

Overpressure preventing quartz cementation? - a reply

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Introduction

We are delighted that our recent contribution on sandstone diagenesis and reservoir quality of the Heron Cluster reservoirs, Central North Sea, UK (Stricker et al., 2016b) has raised further interest and opportunity for discussion on the role played by pore fluid overpressure during burial diagenesis (chemical compaction). Maast (2016) raised several interesting points that merit a reply following the discussion of our paper on the maintenance of reservoir quality within the Heron Cluster reservoir sandstones (Stricker et al., 2016b).

We used a multidisciplinary approach comprising petrographic, SEM, fluid inclusion, and burial history modelling studies to analyse the evolution of reservoir quality in HPHT environments. We highlighted several processes which contribute to the maintenance of exceptional porosity (>30%) and reservoir quality at depth. We concluded that a combination of A) well-developed chlorite and mixed chlorite/illite grain coatings, B) shallow onset of overpressure and vertical effective stress (VES) reduction, and C) continuous overpressure maintenance (low VES) maintained reservoir quality within the fluvial channel sandstones of the Skagerrak Formation. Maast (2016), however, insists in his comment that pore fluid overpressure does not play a role and that reduced VES does not benefit the maintenance of reservoir quality. We will address this comment by not providing a recount of our petrographical observations and modelling (Stricker et al., 2016b) but will refer to further observations and analyses from the Triassic Skagerrak Formation in the North Sea (see Stricker et al., 2016a; Stricker and Jones, 2016).

Alternative interpretations and comments by Maast (2016)

Overpressure preventing grain fracturing, which will expose fresh grain surfaces to quartz cementation.

We agree with Maast (2016) that pore fluid overpressure and low VES is known to prevent extensive grain fracturing in rigid-grained sandstones (Chuhan et al., 2003, 2002). However, we don't see why Maast (2016) raised this point, as the reservoir conditions (i.e., applied stresses) are throughout the entire burial history below reported stresses for grain fracturing (Chuhan et al., 2003, 2002) (see Figure 4; Stricker et al., 2016b). Experimental work focusing on high-pressure testing of compaction of sand shows that the yield strength relates to the onset of grain crushing and varies largely with sand properties (Chuhan et al., 2003; Mesri and Vardhanabhuti, 2009). The Triassic reservoir sandstones of the Heron Cluster fields are very fine grained to fine grained sandstones, show high yield strength, and are less prone to grain fracturing (e.g. Chuhan et al., 2003, 2002). Nevertheless, fractured grains in overpressured reservoirs are in many cases of detrital origin and not linked to the presence of overpressure (e.g. Sathar and Jones, 2016; Stricker et al., 2016a).

Rapid Cenozoic burial is limiting the time of exposure to quartz cementation.

The rapid Cenozoic burial of the Triassic sediments may have shortened the time window for quartz precipitation, but equally increased the quartz precipitation rates due to the

accompanied rapid temperature increase (e.g. Walderhaug, 1996, 1994). We agree with Maast (2016) that the predicted amount of quartz cement (quartz cementation model of Walderhaug (1996)) for the Triassic sandstone reservoirs of the Heron Cluster is low. However, the quartz cementation model of Walderhaug (1996) doesn't include any application of pore fluid pressures and pore fluid chemistry changes. The time frame of 60 Ma in combination with rapidly increasing temperatures (Figure 4; Stricker et al., 2016b) and increasing precipitation rates provide more than acceptable conditions for quartz cementation in the Central Graben, North Sea (e.g. Sheldon et al., 2003; Worden and Morad, 2000).

Evidence for pressure solution

The petrographic data of the Judy Sandstone Member of the Egret, Heron and Skua fields show strong evidence for reduced mechanical and chemical compaction (e.g. anomalously high porosity, high intergranular volume, limited quartz cementation, absence of sutured grain contacts). The increasing overpressure created a reduced or low VES environment, which lead to a reduction of compaction in comparison to similar Triassic reservoir sandstones of the Central Graben area (Grant et al., 2014; Nguyen et al., 2013; Stricker et al., 2016a). Due to the reduced mechanical and chemical compaction, evidence for extensive pressure solution (e.g. sutured grain contacts) is not present in the Judy Sandstone Member of the Heron Cluster and was therefore not presented.

Chemical compaction – a controversial issue

Maast (2016) is in clear favour of the IMID model and described quartz cementation as an exclusively temperature driven and stress insensitive process. He therefore refers to the work of Bjørkum, 1996; Oelkers et al., 1996; and Walderhaug, 1996, which challenged the common notion of pressure solution in the late 1990's. Even though, the IMID model is the current industry standard for reservoir quality, the primary driving forces behind dissolution, transport, and precipitation in the IMID model are still not clearly defined and often physically unrealistic (Sheldon et al., 2004).

We consider the process of quartz cementation, i.e., dissolution, transport, and precipitation, as temperature driven and pressure sensitive (e.g. Sheldon et al., 2003; Worden and Morad, 2000). It has been shown that temperature a key mechanism for quartz precipitation and plays a critical role in the dissolution of silica. However, there is theoretical (e.g. Renard et al., 2000, 1997; Sheldon et al., 2003), experimental (e.g. Gratier, 1993; Gratier et al., 2009) and field based evidence (e.g. Eyal, 1996; Gutiérrez-Alonso and Gross, 1999; Hood and Durney, 2002; Nguyen et al., 2013; Osborne and Swarbrick, 1999) that lends strong support to the role of stress in driving chemical compaction, and is inconsistent with the IMID model (Sheldon et al., 2004).

The stress insensitivity of the IMID model based on the work by Bjørkum, 1996; Oelkers et al., 1996; and Walderhaug, 1996. The evidence of the stress insensitivity claim, however, is scarce and is based on the mechanical properties of a single mica grain. Bjørkum (1996) observed in a sandstone sample of the Norwegian continental shelf a mica grain indenting a quartz grain. After calculating the mechanical properties of the mica grain, Bjørkum concluded that the process of silica solution is pressure insensitive as the mica grain has not

been deformed. However, Bjørkum (1996) provided no conclusive burial history modelling nor any pressure history modelling which could strengthen the pressure insensitivity claim.

Renard et al., (1997) explained Bjørkum's (1996) observation simply by the thickness of water films between the mica layers which represent ideal diffusion pathways allowing an increased silica diffusion. Renard et al., (1997) concluded contrary that the dissolution of silica is stress and temperature dependent. Furthermore, there is inconclusive pressure modelling by Bjørkum (1996) to explain the transfer of the stress insensitivity theory from the mica-quartz to the quartz-quartz dissolution. Even though insufficient stress modelling is provided, research by Oelkers et al. (1996) and Walderhaug (1996), have exclusively referred to Bjørkum (1996) for the stress insensitivity of silica dissolution.

We are not neglecting the catalytic role of sheet silicates on the process of pressure dissolution. We are stating that the stress insensitivity claim by Bjørkum (1996), for the quartz cementation process, implemented in the IMID model, is far from being conclusive and proven (e.g. Gratier et al., 2009; Renard et al., 1997; Sheldon et al., 2004, 2003)

This study and other recent studies investigated the effects of pore fluid overpressure and low VES on the reservoir quality of the Central North Sea reservoir sandstones and highlighted the positive effect of low VES on the evolution of reservoir quality (Grant et al., 2014; Nguyen et al., 2013; Osborne and Swarbrick, 1999; Stricker et al., 2016a). Stricker et al. (2016b) provides a local and more holistic approach to highlight several important processes that contributed to the maintenance of reservoir quality to depth. Pore fluid overpressure is just one of the mechanisms, but should not be neglected as low VES has been proven important for the maintenance of reservoir quality (e.g., Grant et al., 2014; Hart et al., 1995; Osborne and Swarbrick, 1999; Sathar and Jones, 2016). We acknowledge the role played by authigenic mineral grain coatings, e.g. chlorite, illite, microquartz, and more generally the sorting of the fluvial sandstone facies. However, it is important to note the role played by stress during chemical compaction of sandstones (e.g. Gratier et al., 2009; Osborne and Swarbrick, 1999; Renard et al., 1997; Sheldon et al., 2004). The results demonstrate that chemical compaction and porosity loss can be reduced or arrested due to a low-VES/high pore fluid pressure history (Stricker et al., 2016a, 2016b). Stress is an important driver for porosity loss throughout the entire burial history and acts not just exclusively in the mechanical compaction zone. The overpressure timing, the rate of the overpressure built up over time and the VES accrual are important for reservoir quality throughout the mechanical and chemical compaction regime as it can be seen for the Triassic sandstones of the Central North Sea (Stricker et al., 2016a). Clay minerals play an important catalytic role in chemical compaction by increasing the width of the diffusion pathway or by modifying the kinetics of the dissolution (Renard et al., 2000, 1997; Sheldon et al., 2003).

Summary comments

The comment by Maast (2016) shows a strong cognitive bias towards the stress insensitive IMID model, even though theoretical studies (e.g. Renard et al., 1997; Sheldon et al., 2003), experimental studies (e.g. Gratier, 1993; Gratier et al., 2009), and field evidence (e.g. Eyal, 1996; Grant et al., 2014; Gutiérrez-Alonso and Gross, 1999; Hood and Durney, 2002; Osborne and Swarbrick, 1999; Stricker et al., 2016a) lend strong support to the role of stress

in chemical compaction. Furthermore, the driving forces behind dissolution and transport processes in the IMID model remain unclear (Sheldon et al., 2004, 2003).

We have demonstrated that stress plays an important role in the quartz cementation process. However, chemical compaction and the relative importance of the pressure dissolution model and the illite-mica induced dissolution (IMID) model have remained a contentious issue, as is the role played by stress in chemical compaction itself.

The aim of our paper was to demonstrate the importance of accurately identifying the role played by high pore fluid pressure during burial of HPHT sandstone reservoirs. Subsurface reservoirs of the Triassic Skagerrak Formation provides evidence for the role of low-VES in driving chemical compaction as demonstrated across the HPHT provenance of the Central Graben, North Sea (Stricker et al., 2016a).

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