

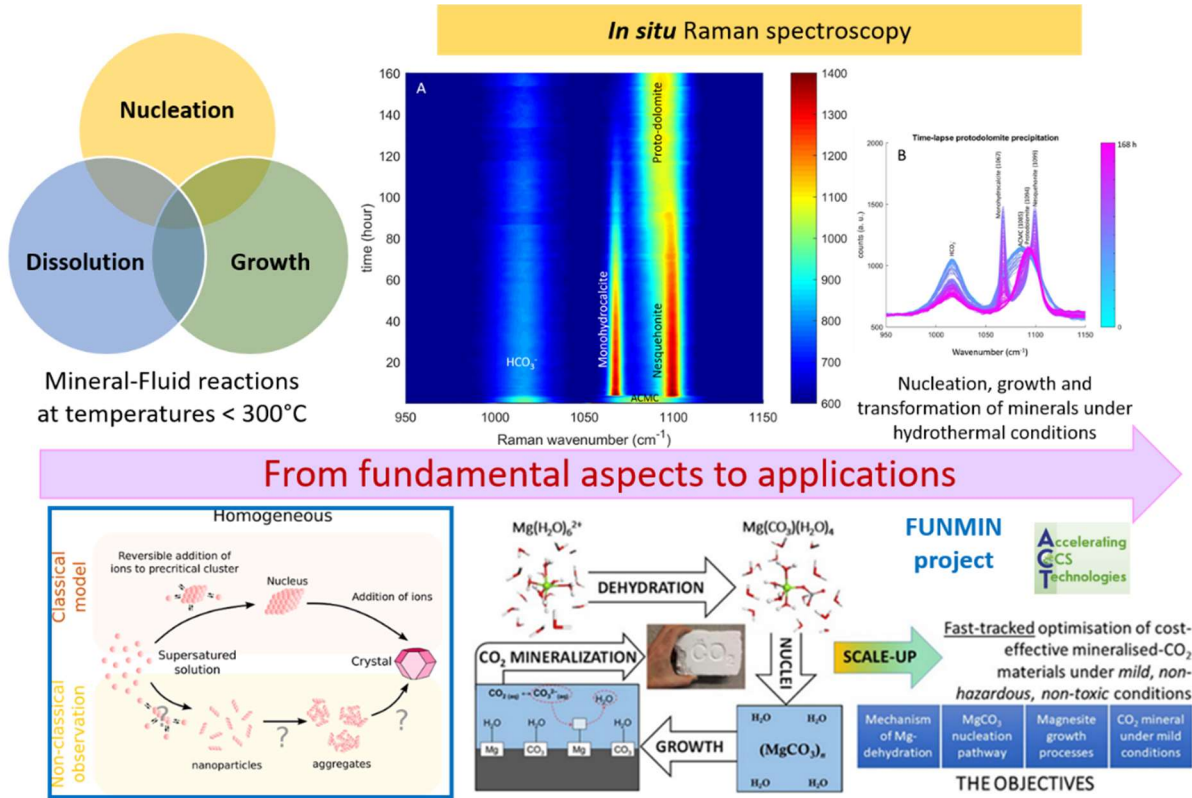
Nucleation, growth and transformation of mineral phases under mild and hydrothermal conditions – from fundamental to applied concepts

Executive Summary of Research Outlook and strategy for next five years

My **NAISSANCE** program will develop new understanding and technologies to progress on the nucleation, growth and transformation of mineral phases widely used in the modern world such as carbonates, phosphates, iron oxyhydr(oxides), sulphates, serpentines and clays. All these minerals play also a crucial role in the global cycle of major and trace elements (including the so-called strategic elements) in the Earth and other telluric planets. In general, these secondary minerals are formed by aqueous alteration of primary minerals such as anhydrous silicates contained in rocks (e.g., peridotites, basalts, granites....) but their formation conditions are frequently ambiguous (e.g., serpentines and clays), poorly known (e.g., carbonates enriched with Earth rare elements, bastnäsite) or enigmatic (e.g., dolomite). In this perspective, the experimental tracking on the nucleation, growth and transformation of strategic minerals under mild and hydrothermal conditions remains a crucial challenge in Geosciences. **NAISSANCE** research program will be then consecrated to design and develop independent but complementary experimental setups to simulate a diversified panel of mineral-fluid reactions in the continuity of my current projects and then to provide insights on the following questions: (1) What is the reactivity of CO₂ during hydrothermal alteration of ultrabasic minerals? (2) What are the roles of amorphous and crystalline transient phases during the formation of minerals? and (3) What is the role of water dynamic in unsaturated gas-solid systems at low T (<0°C) and high T (>100°C)? In this general context, my **NAISSANCE** program searches to provide new insights on the carbonation and serpentinization processes with relevance in hydrothermal systems as well as CO₂ capture, utilisation and storage (CCUS), mineral processing and hydrogen production from hydrothermal mineral alteration. For example, experimental and theoretical studies over the last decade have provided evidence for the existence of multi-step nucleation pathways and aggregation processes that take place during the early stages of mineral formation. These multi-step pathways contrast with the over-simplified traditional view described by the classical nucleation theory (CNT); based exclusively on the nucleation from oversaturated systems and behaviour of size of nucleated particles. Experimental tracking of these pathways by *in situ* Raman spectroscopy in real time, which is challenging because of the small size – in the nm range – and short lifetimes of some of the precursors and/or transient phases, will be the core of my research activities in the coming years, as summarized in the graphical abstract below.

The **NAISSANCE** program and strategy for the next five years is in line with the various topics existing at the ISTerre that concerns mainly the geochemistry and mineralogy teams and the cross-disciplinary axis on the energy transition. Moreover, my leadership in various management and scientific tasks in geochemistry team (as scientific supervisor from 2017 to 2019), in ANR coro (2012-2015), three PhD French thesis (2011-2019), FUNMIN (European collaborative project from 2019 to 2023), CEMENTO project (PEPS-CNRS 2023) and various graduated/ungraduated students (M2, M1, DUT, BUT, L2) have strongly contributed to my current perspective on the nucleation, growth and transformation of minerals. In this way, I aim to build a cross-disciplinary research group at ISTerre, with strong national and international collaborations as implemented from my arrival to Grenoble in 2006, working on the nucleation

and growth processes of minerals and crystalline particles under mild and hydrothermal conditions; and processes preferentially monitored in real time by Raman spectroscopy and/or imagery (optical and atomic force microscopy). Obviously, the mass balance simulation by a classical nucleation approach and the molecular dynamics (MD) simulations are not excluded in the present program.



Graphical abstract of *NAISSANCE* summarizing the chemical processes to be investigated under mild and hydrothermal conditions, with fundamental relevance on the classical and non-classical nucleation of crystals, and the application to magnesite synthesis concerning the carbon capture, utilisation and storage (CCUS). Strategically, I note that the research on the nucleation of minerals or crystal phases needs the monitoring in real-time; in this research program the Raman spectroscopy is suggested as a powerful technique (see below), but this program is open to other real-time techniques and also open to numerical simulations (preferentially in collaboration).

I. Context and positioning

Physicochemical reactions at the solid-fluid interfaces play a crucial role in the global cycle of major and trace elements in the Earth and other telluric planets. Thus, chemical weathering at the Earth's surface, metamorphic reactions in the continental and oceanic crusts, diagenetic reactions in sedimentary basins, hydrothermalism in oceanic ridge and continental crust, and crystal-melt reactions in magmas are critical processes that control the evolution of the Earth and shape its surface and sub-surface. However, many physicochemical and microtextural aspects of these so-called rock-fluid interactions are still poorly understood. Experimental and numerical modelling studies of these interactions are fundamental to understand and predict the fate and transport of chemical elements in natural and engineered geo-environments. The chemical form and the speciation of these elements control their chemical reactivity. In this general picture, I am convinced that the nucleation, growth and dissolution of minerals are among the most fundamental global Earth processes in the first deep-kms, including the so-called critical zone, several natural and/or engineered fluid storage systems and formation of mineral deposits in hydrothermal fields (1-12). In these aqueous media, numerous experimental and theoretical studies in the past two decades have provided evidence for the existence of multi-step nucleation pathways and aggregation processes that take place during the early stages of mineral formation. These multi-step pathways contrast with the over-simplified traditional models described by the classical mineral nucleation theory, i.e. nucleation of seed entities (clusters or nuclei of nanometric size) followed by crystal growth via ion-by-ion or molecule-by-molecule (unit formula) attachment to existing nuclei (formalism exclusively based on the size notion). Herein, *real-time monitoring* of nucleation, growth and transformation of amorphous and/or crystalline particles with microscopic, spectroscopic, chromatographic, thermogravimetric or diffractometric analytic methods, and complementary, or independent, numerical simulations are being developed and are crucial to improve our understanding on these interfacial processes (13-20). In this way, **NAISSANCE** outlook and strategy will focus on the formation of minerals under mild and hydrothermal conditions. All envisaged scenarios with relevance on the functioning of current hydrothermal settings as well as on the mineral processing for societal applications, including carbonates, phosphates, sulphates, serpentines, clays, iron oxides and organo-mineral composites. Because several outstanding questions remain unsolved. The **NAISSANCE** relies on the conviction that the development of novel experimental setups is critical to unlock these questions. Particularly, the nucleation of minerals in aqueous media is affected by a large set of parameters that are often difficult to study under *in situ* conditions such as i) the multi- and inter-dependency of nucleation-growth processes, ii) the nanometer size of interacting and nucleating particles, iii) the elevated particle-number concentration, iv) the high pressure-temperature-concentration conditions, v) the overlap between nucleation and growth processes, and vi) the role of precursors. The novel experimental program proposed in **NAISSANCE** will overcome several of these difficulties. For example, the so-called non-classical crystallization pathway has been proposed to explain the nucleation of precursors (e.g. formation of stable clusters < 3nm) and the role of transient phases that can reduce significantly the interfacial energy during nucleation and growth processes of several minerals in aqueous solutions. The understanding of the kinetics and thermodynamic parameters governing non-classical crystallization pathway is still in its infancy and many reaction mechanisms and particle-aggregation-transformation processes remain enigmatic (21-26). In **NAISSANCE**, I propose to design and develop three experimental setups, two coupled to Raman spectroscopy and pH detection (HP \leq 200bar and HT \leq 300°C) and

one coupled to infrared spectroscopy ($0.005\text{bar} < LP < 2\text{bar}$ and $-120^\circ\text{C} < T < 100^\circ\text{C}$) to overcome existing experimental limitations and progress on the above-mentioned knowledge gaps. I will also use the produced data to incorporate the existence of amorphous and transient mineral phases in existing thermodynamic and kinetics models.

II. Objectives and strategy

The NAISSANCE program will focus on the time-resolved *in situ* measurements of the nucleation, growth and transformation of mineral phases under mild and hydrothermal conditions such as carbonates, phosphates, iron oxyhydr(oxides), sulphates, serpentines, clays and organo-mineral composites. Here, the monitoring in real-time by using adapted techniques will be a crucial tool to obtain realistic and reproducible insights on the nucleation of minerals and crystals. In the last decade various experimental analytical techniques have been developed as summarized in Figure 1, but, other continue to be developed.

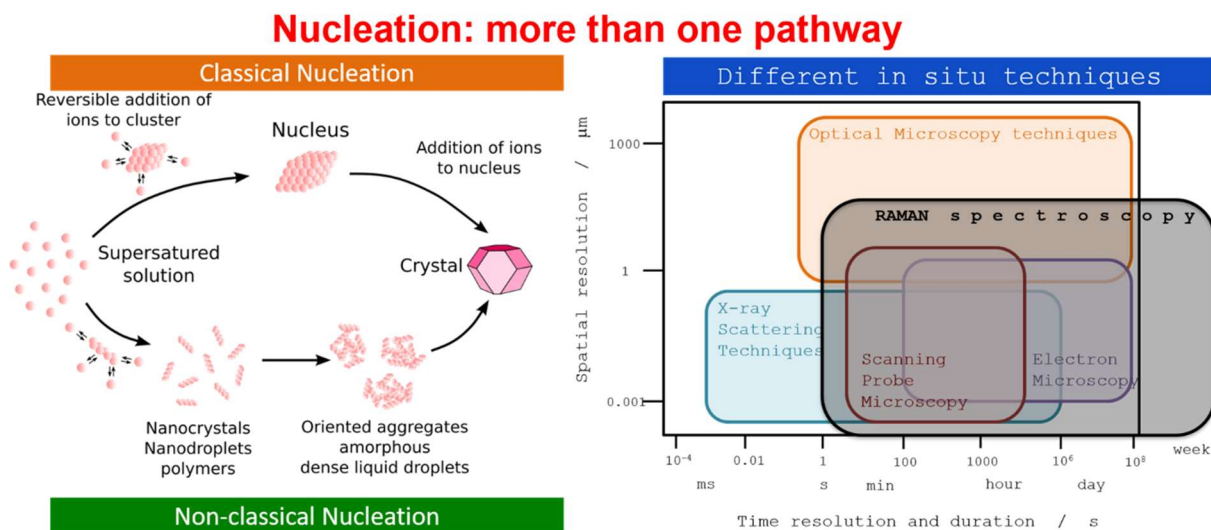


Figure 1. Schematic description of classical and non-classical nucleation of a given crystal from a supersaturated solution (left part). Summary of more relevant analytical techniques used to monitor in real-time the nucleation of crystals (right part).

In NAISSANCE, I will design and develop three independent but complementary experimental setups, linked to thermodynamic and kinetics modelling, to simulate a diversified panel of mineral-fluid reactions and to answer the following scientific questions:

(1) What is the reactivity of CO_2 during hydrothermal alteration of ultrabasic minerals?

The impact of CO_2 on hydrothermal alteration of ultrabasic rocks and model minerals will be investigated using high-pressure vessels (9). Such experiments will be then supplemented with a reactor under high P-T conditions coupled to *in situ* Raman spectroscopy (optical fiber probe immersed in reacting slurry). Time-resolved measurements of carbonate species, mineral composition of nucleating particles (carbonate, iron oxides, serpentines, clays...) and *in situ* produced gases (H_2 , CO , CH_4 , methanol, etc.) will be acquired by Raman spectroscopy. Ca-Mg-Fe-rich carbonates (including dissolved species), iron oxyhydroxides and many other minerals have been studied by my group. I have developed a custom-built experimental setup

using an infrared laser (875 nm) coupled to a Raman spectrometer (19). For example, currently the nucleation of Fe-magnesite under mild and hydrothermal conditions from indirect mineralization of peridotite is being studied (Figure 2) and patented, nucleation of protodolomite concerning amorphous and crystalline transient phases, calcium phosphates from amorphous phases and direct and indirect nucleation of magnetite were also efficiently measured by using this technique that offers new research possibilities and provides original and complementary insights on the so-called non-classical crystallization pathway (27-29).

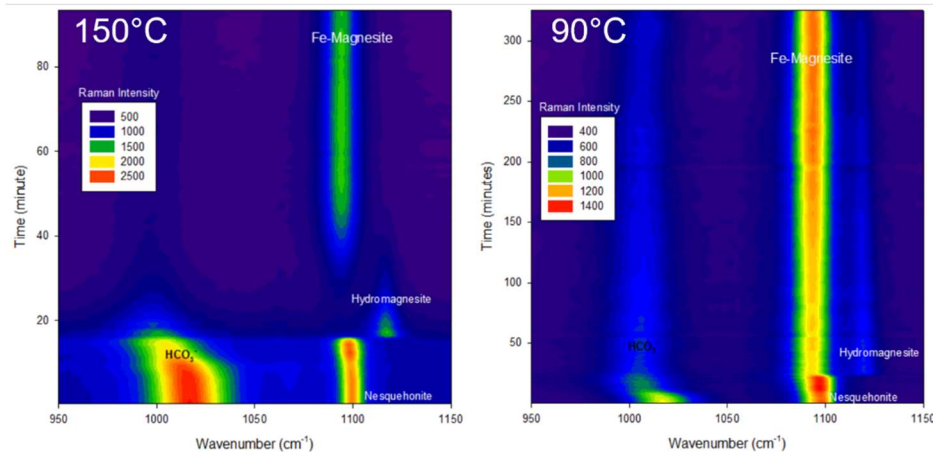


Figure 2. Time-lapse Raman spectroscopy monitoring of the formation of Fe-magnesite under hydrothermal conditions from indirect carbonation of peridotite (1. CO₂ capture in NaOH leading alkaline solution “AS”; 2. Peridotite leaching with HCl leading Mg-Fe-rich solution “LS” and 3. Fe-magnesite precipitation by adding LS into AS under controlled flow mixture and temperature). Fe-magnesite nucleation implied amorphous and crystalline phases (nesquehonite and hydromagnesite) as transient phases as clearly monitored by time-resolved Raman spectroscopy.

In order to extend the time-resolved Raman measurements to hydrogen gas and several silicates phases produced during silicate alteration, I will seek funding for a green laser (514 or 532 nm) spectrometer and upgrade a hydrothermal reactor in a near future. With this new experimental setup, the competition between carbonation and serpentinization reactions and a probable reduction of CO₂ into CO, C and CH₄ will be monitored *in situ* in order to elucidate these complex reaction mechanisms. In addition, hydrogen (H₂) production during a giving serpentinization and/or other redox reactions could be measured in real-time. An ANR proposal (PRC 2024 called “PERTINENT”) was then proposed in order to develop this important and novel experimental setup.

(2) What are the roles of amorphous and crystalline transient phases during the formation of minerals?

The nucleation and growth processes of Ca, Mg and Fe carbonates (including solid solutions and ordered double carbonates), Ca and Mg phosphates and Fe and Al oxyhydroxides (including Mg-Fe-Al-Layered double hydroxides (LDH)) will be monitored in real-time by Raman spectroscopy from ambient to hydrothermal conditions. The influence of organic/inorganic additives will be assessed. Here, I will use a multiphasic gas-liquid-solid batch reactors coupled to Raman and pH probes. These experimental setups are already available in my lab (<https://www.isterre.fr/IMG/pdf/experimental-setups-in-my-lab.pdf>) and

are currently used to explore nucleation, growth and transformation of several minerals under mild and hydrothermal conditions. In this way, important studies have been recently reported on the nucleation of calcite, siderite, brushite, hydroxyapatite, proto-dolomite, magnesite and magnetite (7, 19, 27-30). Here, time-resolved Raman spectroscopy *in situ* monitoring has revealed that amorphous and/or crystalline transient phases play a crucial role in the mineral formation than agrees with the so-called nonclassical crystallization pathway. However, this recent conception on the nucleation of crystals is still in its infancy. In order to provide novel and original insights, the **NAISSANCE** program will be mainly focused on the time-resolved Raman spectroscopy measurements in the continuity of recent studies, but exploring other minerals with relevance in natural and engineered settings as well as their uses in the modern world. Moreover, time-resolved measurements in synchrotron sources (XAS and SAXS/WAXS), *in situ* liquid cell AFM, *in situ* titration and numerical simulations will support this research work via local, national or international collaborations. Various of these techniques are actively developed by researchers of the geochemistry and mineralogy teams at ISTERre as illustrated (Figure 3). I will also collaborate with other groups to develop thermodynamics and kinetics models of mineral nucleation and growth to reproduce my experimental data and then validate reaction mechanisms and kinetics as already demonstrated for calcite nucleation and olivine alteration under hydrothermal conditions (collaboration with Fritz and Noguera teams, see also below). We note that in the absence of a theoretical quantitative formalism to describe the so-called nonclassical nucleation, the improved and/or adapted classical nucleation theory remains the best tool to simulate nonclassical nucleation of crystals and/or particles as commented below in section III.

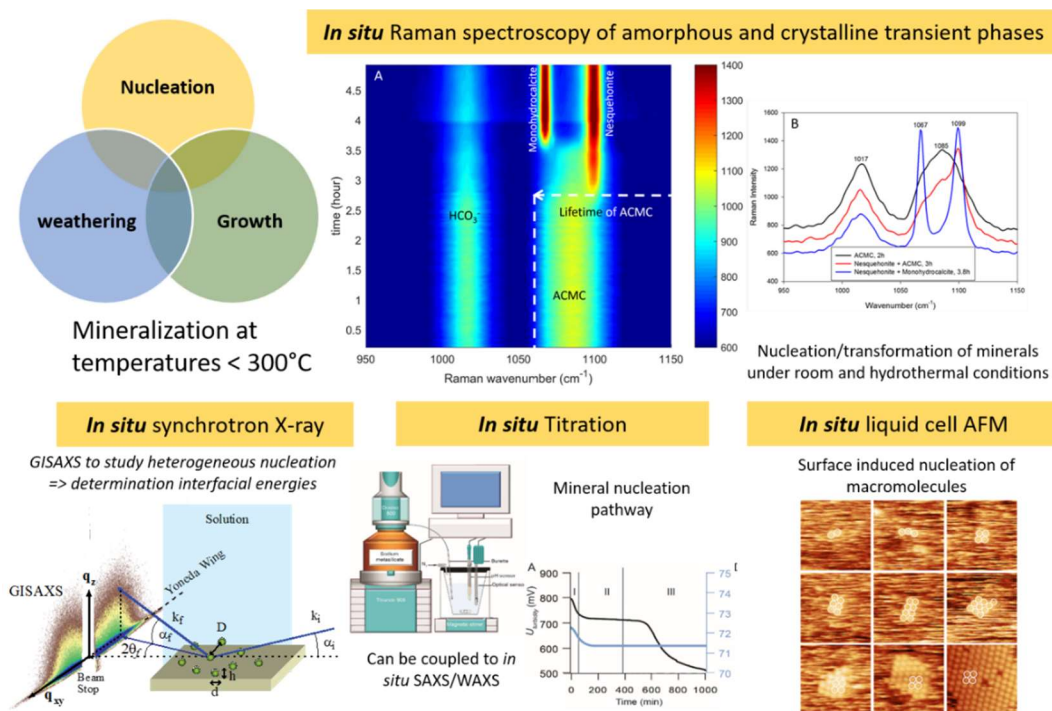


Figure 3. Four examples of techniques for *in situ* measurements of nucleation of crystals currently used and developed in the Geochemistry Team at ISTERre. These developments represent priority topics for the 2020-2024 contract (coordinated under my supervision as leader of geochemistry team) and have been evaluated very positively by the HCERES.

Time-resolved measurements (spectral or imagery) and numerical simulations are highly relevant approaches to investigate on the nucleation, growth and alteration of minerals, glasses or other solids. This research axis concerning a wide spectrum of fluid-mineral interactions (e.g., interactions in the critical zone, mineral hydrothermal alteration, mineral nucleation under mild and hydrothermal conditions...) is actively investigated by four permanent CNRS research scientists at ISTERre (G. Montes-Hernandez, A. Fernandez-Martinez, R. Hellmann and D. Daval) with broad experience in the field of mineral formation and transformation, with strong collaborations with other laboratories in France, Europe and the United States. Many of these projects will rely heavily on the participation of postdocs, and students at the PhD and Master levels. I note that this emerging topic at ISTERre was suggested and organized during my responsibility as leadership of geochemistry group. I note also that this topic concerning precipitation processes of minerals was initiated by my arrival to Grenoble in 2006 and it was then reinforced by the arrival of A. Fernandez-Martinez in 2013, A. Van Driessche in 2016 (now moved to Spain) and D. Daval (in 2022 moved from Strasbourg). This research axis could be still reinforced in the coming years because various CNRS candidates are interested to joint ISTERre each year.

(3) What is the role of water dynamic in unsaturated gas-solid systems at low T (<0°C) and high T (>100°C)?

Unsaturated gas-solid reactive systems are widespread in soils, dusts, aerosols and many other porous or granular materials existing in planetary environments. Unfortunately, several implied reactive processes are ignored or poorly understood. In this way, firstly, the gas-solid carbonation of calcium and magnesium amorphous silicates, binary oxides and hydroxides under wet and dry conditions will be investigated. Two different and complementary experimental setups are proposed. First, I will design a biphasic gas-solid batch reactor coupled to infrared spectroscopy, controlling the relative humidity ($0 \leq RH < 1$) and low CO₂ pressure (<1bar). The first reaction cell that I have designed has produced data for two publications (16, 30), but various improvements are required in order to control efficiently the *in situ* relative humidity. Second, I will design with my collaborator's gas-solid carbonation experiments at high T ($RH \approx 0$) using a thermogravimetric analyzer (31). These experimental setups will allow demonstrating how the formation of carbonates in unsaturated cold and hot environments is possible and may be controlled by the action/dynamic of interfacial water or by high temperatures, as already suggested in pioneering papers (16, 30, 31) and summarized in Figure 4.

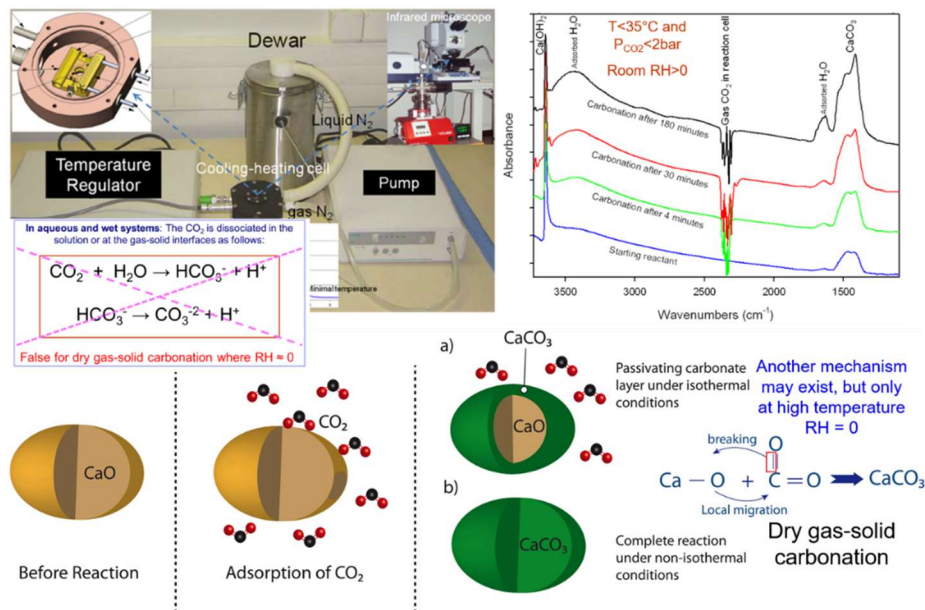


Figure 4. Current experimental setup to investigate gas-solid carbonation without *in situ* control of relative humidity (RH (on the top left of figure)). Infrared spectra collected as a function of time for gas-solid carbonation of portlandite (on the top right of figure). A reaction mechanism for gas-solid carbonation of calcium oxide at high temperature and in absence of molecular water (RH=0) was proposed, where a C-O bond in CO₂ breaks (red rectangle) before bonding with CaO, to produce calcium carbonate as illustrated in the bottom of figure.

The results obtained in these studies will be highly relevant for planetary cold environments (e.g. Mars and Antarctica) (30), and for various industrial applications such as Ca looping process, CO₂ capture by alkaline sorbents (31), the potential of negative emission of CO₂ using alkaline powdered materials (6) and gas-solid alteration of civil constructions.

III. Summary on the expected results and relevance

With my collaborators, we have demonstrated that a triphasic reactor with Raman spectroscopy *in-situ* probe offers unique possibilities for investigating mineral precipitation from aqueous solutions and slurries, and in general for investigating the chemical reactions at solid-fluid interfaces with direct relevance for Earth systems and industrial applications. Data have produced high impact research results (7, 19, 27-30). For example, since the 1970s, it has been shown that calcium phosphate crystals nucleate from one or several early amorphous calcium phosphate phases into several *in vivo* and *in vitro* systems. However, the precise chemical composition, structure, and transformation mechanism of these amorphous phases remain controversial. In a recent study, we characterize the reaction mechanism and kinetics of formation of two phosphate crystals, brushite and hydroxyapatite, by using *in situ* Raman spectroscopy in batch reactors from room T to 90°C. Here, we identified new reactive pathways that characterize the formation of amorphous calcium phosphate phases and their transformation into brushite microcrystals or hydroxyapatite nanocrystals under abiotic conditions as illustrated in the figure 5 (see also ref. (28)), relevant to a wide range of technological applications and natural environments.

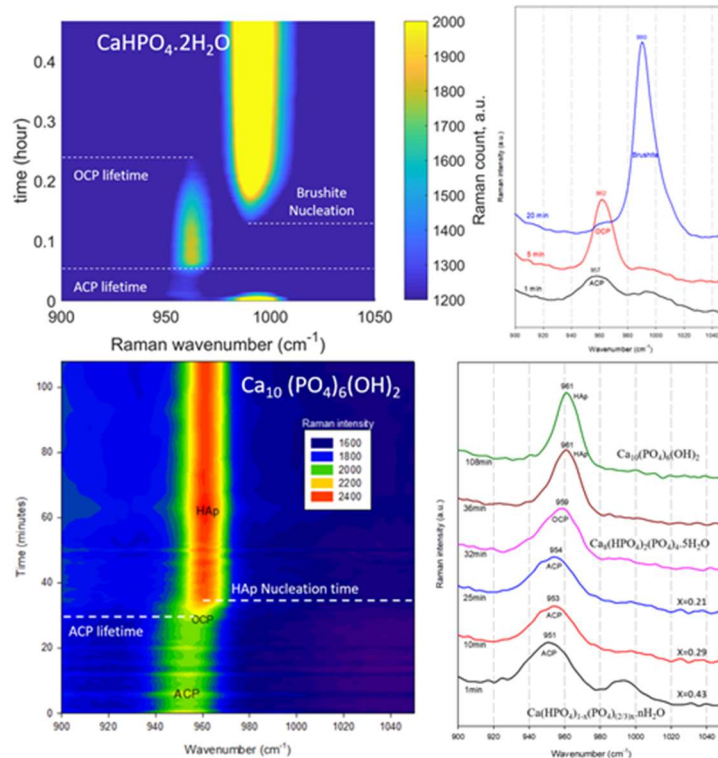


Figure 5. The nucleation of brushite and hydroxyapatite was monitored in real-time by Raman spectroscopy at room T to 90°C . For both minerals, amorphous calcium phosphate ($\text{Ca}(\text{HPO}_4)_{1-x}(\text{PO}_4)_{(2/3)x}\cdot n\text{H}_2\text{O}$) with different Raman signature was instantaneously formed in the initial solution. Then, the amorphous phases transform into OCP, a crystalline transient phase. Finally, OCP transforms into brushite micro-crystals or into hydroxyapatite nanocrystals.

In another fundamental study, real-time Raman measurements have recently suggested that that primary dolomite, as initially defined ($\text{Mg}^{2+} + \text{Ca}^{2+} + 2\text{CO}_3^{2-} \rightarrow \text{CaMg}(\text{CO}_3)_2$), has a very low probability to form at room temperature in abiotic or biotic systems, i.e. through heterogeneous nucleation (pre-existence of reactive surfaces) and a non-classical nucleation mechanism is therefore expected (27). This study has demonstrated that transient amorphous or crystalline phases play a significant role in the formation of disordered dolomite. Such transient phases can decrease the energy barrier under ideal fluid chemistry conditions (e.g. direct transformation of ACMC into disordered dolomite), but they can also retard dolomite precipitation (e.g. via transient formation and concurrent dissolution of nesquehonite and monohydrocalcite) as demonstrated in Figure 6. The important consequence is that my experimental data have shown that dolomite may form, but the mechanism is not direct and involves precursory minerals that nucleate, grow and then dissolve before dolomite can form.

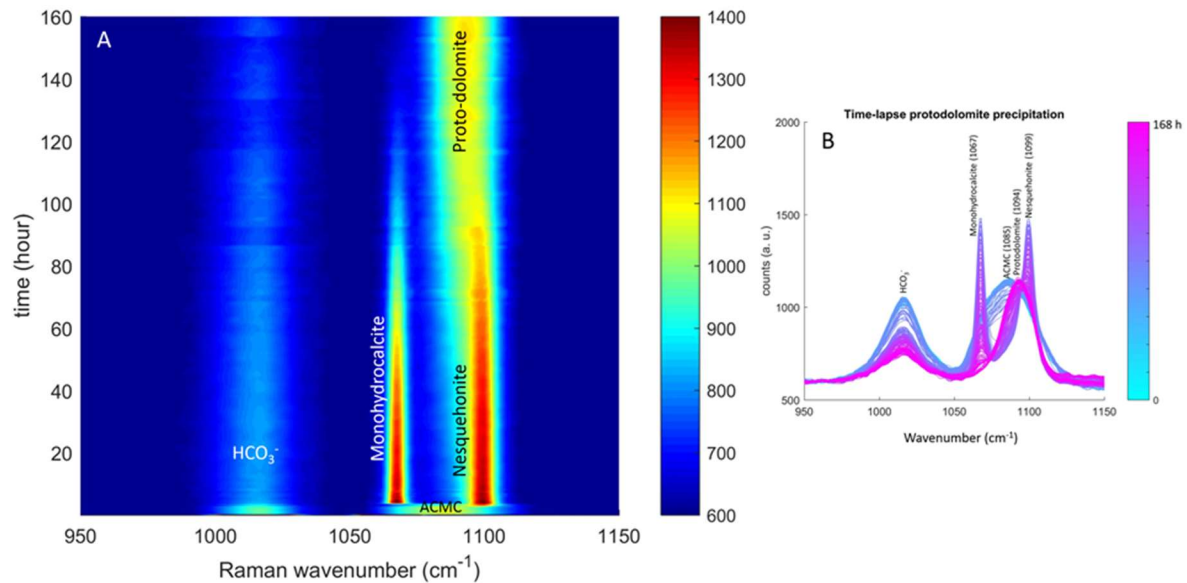


Figure 6. Time-lapse Raman spectroscopy monitoring of the formation of disordered dolomite from ACMC. Left: evolution of the two transient phases, nesquehonite and monohydrocalcite. Right: time-lapse evolution of the main Raman peaks. Details and spectral movie in Montes-Hernandez et al. 2020 (27).

The early formation of amorphous phases and their transformation into transient or stable crystalline phases is now considered to be a generalized reaction pathway during the formation of inorganic and biogenic carbonates and phosphates minerals in aqueous systems. This crystallization pathway agrees with Ostwald's rule, but transient phases are not necessary polymorphs; in fact, they can have different chemical compositions and different particle sizes. Moreover, thermodynamic and kinetic arguments should be considered in the crystallization tendency (28). In this way, multi-steps nucleation events may exist and combine various reaction mechanisms at the solid-fluid interfaces. Thus, solid-state transition, dissolution-recrystallization, self-assembly aggregation and partial dissolution-aggregation may operate together during nucleation and growth processes (e.g., 7, 19, 27-30).

In this case, the classical nucleation theory (CNT), the most common theoretical formalism to quantify nucleation and growth rates (including variation of particles size distribution) cannot be applied successfully in its original formalism as proposed in the last three decades by various research groups (e.g. 21-24). These groups have proposed an alternative conceptual approach called non-classical nucleation and crystallization pathways (including pre-nucleation clusters). However, in the absence of a theoretical quantitative formalism to describe the so-called non-classical nucleation, the improved and/or adapted classical nucleation theory is still considered the best engineering tool to simulate the non-classical nucleation of crystals and amorphous particles (e.g., 25, 33).

In this way, I will associate numerical simulations to the experiments on the formation of diversified minerals. The numerical code Nanokin (34) can be regarded as an efficient option, as recently reported in two studies (33, 35). For example, this approach of mineral precipitation has successfully been used in a combined theoretical/experimental study of calcite formation by portlandite carbonation (33). It allowed us to decipher the various steps in the mineral transformation, behavior of crystal size distribution (Figure 7) and the evolution of the composition of the aqueous solution. The comparison between experiment and simulation was

shown to put strong constraints on simulation parameters (surface energies, nucleation rate, growth law), and also provided information on in situ conditions (e.g. pH and element concentration and speciation).

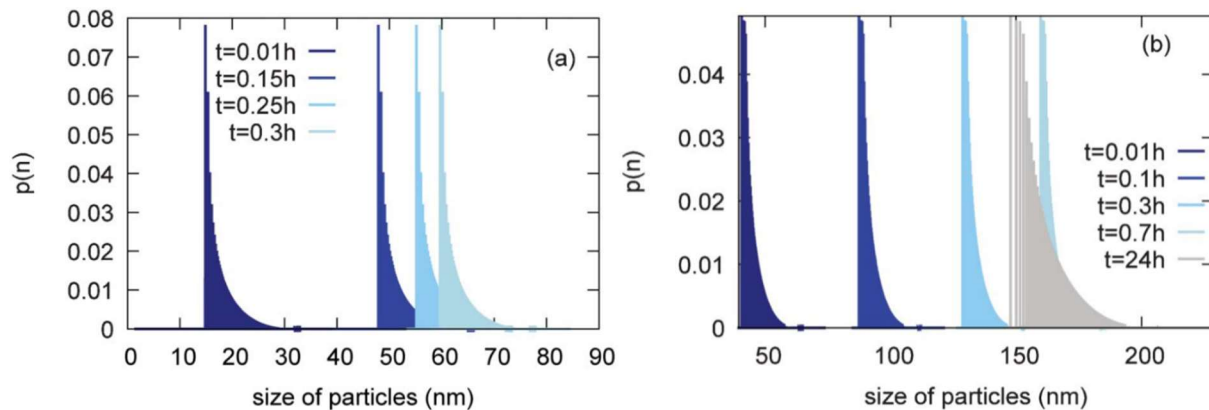


Figure 7. a) Calcite crystal size distribution functions during precipitation of this mineral at $T=30\text{ }^{\circ}\text{C}$, taken at four different times: $t = 0.01, 0.1, 0.2$ and 0.3 h . b) Calcite crystal size distribution functions during precipitation at $T=90\text{ }^{\circ}\text{C}$ taken at four different times: $t = 0.01, 0.1, 0.3, 0.7$ and 24 h (Fritz et al., 2013, ref. (33)).

I will use the same strategy in the context of the present project to complement experimental kinetic results from Raman spectroscopy data. This approach will allow extending our kinetics database, a step that will be of strong interest for both geochemical and chemical engineering communities. It will also help to understand the competition between different mineral phases that may form simultaneously in the solution. The thermodynamic and kinetics simulations will predict the time evolution of the particle sizes and their composition profiles, with continuous feedback effects between the predicted evolutions of the aqueous solution and that of the population of forming particles.

A combination of time-resolved measurements with numerical simulations using the code Nanokin or molecular dynamics (MD) simulation and *ex situ* fine characterizations of solids and fluids will provide a better fundamental understanding on the nucleation and growth processes of minerals, crystals and particles (including solid solutions) under hydrothermal conditions. Results will be strongly relevant to natural hydrothermal settings as well as societal applications in the modern world.

In summary, time-resolved Raman spectroscopy measurements combined with numerical simulations will provide basic knowledge on the classical and non-classical crystallization pathways in homogeneous or heterogeneous systems. The existence and persistence of precursory transient phases during nucleation processes and the role of organic matter in bio-mimetic systems will be investigated for several strategic minerals such as carbonates, phosphates, iron oxides, serpentines and clays. The main outcomes of the NAISSANCE program and strategy for the next five years will be i) the production of unique laboratory experimental data, ii) the development of new kinetics and reaction mechanisms of mineral precipitation that accounts for the existence of transient phases, iii) the optimization of chemical reactions that can be used to reuse and store CO_2 permanently in minerals. The implications of this collaborative project comply with fundamental aspects in Earth and Planetary Sciences and with applied aspects, actively investigated in France, Europe and through the world. The

obtained results will be mainly shared via international publications and patents (see CV of the PI).

IV. Hosting laboratory and consortium

ISTerre (Institut des Sciences de la Terre/Institute of Earth Sciences) is a joint research unit comprised of 300 people. It operates under the supervision of the CNRS, the University Grenoble Alpes, the University Savoie Mont Blanc, the French National Research Institute for Development (IRD) and University Gustave Eiffel. ISTerre is subsidiary of Observatory of Earth Sciences and Astronomy of Grenoble and of the research center Physics-Astrophysics-Geosciences-Environment (PAGE) of the University Grenoble-Alpes.

Organized in 9 research teams, the primary goal of ISTerre is the physical and chemical study of the planet Earth through a combination of observations of natural objects, experimentation, and the modeling of complex processes. In this way, the **NAISSANCE** program is in line with the current structuration at ISTerre and it concerns topics developed in geochemistry and mineralogy teams and also agrees with cross-disciplinary topic on the energy transition. This program and strategy for the next five years involves both junior and senior scientists with complementary backgrounds in geochemistry, material sciences, petrology, mineralogy, geological processes and nucleation and growth processes of crystals. This project will be preferentially supported by Ph.D., B.S and M.S students, and will involve, when possible, post-doctorate fellows and undergraduate students.

I aim to build a cross-disciplinary research group, with strong national and international collaborations, working on the nucleation and growth processes of minerals and crystalline particles. This topic is relevant to Earth systems, e.g. mass transfer in hydrothermal, aquifers, soils and planetary cold environments and biomineralization processes in the ecosystems. My studies are also relevant for several societal applications such as Ca looping process, $M(\text{Ca}, \text{Mg}, \text{Fe} \dots)\text{CO}_3$ production at industrial scale, CO_2 capture by alkaline sorbents, mechanical-chemical alteration of concretes or hydrated cements and CO_2 transformation into energetic molecules (syngas, CH_4 , and methanol). The current local, national and international collaborations will be reinforced and other will be developed in the coming years.

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