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Kilometer-scale chemical reaction boundary patterns and deformation in sedimentary rocks

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Abstract

We use three-dimensional (3D) seismic data to image patterns developed by kilometer-scale chemical reaction boundaries to demonstrate that chemical patterns are scaleable phenomena. The patterns develop in biosiliceous marine successions due to the dissolution of opal-A (biogenic silica) and reprecipitation as opal-CT (Crystobalite and Tridymite) during burial. The reaction boundary patterns comprise roughly circular regions where the reaction boundary has preferentially advanced. These regions are up to 2.7 km wide, and c. 50–200 m in height and are termed cells. The cells form by amalgamation with adjacent juvenile cells. They also form by the incorporation of much smaller regions surrounding the cells where the chemical change has already occurred that we term 'satellites' (50 m wide). The reaction results in enhanced rates of sediment compaction hence differential advancement of reaction boundaries causes differential subsidence of the overburden, inducing folding and faulting of the overburden above the cellular promontories.

We propose three potential mechanisms for the development of kilometer-scale reaction boundary patterns: (a) mass transport of silica by advection (b) perturbation of isotherms as a result of convective or conductive heat transport or (c) establishment of a positive feedback loop between fluid production due to the reaction, hydraulic fracturing and the upward and lateral transport of fluids. This study provides the first insights into how strongly patterned diagenetic reaction boundaries evolve at a basin scale, an initial conceptualization of the potential range of reaction boundary morphologies that could exist in this diagenetic system, and the likely mechanisms that could control them. Furthermore it demonstrates that the discipline of 'seismic diagenesis' could represent a completely new approach for the study of chemical diagenetic processes in sedimentary rocks.

Keywords: reaction boundary; pattern; self-organization; opal-A; opal-CT

1. Introduction

A chemical reaction boundary is an interface marking the boundary layer between initial reactants and final products of a reaction that propagates through a chemical mixture (Scott, 1994). Reaction boundaries have been documented from atomic (nanometer) scale in the laboratory (Sachs et al., 2001) to meter-scale in sedimentary rocks (Seilacher, 2001). They can form patterns and patterned reaction boundaries and the processes by which they form are widely studied, since they are found in chemical, biological and geological systems. They can occur as a result of non-linear

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chemical kinetics, where feedback and therefore self-organization arise (Scott, 1994) and these are readily demonstrated in, for example, laboratory-scale reaction–diffusion chemical experiments.

In sedimentary rocks meter-scale chemical diagenetic patterns form as a result of feedback mechanisms between the reactions that trigger associated physical processes within the host medium. For example a chemical reaction can cause mineral dissolution and therefore locally increased permeability leading to focused fluid transport. The focused transport introduces additional fluids that are not in chemical or thermal equilibrium with the host sedimentary rock and further dissolution occurs. Reaction boundary fingering in carbonate cemented sands is the result of this type of self-organizing process (Chen and Ortoleva, 1990). The margin of a concretion is another type of reaction boundary that can form patterns (Seilacher, 2001) as a result of this simple feedback mechanism or through other reaction-triggered processes in the host sedimentary rock (Seilacher, 2001).

In order to establish whether reaction boundary patterns are scaleable phenomena when considered at large length scales typical of basin scale phenomena (> 10^4 km^2) we have focused on examples of reaction boundaries that form in sedimentary basins. A secondary aim of our study is to investigate the fundamental processes that control the evolution of large-scale reaction boundaries. In this study, we describe large scale, three-dimensional reaction boundary patterns developed during the transformation of opal-A to opal-CT during the first kilometer of burial. This transformation is a dissolution–reprecipitation reaction (Isaacs, 1982; Hesse, 1990), with a reaction boundary a few 10 s of meters thick that can be correlated over areas of 10^1–10^4 km^2. It can result in the development of extraordinary reaction boundary morphologies with vertical relief of 20–200 m. We also describe the deformation that develops in the overburden due to the development of the reaction boundary patterns. Reaction–diffusion or reaction–transport feedback processes have been proposed for most examples of pattern formation in reaction boundaries (Chen and Ortoleva, 1990; Seilacher, 2001). The kilometer-scale patterns we describe instead require a different type of feedback mechanism between chemical and rock deformational processes, and as such raise important questions about the interactions between sediment diagenesis, volume change, and rock deformation in general.

2. Silica reaction boundaries

Much of the Earth's silica is found in fine-grained sedimentary rocks and a significant proportion of this originates from microscopic opaline skeletons of diatoms (and radiolarian) (Hesse, 1990), that form siliceous rich rocks, the purest of which are diatomites. This form of silica is thermally unstable and during sediment burial (usually < 800 m depth) opal-A dissolves and reprecipitates as microcrystalline opal-CT (Isaacs, 1982; Hesse, 1990). Opal-CT is converted to quartz during subsequent burial. The reaction is controlled by temperature, sediment surface area, host sediment composition, time and pore water chemistry (Isaacs, 1982; Hesse, 1990) and usually occurs at temperatures of between 25 and 55 °C. Within a single host lithology, the reaction takes 10^5 to 10^6 yr to complete (Tada, 1991). The opal-A to opal-CT reaction boundary is usually 10–20 m thick and because the sediment density and seismic velocity increase at the boundary, there is a major increase in acoustic impedance. This in turn means that it has a pronounced acoustic expression, and it can be imaged to a high degree of lateral and vertical resolution on 3D reflection seismic surveys that typically cover areas of up to 2×10^4 km^2. This acoustic expression of a diagenetic reaction boundary is unique to the silica diagenetic system: no other major diagenetic reaction has such a basin-wide acoustic expression. This means that reflection seismic data can be used extensively to define the geometry of the reaction boundary across entire basins.

3. Database and geological setting

We present reaction boundary patterns from the Neogene successions within the Vøring and Møre Basins, offshore Norway (Fig. 1). These basins form

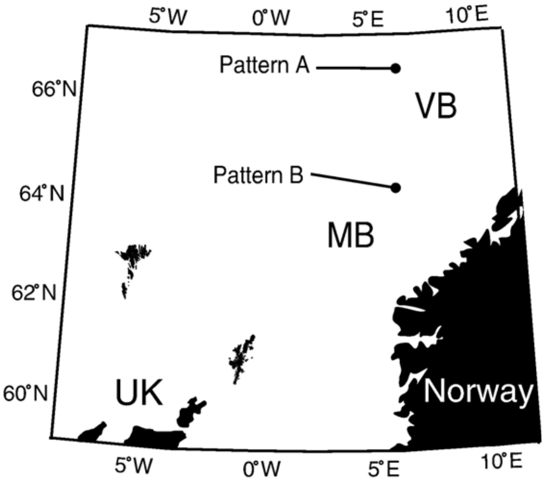

Fig. 1. Location map showing location of reaction boundary patterns A and B. MB—Møre Basin, VB—Vøring Basin.