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Impact of phyllosilicates on amino acid formation under asteroidal conditions

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Abstract

The emergence of life on Earth could have benefitted from an extraterrestrial source of amino acids. Yet the origin of these amino acids is still debated because they may have formed prior to the solar nebula or inside the parent body of meteorites. Here, we experimentally produced amino acids by exposing an interstellar model molecule (hexamethylenetetramine) to asteroid-like hydrothermal conditions (150 °C; pH 10). We conducted additional experiments in the presence of carboxylic acids and phyllosilicates to simulate asteroidal environments. Analyses via liquid chromatography-mass spectrometry show that glycine is the most abundant amino acid formed, but non-proteinogenic α -, β - and γ -amino acids are also produced. This production of amino acids seems to be hampered by the presence of Fe-rich smectite, while the presence of Al-rich smectite largely stimulates it. Our findings evidence 1) the production of amino acids during hydrothermal alteration of a putative interstellar precursor, 2) the importance of the formose reaction from formaldehyde and ammonia, for amino acid synthesis in meteorites, and 3) the impact of organic-mineral interactions on the nature/distribution of the amino acids produced. Altogether, the fact that the production of amino acids, which are so central to living structures, can be achieved via organo-mineral interactions under hydrothermal conditions should put these processes at a focal point for research on the origin of extraterrestrial organic compounds and into the origin of life.

1. Introduction

Amino acids are among the most interesting compounds in extraterrestrial organic matter due to their irreplaceable role in all Earth life systems. These organic compounds are present in non-negligible quantities in carbonaceous chondrites (-up to 300 ppm in CR2) ¹⁻⁵; however, their abiotic origins are still subject of debate. The synthesis of most amino acids is believed to have occurred during hydrothermal processes happening inside the parent body of meteorites, from accreted precursors such as aldehydes, cyanide, ketones and ammonia ^{2,5,6}. Current theories propose that significant amounts of meteorite organic matter, or its precursors, can be first formed in an interstellar environment, such as on icy grains by irradiation and heating processes and then during the protosolar nebula phase ⁷. This heritage is supported by isotopic studies showing noticeable enrichment in heavy stable isotopes of C, N and H in chondritic organics, including amino acids ⁸, likely originating from energetic processing at low temperature (< 50 K) during precursor formation ⁹. From these precursors, different chemical pathways are proposed to elucidate amino acid formation during hydrothermal alteration inside asteroids: the Strecker reaction that produces α -amino acids, the Michael addition to produce β -amino acids, and the decarboxylation of α -amino dicarboxylic acids as a possible formation of γ - and δ -amino acids. Amino acid analyses highlight that the degree of alteration in different parent bodies influences the relative molecular distribution of α , β , γ - and δ -amino acids ⁵. For example, higher degrees of thermal alteration have been linked to higher abundances of *n*- ω -amino acids ¹⁰; in contrast, less aqueously altered carbonaceous chondrites contain higher abundances of α -amino acids, as seen in the Paris meteorite ¹¹, which is considered one of the least altered CM carbonaceous chondrites ¹². Nonetheless, these trends are not always valid and may reflect different compositions of precursor compounds accreted by the parent body, rather than significant differences caused by

aqueous or thermal alterations. Indeed, disparities and diversities in amino acid distribution appear within carbonaceous chondrite groups presenting similar petrological types and alteration degree², suggesting other chemical processes, such as local mineral-organic interactions occurring within the asteroid parent body. Carbonaceous chondrites contain >95 wt % minerals, and the impact of these mineral phases on the formation of amino acids during hydrothermal alteration is currently poorly constrained. Therefore, more experimental studies are required to decipher pathways leading to the formation of amino acids in carbonaceous asteroids during hydrothermal alteration.

Here, we investigate the formation of amino acids under asteroidal conditions from hexamethylenetetramine (HMT). HMT is a molecule representative of the evolution of ices from the interstellar medium (ISM) to the solar nebula¹³ and we assume it could have been accreted on primitive small bodies. Laboratory experiments simulating interstellar ices can reproduce the primary processes affecting the organic matter formed in the ISM and the following transformations of the ices during protoplanetary disk evolution toward the solar nebula. These experiments show that from ices composed of simple molecules such as methanol, ammonia and water, a refractory organic residue, called a protoplanetary residue, made of thousands of species, is produced after processing by ultraviolet irradiation and warming (10 K to 300 K)¹³⁻¹⁵. Among molecules formed in the protoplanetary residue, HMT is of primary interest because it is thermodynamically favored during the warming of the ices (it can remain stable at 130-230 °C at low pressure in solid phase) and can represent 50 % of the protoplanetary residue (as evidenced by infrared spectroscopy)^{13,14,16-19}. Previous studies have shown that HMT can form amino acids (up to 50 µM concentrations) when subjected to acidic hydrolysis²⁰. It is also worth mentioning that the analysis, by hydrolysis, of such protoplanetary residues are known to detect amino acids (up to 50 nM; glycine being the most abundant species found)²¹⁻²⁵.

The formation of amino acids is likely influenced by multiple parameters on the parent bodies: nature of the organic and mineral phases, pH, concentration of reactants, temperature, oxidation state, water to rock ratio, duration of aqueous alteration². In this study we focus on the influence of the nature of organic and mineral phases and the duration of the aqueous alteration. We evaluate the synthesis and molecular distribution of aliphatic amino acids during the hydrothermal processing of HMT alone or when mixed with carboxylic acids or in the presence of phyllosilicates in alkaline solutions (pH 10) with heating at 150 °C for different duration, mimicking hydrothermal alteration conditions²⁶. Carboxylic acids are some of the most abundant organic compounds observed in carbonaceous chondrites⁴. Phyllosilicates are the main hydrated minerals in the matrices of carbonaceous chondrites^{26–28}. Furthermore, phyllosilicates can exert strong interaction with organic molecules²⁹ and have shown intimate association with organic matter in various chondrite groups^{30–32}. In this work, we compare the impact of two synthetic smectites of different compositions: i) a montmorillonite, an aluminium-magnesium-bearing smectite (Al-rich smectite), with well-known properties towards organic-mineral associations^{33–35} and ii) a nontronite, an iron-bearing smectite (Fe-rich smectite), to investigate the roles of the smectite composition and properties, regarding the synthesis of amino acids. Analysis by liquid chromatography coupled to mass spectrometry (with fluorescence detection) was performed on the sample, without a hydrolysis step, to reveal the free amino acids produced in the experiments.

2. Materials and Methods

2.1. Synthesis of phyllosilicates

Synthetic phyllosilicates were used to prevent non-desirable organic contamination. They are smectites from the same synthesis batch as the ones used in our previous studies³⁶. The synthesis

used bulk chemicals (silica, aluminum, magnesium, iron) processed via hydrothermal synthesis following a well-tested method by Jaber et al.^{35,37} and Andrieux and Petit³⁸. Briefly, dioctahedral Al-rich 2:1 smectite was synthesized by mixing deionized water, hydrofluoric acid (HF, Sigma Aldrich, 40%), sodium acetate (Sigma Aldrich, 99%), magnesium acetate tetrahydrate ($\text{Mg}(\text{CH}_3\text{CO}_2)_2 \cdot 4\text{H}_2\text{O}$, Sigma Aldrich, 99%), Al and Si salts. HF was used to reach a higher crystallinity³⁹. The hydrogel was kept for 2 hours at room temperature and then introduced into a poly-(tetrafluoroethylene)-lined stainless-steel autoclave (PTFE reactor) and heated at 200 °C for 72 h. Products were recovered by filtration, washed thoroughly with distilled water, and dried at 60 °C for 12 hours. The empirical formula per half unit cell (mainly determined by X-ray fluorescence) is similar to montmorillonite: $\text{Na}_{0.3}(\text{Mg}_{0.3}\text{Al}_{1.7})\text{Si}_4\text{O}_{10}(\text{OH}_{1.5}\text{F}_{0.5}) \cdot n\text{H}_2\text{O}$, hereafter called Al-rich smectite. This phyllosilicate is called Al-rich smectite in this work. The Fe-rich 2:1 smectite was synthesized by mixing sodium metasilicate (Na_2SiO_3 , Sigma Aldrich, 50-53 % SiO_2), aluminum chloride (AlCl_3 , Sigma Aldrich, 98 %), iron chloride (FeCl_3 , Sigma Aldrich, 97%), and magnesium chloride (MgCl_2 , Sigma Aldrich, 98%). The average composition measured by a multi-technical approach, including Mossbauer and X-Ray fluorescence, is $\text{Na}_{0.42}(\text{Al}_{0.18}\text{Fe}_{1.80}\text{Mg}_{0.02})(\text{Si}_{3.60}\text{Al}_{0.38}\text{Fe}_{0.02})\text{O}_{10}(\text{OH})_2 \cdot n\text{H}_2\text{O}$, hereafter called Fe-rich smectite. Detailed methods for the characterization of the synthetic smectites by infrared and X-ray diffraction are presented in supplementary information (Fig. S11).

2.2. Experimental and analytical procedures

Experimental setup

Our experimental protocol has been described previously for the analysis of HMT under hydrothermal conditions^{36,40}. To prepare the experimental mixtures, solutions were prepared: a pH = 10 solution of double-distilled water with KOH (10^{-4} M) degassed with Argon (hereafter called

alkaline solution) and a carboxylic acid solution made of formic (Sigma Aldrich, 95 %), acetic (Sigma Aldrich, 99.7 %) and propionic (Sigma Aldrich, 99.5 %) acids, at 6 M equal concentration, adjusted to pH = 5 using KOH pellets and degassed with Argon (hereafter called CA solution). For mixtures containing HMT-only, 100 mg of HMT powder (Sigma Aldrich >99%) was dissolved in 1 mL of the alkaline solution to obtain a concentration of 0.7 M, which is below the saturation point of HMT in water (6.1 M at 25 °C). For mixtures containing HMT and CA, 100mg of HMT powder was added with 120 µL of the CA solution and 0.88 mL of the alkaline solution to obtain equal concentrations of HMT and CA (i.e. 0.7 M). For the mixture containing smectite, 100 mg of synthetic phyllosilicate was added in the reactor with 100 mg of HMT and 1 mL of the alkaline solution. These mixtures were prepared under Argon atmosphere (> 99.999 %; Air Liquide, ALPHAGAZ 1) in a glove box (< 0.5 ppm O₂) and loaded into sealed 23 mL PTFE reactors. Reactors were then put in an oven with temperature accurately regulated at 150°C for 2, 7 or 31 days in closed systems ($P \geq 6$ bars based on the vapor pressure of water, note that ammonia, formaldehyde or other products formed from HMT can also increase the pressure). At the end of the experiments, the pH (measured on pH paper) values ranged between 8 and 9 for all the mixtures. Each hydrothermal reactor was thoroughly cleaned prior to experiments with different solvents (water, methanol), then left for at least 2 days in water at 150 °C, dried, and finally heated empty for some days at 150 °C.

After the completion of the experiments, the reactors were opened in air and the mixtures transferred from the reactors to Eppendorf tubes (Biopur certified PCR clean) and centrifuged (2 mL, 6 minutes at 12,000 rpm). The soluble compounds were hence separated from the solid³⁶ or the insoluble macromolecular carbon⁴⁰. Half of the final water solution was used for liquid-liquid

extraction with dichloromethane and gas chromatography-mass spectrometry (GC-MS) analysis (reported previously)⁴⁰. The other half was used in these analyses to search for amino acids.

Starting mixtures (0 day), representing the control experiment in Table S11, are the starting materials mixed together, stirred and left for 24 h at 25 °C in a closed Eppendorf (Biopur). Then, the 0 day samples are treated the same way as the hydrothermal experiments (centrifuged, washed with solvents and dried).

Sample procedure for amino acid analysis

Samples were diluted to 200 mM HMT, and 10 μ L aliquots of that concentration were dried down with 20 μ L of sodium borate (0.1 M) buffer pH= 9 to evaporate any amines that were present in the samples. Each dried residue was brought up in 10 μ L of water, and then 20 μ L of Waters AccQ·Tag derivatizing agent and 70 μ L of AccQ·Tag sodium borate buffer were added. Standards consisting of a set of 9 calibrators of amino acids (0.25 to 250 μ M) were prepared in water and treated in the same way (see Table S12 for a complete list of amino acid standards). Both samples and standards were heated for 10 minutes at 55 °C immediately following the addition of the derivatizing agent. The samples were then analyzed via the commercial Waters AccQ·Tag protocol on a Xevo G2 XS time of flight mass spectrometer equipped with an electrospray ionization source (positive ion mode), mass resolution setting of 5,000 $m/\Delta m$ but without external mass accuracy calibration. The Xevo G2 XS electrospray capillary voltage was set to 0.8 keV, the sampling cone to 30 °C, the source temperature to 120 °C, the cone gas flow to 70 L/h, the desolvation temperature to 500 °C, and the desolvation gas flow to 1000 L/h. Samples were introduced via a Waters Acquity UHPLC with fluorescence detector. For UHPLC analysis a 250 μ L syringe, 50 μ L loop, and 30 μ L needle were used. The total injection volume was 1 μ L. Selected amino acid ion traces were quantitated. A linear least-square model was fitted to each proteinogenic amino acid in the standard

calibration set, and these calibration curves were used to quantify the analytes in the samples. For the non-proteinogenic amino acids, the relative instrument responses for these analytes compared to alanine were calculated using calibration standards prepared and analyzed at a later date, and these responses were used together with the alanine calibration curve to quantify these compounds in the samples. A procedural blank sample, i.e. a sample of pure water that has undergone the same preparation and analytical procedures, was used to determine procedural and laboratory backgrounds. Samples were analyzed in triplicate.

This method is robust and rapid, and has been used for many studies (see for example ⁴¹⁻⁴³). The insensitivity to dissolved salts ⁴⁴ permits the analysis of samples without the need for pre-derivatization desalting, however the fluorescent product is not a diastereomer and does not permit chiral separation of amino acids, seen in other methods ⁴⁵.

3. Results

Four sets of experiments were implemented to evaluate the formation of amino acids: HMT-only, HMT with carboxylic acids (CA; formic, acetic, and propionic acids), HMT with Al-rich smectite, and HMT with Fe-rich smectite. Each experiment was running under hydrothermal alteration conditions at 150 °C and pH 10 for 0, 2, 7, and 31 days (Fig. 1; see Methods section for experimental details). The 0-day samples represent the analysis of the starting materials; for most of these mixtures at 0-day, the amounts of amino acids are near detection limits (Table SI1), demonstrating no glycine contamination in the minerals or the HMT standard. However, glycine contamination is observed at 0 day in the HMT+CA experiment, indicating a contamination from the carboxylic acid standards purchased from Aldrich (see methods) (Fig. 1). After 31 days of hydrothermal conditions, the total concentration of amino acids produced ranges from 270 to 1470

μM (Fig. 2, Table SI1). Glycine is the most abundant amino acid produced in all experiments, it represents around 90% of the total amino acids formed (Figs. 1, 2, and SI2). Its abundance increases with time in all experiments except for HMT+CA for which it remained constant between 7 and 31 days ($\sim 400 \mu\text{M}$; Fig. 1). Overall, after 31 days the highest amount of glycine produced is obtained for the HMT+Al-rich smectite experiment ($\sim 1300 \mu\text{M}$ glycine).

After glycine, the most abundant amino acids are alanine, β -alanine and γ -aminobutyric acid (γ -ABA) (Fig 2.). Only trace amounts of α - and β -aminoisobutyric acid (AIB) and α - and β -ABA are observed (Fig. 2, SI2), and with a few exceptions (in the HMT+CA experiments), there is a clear overall increase with time of the abundances of these amino acids in our experiments (Fig 1). In the HMT-only experiment, the amino acid abundances after 31 days of hydrothermal reaction are inversely correlated to the amino acid molecular weights (glycine (C2) \gg α -alanine (C3) $>$ β -alanine (C3) $>$ γ -ABA (C4) concentrations; Fig SI1, Table SI2). This trend is not consistent in the rest of experiments; HMT+CA resulted in similar concentrations of α - and β -alanine and a lower production of γ -ABA (glycine \gg alanine \approx β -alanine \gg γ -ABA), while HMT+Al-rich and HMT+Fe-rich smectites resulted in molecular distributions which favored the formation of γ -ABA (C4) over α - and β -alanine (C3) (Fig SI2, Table SI2). The HMT+Al-rich smectite reaction exhibited the highest concentration of γ -ABA and the highest total production of amino acids after 31 days, $1470 \mu\text{M}$, which is more than twice the abundance of amino acids from HMT-only (Fig 2, Table SI1). Noted that, the glycine to alanine ratio is consistent at about 20 in all experiments. The mixtures containing CA present their peak in amino acid production after 7 days (Fig. 1, Table SI1). No proteinogenic amino acids other than glycine and alanine were detected, despite being targeted for analysis in our samples and procedural blanks (Fig SI3, Table SI3); it thus indicates that biological contamination can be ruled out in our experiment.

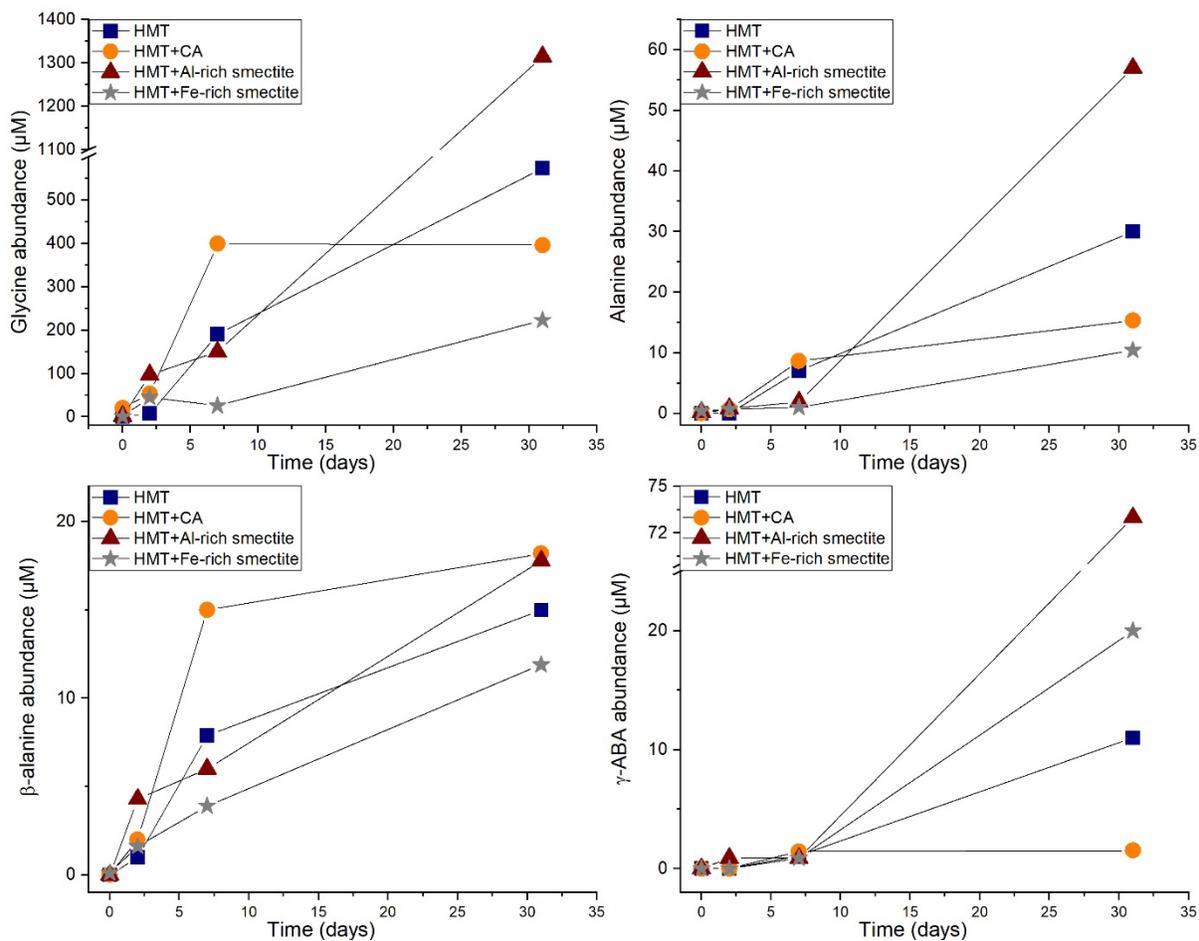


Figure 1. Evolution of glycine, alanine, β -alanine, and γ -ABA abundance formed with time in the four different hydrothermal experiments at 150 °C from HMT, HMT+CA, HMT+Al-rich smectite, HMT+Fe-rich smectite. Values are the average of three measurements from single-ion liquid chromatograms as detailed in the Methods section; standard deviations are smaller than the symbols and are not shown here (Table SI1).

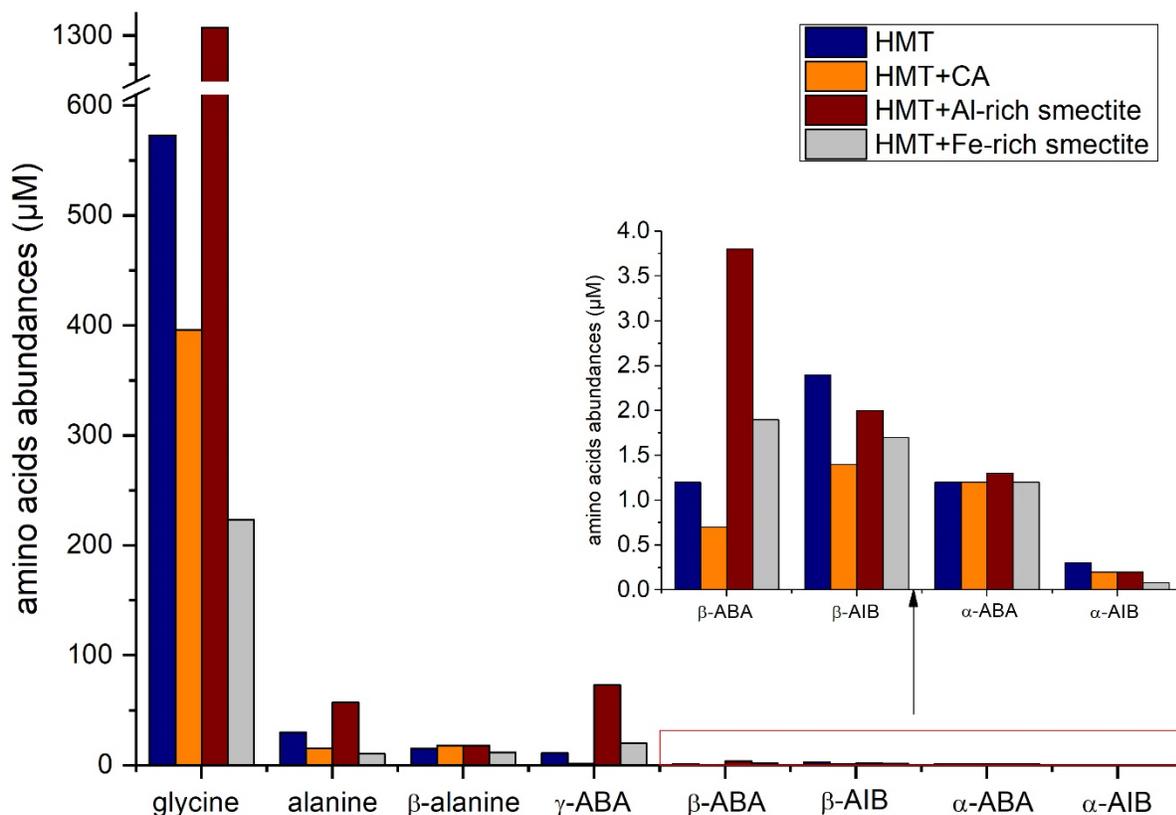


Figure 2. Bar graph showing the abundance of the amino acids formed after 31 days of hydrothermal reaction at 150 °C in the experiments from HMT, HMT+CA, HMT+Al-rich smectite, HMT+Fe-rich smectite. (Analytical error bars are not represented, see table 1).

4. Discussion

4.1. Mechanism of amino acids formation from HMT alone

Our study reveals that amino acids can form in modest abundances, 0.04 to 0.2 yield % (Table SI2) during 31 days of hydrothermal evolution of HMT (0.7 M, 150 °C and pH 10). Previous analyses of these experiments have shown that a complex network of chemical reactions took place^{36,40}. The chemical reaction mechanism that we propose starts from HMT dissociation into

formaldehyde and ammonia, which leads to the condensation of formaldehyde (formose reaction) occurring in parallel to the amine-sugar reactions (Maillard-type reactions). These two reactions result in a rich molecular diversity, dominated by low mass nitrogen-bearing molecules such as aliphatic amines (e.g. methylamine, dimethylamine), nitrogen heterocycle (e.g. pyrazine, imidazole, pyrimidine), amides (e.g. N,N-dimethyl-formamide) and high molecular weight molecules ($m/z > 140$) known as soluble melanoidins⁴⁶⁻⁴⁸. Note that from hydrothermal alteration of HMT-only, insoluble melanoidins were also produced⁴⁰. In presence of phyllosilicates³⁶, previous investigations revealed a lower diversity of free organic products extract in solvent (dichloromethane), with fewer high molecular-weight species. Analyses conducted on the smectite residues displayed the entrapment of organic molecules within the smectites, including ammonium ions (at least 7 wt% of organic matter)³⁶.

Here, the detected amino acids might derive from formaldehyde and ammonia generated by HMT degradation. Because of the absence of a cyanide source in the initial mixture and the unfavorable chemical conditions to form nitriles from formaldehyde and ammonia under our hydrothermal conditions^{49,50}, the Strecker cyanohydrin synthesis may be inactive for the formation of α -amino acids in this work. Our results hence indicate that the formose reaction in the presence of ammonia should be considered as the main reaction mechanism leading to the formation of the amino acids in our experiments^{48,51-53}. The inclusion of ammonia in the formose reaction (also known as the sugar model), has been shown to form glycine through the reaction of glycolic acid with ammonia^{48,54} (Fig. 3). Alanine is expected in lower abundances than glycine, because its formation occurs by the addition of formaldehyde to glycine^{48,53,54}; which is in agreement with the similar glycine/alanine ratio (~ 20) in our experiments after 31 days of reactions. β -Alanine is the product of the reaction between glyceraldehyde and ammonia⁵⁵, while γ -ABA may be formed

from tetrose precursors reacting with ammonia, according to the Sugar model pathways ⁴⁶. Additional formaldehyde additions can lead to the formation of α -AIB and α -ABA but in rather low concentrations ⁵³ (Fig. 3). Since the formose reaction with ammonia can explain the most abundant amino acids detected in our experiments, we suggest that this is the main synthetic pathway for the formation of amino acids from HMT (Fig. 3). This mechanism is consistent with previous experiments starting from formaldehyde and ammonia. Indeed, the relative abundances and molecular distributions of amino acids from the HMT-only reaction are similar to those found in formaldehyde-ammonia-glycolaldehyde systems ^{48,54,56}. In this later system, the reaction is relatively faster with a highest production of alanine (alanine >> glycine > β -alanine > γ -ABA) likely due to the initial presence of glycolaldehyde as starting reagent and the use of Ca(OH)₂, known as formose reaction catalysts ^{46,57,58}, unlike our experiments in which HMT was the only starting reactant.

In addition, previous investigations have shown that the Maillard reaction model ⁴⁷ added to the formose reaction led to an increase in chemical reactivity and molecular diversity ⁴⁰ and thus several routes could have occurred in parallel to the formaldehyde and ammonia reaction in our reaction network to produce amino acids. The non-proteinogenic *n*- ω -amino acids (*i.e.*, β -alanine and γ -ABA) may be the ring-opening decomposition products of aliphatic lactams produced from Maillard-like reactions. The production of lactams, such as methyl-pyrrolidinone observed by GC-MS in our previous work ^{36,40}, could then induce a larger production of γ -ABA ⁵⁹. Therefore, this reaction mechanism may explain the late formation of γ -ABA (production sharply increases after 7 days of reaction, Fig. 1), given that lactams would have to form first, before hydrolyzing into amino acids in our reaction network.

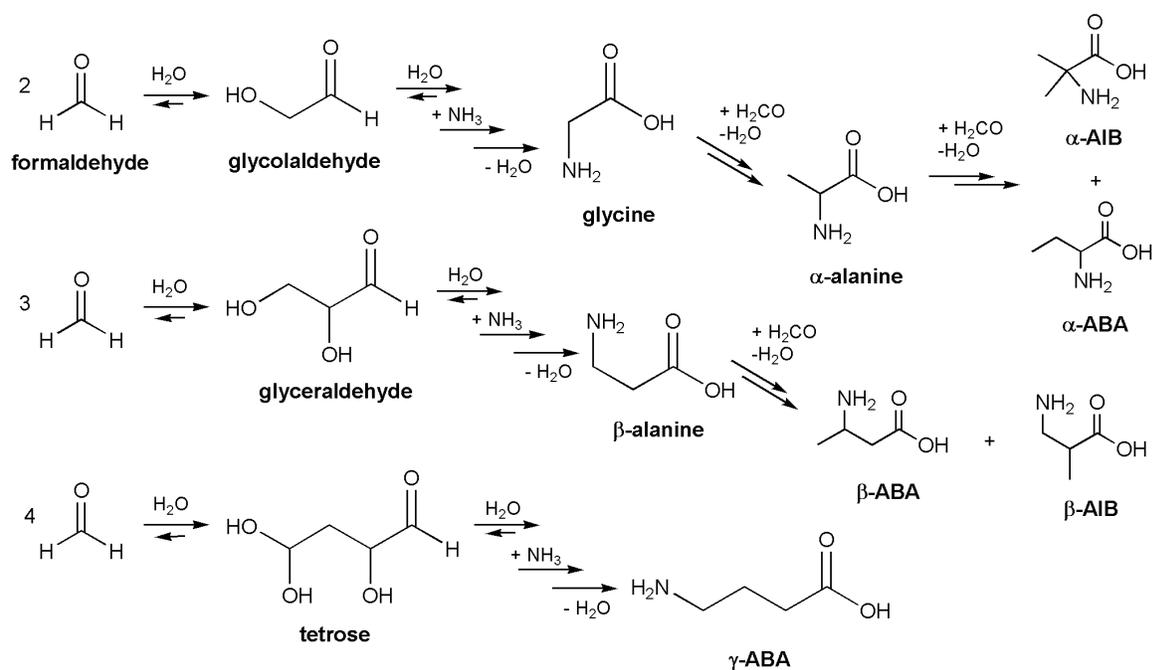


Figure 3. Putative pathways for the formation of the observed amino acids distribution from HMT decomposition (producing formaldehyde and ammonia) via the formose reaction and the sugar model. The first step is the polymerization of formaldehyde in water corresponding to the formose reaction.

4.2. Impact of carboxylic acids and smectites on the production of amino acids

Experiments including carboxylic acids (CA) as part of the starting mixtures, exhibit a plateau in the production of the four main amino acids studied here after seven days of reaction (Fig. 1). Except for β -alanine, a lower abundance of amino acids was even observed from these samples after 31 days of reaction. The yield of amino acids in these experiments is only 66% of that of the 31 days HMT-only experiment (Fig. 2, Table SI1). Two main reasons can be proposed for these observations. Firstly, the formose and Maillard-like reactions compete with the nucleophilic addition of an amine to a carboxylic acid to produce amides⁶⁰⁻⁶². The formation of amides has been observed on non-targeted GC-MS analyses of HMT+CA experiments, reported in supplementary text (see SI). Aliphatic amides are formed after two days of experiments (Fig. SI4, SI5, Table SI4). At the beginning of the hydrothermal reaction (before 7 days), the presence of CA seems to accelerate the formation of glycine, alanine, β -alanine, and γ -ABA compared to HMT-only experiments (Fig. 1, Table SI1); however, the drop in concentration of ammonia and amines caused by reaction with carboxylic acids for the formation of amides, may hamper the production of larger amounts of amino acids. Secondly, because of the presence of CA and the production of amides, the pH of the mixture may have varied through the course of the experiments. Indeed, the large production of amides during the first days, which are neutral species (pH~7) could have reduced optimum conditions for the formose reaction between 2 and 7 days. The formose reaction is favorable in alkaline pH⁴⁶, and thus a decrease of the pH could have stop the production of amino acids. Nonetheless, this should have been transitory since the pH of the 7 days HMT+CA sample ranges between 8 and 9.

In the presence of smectites, the distribution of amino acids changed, most notably for γ -ABA. We propose that γ -ABA may be produced either by the formose reaction or by lactam ring opening;

thus, it might be possible that the smectites used here, favored the production of tetroses⁶³ or the lactam ring opening, enhancing the formation of γ -ABA over α - and β -alanine and the α - and β -ABA isomers. Previously, we have observed that the negatively charged surface of our smectites (edge and interlayer space) can adsorb positive or polar compounds such as sugars or ammonium derivatives³⁶. The surface of smectites, especially montmorillonites, are also known to favor the production of peptides and sugars^{64,65}. The Al-rich smectite used in our experiments may have similar properties to those of montmorillonite, which may explain the higher abundance of amino acids and particularly of γ -ABA from HMT (Fig. 2). Although the chemical interactions between the molecules and the smectite are difficult to fathom³⁶, the formose reaction is known to be sensitive to and catalyzed by multivalent cations (typically Ca^{2+})⁵⁸. In our previous analyses on the smectite residues leftover after 31 days of hydrothermal alteration with HMT³⁶, we noted the partial transformation of the Al-rich smectite into kaolin phyllosilicates ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$). Such mineral transformations for the Al-rich smectite have undoubtedly leached some Mg^{2+} and Al^{3+} in the solution, which could have act as catalyst of the formose reaction. This may explain the twice higher production of amino acids in the HMT+Al-rich smectite samples compared to HMT alone. The smectite residues, reported previously³⁶, also present an increase of the interlayer spacing of the phyllosilicate structure, especially in the Fe-rich smectite hydrothermal residue after 31 days of reactions³⁶. By infrared spectroscopy, we identified ammonium cations (NH_4^+), likely indicating an exchange between Na^+ and NH_4^+ (also in the Al-rich smectite samples), and so the release of Na^+ in the solution. The chemical composition of our Fe-rich smectite remaining unchanged, the presence of Na^+ in the solution seems to be not sufficient to catalyze the formose reaction and the production of amino acids (since the abundance of amino acids formed in the Fe-rich smectite mixture are the lowest). Further experiments are needed to validate such cation

effects (Mg^{2+} or Al^{3+} or Na^{2+}) on the formose/ammonia reaction under hydrothermal conditions. In addition, two other factors can be discussed for the samples with Fe-rich smectite showing the lowest total amino acids production, with γ -ABA remaining the second most abundant amino acid formed (Table SI2). Firstly, the Fe-rich smectite has a specific surface area ($42 \text{ m}^2/\text{g}$) twice as small as the Al-rich smectite ($77 \text{ m}^2/\text{g}$)³⁶, thus probably adsorbing less compounds than the Al-rich smectite. Secondly, previous elemental analysis, infrared and X-ray spectroscopy analyses showed a higher content in N atoms adsorbed in the Fe-rich smectite, mainly related to ammonium/amine cations³⁶. These latter ions could be strongly adsorbed on the negative Fe-rich smectite layers because of the higher negative charge induced by iron located in both tetrahedral and octahedral layers, compared to aluminum ions located only in octahedral layers in the Al-rich smectite^{29,36}. In this case, the surface would be saturated hence not available for enhancing the formose/ammonia reactions.

These results using smectites and HMT, show a manifest link between the chemical composition of the mineral and the production of amino acids, as well as on the C3-C4 amino acid/glycine ratio (Table SI2, Fig. 1).

4.3. Implications for the origin of extraterrestrial amino acids in meteorites

Amino acids in extraterrestrial samples have been investigated for decades, because of their potential implication in the origin of life; nevertheless, their formation and evolution in carbonaceous chondrites remain contentious. Our observations show that the formose reaction with ammonia, or Sugar model, should be considered as a potential synthetic pathway to meteoritic amino acids. While the formose/ammonia reaction is known to lead to amino acids in aqueous environments on Earth^{48,51}, it has not been proposed for extraterrestrial amino acid formation yet.

We especially highlight that α - and n - ω -amino acids can be formed from this formose with ammonia reaction (Fig. 3) and not only from the Strecker cyanohydrin and Michael addition reactions. Hence, the combination of all these reactions and the diverse suite of organic precursors accreted in asteroids may account for the large diversity and abundance of amino acids in carbonaceous chondrites, such as Murchison, Orgueil⁶⁶ and Paris¹¹. The Paris meteorite, the least aqueously altered CM chondrite⁶⁷, is particularly depleted in amino acids compared to Murchison (CM), which could reinforce the importance of the aqueous alteration for the formation of amino acids inside the meteorite parent bodies¹¹. Note that extensive hydrothermal alteration or heating is also known to alter and decrease the abundance of amino acids². Moreover, the production of some amino acids can also reach a maximum after some time of hydrothermal alteration, as observed with HMT+CA experiments, and then decrease if the alteration continues; thus, some amino acids may therefore be only intermediates in a complex chemical network.

While some studies point to the diversity of the organic precursors to explain amino acid variations, the role of the mineral phases during hydrothermal alteration has been barely considered⁶⁸. Organic matter and minerals are intimately associated in the chondrite matrices^{12,30–32,69}, and their co-evolution during hydrothermal alteration has now been proposed by several authors^{12,30–32,36,70}. The present experiments suggest that smectites have a significant impact on the nature and abundance of amino acids formed during hydrothermal alteration of HMT. This may be due to the different adsorption capacity and reactivity of smectites, which favor different chemical pathways. In light of our study, the peculiar distribution of the C4 amino acids such as γ -ABA, analyzed in a wide range of carbonaceous chondrites⁵, can be interpreted in part as the result of the mineral phase composition. While the most abundant meteoritic minerals are phyllosilicates, iron-oxides, sulfates, or carbonates co-exist in meteorites and could also potentially

affect the formation of amino acids⁶⁸. The variable mineralogy of the parent bodies can explain the diverse distribution of amino acids, even considering the hypothesis of the accretion of common precursors among carbonaceous chondrite groups. In addition, hydrothermal alteration occurs mainly in micro-localized environments within the parent body^{30–32,70,71}, which may create independent local surroundings where different reactions with minerals could have occurred. Analysis of amino acid distributions at the same scale as the hydrothermal alteration could allow the observation of larger variability in the amino acid distribution in carbonaceous chondrites.

The large enrichment in deuterium (D) observed for the amino acids in carbonaceous chondrites (δD values ranging from +180 to +3419‰ for amino acids in Murchison)^{8,72–74}, may relate them to interstellar precursors such as HMT. This statement is based on the high D/H fractionation process occurring at low temperature in cold interstellar environments, where different molecules (e.g., methanol, formaldehyde, ammonia) are known to be enriched in D^{9,75}. This scenario suggests a direct continuity between molecules formed in the course of ISM evolution to the solar nebula and the molecules analyzed in carbonaceous chondrites. Deuterated HMT, formed from D-rich molecules in interstellar ices⁷⁶, could have been accreted on the parent bodies of meteorites and hence, would have resulted in D-rich amino acids. Further experiments are planned to investigate this D-rich signature upon evolution of the organic matter in different environments, including in carbonaceous chondrites during hydrothermal alteration.

5. Conclusion

Our study reveals that α -, β -, and γ -amino acids can be synthesized from the hydrothermal alteration in asteroid conditions of HMT, a molecule produced during the evolution of interstellar ice analogs. While amino acid synthesis in extraterrestrial samples was commonly explained by

the Strecker cyanohydrin and Michael addition reactions that require hydrogen cyanide or nitrile sources, we propose that these amino acids may also be formed via the formose reaction with ammonia and Maillard-type reactions. These reactions are induced by formaldehyde and amines, produced from the decomposition of HMT, a potential precursor accreted in the parent body. We further observed the impact of minerals and carboxylic acids on the distribution and abundance of amino acids in our experimental simulation. We highlight the impact of the nature of smectites, which can hamper (Fe-rich smectite) or stimulate (Al-rich smectite) the formation of amino acids. More investigation on organic-mineral interactions are under progress, to improve the understanding of amino acid formation and more widely to organic matter in extraterrestrial environments. Besides meteorites, this pioneering work opens new opportunities for the search of amino acids in prebiotic terrestrial and extraterrestrial environments, such as Mars, by giving first indications on the suitable mineral environment for amino acid formation from hydrothermal alteration of simple universal molecules (formaldehyde and ammonia).

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Author Contributions

V.V. L.R. S.B. M.J. conceived research; M.J. synthesized the phyllosilicates; V.V. designed and performed experiments; V.V. and H.L.M. performed UHPLC analysis. H.L.M. performed data

treatment, helped by J.P.D. J.E.E. J.C.A. and V.V.; V.V. wrote the first version of the manuscript and all authors contributed to the final manuscript.

Supplementary information:

Supplementary information is provided to detail the method used and present more graphic results.

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