Orig Life Evol Biosph (2016) 46:189–202
DOI 10.1007/s11084-015-9472-z

PREBIOTIC CHEMISTRY

Effects of Silicate, Phosphate, and Calcium on the Stability of Aldopentoses

Sakiko Nitta[1] · **Yoshihiro Furukawa**[1] · **Takeshi Kakegawa**[1]

Received: 21 July 2015 / Accepted: 28 October 2015 /
Published online: 11 November 2015

Abstract Ribose is an important constituent of RNA: ribose connects RNA bases and forms a strand of sugar phosphates. Accumulation of ribose on prebiotic Earth was difficult because of its low stability. Improvement in the yield of ribose by the introduction of borate or silicate in a formose-like reaction has been proposed. The effects of borates have been further analyzed and confirmed in subsequent studies. Nonetheless, the effects of silicates and phosphates remain unclear. In the present study, we incubated aldopentoses in a highly alkaline aqueous solution at a moderate temperature to determine the effects of silicate or phosphate on the degradation rates of ribose and its isomeric aldopentoses. The formation of a complex of silicate (or phosphate) with ribose was also analyzed in experiments with ^{29}Si and ^{31}P nuclear magnetic resonance (NMR). We found that silicate or phosphate complexes of ribose were not detectable under our experimental conditions. The stability of ribose and lyxose improved after addition of 40-fold molar excess (relative to a pentose) of sodium silicate or sodium phosphate to the alkaline solution. The stability was not improved further when an 80-fold molar excess of sodium silicate or sodium phosphate was added. Calcium was removed from these solutions by precipitation of calcium salts. The drop in Ca^{2+} concentration might have improved the stability of ribose and lyxose, which are susceptible to aldol addition. The improvement of ribose stability by the removal of Ca^{2+} and by addition of silicate or phosphate was far smaller than the improvement by borate. Furthermore, all aldopentoses showed similar stability in silicate- and phosphate-containing solutions. These results clearly show that selective stabilization of ribose by borate cannot be replaced by the effects of silicate or phosphate; this finding points to the importance of borate in prebiotic RNA formation.

Keywords Ribose · RNA · Silicate · Phosphate · Borate

✉ Yoshihiro Furukawa
furukawa@m.tohoku.ac.jp

[1] Department of Earth Sciences, Tohoku University, Sendai, Japan

Introduction

Catalytic activities as well as the role of a genetic-code carrier have attracted many researchers to RNA as the first biomolecule to support both genetic functions and phenotype (Rich 1962; Crick 1968; Benner et al. 1989; Joyce 1989). In contrast to the attractive biochemical properties of RNA, its spontaneous formation under prebiotic conditions seems rather difficult. One of the problematic steps for the RNA formation is the accumulation of ribose under prebiotic conditions. The simplest source material that was proposed for the abiotic formation of ribose is formaldehyde, which could have been formed by photochemical reactions between carbon dioxide and water (Pinto et al. 1980; Cleaves 2008). Condensation of formaldehyde in alkaline solutions facilitated the synthesis of "formose" including ribose (Butlerow 1860; Breslow 1959; Shapiro 1988; Schwartz and Degraaf 1993). On the other hand, the yield of ribose in the formose process is very low due to the low stability of ribose (El Khadem et al. 1987; Larralde et al. 1995). Furthermore, the formose process itself consumes ribose in its successive condensation reactions (Mizuno and Weiss 1974). To overcome this problem, two stabilizers, mostly borates and silicates, have been proposed. Borate forms a stable complex with pentoses, in particular with ribose in its furanose form (Chapelle and Verchere 1988; Li et al. 2005; Amaral et al. 2008; Šponer et al. 2008; Pepi et al. 2010). The borate ion increases the stability of ribose (Prieur 2001; Scorei and Cimpoiasu 2006). The stability increase is most significant for ribose among other aldopentoses (Kim et al. 2011; Furukawa et al. 2013). The improved yield of ribose has been shown in simplified formose reactions involving borate (Ricardo et al. 2004; Kim et al. 2011).

Formation of a complex between silicate and sugars (such as ribose) was demonstrated a decade ago (Lambert et al. 2004). The ribose-silicate complex is thermodynamically the most flavored form among pentose-silicate complexes (Vazquez-Mayagoitia et al. 2011). A silicate-guided formose reaction was proposed recently (Lambert et al. 2010), but this result was challenged by Kim and Benner (2010). To determine whether the silicate ion is an effective agent for stabilizing ribose (and more effective than borate), experiments that allow for direct comparison between the effects of borate and silicate are needed. Thus, the aim of this study was to analyze the effects of silicate (or phosphate) on the stability of ribose and its isomeric aldopentoses. We also compared these results with the results of similar experiments with borate (Furukawa et al. 2013).

The phosphate group is another constituent of the RNA backbone, alternately connecting ribose units. Thus, phosphate is a plausible stabilizer that is present in the environment during several steps of RNA formation. In this study, therefore, we also examined the effects of phosphate on the stability of ribose and its isomeric aldopentoses.

Experimental

Materials

Sodium silicate ($Na_2SiO_3 \cdot 9H_2O$; >98 % purity), sodium borate ($Na_2B_4O_7 \cdot 10H_2O$; >99.5 %), D-ribose (~99 %), D-arabinose, D-xylose (99 %), and D_2O (99.9 %) were purchased from Wako Pure Chemicals (Japan). Sodium phosphate (Na_3PO_4; >97 % purity), D-ribulose (MP Biomedical; 99.7 %), and D-xylulose (>98 %) were purchased from Sigma-Aldrich. D-lyxose (~99 %) was acquired from Alfa Aesar, and calcium hydroxide (~96 %) from Merck.

Methods

Each aldopentose was separately incubated in a saturated $Ca(OH)_2$ solution (10 mL) at 45 °C ± 3 °C with stirring for 270 min. The pentose concentrations that we tested were 1 mM. Sodium silicate or sodium phosphate (40 or 80-fold molar excess with respect to pentose) was added to the reaction mixture before the addition of $Ca(OH)_2$, after which, some of the components precipitated. Sampling and analysis were conducted after 90 min, in addition to the sampling after the first 5 min. A polytetrafluoroethylene (PTFE) bottle was used as an incubation vessel to avoid contamination of the reaction with Si, B, or Na (from glass).

Samples of the reaction mixture that were collected from the incubation vessel were mixed with acetonitrile and then passed through a PTFE filter (0.2-μm pore size). The solution was analyzed using liquid chromatography with mass spectrometry (LC/MS; Waters 2695 and Quattro micro API). The details of the analytical method were described elsewhere (Furukawa et al. 2013). We identified straight chain pentoses, excluding the formation of branched pentoses. The pH of the reaction mixtures (solutions) was constant during the experiments (12.0–12.2 in calcium hydroxide solution, 12.5–12.9 in silicate-bearing solutions, and 12.6–13.1 in phosphate-bearing solutions).

Formation of esters or complexes was analyzed in experiments with ^{29}Si and ^{31}P nuclear magnetic resonance (NMR) using a 700 MHz NMR instrument (ECA-700; Jeol, Japan). The reaction mixtures contained 600 mM D-ribose with 300 mM sodium silicate or sodium phosphate in deuterated water. The NMR tube that was used for the experiments was made of PTFE to avoid contamination of the reaction with B, Si, or Na from conventional glass NMR tubes.

To determine elemental composition of the solutions, we passed samples of the reaction mixtures (0.25 mL) through a 0.2-μm PTFE filter, diluted them with a 2 wt% nitric acid solution to 50 mL, and then analyzed them using inductively coupled plasma atomic emission spectrometry (iCAP 6300; Thermo Fisher Scientific). For comparison, we also analyzed sodium borate solutions after addition of the calcium hydroxide.

Precipitates were collected after centrifugation. The precipitates were dried and coated with vapor-deposited carbon, then analyzed by means of analytical scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS; Hitachi S-3400 N with Oxford x-act). For comparison, we also analyzed precipitates from the sodium borate solutions (after addition of the calcium hydroxide).

Results

Residual Amounts of Pentose and Formation of Isomers in the Alkaline Solution

Figure 1 shows mass chromatograms of ribose solutions of different chemical composition after 90 min of incubation. The ribose peak that should appear at 13 min (retention time) was absent in the solution containing only calcium hydroxide and ribose, whereas this peak was present in solutions containing silicate or phosphate (Fig. 1). The residual concentrations of each pentose are shown in Figs. 2 and 3.

The concentrations of pentoses significantly decreased during the first 5 min and then decreased exponentially (Figs. 2 and 3). The exponential decrease can be expressed with the

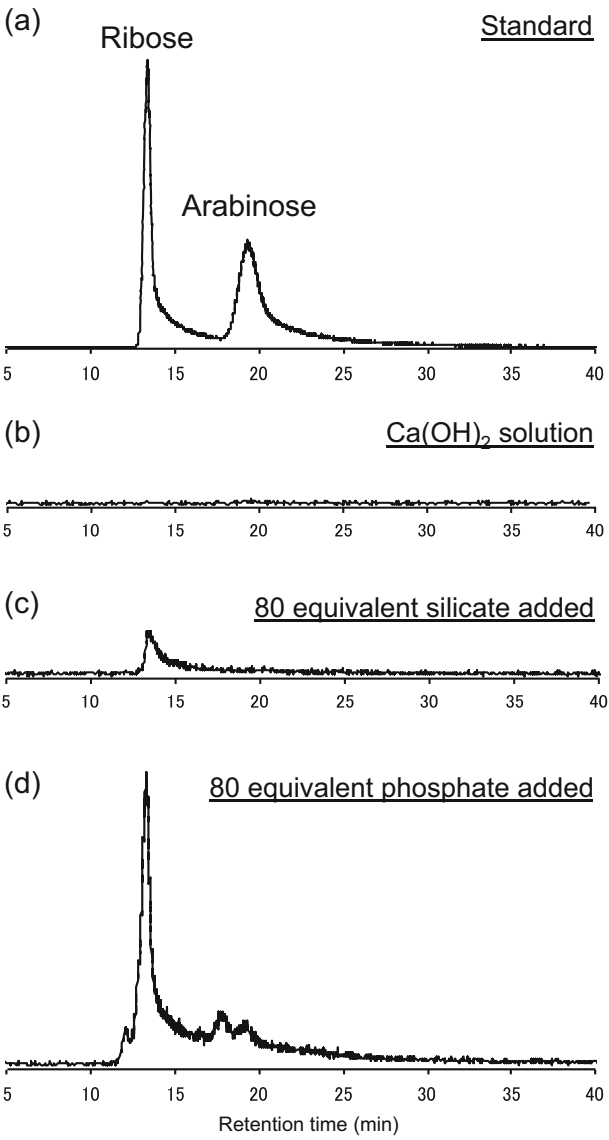

Fig. 1 Single ion chromatograms of the reaction mixtures (solutions) sampled after 90 min and of the standards (m/z = 149). **a** A standard solution of ribose and arabinose. **b** Incubation of ribose in a saturated $Ca(OH)_2$ solution (ribose became undetectable). **c** Incubation of ribose in a saturated $Ca(OH)_2$ solution to which we added 80-fold molar excess of sodium silicate (relative to ribose). **d** Incubation of ribose in the saturated $Ca(OH)_2$ solution to which we added 80-fold molar excess of sodium phosphate. Ribulose (12 min) and xylose (18 min) formed in addition to arabinose

first-order reaction rate constant k [min^{-1}] by the equation $-d[P]/dt = k[P]$, where [P] is the residual concentration of pentose. The residual concentration of ribose decreased most rapidly (k = 0.051 min^{-1} for ribose; 0.033 min^{-1} for lyxose; 0.019 min^{-1} for xylose; and 0.007 min^{-1} for arabinose; Fig. 2a). C-2 epimers formed from ribose and lyxose, but none of the isomers formed from xylose and arabinose. This data is consistent with Furukawa et al. (2013).

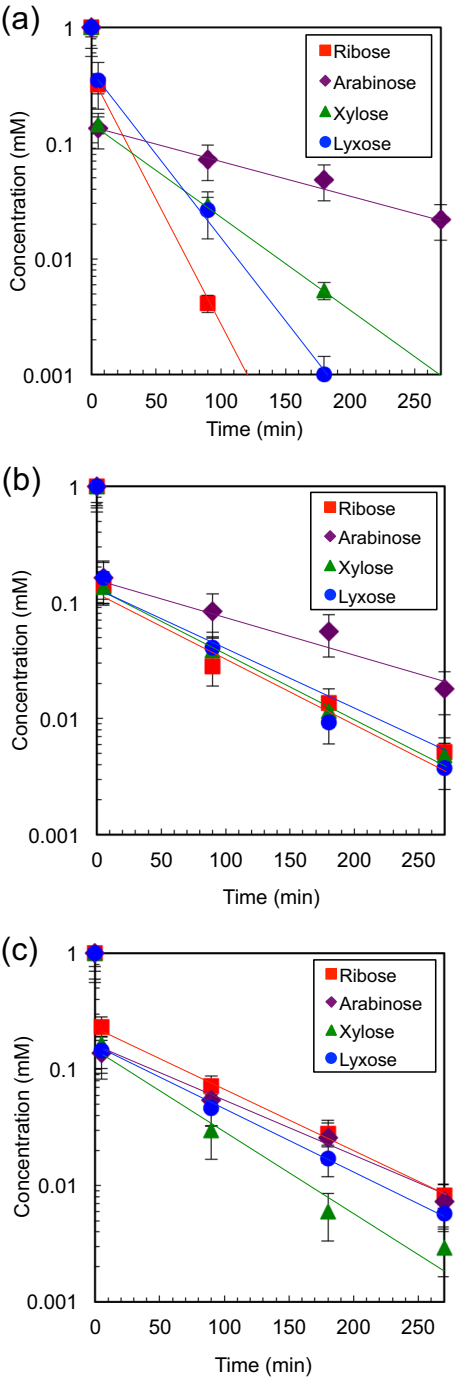

Fig. 2 Concentrations of aldopentoses in the reaction mixtures (solutions) at 45 °C. **a** Incubation without an additive (pH 12.0–12.2). **b** Incubation with 40 mM sodium silicate (pH 12.5–12.9). **c** Incubation with 80 mM sodium silicate (pH 12.5–12.9)

In the reaction mixture to which we added 40-fold molar excess of sodium silicate (Fig. 2b), the concentration of all aldopentoses decreased during the first 5 min. The rate of decrease of ribose or lyxose concentration reduced after 5 min (i.e., k = 0.012 min^{-1} for ribose and 0.014 min^{-1} for lyxose), whereas that of xylose and arabinose showed a negligible change in comparison with that observed in the silicate-free experiment (k = 0.013 min^{-1} for xylose and 0.008 min^{-1} for arabinose). Certain amounts of ribose, xylose, and arabinose were converted to the corresponding C-2 epimers. Xylulose formed from xylose and lyxose, whereas both ribulose and xylulose formed from ribose. These ketopentoses were not detected during the incubation of arabinose.

In the reaction mixture to which we added 80-fold molar excess of sodium silicate, the initial decrease in the pentose concentration was similar to that in reaction mixtures containing 40-fold molar excess of sodium silicate (Fig. 2c). The decrease in the concentration of pentoses in the exponential phase did not show apparent changes either (i.e., k = 0.012 min^{-1} for ribose, 0.012 min^{-1} for lyxose, 0.015 min^{-1} for xylose, and 0.011 min^{-1} for arabinose) with respect to the results of the experiments performed using 40-fold molar excess of silicate. None of the isomers formed from ribose and arabinose. Some of the xylose was isomerized to xylulose, whereas a portion of lyxose was isomerized to xylose and xylulose.

In the reaction mixture to which we added 40-fold molar excess of sodium phosphate (Fig. 3a), the initial decrease in the pentose concentration during the first 5 min was smaller than that observed in the results of the silicate experiments and the silicate−/phosphate-free experiments. The decrease of ribose, lyxose, and xylose decreased to k = 0.011 min^{-1}, 0.013 min^{-1}, and 0.011 min^{-1}, respectively, whereas the decrease for arabinose was not different from those observed in the silicate−/phosphate-free experiment (k = 0.008 min^{-1}). In the reaction mixture to which we added 80-fold molar excess of sodium phosphate (Fig. 3b), the rates of decrease were almost identical to the rates in the reaction mixture containing 40-fold molar excess of sodium phosphate (Table 1). Isomerization was more pronounced in the phosphate solutions than in the silicate solutions. Arabinose, ribulose, and even xylose did form from ribose. Xylose and xylulose formed from lyxose, whereas xylulose formed from xylose. Both ribose and ribulose formed from arabinose.

The Extent of Complex Formation

To evaluate the presence of the ester and the complex of the silicate or phosphate with ribose, we conducted experiments with ^{29}Si and ^{31}P NMR. In the ribose solution containing silicate (i.e., 600 mM ribose with 300 mM sodium silicate), the ^{29}Si NMR spectrum showed only two chemical shifts: at −71.5 and −80.3 ppm (Fig. 4). These data were consistent with chemical shifts corresponding to monosilicate (Q^0) and pyrosilicate (Q^1) groups and were different from chemical shifts corresponding to the complexes reported in another study (Lambert et al. 2004). Thus, the amounts of silicate in the form of a complex were negligible. Actually, the intensity of the peak attributed from the chemical shift reported in Lambert et al. (2004) was very week.

In the ribose solution containing phosphate (600 mM ribose with 300 mM sodium phosphate), the ^{31}P NMR spectrum showed a single chemical shift at 4.5 ppm attributable to the inorganic phosphate (Fig. 5). The ^{31}P NMR signal yields excellent sensitivity. These data do not show any indication of the presence of a phosphate ester suggesting the absence of a phosphate complex with ribose.

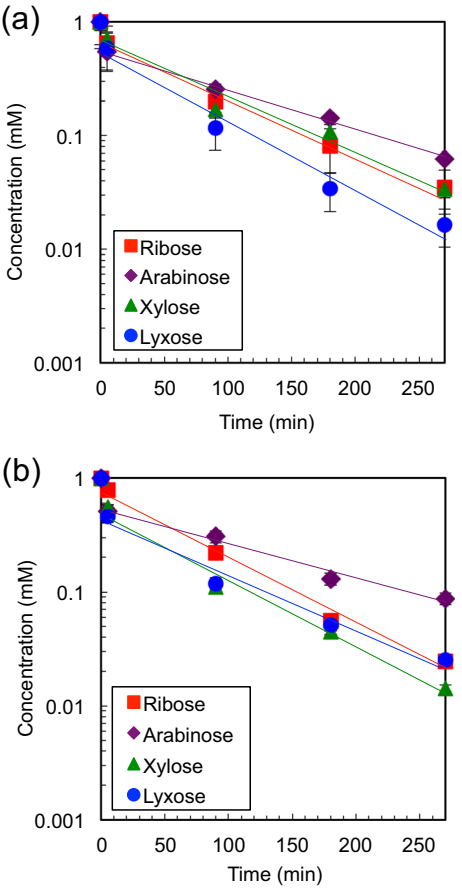

Fig. 3 Concentrations of aldopentoses in the reaction mixtures (solutions) at 45 °C. **a** Incubation with 40 mM sodium phosphate (pH 12.6–13.1). **b** Incubation with 80 mM sodium phosphate (pH 12.6–13.1)

Elemental Concentrations and Precipitates in the Reaction Mixtures

When the silicate or phosphate solution was mixed with the solution of calcium hydroxide, substantial precipitation was observed. Accordingly, we analyzed chemical composition of the precipitates and of the supernatants. In the solution to which we added 40- and 80-fold molar excess of sodium silicate, 55 % and 70 % of the silicate remained in the solution, respectively (Table 2). On the other hand, more than 99 % of Ca^{2+} was removed from the solution (Table 2). The precipitates were mostly composed of fine particles and nanoparticles (Fig. 6). Analysis of the chemical composition indicated that these particles were composed of calcium silicate and sodium silicate (Fig. 6).

In the reaction mixture to which we added 40 and 80-fold molar excess of sodium phosphate, 80 % and 85 % of the added phosphate remained in the solution, respectively. More than 99 % of Ca^{2+} was removed from the solution (Table 2). Dendritic crystals of sodium phosphate and a fine powder of $Ca(OH)_2$ were present in the precipitates (Fig. 7).

In the reaction mixture to which we added 40- and 80-fold molar excess of sodium borate, most of the calcium and borate ions remained in the solution (Table 2).

Table 1 Decrease in aldopentose concentration in experimental solutions

Pentose	Rate constant (min^{-1})				
	Aditive-free	40 equimoles silicate	80 equimoles silicate	40 equimoles phosphate	80 equimoles phosphate
Ribose	0.051	0.012	0.012	0.011	0.013
Lyxose	0.033	0.014	0.012	0.013	0.011
Xylose	0.019	0.013	0.015	0.011	0.013
Arabinose	0.007	0.008	0.011	0.008	0.007

Discussion

Effects of Silicate and Calcium

Pentoses can spontaneously form complexes with several cations and anions including calcium (Lenkinski and Reuben 1976; Symons et al. 1982; Yanagihara et al. 1993). This complex formation quickly drops the concentrations of pentoses when these ions are added to the solutions.

After the initial decrease, the degradation rates of pentoses, which can be seen as the rate of decrease after 5 min, did not improve, even when the silicate concentration was doubled (Figs. 2b and 2c and Table 2). This result implies that silicates did not play an important role in improving the stability of pentoses.

In the course of the experiments here, we observed the characteristic behavior of Ca^{2+}. The calcium hydroxide solution to which we added sodium silicate was depleted of Ca^{2+} because of the precipitation of calcium silicate (Fig. 6). Ca^{2+} has long been known as an effective catalyst for aldol condensation, enhancing enediolate stability of pentoses in their aldehyde form (Mizuno and Weiss 1974). The share of the aldehyde form in the equilibrium states of ribose and lyxose is greater than that of the other aldopentoses (Angyal 1984). Thus, the removal of Ca^{2+} may have contributed to the increased stability of ribose and lyxose more than xylose and arabinose. These effects may have improved the stability of pentoses as shown in Figs. 2b and 2c. The change of cations from Ca^{2+} to Na^{+} in the solution might have changed

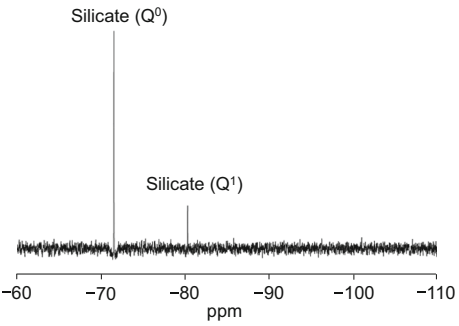

Fig. 4 The 700 MHz ^{29}Si nuclear magnetic resonance (NMR) spectrum of the ribose solution to which we added sodium silicate (600 mM ribose per 300 mM sodium silicate). The strongest signal (at −71.5 ppm) corresponds to an unbound monosilicate (Q^0) group, whereas the second strongest signal (at −80.3 ppm) corresponds to the pyrosilicate (Q^1)

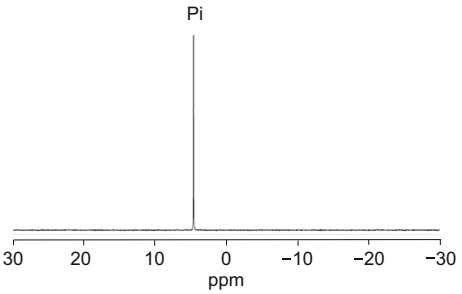

Fig. 5 The 700 MHz ^{31}P nuclear magnetic resonance (NMR) spectrum of a ribose solution to which we added sodium phosphate (600 mM ribose per 300 mM sodium phosphate). The single strong signal corresponding to the inorganic phosphate (P_i) was detected at 4.5 ppm

the main reaction from aldol addition to the Cannizzaro reaction, in which two aldehydes are disproportionately transformed into an alcohol and an carboxylic acid (Mizuno and Weiss 1974), although the aldehyde form is a reactive species in this reaction as well.

Pentose concentrations decreased rapidly within the first 5 min (Figs. 2b and 2c). A similar decrease was observed in silicate-free saturated solutions of calcium hydroxide (Fig. 2a). The initial decrease in pentose concentrations in this silicate-free solution may be due to the formation of a complex with Ca^{2+} as suggested in the literature (Lenkinski and Reuben 1976; Symons et al. 1982; Yanagihara et al. 1993). On the other hand, in the experiments with silicate, the solution was depleted of Ca^{2+} because of the precipitation of calcium silicate. Thus, the initial decrease in pentose concentration was not caused by the formation of a complex with Ca^{2+}.

The ^{29}Si NMR spectrum showed that formation of the ribose-silicate complex was negligible when the reaction mixture contained 600 mM ribose and 300 mM silicate in different experiments, pointing to the difficulties with formation of the ribose-silicate complex. Nonetheless, it is still unclear whether the ribose-silicate complex formed during incubation of our reaction mixtures. The concentration of ribose was 1 mM, whereas the concentrations of silicate were 22 or 56 mM in the series of incubation experiments (this is a large excess of silicate over ribose in the solution). Even if a small fraction of the silicate was used up for formation of the complex, a large fraction of ribose could be removed from the reaction mixture. Adsorption of ribose by precipitates is another possible mechanism of removal of

Table 2 Elemental concentrations of experimental solutions

Materials added (mmol to10 mL water)				Actual concentrations (mM)				
$Na_2SiO_3•9H_2O$	Na_3PO_4	$Na_2B_4O_7•10H_2O$	$Ca(OH)_2$	Si	P	B	Ca	Na
0	0	0	0.29	BD	BD	BD	21	6.2
0.4	0	0	0.29	22	BD	BD	0.087	64
0.8	0	0	0.29	56	BD	BD	0.09	120
0	0.4	0	0.29	BD	32	BD	0.026	95
0	0.8	0	0.29	BD	68	BD	0.053	180
0	0	0.1	0.29	BD	BD	42	24	25
0	0	0.2	0.29	BD	BD	81	24	37

BD below detection

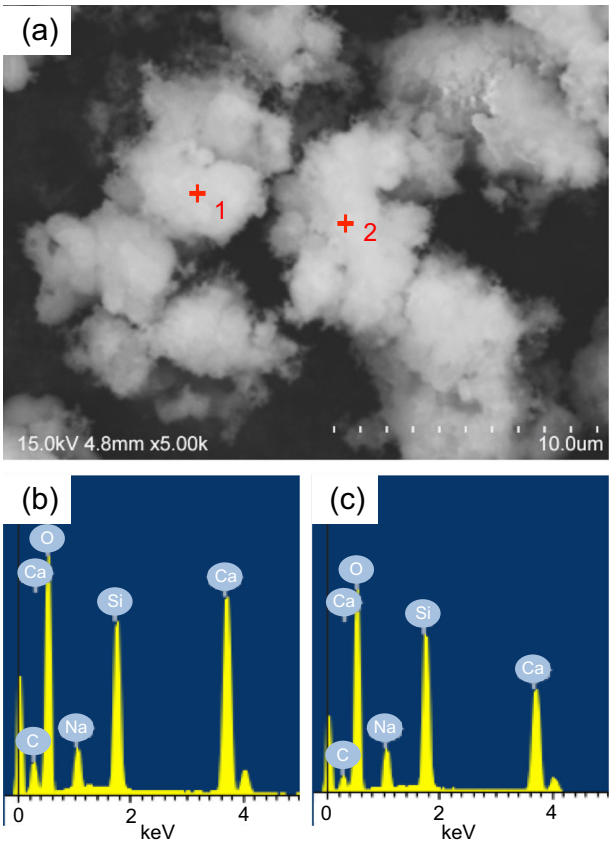

Fig. 6 Scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS) of precipitates that formed in the silicate experiments (80-fold molar excess of silicate was added to the pentose). **a** An SEM image and the sites analyzed by EDS. **b** The EDS spectrum at site 1. The Na/Ca/Si atomic ratio is 12/57/31. **c** The EDS spectrum at site 2. The Na/Ca/Si atomic ratio is 16/43/40. Note that the sample was mounted on a carbon tape and was coated with evaporated carbon for analysis

ribose from the solution. The adsorption might further improve the stabilization of pentoses (Georgelin et al. 2015). Either process might have decreased the concentration of ribose or other pentoses during the first 5 min.

Effects of Phosphate and Calcium

In the experiments where we added 40- and 80-fold molar excess of sodium phosphate (actual phosphorus concentration was 32 and 68 mM, respectively), Ca^{2+} concentrations were negligible (i.e., 0.026 mM and 0.053 mM, respectively), while the sodium concentration was sufficiently high. The reason is the precipitation of calcium phosphate. The results of our NMR experiments did not show formation of a complex of ribose with phosphate. Therefore, all pentoses remained in their free form in the reaction mixture when we added phosphate. This notion is consistent with the small initial decrease in pentose concentrations during the first 5 min.

The rate constants of pentose decrease were not much different from those in the silicate experiments. The stability did not improve in the 40- to 80-fold molar excess phosphate

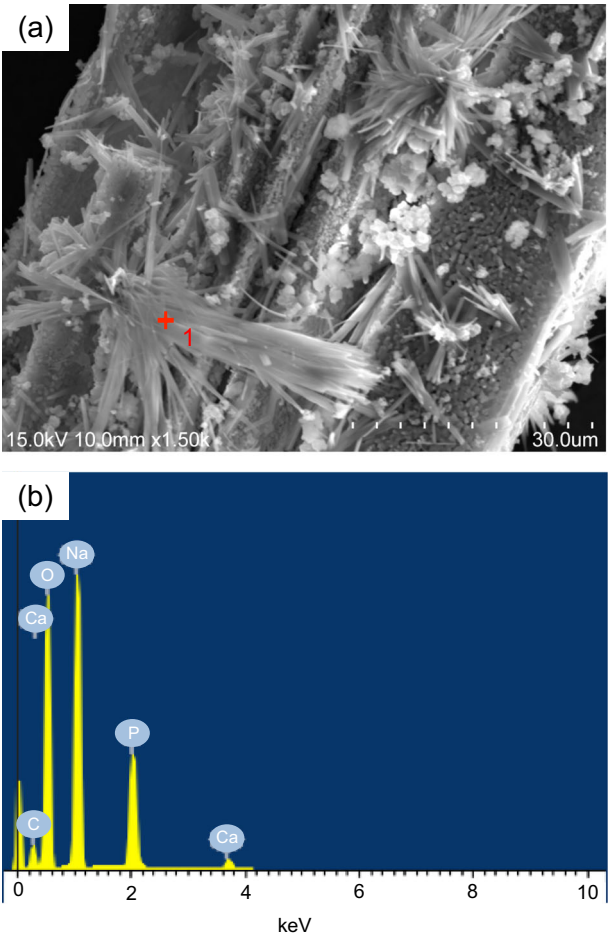

Fig. 7 Scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS) of precipitates from the phosphate solution (80-fold molar excess of phosphate was added to the pentose). **a** An SEM image and the site analyzed by EDS. **b** The EDS spectrum at site 1 in panel a. The Na/Ca/P atomic ratio is 73/3/24. *Note* that the sample was mounted on a carbon tape and was coated with evaporated carbon for analysis

solutions in which the concentration of both sodium and phosphate was increased. These results indicate that the removal of Ca^{2+} increased the stability of pentoses in the experiments with phosphate.

Comparison of Stability Improvement by Borate, Silicate, and Phosphate

Addition of anions could in principal modify the stability of pentoses in two different ways: directly, by the complexation of the anion to the pentose, or indirectly, by removing the calcium ions from the solution and thus preventing them from further aldol addition.

The rates of decrease of pentoses in the silicate solutions were surprisingly comparable to those in the phosphate solutions, where no indication of complex formation was detected (Figs. 2 and 3). This result indirectly suggests that there are no positive effects of silicate on the stability of aldopentoses, even if the pentose-silicate complex is formed.

The removal of Ca^{2+} improved the stability of ribose and lyxose in the present experiments, but this improvement of stability was weaker than that caused by borate (Furukawa et al. 2013). In fact, in solutions to which we added 80-fold molar excess of borate, silicate, or phosphate, the rate constants for pentose decrease were remarkably small in the borate solution: $k = 0.002$ for borate, as opposed to 0.012 for silicate and 0.013 for phosphate (Furukawa et al. 2013). The weaker improvement of ribose stability by silicate is consistent with the data reported by Kim and Benner (2010).

When we compare aldopentoses, addition of borate resulted in the slowest decrease rate for ribose (almost no decrease), whereas the reaction mixture depleted of Ca^{2+} showed comparable decrease rates for ribose and other aldopentoses (Figs. 2 and 3) (Furukawa et al. 2013). These data indicate that the selective stabilization of ribose by borate is not attainable with silicate or phosphate, regardless of whether the coexisting cation is Ca^{2+} or Na^{+}. The significant stabilization of ribose by borate may be explained by the tendency of the borate complex to fix all ribose molecules in the α-furanose form, whereas the silicate complex allows ribose to be in an anomeric equilibrium (Lambert et al. 2004; Amaral et al. 2008).

When borate was used in the aldol addition reaction between glyceraldehyde and glycolaldehyde (i.e., the reaction C2 aldehyde + C3 aldehyde), the yield of ribose increased (Ricardo et al. 2004). One undesirable effect of borate in the formose cycle with the excess of formaldehyde (i.e., the reaction C4 aldehyde + C1 aldehyde) is the increased yield of branched pentoses (Kim et al. 2011). These branched pentoses further converted to straight pentoses (including ribose), reaching to an equilibrium via the Bílik reaction catalyzed by a molybdate or via the Bílik-like rearrangement catalyzed by calcium (Angyal 2001; Petrus et al. 2001; Kim et al. 2011). On prebiotic Earth, calcium was probably more readily available than molybdate. Thus, an environment rich in both borates and calcium or other catalysts for the Bílik reaction was likely conducive to spontaneous and selective accumulation of ribose on prebiotic Earth. The borate/Bílik catalyst ratio and the supply of formaldehyde could have controlled the output.

Conclusions

The stability of ribose and lyxose in a highly alkaline calcium hydroxide solution is improved when 40-fold molar excess of sodium silicate or sodium phosphate was added. Consequently, the stability of all aldopentoses becomes comparable. The stability was not improved further when 80-fold molar excess of sodium silicate or sodium phosphate was added to the reaction mixture (solution). Formation of silicate complexes and phosphate complexes of ribose was negligible. The reduction in the calcium concentration in all solutions to which we added sodium silicate or sodium phosphate may be mostly responsible for the improved stability of ribose and lyxose. The improvement of ribose stability by silicate or phosphate is far smaller than the improvement by borate.

Acknowledgments This work was supported by JSPS KAKENHI, grant numbers 23740402, 15H02144, and 24244084. The authors acknowledge S. A. Benner and H. J. Kim for the discussion on carbohydrate chemistry, F. W. Nara for ICP-AES analysis, and the staff of Tohoku University Research and Analytical Center for Giant Molecules for NMR analysis. We also appreciate an anonymous reviewer for helpful comments to improve the manuscript.

References

Amaral AF, Marques MM, da Silva JAL, da Silva J (2008) Interactions of D-ribose with polyatomic anions, and alkaline and alkaline-earth cations: possible clues to environmental synthesis conditions in the pre-RNA world. New J Chem 32:2043–2049

Angyal SJ (1984) The composition of reducing sugars in solution. Adv Carbohydr Chem Biochem 42:15–68

Angyal SJ (2001) The lobrt de bruyn-alberda van ekenstein transformation and related reactions. In: Sututz AE (ed) Glycoscience: epimerization, isomerization and rearrangement reactions of carbohydrates. Springer-Verlag, Berlin, pp. 1–14

Benner SA, Ellington AD, Tauer A (1989) Modern metabolism as a palimpsest of the RNA world. Proc Natl Acad Sci U S A 86:7054–7058

Breslow R (1959) On the mechanism of the formose reaction. Tetrahedron Lett 1:22–26

Butlerow A (1860) Ueber ein neues methylenderivat. Justus Liebigs Annalen der Chemie 115:322–327

Chapelle S, Verchere JF (1988) A ^{11}B and ^{13}C NMR determination of the structures of borate complexes of pentoses and related sugars. Tetrahedron 44:4469–4482

Cleaves HJ (2008) The prebiotic geochemistry of formaldehyde. Precambrian Res 164:111–118

Crick FHC (1968) Origin of genetic code. J Mol Biol 38:367–379

El Khadem HS, Ennifar S, Isbell HS (1987) Contribution of the reaction pathways involved in the isomerization of monosaccharides by alkali. Carbohydr Res 169:13–21

Furukawa Y, Horiuchi M, Kakegawa T (2013) Selective stabilization of ribose by borate. Orig Life Evol Biosph 43:353–361

Georgelin T, Jaber M, Fournier F, Laurent G, Costa-Torro F, Maurel MC, Lambert JF (2015) Stabilization of ribofuranose by a mineral surface. Carbohydr Res 402:241–244

Joyce GF (1989) RNA evolution and the origins of life. Nature 338:217–224

Kim HJ, Benner SA (2010) Comment on "the silicate-mediated formose reaction: bottom-up synthesis of sugar silicates". Science 329:902

Kim H, Ricardo A, Illangkoon HI, Kim MJ, Carrigan MA, Frye F, Benner SA (2011) Synthesis of carbohydrates in mineral-guided prebiotic cycles. J Am Chem Soc 133:9457–9468

Lambert JB, Lu G, Singer SR, Kolb VM (2004) Silicate complexes of sugars in aqueous solution. J Am Chem Soc 126:9611–9625

Lambert JB, Gurusamy-Thangavelu SA, Ma KBA (2010) The silicate-mediated formose reaction: bottom-up synthesis of sugar silicates. Science 327:984–986

Larralde R, Robertson MP, Miller SL (1995) Rates of decomposition of ribose and other sugars: implications for chemical evolution. Proc Natl Acad Sci U S A 92:8158–8160

Lenkinski RE, Reuben J (1976) Studies of the binding of calcium and lanthanum ions to D-lyxose and D-ribose in aqueous solutions using proton magnetic resonance. J Am Chem Soc 98:3089–3094

Li Q, Ricardo A, Benner SA, Winefordner JD, Powell DH (2005) Desorption/ionization on porous silicon mass spectrometry studies on pentose-borate complexes. Anal Chem 77:4503–4508

Mizuno T, Weiss AH (1974) Synthesis and utilization of formose sugars. Adv Carbohydr Chem Biochem 29: 173–229

Pepi F, Garzoli S, Tata A, Giacomello P (2010) Low-energy collisionally activated dissociation of pentose-borate complexes. Int J Mass Spectrom 289:76–83

Petrus P, Petrusova M, Hricoviniva Z (2001) The bílik reaction. In: Stutz AE (ed) Glycoscience: epimerization, isomerization and rearrangement reactions of carbohydrates. Springer-Verlag, Berlin, pp. 15–42

Pinto JP, Gladstone GR, Yung YL (1980) Photochemical production of formaldehyde in earths primitive atmosphere. Science 210:183–184

Prieur BE (2001) Étude de l'activité prébiotique potentielle de l'acide borique. C. R. Acad. Sci. Paris, Chimie/ Chemistry 4:667–670

Ricardo A, Carrigan MA, Olcott AN, Benner SA (2004) Borate minerals stabilize ribose. Science 303:196–196

Rich A (1962) On the problems of evolution and biochemical information transfer. In: Kasha M, Pullman B (eds) Horizons in biochemistry. Academic Press, New York, pp. 103–126

Schwartz AW, Degraaf RM (1993) The prebiotic synthesis of carbohydrates: a reassessment. J Mol Evol 36:101–106

Scorei R, Cimpoiasu VM (2006) Boron enhances the thermostability of carbohydrates. Orig Life Evol Biosph 36:1–11

Shapiro R (1988) Prebiotic ribose synthesis: a critical analysis. Orig Life Evol Biosph 18:71–85

Šponer JE, Sumpter BG, Leszczynski J, Šponer J, Fuentes-Cabrera M (2008) Theoretical study on the factors controlling the stability of the borate complexes of ribose, arabinose, lyxose, and xylose. Chem Eur J 14: 9990–9998

Symons MCR, Benbow JA, Pelmore H (1982) Study of calcium ion binding to D-ribose in aqueous solutions using hydroxy-proton resonance shifts. J Chem Soc Faraday Trans 1(78):3671–3677

Vazquez-Mayagoitia A, Horton SR, Sumpter BG, Sponer J, Sponer JE, Fuentes-Cabrera M (2011) On the stabilization of ribose by silicate minerals. Astrobiology 11:115–121

Yanagihara R, Soeda K, Shiina S, Osanai S, Yoshikawa S (1993) C-2 epimerization of aldoses by calcium ion in basic solutions: a simple system to transform D-glucose and D-xylose into D-mannose and D-lyxose. Bull Chem Soc Jpn 66:2268–2272