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Flexurally-Induced Stresses in the Northern North Sea: Preliminary Compar Observation and Theory

B. Grollimund, M. D. Zoback, SPE, Dept. of Geophysics, Stanford University, and L. Arnesen, Norsk Hydr

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Abstract

In this work we evaluate the role of lithospheric flexure resulting from post-glacial rebound as a possible source of regional stress variations in the northern North Sea. Compilations of leak-off and pore pressure data, estimates of the full stress tensor from observations of wellbore failure[1], and earthquake focal plane mechanisms indicate high horizontal compression (i.e., $S_{Hmax}>S_V$ and $S_{hmin}{\sim}S_V$) on the west side of the Viking Graben and decreased horizontal stresses on the east side. In this study we extend the available knowledge about regional stress magnitudes by analysis of leak-off and pore pressure data. We use numerical modeling of lithospheric flexure due to post glacial rebound to show that this is a possible cause of the observed high horizontal compression in the Tampen Spur, regional stress variations and possibly the high pore pressures observed at depth west of the Viking Graben.

Introduction

In this paper we investigate one specific mechanism, post-glacial lithospheric flexure, that may contribute to high horizontal stresses observed in the Tampen Spur area of the northern North Sea. More generally, it's important to understand if lithospheric flexure resulting from deglaciation is responsible for regional variations of stress orientations[2,3] and magnitude[4] which in turn may affect reservoir processes as diverse as wellbore stability and hydrocarbon migration.

We analyzed leak-off and pore pressure data in the northern North Sea to document values at depth and to reveal spatial and depth dependent changes. These data supplement information from earthquake focal plane mechanisms[5], and estimates of the full stress tensor in the Visur

Further, we use numerical modeling explain the observed stresses. While nume stress in the North Sea has already been carri which resulted in a good first-order appr regional stress field, the effect of Quater Fennoscandian shield due to deglaciation wa model. Since we believe that this might be a of stress in the northern North Sea we numerical model involving flexural stres deglaciation.

Observation of Stress in the Northern

To determine stress regimes in the northern analyzed leak-off tests from wells located in as well as from wells closer to the Norwe least principal stress (S_3) approaches the v the stress regime is likely to be compressive, horizontal stress (S_{Hmax}) is higher than S_V. is significantly lower than S_V, the stress faulting. Thus leak-off tests can be valuabl approximate state of stress.

To map spatial changes of stress we normalized by S_V deduced from density lo section perpendicular to the Norwegian coa At depths between 1,000 m and 1,500 m, S_3/S_V along the cross section is very small. and 3,000 m S_3/S_V tends to decrease towar Snorre field, S_3 is almost equal to S_V, in slip/reverse faulting stress state. At the sa considerably lower in block 35/9, which slip/normal faulting stress state in this area.

Since leak-off tests only reveal the m complete determination of stress, based ex off tests is impossible. A study of the full observations of wellbore failure[1] is neede wellbore failure it is known that in Visur values between 1.2 and 1.3 at depths betw 3,500 m. Together with the leak-off data, thi slip faulting regime with S_3 being very cl considerably higher than S_V (Fig. 2).

Earthquake data[5] indicate a predominant stress state in the Tampen Spur with a tend faulting closer to the coast (Fig. 1). Howe the earthquake data is poor, and the depth range of the earthquakes is unknown.

Fig. 3 shows the pore pressure, normalized by the vertical stress (P_P/S_V). P_P/S_V is a measure for how strongly a formation is overpressured. To a depth of approximately 1,500 m P_P/S_V is close to 0.5, which means that the pore pressure is hydrostatic along the entire cross section. In block 35/9 the pore pressure remains close to hydrostatic to a depth of 3,000 m. On the other hand in the Tampen Spur area, severe overpressure starts at a much shallower depth of 2,000 m.

In general, all available data agree that the stress field is reverse/strike-slip faulting in the vicinity of the Tampen Spur. Closer to the coast though, S_3 seems to be considerably lower than S_V and the stress field appears to be less compressive although the distribution of earthquake focal mechanisms indicate a strike-slip/reverse stress regime in both areas. Importantly, pore pressure is considerably higher in the Tampen Spur than east of the Viking Graben, e.g. block 35/9.

Modeling Flexural Stresses due to Glacial Loading

Stresses in the northern North Sea are likely caused by a number of mechanisms. Several studies have pointed out the importance of ridge push along the entire Norwegian Margin[2,6]. Since the crust cools down and becomes denser as it moves away from the Mid Atlantic Ridge, gravitational sliding occurs and causes high stresses in the direction of plate motion[7,8]. The observation that S_{Hmax} directions along the Norwegian Margin are more or less parallel to the direction of plate motion[5] indicates the importance of ridge push as a large scale stress source. Observed stress variations in the northern North Sea however, suggest that there are other factors that locally affect the stress field.

In this work we've investigated the importance of flexural stresses caused by glaciation. **Fig. 4** illustrates how glaciation might perturb the stress field. In Fig. 4a we assume that the lithosphere has reached a state of equilibrium before the ice sheet started to melt. At shallow depth, subsequent ice melting causes extension under the ice sheet, and offshore compression. At great depth this effect is reversed. Stein et al.[9] have used this concept to model flexural stress in the Baffin Bay region in Canada to explain the occurrence of a large reverse faulting earthquake at shallow depth in 1933. In Fig. 4b the lithosphere is expected to store flexural stresses over long periods of time. Therefore, flexural stresses at shallow depth are always compressive under the ice sheet, and extensional further offshore[10] approaching an isotropic stress state after the melting of the ice sheet. This however is not consistent with the observed spatial stress variations.

Analytical Model. To get an estimate of the magnitude of stress changes due to glaciation we initially developed a simple two-dimensional analytical model along the cross section shown in Fig. 1. This model assumes the case of Fig. 4a where the lithosphere is fully relaxed before the onset of ice melting. The lithosphere is represented by an elastic plate, and the ice sheet is assumed to have a constant thickness of 1 km with the lateral extent from 15,000 years ago. For these assumptions flexural stresses can be calc
conventional formulae for elastic plate flexure

At shallow depth the model predicts comp
stresses on the order of 20 MPa in the vicinit
Visund. Closer to the coast flexural stresses
and on the order of -20 MPa (**Fig. 5a**). The w
stress perturbation is approximately 200 km
thickness of the stress supporting lithosphe
suggested by Carter and Tsenn[12], which matc
stress variations very well. **Fig. 5b** illustra
decrease of flexural stresses with depth.

It can be concluded that the analytical mod
order approximation of the observed stress v
northern North Sea, and suggests that deglacia
significant influence on the local stress fiel
model's usefulness is limited since shape and
sheet are strongly simplified. Furthermore, the
purely elastic lithosphere is questionabl
deformation in the upper crust, and viscou
lower crust and the mantle are likely to occur[13]

Numerical Model. To explore the effect of
lithosphere with a more realistic rheology
dimensional finite-element model. The use o
also allows the ice sheet to gradually melt ra
removed instantaneously.

Fig. 6a shows the lithospheric model. The
into a brittle and a ductile part. The brittle pa
km thick sediment layer, underlain by 15 km o
model uses Mohr-Coulomb plasticity to acc
behavior of the upper crust (Eq. 1).

$$\sigma_1 = \sigma_3[(\mu^2+1)^{0.5}+\mu]^{-2} + C_0. \quad \ldots\ldots\ldots\ldots\ldots\ldots$$

We are assuming a coefficient of friction
and a cohesion (C_0) of 2 MPa. The brittle-duc
located at a depth of 20 km. The ductile lowe
thick and has a Maxwell viscoelastic rheolog
phenomenologically described by a spring an
in series. Therefore, the modeled low
accommodate time dependent creep strain. The
(τ) of the lower crust is assumed to be on the c
years[17]. The crust is underlain by a viscous
viscosity corresponding to a relaxation time c
The western and eastern ends of the model a
constrained. A summary of the paramete
numerical model is given in **Table 1**.

The model starts 20,000 years ago and ass
are no flexural stresses in the crust (the assum
in Fig. 4a) and that the stress state is isotropic,
S_{hmin} are equal to S_V. While this assumpti
overly simplified, it allows us to focus on the
deglaciation may have induced. To account f
we are using effective stresses (σ).

$$\sigma = S - P_P. \quad \ldots\ldots\ldots\ldots\ldots\ldots$$

The pore pressure is assumed to be hydrost
Subsequently, the ice sheet starts to shrink as s
The huge late Weichselian ice sheet that co

North Sea some 20,000 years ago[18] shrank to a much smaller ice sheet within about 5,000 years[19]. 11,000 years ago the ice sheet retreated to the current coastal line[20] and 9,000 years ago it has melted away entirely.

The findings of the numerical model confirm the rough predictions of the analytical model in that the Tampen Spur is subjected to compressive flexural stresses, and closer to the coast flexural stresses are extensional (**Fig. 7**). The transition from compressive to extensional stresses is located just east of Visund. More specifically, S_{Hmax}/S_V is highest on the west side of the Tampen Spur approaching 1.5 at a depth of 500 m. In the Tampen Spur itself, S_{Hmax}/S_V is rapidly decreasing towards the west, but still higher than 1. Closer to the coast S_{Hmax}/S_V reaches values as small as 0.6 . These variations decrease with depth and are almost negligible at a depth of 3,000 m. S_{hmin}/S_V shows the same trend as S_{Hmax}/S_V, i.e. it's highest to the west of Snorre and drops significantly towards the coast. Therefore, the model predicts a reverse faulting stress state in the Tampen Spur with a tendency to strike-slip faulting in Visund, since S_{hmin} drops below S_V. Closer to the coast both horizontal stresses are predicted to be smaller than S_V. Of course, if compressional stresses existed in the crust prior to deglaciation as generally observed in intraplate regions[21,22] the stress state would be even more compressive west of the Viking Graben, but less extensional east of it.

In **Fig. 8a** we show the change of stress with time as the ice sheet is melting. 15,000 years ago horizontal stresses are highly extensional in the area between the Viking Graben and the coast, which is the result of the rapid melting of the huge late Weichselian ice sheet[18] to a much smaller continental ice sheet[19,20]. The subsequent melting of the continental ice sheet diminishes the extensional stresses between the coast and the Viking Graben and causes compressive stresses in the Tampen Spur, which is characteristic for the present day stress field.

By looking at the relative magnitudes of $S_{west\text{-}east}$ and $S_{north\text{-}south}$ we can also make a rough prediction for the orientation of S_{Hmax} (**Fig. 8b**). If $S_{west\text{-}east}$ is larger than $S_{north\text{-}south}$, S_{Hmax} is striking parallel to the modeled cross section. On the other hand if $S_{west\text{-}east}$ is smaller than $S_{north\text{-}south}$, S_{Hmax} is perpendicular to the cross section. The model therefore predicts a change of the direction of S_{Hmax} from SEE-NWW striking on the western side of the Viking Graben, to NNE-SSW striking towards the coast. Preliminary results from the analysis of wellbore failure in block 35/9 show, that the S_{Hmax} orientation in fact is rotated relative to the orientation of S_{Hmax} in the Tampen Spur (pers. com. D. Wiprut 1998). However, the observed rotation is much smaller than predicted by the deglaciation model, which indicates that ridge push contributes to the local stress field. By adding a SEE-NWW striking compression ridge push is expected to diminish the rotation predicted by the deglaciation model.

Discussion of results

The model shown in Figs. 6-8 is capable of explaining several features of the observed stresses in the northern North Sea. It predicts a compressive stress state in the Tampen Spur with S_{hmin} close to or even higher than S_V. This
off test data that suggest S_3 is very close t
the modeled decrease of the horizontal str
coast can be seen in the leak-off data as w
model predicts that the largest stress pert
shallow depth, but the leak-off data
perturbations to a depth of approximately 1,

It is hard to compare the modeled results
data, as there is almost no data available so
results from observations of wellbore fa
which suggest a S_1/S_V of around 1.25 at a
are matched well by this model. The earth
mechanisms confirm the general trend fro
stresses, i.e. reverse faulting in the Tampe
horizontal stresses closer to the coast, altho
generally poor. The model seems to under
stresses in the proximity of the coast, as the
is below S_V, but no normal faulting ea
observed. As mentioned earlier, modeled str
to be to low, because the model doesn't
push.

The high pore pressures in the Tampen S
elevated horizontal stresses in this area. C
where the horizontal stresses are smaller, th
almost hydrostatic. This close relationship
pore pressure suggests that part of the pore
in the Tampen Spur is caused by a poroela
result of elevated horizontal stresses.

Obviously the model has several short
thing we are only looking at stresses c
rebound. Other stress sources such as ridge
be of great importance. We are also ignori
cause erosion of the glaciated areas and se
the ice sheet rims[23]. Similarly to melting of i
to a differential isostatic response and
flexural stresses as well. Furthermore, by u
oriented two-dimensional model, we are ig
complex structure of the ice sheet. This mig
since 20,000 years ago the change in ice sh
largest towards the northwest (Fig. 1). Als
initially isotropic stress state, we are ignori
field stresses caused by ridge push. Neverth
we can explain high compressive stresses in
and decreased horizontal stresses on the
Viking Graben just by considering the melti
indicates that deglaciation is an important st

Conclusions

1. The combination of available obse
shows that the present day stress field is re
faulting in the Tampen Spur (i.e., S_{Hmax}>S
and less compressive on the east side of t
(i.e., $S_{hmin}<S_V$).

2. The comparison of observed stresses
model shows that deglaciation influences th
northern North Sea by increasing horizont
west side of the Viking Graben, and decre
eastern side.

3. According to the numerical model, the regionally consistent NEE-SWW striking orientation of S_{Hmax} is expected to be rotated by 90 degrees in the proximity of the coast, e.g. block 35/9. However, the preliminary results of an analysis of wellbore failure show that the rotation is much smaller than predicted, thus indicating that ridge push contributes to the local stress field as well.

4. To a depth of 3,000 m the pore pressures are hydrostatic on the east side of the Viking Graben, but severely overpressured on the western side. The model suggests that this overpressure might be due to the poroelastic response to flexural stresses caused by deglaciation.

Nomenclature

P_p = Pore pressure, m/Lt^2, MPa
S_1 = Maximum principal stress, m/Lt^2, MPa
S_2 = Intermediate principal stress, m/Lt^2, MPa
S_3 = Least principal stress, m/Lt^2, MPa
S_v = Vertical stress, m/Lt^2, MPa
S_{Hmax} = Maximum horizontal stress, m/Lt^2, MPa
S_{hmin} = Minimum horizontal stress, m/Lt^2, MPa
σ = Effective stress, m/Lt^2, MPa
μ = Coefficient of friction
C_0 = Cohesion, m/Lt^2, MPa
ρ = Density, m/L^3, kg/m^3
E = Young's Modulus, m/Lt^2, GPa
ν = Poisson's ratio
τ = Maxwell relaxation time, t, years

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TABLE 1 - PARAMETERS USED FOR NUMERICAL MODEL						
Depth unit	ρ (kg/m3)	E (GPa)	ν	τ (years)	μ	C_0 (MPa
Upper crust (sediments)	2,350	35	0.25		0.6	2
Upper crust (basement)	2,700	56	0.25		0.6	2
Lower crust	2,900	71	0.25	100,000		
Mantle	3,300		0.25	10,000		

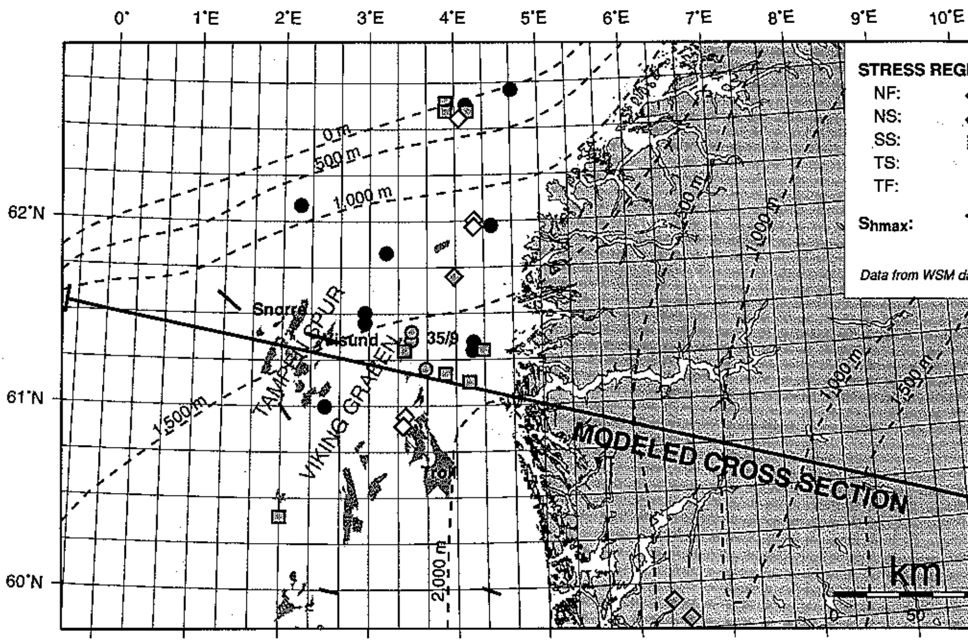

Fig. 1 Location map of the northern North Sea. Earthquake epicenter locations are plotted for different stress states. B orientation of S_{Hmax}. The data is mostly from the World Stress Map database. The S_{Hmax} orientation in Visund is ded induced tensile fractures[1]. The dashed lines illustrate extent and thickness of the ice sheet 20,000 years ago[18]. The cro where the model is performed. The data in subsequent figures are also plotted along the same cross section.

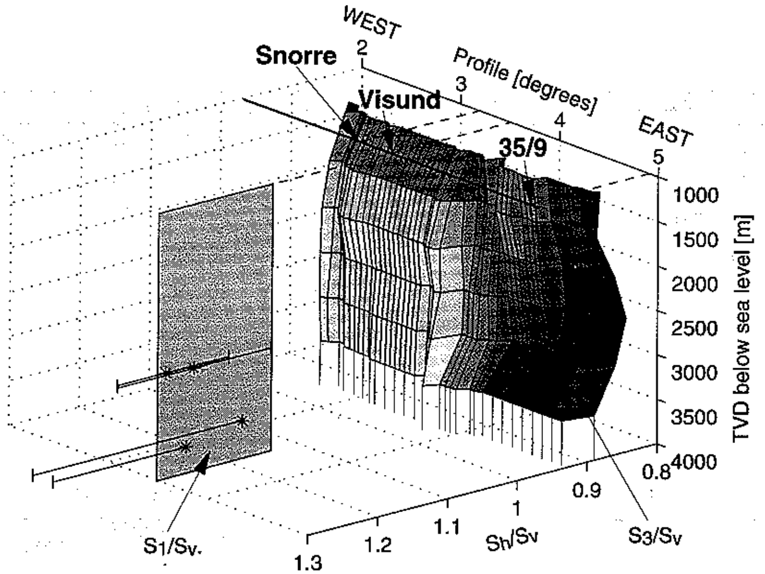

Fig. 2 Depth dependence of horizontal stresses, normalized by S_v along the cross section shown in Fig. 1. The plot sho the analysis of leak-off tests (S_3), as well as the magnitudes of S_1 from observations of wellbore failure in Visund[1]. Note S_3/S_v towards the coast.

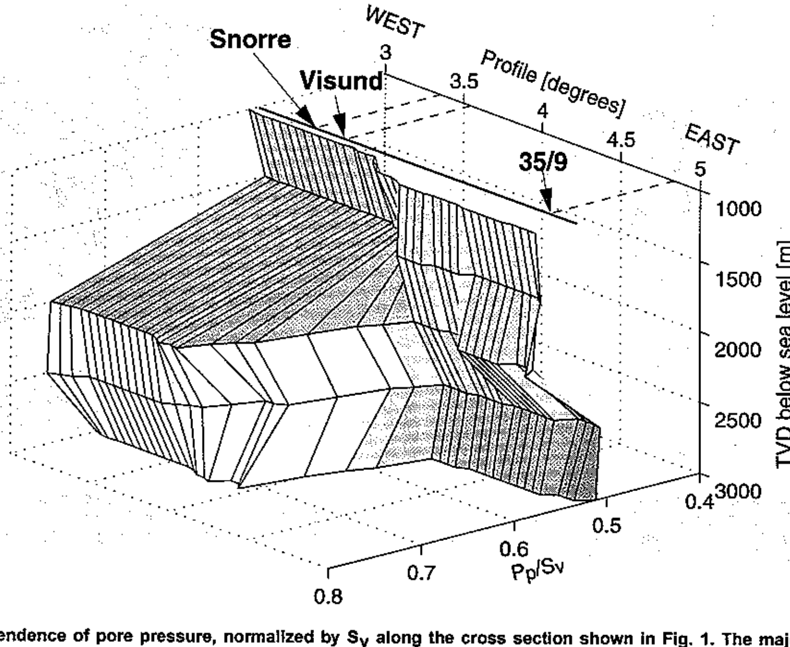

Fig. 3 Depth dependence of pore pressure, normalized by S_v along the cross section shown in Fig. 1. The majority c measurements are from RFT logs. The pore pressure is almost hydrostatic around block 35/9, but overpressured in the Tampe

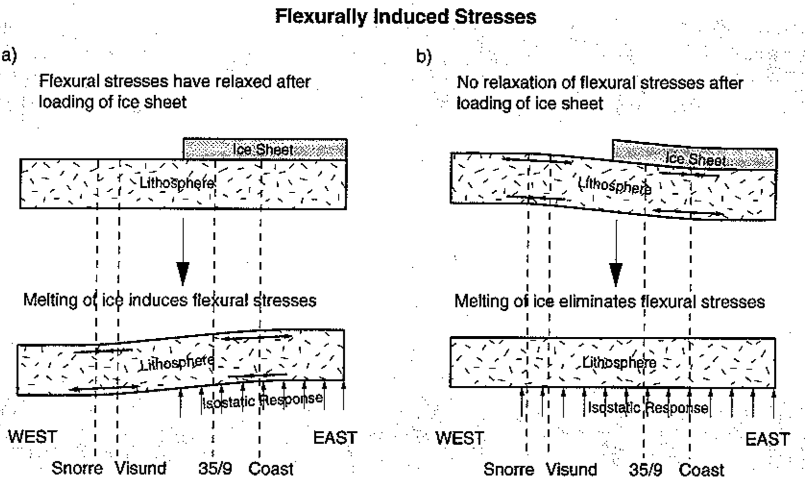

Fig. 4 Illustration of flexural stresses caused by deglaciation. Fig. 4a shows expected flexural stresses for the assumpt et al.[9], that the lithosphere was in stress equilibrium before the ice sheet started to melt. Fig. 4b shows Stephansson's as lithosphere has not reached a stress equilibrium during the existence of the ice sheet.

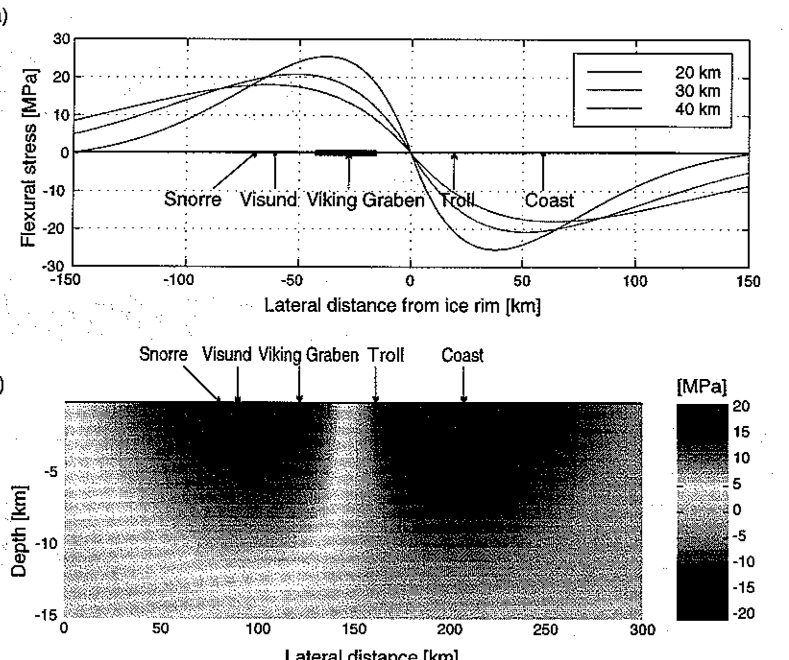

Fig. 5 Analytical model of stresses as a result of the flexure of an elastic plate[11]. Fig. 5a shows expected flexural stress as a function of the distance from the former ice sheet. The stresses are plotted for different elastic thicknesses of the lith a plot of the change of flexural stresses with depth, for an assumed elastic thickness of 30 km.

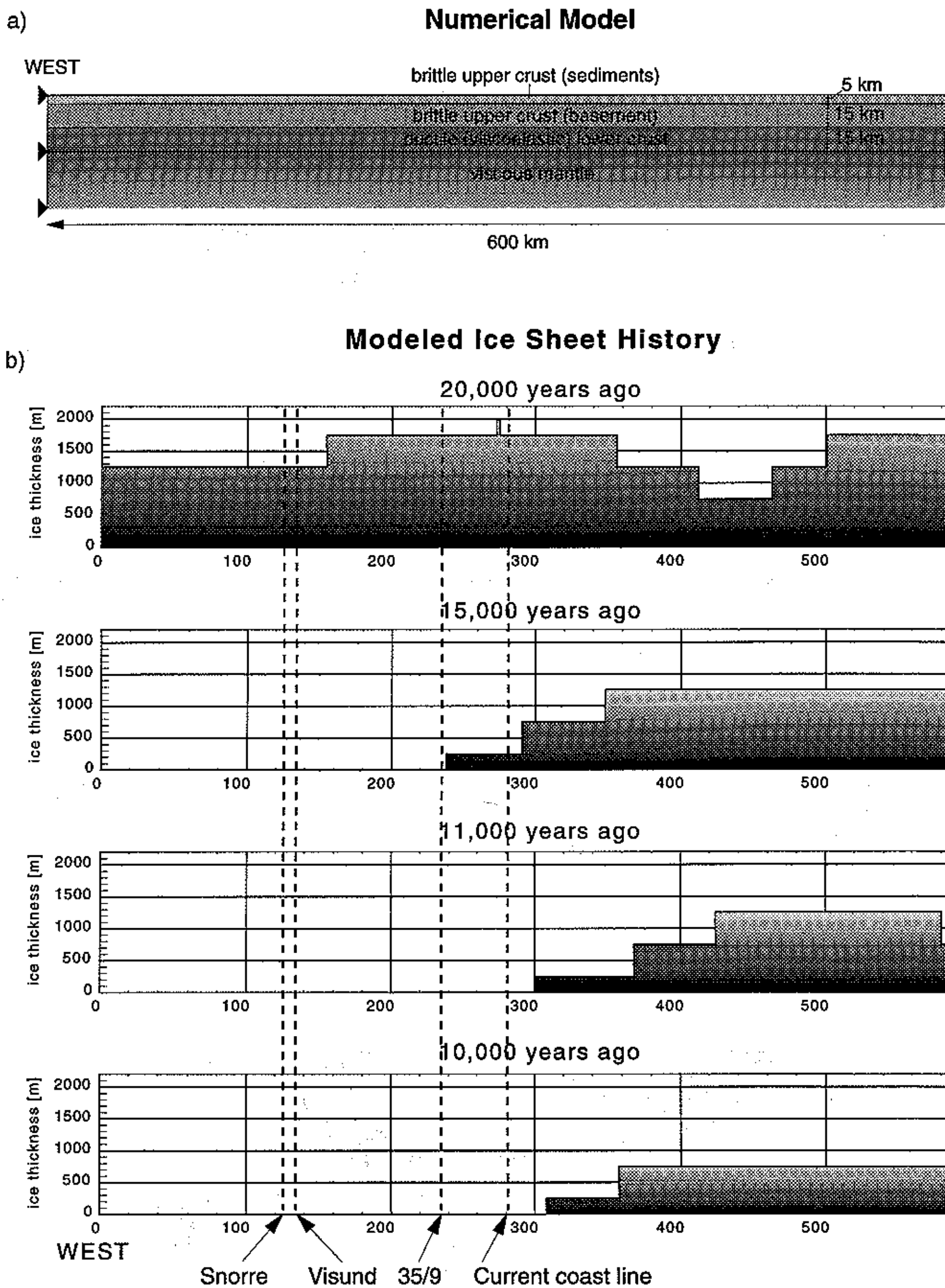

Fig. 6 Setup of the numerical model. Fig. 6a shows assumed rheologies and the geometry of the crust-mantle syst
numerical model. Fig. 6b illustrates the change of the modeled ice sheet with time[18,19,20]. 9,000 years ago the ice sheet is melte

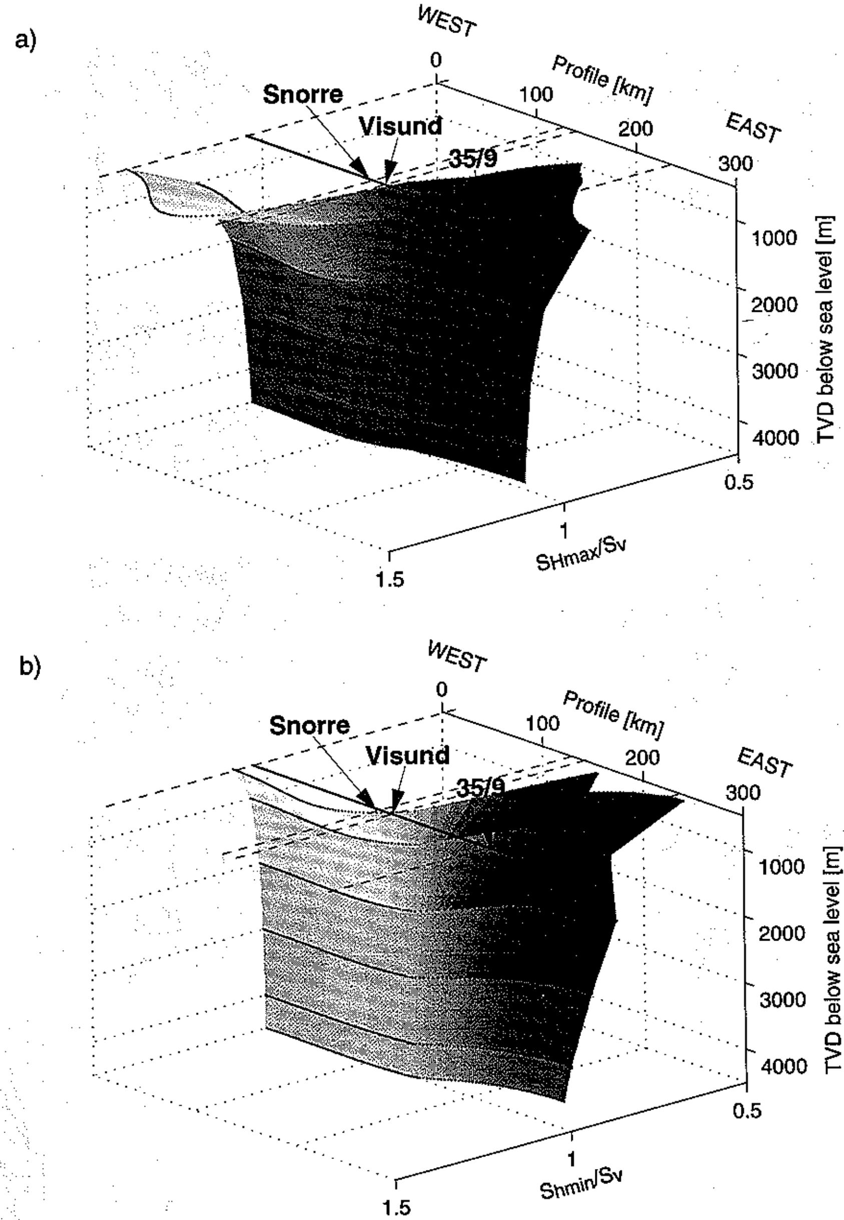

Fig. 7 Results for predicted present day magnitudes of S_{Hmax} and S_{hmin} from the numerical model, plotted along the as Fig. 2 and Fig. 3 as a function of depth. Fig 7a shows that S_{Hmax}/S_V is high in the Tampen Spur and decreases on Viking Graben. S_{hmin}/S_V is plotted in Fig. 7b. Note the strong decrease of S_{hmin}/S_V to the east of the Viking Graben.

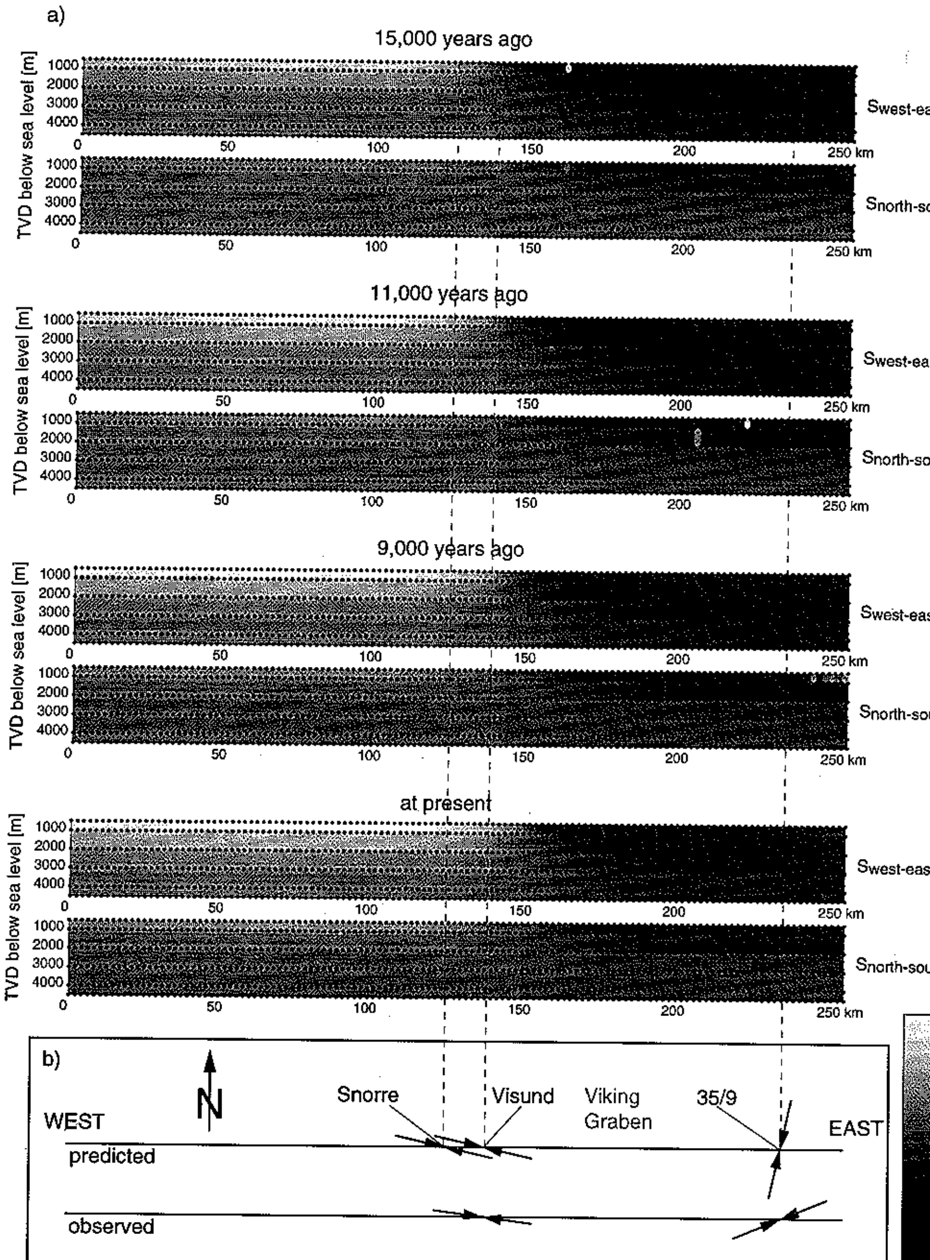

Fig. 8 **Predicted change of horizontal stresses due to deglaciation (Fig. 8a) and implications for the orientation of S_{Hmax} 15,000 years before present, horizontal stresses show a steady increase. At present horizontal stresses are higher than the the west side of the Viking Graben, but still lower on the east side. Since in block 35/9 $S_{west\text{-}east}$ is smaller than S_{n} orientation of S_{Hmax} rotates by 90 degrees.**