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# Review of some significant claimed irregularities in Scandinavian postglacial uplift in time scales from tens to thousands of years: earthquakes?

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## Abstract

The postglacial uplift/subsidence in Scandinavia is regular. And the phenomenon is similar in time scales of tens, hundreds and thousands of years studied via geodesy, seismology and geology. Searches for irregularities in the form of earthquakes claimed in the scientific literature have disclosed many earthquakes right after the Ice Age and some later cases for further evaluation. In a previous report the present author has mentioned doubts about the validity of some of the most significant claimed irregularities. In the present paper a review is made of these significant claimed irregularities in the southwestern flank of the Scandinavian postglacial uplift/subsidence via literature studies of geodetic and geological claims of earthquakes as well as discussions in the field. Geodetic observations exist for all of Scandinavia. Those describe the phenomenon in 10s–100s of years scale. Earthquake observations in seismology are of relevance in the same time scales. Geological studies of dated shore lines describe the postglacial vertical earth-surface motion in a quite different time scale of 100s–1000s of years. There is a need for integration of these observations geographically. This is happening in the various time scales in the DynaQlim project. The review finds the claims improbable about the following: (1) geodynamical motion in the Copenhagen area, (2) a paleo-earthquake in Læsø and (3) the recently proposed water level discrepancy in the southern part of Denmark. The assessment is less certain, but falls to improbable concerning (4) proposed paleo-earthquakes by Hallandsåsen in southwestern Sweden.

## 1 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 to GPS measurements nowadays. Many DynaQlim papers have over the years substantiated the pattern of vertical motion in the time scales 10s–100s of years. Such a good, regular 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 (Morner 2003). The latter gives the pattern of motion since the Ice Age, i.e. approx. 10 000 yr. The comparison of the two patterns is seen in Fig. 1, already presented in Gregersen and Voss (2010). 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. The second observation is that the geographical patterns satisfying the observations are very regular, which means that irregularities are noticeable and worth a review.

## 2 Stresses in the lithosphere of various time scales

In previous papers the stress development after the Ice Age has been treated (e.g. Gregersen and Voss, 2010). The stress field was right after off-loading of the ice, dominated by the uplift stresses bulging upwards and pressing out from the central part of the uplift. Later, the present situation is that the uplift is less important while stresses caused by the present lithospheric plate movements are dominating with compression in a northwest/southeast direction (Gregersen and Voss, 2009; Olesen et al., 2004; Bungum et al., 1991; Lindholm et al., 2000; Gregersen, 1992). In several papers is argued that there is no correlation between the uplift pattern and the earthquake geography (e.g. Gregersen, 2002; Gregersen and Voss, 2009; Zoback et al., 1989; Zoback, 1992; Poutanen et al., 2009), which for all of Scandinavia is displayed in Fig. 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 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





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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 is less earthquake activity as we go south-west 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.

## 3 Uplift pattern and claimed irregularities

Several investigations are available concerning the regional, recent earthquake activity. First of all the prominent geological zone Sorgenfrei-Tornquist Zone is considered inactive, except for a small part in eastern Kattegat (e.g. Arvidsson et al., 1991; Gregersen et al., 1998). An illustration of this inactivity concerning earthquakes is shown in Fig. 3, supplementing the regional activity picture of Fig. 2. The earthquake dots in the two maps of Fig. 3 are the same, and they cover the same area. The purpose of the map without coasts and geology is to show the earthquake activity without prejudice from coast lines and geological zones. The Sorgenfrei-Tornquist Zone passes right through the middle of the illustration, but its trend can not be distinguished through earthquake activity. The Ringkobing-Fyn Ridge can not be distinguished either. This just emphasizes what has been pointed out before (e.g. Gregersen et al., 2011).

The summary of the small earthquake activity in Denmark (Figs. 2 and 3) is that it occurs not in one specific linear zone, but rather scattered in several zones in northwestern Jylland and in Kattegat as well as completely unsystematic in eastern Denmark and southern Sweden (Gregersen et al., 1998). In a general sense the seismicity pattern in Denmark shows us the irregular rheological edge zone of the stiff old Fennoscan-





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dian Shield, not as an active zone but rather as a broad area of transition from some earthquake activity in the shield north east of the zone to quiet area south west of the zone. In the European scale the Tornquist Zone is considered as present-day inactive, as presented in conference proceedings by Gregersen et al. (1995) and seen as lack of earthquakes in the lower right hand corner of Fig. 3, in Poland.

At least a part of Scandinavia has experienced postglacial earthquakes (e.g. Lagerbäck, 1990, 1991). These earthquakes (Fig. 2) in northern Scandinavia were caused by the Ice-Age ice cap melting away within a short time. The present-day stress regime is completely different (Gregersen, 2002; Gregersen and Voss, 2009; Mörner, 2003). Additionally Mörner (2003, 2009) presents paleoseismological arguments on some large Swedish earthquakes further south in Sweden than those of Fig. 2. And in some cases, both in northern and southern Sweden, those earthquakes appear to be younger than 9000 yr, the time when the last ice cap melted away. Those arguments of Mörners (2003, 2009) are less convincing than those giving basis for the earthquake signatures of Fig. 2 where Mörner agrees with Lagerbäck (1990, 1991). An evaluation for Sweden is needed just like that for Norway (Olesen, 2004). A first step is taken by the discussion on claim no. 4 of this paper.

## 4 Assessment of claims in the geologic and geodetic literature of active faulting near Denmark

The present assessment review includes both the long-term geological evidence and the short-term geodetic evidence. Additionally the assessment acknowledges the view, that the small present-day earthquake activity in Scandinavia is caused by a dominating stress field from lithospheric plate motion, supplemented by stresses from the postglacial uplift (Gregersen and Basham, 1989; Zoback et al., 1989; Gregersen, 1990, 1992). Generalized maps of the very regular postglacial uplift of the investigated area have recently been presented from geodetic sources (Knudsen et al., 2012; Hansen et al., 2012) as well as from geological sources (Mertz, 1924; Paasse, 1996; Christensen, 2001). These maps all show a very regular pattern in most of the area, with the exception of a linear area in southern Denmark introduced by Hansen et al. (2011), which will be treated later in this paper. The most complete geodetic map, that by Knudsen et al. (2012), has been chosen as reference for the locations of the treated irregularities (Fig. 4). It takes into account permanent GPS, three campaigns of precise levelling over the last hundred years as well as ten sea level stations in the area.

## Claim 1: Carlsberg Fault in the Copenhagen area

This fault is one of the most significant in the Copenhagen area (e.g. Rosenkrantz, 1937; Nielsen and Thybo, 2004) (marked as Copenhagen on Fig. 4). It is very important to the Carlsberg Brewery. The excellent water flow in the fault zone is used for the brewing. The fault trace has been observed through extensive cracking of house walls (B. Larsen, personal communication, 2009; O. Winther Christensen, personal communication, 1990; Ovesen et al., 2002; L. Nielsen, personal communication, 2009). A very basic remark in assessing these observations is that comparison with the surroundings is necessary. And this comparison has not been done. Motion on the fault stands as a suggestion, not as a result. And the alternative suggestion that irregularities is connected to differential settling of the loose upper sediments is more probable.

It has been suggested by Rosenkrantz (1934, 1937) that the larger-than-usual earthquake which shook Copenhagen in 1930 can possibly be ascribed to this fault. Assessing this today, knowing the large uncertainties of earthquake locations in this area at that time, one must conclude that it could just as well be on another fault, and no indication has been observed for the choice.

The Carlsberg Fault has also been held responsible for misfits in the Danish geodetic systems. The basis of the distance measuring system on Amager island in Copenhagen has been described as deformed (Sand and Madsen, 1916; Ovesen et al., 2002). A large difference of 51 mm was reported between 1838 and 1911 of the basis line length of 2.7 km. The more probable explanation of this (M. Aarestrup, personal communication, 1991; K. Engsager, personal communication, 2009) is near-surface





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sediment motion of one of the end points by temperature effects, especially freezing and thawing, toward which modern geodesists protect their measurements by relying on a group of separated points at each end rather than just one vulnerable point. Comparisons to basis length measurements northwest of Copenhagen show standard errors in the old data, so large that the length change turns out to be insignificant (K. Engsager, personal communication, 2010). Support for a conclusion on stable length of the basis is that the 1838 measurement stands alone, while the 1911 basis length has been confirmed with standard errors 3 mm in 1933, 1934 as well as 1980 and 1993 (O. B. Andersen, personal communication, 1993), i.e. before and after the 1930 earthquake.

Also another basic distance in Amager (in Danish called "prøvebane", trial distance) has been reported deformed (e.g. Ovesen et al., 2002). For this the geodetic problem has been observationally identified as the above-mentioned end point trouble. One of the ends is sloping strangely, so the end must have been disturbed by winter freezing and thawing (K. Engsager, personal communication, 2009).

In a paper on the levelling in the area of Copenhagen, Mark and Jensen (1982) have the following conclusion for the period between the 1940s and the 1970s: "An adjustment of the vertical displacements shows a tilting about twice as big as the one you know for Denmark as a whole, but the direction of the isolines is about the same. Possible displacements in connection with the so-called Carlsberg Fault can't be recognized in the results, but maybe some systematical displacement in Amager can be explained by the graben-structure in the area between the Carlsberg-fault and the Svanemølle-fault."

The assessment of the above discussion will have to conclude that the Carlsberg Fault is not active.

### Claim 2: the island Læsø in the Kattegat Sea

Hansen (1977, 1980, 1986a, b, 1994, 1995) and Bahnson (1986) have made geological investigations of sand deposits of ages less than 7000 yr in Læsø and found



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indications of a large fault of displacement 4 m. An earthquake has been proposed although no other indicators of earthquakes have been identified. The present assessment evaluates how this fault together with other indicators of postglacial movement fits into the tectonic setting close to the Sorgenfrei-Tornquist Zone.

In the 1980s the seismicity of the area was only marginally known (e.g. Lehmann, 1956; Gregersen, 1979), but tectonic activity was assumed by Bahnson (1986) and Hansen (1986) with reference to structural studies showing many steep faults (e.g. Baartman, 1975). It was argued (Hansen, 1977; Bahnson, 1986) that Læsø does not fit in the postglacial uplift pattern of the neighboring Kattegat coasts. In a later paper this argument (Hansen, 1994) was modified to: "Strangely enough the oldest beach line on Læsø is at the same height as by Frederikshavn.". How well the uplift curves of the highest beach lines in Læsø fit into the surroundings has later been illustrated by Christensen (2001) and quoted by Gregersen and Voss (2012).

Now assessing the Læsø observations 25 yr later, we have more data on the region, both in the scale of Kattegat and for Scandinavia, and for other intraplate regions. This has changed the interpretation and understanding of the Læsø case. The question was earlier whether Læsø would fit into its assumed active surroundings. The question is now whether Læsø fits into its quiet, regular uplift surroundings. A review of the most significant arguments gives the following results:

1. As mentioned the maximum uplift of Læsø since the regional flooding after the Ice Age fits nicely into the regional picture. That the island of Læsø should have subsided 4 m and then uplifted the same number of meters within several thousands of years is improbable, since the effects of such an event would be recognisable in neighboring coasts, where nothing is observed. And even more improbable: subsidence and uplift several times as suggested in the book by Hansen (1994) is not a possibility.

2. The alternation between transgressions and regressions in a time interval of several thousand years right after the Litorina Sea transgression, is found similar





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in other locations of the Kattegat area as referred in the overview paper by Noe-Nygård (2006) as well as that by Christensen (2001) and by Bjørnsen et al. (2008). The phenomenon is called the Litorina transgressions (Christensen, 1995). The last one ends 4000–5000 yr ago.

3. The paper by Baartman (1975) told about structural differences. The reference does not give any argument on recent activity. The structural steps and faults are confirmed by the recent projects EUGENO-S (EUGENO-S Working Group, 1989) and Tor (e.g. Gregersen et al., 2009). But as an argument concerning recently active faulting the reference is contradicted by recent evaluations of the earthquake activity (Figs. 2 and 3) (e.g. Gregersen et al., 1995, 1998).

4. A curve showing changes of tilting of successive beach terraces was presented by Hansen (1980). When the slopes were calculated no evaluation was made of uncertainties (Hansen, 1980). The slopes were based on height measurements, averaged over 10–15 individual heights within a spread of approximately one meter. This one meter can be taken as a rough estimate of four times the standard error. The present assessment extends the data handling to take into account this estimated standard error of a quarter of a meter presented in Fig. 5. When these standard errors of the slopes are introduced into the data presentation of Fig. 5 of Hansen (1980) the tilting argument becomes non-significant. The observed differences and the standard errors are of the same size, as shown in Fig. 5. The zig-zag line of Hansen (1980) goes through the average values of the slopes. But the data may as well be explained by the straight line, i.e. within the belt of intervals determined by averages plus/minus one standard error. So the present assessment concludes that the differences in average slopes can not be used as an argument for discontinuous and occasionally reverse tilting. The data does as well agree with steady uplift and tilting.

The errors mentioned above are directly concerned with the old data of Hansen (1980), which were used to show tilting of the beach terraces with re-





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spect to horizontal water level. But it will also apply to modern data, which is now available for Læsø. The same size of standard errors in the use of geological markers for slope measurements and for height measurements with respect to water level, are found in recent work by Nielsen and Clemmensen (2009). They observe similar large measurement scatter in modern data on Anholt, in the Kattegat Sea. When to this is added that the physical circumstances of ocean currents and stormy weather influence the slopes, these observations in Fig. 5 can not give an argument for oscillating tectonic tilting by themselves.

5. An almost vertical fault displacement in the sediments of approx. 4 m can, as said by Hansen (1986a, b), be caused by displacement of various blocks in Læsø. The location of the fault is presented as a coastal cliff at the time of development. And coastal cliffs experience faulting by irregular erosion and gravity. The southern part of Læsø must have experienced a sediment slide along the observed fault, either fast or slow. Sediment slides are more probable in Læsø than an earthquake, for which there is no other evidence.

   A whale in a height of 4 1/2 m, of age approx. 3000 yr as well as other datings have to fit into the regional frame. It may well show that the part of the island on which the whale rests did not follow the steady uplift of the oldest part of the island. A slide in a coastal cliff is naturally of great significance to the detailed geological description of Læsø, but of no significance to the tectonic evolution of the greater Kattegat region. The present topography is convincingly a succession of coastal terraces, which display a recent geological evolution explained in great detail by Hansen (1977, 1980, 1986a, b, 1994, 1995) and followed up in recent further investigations (Hansen et al., 2012).

The present assessment of all of the old and new arguments concludes that the bedrock subsurface below Læsø has been uplifted just as the rest of the Kattegat region, regularly or with minor irregularities. This means that there was no Læsø earthquake 4000–5000 yr ago. The lower parts of Læsø with many well-documented beach





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terraces have their own exciting development history (e.g. Hansen, 1994; Hansen et al., 2011), best explained by regular postglacial uplift together with coastal development by water currents and weather, beyond the scope of this paper.

**Claim 3: line across southern Denmark**

A new map has introduced a hypothetical irregularity line called southern Denmark in Fig. 4. It is based on the geodetic/oceanographic data of water level stations the last 100 yr (Hansen et al., 2011). It includes a few more water level stations in the southern part than in Fig. 4, but is without GPS and levelling, which in Fig. 4 supplemented the water level data. Instead of accepting irregularities in a few stations in southern Denmark as caused by weather and ocean currents Hansen et al. (2011) focus arbitrarily on bedrock differences, that show no motion in the seismological data or in the geodetic levelling and GPS. The uplift picture of Fig. 4 is more representative of the full data set, which does not have a discontinuity in southern Denmark.

South of Læsø in the Kattegat Sea the earthquake activity is interpreted from seismology (Gregersen et al., 1998). The seismicity picture as presented in Figs. 2 and 3 shows a concentration of earthquakes in a short part of the Sorgenfrei-Tornquist Zone, where the zone changes character (e.g. Graversen, 2009). This has been described by Arvidsson et al. (1991), Gregersen et al. (1996) and Jensen et al. (2002) as connected to confirmed recently active basement faults. Here is potential for earthquakes of magnitudes as large as around 5. This is not far from Hallandsaasen (Fig. 4). Does it mean that the claim of postglacial earthquakes there is supported?

**Claim 4: west coast of Sweden**

Several locations on the Swedish west coast have been mentioned by Mörner (2003, 2009). Signs of geological movement in these locations are variations in postglacial uplift of beach lines, faulting and rock deformation in a few cases, and in many in-





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cidences rock slides and liquefaction in several stratigraphic layers. In several places have been observed these liquefaction deformations and in some also signs of tsunami disturbances of the sediments. The evidence for earthquake interpretation is not as overwhelming as in northern Sweden in the layers from the end of the Ice Age (e.g. Lagerbäck, 1991), but it seemed worthwhile investigating Mörners (2003, 2009) claims of postglacial earthquakes. A field trip to Hallandsaasen of 12 seismologists was carried through 27 July 2013. Nils-Axel Mörner added excellent educational details to his publications (Morner, 2003, 2009). Figure 6 is from Mörner (2003) The view, as seen during the field trip, convinces that a rock slide has disturbed the meter high steps of the numbered beach ridges 6 to 9. The following pictures (Figs. 7 and 8) were taken of disturbances of dated water filled sediments (called seismites) and shattered rocks.

The field trip has given the evaluation that the shown signs of paleo-earthquakes each could be caused by earthquake shaking or by its own individual other cause. Misfit of beach lines in neighboring locations 400 meters from each other could have been caused by slow non-earthquake motion or different sea wave and current systems. Talus falls and slides could occur without a starting earthquake. Liquefaction disturbance of sediment layers could be caused by water escape or slumping of layers. Shattering of exposed bedrock could be caused by weather and climate. And tsunami signs in sediments are indications of disturbances, which could happen by non-earthquake-slides as well as by earthquakes. Together one is left with a choice in the evaluation between coincidences or common cause: earthquake. The field trip convinced the participating seismologists that the claimed signs of earthquakes must be seriously taken into account.

Into the interpretation must go the overall pattern of gradual uplift (Fig. 1 and Gregersen and Voss, 2010) of the whole region, into which only small irregularities fit. And when this is seen in connection with the drastic fall-off of stresses since the Ice Age (e.g. Gregersen and Voss 2009) the present assessment results in a category “most probably coincidence”, i.e. “probably no earthquakes”.





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In Skåne, southern Sweden repeated GPS measurements by Pan et al. (1999) have indicated differences between the two sides of the Tornquist Zone. These measurements are not considered statistically significant by our Swedish geodesist colleagues, who now use permanent GPS stations. A small, seldom earthquake happened in Skåne 16 December 2008 on the north-eastern flank of the Tornquist Zone (Fig. 3). This earthquake was small as the others that have been located in the region around (Voss et al., 2009).

## 5 Conclusions

The overall conclusion is that a number of reports, claiming geologic or geodetic recent irregularity in and near Denmark, have been found and discussed. The assessment has uncovered no signs of geologic recent faulting or recent crustal deformations, which contradict the seismicity picture of minor earthquake activity, up to magnitude just below 6. And parallel to other continental intraplate regions a hazard evaluation will then go up to magnitude 6 1/2 with extremely low probability. The earthquake zones are those found by historical and instrumental-seismological investigations in the seas around Denmark as illustrated in Fig. 2. The activity is geographically spread out. Not even the very significant Sorgenfrei-Tornquist Zone is an irregularity zone with earthquakes.

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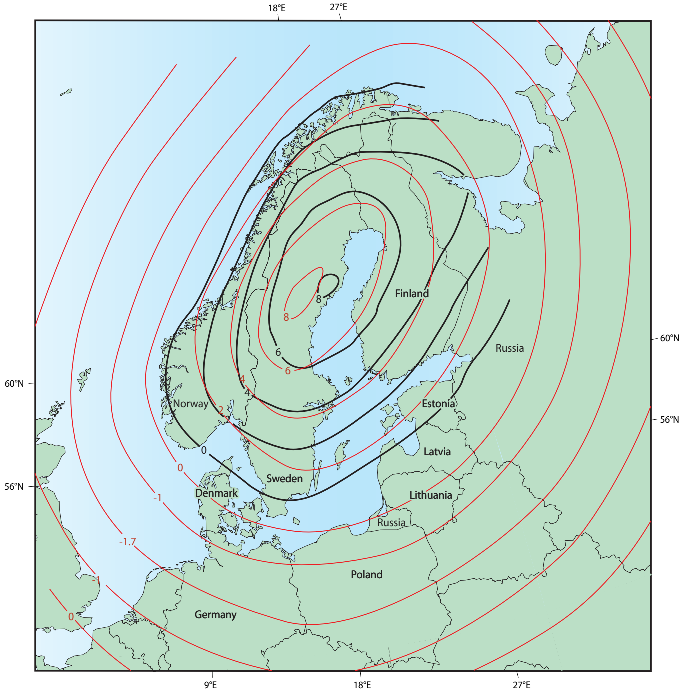


**Fig. 1.** Uplift pattern and surrounding subsidence of time scales 10–100 yr from geodesy observations (Vestøl, 2006; Ågren and Svensson, 2007; K. Engsager, 2007, personal communication) and on time scales 100–1000–10 000 yr (generalized by Mörner, 2003), The geodetic curves, black, are in millimeters per year. The geological curves red, show hundreds of meters since the Ice Age.





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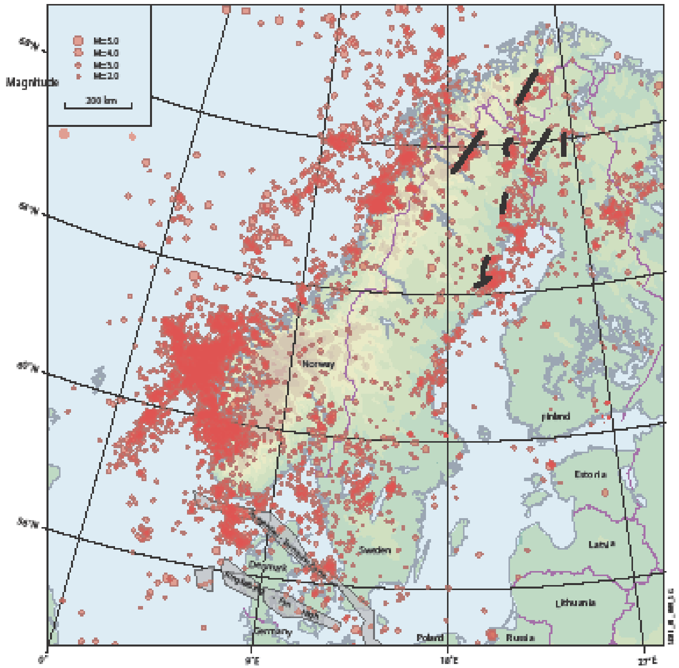


**Fig. 2.** Map of the earthquake geography in Scandinavia covering the years from JAN 1970 to DEC 2004. Earthquakes in the Danish area are extracted from the GEUS earthquake catalogue and earthquakes located outside this area are extracted from the Scandinavian catalogue from Helsinki University. The earthquake magnitude scale is given in the upper left corner. Very thick black lines show the large postglacial faults of age close to 9000 yr (Lagerbäck, 1991). Updated earthquake files for Denmark are available in home page www.geus.dk under seismology, and for the rest of Scandinavia in home page www.seismo.helsinki.fi. From Gregersen and Voss (2009).





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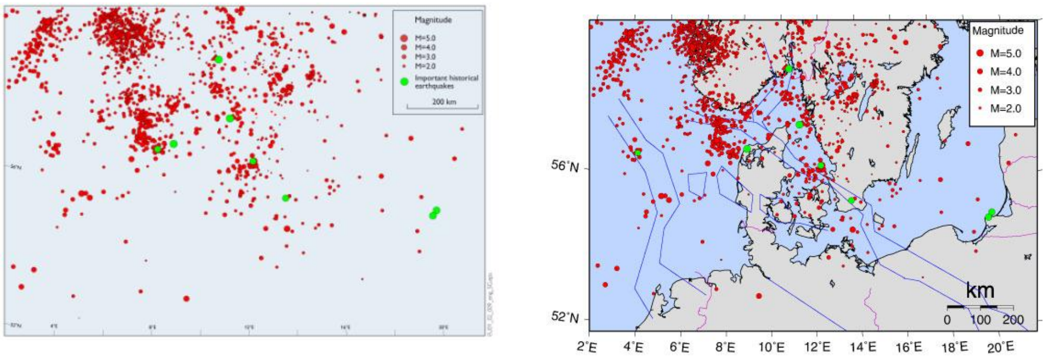


**Fig. 3.** Earthquake activity in and near Denmark without and with coast lines and geological zones. Red dots show modern well-located earthquakes of the last 75 yr, and green dots show the most important relatively larger earthquakes in 1759, 1841, 1904, 1985, 2004, 2008, and 2010. The two maps cover the same area. Denmark is in the middle. Upper right hand corner is inside the Fennoscandian Shield, and in the lower left corner we are outside the shield. A gradual and irregular transition from the shield is noted. This can be termed the edge of the shield in relation to stresses and strains. From Gregersen et al. (2011).





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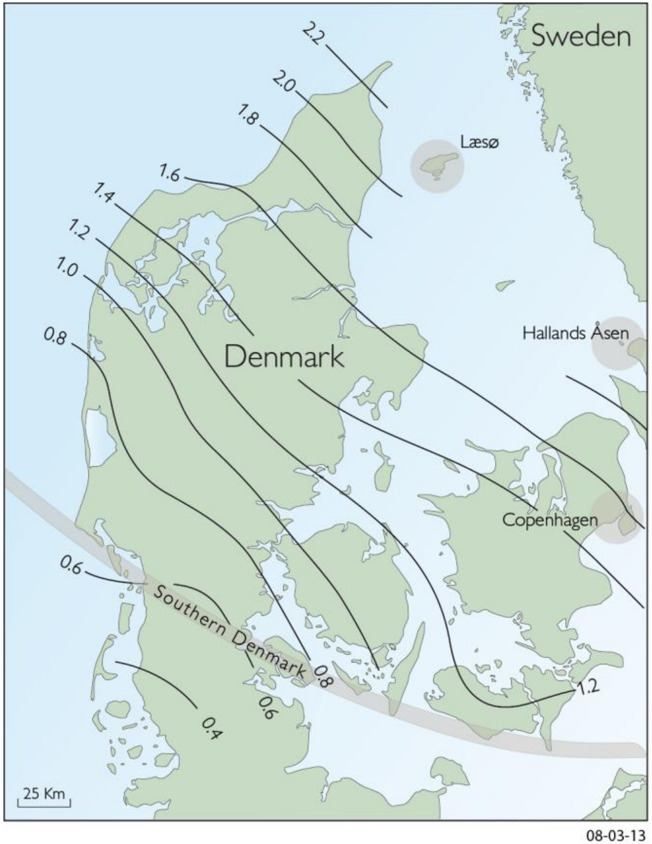


**Fig. 4.** Modern geodetic map (from Knudsen et al., 2012) with postglacial uplift in milimeters per year. Based on GPS, levelling and sea level stations. Four treated claims of earthquakes or other irregularities shown by grey shading.





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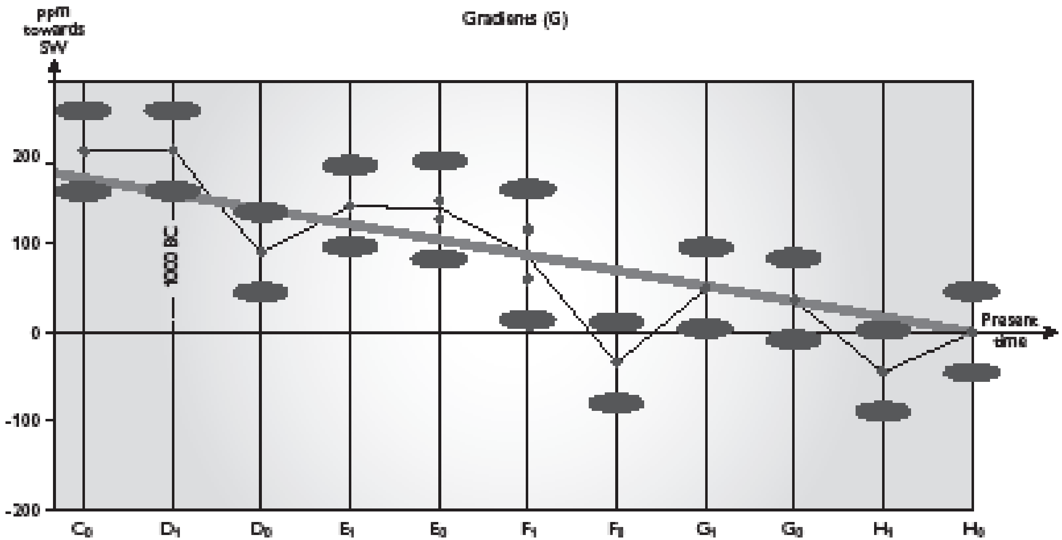


**Fig. 5.** Slopes of successive beach terraces of diminishing age to the right, with estimated standard errors. When standard errors are introduced in this Fig. 5 of Hansen (1980) it is obvious that abrupt changes of slopes are not significant. The slope readings are just as well explained by a steady change of slopes, approximated by the thick sloping line generally inside one standard error and certainly within two standard errors.





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**Fig. 6.** Numbered beach ridges on Hallandsaasen seen from above. A major earth slide in the lower right side of the picture covers the older beach ridges (6–9) but not the younger ones (1–5). The view as seen during the field trip. The photograph numbered by Nils-Axel Mörner.

**Fig. 7.** Seismite? Disturbed water-filled sediment. Liquefaction.





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**Fig. 8.** Bedrock cliffs strongly fractured and moved by shaking or weather changes. Nils-Axel Mörner explaining the phenomenon.





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