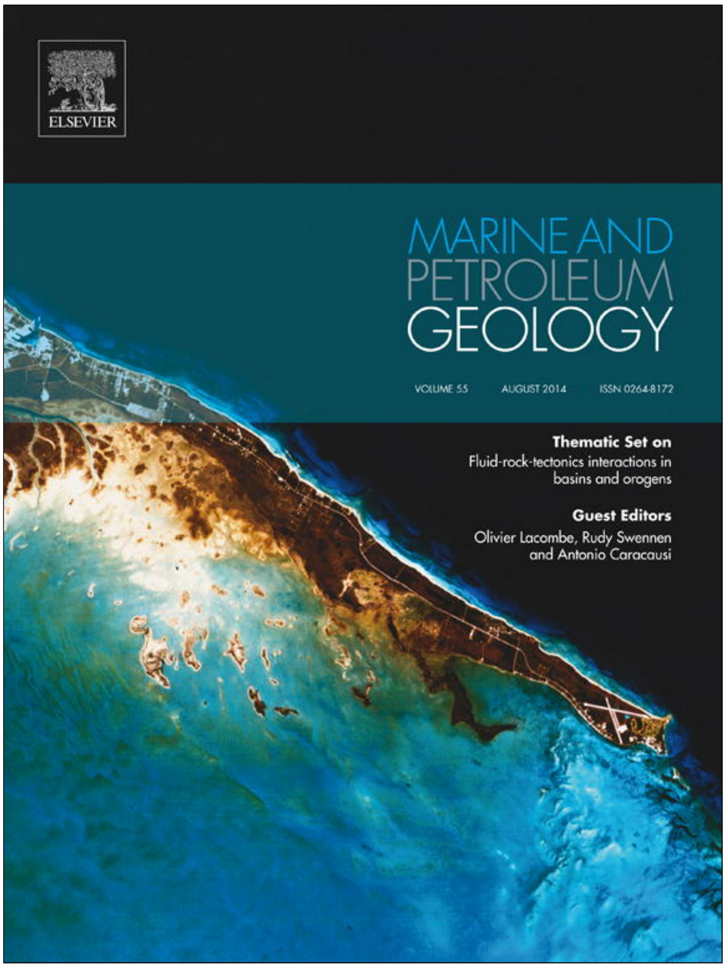
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Thematic Set on
Fluid-rock-tectonics interactions in basins and orogens
Guest Editors
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Introduction

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

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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

44.5 Myr evolution of the Derbyshire Platform and surrounding basins from deposition to burial. Estimates of volumes, sources and timing of fluids supplied to the platform by basinal-compaction are also provided.

(2) Fluid–rock interactions and fluid flow in fractures and deformation bands

Cantarero et al. report fluid flow along fractures and minor faults and cementation of shallow buried Miocene proximal alluvial fan deposits from the Vallès-Penedès basin (northeastern Spain). The structural, petrographical and geochemical data allowed to address across-fault and fault-parallel fluid flows. The authors elaborate on the change in oxido-reduction as well as the timing of the processes. Two meteoric derived cement-types have been differentiated and the presence of palygorskite within fault gouges in relation to interaction of Mg-rich fluids with smectites is discussed.

Warren et al. conducted a stable isotopic study of calcite from bioclasts, cements and veins in folded and fractured Lower and Middle Permian carbonates of the Saraburi Group in central Thailand in order to reconstruct the fluid-cement history. They document a regional post-depositional mesogenetic fluid–rock re-equilibration of the isotope values in ongoing calcite precipitates that occurred until the matrix permeability was occluded via compaction and pressure solution. This regional burial regime was followed by the Indosinian orogeny which drove a set of thrust-related, increasingly warmer fluids through the sequences. The final diagenetic overprint as revealed by the isotopic values of the latest calcite cements occurs in a telogenetic (uplift) setting driven by the Himalayan event. The C–O covariant plot fields in the Permian carbonates of central Thailand are very distinct, so their signatures can be used to separate burial from meteoric cements in drill cuttings and hence recognize equivalent subsurface unconformities and likely zones of porosity development in possible buried hill plays.

Gasparrini et al. examine natural sealed fractures from core and outcrop samples from the organic-rich mudrocks of the Mississippian Barnett Shale (Texas, USA). Petrographical and geochemical characterization of the sealing minerals reveals various fracture generations that are replaced in a time sequence, which in turn allowed inference of burial conditions of fracture development, fracture mechanisms and origin of the parent fluids of sealing minerals. Type 1 fractures formed during early mechanical compaction while type 2 formed during moderate burial consistent with overpressure generated during rapid deposition and differential compaction of Pennsylvanian lithologies at the onset of the Ouachita compression. Type 3 fractures formed during deep burial from silica-rich basinal brines possibly derived from clay diagenesis. Type 4 fractures formed at very deep burial conditions from hot and ^{18}O-rich fluids; they carry light oil and reflect the opening of the fluid system after hydrocarbon migration. Differences from one place to another of the basin in the timing and thermal regimes of fracture formation make the extrapolation of outcrop observations to subsurface hazardous.

From outcrops located in Provence (SE France), **Ballas et al.** describe the distribution, the microstructures and the petrophysical properties of low-permeability deformation band networks related to both compressional and extensional tectonics. In compression, pervasively distributed networks of reverse-sense compactional shear bands are seen in all folded sand units, in contrast with localized networks of clustered reverse-sense shear bands only observed close to a large-scale thrust. In extension, networks of clustered normal-sense shear bands are generally observed adjacent to map-scale faults. Shear bands and faults show cataclastic microstructures with high-permeability reduction whereas compactional shear bands show crush microbreccia or protocataclastic microstructures with moderate permeability reduction. This work underlines the major role played by the tectonic setting and the influence of inherited large-scale faults on the formation/localization of low-permeability shear bands, even though grain size has also a non-negligible effect on band network geometry.

(3) Fluid-rock interactions and fluid flow in fault zones

Trincal et al. quantify mass transfers and mineralogical transformations in the Monte Perdido thrust unit (southern Pyrenees, Spain). By means of X-ray diffraction and Rietveld refinement, and bulk chemical as well as microprobe analyses to calculate modal composition, they compare the mineralogy of the hanging wall and footwall of the thrust with the marly fault rocks. They document a significant loss of calcite during fault activation, the amounts of quartz, chlorite and illite remaining nearly unchanged, as well as a significant volume loss related to dissolution of micritic calcite grains. Pressure solution and phyllosilicates recrystallisation accommodated slip along the thrust; these mechanisms required fluids as catalyst, but did not imply major chemical transfers.

In the **Hatem et al.** paper, Late Jurassic oyster patch reefs from the Boulonnais area (N-France) are used as indicators of fossil hydrocarbon seepage along synsedimentary faults. Based on isotope geochemical data of oyster shells and the matrix between the shells, the authors provide arguments that these reefs are likely related to small-dimension hydrocarbon seepage processes.

Antonellini et al. report numerical fluid-flow experiments of faulted porous carbonates. Reservoir performance during production from porous carbonate grainstones is assessed by integrating data from structural analysis, up-scaling, and inference of power law distributions as well as by using numerical approaches where buffering effects on permeability caused by compactive and cataclastic deformation bands are taken into account.

Gas and oil seepage emissions are known to reflect some of the peculiar fluid flow systems in the geological record. To this respect, **Pennino et al.** describe fluid escape structures, such as pockmarks, from the north Sicily continental margin. Data presented rely on high resolution and multichannel seismic profiles coupled with data from multibeam echosounding. A classification on the basis of morpho-acoustic characteristics of the structures is presented, and their alignment is discussed in terms of tectonics and slope failure. In addition geochemical data from a sediment core are presented which allow to discuss sediment–fluid interaction processes pointing to the possible destablilisation of gas hydrates.

(4) Fluid-rock interactions and fluid flow in folds

Beaudoin et al. report fluid pressure estimates and reconstruction of the fluid pressure evolution in the overpressured Paleozoic Madison-Phosphoria carbonate reservoir during the Sevier-Laramide contractional history of the BigHorn basin (Wyoming, USA). They quantify paleostress magnitudes (i.e., the complete stress tensors) at each stage of fracture and fold development within the basin by combining calcite twinning paleopiezometry with fracture analysis and rock mechanics. They document that supra-hydrostatic pressure values prevailed in the carbonate reservoir during most of its whole Sevier-Laramide history. Estimates of syn-folding strata exhumation are also derived. The results are compared to measurements of fluid pressure in overpressured reservoirs from other oil-producing basins and to reconstructions of paleofluid pressure evolution during fracture opening, and the factors controlling the pressure evolution are discussed.

Morley et al. compare modern fluid distribution, pressure and flow in sediments associated with Neogene anticlines growing in deepwater setting offshore Brunei (shale detachment) and continental arid environments in the Central Basin of Iran (salt detachment). Differences in overpressure mechanism are documented, which arise from the availability of water trapped in pore-space during early burial and the depth/temperature at which chemical processes start to overtake mechanical compaction in controlling overpressure development. In the Brunei water-rich system, overpressure generation and fluid leakage occurred throughout anticline growth, resulting in various upward fluid migration pathways and widespread inflationary-type overpressure. In contrast, in the Central Basin of Iran the environment is water limited, so mechanical and chemical compaction generally led to moderate overpressure, and fluid leakage episodes across the evaporites are absent in most areas. In both regions, crestal normal faults seem to control the transmission of fluids in the upper parts of the folds.

(5) Hydrocarbon fluid systems : modelling and case studies

In their first paper, **Zanella et al.** describe bedding-parallel veins of fibrous calcite or quartz ('beefs') from Early Cretaceous source rocks at the surface in the Magallanes-Austral Basin (South America), which originated in response to fluid overpressures. Independent evidence for overpressure, in the form of source-rock detachments, comes from subsurface data, especially at the southern end of the basin, where the source rocks are not overmature and deformation is relatively intense. The authors argue that hydrocarbon generation has led to overpressure during hydrocarbon maturation, as a result of chemical compaction and load transfer, or volume changes, or both.

To further investigate processes of chemical compaction, overpressure development and hydraulic fracturing ('beefs') in organic-rich source rocks, **Zanella et al.**, in their second paper, performed physical modelling of chemical compaction in a closed system. Models consist of horizontal layers of a mixture of equal initial volumes of silica powder and beeswax micro-spheres, representing source rock and pure silica powder representing overburden. Models were submitted to extension and compression and heated at the base to make the wax melt. Sections across models reveal that molten wax had migrated through pore space and into open hydraulic fractures (sills), most being horizontal and with their roofs bulging upwards in response to internal overpressure and loss of strength of the mixture. It is concluded that the transformation of the wax from solid to liquid led to chemical compaction, overpressure development and hydraulic fracturing. Measurements of overpressure suggest that load transfer was the main mechanism, but volume changes also contributed, producing supra-lithostatic pressure and therefore tensile failure.

Parnell et al. report evidence of preserved Mesoproterozoic age deep burial fluid signatures. They analysed fibrous calcite from bedding-parallel veins in the Stoer Group (NW Scotland) below a level of back shales. The formation of these veins likely required fluid overpressure, and although no direct evidence was found, hydrocarbons possibly generated from the overlying black shales may have contributed to the development of this overpressure. They show that the calcite of these veins reflects the original deep burial fluid, rather than a later overprint, and thus provide evidence for diagenetic fluids of Mesoproterozoic age. The provided geochemical evidence for penetration of oxidizing fluids to the deep subsurface has potential implications for the history of redox-dependent geochemical processes, including development of secondary porosity, weathering and beneficiation of ore deposits, and deep subsurface habitat for aerobic microbial life.

Neveux et al. focuses on an important diagenetic process, namely pressure solution creep (PSC) in aqueous and oil-bearing porous carbonates based on triaxial flow through high-pressure experiments. Different scenarios are tested. Based on mechanical, chemical, petrographical and petrophysical data the authors document that without oil in the pore space the main diagenetic process is the PSC while an early injection of oil prior to water circulation causes the inhibition of PSC, and a late injection does not preserve initial porosity. These data are relevant for understanding porosity preservation/destruction especially in deeply buried reservoirs.

(6) Deep fluids and heat transfer in basins

D'Alessandro et al. report fluids emitted in a fast spreading rift basin in central Greece, i.e., the Sperchios Basin–Evoikos Gulf, a complex region where subduction interacts with the termination of the seismically active North-Anatolian fault. Such an investigation highlights the occurrence of hydrothermal systems at depth with temperature lower than 200 °C. Chemical and isotopic composition of the emitted fluids show a regional variation from east to west. The former are typically crustal-dominated fluids, thermogenic CH_4-rich, the latter are CO_2-dominated. The authors highlight significant addition of mantle-derived volatiles to the crustal end-member. The mantle contributions coupled to the occurrence of hydrothermal systems indicate a mantle up-rise through the North Anatolian System faults or degassing magma accumulations in the crust below the Northern Evoikos Gulf, allowing to reconstruct the crust-mantle tectonic at the regional scale.

In **Nuccio et al.** paper, attention is paid to the geothermal Maschito gas emissions (southern Italy). The location near the boundary between the foredeep and the Apulian foreland as well as its alignment along a regional tectonic discontinuity where maars occur point to a geothermal system in relation to a degassing melt. A mantle-derived fluid discharge is concluded on the basis of a variety of gas analysis and isotope ratios.

The work by **Scheck-Wenderoth et al.** focuses on the mechanisms of heat transfer in the Central European Basin system. For the first time, results of high resolution 3D simulation of heat transport at different scales and in the same region are compared. This allows reconstructing the influence of different configurations of the deeper lithosphere, of the crust-mantle tectonics, of the mechanism of heat transport considered and of the large faults dissecting the sedimentary succession on the resulting thermal field and groundwater flow. Furthermore such 3D simulations allow assessing the contribution of conductive, advective and convective heat transport on the deep thermal field. The reconstruction of the heat distribution at regional and local scale coupled to the mechanism of the heat transport and the role of fluids in the shallower crustal layers are critical in providing tools for a concrete application of these 3D models in geosciences.

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References

Ballentine, C.J., Schoell, M., Coleman, D., Cain, B.A., 2001. 300-Myr-old magmatic CO_2 in natural gas reservoir of the west Texas Permian basin. Nature 409, 327–331.

Beaudoin, N., Bellahsen, N., Lacombe, O., Emmanuel, L., 2011. Fracture-controlled paleohydrogeology in a basement-cored, fault-related fold: Sheep Mountain anticline (Wyoming, USA). Geochem. Geophys. Geosyst. 12, Q06011.
Beaudoin, N., Bellahsen, N., Lacombe, O., Emmanuel, L., Pironon, J., 2014. Crustal-scale fluid flow during the tectonic evolution of the Bighorn Basin (Wyoming, USA). Basin Res. http://dx.doi.org/10.1111/bre.12032.
Bons, P.D., Elburg, M.A., Gomez-Rivas, E., 2012. A review of the formation of tectonic veins and their microstructures. J. Struct. Geol. 43, 33–62.
Bradbury, H.J., Woodwell, G.R., 1987. Ancient fluid flow within foreland terrains. In: Goff, J.C., Williams, B.P.J. (Eds.), Fluid Flow in Sedimentary Basins and Aquifers, Geological Society, London, Special Publications, vol. 34, pp. 87–102.
Buckley, S.J., Kurz, T.H., Howell, J.A., Schneider, D., 2013. Terrestrial lidar and hyperspectral data fusion products for geological outcrop analysis. Comput. Geosci. 54, 249–258.
Burnard, P., 2013. The Noble Gases as Geochemical Tracers. Springer, 391p.
Cappa, F., 2009. Modelling fluid transfer and slip in a fault zone when integrating heterogeneous hydromechanical characteristics in its internal structure. Geophys. J. Int. 178 (3), 1357–1362.
Chiodini, G., Caliro, S., Cardellini, C., Frondini, F., Inguaggiato, S., Matteucci, F., 2011. Geochemical evidence for and characterization of CO_2-rich gas sources in the epicentral area of the Abruzzo 2009 earthquakes. Earth Planet. Sci. Lett. 304 (3–4), 389–398.
Cobbold, P.R., Zanella, A., Rodrigues, N., Løseth, H., 2013. Bedding-parallel fibrous veins (beef and cone-in-cone): worldwide occurrence and possible significance in terms of fluid overpressure, hydrocarbon generation and mineralization. Mar. Pet. Geol. 43, 1–20.
Cobbold P.R. 2005. Hydrocarbon generation, a mechanism of detachment in thin-skinned thrust belts. Joint Earth Science Meeting on 'Thrust belts and Foreland basins', Société Géologique de France and Sociedad Geológica de España (convened by O. Lacombe, J. Lavé and F. Roure), Rueil-Malmaison, France, Abstract Volume, 104–107.
Evans, M.A., 1995. Fluid inclusions in veins from the Middle Devonian shales: a record of deformation conditions and fluid evolution in the Appalachian Plateau. Geol. Soc. Am. Bull. 107, 327–339.
Evans, M.A., Fischer, M.P., 2012. On the distribution of fluids in folds: a review of controlling factors and processes. J. Struct. Geol. 44, 2–24.
Faulkner, D.R., Jackson, C.A.L., Lunn, R.J., Schlische, R.W., Shipton, Z.K., Wibberley, C.A.J., Withjack, M.O., 2010. A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones. J. Struct. Geol. 32, 1557–1575.
Fusseis, F., Regenauer-Lieb, K., Liu, J., Hough, R.M., De Carlo, F., 2009. Creep cavitation can establish a dynamic granular fluid pump in ductile shear zones. Nature 459 (7249), 974–977.
Giggenbach, W.F., 1980. Geothermal gas equilibria. Geochim. Cosmochim. Acta 44, 2021–2032.
Gleeson, S.A., Turner, W.A., 2007. Fluid inclusion constraints on the origin of the brines responsible for Pb-Zn mineralization at pine point and coarse non-saddle and saddle dolomite formation in southern Northwest territories. Geofluids 7, 51–68.
Hunt, J.M., 1990. Generation and migration of petroleum from abnormally pressured fluid reservoirs. Am. Assoc. Pet. Geol. Bull. 74, 1–12.
Huntington, K.W., Budd, D.A., Wernicke, B.P., Eiler, J., 2011. Use of clumped-isotope thermometry to constrain the crystallization temperature of diagenetic calcite. J. Sediment. Res. 81 (9), 656–669.
Jung, A., Fenwick, D., Caers, J., 2013. Training image-based scenario modeling of fractured reservoirs for flow uncertainty quantification. Comput. Geosci. 17, 1015–1031.
Kennedy, B.M., Kharaka, Y.K., Evans, W.C., Ellwood, A., DePaolo, D.J., Thordsen, J., Ambats, G., Mariner, R.H., 1997. Mantle fluids in the San Andreas fault system, California. Science 278, 1278–1281.
Kennedy, B.M., van Soest, M.C., 2007. Flow of mantle fluids through the ductile lower crust: helium isotope trends. Science 318, 1433–1436.
Kulongoski, J.T., Hilton, D.R., Izbicki, J.A., 2005. Source and movement of helium in the eastern Morongo groundwater basin: the influence of regional tectonics on crustal and mantle helium fluxes. Geochim. Cosmochim. Acta 69, 3857–3872.
Kurz, T., Dewit, J., Buckley, S., Thurmond, J., Hunt, D., Swennen, R., 2011. Lidar imaging and hyperspectral analysis of hydrothermal dolomite distribution in the Pozalagua Quarry (Cantabria, NW Spain). Sedimentology 59, 623–645.
Laubach, S.E., Eichhubl, P., Hilgers, C., Lander, R.H., 2010. Structural diagenesis. J. Struct. Geol. 32 (12), 1866–1872.
Lunn, R.J., Willson, J.P., Shipton, Z.K., Moir, H., 2008. Simulating brittle fault growth from linkage of preexisting structures. J. Geophys. Res. 113 (B7).
McCaig, A.M., 1988. Deep fluid circulation in fault zones. Geology 16 (10), 867–870.
O'Nions, R.K., Oxburgh, E.R., 1988. Helium, volatile fluxes and the development of continental crust. Earth Planet. Sci. Lett. 90, 331–347.
Osborne, M.J., Swarbrick, R.E., 1997. Mechanisms for generating overpressure in sedimentary basins: a reevaluation. Am. Assoc. Pet. Geol. Bull. 81, 1023–1041.
Poreda, R.J., Jensen, P.D., Kaplan, I.R., Craig, H., 1986. Mantle helium in Sacramento basin natural gas wells. Geochim. Cosmochim. Acta 50, 2847–2853.
Roure, F., Andriessen, P., Callot, J.P., Faure, J.L., Ferket, H., Gonzales, E., Guilhaumou, N., Lacombe, O., Malandain, J., Sassi, W., Swennen, R., Vilasi, N., 2011. The use of paleo-termo-barometers and coupled thermal, fluid flow and pore fluid pressure modelling for hydrocarbon and reservoir prediction in fold-and-thrust belts. In: Geoffey, G.P., Craig, J., Needham, T., Scott, R. (Eds.), Hydrocarbons in Contractional Belts, Geological Society, London, Special Publications, vol. 348, pp. 87–114.
Sibson, R.H., 1990. Conditions for fault-valve behaviour. In: Knipe, R.J., Rutter, E.H. (Eds.), Deformation Mechanisms, Rheology and Tectonics, Geological Society, London, Special Publication, vol. 54, pp. 15–28.
Sibson, R.H., 2009. Rupturing in overpressured crust during compressional inversion- the case from NE Honshu, Japan. Tectonophysics 473 (3–4), 404–416.
Sleep, N.H., Blanpied, M.L., 1992. Creep, compaction and the weak rheology of major faults. Nature 359, 687–692.
Swarbrick, R.E., Osborne, M.J., Yardley, G.S., 2002. Comparison of overpressure magnitude resulting from the main generating mechanisms. In: Huffman, A.R., Bowers, G.L. (Eds.), Pressure Regimes in Sedimentary Basins and Their Prediction, vol. 76. American Association of Petroleum Geologists Memoir, pp. 1–12.
Torgersen, T., 1993. ^{3}He fluxes in extensional basins: limits on the role of magmatism in extensional basins. J. Geophys. Res. 98, 16,257–16,269.
Trave, A., Labaume, P., Verges, J., 2007. Fluid systems in foreland fold-and-thrust belts: an overview from the southern Pyrenees. In: Lacombe, O., Lave, J., Roure, F., Verges, J. (Eds.), Thrust Belts and Foreland Basins. Springer, Berlin, pp. 93–117.
Wakita, H., Sano, Y., 1983. ^{3}He/^{4}He ratios in CH_4-rich gases suggest magmatic origin. Nature 305, 792–794.
Wibberley, C.A.J., Kurz, W., Imber, J., Holdsworth, R.E., Collettini, C. (Eds.), 2008. Structure of Fault Zones: Implications for Mechanical and Fluid-flow Properties. Geological Society, London Special Publication, vol. 299.

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