



Cite this: DOI: 10.1039/c7cp06790a

The hydrolysis of epoxides catalyzed by inorganic ammonium salts in water: kinetic evidence for hydrogen bond catalysis†

 B. Nozière,^a F. Fache,^b A. Maxut,^a B. Fenet,^c A. Baudouin,^c L. Fine^a and C. Ferronato^a

Naturally-occurring inorganic ammonium ions have been recently reported as efficient catalysts for some organic reactions in water, which contributes to the understanding of the chemistry in some natural environments (soils, seawater, atmospheric aerosols, ...) and biological systems, and is also potentially interesting for green chemistry as many of their salts are cheap and non-toxic. In this work, the effect of NH_4^+ ions on the hydrolysis of small epoxides in water was studied kinetically. The presence of NH_4^+ increased the hydrolysis rate by a factor of 6 to 25 compared to pure water and these catalytic effects were shown not to result from other ions, counter-ions or from acid or base catalysis, general or specific. The small amounts of amino alcohols produced in the reactions were identified as the actual catalysts by obtaining a strong acceleration of the reactions when adding these compounds directly to the epoxides in water. Replacing the amino alcohols by other strong hydrogen-bond donors, such as trifluoroethanol (TFE) or hexafluoroisopropanol (HFIP) gave the same results, demonstrating that the kinetics of these reactions was driven by hydrogen-bond catalysis. Because of the presence of many hydrogen-bond donors in natural environments (for instance amines and hydroxy-containing compounds), hydrogen-bond catalysis is likely to contribute to many reaction rates in these environments.

Received 5th October 2017,
Accepted 8th December 2017

DOI: 10.1039/c7cp06790a

rsc.li/pccp

1. Introduction

Most chemical reactions in natural environments near or at the Earth surface and in biological systems take place in aqueous media containing inorganic ions. The inorganic ammonium ion, NH_4^+ , is one of the most common in these media and is known to interfere with organic or biochemical reactions in soils,¹ seawater,^{2,3} atmospheric aerosols,^{4–8} and biological systems.^{9,10} Understanding the role of NH_4^+ in organic reactions in water thus improves the understanding of the chemistry in these environments. In some reactions NH_4^+ has been shown to act as a catalyst, by a mechanism thought to proceed through iminium and/or enamine intermediates,^{5,8} as in organocatalysis with amines and amino acids.^{11–13} In these cases, the catalytic

effect does not seem to be as impacted by water as with amines or amino acids.¹⁴ In addition, NH_4^+ salts are generally cheaper than organocatalysts and many of them are non-toxic: NH_4Cl and $(\text{NH}_4)_2\text{SO}_4$ are food additives (“salmiak” or E510 and E517, respectively), and NH_4I is a pharmaceutical and cosmetic additive. Thus, inorganic ammonium salts could be interesting catalysts for greener organic synthesis or chemical manufacturing in water.

The present work investigates the role of NH_4^+ ions on reactions that do not proceed by iminium or enamine intermediates: the hydrolysis of epoxides in water. For this, the hydrolysis of 1,2-epoxybutane (1,2-EB), *cis*-2,3-epoxybutane (2,3-EB), 2,3-dimethyl-2,3-epoxybutane (DM-2,3-EB), and *cis*- and *trans*-(2-methyloxirane-2,3-diyl)dimethanol (IEPOX 3 and IEPOX 4), chosen for their environmental relevance,^{15,16} were studied in water at room temperature ($T = 303 \pm 3$ K) and in the presence of various NH_4^+ salts. The products and kinetics of the reactions were studied in the presence of ammonium- and non-ammonium salts. The dependence of the hydrolysis rates on NH_4^+ and the potential contribution of Brønsted acid or base catalysis to these rates were then examined by varying both the NH_4^+ activity, $a_{\text{NH}_4^+}$, and pH of the solutions. Finally, hydrogen bond catalysis was identified as the kinetically-controlling mechanism by examining the hydrolysis rate obtained when

^a Institut de Recherches sur la Catalyse et l'Environnement de Lyon (IRCELYON), CNRS & Université Claude Bernard Lyon 1, Villeurbanne, France.

E-mail: barbara.noziere@ircelyon.univ-lyon1.fr

^b Institut de Chimie et Biochimie Moléculaires et Supramoléculaires (ICBMS), CNRS & Université Claude Bernard Lyon 1, Villeurbanne, France

^c Centre Commun de RMN (CCRMN), Université Claude Bernard Lyon 1 & Ecole Supérieure de Chimie, Physique, Electronique de Lyon (CPE), Villeurbanne, France

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c7cp06790a

adding directly in water the amino alcohols produced in the presence of NH_4^+ or other strong hydrogen-bond donors.


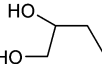
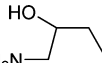
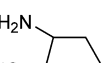

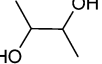
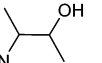

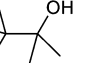
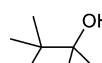
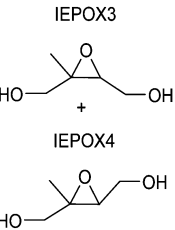
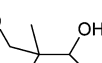
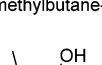
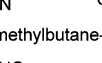
2. Results and discussion

2.1 Specific effect of NH_4^+ on the hydrolysis rate

A complete list of the kinetic experiments and their conditions is given in Table S1 of the ESI.† The kinetic effect of NH_4^+ on

the hydrolysis of epoxides was established by studying the reactions of 1,2-EB and 2,3-EB in pure water and in aqueous solutions of ammonium and non-ammonium salts: NH_4F , $(\text{NH}_4)_2\text{SO}_4$, NaCl , MgSO_4 , and Na_2SO_4 . In all cases, the formation of diols (structures in Table 1) confirmed that hydrolysis took place and the reaction rates were measured from the formation of these compounds (Fig. 1 and Experimental section for details on the kinetic analysis). As the hydrolysis of epoxides in pure water is known to be of the first order¹⁷ and our study will show

Table 1 Reaction products observed, with their retention times ("RT"), main mass fragments in GC/MS analysis, and chemical shifts in $^1\text{H-NMR}$ (in bold = shifts used in the kinetic and yield analysis)

Epoxide	Main chemical shifts, δ_{H} (ppm)	Main products	RT (min)	Main MS fragments (amu)	Main chemical shifts, δ_{H} (ppm)
 1,2-EB	1.0–1.1 2.69–2.72 2.9–3.0 3.1–3.2	1,2-butanediol	9.45	31, 41, 59	0.96–0.99
					1.37–1.59
					3.45–3.51
					3.58–3.68
		Organosulfates (in $(\text{NH}_4)_2\text{SO}_4$ only)			3.75–3.82
 2,3-EB	1.27–1.32 3.21–3.33	2,3-butanediol	9.76	43, 45, 57	1.12–1.17
					3.59–3.62
					3.71–3.77
 DM-2,3-EB	1.37–1.39	2,3-dimethyl-2,3-butanediol	9.87	43, 59, 85	1.22–1.25
					3.15–3.22
					1.34–1.36
 IEPOX3 + IEPOX4	1.39–1.40	2-methylbutane-1,2,3,4-tetrol	—	—	1.12
					3.35–3.85
					??
					??

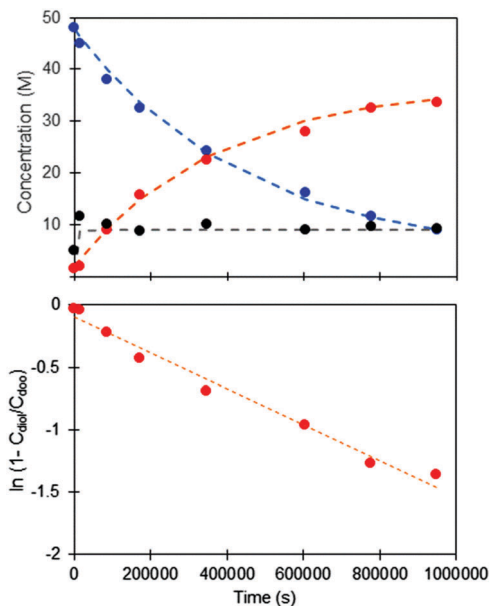


Fig. 1 Experimental time-profiles and kinetic analysis for the hydrolysis of 1,2-EB in an aqueous solution of $(\text{NH}_4)_2\text{SO}_4$ 0.5 M: top: real-time evolution of the concentrations of 1,2-EB (blue), 1,2-butanediol (red) and 1-amino-2butanol (black) observed by NMR. Bottom: First-order analysis for 1,2-butanediol giving the hydrolysis rate, k^1 (s^{-1}).

that this is also the case in salt solutions (below in this section), first-order analyses were applied to the concentration profiles (Fig. 1) to obtain first-order rates, k^1 (s^{-1}) (Table S1, ESI†). The uncertainties of these rates were estimated to $\pm 15\%$, which is typical for absolute reaction rates determined experimentally. The hydrolysis rates measured in pure water for 1,2-EB and 2,3-EB, k_{N}^1 (s^{-1}), were in agreement with those reported in the literature (Table 2).¹⁷ For DM-2,3-EB and IEPOX, the k_{N}^1 was estimated as the lower limits of the rates measured in this work for the respective compounds. The hydrolysis rates in NH_4F

and $(\text{NH}_4)_2\text{SO}_4$ solutions were significantly larger than those in pure water, while those in NaCl, MgSO_4 , or Na_2SO_4 solutions were lower or comparable, even at large salt concentrations (1 M). These results demonstrated the specific effect of NH_4^+ on the reaction kinetics, and the lack of the effect of the other ions (Na^+ , Mg^{2+}) and counter-ions (F^- , Cl^- , SO_4^{2-}). This, in turn, ruled out a catalytic mechanism driven by electrostatic effects (for instance, ionic force).






The order of the reaction in 1,2-EB, 2,3-EB, and DM-2,3-EB in the ammonium solutions was investigated by comparing the initial formation rate for the diols with the initial concentration of epoxide for solutions with $a_{\text{NH}_4^+} = 0.12$ and 0.5 M. The slopes obtained in the ln–ln scale were all close to unity, within uncertainties (1.1, 0.9, 1.0 and 1.3, 1.0, 1.2, respectively), indicating that the reactions were of the first order in epoxide and validating the first-order kinetic analysis. For each of the epoxides studied, the hydrolysis rate measured in ammonium solutions, k^1 , was then corrected for the corresponding rate in pure water,

$$k'^1 = k^1 - k_{\text{N}}^1, \quad (1)$$

and the variations of k'^1 with $a_{\text{NH}_4^+}$ were studied for all the epoxides. The results are shown in Fig. 2.

In all cases, k'^1 increased strongly with $a_{\text{NH}_4^+}$, and exceeded the rate in pure water by a factor of 6 to 25 in the most concentrated ammonium solutions. The slopes of the lines in Fig. 2 (in ln–ln scale) were 1.2, 1.0, 0.7, and 1.1 for 1,2-EB, 2,3-EB, DM-2,3-EB, and IEPOX, respectively, thus implying that the hydrolysis rate k'^1 was of the first order in $a_{\text{NH}_4^+}$. Note that the rates measured for the lowest concentration of ammonium ($a_{\text{NH}_4^+} = 0.12$ M) for DM-2,3-EB were not taken into account as, after subtraction of k_{N}^1 , they contained large uncertainties. As k^1 had been shown above to be of the first order in epoxide, the first order in $a_{\text{NH}_4^+}$ indicated that the rate-limiting step of the

Table 2 Rate coefficients measured in this work for the hydrolysis of epoxides catalyzed by NH_4^+ ($k_{\text{NH}_4^+}^{\text{II}}$), H^+ ($k_{\text{H}^+}^{\text{II}}$), and H_2O ($k_{\text{OH}}^{\text{II}}$) and comparisons with the literature for acid, neutral, and base catalysis (k_{OH}^{I})

Epoxide	$k_{\text{NH}_4^+}^{\text{II}}$ ($\text{M}^{-1} \text{s}^{-1}$)	$k_{\text{H}^+}^{\text{II}}$ ($\text{M}^{-1} \text{s}^{-1}$)	$k_{\text{OH}}^{\text{II}}$ ($\text{M}^{-1} \text{s}^{-1}$)	k_{N}^{I} (s^{-1})
1,2-EB 	$(3.0 \pm 0.5) \times 10^{-6}$	$(5.2 \pm 1.6) \times 10^{-2}$ 7.4×10^{-2} (ref. 18)	1×10^{-4} (ref. 17)	5.5×10^{-7} (ref. 17)
2,3-EB 	$(3.9 \pm 0.9) \times 10^{-6}$	$(2.0 \pm 0.5) \times 10^{-2}$ 1.5×10^{-2} (ref. 17) 0.218	1×10^{-4} (ref. 17)	1×10^{-6} (ref. 17)
DM-2,3-EB 	$(55 \pm 11) \times 10^{-6}$	1.5 ± 0.3 15 (ref. 18)	1×10^{-4} (ref. 17)	5×10^{-6}
IEPOX3 				
IEPOX4 	$(0.16 \pm 0.02) \times 10^{-6}$	$(2.5 \pm 1.5) 10^{-2}$ 3.6×10^{-2} (ref. 19 and 20) 5×10^{-2} (ref. 21 and 22)	1×10^{-4} (ref. 17)	1×10^{-8}

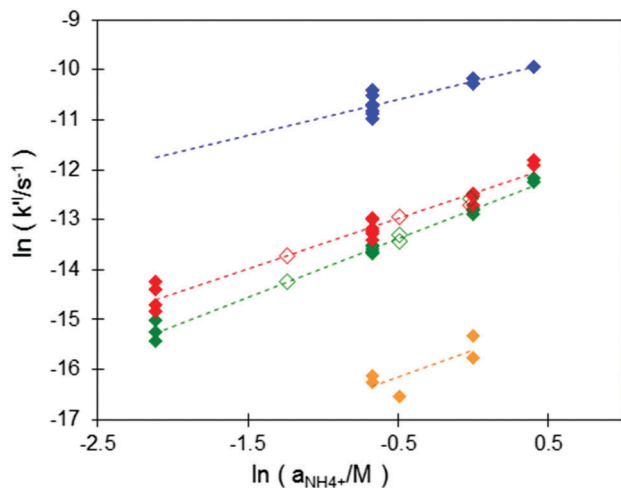


Fig. 2 Variations of the corrected hydrolysis rates, k^I , with $a_{\text{NH}_4^+}$ in aqueous solutions of NH_4F (open symbols) and $(\text{NH}_4)_2\text{SO}_4$ (full symbols) at 303 K for 1,2-EB (green), 2,3-EB (red), DM-2,3-EB (blue), and IEPOX (yellow).

hydrolysis mechanism was the first reaction between the epoxide and NH_4^+ . Second-order rate coefficients, $k_{\text{NH}_4^+}^{\text{II}}$ ($\text{M}^{-1} \text{s}^{-1}$), were then obtained for each epoxide by dividing k^I by $a_{\text{NH}_4^+}$. The results are given in Table 2 and show that these rate coefficients vary widely with the structure of the epoxide, increasing by over a factor of 10 from a single alkyl-substituted to a four-time substituted epoxide (from 1,2-EB to DM-2,3-EB), and decreasing by over a factor of 20 with the presence of two hydroxyl groups on the epoxide (from 1,2-EB to the IEPOX).

2.2 Potential contributions of general and specific acid or base catalysis to the hydrolysis rate

The potential contribution of acid or base catalysis to the corrected reaction rate, k^I , was investigated by measuring this rate in ammonium solutions with a pH value between 5.7 and 10. This allowed checking both for the potential contribution of strong (or “specific”) acid or base catalysis, indicated by the variations of k^I over a wide range of pH, and for the contribution of weak (or “general”) acid catalysis by various species present in the reaction mixtures, indicated by a local variation of k^I near $\text{pH} = \text{p}K_{\text{a}}$.²³ In particular, the range of pH studied here allowed examining the potential role as weak acid catalyst of $\text{NH}_4^+/\text{NH}_3$ ($\text{p}K_{\text{a}} = 9.25$) and of the amino alcohols produced in the reactions (*cf.* Section 2.3, $\text{p}K_{\text{a}} = 8\text{--}10$). The values of k^I obtained at these different pH values are shown in Fig. 3 for $a_{\text{NH}_4^+} = 0.51 \text{ M}$ (full symbols) and given in Table S1, ESI† for all the other values of $a_{\text{NH}_4^+}$ studied. These results clearly show that k^I did not vary with pH over the range studied, which ruled out the contribution of both strong and weak acid or base catalysis to the measured hydrolysis rate in this work, including the potential roles of NH_4^+ or amino alcohols.

For comparison, the hydrolysis rates resulting from specific (strong) acid catalysis were also measured for each epoxide in sulfuric acid solutions. The reaction rates obtained by first-order analyses are listed in Table S1, ESI.† They were corrected

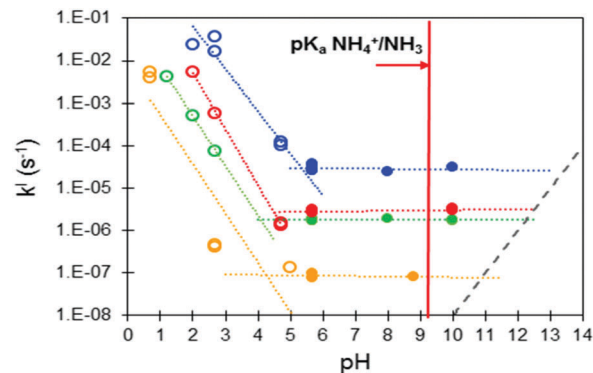


Fig. 3 Variations of the corrected hydrolysis rates, k^I (s^{-1}), with pH in ammonium solutions with $a_{\text{NH}_4^+} = 0.51 \text{ M}$ (full symbols) and in sulfuric acid solutions (open symbols) and expected variations due to strong base catalysis (black dashed line). The dashed lines represent the best fits to linear regressions. Green = 1,2-EB; red = 2,3-EB, blue = DM-2,3-EB, yellow = IEPOX.

for the rates in pure water and the resulting k^I (s^{-1}) are shown in Fig. 3 (open symbols) and listed in Table S6, ESI.† The corresponding second-order rate coefficients, $k_{\text{H}^+}^{\text{II}}$ ($\text{M}^{-1} \text{s}^{-1}$), obtained by dividing k^I by the activity of H^+ , a_{H^+} , are given in Table 2. They were generally in good agreement with those reported in the literature, especially those reported in ref. 17, thus confirming the validity of our measurements and analyses.

The potential contribution of strong base catalysis to the measured hydrolysis rates was also determined from the corresponding rate coefficients reported in the literature (see Table 2). The results are reported in Fig. 3 (black dashed line). Fig. 3 thus clearly shows that, in ammonium solutions (full symbols), k^I does not display any of the strong variations with pH that are typical for strong acid or strong base catalysis. In Table S6, ESI,† the contribution of the strong acid to k^I is shown not to exceed 10% in most cases and that of the strong base catalysis to be negligible over the entire range of $a_{\text{NH}_4^+}$ studied.

2.3 Product identification and yields

As indicated in the Experimental section, the products of all the reactions studied were analyzed by NMR and GC-FID. For all the reactions, the NMR spectra at a large conversion ($> 50\%$) displayed characteristic shifts identical to those of the authentic standards of the expected diol or tetrol products (Fig. 4 for the reaction of 1,2-EB and Section S2, ESI† for the others), confirming that these compounds were the main products. For the reactions of 1,2-EB, 2,3-EB, and DM-2,3-EB this was also confirmed by GC/MS analyses, where the chromatograms at large conversion displayed one prominent peak (Section S3, ESI†), with a retention time and mass spectrum identical to those of the standards of 1,2-butanediol, 2,3-butanediol, and 2,3-dimethyl-2,3-butanediol, respectively (Table 1). The NMR spectra also indicated the formation of amino alcohols in the reactions (Fig. 4 and Section S2, ESI†). For 1,2-EB the formation of 1-amino-2-butanol and 2-amino-1-butanol was unambiguously confirmed by comparison with authentic standards (Fig. 4). In the reaction of 2,3-EB,

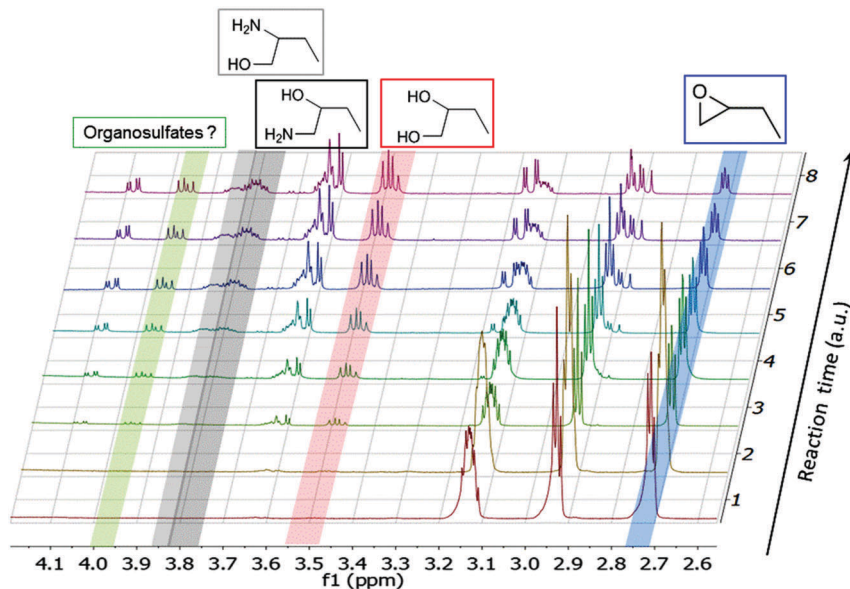


Fig. 4 Evolution of the ^1H -NMR spectrum during the reaction of 1,2-EB in aqueous solutions ($(\text{NH}_4)_2\text{SO}_4$ 0.5 M), evidencing the formation of 1,2-butanediol (red region), 1-amino-2-butanol and 2-amino-1-butanol (grey regions) and possibly organosulfates (green region).

the formation of amino alcohol was indicated by a triplet at 3.15 ppm, typical of protons adjacent to $-\text{NH}_2$ groups.

For the reaction of DM-2,3-EB the formation of amino alcohol was only indicated by the formation of a singlet at 1.34 ppm, corresponding to the methyl groups on the quaternary carbon bearing the $-\text{NH}_2$ substituent, as expected from the structure in Table 1. For the IEPOX, the formation of amino alcohol (expected structures in Table 1) could not be confirmed because of the complexity of the spectra. Finally, in the reaction of 1,2-EB in $(\text{NH}_4)_2\text{SO}_4$ solutions the formation of triplets near 4 ppm, that did not form in NH_4F solutions, suggested the formation of small amounts of organosulfates. The product yields were quantified by NMR and, for the alcohols, also by GC/FID (Table S1, ESI † and Experimental section for details on the quantifications). In the reaction of 1,2-EB, the yield of 1,2-butanediol decreased with $a_{\text{NH}_4^+}$, from about 85% with $a_{\text{NH}_4^+} = 0.1$ M to 25% with $a_{\text{NH}_4^+} = 1.5$ M. Correspondingly, the amino alcohol yield increased from 30% with $a_{\text{NH}_4^+} = 0.3$ M to 65% with $a_{\text{NH}_4^+} = 1$ M (Fig. 5), where 1-amino-2-butanol represented about 2/3 and 2-amino-1-butanol about 1/3, which was consistent with previous studies.²⁴ The diol and amino alcohols thus accounted, together, for 85 to 90% of the products of 1,2-EB in all the solutions. In the $(\text{NH}_4)_2\text{SO}_4$ solutions, the organosulfate yield was estimated to be 15% or less. In the reactions of 2,3-EB, and DM-2,3-EB the diol yields were larger and decreased less with $a_{\text{NH}_4^+}$ than for 1,2-EB (93 to 70% and 100 to 79%, respectively. Fig. 5). For 2,3-EB the amino alcohol yield measured was between 8 and 15% and increased with $a_{\text{NH}_4^+}$ so that the diol and amino alcohol together accounted for about 100% of the products (Fig. 5). For DM-2,3-EB, the amino alcohol yield measured was about 2%. For the hydroxy-substituted epoxides, IEPOX3 and 4, the tetrol yields were 78 and 67%, respectively. Thus, all the epoxides studied produced some amounts of amino-alcohols, and in quantities increasing

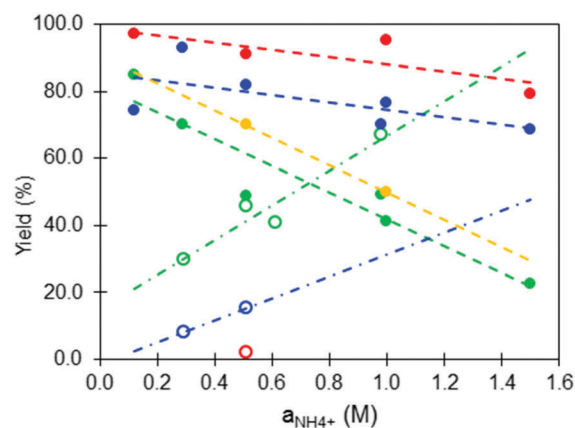


Fig. 5 Variations of the yields for alcohols (full symbols) and amino alcohols (open symbols) with $a_{\text{NH}_4^+}$ in the hydrolysis of 1,2-EB (green), 2,3-EB (blue), DM-2,3-EB (red), IEPOX (yellow).

with $a_{\text{NH}_4^+}$. In H_2SO_4 solutions, the alcohol yields measured were all close to 100%, within uncertainties (102 ± 1 , 99 ± 2 , 97 ± 6 , 92 ± 3 for 1,2-EB, 2,3-EB, DM-2,3-EB and IEPOX, respectively) and independent of pH, in agreement with the literature.¹⁸

2.4 Identification of the catalytic mechanism

Monitoring the reactions in real time showed that the amino alcohols produced were not further consumed and that their concentrations remained constant (Fig. 1). As these compounds are known to be efficient catalysts for the hydrolysis of epoxides^{25,26} and no other type of intermediates resulting from the epoxy and NH_4^+ could be proposed, their potential role as the actual catalysts for the reactions in ammonium solutions was investigated. The hydrolysis of 1,2-EB and 2,3-EB were thus studied in water and in the presence of 1-amino-2-butanol only (Table S1, ESI †).

In both cases hydrolysis took place and the expected diols were produced with large hydrolysis rates, k^l , comparable or larger than those measured in the most concentrated ammonium solutions (Table S1, ESI[†]), while the amino alcohol was not consumed. This confirmed the role of the amino alcohols as the actual catalysts in the ammonium solutions. Based on similar reactions in the literature, the mechanism proposed for the observed catalytic effect is hydrogen bond catalysis,^{25–36} in which the opening of each epoxide is activated by hydrogen bonds between the oxygen atom and the protons from two H-bonding catalysts (Scheme 1).^{27–30,33,34} The reason for the smaller rate obtained with 2,3-EB than with 1,2-EB, while this was the other way around in ammonium solutions, was thus likely due to the fact that 1-amino-2-butanol is not the product of 2,3-EB in ammonium solutions (Table 1) and that its actual product, 2-amino-3-butanol, is more substituted and thus a more efficient H-bond donor.^{25,26,33} To confirm the hydrogen-bonding mechanism, the hydrolysis of 1,2-EB was studied in pure water again, but adding other stronger hydrogen bond donors than the amino alcohols: trifluoroethanol (TFE) or hexafluoroisopropanol (HFIP)³⁷ (Table S1, ESI[†]). The obtained hydrolysis rates, once corrected for the single hydrogen available in TFE and HFIP instead of the two available in the amino alcohols, were identical to those obtained with the same concentration of amino alcohol. This confirmed that hydrogen bond catalysis was the kinetically-driving mechanism. Note that it cannot be excluded that at a later stage of the reaction the diols (or tetrols) produced by the reactions may also contribute to the catalysis by becoming the most abundant hydrogen-bond donors. In that case, hydrogen bonding by the diols or tetrols might also enhance the hydrolysis rates in acid-catalyzed mechanisms.

3. Experimental

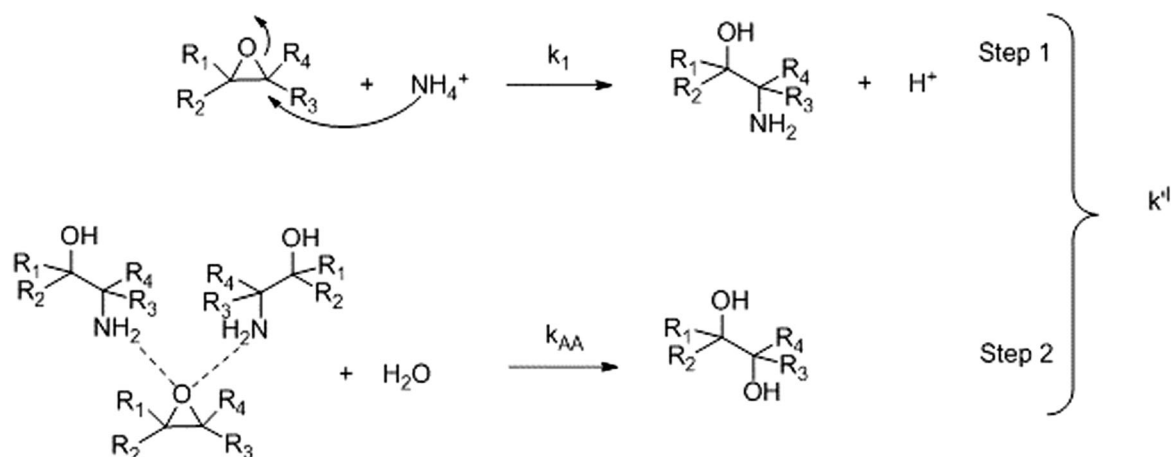
All the reactions studied were performed in small glass vials, in 15 mL of solution in H₂O for the GC analyses, and in 2–6 mL of D₂O solution for the NMR analyses. The salt concentration used

was between 0 and 1.5 M, and the range of epoxide concentrations was 20–130 mM. To examine the potential contribution of acid or base catalysis, the pH of the solutions was varied from about 5.7 to 10.0 by adding small amounts of NaOH. The mixtures were continuously stirred over the duration of the experiments.

3.1 Product investigations

The reaction products were identified by ¹H-NMR and GC/MS. For ¹H-NMR a Bruker AV 500 or Av 400 Avance III spectrometer (respectively 500.13 and 400.13 MHz) was used. The spectra were recorded using the basic pulse zg sequence with a spectral width of 8 kHz, and a relaxation delay of 60 s. The excitation pulse width was calibrated for each solution. Tetradeuterated sodium trimethylsilylpropionate (TSPD₄) was added to the reaction mixtures as an internal standard for the absolute quantification of the reactants and products. All spectra were processed with MestReNova software (Mestrelab Research). In these experiments, the epoxides and their products were unambiguously identified by comparison with the spectra of the reference compounds (characteristic shifts, δ_H , in Table 1). The product yields were determined by dividing the product concentration at each reaction time by the amount of epoxide reacted.

The reactions of 1,2-EB, 2,3-EB, and DM-2,3-EB were also studied by GC/MS and GC/FID using an Agilent Hewlett-Packard 6890 chromatograph coupled both to a 5975 quadrupole Mass Spectrometer using Electron Impact ionization (70 eV) and to a Flame Ionization Detector. The chromatograph was equipped with an Agilent DB-VRX capillary column (60 m × 0.25 mm i.d.; 1.4 μm thickness). These analyses required extracting the aqueous reaction mixtures in an organic solvent. This was performed by adding ethyl acetate, stirring for 5 min, and letting the solutions settle for 10 min. The organic phase was then extracted three times (1 mL each time), and the combined extracts dried under a stream of nitrogen and re-dissolved in 1 mL of methanol. 1 μL of these extracts was injected in the capillary in split mode (ratio 50:1) at 250 °C. The carrier gas was helium, used at a flow-rate of 1.0 mL/min. The temperature program consisted of



Scheme 1 Proposed mechanism for the hydrolysis of epoxides in aqueous ammonium solutions.

an initial temperature at 70 °C followed by a gradient of 5 °C min⁻¹ up to 260 °C. For the reactions studied, all the products eluted within 12.67 min. These GC analyses allowed monitoring only the diol or tetrol products, which were identified by their retention times on the chromatograms and by their mass spectra by comparison with authentic standards and with the NIST library (National Institute of Standards and Technology) (Section S3, ESI†).

The reactions kinetics were monitored in GC/FID by taking 1 mL of reaction mixtures at regular intervals and performing the extraction described above. 1,3-Dibromopropane (2 mM) was used as an internal standard. Calibration curves (Section S4, ESI†) were established for known solutions of reference compounds in methanol, which were directly injected in the GC column. The quantification of the products extracted from the reaction mixtures also took into account extraction efficiencies, E , defined as:

$$E = C_{\text{extr}}/C_{\text{init}}, \quad (2)$$

where C_{init} and C_{extr} are the concentrations before and after extraction, respectively. These efficiencies (given in Section S5, ESI†) were specific to compounds and solution concentrations, and established by extracting known solutions of reference compounds. In GC/FID the product yields were determined from the product concentration at a large degree of conversion, assuming complete conversion of the epoxide. The uncertainties of the yields were estimated at $\pm 15\%$.

3.2 Kinetic analyses

The reaction kinetics were studied at 303 ± 3 K by ¹H-NMR and GC/FID. To avoid taking into account potential side-reactions, the kinetics were all determined from the formation of the main diol or tetrol product. Typical time-dependent profiles for the concentration of 1,2-EB and 1,2-butanediol during a reaction in (NH₄)₂SO₄ solution obtained by MR are shown in Fig. 1. Before applying a kinetic analysis, the order of reaction in epoxide was determined from the variations of the initial rate of product formation with the initial concentration of epoxide. As explained in the Results section, this order was unity in this work, thus the time profiles were analysed with the following equation:

$$C_t = C_\infty \times (1 - e^{-k^1 t}), \quad (3)$$

where C_t and C_∞ are the product concentrations at time t and complete conversion, respectively. The value of C_∞ was determined experimentally in each experiment by fitting eqn (2) to the time profiles (Fig. 1), and first-order reaction rates, k^1 (s⁻¹) were obtained from the slopes of the following expression (Fig. 1):

$$\ln(1 - C_t/C_\infty) = -k^1 t. \quad (4)$$

The combination of the uncertainties in the measured concentrations, the determination of C_∞ , and the linear regressions led to overall uncertainties of $\pm 15\%$ in the obtained first-order rates, k^1 . Second-order rate coefficients in the catalyst, k^{II} (M⁻¹ s⁻¹), were then obtained by dividing k^1 by the activity of the catalyst, generally $a_{\text{NH}_4^+}$. $a_{\text{NH}_4^+}$ was calculated with the

AIM model II (<http://www.aim.env.uea.ac.uk/aim/model2/model2a.php>).³⁸ The results are given in Table S1, ESI† where it can be seen that the activity coefficient for NH₄⁺ in the solutions studied was significantly different from 1 (closer to 0.5). No significant variation of $a_{\text{NH}_4^+}$ with pH was predicted by the model over pH values = 5–10. For the few experiments performed in H₂SO₄, a_{H^+} was assumed identical to the concentration of proton, determined from the pH.

Product yields, in particular for the diols and tetrols, Y_{ol} , and for the amino alcohols, Y_{AA} , could be obtained for all the reactions monitored by NMR by extrapolating to $t = 0$ the time-evolution of the ratio:

$$Y_{\text{ol}} = \frac{C_t}{\Delta[\text{epoxide}]}, \quad (5)$$

where, as above, C_t is the concentration of the diol or tetrol produced at time t and $\Delta[\text{epoxide}]$ is the difference between the initial concentration of the epoxide and its concentration at time t , all monitored directly by NMR. Extrapolating these ratios to $t = 0$ allowed compensating for the potential consumption of the products in the reactions.

3.3 Chemicals

cis- and *trans*-(2-methyloxirane-2,3-diyl)dimethanol (IEPOX3 and 4), 2C-methyl-threitol and 2C-Methyl-erythritol were custom-synthesized by SICHEM GmbH, Germany. Their identity and purity were confirmed by ¹H NMR: *cis*-(2-methyloxirane-2,3-diyl)dimethanol $\geq 99.9\%$; *trans*-(2-methyloxirane-2,3-diyl)dimethanol $\geq 97.5\%$; 2C-methyl-threitol $\geq 98\%$; 2C-methyl-erythritol $\geq 98\%$. The following reagents were purchased from Sigma Aldrich: 1,2-epoxybutane (99%); 2,3-dimethyl-2,3-epoxybutane (99%); 1,2-butanediol (98%); 2,3-butanediol (98%); 2,3-dimethyl-2,3-butanediol (99,9%); 1-amino-2-butanol; 2-amino-1butanol, 97%; ammonium sulfate (99%); methanol Chromasolv (HPLC); 1,3-dibromopropane 99.9%; sulfuric acid (99%); ethyl acetate Chromasolv Plus (HPLC); tetradeuterated sodium trimethylsilylpropionate (TSPD4) 98 atom% D; D₂SO₄ 96–98 wt% D₂O; D₂O 99.9 atom% D. *cis*-2,3-Epoxybutane (98%) was purchased from Alfa Aesar.

4. Conclusions

A systematic study of the hydrolysis of 1,2-EB, 2,3-EB, DM-2,3-EB, and IEPOX in aqueous solutions of ammonium salts has shown that the specific presence of NH₄⁺ ions increases the hydrolysis rate of all epoxides by up to a factor of 25 compared to that of pure water. Contributions of the counter ions, of electrostatically-driven catalysis (ionic force...), and of acid or base catalysis to these hydrolysis rates were all ruled out. The catalytic effects were shown to result from the hydrogen bonding mechanism driven by the amino alcohols produced in the first step of the reaction, and possibly also by the diols or tetrols produced by the hydrolysis.

Extrapolating the hydrolysis rates obtained in this study to NH₄⁺ concentrations that are relevant in atmospheric aerosols ($a_{\text{NH}_4^+}$ up to 3 or 5 M) shows, by a comparison similar to Fig. 3, that NH₄⁺/hydrogen-bonding catalysis should dominate over

acid and base catalysis in aerosol particles with a pH in the range ~4–11. In practice, as many hydrogen-bond donors are present in these natural environments (amines, hydroxyl-containing compounds. . .), in addition to those directly involved in the reactions, the pH range over which hydrogen bonding catalysis should dominate over acid catalysis is likely to be even wider than that estimated above.

Note that, although the hydrolysis of epoxides, in particular of IEPOX, in atmospheric aerosols has been extensively studied, many studies were based on monitoring the growth of Secondary Organic Aerosols³⁹ and can thus not be compared with liquid-phase (bulk) kinetic studies, as in this work. To our knowledge, previous liquid-phase kinetic studies have focused on acid catalysis and neutral catalysis by water only.^{17–19,21}

As many hydrogen bond donors are present in natural and biological environments, hydrogen bond catalysis is likely to enhance many reactions in these media,^{27,29,37} which would be interesting to explore in future studies.

Conflicts of interest

The authors declare no conflict of interest.

Acknowledgements

This work was partly funded by CNRS/INSU (atmospheric chemistry program). A. Maxut was funded by a grant from the French Minister for Higher Education and Research.

Notes and references

- G. Keerthisinghe, S. K. Dedatta and K. Mengel, *Soil Sci.*, 1985, **140**, 194.
- J. M. Smith, F. P. Chavez and C. A. Francis, *PLoS One*, 2014, **9**, e108173.
- L. Goeyens, P. Treguer, M. E. M. Baumann, W. Baeyens and F. Dehairs, *J. Mar. Syst.*, 1995, **6**, 345.
- B. Nozière and A. Cordova, Pat. WO 2009045156, 2007.
- B. Nozière, P. Dziedzic and A. Cordova, *J. Phys. Chem. A*, 2009, **113**, 231.
- M. M. Galloway, P. S. Chhabra, A. W. H. Chan, J. D. Surratt, R. C. Flagan, J. H. Seinfeld and F. N. Keutsch, *Atmos. Chem. Phys.*, 2009, **9**, 3331.
- E. L. Shapiro, J. Szprengiel, N. Sareen, C. N. Jen, M. R. Giordano and V. F. McNeill, *Atmos. Chem. Phys.*, 2009, **9**, 2289.
- B. Nozière, P. Dziedzic and A. Cordova, *Phys. Chem. Chem. Phys.*, 2010, **12**, 3864.
- C. R. Bosoi and C. F. Rose, *Metab. Brain Dis.*, 2009, **24**, 95.
- S. Weiss, G. Hausl, M. Famulok and B. Konig, *Nucleic Acids Res.*, 1993, **21**, 4879.
- M. Movassaghi and E. N. Jacobsen, *Science*, 2002, **298**, 1904.
- A. Erkkilä, I. Majander and P. M. Pihko, *Chem. Rev.*, 2007, **107**, 5416.
- P. I. Dalko and L. Moisan, *Angew. Chem., Int. Ed.*, 2004, **43**, 5138.
- N. Zotova, A. Franzke, A. Armstrong and D. G. Blackmond, *J. Am. Chem. Soc.*, 2007, **129**, 15100.
- M. Claeys, B. Graham, G. Vas, W. Wang, R. Vermeylen, V. Pashynska, J. Cafmeyer, P. Guyon, M. O. Andreae, P. Artaxo and W. Maenhaut, *Science*, 2004, **303**, 1173.
- F. Paulot, J. D. Crouse, H. G. Kjaergaard, A. Kürten, J. M. St. Clair, J. H. Seinfeld and P. O. Wennberg, *Science*, 2009, **325**, 730.
- W. Mabey and T. Mill, *J. Phys. Chem. Ref. Data*, 1978, **7**, 383.
- E. C. Minerath, M. P. Schultz and M. J. Elrod, *Environ. Sci. Technol.*, 2009, **43**, 8133.
- N. C. Cole-Filipiak, A. E. O'Connor and M. J. Elrod, *Environ. Sci. Technol.*, 2010, **44**, 6718.
- C. J. Gaston, T. P. Riedel, Z. Zhang, A. Gold, J. D. Surratt and J. A. Thornton, *Environ. Sci. Technol.*, 2014, **48**, 11178.
- N. C. Eddingsaas, D. G. VanderVelde and P. O. Wennberg, *J. Phys. Chem. A*, 2010, **114**, 8106.
- I. R. Piletic, E. O. Edney and L. J. Bartolotti, *Phys. Chem. Chem. Phys.*, 2013, **15**, 18065.
- E. V. Anslyn and D. A. Dougherty, in *Modern Physical Organic Chemistry*, University Science Books, 2006, ch. 9.3, p. 507.
- S. Meninno and A. Lattanzi, *Chem. – Eur. J.*, 2016, **22**, 3632.
- T. Aral, M. Karakaplan and H. Hoşgören, *Catal. Lett.*, 2012, **142**, 794.
- R. Chawla, A. K. Singh and L. D. S. Yadav, *Tetrahedron Lett.*, 2012, **53**, 3382.
- P. R. Schreiner, *Chem. Soc. Rev.*, 2003, **32**, 289.
- C. M. Kleiner and P. R. Schreiner, *Chem. Commun.*, 2006, 4315.
- M. Kotke and P. R. Schreiner, *Tetrahedron*, 2006, **62**, 434.
- M. S. Taylor and E. N. Jacobsen, *Angew. Chem., Int. Ed.*, 2006, **45**, 1520.
- I. Vilotijevic and T. F. Jamison, *Science*, 2007, **317**, 1189.
- A. G. Doyle and E. N. Jacobsen, *Chem. Rev.*, 2007, **107**, 5713.
- A. Russo and A. Lattanzi, *Eur. J. Org. Chem.*, 2008, 2767.
- A. A. Rodriguez, H. Yoo, J. W. Ziller and K. J. Shea, *Tetrahedron Lett.*, 2009, **50**, 6830.
- R. Chawla, A. K. Singh and L. D. S. Yadav, *RSC Adv.*, 2013, **3**, 11385.
- M. Rumyantsev, N. S. Sitnikov and N. V. Somov, *J. Phys. Chem. A*, 2015, **119**, 4108.
- J.-P. Bégué, D. Bonnet-Delpon and B. Crousse, *Synlett*, 2004, 18.
- S. L. Clegg, P. Brimblecombe and A. S. Wexler, *J. Phys. Chem. A*, 1998, **102**, 2137.
- T. B. Nguyen, M. M. Coggon, K. H. Bates, X. Zhang, R. H. Schwantes, K. A. Schilling, C. L. Loza, R. C. Flagan, P. O. Wennberg and J. H. Seinfeld, *Atmos. Chem. Phys.*, 2014, **14**, 3497.