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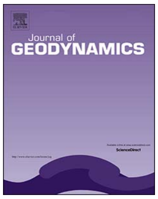

Effects of glaciations on sedimentary basins

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ABSTRACT

Many of the Earth's sedimentary basins are affected by glaciations. Repeated glaciations over the last millions of years had great influence on the physical conditions in sedimentary basins and on basin structuring. This paper presents some of the major effects that glaciations have on sedimentary basins including examples of quantifications of their significance.

Ice sheets are capable of eroding, transporting and depositing huge amount of sediments. The shape of ice sheets changes over time, and in general the erosion will have concentric pattern forms due to the low ice velocity under the center of the continental glaciers, and the more rapid basal ice velocity near the margins. Glaciations add a degree of difficulty to petroleum exploration. Erosion leads to cooling, which implies that the source rocks will be at a higher degree of maturation than expected from their present depth. The temperature effects of the glacial cycles will add to the erosion effect. A sedimentary basin covered by glacier ice during the last ice age is not in thermal equilibrium, maybe as far as 10–15 °C from equilibrium at 2 km depth.

Among the most important effects are also movements of the solid Earth caused by glacier loading and lateral movements of sediments. The driving factor of these movements is isostasy. Sedimentary basins near the former ice margin can be tilted as much as 4 m/km which might significantly alter pathways of hydrocarbon migration.

The modeled examples are from Northern Europe, but the conclusions are valid for sedimentary basins beyond this area.

1. Introduction

As much as 30 percent of the Earth's land surface was covered by glacier ice during the Quaternary (Coates, 1974). The presence of so much ice upon the continents had a profound effect upon almost every aspect of Earth's hydrologic system. The most obvious effects are the landscapes fashioned both by glacial erosion and deposition, and this happened in a relatively short period of geologic time. In addition, the vast bodies of glacial ice affected Earth well beyond the glacier margins. Directly or indirectly, the glaciations effects were felt all over the globe. The Earth is currently in an interglacial period, and all that remains of the continental ice sheets are the Greenland and Antarctic ice sheets in addition to a number of smaller glaciers.

During the Quaternary (last 2.6 million years) there have probably been more than 30 glaciations. Repeated episodes of growth and withdrawal of huge glaciers, glacial erosion and associated sediment deposition lead to geologically dramatic changes in surface loading. The lithosphere responds to these changes by subsiding under loading, and by uplifting when loading is removed. The driving mechanism for this is isostasy.

The ice on both North America and Europe was probably about 2–4 km thick near the centres of maximum accumulation (cf. e.g. Peltier et al., 2015), but it tapered toward the glacier margins. Differential vertical movement of the lithosphere related to glacial isostasy lead to repeated tilting of sedimentary formations and potential petroleum reservoirs therein, which may have greatly affected hydrocarbon migration pathways in the former glaciated areas (Kjemperud and Fjeldskaar, 1992). In addition, the upward and downward bending of the lithosphere lead to flexural stresses (Grunnaleite et al., 2009) likely to affect faults and their permeability, which could add to the changes in hydrocarbon migration pathways.

Ice sheets are capable of eroding and transporting huge amount of sediments. A sometimes used term connected to uplifted, eroded sedimentary basins where removal of overburden has taken place is ‘exhumation’. Exhumed basins evaluated in the same way as ‘normal’ subsiding basins, leads to errors and unrealistic expectations (Doré et al., 2002b) in petroleum exploration. Exhumation leads to cooling and pressure decrease and these factors add a degree of difficulty to petroleum exploration. Some key implications that exhumation can have on petroleum systems are summarized by et al. (2002a,b); : 1)

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sealing horizons are removed and/or their effectiveness is severely reduced; 2) faults might be reactivated causing them to become conduits for hydrocarbon leakage to the surface; 3) source rocks will be at a higher degree of maturation than expected from their present depth and will cease to generate upon cooling; 4) potentially attractive reservoirs may be over-compacted and downgraded; 5) pressure reduction during exhumation causes oil accumulations and formation water to exsolve gas, causing gas flushing and the spillage of oil; 6) regional tilting during uplift results in changes to trap configuration and fluid migration deposits.

In some areas there are clear indications of hydrocarbon spillage (e.g. Vadakkepuliyambatta et al., 2013). Some of the hydrocarbon spillage is linked to isostatic movements due to cycles of Pliocene-Pleistocene ice sheet loading/unloading and glacial sediment redistribution (Cavanagh et al., 2006; Doré and Jensen, 1996; Duran et al., 2013; Zieba and Grover, 2017; Lerche et al., 1997). The recent discovery of the giant Johan Sverdrup oil field in the Norwegian North Sea is suggested to be oil charged during Quaternary, and that the area more than likely underwent tilting and possible leakage several times in the last 1 million years (Stoddart et al., 2015). Detailed control on the glaciation history and glacial isostasy is important and so far an insufficiently utilized factor for identification of the remaining hydrocarbon resources in sedimentary basins formerly covered by glacier ice.

This paper present quantifications of some important effects of the glaciations on sedimentary basins, exemplified by the European glaciations and sedimentary basins. We will specifically cover the following aspects of the glaciations: Glacial isostasy, paleo permafrost and temperature effects, sediment redistribution with subsequent isostatic response, and their effects on the sedimentary basins and petroleum systems.

Even if we have used data from Northern Europe, our results demonstrate in a general perspective that both large ice sheets and cyclic glaciation frequency have major influences on the physical conditions in a sedimentary basin and on basin structuring.

2. Glaciations

It is commonly accepted that major changes in Earth's climate started in Gelasian (~2.588 million years ago), and the spread of ice sheets in the Northern Hemisphere began (e.g. Gibbard et al., 2009). Since then, the world has seen cycles of glaciers advancing and retreating on 40,000- and 100,000-year time scales. 40 000 years glaciation cycle dominated in the early period, while 100 000 years cycle dominated in the past million years or so (Mangerud et al., 2011). The most extensive glaciations are traditionally referenced to the last million years (Late Quaternary; cf. Fig. 1).

The last glacial period began about 110 000 years ago and ended 10 000 years ago. A model of the deglaciation history for our area is given in Fjeldskaar and Amantov (2017). The glaciations that occurred during this glacial period covered many areas of the Northern Hemisphere and have different names, depending on their geographic distributions. The extent of the Eurasian Ice Sheet during the Last Glacial Maximum (LGM) has been long debated in literature. Larsen et al. (2016) argue for a highly asynchronous ice sheet with regional differences in the age of maximum ice-sheet positions. In this paper we use the LGM (20 000 BP) reconstruction of Svendsen et al. (2004).

3. Ice thickness

Glacial isostasy is calculated based on the palaeo ice extent (from dated marginal moraines) and models of the ice thicknesses. Observational data increasingly constrain the extent of the Quaternary ice sheets. The thickness and volume of these ice sheets are much harder to reconstruct and generally need to be inferred from indirect evidence and modeling.

Several models of ice thickness of LGM and the late-glacial deglaciation are published; the loading scenarios are produced using different methods and sets of constraints. Some of them consider thermomechanical coupling (e.g. Zweck and Huybrechts, 2005). Auriac et al. (2016) present some of the models of LGM ice thickness. To our knowledge ice thickness models of earlier glaciatons are not published.

In this paper we focus on two ice thickness models − LGM and typical Late Quaternary glacier, shown in Fig. 1. The method used to compute ice-sheet thicknesses consists of (more details are given in Amantov and Fjeldskaar, 2013):

1. Estimate of a general ice-sheet with averaged values and shapes associated with viscoplastic flow as we know from present ice-sheets,
2. Modification of ice-thickness distribution due to sub-glacial topography,
3. Corrections of ice-thickness due to approximations of possible ice-streams, variable substratum of ice-sheets, areas of different discharge, etc.

4. Glacial isostasy

The isostatic effect of sedimentation/erosion is due to buoyancy, and will be caused by the density contrast between the load/unload and mantle. If the density of the eroded sediments is 1.7 g/cm^3, the uplift will be approximately 50% of the erosion amplitude (since the mantle density is ~3.3 g/cm^3). The isostasy caused by loading (or deloading) of glaciers is approximately 30% of the ice thickness (since the ice density is 0.9174 g/cm^3).

These simple estimates are based on Airy isostasy, which assumes that the compensation takes place locally and instantaneously over geological time scales. However, the Earth's response to deglaciation shows that the lithosphere acts as an elastic shell overlying a viscous mantle. If a load is applied to the elastic lithosphere, part of the applied load will be supported by the elastic lithosphere, and part by buoyant forces of the mantle underneath, acting through the lithosphere.

In literature there is disagreement on the effective elastic thickness of the lithosphere; the elastic effective thickness of Fennoscandia varies in literature from 30 to 160 km (cf. Fjeldskaar and Amantov, 2017). Our modeling of the post-glacial isostatic response, calibrated with the observations onshore Norway, gave best fit with an effective elastic thickness of 30 km; see Fjeldskaar and Amantov (2017).

We have now calculated the isostatic response of the solid Earth based on models of the last glacial maximum (LGM) and Late Quaternary glacier (Fig. 1), with the above mentioned lithosphere rheology for the entire Quaternary. The calculated glacial isostatic response for the Late Quaternary is shown in Fig. 2a. The method used in the isostatic calculations is described in Fjeldskaar (1997).

As seen from Fig. 2a there will be significant subsidence (~ 700 m) of potential sedimentary basins formerly covered by ice sheets. Sedimentary basins that are located in the periphery of the former ice sheet will be significantly affected by tilting as the subsidence (or uplift after the melting) is gradually decreasing towards the periphery of the former ice sheet. This is clearly seen along the entire Norwegian coast and in the Barents Sea. Sedimentary basins located in this area could be tilted by as much as 3 m/km for the LGM ice sheet (Fig. 2b), and even more in the previous glaciations. The largest tilts of the Earths surface are found in the more peripheral areas of the former ice sheet.

One important issue regarding the isostatic calculations is related to possible remaining response from previous glaciations. This can be answered by referring to potential remaining post-glacial rebound from the latest glaciation. Fig. 3 shows the calculated present remaining isostatic uplift after the last glaciation when the deglaciation history is taken into account (more details in Amantov and Fjeldskaar, 2016; Fjeldskaar and Amantov, 2017). In central Fennoscandia there is still ~40 m remaining uplift, due to the late deglaciation of this area. The remaining uplift is ~5% of the total post-glacial uplift, only 10 000