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Modelled palaeo-temperature on Vøring, offshore mid-Norway — The effect of the Lower Crustal Body

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ABSTRACT

The Vøring area, offshore mid-Norway has a complex geological history, has experienced several extensional phases and was significantly influenced by the break-up of the North Atlantic. We have modelled a cross-section over the Vøring Basin aiming to 1) reconstruct the basin evolution in a realistic way, and 2) to investigate the heat flow and temperature history in the basin.

For the modelling we used the following tectonic events: the opening of the basin during the Permo-Triassic, an event during the Middle to Late Cretaceous and an event in the Late Cretaceous/Paleocene. The theoretical effects of the lithospheric stretching are depending on the palaeo-water depths of the area. We present a prediction of the palaeo-water depth, and a sensitivity analysis of the influence of the palaeo-water depth on the estimated beta-factors in the area.

A lower crustal high-velocity body found in the area is often interpreted as magmatic underplating related to the break-up of the Norwegian Sea. We show the temperature history calculated by models that were run with and without assumption of underplating by a magmatic body emplaced during the Early Tertiary. The observed vitrinite reflectance in the Vøring area is best explained by numerical calculations of the vitrinite reflectance without a magmatic underplating. Our conclusion is that the Lower Crustal Body is not related to magmatic underplating or to significant sill intrusions. The body may consist of older mafic rocks, or a mixture of old continental crust and mafic intrusions.

1. Introduction

The mid-Norwegian shelf has undergone a complex geological history since Late Mesozoic time with dramatic changes in processes associated with large variety (both in time and space) of stresses affecting the area. A Jurassic–Early Cretaceous extensional phase was followed by a long period of strong post-rift subsidence. The break-up of the North Atlantic started at the Paleocene–Eocene transition with strong volcanism and development of the volcanic Vøring- and Møre-Marginal Highs between the outer basin areas and the developing oceanic crust. The opening history of the North Atlantic involved volcanism on both sides of the Atlantic and creation of large volcanic provinces and marginal highs along the continent–ocean transition both on the Greenland side and along the margins of Møre Basin and Vøring Basin and evolution of the Vestbakken Volcanic Province in the Barents Sea in Early Tertiary time (Talwani and Eldholm, 1972, 1977; Mutter and Zender, 1988; Skogseid and Eldholm, 1988; and others). A hotspot model for volcanism had been suggested since the sixties (Wilson, 1963; and others) and a model was presented by White (1988) indicating a lower mantle plume rising near Iceland, heating and uplifting areas in a radius of 2000 km. This model has been used and discussed by many later authors (Brodie and White, 1995; Nadin et al., 1995; Skogseid, 2001; Ren et al., 2003; and others).

Swarms of sill intrusions and possibly larger volcanic bodies were emplaced in the lower crust within the western part of the basins which led to heating (Fjeldskaar et al., 2008) and strong thermal uplift of the western and central part of the basins. Thermal cooling followed, and the marginal highs and the western basin areas were again subsiding.

Modelling of Ocean Bottom Seismograph (OBS) data acquired off Lofoten and in the central part of the Vøring Basin (Mjelde et al., 1992, 1997, 1998; Digranes et al., 1998; Raum et al., 2006) demonstrated that the seismic wide-angle technique by use of OBSs provide important constraints on the crustal structure and distributions of magmatic material emplaced in the sedimentary layers, as well as high-velocity bodies in the lower crust.

In the Vøring Basin a high-velocity and high-density layer (LCB) is inferred below the crystalline basement. Similar high-velocity bodies

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have also been identified beneath the eastern Møre Basin (Olafsson, 1987; Planke et al., 1991) beneath the Nyk High and Træna Basin (Skogseid et al., 2000), beneath the Horda Platform (Christiansson et al., 2000 and Odinsen et al., 2000).

In this study we have analyzed and modelled basin dynamics and factors controlling basin formation and palaeo-heat flow. The study has focused on modelling along a 2D seismic profile over the Vøring Basin, and the main goal has been to reconstruct the geohistory, tectonic, isostatic and temperature history along a regional seismic profile across the Vøring Basin. The resulting modelled temperature history and vitrinite reflectance give indications that the LCB is not of magmatic origin.

2. Crystalline basement

The area under discussion is the Norwegian Continental margin between 62° and 69° N, which consist of a central area of NE-SW trending deep Cretaceous basins, the Vøring and Møre Basins, flanked by palaeo-highs and platforms and the elevated mainland. The area and the seismic section that was modelled are shown in Fig. 1.

OBS data suggest that the continental crystalline basement thickens and deepens towards the east in the SW Vøring Basin (Raum et al., 2006). Towards the Møre- and Vøring Marginal Highs the crystalline basement is shallower and thinner (cf. Fig. 1). The Moho is inferred by refracted arrivals modelled with P-wave velocity higher than 8.0 km/s. The depth to the Moho is generally 20–23 km at the landward part, but seawards the depth decreases to approximately 15 km (Olesen et al., 2002). The Moho shallows significantly crossing the Jan Mayen Fracture Zone entering the Møre Marginal High. The signature of this transition zone is most likely caused by the transform movement along the fracture zone during the Early Tertiary, where the Møre and Vøring Margins were offset in the dip direction. An important observation of the Moho topography is the shallowing found along NE-SW trending profiles along the Vigrid Synclinal (Raum et al., 2006). A significant shallowing of approximately 5 km, from 20 to 15 km, is inferred at the SW part of the Vigrid Syncline. A similar feature where the Moho is shallowing from 25 to 18 km SW of the Fles Fault Complex, and a significant southwestward shallowing of the Moho is observed below the Modgunn Arch. Raum et al. (2006) interpreted these as local features as regional magnetic and gravity maps do not suggest any link between these structures.

Anomalous crustal thickening below the marginal highs was proposed to be the result of underplating (i.e. emplacement of high-velocity volcanic bodies) (e.g. Planke et al., 1991; Clift and Turner, 1995). Skogseid (2001) described how igneous provinces and plume emplacement occur worldwide along passive margins, and that high-velocity bodies interpreted as bodies of magmatic underplating often are found at the base of the crust in these regions. During the early stages of rifting, the thinning of the continental crust resulted in upwelling and partial melting of asthenospheric material. The temperature of this material was 100–200 °C higher than normal mantle temperature (White and McKenzie, 1989). As the rifting commenced, the melt penetrated the crust and its densest portions were intruded along the Moho.

Gravity modelling gives densities corresponding to upper mantle materials (Barton, 1986). A slight decrease in density is modelled as the Moho shallows towards SW, but the high velocity and density suggest material of ultramafic origin. Several gravity high belts are observed extending from offshore Scotland to the coast of Norway (Talwani and Eldholm, 1972) and are interpreted as intra-basement mafic or ultra-mafic high-density bodies, probably emplaced during the Caledonian orogeny.

2.1. Lower crustal high-velocity body

The lower crustal high-velocity layer (LCB) observed along the Vøring Margin consists of two distinct bodies (Fig. 2). The P-wave velocity is estimated to c. 8.35 km/s south of the Rån Lineament and 7.2–7.6 km/s between the Rån and Bivrost lineaments (Mjelde et al., 2005; Raum et al., 2006). The corresponding densities are c. 3.5 g/cm^3 and 2.9–3.2 g/cm^3, respectively, and the Vp/Vs-ratio is estimated to 1.80–1.85 within both bodies. The Lower Crustal Body located south of the Rån Lineament expresses P-wave velocities and densities higher than generally encountered for all crustal (crystalline) rocks (Vp = 6.0–7.7 km/s) and upper mantle peridotites (Vp = 8.0–8.2 km/s). The measured physical properties strongly suggest that this body represents eclogite (e.g. Christensen 1996). Such bodies of Caledonian eclogites are well documented from western Norway (e.g. Andersen and Jamtveit, 1990), and they have been inferred from wide-angle seismic data in the lower crust in the Møre Basin (Fig. 1; Olafsson et al., 1992).

The P-wave velocities in low-grade crystalline rocks are found to increase from c. 6.0 km/s in granite (felsic) to c. 6.9 in gabbro (mafic). The Vp/Vs-ratio increases correspondingly from c. 1.70 to c. 1.85 (e.g. Holbrook et al., 1992). Increasing the metamorphic grade will increase the P-wave velocities, but even for granulite facies the P-wave velocities will not exceed c. 7.0 km/s in felsic and intermediate rocks (Holbrook et al., 1992). It can thus be concluded that the observed 7.2–7.6 km/s body dominantly represents mafic rocks. Increasing the P-wave velocity in gabbro to the range observed in the Vøring Basin can be achieved by; 1) Increasing the temperature of the melt and thereby the MgO content. This will increase the P-wave velocities to fit the observations, independent of metamorphic grade (White and McKenzie, 1989). 2) Increasing the metamorphic grade to granulite facies (Hurich et al., 2001). The observed densities and Vp/Vs-ratios are compatible with both hypotheses.

Lower crustal P-wave velocities in the range 7.2–7.6 km/s are compatible with partly serpentinized peridotites, which existence has been postulated in the area (e.g. Ren et al., 1998). However, the low Vp/Vs-ratios observed on the Vøring Plateau and in the northern Vøring Basin are inconsistent with serpentinized peridotites (Mjelde et al., 2002). These authors also argue against the serpentinized peridotite hypothesis in the central and southern Vøring Basin based on the following constraints; the existence of Moho reflections, the existence of S-wave anisotropy but absence of P-wave anisotropy, uncertainties regarding supply of water to allow for significant serpentinization and low stretching factors. The same conclusion was drawn by Gernigon et al. (2004), primarily based on arguments related to the stretching factors and fluid budget.

Although various models may explain the excess magmatism observed on the Vøring Plateau, there appears to be consensus concerning the composition of the lower crustal high-velocity layer within the continent–ocean-transition; i.e. that it represents mafic rocks emplaced during the final stage of rifting, break-up and first phase of oceanic spreading (e.g. White and McKenzie, 1989; Mjelde et al. 2008, 2009).

The sedimentary sequences above the lower crustal 7.2–7.6 km/s body in the Vøring Basin are strongly intruded by sills (e.g. Brekke, 2000; Planke et al., 2005), and the concentration of sills appears to be highest in the central part of the basin where the high-velocity body is thickest. Narrow, vertical zones of deteriorated seismic data, which are interpreted as wrench fractures, are thought to be the loci of feeder dykes to the sill system. The stratigraphic position of these wrench fractures and related structures indicates that the main magmatic activity occurred in Paleocene–Early Eocene (Brekke, 2000). This is in agreement with the model for emplacement of the Lower Crustal Body, as discussed by Mjelde et al. (2003). According to this model, the magma will migrate within dykes upwards through the upper mantle lithosphere and when reaching the weaker, ductile lower crust, the magma will preferably intrude laterally. The reason for this is twofold; 1) The density-contrast at the crust–mantle boundary implies that rising magma will loose buoyancy when reaching the lower crust; 2) The process of stress-concentration at the tip of cracks and propagating dikes is far less efficient in ductile rocks, compared with brittle rheology (e.g. Putirka et al., 1996). The lightest