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Editorial

Structural Controls on Basin- and Crustal-Scale Fluid Flow and Resulting Mineral Reactions

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1. Introduction

There has been a significant increase in the scientific interest and number of publications in the field of geofluids during the last two decades. Following its inception in 2001, the success of the journal Geofluids itself [1], as well as that of the Geofluids conference series [2–8], is a clear example of the relevance of this topic in Earth Sciences. It is well known that tectonic structures exert a strong control on flow of different types of geofluids at multiple scales [9–14]. For example, fracture networks typically determine fluid migration in basins and orogens, and crustal fault zones are often primary sites for economic ore mineral deposition [15–19]. Moreover, fluids play a key role in triggering the activation of shear zones and faults in the Earth's crust [20, 21], among many other processes.

Despite the remarkable advances in the study of how rock deformation structures control the flow of geofluids, and therefore how they govern the transport of heat and solutes and resulting mineral reactions in the Earth, there are still many open questions that need to be addressed. The scientific community still debates about what factors control the dynamic behaviour of fluid flow in the Earth's crust (from steady to highly transient systems), the mechanisms that determine the transitions between different fluid flow regimes, what the hydrodynamics of fluid infiltration and mixing are, or the formation and release of overpressure in the form of hydrofractures. Other key aspects that need attention are the analysis of deformation- versus reaction-induced permeability, the role of inherited structures as potential controls on fluid flow and reactions, and in what cases structures can trap fluids or compartmentalize flow systems. In terms of fluid geochemistry, there is ongoing debate on how to successfully characterize the sources and impact of different types of fluids during diagenesis and metamorphism by analyzing their fingerprints in the form of veins, cements and mineralization, and rock alteration products, as well as the chemical and isotopic signatures of all of these. Characterizing pressure (P), volumes of fluids involved (V), their chemical composition (x), temperature (T), and timing (t) is also a challenging but essential task, because they are key parameters for PVXTt-modeling.

This Special Issue is a collection of 16 articles that together provide a significant advance in the study of structural controls on fluid flow and mineral reactions in a wide range of settings, from shallow levels of sedimentary basins to metamorphic basements. These contributions span multiple scales and processes addressing both fundamental and applied scientific questions along the lines stated above. They utilize combinations of state-of-the-art methods, including optical, cathodoluminescence and electronic petrography, geochemical analysis, rock mechanics and petrophysic laboratory experiments, as well as numerical simulations. Most of these contributions are based on field examples, which continue to be fundamental in geology.

This preface summarizes the main contents of the special issue, organized by topic. The description of contributions starts with those addressing crustal-scale processes, followed by studies of relatively shallower fluid flow mechanisms and their consequences. The final subsection summarizes contributions on structural controls on mineral reactions, as well as those evaluating how they impact geothermal reservoir properties.

2. Contents of This Volume

2.1. Structural Controls on Crustal-Scale Fluid Flow. There is clear evidence that fluid flow in the Earth's crust can be localized in space and time. Fluid flow and transport of elements and solutes can be described as a diffusional system when the hydraulic head (or fluid pressure) gradients are low, thus following a Darcian behavior. However, when fluid pressure gradients are high, fluid transport can operate as a pulsating or "ballistic" mechanism, resulting in highly localized fluid flow pulses. Such a ballistic transport mode is activated when diffusion cannot decrease fluid overpressure, thus resulting in fast fluid flow with mobile hydrofractures ascending through the crust. Through novel numerical simulations, de Riese et al. [22] analyze the transition between a diffusive and a ballistic fluid transport system and describe the patterns arising from such bimodal transport mechanisms. Their model combines diffusive transport, with hydrofracture initiation, propagation, and healing. The results reveal that hydrofractures of different sizes, following a power-law distribution, can form when the host rock's permeability is low for a given fluid flux. Such hydrofractures can self-organize in larger scale hydrofractures that are able to quickly ascend through the crust and drain fluids in flow pulses strongly localized in space and time. These results are compared with natural cases to discriminate between systems with abundant hydrofacture networks near the fluid source versus those in which only a few, but large bursts, are able to ascend to shallow levels create structures such as hydrothermal breccias.

The flow of high-temperature fluids in low-permeability crystalline basements of the continental crust has not been systematically investigated to date. Fluids present in such systems tend to be consumed in retrograde metamorphic reactions. To contribute to filling this gap, Dempster et al. [23] study the spatial distribution of greenschist-facies retrograde reaction products in metabasic gneisses from Iona, exposed on the west coast of Scotland. They aim to understand the role of deformation- and reaction-induced permeability as controls on the input of fluids to crystalline basement rocks subjected to high-grade metamorphism. In particular, they carry out a study combining field descriptions and petrographic analysis to decipher the mechanisms controlling the alteration of plagioclase to epidote. They find that two generations of epidote are formed and are related to deformation and fluid flow in cataclasite zones. Contrarily, the replacement of Ca-plagioclase and pyroxene by albite and chlorite in gneisses, which takes place prior to epidotization, is more widespread. Dempster et al. [23] conclude that gneiss retrogression is controlled by reaction-dependent permeability, the reaction kinetics, changes in fluid composition, and transient local migration of fluids related to fault activity, all resulting in complex epidote distribution patterns.

Despite the typical low permeability, absence of fluids and water undersaturation of midcrustal retrograde metamorphic rocks, exhumed faults in such retrograde conditions present signs of weakening mechanisms influenced by fluids. Stenvall et al. [24] analyze the Kuckaus Mylonite Zone in the southern Namibian Namaqua Metamorphic Complex to understand the source and impact of fluids in retrograde faults. This exhumed Mesoproterozoic crustal-scale strike-slip shear zone affected gneisses under retrograde conditions, resulting in hydrated mineral assemblages. Stenvall et al. [24] combine outcrop descriptions, petrographic analyses of rock composition and microstructures, and geochemistry (elemental and oxygen isotope analysis). Their results indicate that some of the fluids involved have a meteoric signature. Despite the inferred low degree of fluid-rock interaction, the presence of water induced weakening and diffusion-precipitation mechanisms, even resulting in grain size sensitive creep in the most deformed (ultramylonite) zones. They also propose that high fluid pressures could only arise after the rocks underwent weakening, and that high fluid pressures are thus not necessary to explain seismic styles of retrograde transform faults that deform by mixed frictional and viscous deformation mechanisms.

Geochemical data, such as stable isotopes, are typically used to unravel fluid transport modes, as well as the fluid sources responsible for rock alteration and mineralization. For example, oxygen and hydrogen isotope ratios from veins and shear zones have been utilized to describe the involvement of meteoric fluids at relatively deep crustal levels. A key question is how and when such fluids infiltrate into the crust. Classical models propose simultaneous downward infiltration of meteoric fluids (i.e., rainwater) into crustal levels as deep as 20 km and upward release of the same fluids, both using large-scale extensional faults and detachments as flow pathways and requiring a hydrostatic fluid pressure gradient. Bons and Gomez-Rivas [25] propose a simple model of fluid and rock pressure equilibration rates to demonstrate that fluids in spherical pores in a quartz ductile rock at temperatures of 250-400°C would quickly physically equilibrate, thus resulting in a partly lithostatic fluid pressure gradient that invalidates simultaneous downward and upward flow models. They propose an alternative explanation for deep meteoric fluid infiltration in which pores within exhumed rocks below an unconformity are first filled with rainwater. Such rocks are buried, while the fluids retain their meteoric signature for tens or hundreds of millions of years if temperatures stay below about 350°. Decompression by extension, rapid exhumation, or fluid heating can release such old fluids that then leave their meteoric signature along their ascent pathways, for example, in veins and altered shear zones.

2.2. Structural Controls on Fluid Flow in the Shallow Crust. Several studies have pointed out the importance of the depositional architecture of sedimentary rocks, as well as rock deformation structures, as fundamental controls on fluid flow. To understand their interplay, Dimmen et al. [26] utilize outcrops in New Zealand, Malta, and Utah (USA) to analyze the distribution of iron oxide precipitates as proxies for paleofluid flow. They also review literature and conclude that fluid flow is mainly controlled by the types of deformation structures (including fractures, joints, faults, and deformation bands), their geometry, their connectivity when they form networks, their kinematics and how they interact and connect with other structures and sedimentary features such as permeable layers, thus forming the so-called hybrid networks. These authors also explain that, on top of geological structures, the depositional architecture, rock properties, and sedimentary structures, such as bedding and lamination, are key controls on fluid flow.

Orogenic zones are areas of preferred fluid flow strongly controlled by deformation structures. As an example, the fluid flow evolution of an exhumed thrust zone of the southern limb of the Sant Corneli-Bóixols anticline in the Southern Pyrenees is examined by Muñoz-López et al. [27]. These authors combine vein orientation data, optical and cathodoluminescence petrography, carbon-oxygen, strontium and clumped isotope data, and elemental analysis to unravel the chronology and fluid signatures of different vein-filling calcites. The results show that the studied thrust fault zone acted as a barrier for fluid flow, compartmentalizing the system in two distinct zones. Fracture formation and sealing were a transient process in the footwall, with calcite veins in this fault block recording a change of fluid source from meteoric to evolved meteoric and with different degrees of fluid-rock interaction. On the contrary, the thrust hanging-wall hosts randomly oriented fractures and breccias sealed by a late calcite cement derived from formation fluids.

Although tectonic plates are normally regarded as rigid plates, intraplate deformation is widespread, with areas far away from plate boundaries undergoing folding, fracturing, and reactivation of faults from previous deformation events. This deformation can potentially result in fluid flow and associated mineralization. In order to better understand the nature, origin, and relative age of intraplate deformation events, Parizot et al. [28] analyze examples of the Grands Causses area in the northern foreland basin of the French Pyrenees. This zone was influenced by different neighboring areas, each with their own tectonic evolution. By carrying out a tectonic analysis combined with geochronology of fault-related calcite cements, they demonstrate how the studied faults record a long deformation history characterized by different events. In particular, the Mesozoic extension spanned events from the Early Jurassic (opening of the Tethys Ocean) to the end of the Early Cretaceous (formation of the extensional basins of the Pyrenees), while compression of the Pyrenean orogeny started in the study area as early as 100 Ma ago and lasted until the late Eocene. This study illustrates how tectonic events mainly happening at plate boundaries can also cause the formation and reactivation of structures in intraplate domains, thus controlling fluid flow.

Fluid overpressure in different geological settings can lead to the formation and propagation of hydrofractures, as well as dilating high-porosity zones. By means of novel numerical simulations, Koehn et al. [29] systematically evaluate the influence of effective stress fields on failure mechanisms, fracture patterns, and fluid drainage. They consider three different scenarios of pressure buildup and hydrofracturing typically encountered in nature, including a sedimentary basin, a vertical zone, and a horizontal layer offset by a fault. Their results indicate that the geometry of the area where fluid pressure builds up exerts a first-order control on the successive porosity changes, fracture formation, and fluid pressure that can be sustained without failure. They describe the formation of hydraulic breccias, subhorizontal fractures, and extensional as well as shear-mode fractures depending on the fluid pressure evolution for the different initial settings. The results by Koehn et al. [29] reveal a complex porosity evolution for the different systems and highlight the importance of knowing the geometry of the geological system (including porous layers, seals and faults) when predictions of overpressure distribution and thus of hydrofracture formation have to be made.

Many types of mineralization require structural traps to constrain migrating fluids and geochemical traps with the right agents to trigger mineral precipitation. Understanding structural traps as fundamental controls on fluid flow and mineralization is thus essential for the exploration for ore, such as uranium deposits. Benedicto et al. [30] study the meso- and deposit-scale structural controls of the unconformity-related uranium mineralization of the Athabasca Basin (Canada). They examine drill core data to identify mesoscale structural traps and to decipher the influence of shear zone reactivation on the mineralisation system. Benedicto et al. [30] identify 3D dilatational jog zones where shear zones bend and change their orientation as well as reactivated conjugated shears. They describe how foliation was opened and then filled with uranium veins parallel or oblique to it. This study emphasizes the importance of understanding the role of inherited ductile fabrics for the onset of brittle structures that control permeability evolution.

Also focusing on a case of inherited ductile structures, Holbek et al. [31] evaluate the structural controls on shallow Cenozoic fluid flow in the Otago Schist of New Zealand, an exhumed Mesozoic accretionary prism. They study hydrothermal systems that caused fluid flow and mineral reactions at shallow depths. Metamorphic ductile fabrics that formed in the Triassic and Jurassic are affected by joints that formed by exhumation during the Cretaceous. They describe how such joints were reactivated as strike-slip fault networks that contain veins and cemented fault breccias both characterized by the precipitation of hydrothermal carbonates, whose temperature is estimated from oxygen isotopes and calcite twin analysis. Their geochemistry reveals variable degrees of interaction between the fluids involved and the host schists, as well as strongly localized fluid flow along joints and faults. They interpret that the vein and breccia mineralizing fluids had a metamorphic source following breakdown reactions. Holbek et al. [31] identify foliation, joints, and fault networks as the main structural controls on fluid flow, which is inferred to have taken place due to compression in the Early Miocene.

Paleokarst structures are main controls on fluid flow in sedimentary basins and can play a key role as petroleum system elements. For example, there are major deep hydrocarbon reservoirs in paleokarst systems of the Tarim Basin (China). Through a study that combines petrography, isotope analyses, and microthermometry, Baqués et al. [32] evaluate the paleofluid systems that caused dissolution and the formation of cavities in the Yijianfang Formation of the Tabei Uplift in the Tarim Basin. They find that dissolution took place in burial conditions and was due to the flow of fluids of various origins during different geological times. They propose that acidic fluids associated with hydrocarbon generation and maturation caused dissolution during the Silurian or the Devonian-Permian. Their results also describe dissolution related to high-temperature fluids derived from igneous activity in the Late Permian and by the flow of formation fluids in the Mesozoic. Baqués et al. [32] identify seven events of fracture formation, dissolution, and cementation. They also discuss the burial origin of the studied paleokarsts, in contrast with the model of near-surface dissolution previously proposed in other studies.

2.3. Structural Controls on Mineral Reactions and Implications for Geothermal Reservoirs. The circulation of fluids in sedimentary basins can result in the formation of diagenetic alterations, such as dolomitization, that change the rock's porosity-permeability and thus the reservoir quality characteristics. Shah et al. [33] investigate how igneous intrusions into basins influence such alterations. By means of a combination of petrography, elemental and stable isotope analysis, and petrophysical characterization, they study the influence of dolerite intrusions on the diagenetic and porosity-permeability evolution of the Devonian Khyber Limestone in NW Pakistan. These authors describe saddle dolomite formation resulting from hydrothermal fluids sourced from the dolerite dykes, whose emplacement caused contact metamorphism and thus limestone to marble transformation. After dyke emplacement, a second dolomite phase formed, followed by meteoric diagenesis characterized by calcitization, dissolution, and calcite cementation. Shah et al. [33] discuss the porosity and permeability evolution during the different diagenetic events of the area.

Although burial normally decreases porosity, sedimentary rocks can undergo dissolution processes at depth, which may lead to an increase of secondary porosity. A detailed petrographic and geochemical study by Laczkó-Dobos et al. [34] of the deeply buried Upper Miocene lacustrine sandstones of the Pannonian Basin (Hungary) allows reconstructing their diagenetic evolution. They analyze core samples from wells located at different positions within the Makó Trough to reconstruct the paragenetic sequence of three formations that include open-water marls and confined and slope-related unconfined turbidites. In the Makó Trough system, the marls are hydrocarbon source rocks and the uppermost turbidites reservoirs, while the lower (confined) turbidites have no reservoir potential. Laczkó-Dobos et al. [34] describe how strong compaction, cementation, and mineral precipitation preceded hydrocarbon migration, while secondary porosity by dissolution developed under burial conditions during late diagenesis due to the circulation of external fluids in an open system. The authors also discuss a hydrogeological model involving basement blocks and basin deposits.

Also focusing on the Pannonian Basin, Fintor and Varga [35] propose new paleogeographic reconstructions of Variscan basement blocks based on the fingerprints (veins and their fluid inclusions) of paleohydrological systems of the Tisia terrane. Their study of veins, dominated by quartz and carbonate minerals, and their host rock alterations, reveals three stages of fluid flow and mineral reactions. By reconstructing the paleofluid flow evolution of the area, Fintor and Varga [35] conclude that the systems of the Hungarian part of the West Tisia area match the characteristic hydrothermal events of the Central European Variscan belt. They propose that this system belonged to the Bohemian Massif until the onset of the Alpine orogeny, and that its Late Paleozoic position was north of the Moravo-Silesian Zone. Their study is an excellent example of the use of veins and rock alterations to reconstruct the geological evolution of an area.

Heat and mass transfer due to fluid convection are typical for hydrothermal and geothermal systems in volcanic provinces. The fast-cooling rates and high pressure in subaqueous or subglacial volcanic environments in high latitudes enhance quench-induced fragmentation which, during basaltic eruptions, results in the formation of hyaloclastites. Hyaloclastites, which are formed by angular glass fragments, are often highly porous and permeable and thus considered as good reservoir rocks for aquifers and geothermal energy systems. However, hyaloclastic glass can be easily altered to clay minerals and zeolite. This, together with other alteration processes and compaction, as well as precipitation of other mineral phases, results in changes in their mechanical properties and porosity and permeability distribution. Eggertsson et al. [36] examine the effects of compaction on the petrophysical and mechanical evolution of hyaloclastites from an active geothermal system of the Krafla volcano in northeast Iceland. They compare experimental results of yield points and porosity and permeability evolution of hyaloclastite samples collected from the surface with those from subsurface drill core. The results show that subsurface samples display higher strengths due to their lower porosity and permeability. Eggertsson et al. [36] conclude that burial-induced compaction cannot alone account for the physical and mechanical properties of hyaloclastites of the Krafla volcano subsurface geothermal reservoir. By examining samples with optical and electron microscopy, they suggest that pore networks were modified by mineral precipitation and alteration associated with the flow of high-temperature fluids, resulting in rock strengthening. Their study reveals how important it is to understand the interplay between mechanical and mineral processes for the prediction of such type of geothermal reservoir.

Weaver et al. [37] also study hyaloclastite behavior in geothermal systems, focusing on how phyllosilicate reactions influence reservoir porosity and permeability as well as mechanical properties. Through a combination of petrographic, mineralogical and rock-mechanics analyses, they also study examples from the Krafla volcanic system to understand dehydration reactions of the clay-dominated hyaloclastite matrix (termed palagonite), which can potentially affect the geothermal reservoir properties. The results show that smectite dehydration reactions, which cause mass loss and contraction, take place at temperatures that are common in geothermal systems. This implies a positive relationship between temperature and porosity as well as permeability, meaning that thermal treatment at high temperature (600°C in their case study) results in an improvement of the flow properties of the reservoir. This study also shows how brittle failure of hyaloclastites depends on porosity and, accordingly, affects the geothermal reservoir behavior. Weaver et al. [37] compare their experimental analysis with subsurface hyaloclastite samples to evaluate how temperature changes impact mechanical properties and thus fluid flow properties.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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