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Magnesite formation from nesquehonite slurry at 90 °C using some soluble Mg salts: Eitelite as an atypical transient mineral phase

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ABSTRACT

The production of engineered magnesite ($MgCO_3$) under mild conditions remains an important fundamental challenge in order to store permanently the industrial captured CO_2. Because, the magnesite is the more-known-stable carbonate at the Earth surface conditions and it is ready-to-use as profitable construction materials. In the present study, time-resolved Raman spectroscopy experiments have been conducted to characterize magnesite formation from nesquehonite slurry at 90 °C in an ionic carbonate alkaline medium (CO_3^{2-}/HCO_3^- close to 1) using four different soluble Mg salts (acetate, sulphate, nitrate and chloride of magnesium). The investigated experimental conditions have revealed that only nesquehonite ($MgCO_3{\cdot}3H_2O$) via un amorphous phase transformation is produced at room temperature. However, magnesite was systematically formed from nesquehonite slurry when temperature increase to 90 °C (heat-ageing step). Here, hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$) and eitelite ($Na_2Mg(CO_3)_2$) with long lifetimes were the main characterized transient phases prior to magnesite formation depending of the counterions. Moreover, eitelite rare mineral has not been reported as transient phase during magnesite formation. In summary, the imposed carbonate concentration, carbonate speciation, counterions, competitive divalent cations and pH have played a critical role on the magnesite formation at 90 °C. The discovered experimental mild conditions are promising; however, 2–3 days were required in single Mg system, except when dissolved calcium is added (Ca/Mg≈0.15) in the chloride counterion system; for such case only one hour is required to produce Ca-magnesite and protodolomite at 90 °C, i.e., the production of anhydrous Mg-Ca carbonates phases in very reduced time. In this latter case, the monohydrocalcite ($CaCO_3{\cdot}H_2O$) and the nesquehonite precursors produced at room temperature were rapidly transformed via concurrent dissolution into Ca-magnesite ($Ca_xMg_{1-x}CO_3$) and protodolomite ($Ca_{0.5}Mg_{0.5}CO_3$). In conclusion, these novel insights are relevant for fundamental (direct monitoring of multi-nucleation events in complex ionic and/or slurries systems) and applied (permanent storage of CO_2) research on the formation of anhydrous Mg carbonates (e.g., magnesite and dolomite) debated in the last two centuries.

1. Introduction

Magnesite ($MgCO_3$) and dolomite ($MgCa(CO_3)_2$) are the most stable carbonate minerals under typical Earth surface conditions, with the highest resistance to leaching and weathering. Their dissolution rates are for example 100–1000 times lower than that of calcite in a wide range of conditions, from ambient temperature to 150 °C and pH from 1 to 14 (Pokrovski et al., 2009). For this reason, engineered magnesite and dolomite have been considered as relevant minerals to store permanently anthropogenic carbon dioxide. Moreover, both minerals are ready-to-use as profitable construction materials (Montes-Hernandez et al., 2020). Magnesite and dolomite precipitation kinetics have been widely studied because their abiotic precipitation at ambient temperature (~25 °C) is virtually impossible within typical experimental time scales, which has led to long-lasting scientific debates in the last two centuries (Deelman, 2001; Hänchen et al., 2008; Xu et al., 2013). The strong solvation shells of magnesium ions in aqueous media produces this limitation (Deelman, 2001). However, the sole effect of Mg hydration might not be the only factor of inhibition of magnesite and/or dolomite formation. Recent studies claim that a more intrinsic crystallization barrier and the influence of fluid chemistry (e.g., relative size of the constituting cations, carbonate alkalinity, ion concentration, counterion nature, etc.) prevent the formation of a long-range ordered crystallographic structures at ambient conditions (Xu et al., 2013; Pimentel and Pina, 2014; Montes-Hernandez and Renard, 2016; Montes-Hernandez et al., 2020). In this way, real-time Raman spectroscopy measurements have recently suggested that primary dolomite, as initially defined ($Mg^{2+} + Ca^{2+} + 2CO_3^{2-} \rightarrow CaMg(CO_3)_2$), has a very low

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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 (e.g. via amorphous and crystalline transient phases) is therefore expected; probably higher temperature is also required to form dolomite (Montes-Hernandez et al., 2020). The early formation of amorphous phases and their transformation into transient or stables 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. 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., (Montes-Hernandez et al., 2020; Montes-Hernandez and Renard, 2016; Montes-Hernandez et al., 2020; Montes-Hernandez and Renard, 2020; Montes-Hernandez et al., 2021). Concerning the magnesite, time-resolved Raman spectroscopy measurements have also revealed that its precipitation from $Mg(OH)_2$-NaOH-H_2O-CO_2 system was inhibited by nesquehonite formation at 25 °C. Conversely, magnesite formation was rapidly obtained at 90 °C and only 15 h were required to produce high-purity magnesite (Montes-Hernandez et al., 2020). In the continuity of this comprehension effort, time-resolved Raman spectroscopy experiments have now conducted to characterize magnesite formation from nesquehonite slurry at 90 °C in an ionic carbonate alkaline medium (CO_3^{2-}/HCO_3^- close to 1) and by using four different soluble salts such as acetate, sulphate, nitrate and chloride of magnesium. In order to assess the role of counterions during Mg carbonate formation. Herein, a given amount of Mg salt were abruptly mixed with an ionic carbonate alkaline solution (CO_3^{2-}/HCO_3^- close to 1, 2 M of carbonate ions in total) at room T until spectral stabilization and then heated at 90 °C for various days. Real-time monitoring by Raman spectroscopy have surprisingly revealed the magnesite production in all cases, but, kinetics and reaction mechanism were significantly influenced by counterions and by presence of other divalent cations. These novel and original insights have significant relevance for fundamental (direct monitoring of multi-nucleation events) and applied (utilization of CO_2) research on the formation of anhydrous Mg carbonates (e.g., magnesite and dolomite) debated in the last two centuries.

2. Materials and methods

2.1. Mg carbonate formation at room temperature

A given amount of magnesium compound (acetate, sulfate, nitrate, chloride and hydroxide of magnesium), necessary to form a 1 M solution/suspension of Mg in the system, were placed into a Hastelloy C22 reactor (Parr, total internal volume of 600 ml) coupled with a Raman probe in order to monitor in real-time precipitating carbonate particles and aqueous carbonate species. This experimental setup was reported previously in Montes-Hernandez and Renard (Montes-Hernandez and Renard, 2016). Raman spectra were collected with a Raman RXN1, Kaiser Optical Systems with an exposure time of three seconds and averaged over three scans. Then, 300 ml of carbonate alkaline solution (2 M of bicarbonate/carbonate ions, pH = 10.2) was manually injected in the reactor using a simple syringe and then mechanical agitation was activated at 400 rpm in order to homogenize de reaction system. Following this injection step, the carbonate speciation and precipitated particles were monitored at room temperature by Raman spectroscopy for one to four days, with an acquisition frequency of one Raman spectra every minute during the first three hours and every five or ten minutes in the remaining time.

2.2. Magnesite formation at 90 °C by a heat-ageing step

The obtained suspensions at room temperature containing mainly nesquehonite (hydrated Mg carbonate) were then heated at 90 °C without any physicochemical modification for three to five days in order to monitor in real-time the transformation of hydrated magnesium carbonates into magnesite. Raman spectra were collected with the same above conditions.

Effect of dissolved calcium (Ca/Mg ratio ≈ 0.15) was also assessed in order to optimize the magnesite precipitation under lower energy conditions (e.g. lower reaction time and/or lower reaction temperature).

All experimentations were repeated at least 2–3 times in order to confirm their reproducibility.

At the end of the experiment, the solid product was recovered by simple settling and washed twice with tap water and then was dried directly in the centrifugation flasks at 65 °C for 48 h. The dry solid products were stored in plastic flasks for subsequent characterization by Raman spectroscopy, Field Emission Gun Scanning Electron Microscopy (FESEM) and powder X-ray diffraction (XRD).

2.3. Ex situ characterization of recovered solids products

XRD analyses were performed for final recovered magnesite-rich material using a Siemens D5000 diffractometer in Bragg-Brentano geometry, equipped with a theta-theta goniometer with a rotating sample holder. Diffraction patterns were collected using Cu $k\alpha_1$ ($\lambda_{k\alpha1}$ = 1.5406 Å) and $k\alpha_2$ ($\lambda_{k\alpha2}$ = 1.5444 Å) radiation in the range 2θ = 10–70°, with a step size of 0.04° and a counting time of 6 s per step. For high-resolution imaging, the solid products were dispersed by ultrasonic treatment in absolute ethanol for five to ten minutes. One or two droplets of the suspension were then deposited directly on an aluminum support and coated with platinum. The morphology of the crystals was imaged using a Zeiss Ultra 55 FESEM with a maximum spatial resolution of approximately 1 nm at 15 kV.

3. Results and discussion

3.1. Mg carbonates at room temperature

In summary, the magnesite nucleation was not observed at room temperature in all performed experiments (See also Table 1). Here, nesquehonite ($Mg(HCO_3)(OH).2H_2O$) was mainly nucleated from amorphous magnesium carbonate (AMC). For example, when sulfate of magnesium was used, the AMC is immediately formed and it persists for about 10 min (lifetime). Then it starts to be transformed into nesquehonite (see Fig. 1). The stronger peak of nesquehonite at 1101 cm^{-1} reaches a maximum intensity in only 5 min. This means that about 15 min were only required to produce high-purity nesquehonite from Mg sulphate at room T.

In the acetate and nitrate systems, the reaction mechanism is identical, i.e., instantaneous formation of amorphous magnesium carbonate (AMC) and its fast transformation into nesquehonite; but in these cases, the lifetime of amorphous phase was slightly smaller, 5 and 8 min, respectively, instead of 10 for sulfate system (see Figs. 3, 2 and 1). In this study, lifetime or persistence time of AMC concerns only the time prior to detection of nesquehonite signature; in this manner the lifetime corresponds also to nucleation time of nesquehonite as indicated in Figs. 1 and 2 (see also Table 1). Similar results were obtained for chloride of magnesium. Based on these real-time monitoring results by using Raman spectroscopy, the reaction mechanism for nesquehonite formation can be described as follows:

$$Mg^{2+} + CO_3^{2-} + (3+x)\,H_2O \rightarrow MgCO_3.(3+x)\,H_2O \ \text{(AMC formation)} \quad (1)$$

Table 1
Experiments of magnesium carbonates formation using soluble Mg salts and $Mg(OH)_2$ in a concentrated ionic carbonate solution (CO_3^{2-}/HCO_3^- close to 1, pH≈10.2). Batch experiments concerning 0.3 mol of a given Mg compound and 300 ml of ionic carbonate solution with real-time monitoring by Raman spectroscopy.

Run	Temperature (°C)	Mg Source	Duration	Mineral transient phase (s)	Lifetime of transient phase (s)	Final mineral phase (s)
1	25	$Mg(CH_3COO)_2{\cdot}4H_2O$	24 h	AMC	5 min	Nesquehonite
2	25	$Mg(CH_3COO)_2{\cdot}4H_2O$	4 days	AMC	6 min	Nesquehonite
3	25	$MgSO4{\cdot}7H_2O$	24 h	AMC	10 min	Nesquehonite
4	25	$MgSO4{\cdot}7H_2O$	3 days	AMC	12 min	Nesquehonite
5	25	$Mg(NO_3)_2{\cdot}6H_2O$	24 h	AMC	8 min	Nesquehonite
6	25	$Mg(NO_3)_2{\cdot}6H_2O$	5 days	AMC	8 min	Nesquehonite
7	25	$MgCl_2{\cdot}6H_2O$	24 h	AMC	6 min	Nesquehonite
8	25	$Mg(OH)_2$	7 days	nesquehonite	24 h	Dypingite
9	25	$MgCl_2{\cdot}6H_2O$ + $CaCl_2{\cdot}2H_2O$	24 h	ACMC	30 min	Nesquehonite Monohydrocalcite
10	90	Nesquehonite slurry from acetate system	3 days	Hydromagnesite	20 h	Magnesite
11	90	Nesquehonite slurry from sulphate system	2 days	Hydromagnesite Eitelite	10 h 40 h	Magnesite
12	90	Nesquehonite slurry from nitrate system	5 days	Hydromagnesite Eitelite	13 h 20 h	Magnesite
13	90	Nesquehonite slurry from chloride system	5 days	Hydromagnesite Eitelite	5 h 50 h	Magnesite Eitelite
14	90	Nesquehonite-Monohydrocalcite slurry from Mg-Ca chloride system	24 h	Mg-Calcite	10 min	Ca-Magnesite Protodolomite

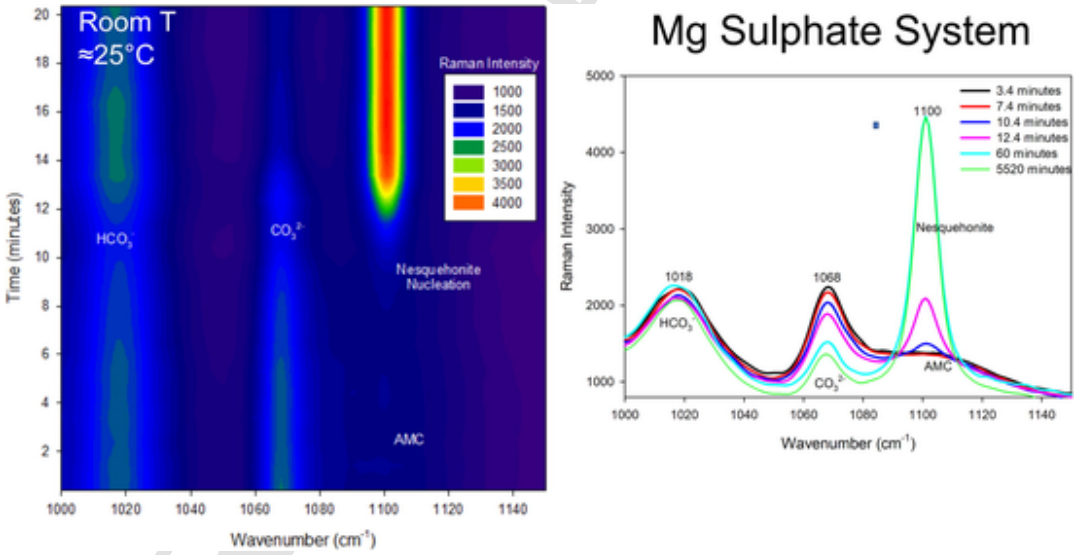

Fig. 1. Time-lapse Raman spectroscopy monitoring of nesquehonite nucleation from amorphous magnesium carbonate (AMC) when magnesium sulphate was used. The lifetime of AMC and positions of crystalline phases are indicated.

$$MgCO_3.(3+x)H_2O \rightarrow Mg(HCO_3)(OH).2H_2O + xH_2O \quad (\text{AMC} - \text{to} - \text{Nesquehonite}) \tag{2}$$

The AMC-to-nesquehonite transformation could take place via a solid-state transition because less than 8 min were only required to reach a spectral equilibration of stronger nesquehonite peak at 1101 cm^{-1} (Fig. 3). However, a partial dissolution-aggregation pathway cannot be excluded. In practice, the AMC-to-nesquehonite transformation kinetics can be empirically fitted by a simple sigmoidal model with only 2 parameters ($f = 1/(1\text{-}\exp(\text{-}(t\text{-}t_{1/2})/b))$). Moreover, high-purity nesquehonite can be massively produced at room T in only 15 min with similar Raman signatures, independently on the used Mg salt (see Fig. 4). Nesquehonite is a metastable magnesium carbonate that has recently suggested as a green building material (Kastrinakis et al., 2021), but, its high reactivity under unsaturated water conditions could limit its application. For this simple reason magnesite is the better candidate to store permanently industrial carbon dioxide (Montes-Hernandez et al., 2020).

3.2. Magnesite formation at 90 °C from nesquehonite slurry

As expected, when the nesquehonite slurries are heated from room temperature to 90 °C (heat-ageing step), magnesite can be formed after several hours via a complex reaction mechanism. For example, in acetate system, nesquehonite is rapidly transformed into hydromagnesite in the first hour. Then, the transient hydromagnesite is slowly transformed into magnesite via dissolution–recrystallization coupled processes as early claimed in Montes-Hernandez et al. (Montes-Hernandez et al., 2020; Montes-Hernandez and Renard, 2016) and only magnesite is detected after 72 h from time-resolved Raman spectroscopy measurements as illustrated in Fig. 5. The fast transformation of nesquehonite in first hour (Fig. 6 on the left) may be explained by a dissolution process coupled with nucleation and growth processes of hydromagnesite. These processes remain active during about five hours

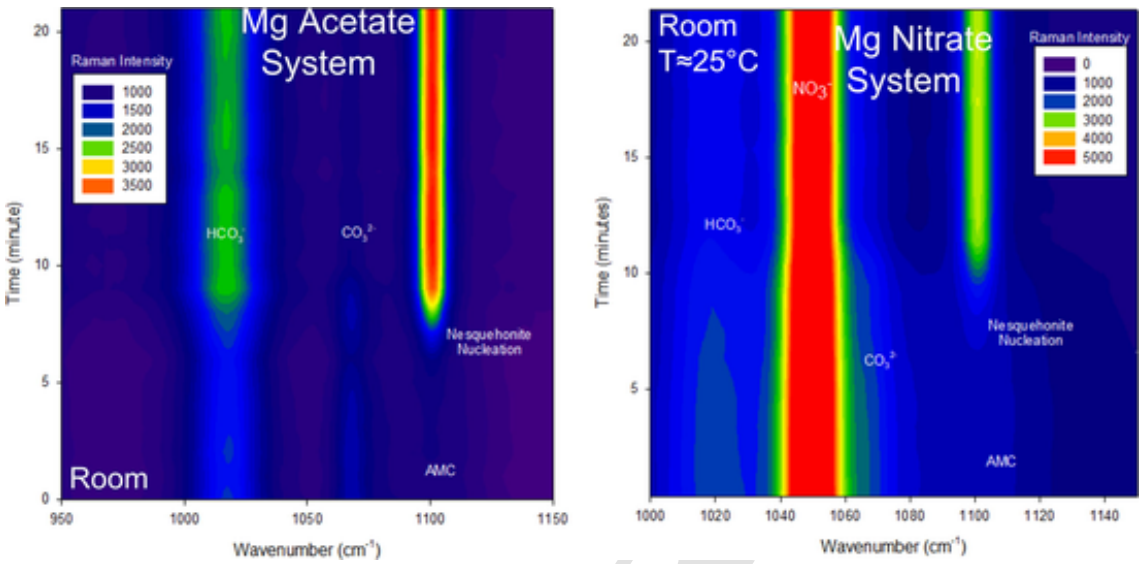

Fig. 2. Time-lapse Raman spectroscopy monitoring of nesquehonite nucleation from amorphous magnesium carbonate (AMC) when acetate and nitrate of Mg were used. The lifetime of AMC is similar (5–6 min) for both systems.

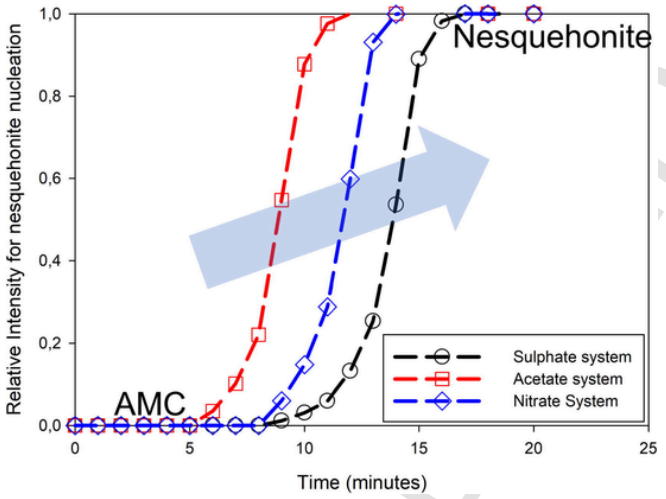

Fig. 3. Nucleation of nesquehonite from amorphous magnesium carbonate (AMC) and kinetic behavior during transformation. Data concerns the relative intensity of nesquehonite peak at 1101 cm^{-1} for sulphate, acetate and nitrate systems (intensity error ≈ 5 % after line-base correction).

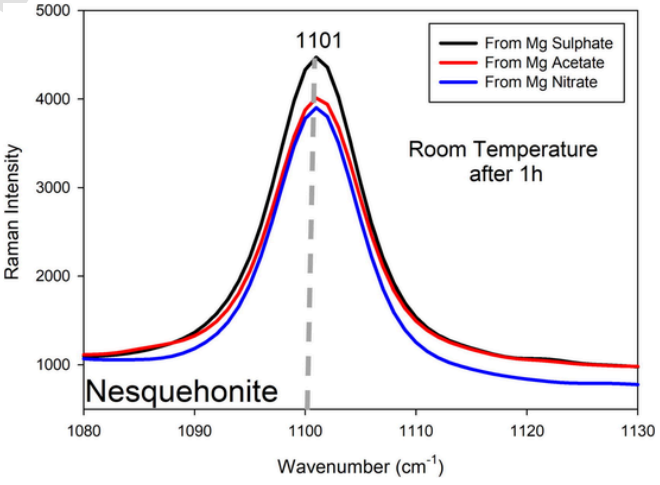

Fig. 4. Stronger peak for nesquehonite at 1101 cm^{-1} in Raman spectra concerning nesquehonite formation from AMC after 1 h for acetate, sulphate and nitrate systems.

(maximum of Raman intensity signal for hydromagnesite). Hydromagnesite in turn is slowly transformed into magnesite as represented by relative Raman intensity in Fig. 6 (on the right). The overall mineral transformations for acetate system can be then described as follows:

$$5Mg(HCO_3)(OH).2H_2O \rightarrow Mg_5(CO_3)_4(OH)_2.4H_2O + HCO_3^- + H^+ + 9H_2O \quad (3)$$

$$Mg_5(CO_3)_4(OH)_2.4H_2O + HCO_3^- + H^+ \rightarrow 5MgCO_3 + 6H_2O \quad (4)$$

Both above reactions and the kinetic behavior of each phase were directedly monitored in real-time by Raman spectroscopy as summarized in Fig. 6 for acetate system. The hydromagnesite-to-magnesite transformation seems a typical reaction pathway at moderate temperature (<100 °C) because same reaction pathway was claimed by using $Mg(OH)_2$ as Mg source in contact with compressed CO_2 and NaOH as accelerating agent (Montes-Hernandez et al., 2020; Montes-Hernandez et al., 2012). However, in the present study a more complex and new reaction pathway for magnesite formation was depicted from time-resolved Raman spectroscopy than concerns also the eitelite mineral as a concurrent transient phase during the magnesite formation at 90 °C (Fig. 5 on the right). In this surprisingly case, the eitelite mineral ($Na_2Mg(CO_3)_2$) competes with magnesite nucleation and it is simultaneously formed during hydromagnesite consumption in the sulphate system as clearly illustrated from relative Raman intensity for each concerned mineral phase (see Fig. 7). When hydromagnesite is completely transformed in the system, the eitelite in turn is rapidly transformed and the liberated Mg nourishes then the magnesite formation until the equilibration of the system. Eitelite transient phase was also monitored for nitrate system, but, the kinetic behavior differs drastically with respect to sulfate system. In fact, for nitrate system, the eitelite reaches a maximun intensity in the first 20 h of reaction coexisting with hydromagnesite. Then, slow simultaneous dissolution of hydromagnesite and eitelite nourish the magnesite formation until spectral equilibration as illustrated in Fig. 8. This means that counterion in Mg soluble salts could play a significant role on the reaction pathway and kinetics during magnesite formation. In summary, counterions seem to have a significant influence on the kinetics and reaction mechanism during mag-

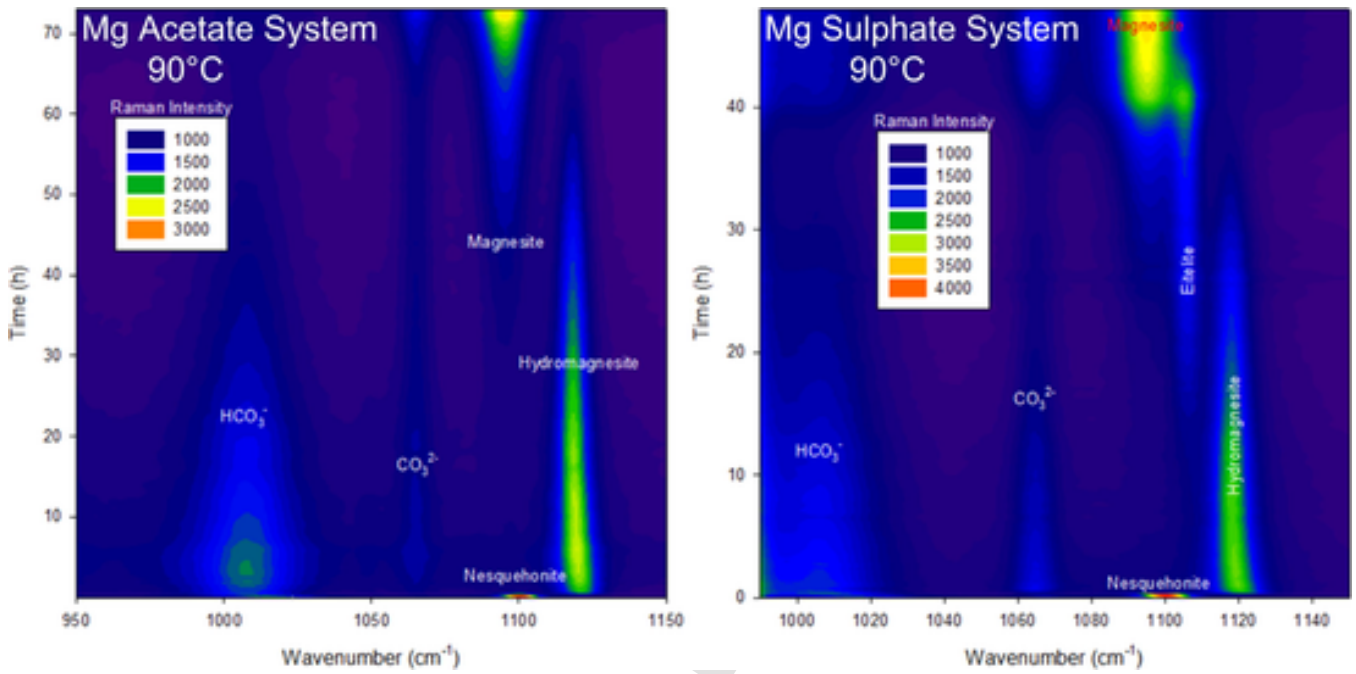

Fig. 5. Time-lapse Raman spectroscopy monitoring of magnesite formation from nesquehonite slurry heated at 90 °C for acetate and sulphate systems. In acetate systems two nucleation steps were measured while in sulphate system three nucleation steps were clearly monitored.

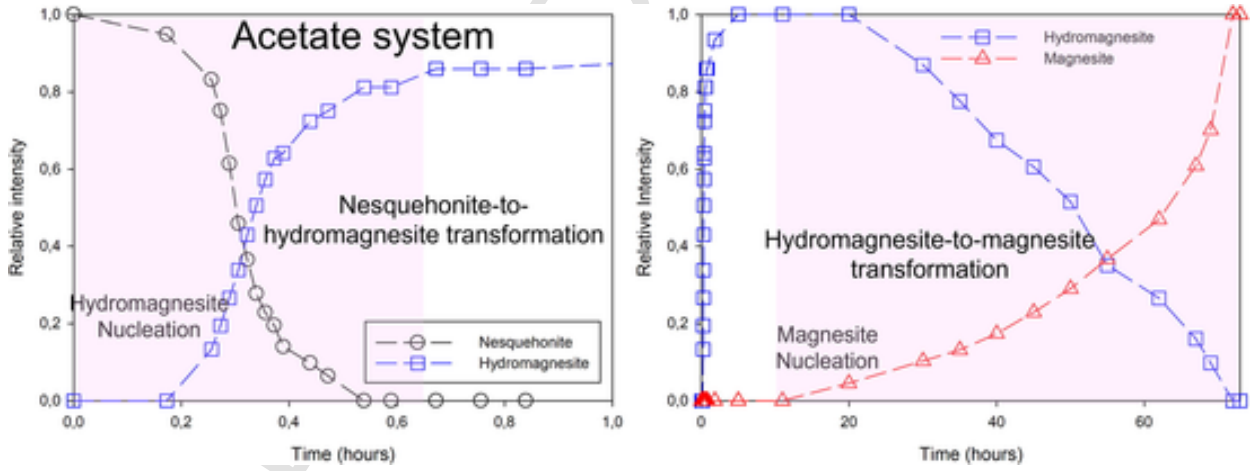

Fig. 6. Kinetic behavior of mineral phases during magnesite formation at 90 °C in acetate system. Two nucleation steps and hydromagnesite acting as a typical transient phase prior to magnesite formation. Data concerns the relative intensity of nesquehonite (stronger peak at 1099 cm^{-1}), hydromagnesite (stronger peak at 1122 cm^{-1}) and magnesite (stronger peak at 1095 cm^{-1}) for acetate system (intensity error ≈ 5 % after line-base correction).

nesite formation at 90 °C in this concentrated ionic carbonate medium. Herein, 2–3 days are required to produce significant amounts of high-purity magnesite, except to nitrate system where 5 days were required. These required durations by using soluble salts are significantly higher with respect to required time (15 h) in a $Mg(OH)_2$-NaOH-H_2O-CO_2 using compressed CO_2 and NaOH as CO_2 sequestering agent (Montes-Hernandez et al., 2020). However, more conventional equipment is required for magnesite production using Mg soluble salts where gas pressure is not required and/or implied during carbonation process. Moreover, when divalent cations (e.g., Ca and Mg) from soluble salts are mixed in the system, anhydrous Mg-Ca carbonate solid-solutions can be formed in a very reduced time (1 h). In this way, inspired in a recent study of my research team on the proto-dolomite nucleation (Montes-Hernandez et al., 2020), the effect of dissolved Ca was also assessed (Ca/Mg ratio ≈ 0.15), herein a promising result was then obtained revealing that the proto-dolomite coexisting with Ca-magnesite can be produced in only one hour of reaction at 90 °C as illustrated in the Fig. 9. This promising result has then revealed that Nesquehonite and monohydrocalcite formed at room temperature are rapidly transformed via concurrent dissolution into Ca-magnesite ($Ca_xMg_{1-x}CO_3$) and protodolomite ($Ca_{0.5}Mg_{0.5}CO_3$). Remarking that both cited anhydrous minerals have comparable textural and mechanical properties than magnesite and probably similar and additional industrial applications.

3.3. CO_2 mineralization implications

High-soluble Mg hygroscopic salts such chloride, sulfate, nitrate and acetate of magnesium may be produced from serpentine, peridotite and other Mg-rich silicates by corresponding acidic leaching (El-Sayed et al., 2023). All these obtained soluble Mg salts have numerous industrial applications, and have been also proposed as sinks to store anthropogenic carbon dioxide by transforming the carbon dioxide into magne-

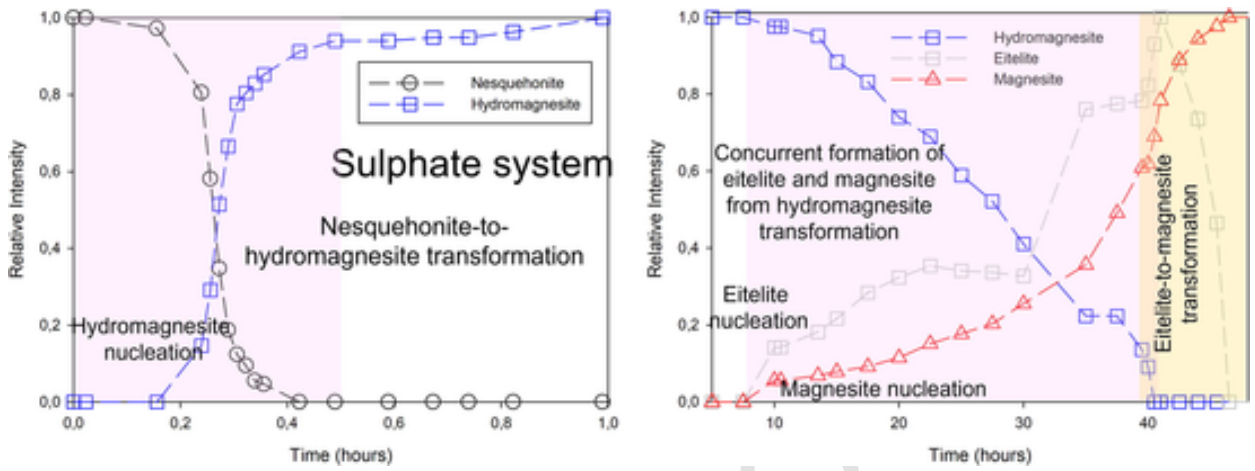

Fig. 7. Kinetic behavior of mineral phases during magnesite formation at 90 °C in sulphate system. Three nucleation steps with hydromagnesite and eitelite acting as atypical transient phases during magnesite formation. Data concerns the relative intensity of nesquehonite (stronger peak at 1099 cm^{-1}), hydromagnesite (stronger peak at 1122 cm^{-1}), eitelite (stronger peak at 1106 cm^{-1}) and magnesite (stronger peak at 1095 cm^{-1}) for sulphate system (intensity error ≈ 5 % after line-base correction).

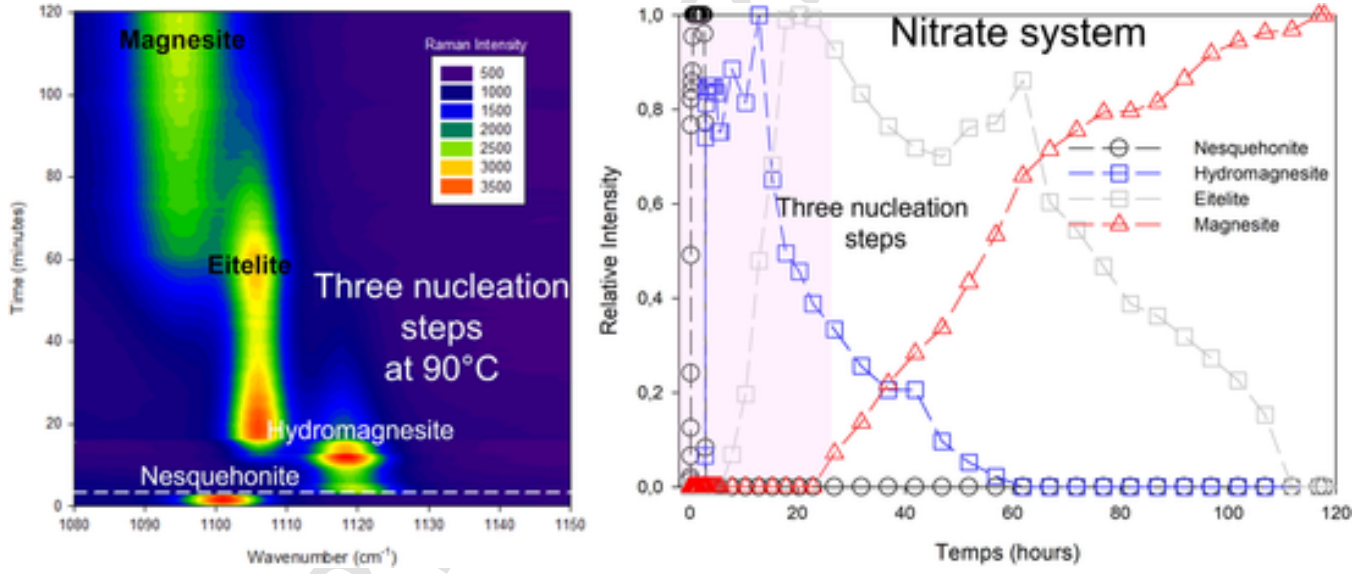

Fig. 8. Time-lapse Raman spectroscopy monitoring of magnesite formation from nesquehonite slurry heated at 90 °C for nitrate system. Kinetic behavior of mineral phases during magnesite formation at 90 °C in nitrate system. Three nucleation steps where hydromagnesite and eitelite act as transient phases prior magnesite formation.

sium carbonate minerals via a so-called indirect carbonation process (Sanna et al., 2014). Magnesite ($MgCO_3$) is considered as an ideal option because of its high chemical stability in both saturated and unsaturated aqueous media. In addition, engineered powdered magnesite is ready-to-use for construction materials. For example, as partial substituting of fresh cement in concrete fabrication, this allowing a permanent storage of CO_2 and then a significant reduction of CO_2 emissions from cement industry as recently invoked in the literature [e.g., (Chikkanagoudar et al., 2020; Kremer et al., 2022; Naqi and Jang, 2019). Unfortunately, the magnesite formation at room temperature (< 30 °C) from the aqueous carbonation of Mg soluble salts and Mg hydroxide remains a scientific challenge, but, important advances on the reaction mechanism and kinetics are provided in the present study by using time-resolved Raman spectroscopy measurements.

4. Conclusion

Nesquehonite mineral can be mainly produced via amorphous magnesium carbonate (AMC) precursor at room temperature and its formation has not need a long duration of production because in all cases the maximum intensity for nesquehonite was reached after about 20 min, independently on the counterion nature. Counterion has only slight impact on the lifetime of AMC. Conversely counterions seem to have significant influence on the magnesite formation at 90 °C, mainly on the formation kinetics and reaction mechanism as clearly depicted from real-time monitoring by Raman spectroscopy. Herein, two different reaction mechanisms for magnesite formation were measured; firstly, a typical hydromagnesite-to-magnesite transformation via a coupled dissolution-crystallization pathway for acetate system. Secondly, an atypical hydromagnesite-to-eitelite-to-magnesite transformation, implying then three nucleation steps. This latter reaction mechanism has concerned sulphate, nitrate and chloride systems at the investigated conditions. Kinetics, i.e. lifetime of transient phases, nucleation time and dis-

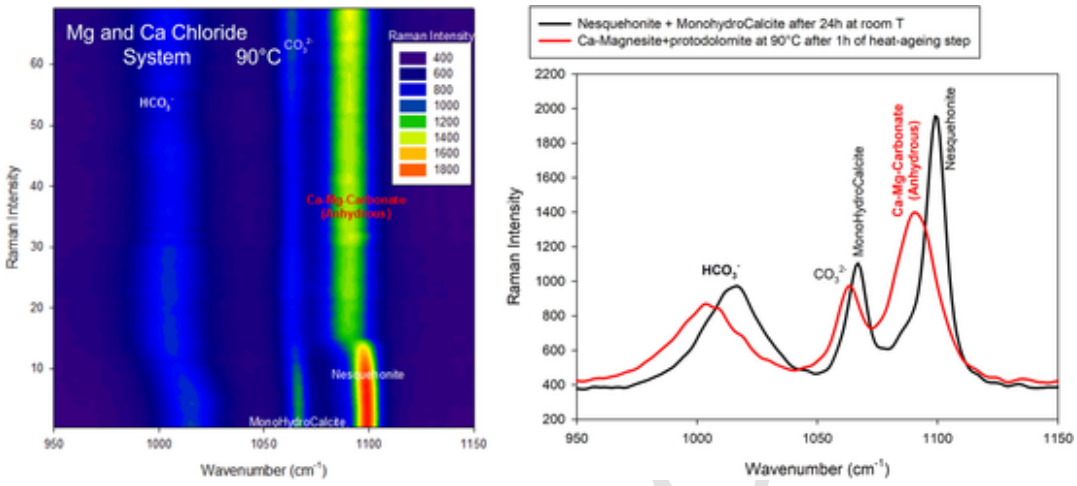

Fig. 9. Time-lapse Raman spectroscopy monitoring of anhydrous Mg-Ca carbonates nucleation from nesquehonite and monohydrocalcite transformation at 90 °C in chloride system. The lifetime of nesquehonite and monohydrocalcite (mineral precursors obtained at room temperature) are illustrated. Anhydrous Mg-Ca carbonates were rapidly nucleated via concurrent dissolution of nesquehonite and monohydrocalcite (crystalline phases initially obtained at room temperature).

solution-growth rates were also impacted by counterions, but, in general 2–3 days are required to obtain high-purity magnesite. This production duration was considerable reduced when Ca was added in the system. Here, Ca-magnesite and protodolomite (both anhydrous phases) were obtained in only one hour at 90 °C. In summary, our time-resolved Raman measurements allowed a detailed description of reaction mechanism and kinetics of magnesite production.

CRediT authorship contribution statement

German Montes-Hernandez: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: German MONTES-HERNANDEZ reports financial support and administrative support were provided by The French Agency for Ecological Transition.

Data availability

Data will be made available on request.

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