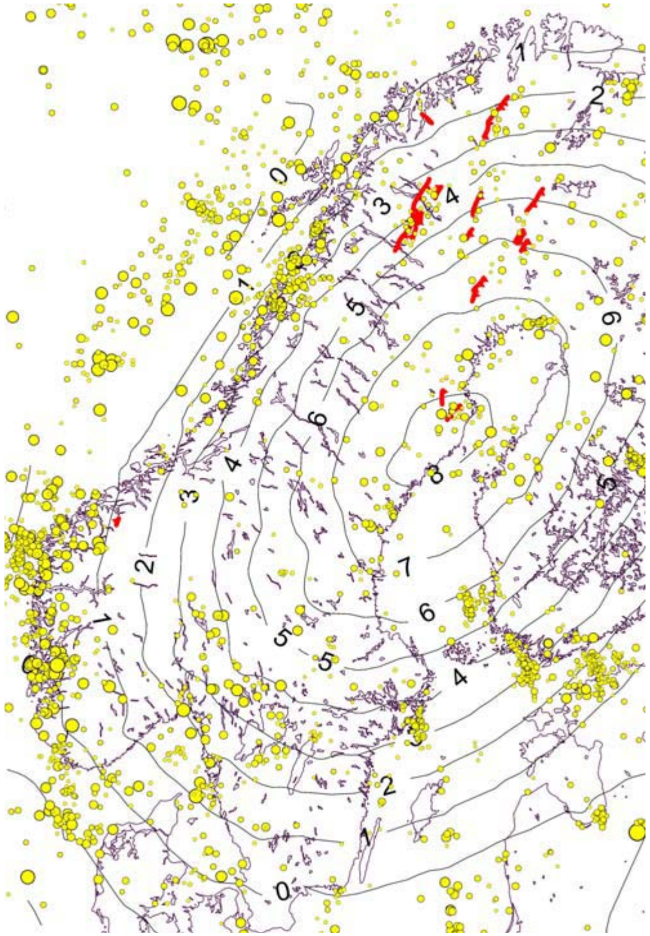
- Earthquakes, postglacial faults, Neogene domes and areas of interpreted Plio-Pleistocene depositions and erosion along the Norwegian continental margin.
- Areas of Plio-Pleistocene sedimentation and erosion are coinciding with present day seismicity indicating that recent loading/unloading is causing flexuring and faulting in the lithosphere.
- The erosion of the central and southwestern Barents Sea may be older that the erosion of the Svalbard region and the coastal areas of northern, western and southeastern Norway since the seismicity of the former area is low.
- Focal plane solutions indicate dominating compressional events in the areas with loading while the regions with recent unloading have dominating extensional or strike slip events.

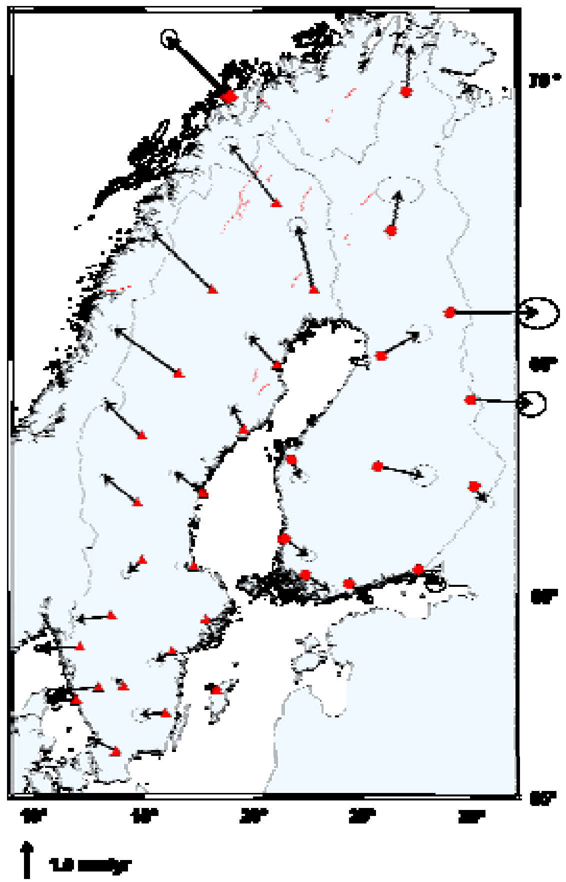


From Olesen et al. (2008)

**Left**: Present annual velocity of the Fennoscandian bedrock, with uplift in mm/year and earthquake epicentres (1758-2007). There is no direct correlation between uplift pattern and seismicity in Fennoscandia.

**Right**: Horizontal velocity vectors estimated at BIFROST GPS sites. The scale is represented by each of these vectors (with error ellipses). Red lines show the locations of postglacial faults.

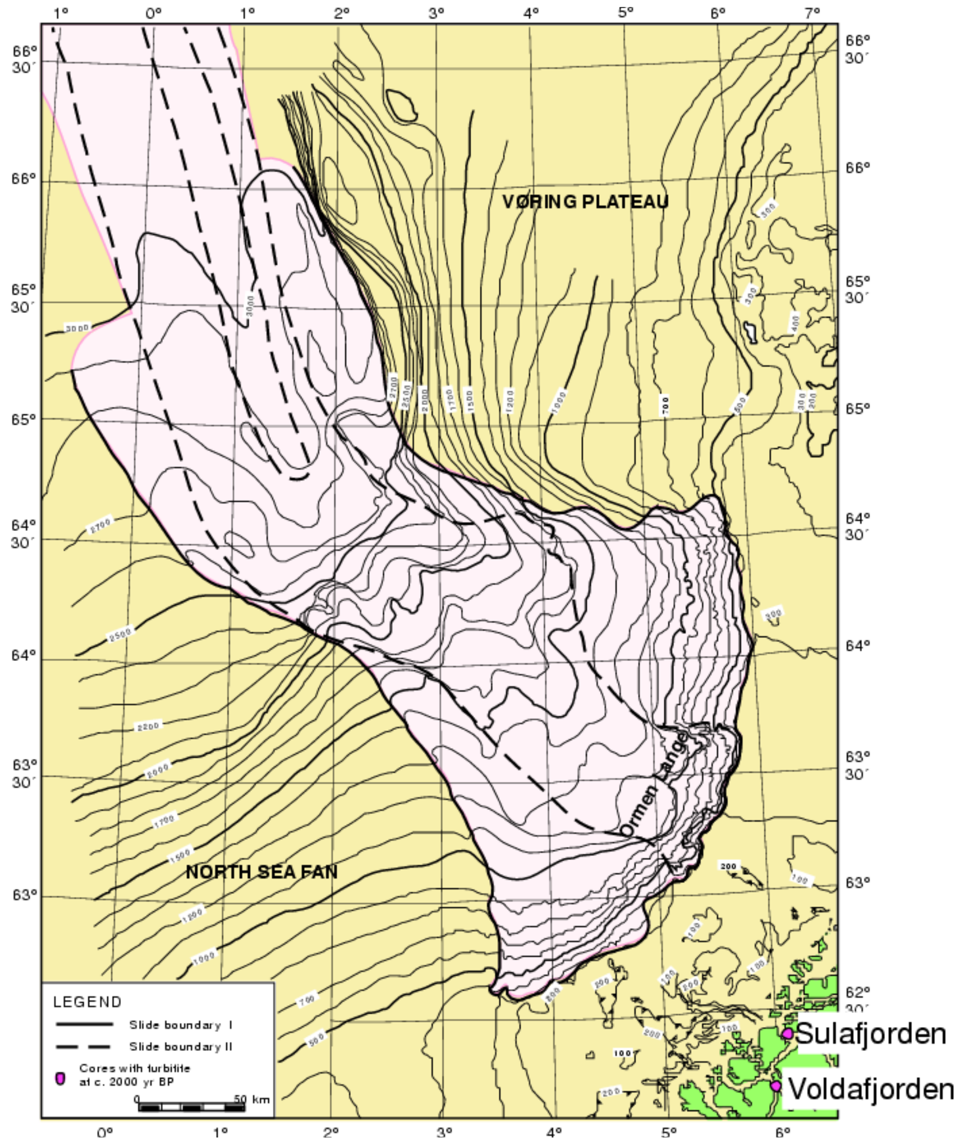




**From Olesen et al. (2008)**

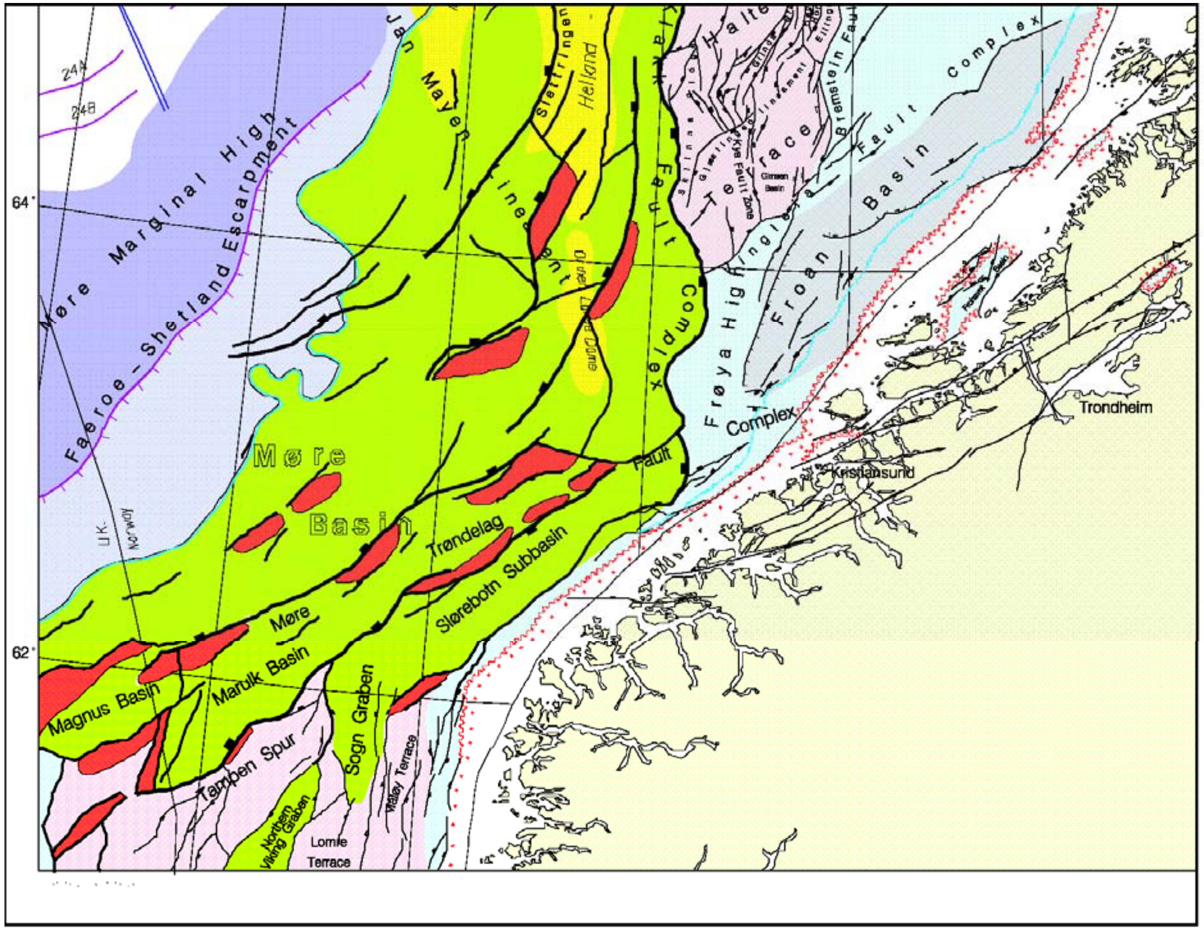
# The giant Storegga subaqueous slide

- The Storegga mega-slide:
  - Dated to ~8200 ybp
  - Run-out distance 850 km
  - Maximum thickness 430 m
  - Slide scar area 430 $km^2$
  - Influenced area 112,500 $km^2$
  - Major tsunami effects mapped
- Most likely earthquake triggered
  - Which earthquake?
  - Which fault?



# Map of major faults, Møre Basin

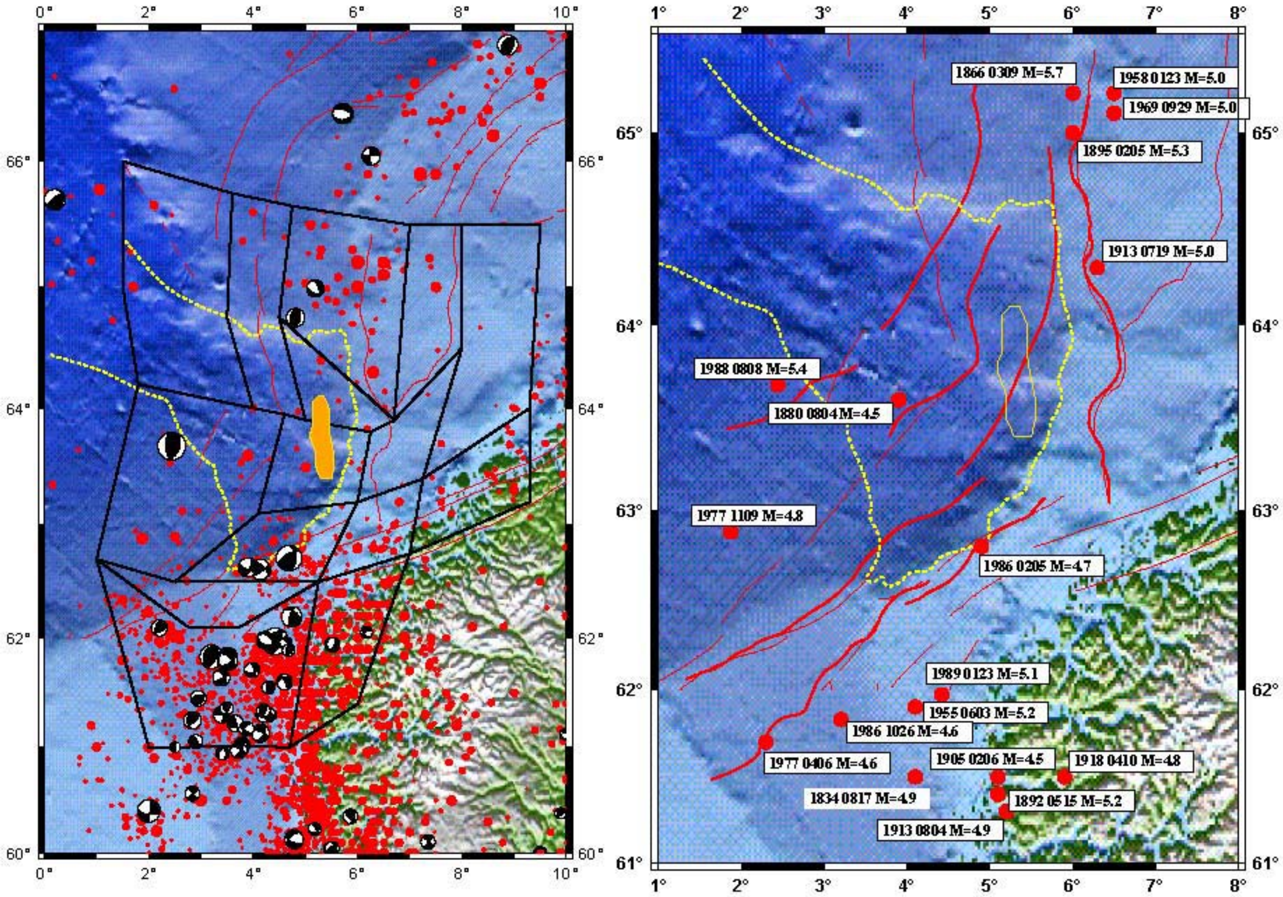
- Updated map of major basement related faults for mid-Norway
- Based on analysis of reflection, refraction and potential field data
- Six major fault complexes:
  - Tampen Spur – Gossa
  - Manet Ridge – Ona High
  - Vigra High – Grip High
  - Ormen Lange
  - Slettringen Ridge
  - Klakk Fault Complex
- Weak correlation with present seismicity




Courtesy of Jan Inge Faleide

# Historical earthquakes, mid Norway

- Left: Long term seismicity and focal mechanisms; old fault map
- Right: Larger earthquakes together with a new map (Faleide) of deep and major fault structures
- Basically only a broad regional correlation between earthquakes and mapped faults
- Dotted line indicates the giant 8200 ybp subaqueous Storegga slide
- Several structures could have accomodated earthquakes large enough (M~7) to trigger the Storegga slide

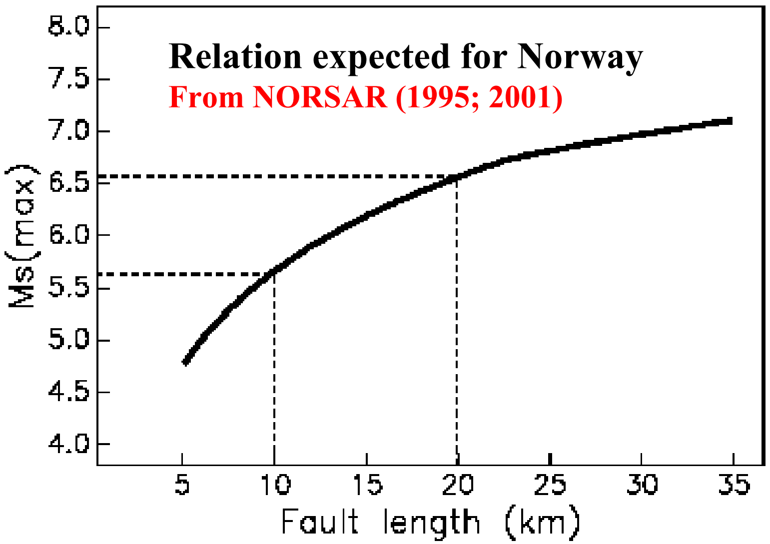


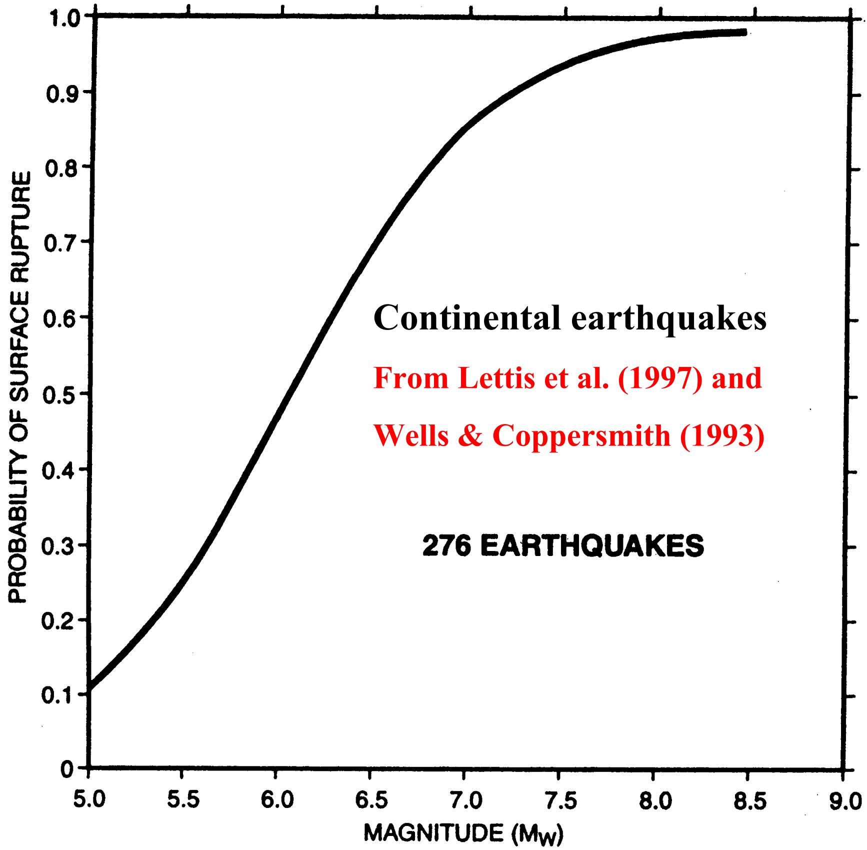



From Bungum et al. (2002)

# Hidden postglacial (thrust) faulting?

- Extensive search for NCS surface neotectonic faulting without finding anything (except Beril)
- Thrust faults with M>6.5 may have occurred without breaking the surface
- Most likely that such earthquakes have occurred during Holocene



# Large earthquakes in Stable Continental Regions

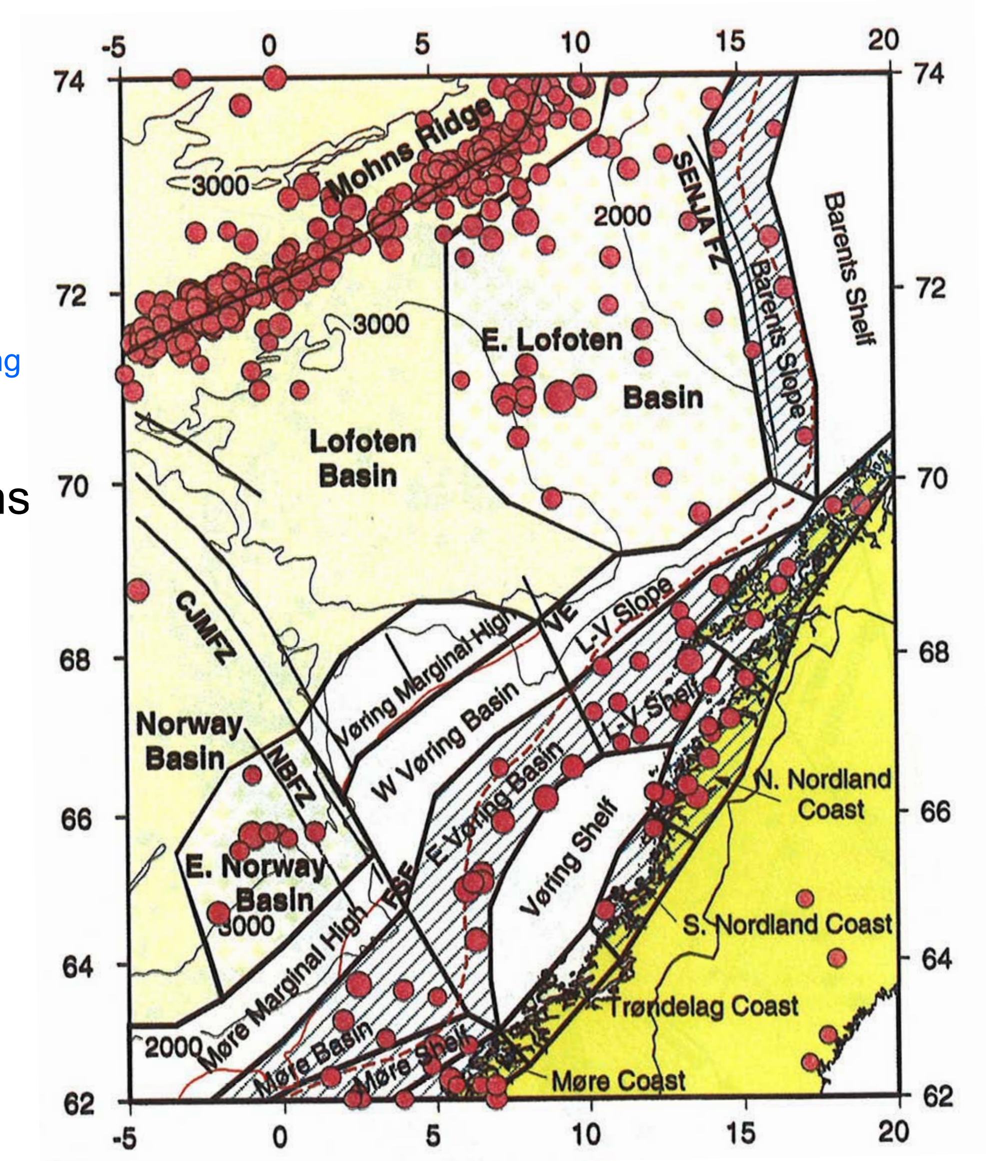
- Results from EPRI (Electric Power Research Institute) study (Johnston et al., 1994)
- Sheared (rifted) margins and failed rift zones particularly vulnerable
- Using the ergodicity principle (exchanging time for space)
- Large earthquakes do occur in geologically similar areas
- Very long return periods (up to thousands of years)
- Indicating a possible earthquake deficit (or larger potentials than often assumed) along the Norwegian margin

| Earthquake | Year | Host Structure | Mag. |
|---|---|---|---|
| Basel | 1356 | rift | 7.4 |
| Taiwan Straits | 1604 | margin | 7.7 |
| Hainan Island | 1605 | rift | 7.3 |
| New Madrid | 1811 | rift | 7.6 |
| New Madrid | 1812 | rift | 7.5 |
| New Madrid | 1812 | rift | 7.8 |
| Portugal | 1858 | margin | 7.1 |
| Kutch (Gujarat, Bhuj) | 1819 | rift | 7.8 |
| South Carolina | 1886 | margin | 7.6 |
| Exmouth Plateau | 1906 | margin | 7.2 |
| Nanai | 1918 | margin | 7.4 |
| Grand Banks | 1929 | margin | 7.4 |
| Baffin Bay | 1933 | margin | 7.7 |
| Libya | 1935 | margin | 7.1 |
| South Tasman Rise | 1951 | margin | 7.0 |
| Kutch (Gujarat, Bhuj) | 2001 | rift | 7.9 |

From Bungum et al. (2005)

# Seismotectonic provinces and processes, mid-Norway

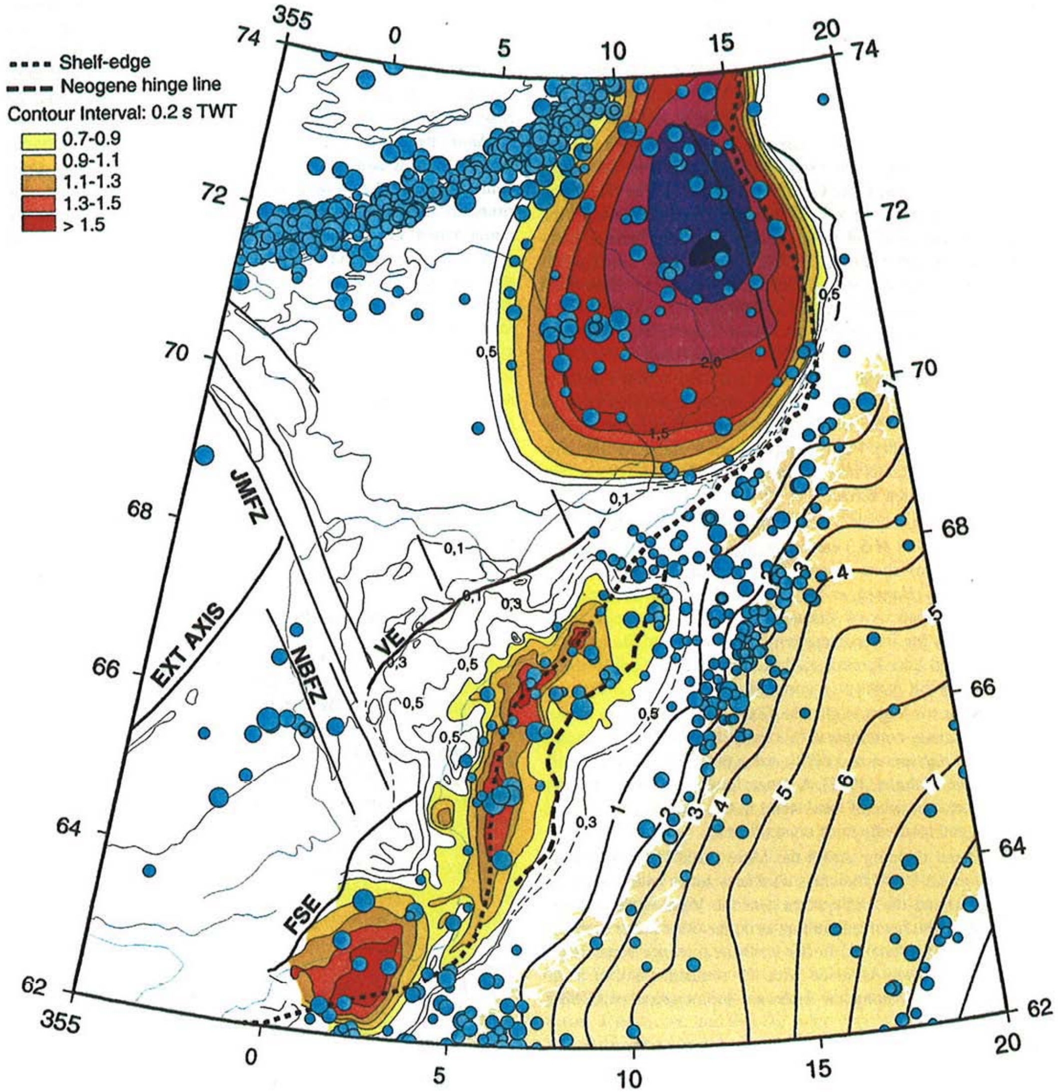
- Oceanic crust
  - Mostly fully aseismic
  - However, seismically active in areas with rapid glacial loading, particularly in
  - East Lofoten and East Norway Basins
- Marginal highs and adjacent basins
  - Experienced rifting prior to breakup
  - Crustal thickening and underplating, strengthning the crust
  - Therefore, seismically inactive
- The margin: Vøring and Møre Basins
  - Crustal thinning, fractured crust
  - Sediment loading
  - Seismically active
  - Margin-perpendicular compression
- Vøring Shelf (Trøndelag Platform)
  - Thick crust, stable for 200 Myr
  - Fully aseismic
- Coastal areas
  - Shallow crustal extension
  - High rebound rates
  - Seismicity related to uplift




From Byrkjeland et al. (2000)

# Mid Norway - Stress and seismicity effects of Glacial Wedges

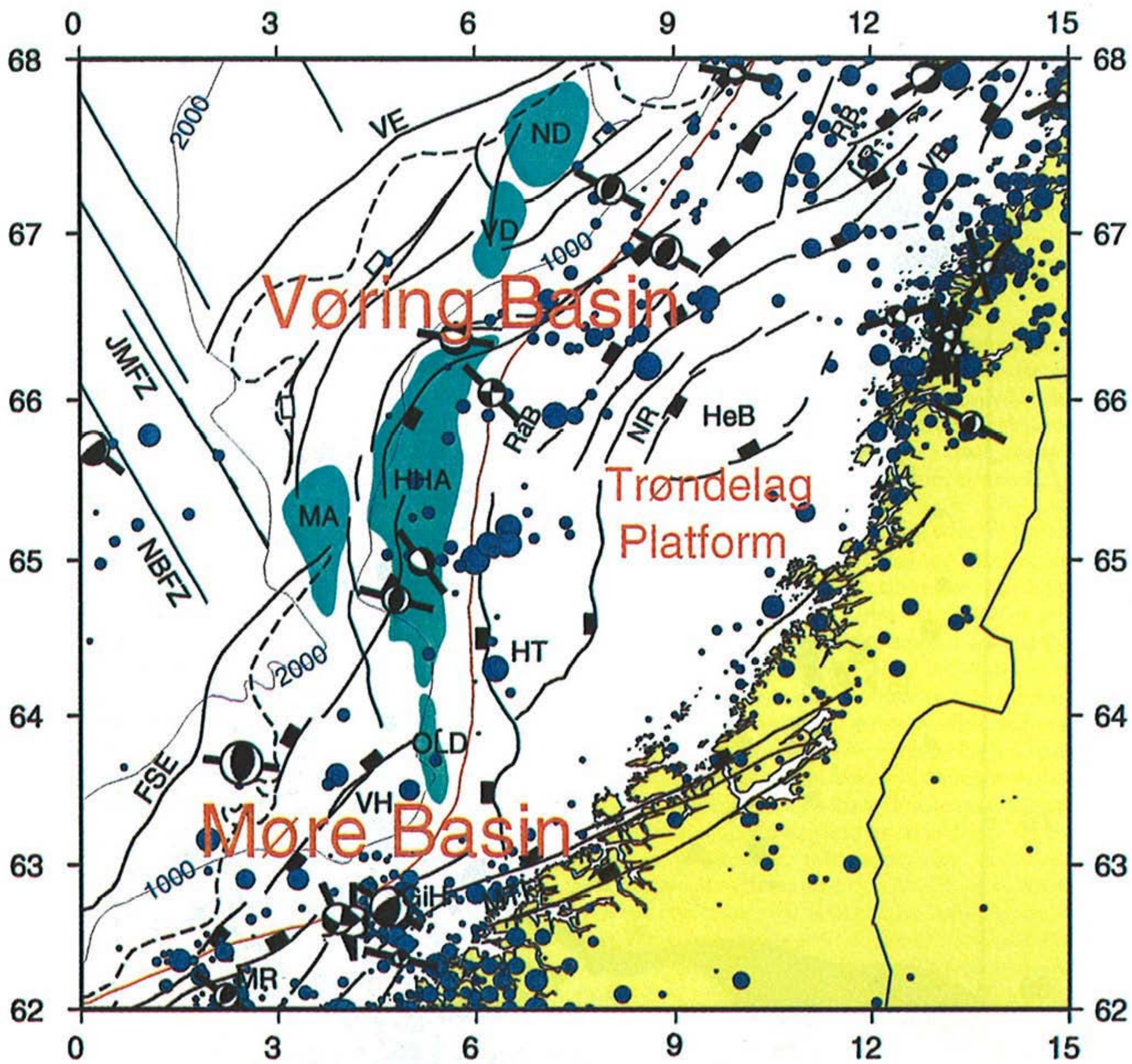
- Glacial wedges
  - Plio-Pleistocene age
  - Rapid sedimentation
  - Rejuvenation of Early Cretaceous faults
  - Modifying stress field in underlying crust
  - Spatial correlation with seismicity




From Byrkjeland et al. (2000)

# Vøring and Møre Basins

- Regional correlation with structures (crustal weakening)
- No real one-to-one correlation with mapped faults
- EW compressional stress field offshore, deep events
- Shallow seismicity onshore, EW extension




From Byrkjeland et al. (2000)

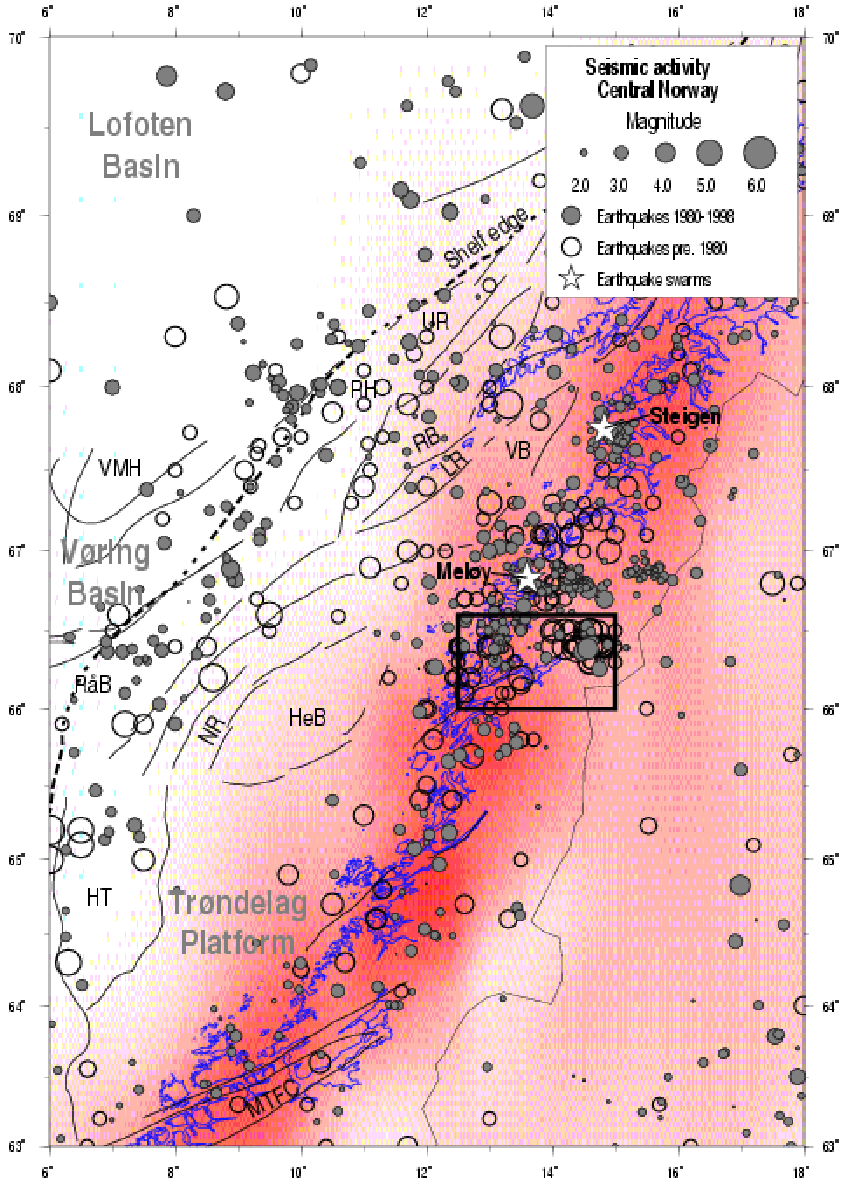
# Earthquakes and postglacial uplift

General:

- Seismicity along the margin is related to major structures and depocenters with high deposit rates

Moreover:

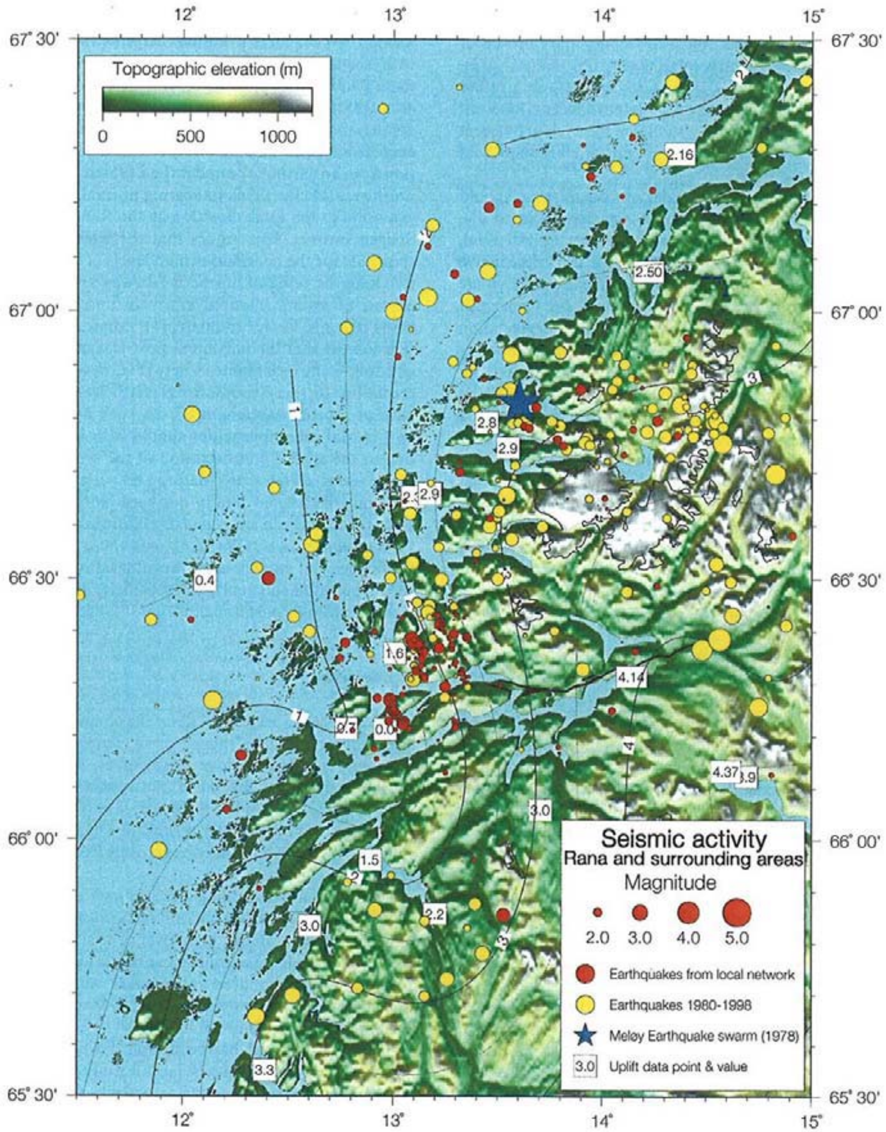
- Maximum uplift gradient is found along the coast, indicating flexuring effects
- Seismicity along the coast is dominated by normal mechanisms and shallow foci, as expected from flexuring
- Indicating a direct relation between postglacial uplift and seismicity, contrary to what is found elsewhere in Fennoscandia




From Hicks et al. (2000)

# Detailed study in the Rana region – significant earthquake potentials

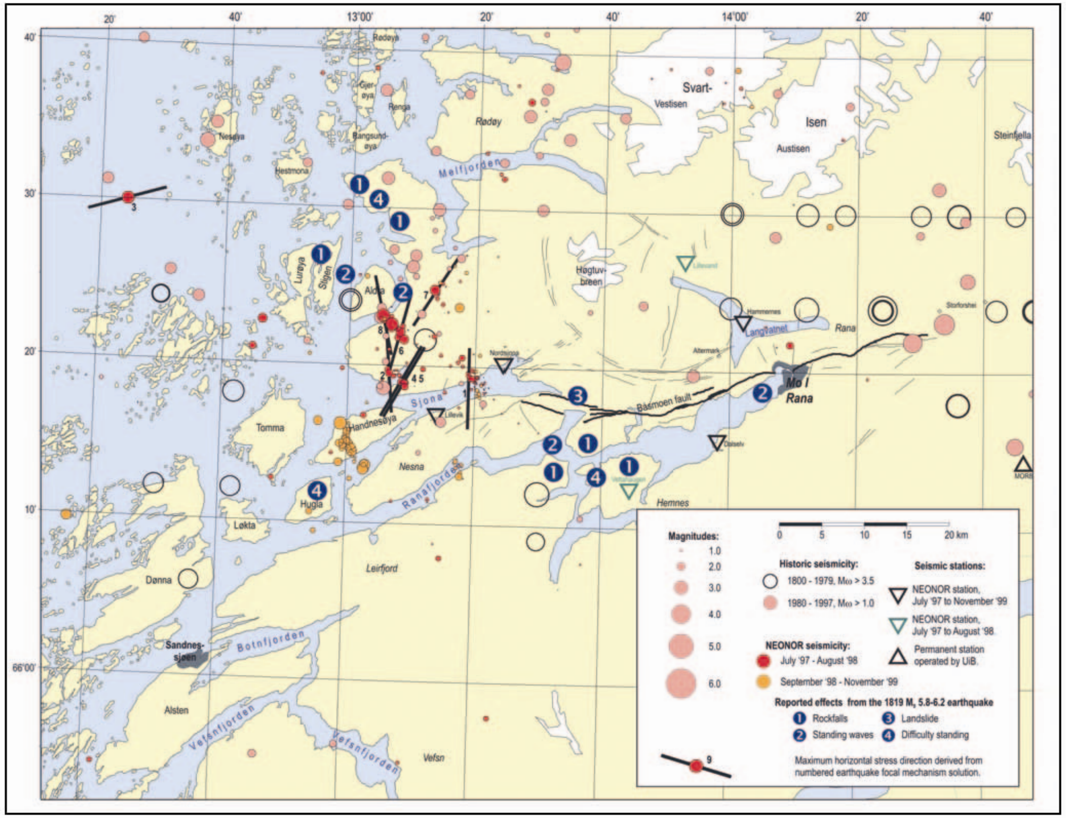
- Recent (1997-1999) and longer term (1980-1998) seismicity in the Rana region
- Site of largest historical earthquake in Norway (1819, M 5.8)
- Shallow seismicity, extensional stress regime
- Anomalous and irregional crustal uplift patterns
- Region characterized by swarms (Meløy, Steigen, Rana)
- Influence of glacio-isostatic adjustments




From Hicks et al. (2000)

# The 1819 M 5.8 N. Norway earthquake

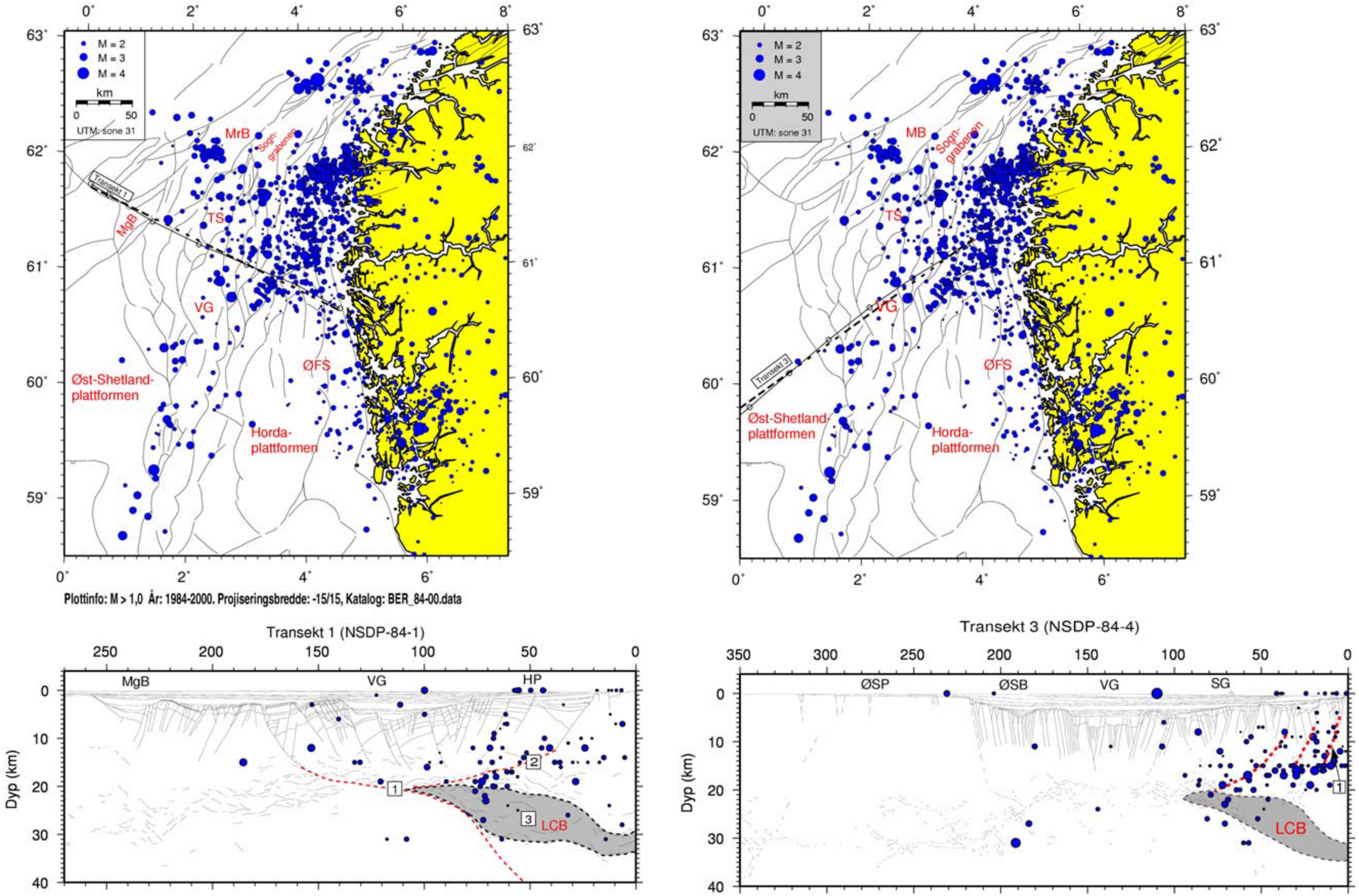
- Largest historical earthquake in Fennoscandia
- Rock falls, waves, landslides, difficulties standing
- Relatively high seismic activity also presently; swarms


From Bungum & Olesen (2005)

# Northern North Sea seismotectonics

## Viking Graben seismicity depth profiles - lower crustal high-density bodies

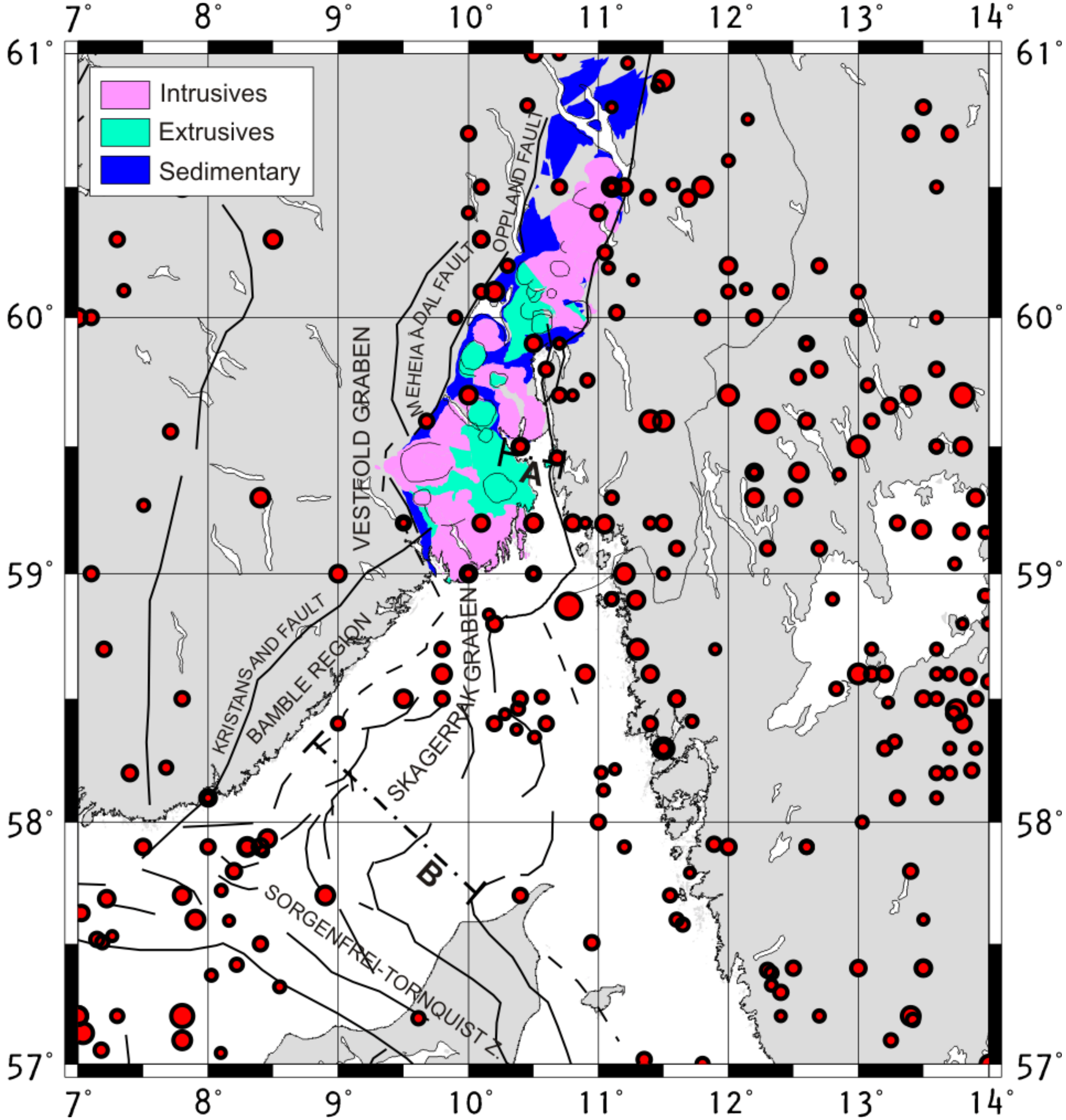





**From Møllegaard (2000)**

# Oslo Rift Zone

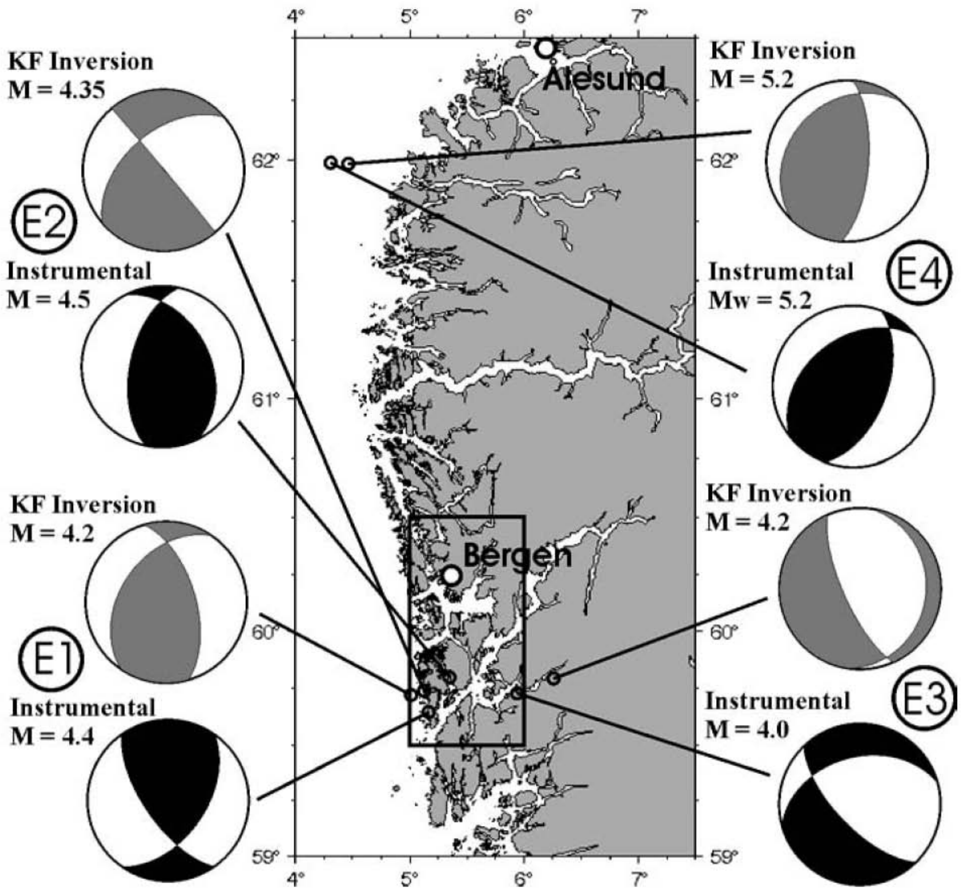
- Structural map of the Oslo Rift and adjacent areas (after Heeremans and Faleide, 2004).
- Onshore geology of the Oslo Graben is shown with Permian intrusives (pink), extrusives (green) and Lower Paleozoic sedimentary strata (blue). The round shapes inside the rift are calderas.
- Red circles are seismicity since 1980 for magnitude 2.5 and above (symbol size proportional to magnitude




From Bungum et al. (2008)

# Inversion of the macroseismic intensity field Western Norway

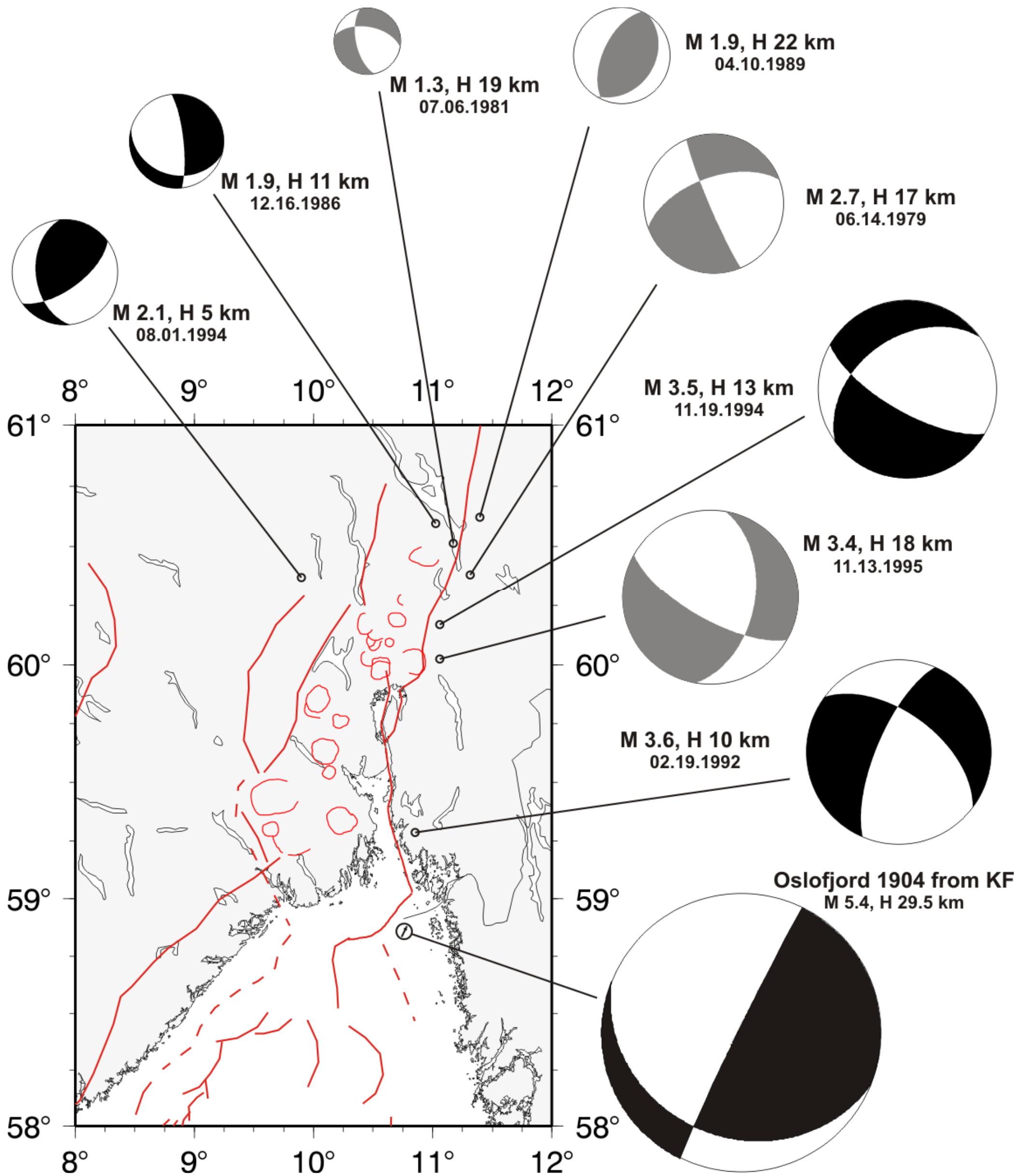
- KF (Kinematic Function) inversion of macroseismic intensities using a method developed by Livio Sirovich and Franco Pettenati (OGS).
- Tested here on four small but well-recorded events where instrumental solutions are available.
- The match is very good which makes the method interesting to use on older events such as the 1904 M=5.4 Oslofjord earthquake.




From Pettenati et al. (2005)

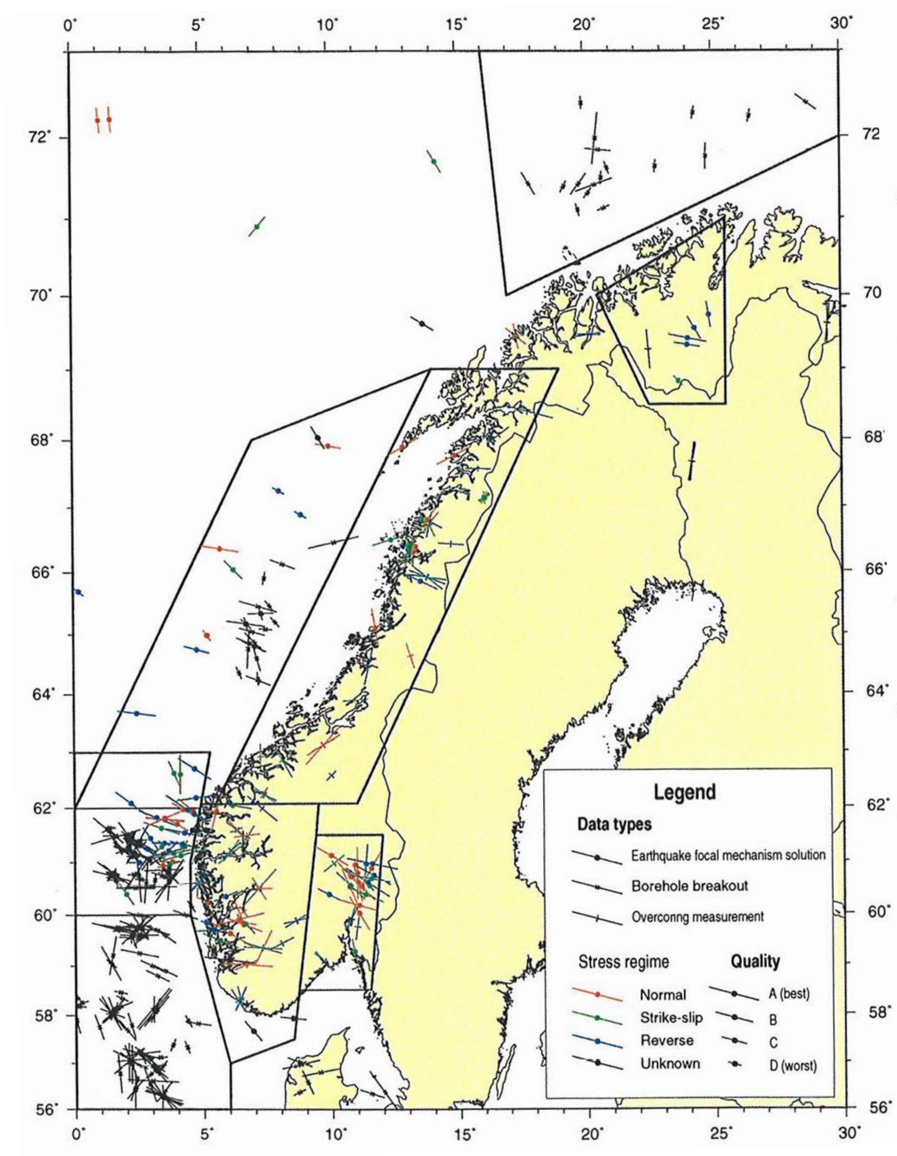
# The 1904 Oslofjord M 5.4 earthquake

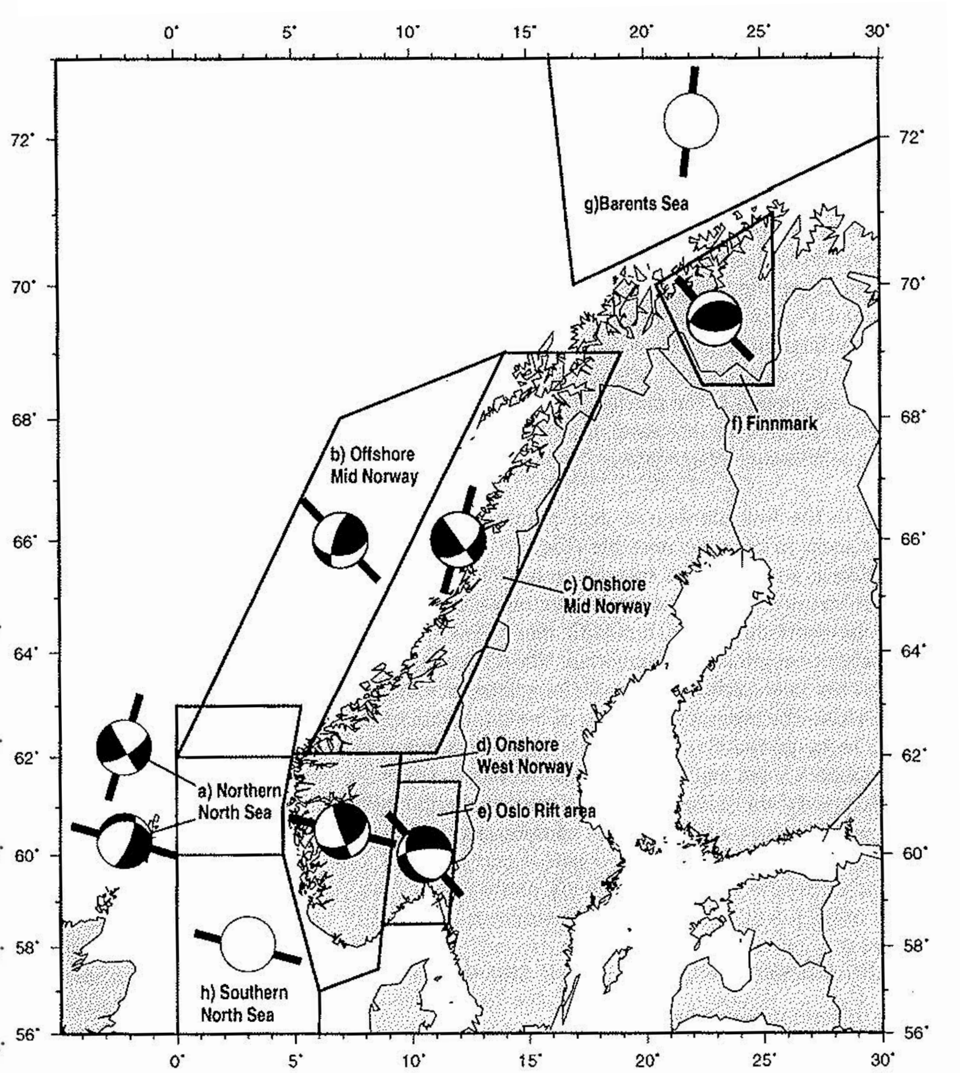
- Major faults of the Oslo Rift zone and recent fault-plane solutions after Hicks et al. (2000).
- The beach ball of the 1904 earthquake comes from a new inversion of the macroseismic field.
- The 1904 event is located close to a major fault junction and with a NE-SW orientation.
- Oslo Rift events are located throughout the crust and with a variety of focal mechanisms.




From Bungum et al. (2008)

# Stress directions onshore and offshore Norway



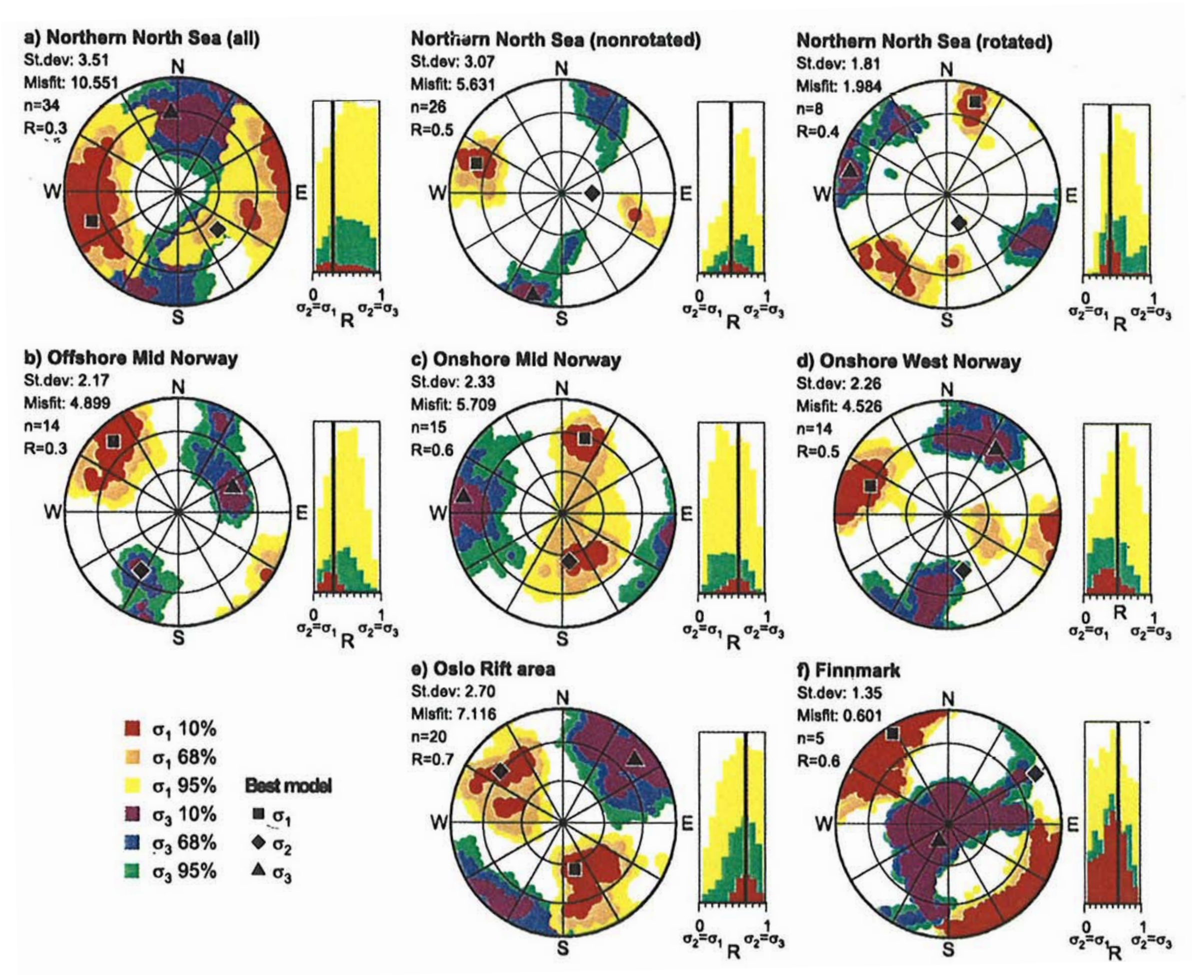




**From Hicks et al. (2000)**

# Regionalized stress directions

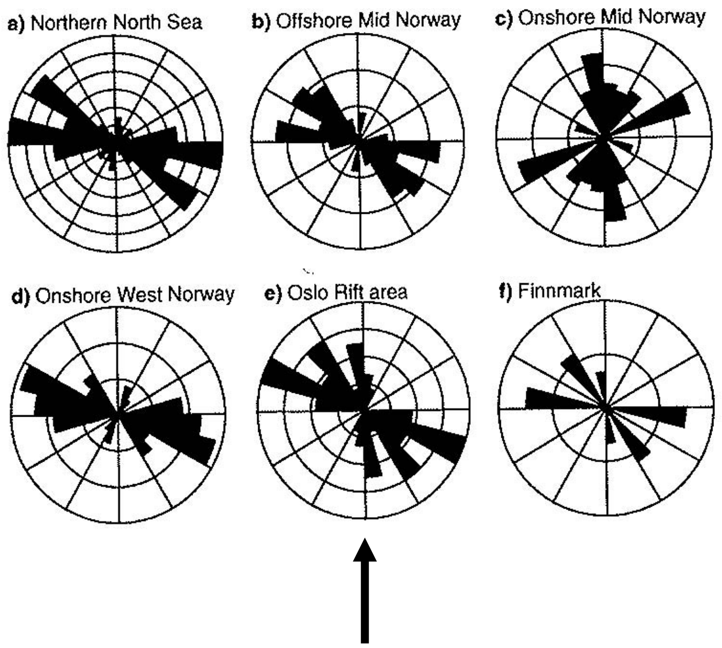
## Simultaneous inversion of earthquake focal mechanism inferred stress

- Based on Gephard & Forsyth's (1984) inversion method
- Inverting all focal mechanisms in one region for a common stress field
- More stable and regionally representative values than those from single earthquakes
- Provides also confidence assessments for the stress exes ($\sigma_1$, $\sigma_2$, $\sigma_3$)
- Results dominated by NW-SE compressional stress (with some important exceptions)
- Indicating ridge push (with some important exceptions)




From Hicks et al. (2000)

# Regionalized stress directions onshore and offshore Norway

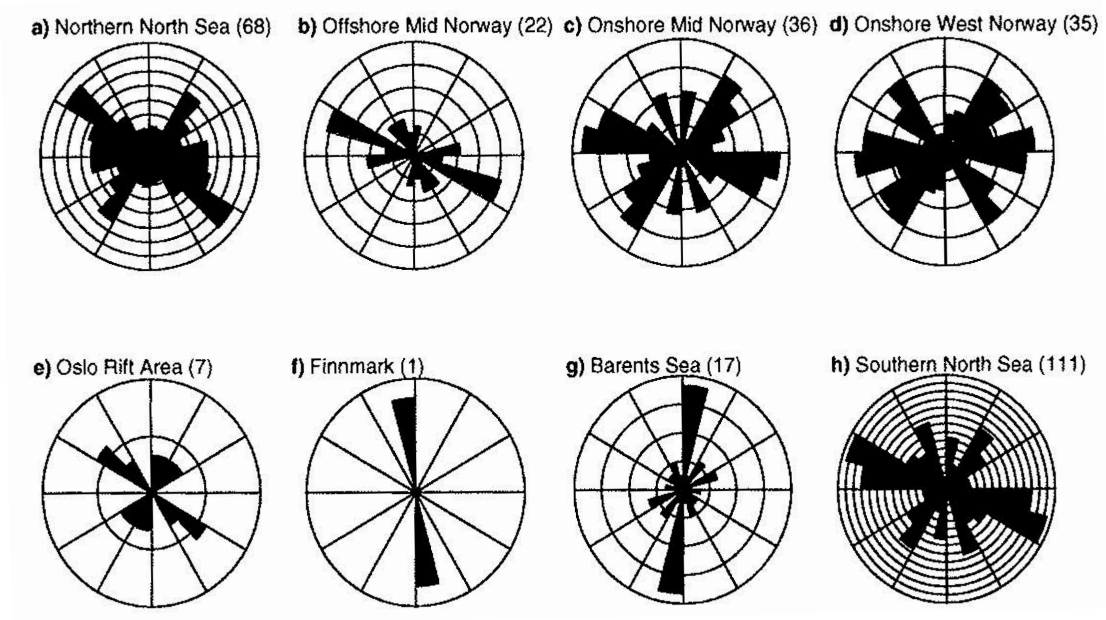



**Inferred from earthquakes**

**(individual estimates)**

**In-situ measurements**

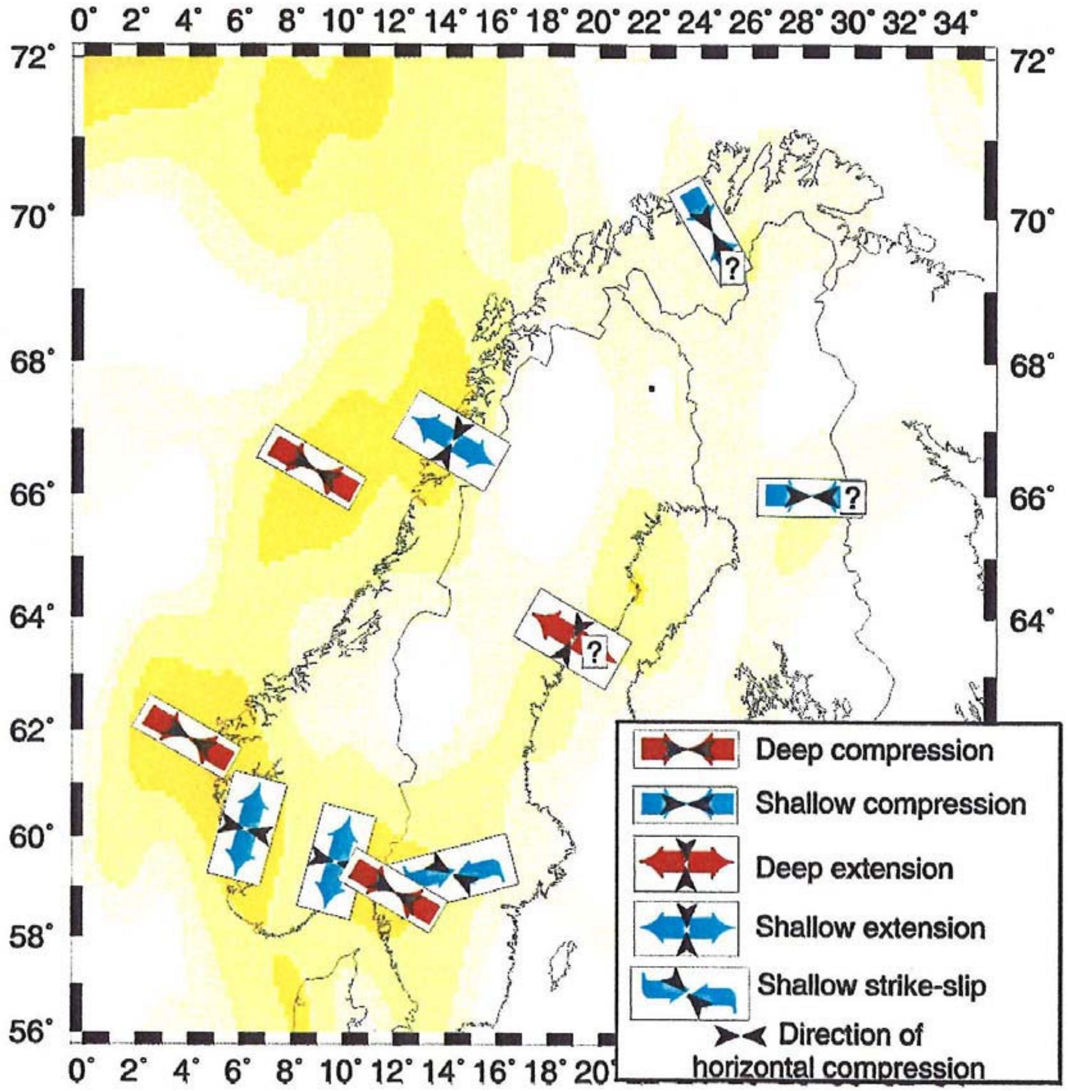
**(borehole breakouts, overcoring)**




**From Hicks et al. (2000)**

# Summary of stress directions, modes of faulting and focal depths

- Offshore: Deep earthquakes, consistently reverse faulting (ridge push)
- Coastal N. Norway: Shallow earthquakes, swarms, normal faulting, (glacio-isostatic adjustment)
- SW Norway: Mixed modes, including shallow normal
- Oslo Rift: Earthquakes in the entire crust, shallow normal, deeper strike-slip and reverse




From Fjeldskaar et al. (2000)

# Intraplate stress generating mechanisms

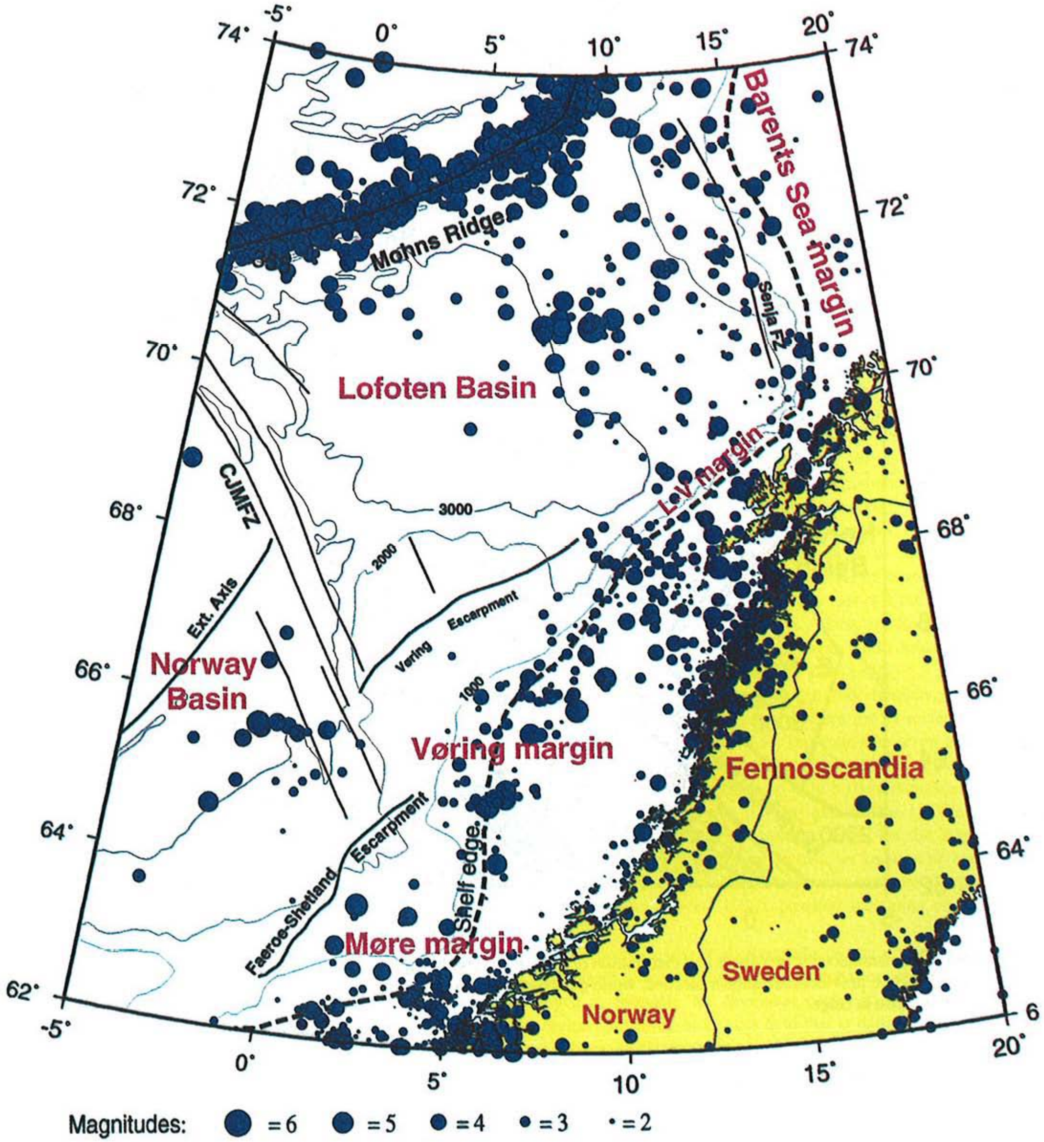
- Continental Scale (> 1000 km)
  - Plate Tectonic Forces
- Regional Scale (100-1000 km)
  - Density Inhomogeneities
  - Flexural stresses
  - Topographic loads
- Local Scale (< 100 km)
  - Topography
  - Geological Features
- Conclusions
  - Ridge Push not sufficient, regional and local sources needed, plus favorably oriented and sufficiently weak faults.

# Fennoscandian Holocene seismicity development

- High seismicity (M7+) in response to initial deglaciation
  - Large faults in northern Fennoscandia
  - Hidden thrust fault potentials offshore
  - Responsible for landslides, rockfalls and turbidites
- Low (to intermediate) seismicity at present
  - "Stable Continental Region"; larger earthquakes well known
  - Events confined to rifted passive margins and failed rifts
  - Earthquake potentials for M6.5+, but with long return times
  - Seismotectonics is complex but still fairly well understood
  - Governed by laws but still strongly affected by randomness
  - 20-year "quiescence" at present (expecting a large one soon …)
- Gradual decrease between the two
  - The seismicity has been largely following the uplift rates
  - Small amount of energy released seismically, compared to strain rates
  - Present effects of rebound remaining only along coast of N. Norway

# Present-day seismotectonics

- Many simultaneous sources of stress
  - Continental, regional and local scales
  - Ridge push
  - Postglacial uplift
  - Depocenters
  - Morphology and crustal structure
- Interaction with geological structures
  - Favorably oriented faults and fault zones
  - Regions of earlier deformation
  - Basins and marginal highs




From Byrkjeland et al. (2000)

# Driving forces for Fennoscandian earthquakes

- A variety of sources of stress are responsible for earthquakes in Norway, ranging from plate related through regional to local
- Some of these are
  - Ridge push forces
  - Sedimentation induced flexures
  - Postglacial uplift
  - Crustal inhomogeneities
- Local zones of weakness are necessary for releasing the stress from these sources