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Introduction

An introduction to the Special Issue of Marine and Petroleum Geology: Fluid–rock–tectonics interactions in basins and orogens

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Tectonics
Hydrocarbon systems
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Heat transfer

1. Introduction

Fluid flow is a first-order feature of the geodynamic evolution of basins and orogens. Fluids interact with rocks from the earliest stages of sedimentation until these rocks are deformed and/or metamorphosed and then possibly exhumed. Fluids are major contributors to mineralization and ore deposition, hence to resources. The interactions between fluids and rocks lead to the evolution of rock physical properties hence affect hydrocarbon potential (e.g., in porous media/reservoirs). Fractures and faults are preferred pathways for fluids, and in turn physical and chemical interactions between fluid flow and tectonic structures, such as fault zones, strongly influence the mechanical behaviour of the crust at different space and time scales.

Where in the past attention was paid to specific diagenetic products and processes, such as for example hydrothermal dolomitisation or dickite formation, today diagenesis is more often placed in the geodynamic evolution of the area under investigation. Thus a change from a more static towards a more dynamic approach took place as exemplified by the concept of "structural diagenesis" (Laubach et al., 2010). In this context one of the challenges remains to reconstruct the evolution of the Pressure (*P*), Volume (*V*), Temperature (*T*), chemical composition (*X*) through time (*t*) during deformational stages such as the development of a foreland fold-and-thrust belt (Roure et al., 2011). New analytical as well as numerical tools were developed that helped unravel the fluid–rock–tectonics relationships. Furthermore over the last years research results became more quantitative and precise, e.g. by the use of Lidar imaging techniques (with or without hyperspectral analysis; Kurz et al., 2011; Buckley et al., 2013) to acquire large datasets for example on fracture patterns or distribution of dolomite bodies, or by the application of computed tomography as a 3D quantitative petrographical technique. Also in the field of statistical analysis of data the development of multiple point geostatistics (Jung et al., 2013) set new avenues to explore for the future. With respect to analytical development of crush – leach analysis (Gleeson and Turner, 2007) and the use of laser ablation fluid inclusion analysis, stable isotope analysis of fluid inclusions, microprobe analysis of individual cement phases as well as micro-milling of individual diagenetic products for isotope studies are new developments that allowed to acquire unique datasets that help unravel the fluid-rock interactions. Another emerging field deals with the use of clumped isotopes to infer the temperatures at which specific diagenetic reactions took place (Huntington et al., 2011). Finally the use of noble gases as geochemical tracers to understand the multiphase crustal fluid system useful to identify hydrocarbons and fluid migration from mantle into the crust and across the crust (Burnard, 2013).

In basins and orogens, fluid-rock interactions occur in relation to tectonic structures such as folds, diffuse fracture sets and fault zones. A complex interplay exists in folds between fluids, (mechanical) stratigraphy, stages of fold development and fold style (Evans and Fischer, 2012), and many studies have focused on the changes in fluid *P–T–X* conditions during folding (e.g. Bradbury and Woodwell, 1987; Evans, 1995; Beaudoin et al., 2011). Despite some (but few) attempts at upscaling local fluid flow reconstructions to the scale of the basin or the fold-and-thrust belt (e.g., Trave et al., 2007; Beaudoin et al., 2014), the variability of the fluid system at the scale of the individual fold makes it to date still difficult to extrapolate local reconstructions and to build reliable basin/fold-and-thrust belt scale paleohydrogeological models.

Fluids exert an effect on crustal rock strength. They for instance permit pressure solution and chemical reactions to occur, thus stiffening the rock by depositing cements and/or weakening it through development of low-strength hydrated mineral phases such as phyllosilicates, and they reduce rock strength by overpressure. Conversely, the structural and stratigraphic permeability architecture influences fluid migration pathways. In recent years our understanding of fluid flow through faults has been improved through the combination of laboratory measurements of fluid flow properties of natural and synthetic fault rocks and observations in nature of migrating seismicity at depth, shallow reservoir-induced seismicity and in situ behaviour of geothermal systems. The permeability of a fault zone, both along-plane and across-plane, is controlled by the permeability of the individual fault rocks/fractures and by their 3D geometric architecture (Lunn et al., 2008). Open fractures and slip surfaces have a permeability governed by their aperture distribution (which is in turn influenced by their orientation with respect to the (local) stress field) and by their healing capacity in relation to the fluid *P–T–X* properties, but their influence on the permeability of the fault zone strongly depends on their connectivity and their ability to cut across lower permeability units at the time of fault activity (Wibberley et al., 2008; Faulkner

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et al., 2010). The hydromechanical behaviour of fault zones is also increasingly receiving attention (e.g., Cappa, 2009), with potential important issues in seismic hazard assessment, and about 20 years after the pioneering work of McCaig (1988) and the fault-valve model of Sibson (1990), recent investigation at deeper crustal levels highlighted for instance that creep cavitation can establish a dynamic granular fluid pump in ductile shear zones (Fusseis et al., 2009). The relationships between fluid migration and rock deformation still remain to be further documented, quantified and integrated in comprehensive models of short-term and long-term fault zone behaviour and crustal mechanics.

Many sedimentary basins experience supra-hydrostatic fluid pressures, i.e. fluid overpressures (e.g. Hunt, 1990). Osborne and Swarbrick (1997) described three main mechanisms for the generation of fluid overpressures in sedimentary basins: diagenetic reactions, disequilibrium compaction and hydrocarbon generation, but new lines of evidence support that the mechanical stratigraphy and the governing stress regime are also important controlling factors. The evolution of fluid overpressures in space and time is a key issue for understanding processes as various as inherited fault reactivation and seismic cycle in various P-T conditions (Sibson, 2009), pervasive hydrofracturing (Bons et al., 2012) or hydrocarbon migration. Fluid overpressures are common within petroleum-rich sedimentary basins (Swarbrick et al., 2002), where they can cause widespread development of bedding-parallel fractures through seepage forces (Cobbold et al., 2013) and regional decollement (Cobbold, 2005). Performing and combining new techniques for better quantifying fluid overpressures and their spatial/temporal variations in basins and fold-and-thrust belts is a challenge for the forthcoming years for both academy and industry.

Although continental basins are mainly dominated by crustal fluid sources, there is increasing evidence for occurrence of mantle-derived fluids, often coupled to heat flow anomalies, especially in active tectonic and volcanic regions (O'Nions and Oxburgh, 1988; Torgersen, 1993). Fluids of undoubted mantle origin (e.g., He) allowed discovering magmatic CO_2 trapped into the crust for 300 millions of years (Ballentine et al., 2001) and the possible role of mantle fluids in the production of CH_4 (Poreda et al., 1986; Wakita and Sano, 1983). Circulating fluids carry information regarding temperature, pressure, fluid-rock interactions and chemical conditions within a geothermal system (Giggenbach, 1980). Discrimination between mantle, crustal fluids and fluid-rock interactions in continental areas is critical in providing useful tools to develop regional strategies for natural gas, ore and geothermal explorations but also in helping investigate crustal- mantle tectonics (Kennedy and van Soest, 2007) as well as seismogenic processes (Chiodini et al., 2011). Nevertheless a key point is the transfer of fluids through the crust, which mainly occurs by diffusion and advection. In particular fluids coming from the mantle need to pass the brittle to viscous transition that is considered to be an impermeable barrier because of the inability to maintain open fractures on long time scales even with the presence of faults (Sleep and Blanpied, 1992). However, recent studies in areas devoid of recent volcanism (Kennedy et al., 1997; Kennedy and van Soest, 2007; Kulongoski et al., 2005) provided evidence for fault-controlled advective flow of mantle fluids through the ductile boundary. How and why this occurs is still not well understood.

Following the Geofluids 2012 meeting in Rueil-Malmaison and the successful session dedicated to fluid–rock–tectonics interactions in the 2013 EGU meeting in Vienna, this Marine and Petroleum Geology Special Issue aims at making the point on our knowledge of fluid–rock–tectonics interactions in basins and orogens and to evaluate to what extent fluids influence, and in turn are influenced by, rock composition and physical/rheological properties and structural evolution at different levels of the continental crust. The 21 contributions cover a large range of topics, including fluid-rock interactions and fluid signatures in fractures, fault zones and folds, fluid pathways reconstruction and modelling of fluid–rock–tectonics interactions during chemical and physical diagenesis. They consider a variety of fluids, such as hydrocarbon fluids, meteoric, mantle-derived hydrothermal and/or basinal fluids. They also address the origin of fluids at different depth levels of the lithosphere and their role in basin thermicity, hence in basin dynamics.

2. Content of the volume

The volume is divided into six chapters.

(1) Fluid–rock interactions, diagenetic processes and resources

Dewit et al. investigated a complex of hydrothermal dolomite (HTD) in an extensional basin at Matienzo, Basque-Cantabrian Basin, northern Spain. The Matienzo HTD body represents an excellent reservoir analogue for the hydrocarbon reservoirs hosted by stratabound HTDs producing hydrocarbon reservoirs in USA. Three types of dolomites have been differentiated: 1) matrix, 2) coarse crystalline and 3) zebra dolomite, their distribution being attributed to ascending fluid flow and changing degree of dolomite oversaturation. The high resolution of this investigation allows to recognize evaporated seawater as dolomitizing fluids and to demonstrate that its circulation occurred during tectonic phases. The obtained porosity and permeability values of the stratabound HTD highlight that these parameters are not correlated.

Gomez-Rivas et al. document dolomitization mechanisms of an Early Cretaceous ramp in Benicàssim (Maestrat basin, eastern Spain), where stratabound dolostone bodies extend over several kilometres away from large-scale faults. Field observations, $\delta^{13}C$ and $\delta^{18}O$ as well as radiogenic $^{87}Sr/^{86}Sr$ isotopes indicate that dolomitization at Benicàssim was produced by a high T fluid (>80 °C), and the Mg source analysis reveals that the most likely dolomitizing fluid was a seawater-derived brine. By means of mass-balance calculations, the authors show that a pervasive fluid circulation mechanism, like thermal convection, is required to provide a sufficient volume of dolomitizing fluid. This emphasizes the importance of quantifying the fluid budget in order to critically evaluate genetic models for dolomitization and other diagenetic processes.

Jacquemyn et al. investigated the sedimentary, magmatic, and diagenetic features of the dolomitized carbonate reservoirs in the Anisian-Ladinian Latemar platform (southern Alps, Italy). Their work is based on geochemical and petrographical analyses carried out at a wide range of scales. From field observations and petrography, they established a detailed paragenesis and the relationship between dolomitization and magmatic dike emplacement. It is highlighted that the controls on the distribution of the dolomitizing fluid depend on the scale of circulation. Dikes play also an important role in facilitating platform-wide fluid flow. The combination of stable, $\delta^{13}C$ and $\delta^{18}O$, and radiogenic, $^{87}Sr/^{86}Sr$ isotopes indicates that the dolomitizing fluid was probably originally the Carnian seawater. This study provides additional data to evaluate the potentiality of igneous rocks to develop elevated porosity and permeability, migration pathways, traps and seals in relation to hydrocarbon reservoir.

Frazer et al., present results of simulations addressing the critical assessment of the potential impact of compaction-driven flow on diagenesis. They discuss a case where the conditions for compaction-driven fluid supply to a carbonate platform are thought to have been favourable and where this fluid supply has likely driven the diagenesis of a large volume of rocks. Simulations coupling sedimentation and hydrology allow to reconstruct the