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Editorial The role of fluids in the lower crust and upper mantle: A tribute to Jacques Touret

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1. Introduction

This special issue of Geoscience Frontiers is a tribute volume honoring the life and career of Jacques Touret. A set of research papers has been assembled, which broadly reflect his research interests over his 50 plus year career. These papers focus on the role that fluids play during the formation and evolution of the Earth's crust. Below I provide a brief summary of the life of Jacques Touret, along with a select bibliography of his more important papers. This is then followed by a brief introduction to the papers assembled for this special issue.

2. Life and career of Jacques Touret

Jacques Léon Robert Touret (Fig. 1) was born on January 2, 1936 in Fumay (Ardennes, France), which is located very close to the Belgian border. His parents were both school teachers in Fumay. From 1938 on until the end of their careers in the 1960's, they were school teachers in the small village of Eteignières near Rocroi and the Belgian border, which is in the core of the Ardennes massif.

At the beginning of the second world war (1940), his mother, with Jacques and his sister, fled from the German armies to find a refuge with other family members living in the south of France, near the Pyrenées. His father, then a soldier in the French army, was able to make his way through German lines and rejoin them. Both his parents resumed their work as school teachers in Quillan and Esperaza. In 1943, the whole family, now with 4 children, returned to the Ardennes in the German occupied zone. Despite occasional crises (Eteignières is about 40 km away from Bastogne), life was almost normal with his primary education being provided for by his parents. His secondary education was completed at the Lycée Chanzy, Charleville, Ardennes where he had extremely good and dedicated teachers, eager to reconstruct their country after the war.

In 1953 he earned a Baccalauréat (Mathematiques Elementaires) with honors, which allowed him to enter university. From 1953 to 1955 he attend Classes Préparatoires (Preparatory Classes) for the

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INA (Institut National Agronomique, Paris) and ENSG (Ecole Nationale Supérieure de Géologie, Nancy). In June 1955 he passed the competitive entrance examination for both institutions and chose the ENSG, opting for Geology instead of Agronomy. From 1955 to 1958 he studied engineering at the ENSG and University of Nancy, which were integrated at this time. He graduated with a Diploms 'Ingénieur Géologue' and 'Licencié es Sciences', which is roughly equivalent to a Masters degree.

From 1959 to 1962 he engaged in postgraduate studies and was a tenured lecturer (somewhat lower in grade than an assistant professor) at the ENSG. While teaching at the ENSG (mainly petrology, but occasionally other courses, including stratigraphy, paleontology, and engineering geology), he began his Ph.D. thesis (Thèse d'Etat) focusing on the geology, petrology, and geochemistry of the Bamble sector, southern Norway, under the direction of both Prof. Marcel Roubault, director of the ENSG, whom was the formal supervisor of the Ph.D. thesis, and Prof. Tom F.W. Barth, Mineralogisk Geologisk Museum, Oslo, whom was effectively the actual supervisor. From 1963 to 1964 he performed his military service in the Air Force corps of engineers (Génie de l'Air) as a lieutenant and then a Captain. This was the only time during his entire career in which he could make some use of his training as an Ingénieur Géologue. A retrospective of his early career, including his postgraduate education and subsequent Ph.D. work in the Bamble sector, southern Norway, is contained in the second paper of this volume (Touret, 2014).

From 1965 to 1969 he was an assistant professor at the ENSG, until the defense of his thesis in January of 1969. It was at this time that he started a long period of collaboration with two other former ENSG students, Bernard Poty and Alain Weisbrod (see Touret, 2014). From 1969 to 1972 he was an assistant, then associate professor (Professeur sans chaire) at the University of Nancy (now Université Henri Poincaré), which at this time had just separated from the ENSG. Here he was an associate professor of structural geology, since the professorship for petrology was occupied by an older colleague, G. Rocci. Being a professor of structural geology was a good experience in that it proved very helpful in the study of fluid inclusions with respect to understanding micro-cracks. The focus of his research was still mainly on the Bamble sector in Norway, where he had contact with other teams also working there. Besides Norwegian colleagues, (e.g. Tom Andersen, Sven Dahlgren, Per Hagelia, Olav Albert Christophersen), these included D. Field and Ian Starmer from the United Kingdom, J. Michot and J.C. Duchesne from Belgium, and especially A. Tobi, H. Zwart, Olav Schuiling, Timo Nijland, and Cees Maijer, amongst many others, from the Netherlands.

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Figure 1. Jacques Touret.

From 1972 to 1980 he was an associate professor of mineralogy and petrology at the University of Paris 7 (now Université Denis Diderot), which had just separated from the other Paris university, i.e. the Sorbonne = Paris 6 (now Université Pierre and Marie Curie), in a department which at that time was headed by Claude Allègre. For a variety of reasons he established his research lab at the Museum d'Histoire Naturelle, headed then by Jacques Fabriès. From the start of his tenure here, his research was centered on fluids in granulites, including not only examples from Norway, but also from Africa (the Sahara) and Madagascar, which were places where J. Fabriès and his team were then working. There was also an outstanding sample collection from both regions at the Museum.

From 1980 to 2001, until compulsory retirement at the age of 65, he was a full professor of mineralogy, petrology, and ore geology at the Vrije Universiteit, Amsterdam, the Netherlands (VUA). The 1980s was a period of great development for Dutch universities. At that time he benefited from the outstanding facilities, which allowed him to develop a lab specifically oriented towards the study of fluid inclusions in rocks, utilizing all the possible instruments then available, e.g. the first commercially available and specially dedicated Raman microspectrometer, low and high temperature freezing-heating stages, the scanning electron microscope, the electron microprobe, stable isotopes, etc. These instruments were conveniently located in rooms adjacent to his own lab. Thanks to the outstanding supporting staff (E.A.J. Burke for Raman and W. Lustenhouwer for other analytical instruments), his lab was visited for shorter or longer periods by virtually all people who were at that time studying fluid inclusions in rocks. This included a series of research projects in Sweden and Finland in addition to cooperative programs in Botswana, Zimbabwe, and later South Africa. He continued to be personally interested in southern Norway, but his work there on the Bamble sector was continued at Utrecht University by A.C. Tobi and C. Maijer, and currently is being continued by Timo Nijland (Nijland et al., 2014), Ane Engvik (Engvik et al., 2014), and Håkon Austrheim, amongst others.

From 2001 to the present day, he first found a place at the Musée de Mineralogie of the Ecole des Mines (Paris), where his wife has been curator since 1990. Unfortunately he had no access to research facilities. He continued to be interested in granulite-facies fluids, working only on the material that he had accumulated while in Amsterdam. He concentrated on this field until about 2005 at which point he became aware of the extensive work on mineral solubility's in brines at granulite-facies P-T being done by Robert Newton in the lab of Craig Manning at UCLA as well as the extensive work of former students such as Jan Marten Huizenga (Huizenga et al., 2014), Maria Luce Frezzotti (Frezzotti and Touret, 2014), and Alfons M. van den Kerkhof (van den Kerkhof et al., 2014) and others on the role of fluids during dehydration of the deep crust as well as mass transfer in the deep crust. He currently has a volunteer position at the University of Paris (Université Pierre et Marie Curie - Paris 6), which has once again given him access to research facilities. A select bibliography taken from the complete publications of Jacques Touret is given below.

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3. Fluids, fluid inclusions, and the role of fluids in the mid to lower crust and upper mantle

The first paper in this volume, by Jacques Touret (Touret, 2014), is an autobiographical retrospective of his education and the first half of his career covering his introduction to and extensive investigations of the Bamble sector with regard to its geology, petrology, and fluid inclusions; all of which contributed to his ideas regarding the role of fluids in granulite-facies metamorphism.

The second paper in this volume, by Timo Nijland, Daniel Harlov, and Tom Andersen (Nijland et al., 2014), reviews the extensive literature associated with the well-studied Bamble sector located along the southeastern Skaggark coast of Norway. The Bamble sector consists of a Proterozoic amphibolite- to granulite-facies transition zone, which is characterized by a well-developed isograd sequence, with isolated 'granulite-facies islands' in the amphibolite-facies portion of the transition zone. The granulite-facies rocks are characterized by CO₂-dominated fluid inclusions, which helped to trigger a lengthy discussion concerning the role of carbonic fluids during granulite genesis. The aim of this review is to provide an overview of the current state of knowledge of the Bamble sector, with an emphasis on the Arendal-Froland-Nelaug-Tvedestrand area and off shore islands (most prominantly Tromøy and Hisøy) where the transtion zone is best developed. After a brief overview of the history of geological research and mining in the area, aspects of sedimentary, metamorphic and magmatic petrology of the Bamble sector are discussed, including the role of fluids. Issues relevant to current geotectonic models for SW Scandinavia, directly related to the Bamble sector, are discussed at the end of the review.

The third paper, by Ane Engvik, Peter Ihlen, and Håkon Austrheim (Engvik et al., 2014), focuses on the role of regional albitisation (NaCl-metasomatism) in the Precambrian crust of southern Norway. Albitisation is particularly widespread in the Bamble sector, the Kongsberg-Modum sector, and the Norwegian part of the Mylonite Zone. Sites of albitisation outside these belts are associated with hydrothermal breccia pipes and fracture-bound alteration. The albitites are composed of near end-member sodic plagioclase (An₀₋₅, Ab₉₄₋₉₉) with minor carbonate (calcite and dolomite), rutile, clinopyroxene (En₃₀, Fs₂₁₋₂₃, Wo₄₇₋₄₉), amphibole (edenite-pargasite), quartz, titanite, tourmaline, epidote (Fe³⁺ = 0.20-0.85 a.p.f.u.), and chlorite (Mg[#] = 0.81-0.89). One focus of the paper is the albitites from the Kragerø area. These

are described as megascale clinopyroxene-titanite-bearing albitite, and also occur as albitisation along veining, as breccias, albitic felsites, and albite-carbonate deposits. The strong fluid control on their formation is characterized by veining and mineral replacement reactions. Mass balance calculations suggest that fluid transport was by a H₂O-CO₂ fluid rich in Na, which also acted to transport Fe and Mg away. Mineralogical replacement reactions on the regional scale indicate a relationship between metasomatic processes and the formation of apatite and rutile deposits and related Fe ores deposits. The albitites are spatially associated with the scapolitised metagabbros, as well as with Mg-Al-rich rocks such as orthoamphibole-cordierite schists. In addition, albitisation can be shown to have caused deformation in the form of brecciation and progressive ductile deformation resulting in foliated albitic felsites.

In the fourth paper by Jan Marten Huizenga, Dirk Van Reenen, and Jacques Touret (Huizenga et al., 2014), evidence for fluid infiltration, during retrogression of granulites located in the southern marginal zone of the Limpopo Belt, South Africa, is seen in the form of hydration reactions, shear zone hosted metasomatism, and lode gold mineralization. Hydration reactions include the breakdown of cordierite and orthopyroxene to gedrite + kyanite, and anthophyllite, respectively. Metamorphic petrology, fluid inclusions, and field data indicate that a low H₂O-activity carbonsaturated CO₂-rich and a saline aqueous fluid infiltrated the southern marginal zone during exhumation. The formation of anthophyllite, after orthopyroxene, established a regional retrograde anthophyllite-in isograd and occurred at P-T conditions of ~6 kbar and 610 °C, which fixes the minimum mole fraction of H_2O in the CO₂-rich fluid phase at ~0.1. The maximum H_2O mole fraction is fixed by the lower temperature limit (~800 °C) for partial melting at ~ 0.3 . C-O-H fluid calculations show that the CO₂rich fluid had an oxygen fugacity that was 0.6 log₁₀ units higher than that of the fayalite-magnetite-quartz buffer and that the $CO_2/(CO_2 + CH_4)$ mole ratio of this fluid was 1. The presence of dominant low density CO2-rich fluid inclusions in the hydrated granulites indicates that the fluid pressure was less than the lithostatic pressure. This can be explained by strike slip faulting and/or by an increase of the rock permeability caused by hydration reactions.

In the fifth paper by Alfons van den Kerkhof, Andreas Kronz, and Klaus Simon (van den Kerkhof et al., 2014), a comprehensive survey is made of the study of fluid inclusions in high-grade rocks. Study of these fluid inclusions is especially challenging as the host minerals have been normally subjected to deformation, recrystallization and fluid-rock interaction such that primary fluid inclusions, formed at the peak of metamorphism, typically are rare. The large majority of fluid inclusions found in metamorphic minerals have generally been modified during uplift. These later-stage processes can strongly disguise the characteristics of the "original" peak metamorphic fluid. A detailed microstructural analysis of the host minerals, notably quartz, is therefore indispensable for a proper interpretation of the fluid inclusions. Cathodoluminescence (CL) techniques combined with trace element analysis of quartz utilizing electron probe microanalysis and laser ablation ion coupled mass spectrometry have been shown to be very helpful in deciphering the rock-fluid evolution. Whereas high-grade metamorphic quartz may have relatively high contents of trace elements like Ti and Al, low-temperature re-equilibrated quartz typically shows reduced trace element concentrations. The resulting microstructures in CL can be basically distinguished by diffusion patterns (along micro-fractures and grain boundaries), and secondary quartz formed by dissolution-precipitation. Most of these textures formed by retrograde fluid-controlled processes between ca. 220 and 500 °C, i.e. the range of semi-brittle deformation

(greenschist-facies) and can be correlated with the fluid inclusions. In this way modified and re-trapped fluids can be identified, even when there are no optical features observed under the microscope.

In the sixth paper of this volume, Maria-Luce Frezzotti and Jacques Touret (Frezzotti and Touret, 2014) make a comprehensive survey of fluid inclusions from ultramafic xenoliths. Information gleaned from these fluid inclusions provides a framework for interpreting the chemistry of fluids in the upper mantle in different geodynamic settings. They show that at depths of <80–100 km, the dominant fluid phase is $CO_2 \pm$ brines. With rising pressure the dominant fluid changes to carbonate melts. Solutes in the brines are chlorides, silica, and alkalis. In CO_2 -brine fluids, the fluid inclusion data suggest intermediate properties between a carbonate silicate hydrous melt and a fluid. Deep Earth degassing liberates fluxes of mantle-derived $CO_2 \pm$ brines, which, after a complex history, may eventually reach upper crustal levels, including the atmosphere.

The seventh paper, by Oleg Safonov and Leonid Aranovich (Safonov and Aranovich, 2014), surveys petrologic observations of reaction textures from high-grade rocks that suggest the passage of fluids with variable alkali activities. Development of these reaction textures is accompanied by regular compositional variations in the plagioclase, pyroxenes, biotite, amphibole, and garnet. The textures are interpreted in terms of exchange and net-transfer reactions controlled by the K and Na activities in the fluids. On the regional scale, these reactions operate in granitised, charnockitised, and syenitised shear zones within high-grade complexes. Thermodynamic calculations for simple chemical systems show that changes in mineral assemblages, including the transition from a hydrous to anhydrous state, may occur at constant pressure and temperature due only to variations in the water and the alkali activities. A simple procedure for estimating the activity of the two major alkali oxides, K₂O and Na₂O, is implemented utilizing the TWQ software. Examples of such calculations are presented for welldocumented dehydration zones from South Africa, southern India, and Sri Lanka. These calculations reveal that there are two endmember alkalis regimes during specific metamorphic processes: (1) rock buffered, which is characteristic for precursor rocks containing two feldspars, and (2) fluid-buffered for precursor rocks without K-feldspar. Reaction textures observed in nature and the results from thermodynamic modeling are then compared with results available from experimental studies on the interaction of alkali chloride and carbonate-bearing fluids with metamorphic rocks under mid-crustal P-T conditions. These experiments demonstrate the complex effect of alkali activities in the fluid phase on the mineral assemblages. Both the thermodynamic calculations and the experiments closely reproduce paragenetic relations theoretically predicted by D.S. Korzhinskii in the 1940's.

The eighth paper, by Michel Cuney and Pierre Barbey (Cuney and Barbey, 2014), focuses on the behavior of LIL and rare metals during granulite-facies metamorphism of metasedimentary rocks and/or granitoids and the role that infiltrating carbonic fluids play during the conversion of hydrated minerals, such as biotite and muscovite, to orthopyroxene, clinopyroxene, and aluminosilicates. This leads to the liberation of aqueous fluids strongly enriched in F, Cl, LIL, and rare metals (e.g., Sn, W, Rb, Li, U, Th, Ta, Nb, etc.), formerly hosted by biotite and muscovite and accessory minerals such as apatite, monazite, and zircon. One typical case study of this type of depletion includes granulite-facies metasediments located in Lapland, northern Finland. Here, fluids, liberated during granulite-facies metamorphism, were the source of the extreme enrichment in U, Th, and other incompatible elements seen in related granites at shallower crustal levels. A second example is the metasomatised marble layers from the Tranomaro area, southwest Madagascar, which were recrystallized under

granulite-facies conditions and where all the hydroxyl-bearing minerals are nearly saturated by F. They represent a demonstrative example of fluid transfer from granulite-facies supracrustals to traps represented by skarns, which developed on the regional scale. It is also proposed that these halogen-rich fluids may be responsible for the incompatible element enrichment detected in leucosomes in anatectic domains located above the granulite-facies domains, as seen in the St Malo migmatites, Brittany, France and migmatites from the Black Hills, South Dakota, USA. A potential association between the enrichment of incompatible elements in granitic melts and granulite-facies rocks is seen in the northern Massif Central, France. Here, late Variscan granulite-facies metamorphism of the lower crust, induced by a thermal anomaly created by the post-orogenic delamination of the lithospheric mantle, coincides with the emplacement of strongly peraluminous and high phosphorus rare metal granites, pegmatites, and rhyolites at shallow crustal levels. Uranium- and F-enriched, fine-grained granites, intrusive within the large peraluminous leucogranitic complex of St Sylvestre, were emplaced along an 8 km long shear zone active during granite emplacement. It is proposed that such crustal scale shear zones control: (i) granulite-facies metamorphism dominated by a carbonic wave through a deep segment of the continental crust; (ii) the percolation of fluids enriched in F, LIL, and Rare Metals primarily released during the breakdown of biotite; (iii) enhanced partial melting by F-rich fluids at intermediate crustal levels resulting in the generation of granitic melts enriched in F, LIL, and Rare Metals; (iv) the transfer of these melts through the crust through protracted fractionation, which was facilitated by their low viscosity due to high F and Li contents; and finally (v) the emplacement of these melts as rare metal granites or pegmatites at shallow crustal levels.

Lastly, the ninth paper in this volume, by Bin Fu and Jacques Touret (Fu and Touret, 2014), surveys the fluid-aided mobility of Au along quartz-carbonate megashear zones. At peak granulitefacies metamorphic conditions, the lower continental crust is generally thought to be permeated by high-density CO₂ fluids and/or brines. During both peak and post-peak metamorphism, these fluids are expelled, except for those, which remain in fluid inclusions. During fluid expulsion, two major processes are involved: (1) during peak metamorphic conditions, granitoid magmas are formed, migrate upwards, and are crystallized as shallow intrusions in the upper crust (mineralized porphyry types); and (2) during rapid decompression, which almost systematically follows a period of post-peak isobaric cooling, especially for ultrahigh-temperature granulites (anticlockwise P-T paths), quartz – carbonate megashear zones are caused by repeated periods of seismic activity. Seismic activity may continue till all free fluids have disappeared, resulting in the ultramylonites and pseudotachylites that are found in many granulite domes. A majority of vein-type Au deposits worldwide occurs in the above-mentioned settings or nearby. This suggests that the Au was scavenged by fluids originating during granulitefacies metamorphism, and then was redistributed and concentrated in veins associated with these settings.

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Daniel Harlov

GeoForschungsZentrum Potsdam, Telegrafenberg, D-14473 Potsdam, Germany

Department of Geology, University of Johannesburg P.O. Box 524, Auckland Park, 2006, South Africa E-mail address: dharlov@gfz-potsdam.de

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