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Søren Gregersen, Peter Voss. Irregularities in Scandinavian postglacial uplift/subsidence in time scales tens, hundreds, thousands of years. *Journal of Geodynamics*, 2010, 50 (1), pp.27. 10.1016/j.jog.2009.11.004 . hal-00634695

**HAL Id: hal-00634695**

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Submitted on 22 Oct 2011

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## Accepted Manuscript

Title: Irregularities in Scandinavian postglacial uplift/subsidence in time scales tens, hundreds, thousands of years

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PII: S0264-3707(09)00160-4  
DOI: doi:10.1016/j.jog.2009.11.004  
Reference: GEOD 953

To appear in: *Journal of Geodynamics*

Received date: 31-10-2008  
Revised date: 21-8-2009  
Accepted date: 16-11-2009

Please cite this article as: Gregersen, S., Irregularities in Scandinavian postglacial uplift/subsidence in time scales tens, hundreds, thousands of years, *Journal of Geodynamics* (2008), doi:10.1016/j.jog.2009.11.004

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## **Irregularities in Scandinavian postglacial uplift/subsidence in time scales tens, hundreds, thousands of years.**

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### **Abstract**

Discussions continue on uplift/subsidence in Denmark/southern Scandinavia. The patterns in time scales of 10s, 100s and 1000s of years show some similarities and some differences. Geodetic observations exist for all of Scandinavia. Those describe the phenomenon in 10s – 100s of years scale. Earthquake observations in seismology are of relevance to the same time scales. Geological studies of dated shore lines describe the postglacial earth-surface motion in a quite different time scale of 100s – 1000s of years. There is a need for integration of these observations geographically. Present integration of the data of various time scales is that the overall uplift pattern of all time scales 10s, 100s, 1000s and 10,000 years are coincident. But a few geodynamics irregularities are found. Further observations in the various time scales will be collected together with process descriptions of the observed similarities and differences in the DynaQlim project.

### **Introduction**

Our geodesist colleagues are making more and more definitive observations of the uplift pattern of Scandinavia and the surrounding subsidence. Methods are improving from levelling and sea level observations, where observations improved as period of observation grew from tens of years to more than hundred years, to GPS measurements nowadays. Many of the DynaQlim papers of this volume present the good modern picture of these time scales. Such a good reference pattern NKG2005LU (Vestøl, 2006; Ågren and Svensson, 2007; Engsager et al. 2006, personal communication) is in the present paper displayed together with the longer term geological pattern of thousands of years. The latter gives the pattern of motion since the Ice Age, i.e. approx. 10,000 years. The comparison of the two patterns is seen in Figure 1. The differences in the broad scale picture are obviously small. This emphasizes that it is the same phenomenon which uplifts Scandinavia in the time scales tens, hundreds and thousands of years.

The first irregularity to be noticed is that the uplift rate has changed drastically from very fast right after the Ice Age to much slower nowadays.

### **Stresses in the lithosphere of various time scales**

For a description of the stresses in the Scandinavian lithosphere the uplift pattern may well be of some significance. But from a point of view of seismology, which can give information of the same short time scales as the geodetic observations, the uplift is one factor of several, which are dominated by the stresses caused by the present lithospheric plate movements (Gregersen and Voss, 2009; Olesen et al. 2004; Bungum et al. 1991; Lindholm et al. 2000; Gregersen, 1992). The earthquake geography in Scandinavia is displayed in Figure 2. Like displays of earthquake activity in other parts of the world it does not matter much which is the time period displayed. The general

pattern is the same in any time period, while small details can be different. The figure shows that the earthquake activity is most concentrated along the Norwegian coast and continental margin, along the Swedish east coast, and in and around the Oslo Fjord. It is well established that the earthquake activity in Denmark is the southern limitation of the Scandinavian seismicity (Gregersen et al., 1998). And there are no recent earthquakes in Jylland in the middle of Denmark. It is also established with good credibility that the earthquake activity is smaller in northern Germany, in Poland and in the Baltic states (e.g. Grünthal et al, 2008). In the latter areas the seismograph coverage has until recently been significantly poorer, so the information in the map is influenced by less sensitivity to small earthquakes. But there is not much doubt that the Kaliningrad events in 2004 of magnitudes just over 5 are very unusual for the coast of Poland, Russia and Lithuania (Gregersen et al. 2007). The map should be complete down to magnitude 4.

Also shown in Figure 2 are short heavy lines in northern Norway, Sweden and Finland. These show the locations of large postglacial faults, which are convincingly argued to be developed in large earthquakes (e.g. Lagerbäck, 1991; Olesen, 1991; Olesen et al. 2004). The dating of these earthquakes is very accurate via disturbances of sediments in liquefaction, and counting of varve layers. Coincident with the liquefaction phenomena are large landslides, which support the interpretation of these large faults as signs of earthquakes 9,000 years ago.

The central part of the postglacial uplift area is indicated in Figure 2 for comparison to the earthquake pattern. We have in several papers argued that there is no correlation between the uplift pattern and the earthquake geography (Gregersen, 2002; Gregersen and Voss, 2009). In those papers we have argued that the stresses have changed drastically during the 10,000 years of these investigated phenomena. Right after the Ice Age the uplift was dominating, while now the plate motions in plate tectonics sense are dominating. This is demonstrated by the lack of correlation of the seismicity and the uplift pattern. And it is confirmed by the overwhelming regularity of the compressional orientations of focal mechanisms in the area (Fig. 3) as well as other data of the World Stress Map Project (Zoback et al. 1989, 1992; Zoback 1992; Poutanen et al., 2009). Northwest – southeast compression is dominating, along the absolute lithosphere plate motions, although also many other scattered compression orientations are found. We note that the same conclusion of change of dominating stress is emphasized also by Mörner (2003) with overlapping as well as different arguments.

### **Uplift pattern and irregularities**

Going into the description of the general uplift pattern are the works of many scientists over the years (e.g. Mertz, 1924 and Paasse, 1996). The geological uplift pattern in Figure 1 is a generalisation of all of these investigations (Mörner, 2003). When one looks at a smaller area (Fig. 4) one finds more irregularities in the curves, even if these are also generalized and smoothed. With small kinks in the regional pattern it is seen that a very consistent pattern is revealed. Various claims of irregularities have been postulated though, in the points of Figure 4 marked by circles. Geological signs of motion, which have been promoted, are the following:

**Læsø, Denmark.** Hansen (1994) has investigated sand deposits of ages less than 10,000 years in Læsø and found indications of a large fault of displacement 4 meters. No other indicators of earthquakes have been identified. So it can not be distinguished whether this fault developed as an earthquake of any regional significance, a sediment slide or just a slow motion displacement. As seen in Figure 4 the uplift of the island Læsø fits exactly the 12 meters in the regional pattern. That

the island of Læsø should have subsided 4 meters and then uplifted the same number of meters within several thousands of years seems improbable. More supporting evidence is necessary to substantiate the claim of an earthquake 4-5,000 years ago in Læsø.

**West coast of Sweden and Northern Sweden.** Other claims of irregularities have been presented by Mörner (2003). Several locations on the Swedish west coast have been pointed out. The signs of geological movement are faults and rock deformation in a few cases, and in many incidences rock slides and liquefaction in several stratigraphic layers. In several places have been observed sediment deformations and in some also signs of tsunami disturbances of the sediments. Drastic coincident deformations are demonstrated in Mörners (2003) paper. The evidence is not as overwhelming as in northern Sweden in the layers from the end of the Ice Age (e.g. Lagerbäck, 1991), but it could be that some irregularities in the pattern of Figure 4 are in accord with Mörners (2003) observations. The present paper just points to the possibility of earthquakes and irregularities near the coast of southwestern Sweden.

**North Jylland, Denmark.** In the recent paper by Sørensen et al. (2009) it is indicated that the northern grouping of the earthquakes in the Skagerrak between Norway and Denmark (Fig. 2) is happening in the Tornquist Zone, which is one of the most significant geological lineaments in Scandinavia (e.g. Gregersen et al. 2006 and 2009). Also further southeast the Tornquist Zone is delineated by small earthquakes (Fig. 2) (Gregersen et al. 1998; Jensen et al. 2002). In the middle of Denmark, in the area around the road Hobro – Aalborg – Frederikshavn (Fig. 5) no earthquakes have been found. And this has given rise to previous statements (e.g. Gregersen et al. 1998) that this part of the Tornquist Zone is not active. Recent geological as well as geodetic investigations modify this by what is presented in Figure 5. Here is presented a bend in the uplift pattern in all investigated time scales from 10s to 10,000s of years. This bend is a description of observations which south of Aalborg show a trend of uplift as a stiff plate with a constant gradient, and another gradient, i.e. another stiff plate uplift north of Aalborg. The bend is just where earthquakes are missing, so we tend to describe this bending as a creep phenomenon. In **Skåne, southern Sweden** repeated GPS measurements by Pan et al. (1999) have indicated differences on the two sides of the Tornquist Zone.

**Rügen, Germany.** And this bending phenomenon in the middle of Denmark does not stand alone. When the evidence was presented recently in a conference, the authors have been told of a similar observation by Dietrich (personal communication, 2008) of a systematic, and repeated change in trend in geodetic levelling in the island of Rügen in northern Germany. The location is marked in Figure 5 by a circle. These are the kinds of observations we seek in Project DynaQlim.

**Karelia, Russia.** Many faults in Karelia have been interpreted as postglacial earthquakes, with supporting evidence in rockfalls/landslides (Lukashov 1995).

**Resulting status is:**

**Overall coincident uplift pattern of all time scales 10s, 100 s, 1000s and 10,000 years confirmed in Scandinavia.**

**Some geodynamics irregularities found. They may be connected to earthquakes or to slower creep. Hopefully more is to be disclosed in Project DynaQlim by further investigations.**

**And some of the irregularities are seriously doubtful.**

## Acknowledgments

Many students have over the years contributed to the computation of the Danish earthquake locations. Our colleague H.P. Rasmussen has made many of the P and S arrival readings.

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## Figure captions

Figure 1. Uplift pattern and surrounding subsidence of time scales 10 – 100 years from geodesy observations (Vestøl, 2006; Ågren and Svensson, 2007; K. Engstager, 2007, personal communication) and on time scales 100 – 1,000 – 10,000 years (generalized by Mörner (2003)). The geodetic curves, black, are in millimeters per year. The geological curves red, show hundreds of meters since the Ice Age.

Figure 2. Map of the earthquake geography in Scandinavia covering the years from JAN 1970 to DEC 2004. Earthquakes in the Danish area are extracted from the GEUS earthquake catalogue and earthquakes located outside this area are extracted from the Scandinavian catalogue from Helsinki University. The earthquake magnitude scale is given in the upper left corner. Very thick black lines show the large postglacial faults of age close to 9,000 years (Lagerbäck, 1991). Updated earthquake files for Denmark are available in home page [www.geus.dk](http://www.geus.dk) under seismology, and for the rest of Scandinavia in home page [www.seismo.helsinki.fi](http://www.seismo.helsinki.fi). From Gregersen and Voss (2009).

Figure 3. Earthquake focal mechanisms in Scandinavia.

Figure 4. Geological/archeological uplift pattern of the southwestern part of Scandinavia, Denmark – Sweden from Christensen (2001). Full lines as well as interpolated dashed and dotted lines show uplift in meters since last flooding after the Ice Age. Dates when these lines were at sea level are given BC, before Christ. With open circles at Læsø, Rügen and in southern Sweden are marked locations which are specifically mentioned in the text on irregularities. The map is based on more limited maps of Mertz (1924) and Paasse (1996) as well as dating by Christensen (2001). The Hobro- Aalborg-Frederikshavn line shows the location of the diagrams in Figure 5.

Figure 5. The 2 upper diagrams show uplift of late glacial and post glacial shore lines. Data from Mertz (1924) extracted by Lykke-Andersen and Borre (2000)). The geodetic curve 1890 – 1950 was also extracted by Lykke-Andersen and Borre, here based on Bedsted Andersen et al. (1974). The curve 1890 – 1990 is from Gregersen and Schmidt (2001) based on the newest available data. Note the coincident bend in all the curves around Aalborg.

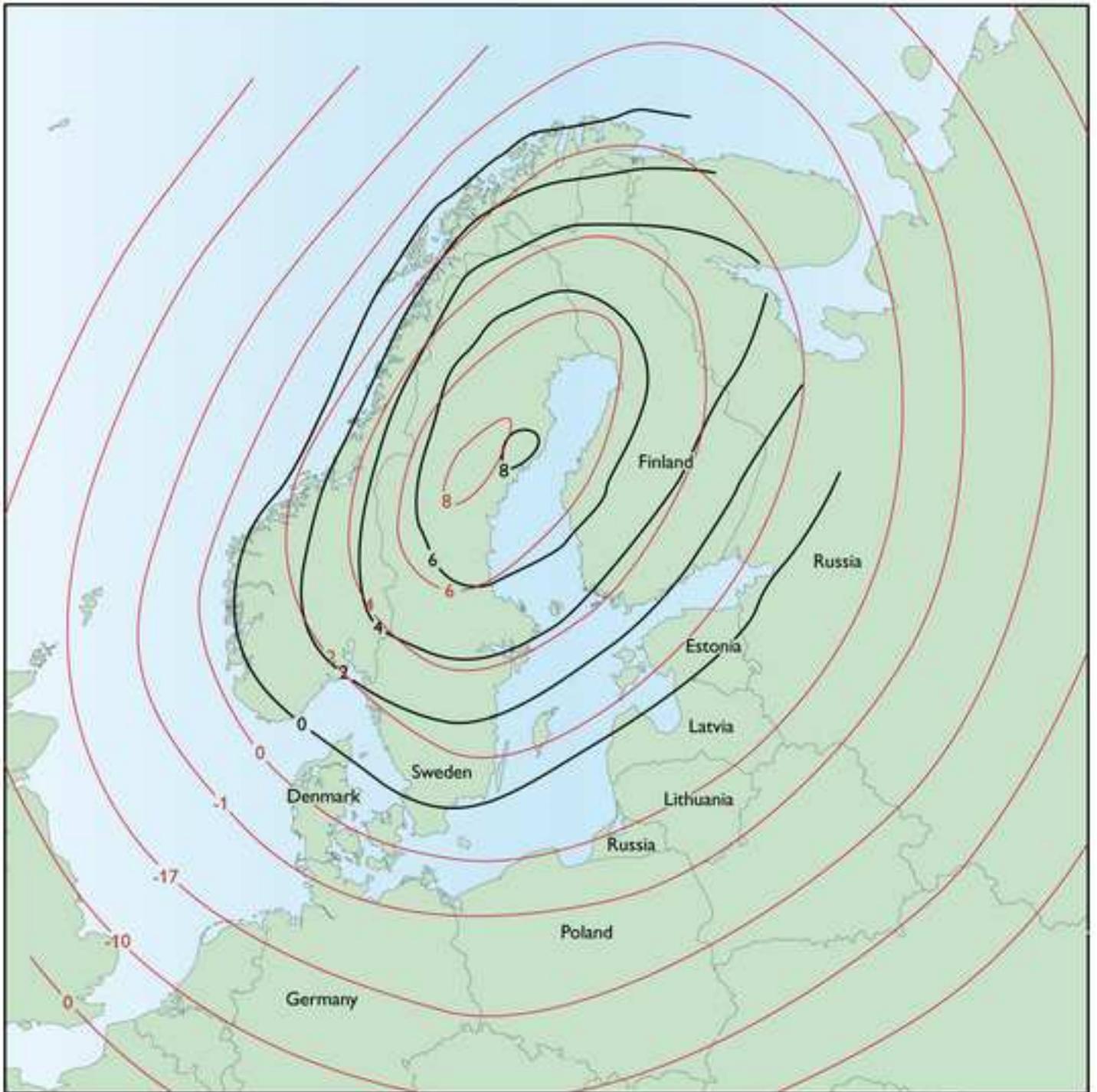
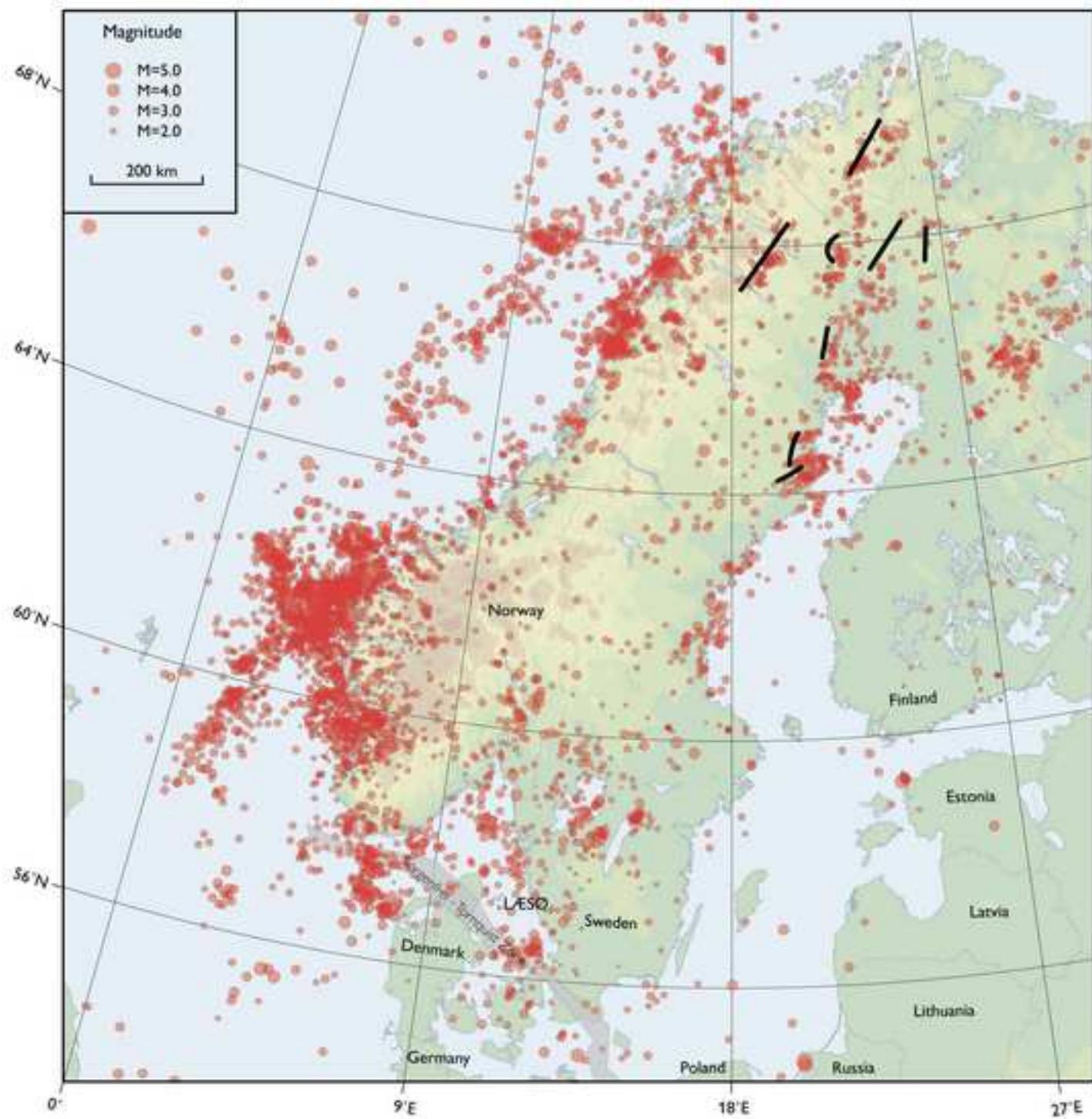


Fig.15G2



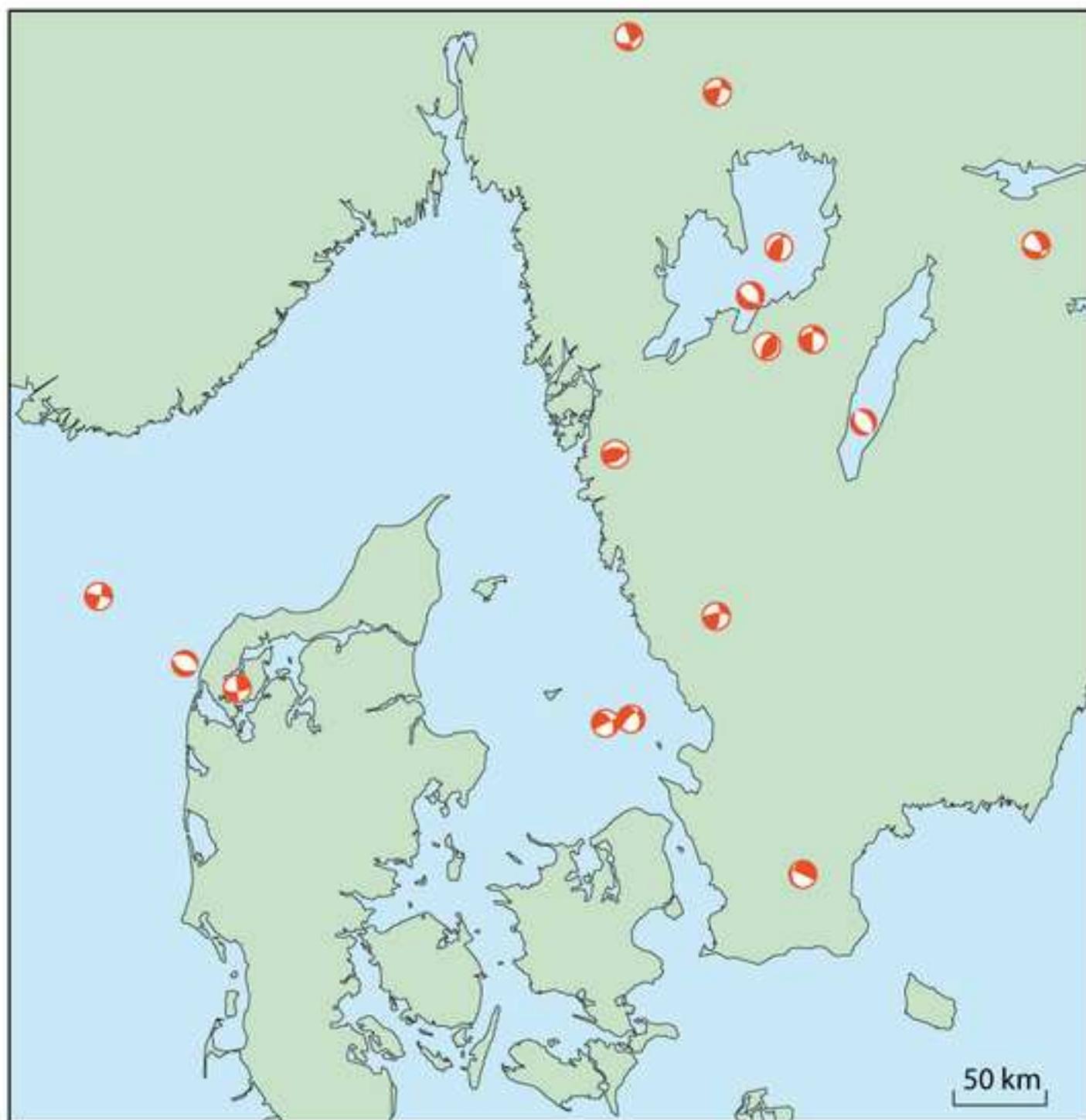


Fig.3\_SG2  
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Figure 4

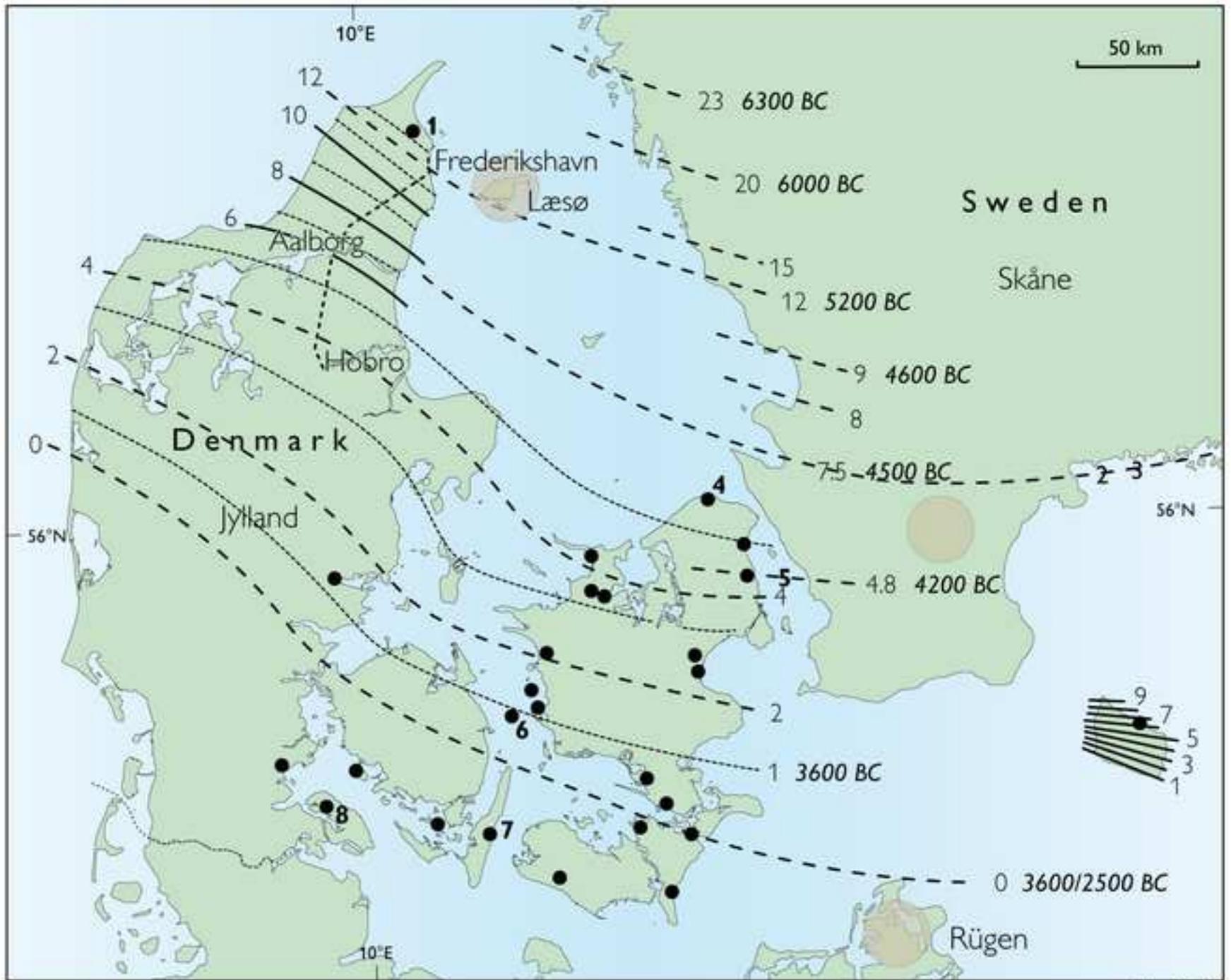


Fig.4\_SG2

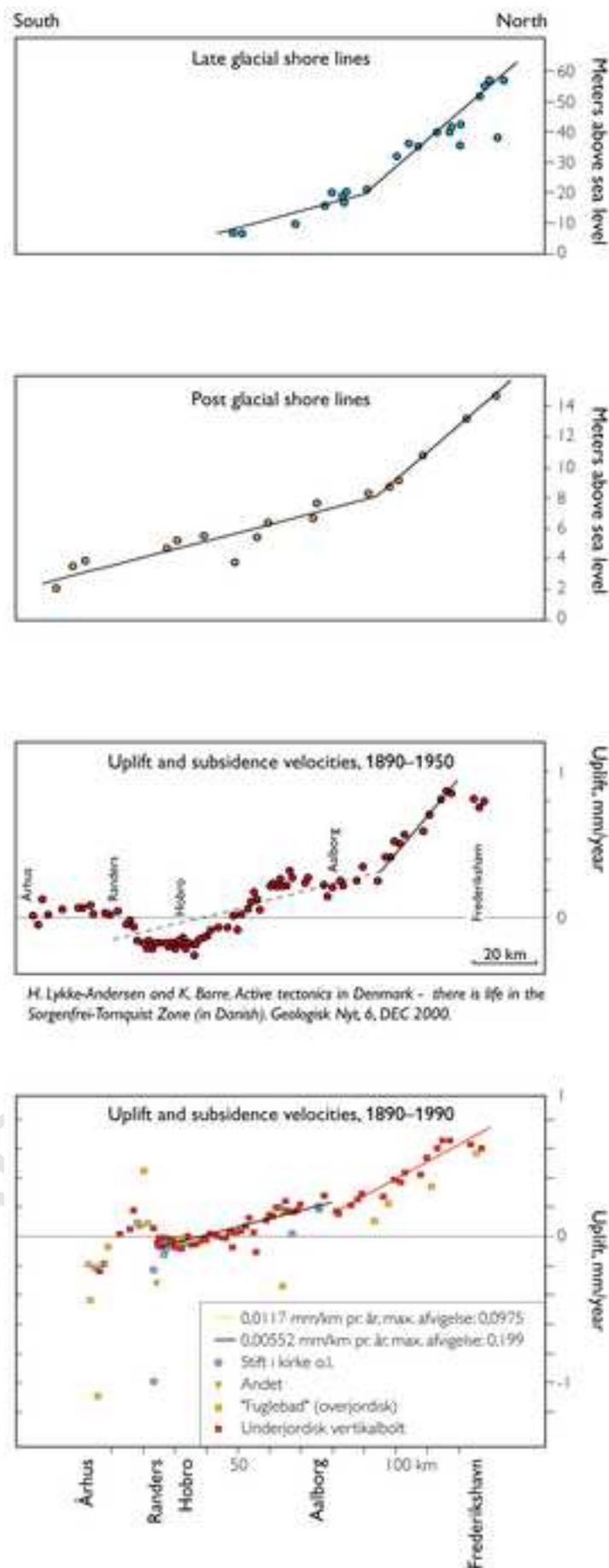


Fig.5\_SG2  
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