Pleistocene glacial isostasy — implications for petroleum geology

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The theory of glacial isostasy evolved in the second half of the 19th century and by the beginning of the 20th century it was fully accepted. The onshore data in Fennoscandia were overwhelming with traces of marine influence 200–300 m above the present shoreline. Very few studies have, however, been performed in offshore areas. Only recently, Quaternary research has reported phenomena interpreted as a result of glacial isostatic movements. Among petroleum geologists the effect has been almost neglected, and no public reports on how glacial isostasy may effect hydrocarbon bearing rocks (source or reservoir) exist.

Data from the Quaternary and latest Tertiary research have been compiled to establish a stratigraphic framework for the last 2–3 million years. Realistic ice models have been made which incorporate the observations made on three different sizes of ice sheets in northern Europe. These ice sheet models form the input for the modelling of isostatic deformation of the crust. The earth is modelled by a non-spherical viscous fluid, overlain by a uniform thick elastic lithosphere. The isostatic problem is treated using the Fourier transform technique.

The main product of the modelling is isobase maps describing the equilibrium deformation of the crust during the different glacial events. The model is calibrated using Fennoscandian sea-level curves after the last glaciation. The maps are therefore supposed to be valid also in the offshore parts of northern Europe including shelf areas with considerable oil and gas accumulations.

At least once and perhaps several times during the last 2–3 million years the central North Sea has been downwarped and subsequently uplifted by up to 400 m, on the Haltenbanken up to 250 m and in the Barents Sea as much as 650 m. The vertical movements have been differential in the sense that the areas overlain by thick ice domes have been downwarped more than peripheral areas. The modelled gradients are more than 1.0 m/km in graben areas of the North Sea and parts of Haltenbanken and about 1.3 m/km in the western parts of the Barents Sea.

The differential movements will have affected the entire crust including the sediments with their fluid content. The geometric change during the maximum downwarping may have important implications for the secondary migration of hydrocarbons. Hydrocarbons in traps filled to the spill point will start to spill during the isostatic movements and today the structure may be only partly filled. This effect can be severe in flat and in areally large structures. Our calculations show that as much as 30% of the total hydrocarbon volume can be lost during maximum glacial isostatic downwarping.

Introduction

It is generally accepted that crustal layers have a tendency to approach a position of hydrostatic equilibrium. Dutton (1889) proposed the term isostasy for this process. However, there are different mechanisms by which this may be achieved. Pratt (1855) postulated that mountains are composed of rocks which are less dense than average, while Airy (1855) suggested that mountains have roots, i.e., material of uniform density which extends deeper into the underlying denser material beneath the mountain than beneath the lowlands.

Realizing that the Earth's mantle is not rigid, Jamieson (1865) postulated that the load of an ice cap will deform the surface of the earth, giving rise to glacial isostasy.

The theory of glacial isostasy as an explanation for the marine deposits found high above the present shoreline in Scandinavia was generally accepted in the late 19th century when De Geer (1888, 1890) published his famous work on the uplift of Fennoscandia. A full understanding of the interplay between glacial isostasy and eustasy was, however, not reached before the work of Nansen (1922, 1927) and Ramsey (1924). Nansen (1922) was also the first to point out the possibility of a peripheral forebulge around an ice sheet

Large isostatic adjustments have occurred in Fennoscandia and adjacent areas in the last 2–3 million years. The cause of these adjustments is extensive glaciations with ice caps up to several kilometres thick in some areas. A number of glaciations have taken place during the Quaternary, but the

Structural and Tectonic Modelling and its Application to Petroleum Geology edited by R.M. Larsen, H. Brekke, B.T. Larsen and E. Talleraas. NPF Special Publication 1, pp. 187–195. Elsevier, Amsterdam.

isostatic movements will in principle be the same for all, although the magnitude and duration will be different.

Since the mid-sixties an extensive exploration for oil and gas has taken place in the North Sea, and somewhat later in the Haltenbanken area and in the Barents Sea. It has long been clear that these areas have been completely or partly covered by glaciers at least once and perhaps several times during the Quaternary. However, very little attention has been paid to the effects of glaciations on hydrocarbon generation, migration and trapping. The objective of this study is to examine the implications of glacial isostasy for petroleum geology.

Pleistocene glaciations in Northern Europe

Timing of glaciations

The initiation of northern hemisphere glaciations has been a subject of debate. Based on early DSDP results several authors (Laughton et al., 1970; Berggren, 1972; Berggren and Van Couvering, 1974) defined the onset of glaciations to approximately 3 Ma. Dating of glacial marine deposits from the Amarasian basin in the central Arctic ocean (Clark et al., 1980) gave approximately 5.3 Ma for the first ice-rafted material. The chronostratigraphy of this report has, however, been questioned (Grantz et al., 1982).

Based on results from Pacific cores (Shackleton and Opdyke, 1976; 1977) suggest initiation of northern hemisphere glaciation at 3.2 Ma, with a severe deterioration at 2.5 Ma. A correlation of the oxygen isotope stage zonation of four detailed Pleistocene oxygen isotope records from the Pacific (V28-239, DSDP 504), Caribbean (DSDP 502B) and the North Atlantic (DSDP 552) (Williams 1988) show a good correlation of nine cold events in the last 0.8 million years and in the time interval between 2.2 Ma and 0.8 Ma as much as 17 cold events are interpreted in one or all three areas. We have used the most complete oxygen isotope curve from the Pacific (Fig. 1), which is shown to correlate with the North Atlantic curves (Williams, 1988), to construct a eustatic curve (actually a curve showing the ocean water volume change given in metres of global change, cf., Fjeldskaar, 1989) which may represent the magnitude and importance of the glacial events in the last 2 million years A calibration of 0.11‰ $\delta^{18}O$ per 10 m of sea-level change has been used (Fairbanks and Matthews, 1978).

A recent investigation (Jansen et al., 1988) concluded that a major advance of the Scandinavian ice sheet took place at approximately 2.6 Ma based

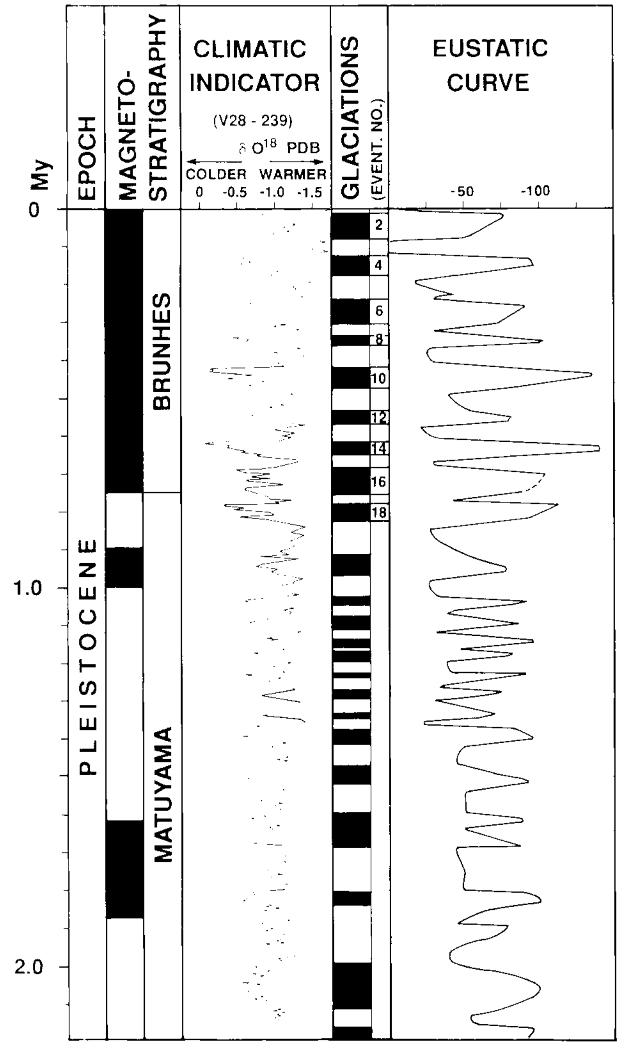

Fig. 1. Isotope records and deduced glacial events and eustatic curve (isotope curve from Schackleton and Opdyke, 1977)

on material from DSDP and ODP cores from the North Atlantic and the Norwegian Sea. This is based on oxygen isotope analyses, magnetostratigraphy and observation of ice-rafted debris. Several severe glaciations took place in the period 2.6–2.0 Ma. Between 2.0 and 1.2 Ma the glaciations in Scandinavia were small, while a transition towards larger glaciations took place during the period 1.2–0.6 Ma. In the last 0.6 million years the climate has been more variable with short warm interglacial periods between period with extensive glaciations seen as pulses of ice-rafted material in the cored material. The oxygen benthic isotope record in the Norwegian Sea (borehole ODP 644 A) shows relative changes of up to 1‰ (occasionally 2 units), which represent approximately 100 m (occasionally 200 m) of eustatic change, using the same method as for the Pacific core.

The extent and thickness of ice sheets

The regional extent and the thickness of ice sheets are the two controlling factors for glacial isostasy. From the stratigraphical record it seems to be certain that the North European area has been influenced by both small and large ice sheets during the last 2–3 million years

Ice sheets can be reconstructed on the basis of analogy with observational data from recent sheets and traces left behind by ancient sheets. The ice sheets used in this study have been reconstructed by the method of Hughes (1981). The most important input for determining the size of the ice-covered area has been the reported observations of dated or age estimated end moraines, while ice sheet gradients from recent sheets are the major input for estimating ice thickness and volume.

As a basis for our calculations of isostatic effects, three different ice sheets have been reconstructed. They are all based on different interpretations of observations from the last glaciation. The three ice models thus represent realistic geometries which most probably closely resemble the real situation in one or several of the previous glacial events.

Ice model I (Fig. 2). The ice sheet is characterized by three large ice domes. One over Novaya Zemlya in the East Barents Sea reaching 3200 m, one in central Fennoscandia of the same thickness and one in northern Great Britain reaching 2000 m. These three domes represent the growth centre of the ice sheets which has coalesced in the saddle areas in the south east Barents Sea and in the central North Sea.

An ice distribution like this has been proposed for the last ice age by Grosswald (1980) and Andersen (1981, maximum alternative). There is, however, an ongoing discussion as to whether the North Sea and the Barents sea were glaciated during the last ice age (see discussion in Boulton, 1979; Grosswald, 1980; Andersen, 1981; Solheim and Kristoffersen, 1984; Sejrup et al., 1987; and Vorren et al. 1989).

It can, however, be concluded that both areas were glaciated once or most probably several times during the Pleistocene. Sejrup et al. (1987) conclude that in the North Sea the central area (Fladen Ground) was overridden by ice several times in the time interval 1–0.7 Ma. The area was also glaciated sometime between 0.2 and 0.13 Ma (the Saalian). In the Barents Sea glacigenic processes have been active at least four times during the Pleistocene and as far west as the shelf break according to Elverhøi and Solheim (1987) and Vorren et al. (1989).

In the Haltenbanken area marginal moraines situated at the shelf edge have been mapped by Andersen (1979). Between 64°N and 66°N the marginal moraines are found approximately west of 6°E, which means that the entire shelf area most probably was covered by ice during the last glacial event. Since the Haltenbanken is situated relatively close to the mountainous area and central Fennoscandia, even minor glacial events could have covered the shelf.

Ice model II (Fig. 3). A large ice dome in central Fennoscandia (thickness 3200 m) is isolated from an ice dome in northern Great Britain (thickness

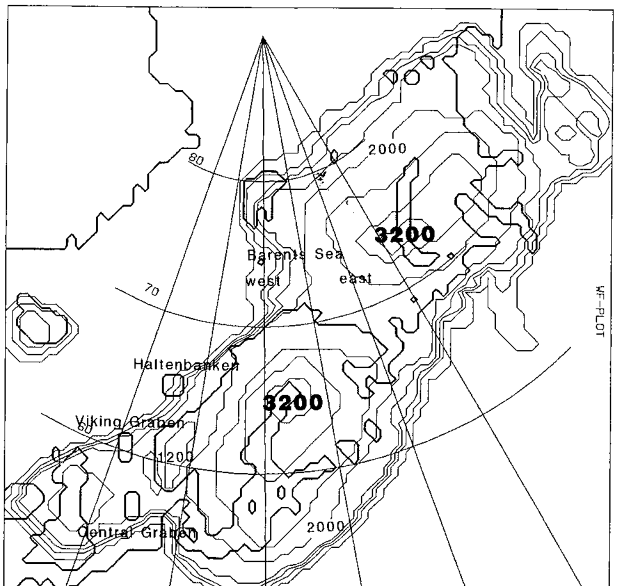

Fig. 2. Ice model I. Based on the maximum model of Andersen (1981). Isopacks are each 400 m. Outer line 400 m.

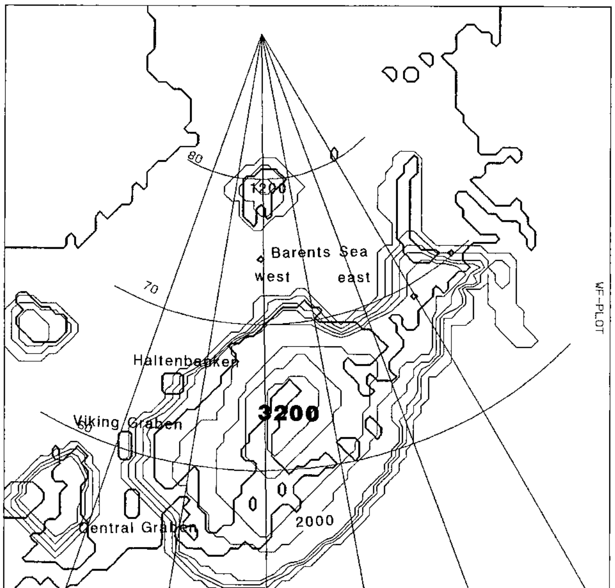

Fig. 3. Ice model II. Based on the minimum model of Andersen (1981) for the Barents Sea and on Sejrup et al. (1987) for the North Sea. Isopacks are each 400 m. Outer line 400 m.

1600 m) and one in Svalbard (thickness 1200 m). Most of the North Sea and the entire Barents Sea are ice free. The ice cover in the Haltenbanken area is the same as in ice model I. The model is based on Andersen's (1981) minimum alternative for the Barents Sea, and that of Sejrup et al. (1987) for the North Sea.

This model can represent the last glaciation (Weichselian) in the North Sea. Data from the western part of the North Sea and from Scotland (Sutherland, 1984) indicate that the British ice sheet did not reach much further east than today's land area. This supports the conclusions made by Sejrup et al. (1987) that the British and the Scandinavian ice did not coalesce in the Fladen Ground area (Sleipner Field).

Ice model III. This model is similar to model II except for a reduced ice thickness in the mountain areas in the eastern part of Norway according to the theory of Nesje et al. (1988). This isostatic modelling, however, gives results very similar to those obtained when using model II (Table 1).

A detailed history of outbuilding and downmelting of the ice sheets has not been applied in any of the models. Both processes are modelled as being instantaneous.

Methods of glacial isostatic modelling

The Earth is modelled by a non-spherical viscoelastic fluid in which the viscosity may vary with depth, overlain by a uniform thick elastic lithosphere. With this flat earth model, we are able to treat the isostatic problem analytically using the Fourier transform technique. The method used is developed by Cathles (1975).

The Fourier transform allows a function such as the ice sheet configuration to be expressed as the sum of harmonic components of different wavelengths.

The asthenosphere is treated as a viscous fluid in which the rate of displacement varies with the wavelength of the harmonic component of the load. The elastic lithosphere is treated as a low-pass filter, because loads of small size tends to be balanced by the lithosphere itself and not by buoyancy.

Mantle viscosity

Data on the present rate of uplift and sea-level changes after the last glaciation show that the mantle is of low viscosity (Fjeldskaar and Cathles, 1991a, b).

In calculations of the time-dependent isostatic deflections, a detailed glacial history must be taken into account. This is not done in the present study. Only the situation at isostatic equilibrium (which is achieved 20 000 years after loading/unloading) is modelled. The isostatic model is then rather simple, as the important parameter is only the lithospheric rigidity.

Lithosphere modelling

If an ice load is applied to a fluid, the surface of the fluid will deform until the weight of the fluid displaced from the equilibrium level balances the applied load (local isostatic compensation). If an elastic lithosphere covers the fluid the applied load will be supported partly by the lithosphere and partly by the buoyant forces of the fluid beneath acting through the lithosphere (regional isostatic compensation). If the size of the load is small compared to the lithospheric thickness, the base of the lithosphere is not deformed at all and the entire load is balanced by the lithosphere. If the load is large, the lithosphere supports none of the load, and the deformation at the base of the lithosphere is the full isostatic deformation.

The lithosphere thus acts as a lowpass filter. The characteristics of this filter depend on the elastic strength of the lithosphere. A measure of the elastic strength of the lithosphere is a parameter called the flexural rigidity. The elastic strength of the lithosphere is a function of mechanical thickness and is determined by the following equation:

$$\text{Flexural rigidity } D = \frac{EH^3}{12(1-\nu^2)}$$

where H is elastic thickness, E is Young's modulus, ν is Poisson's ratio.

The regional isostatic equilibrium compensation due to a harmonic load $F(x)$ is achieved by subsidence (Cathles, 1975):

$$h_0 = \frac{F(k)}{\rho g \alpha(k)}$$

For a local compensation model the subsidence is:

$$h_0 = \frac{F(k)}{\rho g}$$

where $F(k)$ is Fourier transformed ice load, ρ is density of the upper mantle, and g is gravity.

The "lithosphere filter" is:

$$\alpha(k) = \frac{\frac{2\mu k}{\rho g}(S^2 - k^2H^2) + (CS + kH)}{S + kHC}$$

where $S = \sinh kH$; $C = \cosh kH$, H is mechanical thickness of the lithosphere, μ is Lame's parameter, and k is wavelength.

In this study we use a mechanical thickness of the lithosphere equal to 70 km (flexural rigidity of 50×10^{23} Nm). This is based on a study by Fjeldskaar and Cathles (1991a) concerning data on the present rate of uplift and sea-level changes after the last glaciation in Scandinavia (Kjemperud 1986).

The model presumes a uniformly thin lithosphere. This is of course a simplification. The spatial variation of the lithosphere thickness is, however, difficult to estimate. Moreover, the effects introduced by this presumption are probably of second-order only.

The flexural rigidity for the shelf areas is not known, the study mentioned above is based on data from the Scandinavian mainland. It is, however, reasonable to assume the same rigidity as for Scandinavia, because the shelf areas also have continental crust. The large sediment thickness on the shelfs does not influence the flexural rigidity; the elastic thickness of the lithosphere is almost 70 km, while the sediment package is only 5–10 km thick.

The geophysical model of the Earth used in this study is shown in Fig. 4. The geological and geophysical processes associated with periods of glaciations/deglaciations are also shown. These processes are isostasy, eustasy, flow in asthenosphere, glacial erosion and deposition.

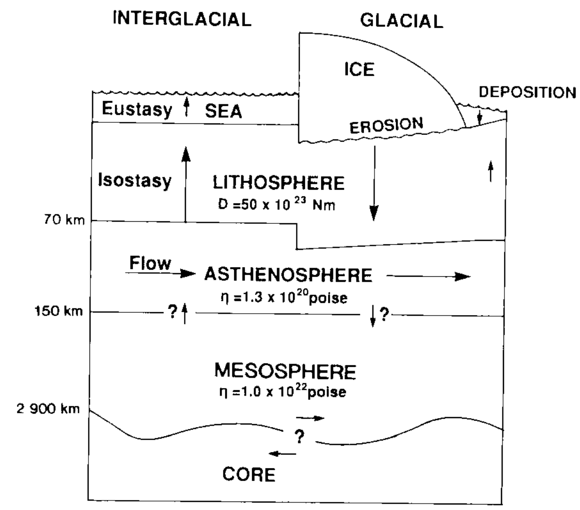

Fig. 4. Geophysical model of the earth as used in this study. Geological and geophysical processes during interglacial periods (left) and glacial periods (right) are shown.

Results from isostatic modelling

The results from the isostatic modelling are given in the isobase maps (Figs. 5 and 6) and in Table 1.

The largest downwarping of the lithosphere seen is in the eastern Barents Sea where values of more than 600 m are reached by applying ice model I. In the North Sea the maximum values exceed 400 m and on Haltenbanken it reaches 250 m.

The largest gradients, 1.3 m/km east–west, are seen in the western Barents Sea. However, the other areas also show values above 1.0 m/km when applying ice model I.

Because of the lack of a deglaciation history, the time-dependent forebulge is not represented in the modelling results (Table 1). A transient model has, however, been applied in the North Sea and in the Haltenbanken; indicating that the forebulge reaches a maximum just after the deglaciation and is somewhat higher than the values shown

TABLE 1

Isostatic effects in key areas of the Norwegian shelf

Ice models	Central graben	North Viking graben	Halten banken	Barents Sea west of 22°E	Barents Sea east
Ice model I					
Ice cover (m)	1200 to 1600	1200 to 1600	400 to 800	400 to 1200	1200 to 2400
Isostasy (max) (m)	400	450	230	400	650
Forebulge	no	no	no	no	no
Gradients N–S	−1.1	1.2	0.6	0.4	0.3
Gradients E–W	−0.5	0.4	1.0	1.3	0.8
Ice model II					
Ice cover (m)	0	0	400 to 800	0	0
Isostasy (max) (m)	−25 to +70	110	250	−10 to +160	−30 to +160
Forebulge	yes	no	no	yes	yes
Gradients N–S	−0.4	0.2	0.8	0.9	0.8
Gradients E–W	−0.3	0.8	1.0	0.5	0.3
Ice model III					
Ice cover (m)	0	0	0 to 800	0	0
Isostasy (max) (m)	−5 to +40	50	230	−10 to +160	−30 to +160
Forebulge	insignificant	no	no	yes	yes
Gradients N–S	−0.3	0.1	0.7	0.9	0.8
Gradients E–W	−0.3	0.5	1.1	0.5	0.3

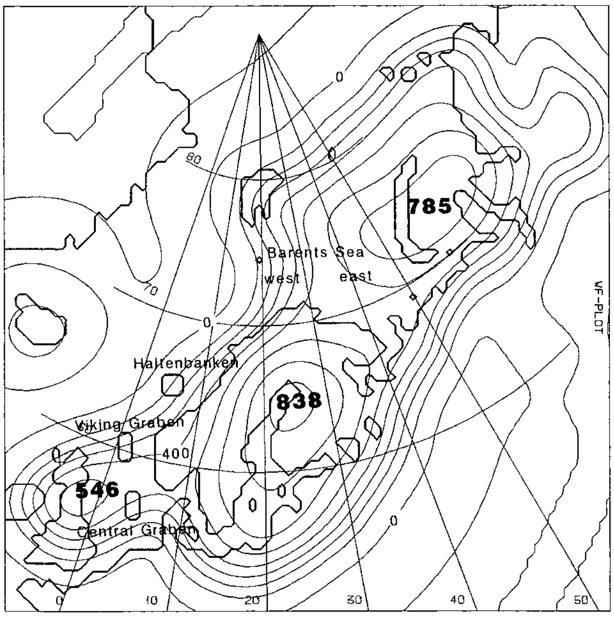

Fig. 5. Modelled isostatic effect of ice model I. Isobases each 100 m.

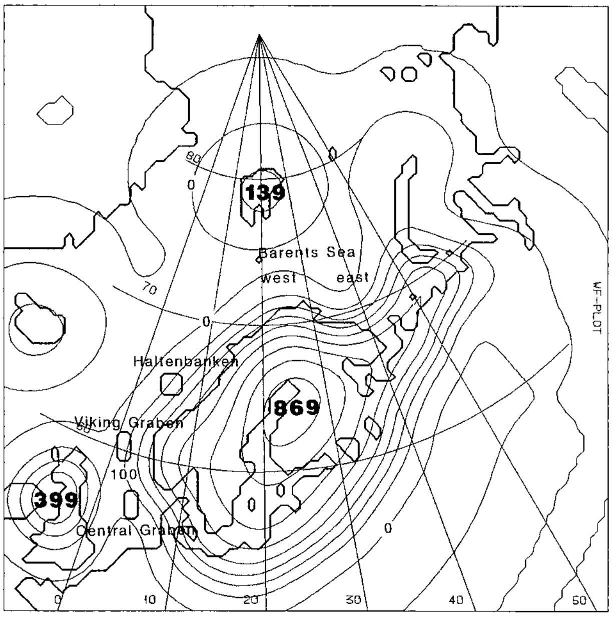

Fig. 6. Modelled isostatic effect of ice model II. Isobases each 100 m.

Table 1. The height of the forebulge does not seem to exceed 60–70 m.

Implications for hydrocarbon migration and trapping

The theory of glacially isostatic induced hydrocarbon migration combines the glacial isostatic effects with the fact that liquid interfaces are equipotential surfaces. In normal pressure areas they are parallel to the geoid. Figure 7 shows how a simple structure behaves during one glacial cycle. It is assumed that the structure is filled with hydrocarbons to the spill point at the onset of vertical movements.

When the lithosphere and the structure are downwarped differentially due to glaciation, hydrocarbons start to spill out of the structure. This goes on until the maximum tilt situation is reached (Fig. 7b). The closure volume is now reduced proportional to the differential movements.

When the lithosphere and the structure are uplifted to the starting position due to deglaciation, a new hydrocarbon-water contact (HCWC) is established (Fig. 7c). The freeboard which is the vertical difference between the HCWC and the spill point will be defined by the magnitude of the differential movement.

Fossil HCWCs can theoretically be found at the spill point level for the two extreme positions. Residual oil can be found in the water zone down to the original spill point level. In a gas-filled reservoir with an oil leg originally, residual oil can also be found in the gas-filled part, limited by the uppermost fossil HCWC.

The effect of the glacially induced hydrocarbon migration is determined by several factors:

– *The gradient of the deformation*. The gradient is dependent on the geometry of the ice sheet. The result observed today is the effect of the ice sheet creating the highest gradients through time.

– *The number of isostatic events*. Tilting will be the result of each isostatic event. A number of isostatic events will create overlapping and chaotic patterns of fossil contacts and residual oil which will be very difficult to interpret.

– *The orientation of the long axis of the hydrocarbon-filled structure*. The direction of the length axis of the field will greatly influence the volume changes during the isostatic events. The differential downwarping will be highest when the longest axis is parallel to the main gradient. A 30 x 5 km field directed along a 1 m/km gradient give a differential tilt value of 30 m, while the perpendicular orientation would give a differential value of only 5 m.

– *The initial fill of the trap*. An incompletely filled trap could possess enough freeboard to accommodate for the differential changes. The *freeboard height* is the difference between the spill points of the trap at maximum uplift and maximum downwarping.

– *The spill point orientation*. If the spill point is situated in the area of least relative downwarping the entrapped volume will be reduced and vice versa. In light of the isobase maps (Figs. 5 and 6) fields in the Barents Sea with spill points in the west and north, and fields on Haltenbanken with spill points towards

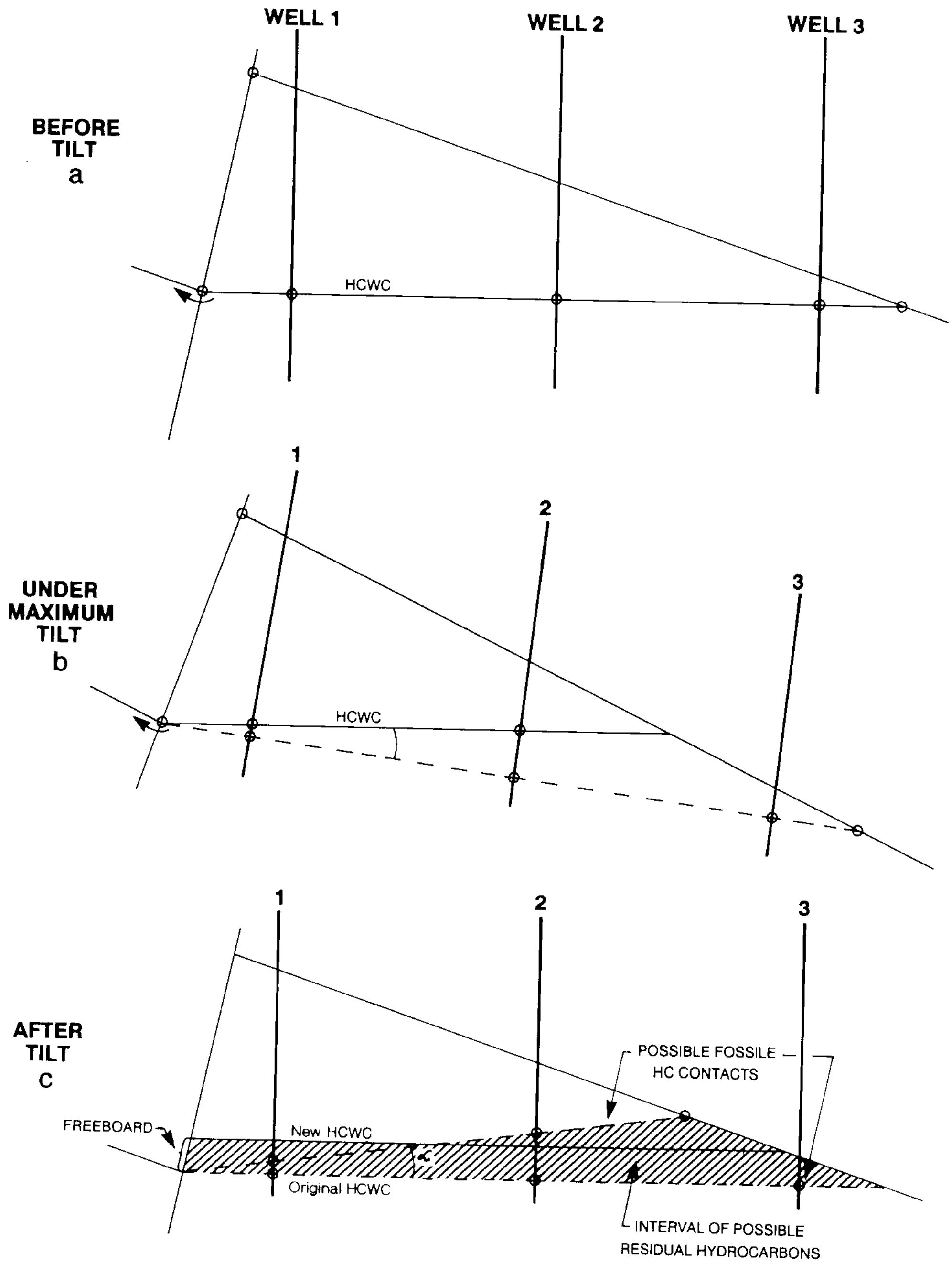

Fig. 7. Geometric changes of schematic reservoir during one cycle of glacial isostatic deformation.

the north/west will get a reduced closure volume during glaciation. In the northern North Sea a spill point in the north and east will give reduced closure volume, while in the southern North Sea a spill point in the east and south will give the same effect.

– *The geometry of the receiving area.* The geometry of the receiving area can give several scenarios for the fluids migrating out of the trap. If a saddle area is opened, the fluids can migrate into a higher lying trap or be lost to the surface. Alternatively, a surrounding flat area can become a part of the trap during the downwarping and fluids will migrate back into the trap under uplift.

A hypothetical example from the Barents Sea

By using a realistic geological model for the last 0.3 million years we have calculated the changes in closure volume in a hypothetical field in the western Barents Sea. Three isostatic events are seen in this period of time, i.e., the Elsterian (event 6 in Fig. 1) the Saalian (event 4) and the Weichselian (event 2).

The field has the following characteristics:

Dimensions:	length, 30 km; width, 5 km
Orientation:	east–west
Spill point:	west
Initial freeboard:	0 m

TABLE 2

Glacial isostatic induced migration in a hypothetic oil/gas field in the western Barents Sea

Glacial event (ice model)	Vertical movement (maximum) (m)	Diff. vertical movement of spillpoint (m)	HC-column (m)	Freeboard (m)	Relative volume
Initial	0	–	100	0	1.0
During 6 (II)	−160	−15	–	0	1.0–0.9
After 6	+160	+15	92	7	0.9
During 4 (I)	−300	−40	–	0	0.9–0.7
After 4	+300	+40	80	20	0.7
During 2 (I)	−300	−40	–	0	0.7
Present	−250	30	85	15	0.7

The calculations are based on isostatic compensation for the two first events, and a remaining uplift of 50 m after the last.

Fluid:	gas and oil
Initial volume:	1
Initial HC column:	100 m
Field geometry:	bar triangular in section

The results of the calculations based on the isobase maps of ice model I (for event 2 and 4) and ice model II (for event 6) are given in Table 2.

During event 6 (Elsterian) the field is tilted to the south and east with gradients of 0.9 and 0.5 m/km, respectively (Table 1). This gives a differential vertical movement of 17 m and a loss in volume of approximately 10%.

During event 4 (Saalian) the change is more drastic. The gradients are 1.3 m/km towards the east and 0.4 m/km towards the south. The differential vertical movement will be 40 m and the total loss of volume will now add up to nearly 30% compared to the initial value. The field will reach a maximum downwarping of 300 m during this event.

During event 2 (Weichselian) there will not be any dramatic effect because a high freeboard is established after event 4, and although the isostatic effect is of similar magnitude during event 2 the implications for the volume are insignificant.

The present situation is not in isostatic equilibrium and a remaining uplift of some 50 m will give 5 m remaining differential uplift at the spill point.

The effects of pressure differences and fluid equilibrium are not taken into account, but are believed to be of minor importance.

This exercise, although hypothetical, is realistic and shows that up to 30% of the initial bulk volume can be affected during the glacial isostatic downwarping. In a more or less homogeneous reservoir this would mean that nearly 30% of the hydrocarbon volume would be lost. In fields where there is an oil leg this lost volume would mainly be oil. The lost volume is controlled by field geometry to a large extent and the 30% is only related to the example given.

Summary and conclusions

Northern Europe including the continental shelf areas has been covered by extensive ice sheets at least once and perhaps several times during the last 2–3 million years

Three ice sheet models have been established based on stratigraphic and geomorphologic data from the North European mainland and shelf areas.

The most extensive ice sheet model covers both the entire North Sea and the Barents Sea with ice thicknesses in excess of 1500 and 2000 m, respectively. The least extensive ice sheet model covers only parts of the shelfs, except for in the Haltenbanken area where the shelf edge is the ice limit. All models fulfil the onland data of glacial uplift after the last glaciation.

The isostatic response to the ice load is modelled by a flat earth model and the Fourier transform technique. Isobase maps for the ice sheet models have been calculated. In the shelf areas the largest isostatic effect, more than 600 m, is found in the eastern Barents Sea when the most extensive ice model is used. The highest deflection gradients are seen in the western Barents Sea reaching 1.3 m/km.

A theory of glacial isostatic induced hydrocarbon migration is established and a hypothetical hydrocarbon accumulation in the western Barents Sea is being modelled using a realistic geological history for the last 0.3 million years The results show that as much as 30% of the closure volume can be lost during the most extensive glacial events.

Acknowledgements

This study was supported by funding from the Norwegian Council for Technology (NTNF).

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