Journal of Geodynamics 101 (2016) 1–4

Contents lists available at ScienceDirect

Journal of Geodynamics

journal homepage: http://www.elsevier.com/locate/jog

Editorial

Fluids in crustal deformation: Fluid flow, fluid-rock interactions, rheology, melting and resources

Fluids exert a first-order control on the structural, petrological and rheological evolution of the continental crust. Fluids interact with rocks from the earliest stages of sedimentation and diagenesis in basins until these rocks are deformed and/or buried and metamorphosed in orogens, then possibly exhumed. Fluid-rock interactions lead to the evolution of rock physical properties and rock strength. 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. Fluid (over)pressure is associated with a variety of geological phenomena, such as seismic cycle in various P-T conditions, hydrofracturing (including formation of sub-horizontal, bedding-parallel veins), fault (re)activation or gravitational sliding of rocks, among others. Fluid (over)pressure is a governing factor for the evolution of permeability and porosity of rocks and controls the generation, maturation and migration of economic fluids like hydrocarbons or ore forming hydrothermal fluids, and is therefore a key parameter in reservoir studies and basin modeling. Fluids may also help the crust partially melt, and in turn the resulting melt may dramatically change the rheology of the crust.

In sedimentary basins, fluids interact with rocks during all stages of diagenesis. Diagenetic fluids make the rock chemical composition evolve. Fluids also exert an effect on rock strength, since they permit pressure solution and chemical reactions to occur, thus stiffening the rock by depositing cements and subsequently reducing its porosity. One challenge remains to accurately reconstruct the evolution of pressure, volume, temperature and chemical composition through time during deformational stages of basins that may ultimately be incorporated as parts of fold-and- thrust belts. To this aim, analytical and numerical tools were recently developed to help unravel fluid-rock-tectonics interactions: e.g., 3D computed tomography to describe pore network and connectivity, laser ablation and stable isotope analysis of fluid inclusions, clumped isotope paleothermometry to infer the temperatures at which specific diagenetic reactions took place and U-Pb dating of calcite cements to provide time constraints on diagenetic evolution. In tectonized sedimentary basins, fluid-rock interactions occur in relation to tectonic structures such as folds, diffuse fracture sets and fault zones. A complex interplay exists between fluids, (mechanical) stratigraphy, stages of fold development and fold style (Lacombe et al., 2012). Understanding the origin, pathways and interactions with rocks of fluids migrating in basins is also an important issue: large-scale faults may behave either as efficient drains or as barriers for fluids, which is a first-order input for fluid-flow modeling. Conversely, the structural and stratigraphic permeability architecture influences fluid migration pathways.

Fluids (whatever their nature and origin – meteoric, crustal and even mantle-derived) play an important role in controlling the short-term and long-term activity of faults in the continental crust. Seismic swarms have been described in volcanic regions where their occurrence is related to magma intrusion and/or to fluid degassing, inducing pore pressure increase and fault reactivation. Their occurrence has also been discussed in non-volcanic areas where mantle volatiles, or meteoric water, can be the common trigger for seismic activity. An increase in fluid pressure reduces the effective normal stress acting on a fault, hence promotes its reactivation and triggers seismicity. Even faults severely misoriented with respect to the ambient stress field and therefore otherwise stable can be reactivated in the presence of fluid overpressure. Therefore, earthquakes may be correlated to pore pressure diffusion and stress transfer that may reduce crustal strength and promote a great number of earthquakes with a large range of magnitudes. However, if fluid pressurization is a viable mechanism for fault weakening and for earthquake triggering in the seismogenic upper crust, the build-up, maintenance, and diffusion of fluid overpressures in faults still remain unclear: depending on models, build-up of fluid overpressure can develop by cyclic syn/post-seismic pumping of fluids in the fault zone, that are subsequently trapped by a hydraulic barrier when fractures are sealed and mineralized; by continuous (even limited) fluid flux coming from depth in the core of the fault zone; by reduction of porosity during compaction and healing of the fault core surrounded by an impervious damage zone, among others.

At mid-crustal level, shear zones that developed in crystalline rocks act as zones of intense fluid circulation during crustal deformation, should they be thrust, wrench or extensional (detachments) in type. Meteoric fluids circulate downward through the brittle upper crust and penetrate into the shear zone where fluid circulation is focused as a result of deformation-induced permeability enhancement. Fluid flow results in significant mass and heat transport, which may in turn control the stability of mineral assemblages and the rheology of rocks through fluid-induced softening reactions (e.g., development of low-strength hydrated mineral phases such as phyllosilicates). Exhumed shear zones therefore provide a record of dynamic mid-crustal fluid-rock interactions,

http://dx.doi.org/10.1016/j.jog.2016.08.004

documenting mixing of meteoric and magmatic or metamorphic fluid reservoirs and intimate association between deformation processes and fluid flow.

Still a matter of discussion is the behaviour of the brittle to viscous transition that is usually considered to be an impervious barrier separating the upper crust with overall hydrostatic fluid pressure from the lower crust where lithostatic fluid pressure prevails, because of the inability to maintain fractures opened on long time scales even in presence of crustal faults.

In the lower crust, i.e., at high temperature, fluids promote ductile creep, but the causal relationship between fluids and recrystallization is still to be better documented. Controversies also exist about the amount of fluids flowing in the deep crust: either the amount of fluids in rocks is limited to small disconnected pores, because of the small fluid/rock wetting angle at thermodynamic equilibrium and the efficiency of fluid escape through open brittle fractures up to the surface; or there is, at least locally and transiently, a continuous fluid network, which is consistent with physical-chemical characteristics of fluids trapped in metamorphic rocks. In addition, pervasive partial melting of large rock volumes and magma generation commonly occur at middle to lower crustal levels in response to high geothermal gradients, decompression and/or addition of fluids. In migmatitic regions, the heterogeneous distribution of melt may cause competence contrasts between melanosome and leucosome layers, thus influencing crustal rheology hence the way strain is accommodated. Production of fluids through magma crystallization may also increase the fluid/rock ratio and destabilize the thermodynamic equilibrium between fluids and minerals.

Following a previous thematic issue on fluid-rock-tectonics interactions in basins and orogens of *Marine and Petroleum Geology* in 2014 (Lacombe et al., 2014), this special issue of *Journal of Geodynamics* presents a new collection of 12 papers dealing with different aspects of crustal deformation involving fluids in a general sense. Some of these contributions were presented as part of a session devoted to this topic at the 2015 European Geosciences Union General Assembly in Vienna (Austria). The aim of this session was to assemble a broad group of Earth scientists interested in the role of fluids in crustal deformation spanning a broad array of tectonic settings, geographical locations, and geological times. This volume presents a collection of some of the diverse research that is currently being carried out on this topic. We believe that these studies contribute to a better understanding of the petrological and geodynamic processes at work within the continental crust as well as of its overall short-term and long-term rheological properties.

The table of content of the Special Issue covers a large range of contributions:

1. Fluid-rock interactions at shallow crustal levels: fracturing and diagenetic evolution in sedimentary basins and fold-and-thrust belts

Nader et al. (2016) investigate the impact of compaction diagenesis on reservoir properties based on observations in well cores with different burial histories of the Lower Callovian 'Dalle Nacrée' Formation in the Paris Basin. Petrographic and X-ray computer tomography analyses were carried out in order to investigate the rock-texture, pore space types, volume and micro-fabrics in order to unravel the sequence of diagenetic events. Their results show that basin margin grainstones underwent a different burial diagenesis compared to basin centre lithologies, and that compaction fluids may have migrated at the time of burial from the basin centre towards its margins, affecting the reservoir properties of similar rock textures and facies and resulting in cross-basin spatial diagenetic heterogeneities.

Cruset et al. (2016) report an integrated fluid-fracture study carried out in the crestal domain of the Puig-reig anticline in the South Pyrenean fold and thrust belt. They use structural, petrographic and geochemical studies, including clumped isotopes thermometry to constrain temperatures of calcite precipitation within host rocks, veins and faults and to define which factors controlled deformation at the mesoscale and at the microscale. Their results highlight that hydrothermal fluids circulated during the layer-parallel shortening stage, while meteoric fluids circulated downward during fold growth and mixed at depth with the previous hydrothermal fluids, both fluids using faults and diffuse vein sets as main pathways.

2. Fluid-rock interactions at deep crustal levels

Verlaguet et al. (2016) investigate processes of selective mass transfer in Alpine metabauxites at high pressure (blueschist) metamorphic conditions. Their study shows that phyllosilicates are preferentially transferred to veins by a dissolution-diffusion-precipitation process without any fluid infiltration or associated reactions. Chemical profiles across host-rocks between successive veins using Laser Induced Breakdown Spectroscopy (LIBS) associated to a microstructural study suggest a diffusion distance of 2–4 cm for Li, and availability of an aqueous fluid during most of the metamorphic cycle. The authors propose that mineral solubility variation with pressure seems to be the key controlling parameter for pressure-solution creep. Lithium, which is a strategic element, is observed to preferentially migrate and segregate into veins during metamorphic processes, which may be of importance for exploration purposes.

In contrast to the above study that investigates fluid-rock interaction in the mass of metamorphic rocks, Pennacchioni et al. (2016) rather focus on fluid-rock interaction processes in fault zones cutting across the crystalline basement in the Tauern tectonic window (Eastern Alps) during Alpine (~30 Ma) amphibolite-facies metamorphism. Their study sheds some light onto the formation of "episyenites", which are zones of dissolved crystalline rocks resulting from the flow of fluids. They use a combination of field mapping, microstructure analysis and geochemistry. They show that episyenites form in narrow localized zones, which represent a section of a vertical pipe structure exploiting a portion of the fault network. Successive dissolution of quartz and feldspars accounts for porosity increase up to 35%, followed by the precipitation of multiple minerals including calcite. Isotopic data from the calcite filling of the pores suggest a surficial source of fluids associated with this calcite, in contrast to syn-kinematic fluids, which had a deeper origin. The authors conclude that episyenites mark the transition from diffuse deformation to almost rigid-block behaviour, during progressive exhumation and cooling (at $T < 300\,^{\circ}C$).

3. Fluids in crustal shear zones

Rolland and Rossi (2016) report a study of fluid flow and element transfers in shear zones during a collision burial-exhumation cycle of the Mont Blanc Crystalline Massif (Western Alps). During the underthrusting stage at c. 30 Ma and the subsequent uplift/exhumation stage at 22-11 Ma, mid-crustal shear zones and alpine veins have localized intense fluid flow, which produced substantial changes in mineralogy and whole-rock geochemistry. The variations of whole-rock composition and mineral chemistry in shear zones reflect variations in fluid/rock ratios and fluid chemistry, which have produced specific mineral reactions. The results of the study highlight the presence of an upper-crustal fluid convection cell, with up-going fluids through the lower crust and likely down-going fluids in the 15 km upper crust.

Quilichini et al. (2016) present the study of a large shear zone, the Bitterroot shear zone, with a high strain gradient over ~1 km, which developed as a rolling-hinge detachment system. A syntectonic granodiorite was progressively exhumed in the footwall of the detachment, providing a record of deformation and of fluid-rock interaction during progressive exhumation and cooling. The authors measured the stable isotope composition of crystallizing metamorphic minerals across the shear zone, the hydrogen isotope ratios of hydrous minerals and of quartz fluid inclusions, and estimated the corresponding equilibrium temperatures. These data document, from ductile to brittle, the spatial and temporal record of the interaction between deformation and fluid flow in a crustal-scale detachment. The data record the onset of deformation with magmatic fluids after the emplacement of the granodiorite at 500–600 °C. During stages of mylonitic deformation, the mixing of fluid sources between the magmatic and meteoric reservoirs occurred between 500 and 300 °C.

Siebenaller et al. (2016) document the spatial distribution of multiple fluid inclusion generations relative to microstructures in quartz grains and aggregates from veins sampled in ductilely sheared amphibolite facies metamorphic rocks in the island of Naxos (Greece). The fluid inclusions are hybrid CO_2-H_2O, ranging from CO_2-rich in the most primary fluids to H_2O-rich fluids in the late brittle deformation stages. Microstructural analysis indicates that recrystallization and fluid redistribution are intimately linked at the grain scale through a cycle involving (1) redistribution of fluids caused by recrystallization and grain boundary migration at the scale of quartz veins, (2) accumulation of fluids and build-up of fluid pressure along grain boundaries and within quartz grains. The outcome of the study is that, in the ductile metamorphic crust, fluid redistribution is intimately linked to recrystallization mechanisms allowing for fluid circulation under lithostatic pressure.

4. Fluid flow and deformation in magmatic environments

Japas et al. (2016) investigate epithermal vein systems emplaced in Precambrian – Early Palaeozoic igneous-metamorphic basement, Late Miocene sedimentary rocks and Early Pliocene volcaniclastic rocks in the Cerro Tiporco volcanic field in the Sierras Pampeanas (southern Central Andes). Onyx and aragonite mineralizations fill vertical reverse-sinistral faults as well as nearly horizontal veins that show evidence of crack-seal growth, which suggest opening under low differential stresses and supra-lithostatic fluid pressure, as well as cyclic changes in pore pressure and high mineral-deposition/fracture-opening ratio, in agreement with a fault-valve mechanism. Late aragonite and calcite veins are instead interpreted as reflecting a change in kinematics and indicating the onset of tectonic-load conditions.

Famin et al. (2016) document interaction of magmatism and hydrothermal alteration with deformation localized along a shallow-dipping detachment in a now inactive basaltic volcano (Piton des Neiges, La Réunion Island). The authors combine a structural and a mineralogical and geochemical study of the detachment zone. The detachment is evidenced by hydrothermal alteration in the greenschist facies linked to a brittle-ductile shear deformation at the top of a kilometer-scale plutonic complex. Deformation evolves from cataclastic to mylonitic, and is followed by hydrothermal crystallization and hydrofracturing. In contrast with current models of volcano spreading, the Piton des Neiges volcano did not deform by creep of a large hydrothermal system or a plutonic complex below its solidus. Instead, the interface between the already cooled plutonic complex and the host rock acted as a brittle failure zone and was repeatedly intruded by magma injections, further promoting hydrothermal alteration and low temperature creep in and around the discontinuity. Such magmatism-related weakening might also occur on active volcanoes.

Martínez-Poza and Druguet (2016) investigate the interaction between deformation and dyke emplacement in the SE Sardinia Permian mafic dyke swarm that intruded the Late Variscan granitoids of the Sàrrabus massif. The authors characterize the structure of the dyke swarm in order to assess both the stress state and the tectonic regime at the time of dyking, combining paleostress analysis from Mohr circle construction and estimates of crustal extension from dyke thickness/spacing ratios and of true dilation direction from the matching geometry of offsets. The fracture network of the massif exhibits multiple orientations. Some of the pre-existing joints were exploited by the dykes, while others were reactivated as faults during and after dyke intrusion. Paleostress analysis indicates that intrusion of the dyke swarm occurred during a regional extensional event, under low magma pressure conditions and preferentially into a pre-existing joint network.

5. Partial melting and crustal rheology

Cavalcante et al. (2016) investigate the influence of partial melting and melt migration on the rheology of the continental crust. They focus on two different mid-crustal settings formed during the Brasiliano orogeny: the Carlos Chagas anatexite formed in an orthogonal collision belt and the Espinho Branco anatexite formed in the Patos strike-slip shear zone. Based on the synthesis of previous petrostructural and AMS studies, the authors discuss the rheological implications caused by the accumulation of large volumes of melt “trapped” at mid-crustal levels, and by the efficient melt extraction along steep shear zones. Their results suggest that rocks undergoing partial melting along shear settings exhibit layers with contrasting competence, implying successive periods of weakening and strengthening, while regions where a large amount of magma accumulates lack clear evidence of competence contrast between layers, indicating that they experienced only one major stage of dramatic strength drop. The study also highlights that the middle part of both belts contained large volumes of migmatites, supporting the idea that the orogenic root was partially molten with more than 30% of granitic melt at the time of deformation.

6. Fluids and crustal seismicity

Cheng and Chang (2016) study a seismic cluster that occurred in northern Taiwan just after the 1999 Chi-Chi earthquake. The cluster is distributed nearly along the surface trace of the Lishan Fault, a still active major structural boundary that corresponds to a former normal fault of the Chinese passive margin now inverted with an oblique thrust movement. In order to investigate the possible causes of the seismic cluster and its relationship to the presence of fluids, high-resolution 3D tomographic images of the crust were obtained by inverting a large number of arrival time data of P and S waves. The results show that the Lishan Fault cluster extends down to about 10 km depth and seems to be distributed in or around low Vp, high Vp/Vs zones, which suggests that it may be related to fluid diffusion. The tomographic images demonstrate a series of east dipping, relatively high Vp/Vs anomalies which seem to form a fluid upwelling conduit beneath the Central Range. The authors thus suggest that the Lishan Fault might play the role of an active conduit for fluids originated from the Philippine Sea plate, released along the east-dipping conduit and flowing upward into the upper crust.

Acknowledgements

The Guest Editors would like to thank all the authors for their contributions to this special issue and all the reviewers who have played an important part in maintaining a high level of quality of the manuscripts. Journal Editor-in-Chief Wouter Schellart is warmly thanked for his support.

References

Cavalcante, G.C.G., Viegas, G., Archanjo, C.J., Egydio da Silva, M., 2016. The influence of partial melting and melt migration on the rheology of the continental crust. J. Geodyn. 101, 186–199, http://dx.doi.org/10.1016/j.jog.2016.06.002.

Cheng, W.-B., Chang, C.H., 2016. Tomographic imaging of a seismic cluster in northern Taiwan and its implications for crustal fluid migration. J. Geodyn. 101, 200–214, http://dx.doi.org/10.1016/j.jog.2016.08.002.

Cruset, D., Cantarero, I., Travé, A., Vergés, J., John, C.M., 2016. Crestal graben fluid evolution during growth of the Puig-reig anticline (South Pyrenean fold and thrust belt). J. Geodyn. 101, 30–50, http://dx.doi.org/10.1016/j.jog.2016.05.004.

Famin, V., Berthod, C., Michon, L., Eychenne, J., Brothelande, E., Mahabot, M.-M., Chaput, M., 2016. Localization of magma injections, hydrothermal alteration, and deformation in a volcanic detachment (Piton des Neiges, La Réunion). J. Geodyn. 101, 155–169, http://dx.doi.org/10.1016/j.jog.2016.05.007.

Japas, M.S., Urbina, N.E., Sruoga, P., Garro, J.M., Ibañes, O., 2016. A transient fault-valve mechanism operating in upper crustal level, Sierras Pampeanas, Argentina. J. Geodyn. 1011, 142–154, http://dx.doi.org/10.1016/j.jog.2016.06.004.

Lacombe, O., Tavani, S., Soto, R., 2012. Introduction to the special issue: into the deformation history of folded rocks. Tectonophysics 576–577, 1–3, http://dx.doi.org/10.1016/j.tecto.2012.08.036.

Lacombe, O., Swennen, R., Caracausi, A., 2014. Introduction to the special issue: fluid-rock-tectonics interactions in basins and orogens. Mar. Petrol. Geol. 55, 1–5, http://dx.doi.org/10.1016/j.marpetgeo.2014.03.007.

Martínez-Poza, A.I., Druguet, E., 2016. Structure and tectonic setting of the SE Sardinia mafic dyke swarm. J. Geodyn. 101, 170–185, http://dx.doi.org/10.1016/j.jog.2016.05.012.

Nader, F.H., Champenois, F., Barbier, M., Adelinet, M., Rosenberg, E., Houel, P., Delmas, J., Swennen, R., 2016. Diagenetic effects of compaction on reservoir properties: the case of early callovian Dalle Nacrée formation (Paris basin, France). J. Geodyn. 101, 5–29, http://dx.doi.org/10.1016/j.jog.2016.05.010.

Pennacchioni, G., Ceccato, A., Fioretti, A.M., Mazzoli, C., Zorzi, F., Ferretti, P., 2016. Episyenites in meta-granitoids of the Tauern Window (Eastern Alps): unpredictable? J. Geodyn. 101, 73–87, http://dx.doi.org/10.1016/j.jog.2016.04.001.

Quilichini, A., Siebenaller, L., Teyssier, C., Vennemann, T., 2016. Magmatic and meteoric fluid flow in the Bitterroot extensional detachment shear zone (MT, USA) from ductile to brittle conditions. J. Geodyn. 101, 109–128, http://dx.doi.org/10.1016/j.jog.2016.05.006.

Rolland, Y., Rossi, M., 2016. Two-stage fluid flow and element transfers in shear zones during collision burial-exhumation cycle: insights from the Mont Blanc Crystalline Massif (Western Alps). J. Geodyn. 101, 88–108, http://dx.doi.org/10.1016/j.jog.2016.03.016.

Siebenaller, L., Vanderhaeghe, O., Jessell, M., Boiron, M.-C., Hibsch, C., 2016. Syntectonic fluids redistribution and circulation coupled to quartz recrystallization in the ductile crust (Naxos Island, Cyclades, Greece). J. Geodyn. 101, 129–141, http://dx.doi.org/10.1016/j.jog.2016.07.001.

Verlaguet, A., Brunet, F., Goffé, B., Menut, D., Findling, N., Poinssot, C., Huet, B., 2016. Selective transfer of Li-Al-rich phyllosilicate to metamorphic veins (Western Alps): Laser Induced Breakdown Spectroscopy (LIBS) compositional profiles and microstructural characterization. J. Geodyn. 101, 51–72, http://dx.doi.org/10.1016/j.jog.2016.05.011.

Olivier Lacombe*
Sorbonne Universités, UPMC Univ Paris 06, CNRS, Institut des Sciences de la Terre de Paris (iSTeP), 4 Place Jussieu 75005 Paris, France

Yann Rolland
Université Côte d'Azur, CNRS, OCA, IRD, Géoazur, France

* Corresponding author.
E-mail address: olivier.lacombe@upmc.fr (O. Lacombe)

Available online 24 August 2016