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Review article

Messinian evaporites and fluid flow

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ABSTRACT

Thick evaporite sequences deposited in saline giant basins are traditionally viewed as impermeable barriers to fluid flow. This paradigm has recently been challenged by documented evidence of fluid migration pathways through several-km thick series of evaporites, such as the late Miocene (Messinian) sediments in the Mediterranean basin, deposited during the Messinian Salinity Crisis (MSC). Our paper reviews the occurrence of fluid expulsion events in these evaporites in the depocentres of the basin, and analyses their potential as seal-bypass systems.

The Messinian salt giant was deposited in peculiar conditions where massive sea-level changes occurred in a relatively limited time interval, and a thick basin-centre evaporitic series was deposited between pre-MSC and post-MSC deep-water sediments. Consequently, rapid water and sediment loading/unloading events contributed to the creation of overpressures up to fracture and possibly lithostatic gradient, causing the fluids to be released in explosive events.

Examples of fluid expulsion events are here grouped and classified in relation to the long and short term effects of the Messinian Salinity Crisis, as well as the local controls and pre-conditioning basin factors. While peaks of fluid expulsion activity during the short time-frame of the MSC can be mainly linked to Mediterranean-wide events, local controls appear to play a major role in post-MSC fluid mobilisation. In these cases, evaporite breach is largely dependent on the availability of pre-MSC undersaturated fluid sources and the capability of the pre-MSC sediments to be overpressured.

The analysis here presented can be used as a basis to understand the controls on syn- and post-depositional movement of fluids in sedimentary basins. Moreover, the analysis of temporal and spatial distribution of fluid expulsion events can help define hydrocarbon migration style and pathways in deep-seated petroleum plays.

1. Introduction

Syn- and post-depositional movement of fluids through sediments is one of the least understood aspects in the evolution of a basin. In standard hydrostratigraphic settings, the first few kms of the sedimentary column of a basin are dominated by pore waters of meteoric or marine origin (Giles, 1997). As sediments go through burial, the water is released from the pore space and expelled in a combination of vertical and lateral fluid flow. The main loss of porosity is concentrated in the first few 100s of meters of burial (Kominz et al., 2011; Velde, 1996). The net fluid expulsion related to burial will be substantially reduced after the first km (Giles, 1997). Consequently, it is expected that subsidence rates overcome upwards migrating flow in the deeper part of the basin, such that pore fluid moves downwards relative to the surface datum although still relatively upwards relative to the sediment matrix reference frame (Bjørlykke, 1993).

Whereas the shallower portions of the gross basin fill tend to be dominated by meteoric and compactional fluids, in the deeper realm diagenetic transformations, hydrocarbon generation, volcanic fluids and thermobaric regimes, are responsible for fluid transfer (Einsele, 2000; Gayer et al., 1998; Giles, 1997). A clear example, as well as its impact on petroleum exploration, is presented by deep-burial or hydrothermal karst on carbonate fields (Heward et al., 2000; Sun et al., 2013).

Recent research on basin fluid flow shows that in exceptional high-pressure and temperature conditions, compactional and meteoric groundwater fluid circulation can be overpowered by the occurrence of instantaneous and catastrophic release of focused fluids, as reviewed by Andresen (2012). These sudden expulsion events have been widely documented in the past years (Berndt, 2005; Hustoft et al., 2009; Vétel and Cartwright, 2010). In basins

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hosting a saline giant, the evaporite–fluid interaction is usually studied in association with the salt-tectonic activity in which salt diapirs, welds and domes are implicated in shaping the thermal and dynamic fluid circulation (Andresen and Huuse, 2011; Anka et al., 2013; Hanor, 1994; Ranganathan, 1992; Williams and Ranganathan, 1994). However, even in basins dominated by a thick undeformed evaporite sequence, fluid flow can be substantially modified (Fig. 1).

The peculiar physical–chemical properties of evaporitic minerals and sediments strongly influence the burial history of basins hosting a so called 'salt giant', such as the North Sea, Gulf of Mexico, Cretaceous Atlantic salt province and the Mediterranean, which in this latter case is the focus of this study. Uncompacted salt crystals can have the same permeability as an unconsolidated clastic deposit with an equivalent hydraulic grain radius. However, after a few 100s m of burial the permeability may be reduced to the order of nD or 10^{-21} m^2 (Ingebritsen et al., 2006). Therefore, halite-dominated evaporites can act as a barrier to subjacent upwelling fluids, and potentially generate overpressure in the sediments underlying the evaporites (Fig. 1). This rapid drop in permeability to the nano-Darcy range has led to the traditional view of salt giants as representing effectively impermeable barriers to fluid flow (Downey, 1984; Gluyas and Swarbrick, 2009; Warren, 2006). However, this view has been challenged in the last decade, by the documented evidence of fluid migration pathways through faults or fractures, bypassing thick evaporites (e.g. Davison, 2009; Schoenherr et al., 2007).

Additionally, the predisposition of evaporites to be dissolved and altered creates chemical and pressure gradients that exert significant influence on the style and patterns of subsurface fluid flow (Warren, 2006). Basinal fluids, undersaturated with respect to evaporite minerals, can dissolve evaporites, and hypothetically create density-driven convective flow (Warren, 2006) (Fig. 1). Corroding fluids can be also generated internally in the evaporitic system, by the burial-driven diagenetic transformation of gypsum into anhydrite, or carnallite into sylvite (Jowett et al., 1993; Testa and Lugli, 2000) (Fig. 1). If the dissolution is pervasive in time and space, the evaporites can be breached creating preferential fluid pathways.

Depth dependence of halite permeability may also reverse, once burial becomes deep enough, due to crystallographic changes (Lewis and Holness, 1996; Schoenherr et al., 2007). If evaporite deposits are buried to several km depth (greater than 3 km for standard geothermal gradients), the salt beds could have permeabilities comparable to those of sandstones, and therefore potentially act as fluid conduits (Lewis and Holness, 1996).

The late Miocene (Messinian) evaporites in the Mediterranean basin offer the opportunity to understand the interaction of basinal fluid flow with a relatively undeformed saline giant. Fluid-evaporite interaction occurs here in a system not yet substantially deformed by halokinesis, where original depositional controls on the evaporites still play an important role in controlling fluid flow patterns. We review the occurrence of fluid expulsion events in the km-thick subcropping Messinian evaporites in the depocentres of the Mediterranean Basin, based on seismic data (especially 3D) and bathymetry surveys. These data provide direct evidence of fluid flow through the thick evaporites (Bertoni et al., 2013, 2009; Dupré et al., 2010; Hübscher and Dümmong, 2011; Huguen et al., 2009; Loncke and Mascle, 2004). We complete the analysis of patterns of fluid circulation in buried sediments with observations made on outcrops and cores, based on facies or physical–chemical variations in the sedimentary column.

Whereas many of these phenomena have been previously reported, this article is the first attempt to group and classify the range of observed fluid flow phenomena, placing them in a basinal context, relative to specific events that occurred during the Messinian Salinity Crisis. This subdivision can provide an aid to future interpretations of the increasingly widespread subsurface seismic database in the region, and shed light on the long and short term effects of the MSC on the basinal fluid history and on its still much debated environmental changes. Specifically, this analysis can facilitate the evaluation of local versus global controls on fluid flow history and on the factors that preconditioned the sediment column for the subsequent highly focused fluid expulsion.

Understanding focused fluid flow in the context of the general basinal setting also has substantial implications for the analysis of petroleum systems: fluid venting can be instrumental for secondary and tertiary hydrocarbon migration, and its observed evidence can therefore be used as a tool to understand both the source rock charge system, and possible leakage from the reservoir in post-Messinian sediments. The final aim of this paper is to analyse this results in terms of seal-breach risk and the creation of seal-bypass systems through the evaporites. The fluid flow phenomena here reviewed can be used as 'tracers' for modelling fluid movement and subsurface pressure in evaporite-bearing sedimentary basins worldwide.

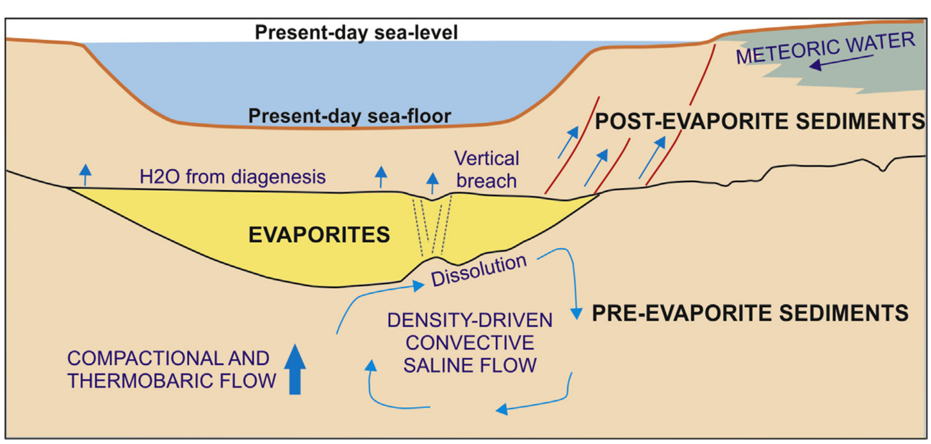

Figure 1. Schematic diagram illustrating the effects of the presence of a thick evaporitic sequence on basinal fluid flow, and associated processes. Compiled after Warren (2006), Bjørlykke (1993), Ingebritsen et al. (2006).