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Effect of mineral phase transitions on sedimentary basin subsidence and uplift

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Abstract

Metamorphic phase transitions influence rock density, which is a major parameter affecting lithosphere dynamics and basin subsidence. To assess the importance of these effects, we have computed realistic density models for a range of crustal and mantle mineralogies from thermodynamic data by free-energy minimization. These density distributions are incorporated into one- and two-dimensional kinematic models of basin subsidence. The results demonstrate that, compared to models in which density is solely temperature dependent, phase transitions have the effect of increasing post-rift subsidence while decreasing syn-rift subsidence. Discrepancies between our model results and those obtained with the conventional uniform stretching models can be up to 95% for reasonable parameter choices. The models also predict up to 1 km of syn-rift uplift as a consequence of phase transitions. Mantle phase transitions, in particular the spinel–garnet–plagioclase–lherzolite transitions are responsible for the most significant effects on subsidence. Differences in mantle composition are shown to be a second-order effect. Parameterized density models are derived for crustal and mantle rocks, which reproduce the main effects of the phase transitions on subsidence.

Keywords: sedimentary basins; subsidence; mineral phase transitions; uplift

1. Introduction

One of the most widely used models for subsidence of sedimentary basins formed by extension is the uniform stretching model (USM), which assumes that subsidence is caused by crustal thinning and by thermal cooling [1]. An important feature of the USM formulation is that lithospheric density is assumed to depend only on temperature, a model we designate as the temperature-dependent density (TDD) formulation. The TDD formulation has been applied successfully in many situations, but it cannot

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explain certain common observations (e.g., [2], and references therein). The most prominent difficulty is that many basins have relatively thin syn-rift sediments, but thick post-rift sediments [3–7]. To explain the thickness of the post-rift sediments with the TDD formulation, extensive stretching is required; this is at odds with the small thickness of syn-rift sediments. The widespread phenomenon of basin uplift during overall extension of the lithosphere (e.g., in the Vøring Basin; see [8]) creates a second difficulty for the TDD formulation. A thin crust is required (<1/7 of the lithospheric thickness) to explain this phenomenon. Such crustal thicknesses contradict geophysical observations suggesting crustal thickness is typically 30–40 km. Uplift usually occurs preceding rifting or after a finite amount of extension. An additional problem with the TDD formulation is posed by the fact that many basins have a phase of accelerated subsidence rates during the post-rift thermal subsidence phase [9,10]. The TDD formulation predicts that the subsidence rate decreases with time t as $t^{-0.5}$, and thus this can only be explained with non-thermal mechanisms [10–12]. To rectify these problems refinements of the TDD formulation have been proposed that include depth-dependent stretching [4,5], active rifting [13], interaction between lithospheric rheology and erosion [14] or mineral phase transitions (e.g., [11,15–17]. Here we focus on a refinement of this model in which lithospheric density is adjusted to account for phase transitions that occur in response to the geodynamic cycle.

Most of the models that have been proposed to explain shortcomings of the TDD formulation involve complexity or rely on parameters such as the lithospheric rheology, which are poorly constrained. However, the conditions and consequences of the metamorphic phase transitions that occur during lithospheric thinning are constrained from field observations, experimental studies and thermodynamic theory. We exploit the latter to construct a realistic lithospheric density model and to assess its consequences for basin subsidence.

That metamorphic phase transitions influence basin subsidence has been recognized for several decades. It has been suggested in [18] and [19] that crustal phase transitions around the Moho could affect uplift and subsidence. Numerical and analytical studies that concentrated on phase transitions in crustal rocks [9,10,12,17,20,21], in mantle rocks [11,15], or in both [22] demonstrated that phase transitions cause syn-rift uplift preceding rifting, greater post-rift subsidence then in the TDD formulation and periods of accelerated subsidence. Lobkovsky and coworkers [23,24] proposed a model in which partial melt, emplaced and solidified in lenses below the rift center, is transformed into eclogite causing accelerated post-rift subsidence. Their model requires a nearly impermeable Moho and predicts that eclogite lenses remain present after the completion of extension, which may be seismically detectable.

The applicability of most of the models described above is limited, since they typically only consider a single discontinuous phase transition. Natural rocks have continuous reactions. Many of these reactions have only small density effects, but the cumulative effect of these reactions can be significant. The optimal approach is to consider all the reactions that may occur in the lithosphere. Such an analysis in combination with basin subsidence was done by Petrini et al. [22], who used a realistic density distribution for both mantle and crustal rocks and demonstrated that phase changes lead to more post-rift subsidence and less syn-rift subsidence. However, they restricted their analysis to small stretching factors (δ=1.5) and did not detect syn-rift uplift as observed in [11] and [15].

Here we follow the same approach by coupling realistic density distributions with a kinematic subsidence model. To estimate the sensitivity of the results to the chemical composition of the lithosphere, we compute density models for a range of different mantle and crustal compositions. The results are then compared with the TDD formulation and parameterized density maps are derived that reproduce results of 'real' density maps up to reasonable accuracy and thus yield additional insight into the way phase transitions influence subsidence.

2. Representative phase diagrams and density distributions for crustal and upper mantle rocks

Phase assemblages at the pressure (P) and temperature (T) conditions of interest were computed using