Causes and Consequences of Mantle Serpentinization During Passive Margin Formation*

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Abstract

The main goal of this study is to develop a better understanding of the impact of serpentinization reactions on petroleum systems. Serpentinization has a strong effect on the material properties of mantle rocks. Apart from magnetic properties, the main impact is on density. Serpentinite has a much lower density than mantle rocks and this greatly affects the isostatic balance and may lead to uplift. In this study, we present the results of integrated basin modeling that resolves the coupled structural, thermal, stratigraphic, and petrological evolutions of passive continental margins. The key objectives are to test whether 1) lower crustal bodies (LCB) imaged along the Norwegian continental margin can be of serpentinized mantle origin, 2) uplift and erosion events could be explained by isostatic adjustments caused by mantle hydration reactions, and 3) sedimentation suppresses water supply to mantle rocks and affects the thermal stability of serpentine at sub-Moho levels

Review of Mantle Serpentinization

Serpentinization reactions, the transformation of a dry peridodite to a wet serpentinite, have received considerable attention in the passive margin community (e.g. (Skelton et al., 2005)). One reason is that non-volcanic rifted margins show wide ocean-continent transitions zones of serpentinized mantle that is unroofed prior to oceanization and seafloor spreading. The Iberian margin is the most well known example of this (e.g. (Perez-Gussinye and Reston, 2001)). Another reason is that lower crustal bodies imaged frequently beneath volcanic passive margins might also be partially serpentinized mantle (Gernigon, 2004; Lundin and Dore, 2011).

The conditions under which mantle serpentinization occurs during passive margin formation have been explored by Perez-Gussinye et al., (2006) and Perez-Gussinye and Reston, (2001). The basic idea is that seawater needs to get in contact with cold (<~500°C) lithospheric mantle rocks. For this to occur, crustal scale brittle faulting is necessary. However, in "normal" continental crust, the lower crust is ductile which inhibits crustal scale faulting and thereby mantle serpentinization. During extension, the lower crust is "de-pressurized" and progressively cooled so that it eventually becomes entirely brittle. At this stage, crustal scale faulting becomes possible which can provide the pathways for seawater to reach and react with cold mantle rocks to make serpentine.

Modeling Framework

We simulate the thermotectonostratigraphic evolution of sedimentary basins and passive margins using the software package TecMod. TecMod couples a forward model for margin formation with an inversion scheme for automatic model parameter updates. The details of this modeling approach are described by Rüpke et al., (2008) and Rüpke et al., (2010). Serpentinization reactions are implemented into this modeling framework following the approach of Perez-Gussinye and Reston, (2001): the rheological evolution of the sediments, crust, and mantle is tracked throughout a forward run. If the entire crust and sedimentary cover becomes brittle, mantle rocks within the stability field of serpentine are reacting with seawater to make serpentine with a kinetic rate given by Martin and Fyfe (1970). If previously serpentinized rocks heat beyond their thermal stability limit, deserpentinization occurs instantly. The latent heat of reactions is included in the energy balance. This framework allows us to study the feedbacks between serpentinization reactions and lithosphere- as well as basin-scale processes.

Results

A first major finding of this research project is that published studies underestimate the effects of sediments on the formation and stability of serpentine. Ignoring the effect of sediments is surprisingly, in the context of sedimentary basins, a recurring problem that goes back to the seminal work of McKenzie (1978). In terms of the effects of serpentinization in margin formation, much of the focus has been on hyper-extended margins such as Iberia. If we are to bring these concepts to offshore Norway, we need to account for thick sedimentary sequences. To a large extent these sediments can be effectively treated as crust for the purpose of serpentinization, i.e. 1) they limit the access to water, which is required for serpentinization to happen, 2) they keep the remaining crust at elevated temperatures, favoring viscous creep instead of brittle failure and thereby restricting effective fluid pathway generation, and 3) may heat serpentinized mantle out of its thermal stability field. This dampens the effect of serpentinization compared to what has been established for the hyper-extended margins.

Nevertheless, a first case study for the Norwegian continental slope (Figure 1) showed that serpentinization reaction could occur during margin formation. One model scenario shows that at Base Cretaceous time, the entire crust and sedimentary cover becomes brittle and a ~10km thick body of partially serpentinized mantle forms. Although this LCB of serpentinized mantle is during later burial partially moved out of its stability limit, parts of it remain stable until the present (Figure 2).

Conclusions

The causes and consequences of serpentinization reactions during passive margin formation have been explored using a self-consistent tectonostratigraphic modeling approach. The key findings are:

- Serpentinization reactions can have first order effects on margin evolution as they can cause uplift and erosion as well as temperature changes by latent heat effects.

- Most concepts and ideas on serpentinization reactions have been developed for sediment-starved margins (e.g. Iberia). We show that sedimentation dampens the impact of serpentinization by limiting water supply and by thermal blanketing effects.
- Lower crustal bodies along the Norwegian margin may indeed form by serpentinization reactions although the thick sediment cover greatly limits the volume of mantle rocks within the stability limit of serpentine.

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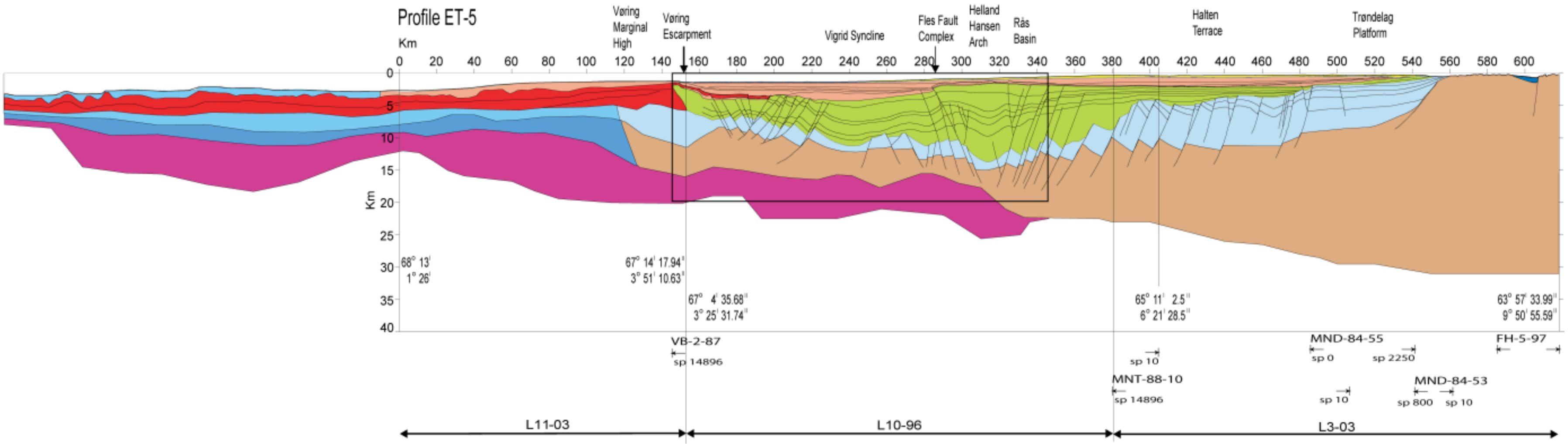

Figure 1. EUROMARGIN transect 5 across the Norwegian continental margin.

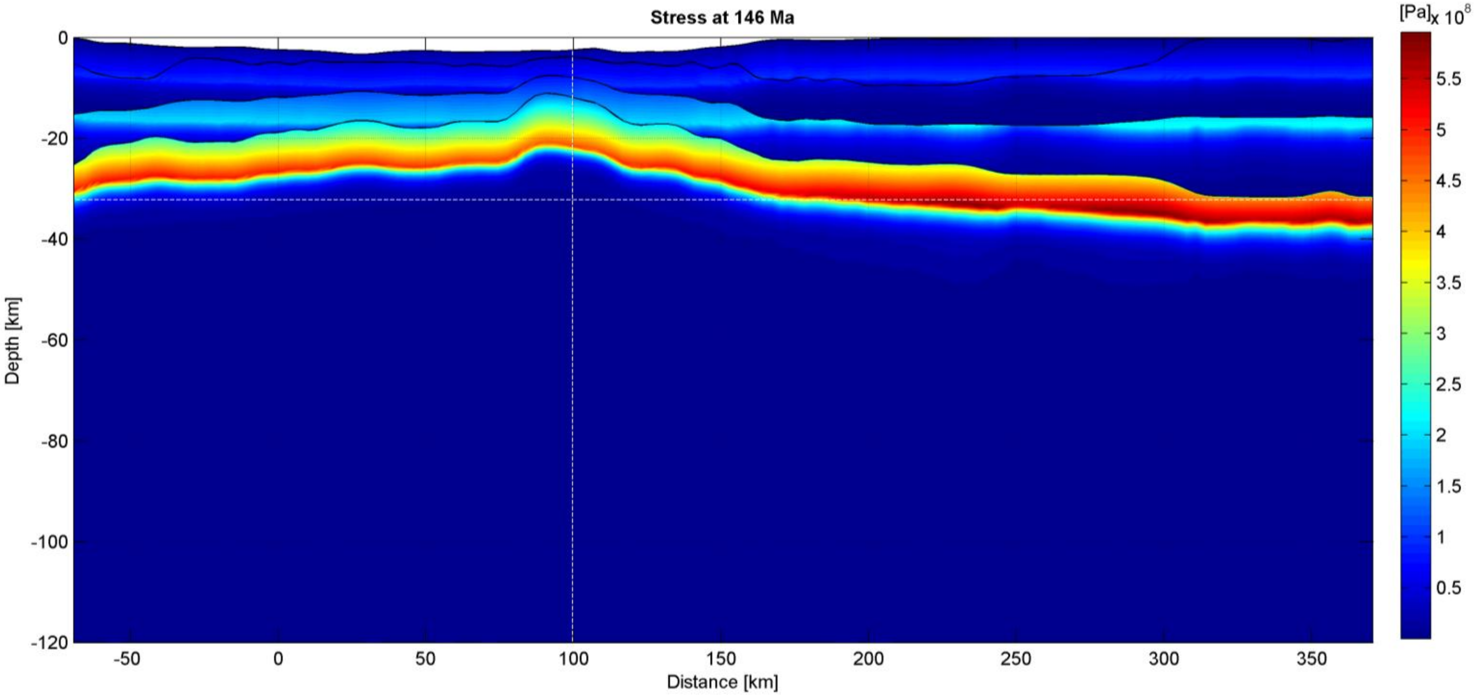

Figure 2. Predicted stress distribution at the end of the Jurassic rift phase.