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Review article

Heat flow of Norway and its continental shelf

Christophe Pascal

Institute of Geology, Mineralogy and Geophysics, Ruhr University Bochum, Germany

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ABSTRACT

Terrestrial heat flow influences a large collection of geological phenomena. Its determination and understanding is of prime interest for oil industry because geothermal processes impact directly maturation histories and economic potential of oil fields and reservoirs. Published systematic heat flow determinations from major oil provinces are however seldom. Robust heat flow determinations in drillholes require logging of undisturbed temperatures and intensive sampling of core material for petrophysical measurements. Temperature logging in exploration drillholes is traditionally conducted during drilling breaks or shortly after drilling, resulting in temperatures severely disturbed by mud circulation and coring is restricted to selected intervals. Alternatively, test temperatures, information from electric logs and lithological descriptions of drill cuttings can be used to overcome these limitations.

The present contribution introduces new heat flow determinations based on 63 exploration drillholes from the Norwegian North Sea, the Mid Norway Margin and the Barents Shelf. Our analyses are based on released DST temperatures, precise lithological descriptions of drill cuttings, previously measured rock matrix thermal conductivities and established porosity laws. For the sake of comparison, we carefully review previous heat flow studies carried out both onshore and offshore Norway.

Our results suggest median heat flow values of 64 mW/m^2, 65 mW/m^2 and 72 mW/m^2 for the North Sea, the Mid Norway Margin (mainly the Trøndelag Platform) and the SW Barents Shelf respectively. In detail, heat flow increases by ~10 mW/m^2 from the southern Norwegian North Sea towards the Mid Norway Margin. This result appears to be in very good agreement with seismic tomographic studies suggesting northward thinning of the underlying mantle lithosphere. Our results together with published marine heat flow data from the Mid Norway Margin suggest a gradual decrease in heat flow levels from both the North Sea and the Trøndelag Platform towards the centres of the deep Møre and Vøring basins. This latter effect is attributed to reduced heat input from crustal sources caused by the extreme attenuation of the crystalline basement below these two basins. Heat flow in the SW Barents Shelf increases westwards. This is interpreted as lateral heat transfer from the adjacent young ocean. Tentative corrections for Quaternary sedimentation/erosion effects suggest similar heat flow levels for the three studied areas but the above mentioned regional trends remain unchanged.

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E-mail address: christophe.pascal@rub.de.

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1. Introduction

Terrestrial heat flow is a fundamental quantity in the understanding of a broad collection of geological and geodynamical processes. In particular, the knowledge of heat flow is crucial in basin modelling and hydrocarbon maturation studies (Hantschel and Kauerauf, 2010). Despite the importance of this latter parameter, systematic heat flow determinations in major oil provinces are seldom, at least in the public domain. Until now, the most reliable heat flow estimates have been derived from scientific drillholes, where high-resolution temperature logging long time after drilling and extensive petrophysical studies of core material were made possible (e.g. Kukkonen et al., 2011), and gravity probe measurements in deep oceanic basins, where thick water layers maintain constant temperatures in sea sediments (e.g. Langseth and Zielinski, 1974). Concerning commercial drillholes, temperature logging is traditionally conducted during drilling breaks or shortly after drilling, resulting in temperatures severely disturbed by mud circulation and coring is restricted to selected intervals. These difficulties have prompted methodological improvements to correct drillhole temperatures from drilling disturbances (Goutorbe et al., 2007) and to determine in-situ thermal conductivities using geophysical logging data (Brigaud et al., 1992; Hartmann et al., 2005). Nevertheless, complete information about temperature logs (e.g. times since circulation) is often unavailable and, furthermore, commercial digital logs are not always released.

Published heat flow data of the Norwegian Shelf (i.e. Norwegian North Sea, Mid Norway Margin and Western Barents Sea) consist mostly in marine heat flow measurements (Sundvor et al., 2000 and references therein, Ritter et al., 2004) supplemented with determinations based on five shallow drillings (Zielinski et al., 1986; Eldholm et al., 1987; Sættem, 1988 and Løseth et al., 1992) and on exploration wells in the North Sea and the Mid Norway Margin (Evans, 1977; Eggen, 1984; Brigaud et al., 1992 and Ritter et al., 2004). The present contribution aims to review and complement the database at hand. We focused on 63 drillholes whose published information by the Norwegian Petroleum Directorate allows for robust heat flow estimates. After having introduced the geological context of the Norwegian Shelf and reviewed previous heat flow studies, we will detail the data and methods adopted here in Section 4. Section 5 will present our heat flow results and will be followed by a subsequent discussion section before concluding.

2. Geological setting

The study area extends from 56°N to 74°N and encompasses the three major geographic domains of the Norwegian Shelf: the Norwegian North Sea, the Mid Norway Margin and the western Barents Sea (Fig. 1). The basement of most of Norway mainland and of its shelf was consolidated during the Caledonian orogeny (~500-390 Ma) and, in particular, during its final docking phases that involved Laurentia, Baltica and Avalonia (Gee et al., 2008). Nappe transport directions and metamorphic isograds in Scotland, Greenland and Norway show that the former Caledonian hinterland, hence the area of maximum thermotectonic resetting of the lithosphere during this orogenesis, corresponds mainly to the present-day Norwegian Shelf. Exploration drillholes that penetrated the crystalline basement offshore showed a diversity of metamorphic and plutonic rocks, Caledonian in age (Slagstad et al., 2011). Furthermore, potential field studies and extrapolation of the onshore geology suggest a highly heterogeneous crystalline basement below the offshore basins (Olesen et al., 2010). Local variations in surface heat flow should therefore be anticipated as a result of lithological heterogeneity and variable content in heat-producing elements in the crust.

The Caledonian orogeny was followed by a long period of successive rifting phases beginning in Early Devonian with the collapse of the mountain chain and terminating in Early Tertiary with continental breakup between Norway and Greenland (Ziegler, 1990; Faleide et al., 2008). Dramatic thinning of the shelf lithosphere occurred mostly during the Devonian and Late Jurassic-Early Cretaceous rifting events while Late Cretaceous-Paleocene rifting, preceding continental separation, was focussed on the present-day distal parts of the Norwegian and Barents Sea margins (Nirrengarten et al., 2014). Continental breakup in the NE Atlantic began in early Eocene (i.e. ~55–54 Ma) and was associated with massive volcanic floods. At that time, the Barents margin developed as a megashear zone until the mid-Atlantic oceanic ridge system propagated farther north and linked to the Gakkel Ridge in the Arctic, producing complete separation between the Barents Shelf and northern Greenland in Miocene times (Faleide et al., 1996). Post-rift subsidence, which was initiated in Early to middle Cretaceous times for most basins of the North Sea, the Mid Norway Margin and the western Barents Shelf, prevailed during the Cenozoic. Positive inversion albeit moderate and localised is recorded along major pre-existing fault zones in the Mid Norway Margin (Doré et al., 2008) and the SW Barents shelf (Gabrielsen et al., 1997). In the context of regional post-rift subsidence, the western Barents Shelf presents the particularly of having been uplifted in Late (?) Tertiary and deeply eroded during Quaternary glaciations (Dimakis et al., 1998), as suggested by the relatively highly compacted Paleozoic and Mesozoic rocks exposed at sea bottom.

3. Overview of previous heat flow studies

3.1. Onshore Norway

The very first heat flow studies onshore Norway were conducted from 1969 until the end of the 70s and are summarised in Heier and Grønlie (1977) and Hänel et al. (1979). The main goal was initially