because in these instances the original standard deviations are made artifactually small by the manner of definition of the original **BCDEF** values.

As a final assessment of the **BC(DEF)**-based predictions, existing additive-constitutive schemes were used to "predict" the values of activity coefficient, partition coefficient, molar refractivity, boiling point, and magnetic susceptibility for all applicable compounds in Table I. Their average errors of prediction are compared in Table IX with the **BCDEF** structure-based predictions for the same compounds. These comparisons must be assessed cautiously, because (1) all of the literature additive-constitutive schemes were forced into a fragment pattern much like that of Table IV, in particular by requiring a general "C═C—X" correction instead of separate aromatic and aliphatic parameters for every function; (2) some of the compounds in Table I were probably used to *define* fragment values in previously existing schemes, and thus "prediction" of those properties is not a prediction at all. However, the rms ratios in Table IX do suggest that the general additive-constitutive **BCDEF** model, if anything, tends to be more accurate than these individual property additive-constitutive models. Furthermore, the existing models often cannot be applied to as wide a variety of structures. Thus it seems appropriate to seek a **BC(DEF)** model rather than a new additive-constitutive model when one hopes to predict a physical property which depends upon nonspecific intermolecular interactions.

Conclusions

Prediction of any property which depends mostly upon nonspecific and noncovalent intermolecular interactions, from structure alone, appears from the foregoing to be technically feasible within established error limits. On an absolute basis, the ability to forecast 94% of the variance in many properties of the most commonly encountered compounds would seem to have areas of practical applicability. On a relative basis, the **BC(DEF)** model is as accurate as previously existing prediction schemes, and might be considered preferable to these on the grounds of demonstrated compatibility with the widest variety of experimental observations.

Further studies now underway are intended to extend the range of **BC(DEF)** predictions, both to compound types not yet considered, such as multiply functionalized substances usually existing as solids, and to other properties, such as boiling points or partition coefficients under different conditions, or those aspects of biological behavior which are not structurally specific.

Supplementary Material Available: Experimental and calculated values for the indicated properties of the compounds in Table I of this paper and the structural fragments and resulting calculated **BCDEF** values for all compounds in Tables I of this and the preceding paper (40 pages). Ordering information is given on any current masthead page.

References and Notes

(1) R. D. Cramer, III, *J. Am. Chem. Soc.*, preceding paper in this issue.

(2) (a) The activity coefficient scheme is from J. Hine and P. R. Mookerjee, *J. Org. Chem.*, **40**, 292 (1975). (b) The partition coefficient scheme is that of A. Leo, P. Y. C. Jow, C. Silipo, and C. Hansch, *J. Med. Chem.*, **18**, 865 (1975). (c) The molar refractivity scheme is from A. I. Vogel, *J. Chem. Soc.*, 1833 (1948), as adapted by C. Hansch, A. Leo, S. H. Unger, K. H. Kim, D. Nikaitani, and E. J. Lien, *J. Med. Chem.*, **16**, 1207 (1973). (d) The boiling-point scheme is that of C. R. Kinney, *J. Am. Chem. Soc.*, **60**, 3032 (1938), as cited by (e) H. F. Herbrandson and F. C. Nachod in "Determination of Organic Structures by Physical Methods", E. A. Braude and F. C. Nachod, Eds., Academic Press, New York, 1955, p 16. (f) The magnetic susceptibility scheme is that of Pascal, *C. R. Acad. Sci.*, **156**, 323 (1913), as cited by A. Hutchison in ref 2e, p 300.

(3) O. Exner, *Collect. Czech. Chem. Commun.*, **32**, 1, 24 (1967).

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(5) S. W. Benson and J. H. Buss, *J. Chem. Phys.*, **29**, 546 (1958), and ref 3.

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Kinetics and Mechanism of Hydrolysis of a Silicate Triester, Tris(2-methoxyethoxy)phenylsilane

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Abstract: The kinetics of hydrolysis in dilute aqueous solution of tris(2-methoxyethoxy)phenylsilane to phenylsilanetriol have been studied. The hydrolysis exhibits specific acid and general base catalysis, the latter with a Brønsted β value of 0.7. The specific acid catalysis mechanism is probably A-2 ($k_{H_3O^+/D_3O^+} = 1.24$, $\Delta S^{\ddagger} = -39$ cal deg^{-1} mol^{-1}). At high pH (>10) the rate of appearance of the triol is limited by the rate of hydrolysis of one of the intermediates in the hydrolysis sequence, bis(2-methoxyethoxy)phenylsilanol, which, under these conditions, forms an inert anion. At lower pH the hydrolysis of bis(2-methoxyethoxy)phenylsilanol is several times faster than that of tris(2-methoxyethoxy)phenylsilane while that of the second intermediate, 2-methoxyethoxyphenylsilanediol, is probably faster than the above two hydrolyses at all pHs. It is argued that the form of general base catalysis observed suggests that the base-catalyzed reactions involve either an S_N2^{**}-Si or S_N2^{*}-Si mechanism with formation of a pentacoordinate intermediate. Generalization of the argument used here is explored.

Many processes of importance to both geology[1] and, as is being increasingly appreciated, biology[2] involve the reactions in aqueous solution of simple silicates, i.e., of the $Si(OX)_n$ functional group, where X = H, C, or Si and $n > 1$. Although many qualitative and semiquantitative studies have been made of the hydrolyses of such compounds,[3] practically no systematic kinetic/mechanistic or thermodynamic studies have been made. Quantitative interpretation of much of the early work is complicated by the presence of polymerization phenomena and by the use of a variety of mixed aqueous–organic solvent systems.

We present here what appears to be the first example of a kinetic study of the hydrolysis in a homogeneous, purely aqueous medium of a silicate triester, tris(2-methoxyethoxy)-

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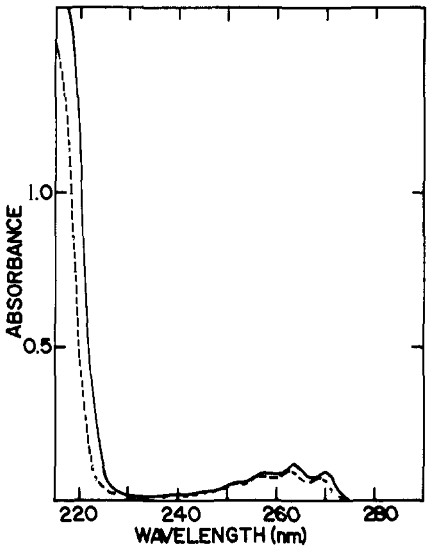
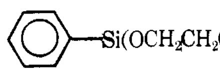


Figure 1. Ultraviolet spectra of **1** (ca. 0.3 mM) before (——) and after (- - -) hydrolysis in 0.05 M phosphate buffer at pH 7.0 and at 30 °C.



1

phenylsilane (**1**). This gives information both on the lability of $Si(OR)_n$ systems, where $n > 1$, in aqueous solution and on the mechanisms of hydrolysis involved and also permits instructive comparisons to be made with analogous carbon compounds where reaction mechanisms are well defined. Previously, essentially all mechanistic information on the solvolytic properties of the Si-O-C group has come from solvolyses in organic or mixed aqueous-organic solvents of compounds of the type $R_3/Ar_3SiOR/Ar$[4] which lack the multiple oxygen substitution of naturally occurring silicates.

Experimental Section

Materials. Tris(2-methoxyethoxy)phenylsilane (**1**) was prepared from the reaction of phenyltrichlorosilane with an excess of 2-methoxyethanol as described by Burkhard[5] and purified by distillation (bp 142 °C (0.2 mm), $n^{25}{}_D$ 1.4719; lit.[5] bp 204 °C (15 mm), $n^{20}{}_D$ 1.4727). Aqueous solutions of phenylsilanetriol (**4**) were prepared by complete hydrolysis of **1** in dilute (<1 mM) solution or by dissolution of the solid triol, the latter prepared by the method of Takiguchi.[6] Buffers were prepared in distilled deionized water from reagent grade materials where available and from commercial samples purified by recrystallization or distillation where not. Acetonitrile was dried and purified by distillation from phosphorus pentoxide and stored over molecular sieves. Deuterium oxide (99.8%) and deuterium chloride solution (99%) were obtained from Aldrich Chemical Co.

Kinetic Measurements. Rates of hydrolysis of **1** and **2** were routinely determined spectrophotometrically with a Cary 14 or Gilford 2400 spectrophotometer by monitoring the decrease in absorbance at 220 nm. Reactions of **1** were initiated by addition of small aliquots, typically 0.01 mL, of an acetonitrile solution of **1** to 3.0 mL of an appropriate buffer solution in a thermally equilibrated (±0.1 °C) cuvette to yield a final concentration of **1** of between 0.1 and 0.5 mM. The ionic strength of all buffer solutions was adjusted to 1.0 with potassium chloride. In the case of **2**, reactions were initiated by addition of 0.5-mL aliquots of dilute phosphate solutions of **2**, prepared as described below, to 2.0-mL aliquots of the required buffer. Absorbance measurements were then made for at least 3 half-times of reaction and pseudo-first-order rate constants calculated in the usual way from infinite time (>10 half-time) absorbance measurements or, in the case of a few of the slowest reactions, by the method of Guggenheim.[7] Rate constants obtained in this way were reproducible to within 5%. In strongly acidic and alkaline solutions the faster reactions were followed using a Durrum D-10 stopped-flow spectrophotometer. All kinetic studies except those leading to the determination of activation parameters were carried out at 30.0 ± 0.1 °C. Reaction temperatures were measured in solution in the cuvettes by means of a copper/constantan thermocouple.

An extraction method was also used to determine reaction rates. Aliquots taken from a reaction mixture containing **1** in an appropriate buffer at 30.0 °C were extracted with hexane. Control experiments showed that this procedure removed **1** quantitatively from aqueous solution while **4** was left. After clarification of the aqueous solution by gentle nitrogen bubbling **4** could be determined by absorbance measurement at 262 nm. From the increase in the concentration of **4** as a function of time first-order rate constants were again calculated. The hydrolysis of **2** could also be followed in this way using chloroform as the organic solvent since it was found to extract **2** but not **4** from aqueous solution.

The pK_a of Phenylsilanetriol. The pK_a of **4** was determined spectrophotometrically at 30.0 °C from measurements of the absorbance at 262 nm as a function of pH in a series of tris(hydroxymethyl)aminomethane and carbonate buffers and in dilute potassium hydroxide solutions (ionic strength adjusted to 1.0 with potassium chloride). A least-squares analysis of a plot of log $[A^-]/[HA]$ vs. pH then yielded the pK_a.

Results and Discussion

Hydrolysis of Tris(2-methoxyethoxy)phenylsilane. This compound, **1**, was chosen for study firstly because of the presence of the phenyl chromophore, allowing the possibility of facile spectrophotometric rate measurements, and secondly because the 2-methoxyethoxy substituents, in contrast to simple alkoxy substituents, lead to sufficient water solubility[5] to allow the hydrolysis to be studied in purely aqueous solution.

The ultraviolet absorption spectrum of **1** in 0.05 M phosphate buffer at pH 7.0 before and after hydrolysis is given in Figure 1. The most significant spectral change occurs at low wavelength and 220 nm was chosen for subsequent kinetic studies. At this wavelength the hydrolysis of **1** could be conveniently followed as a pseudo-first-order process. Pseudo-first-order rate constants for hydrolysis of 0.138, 0.276, and 0.553 mM **1** in the above-mentioned buffer were 1.50×10^{-4}, 1.60×10^{-4}, and $1.60 \times 10^{-4}\ s^{-1}$, respectively, showing that the hydrolysis is indeed first order in **1** and thus not complicated by polymerization reactions. The rate of hydrolysis of **1** in the same buffer was also determined by the extraction method described in the Experimental Section, yielding a first-order rate constant of $1.48 \times 10^{-4}\ s^{-1}$.

The product of the hydrolysis of **1** was identified as phenylsilanetriol (**4**) from the identity of its absorption spectrum (Figure 1) with that of **4** and by measurement of its solvent partition behavior. After two extractions of phenylsilanetriol into ethyl formate, diethyl ether, and 1-butanol from an equal volume of 0.1 M phosphate buffer at pH 7.0, 87 ± 8, 87 ± 3, and 31 ± 3%, respectively, of **4** remained in the aqueous phase, as monitored by absorbance measurements at 262 nm. Under the same conditions the corresponding values for extraction of the hydrolysis product were 82 ± 8, 90 ± 8, and 30 ± 2%, respectively.

These data indicate that, under the chosen conditions at least, **1** is hydrolyzed to **4** in an apparently simple first-order manner. Hence if the hydrolysis proceeds, as would be expected, through bis(2-methoxyethoxy)phenylsilanol (**2**) and 2-methoxyethoxyphenylsilanediol (**3**) (eq 1), then the hydrolysis of these latter species must be more rapid than that of **1**.

$$\underset{\mathbf{1}}{PhSi(OR)_3} \xrightarrow{H_2O} \underset{\mathbf{2}}{PhSi(OR)_2(OH)} \xrightarrow{H_2O} \underset{\mathbf{3}}{PhSi(OR)(OH)_2} \xrightarrow{H_2O} \underset{\mathbf{4}}{PhSi(OH)_3} \quad (1)$$

$$R = -CH_2CH_2OCH_3$$

Since it was soon evident that the hydrolysis was buffer catalyzed (details below) spontaneous first-order rate constants

Table I. Second-Order Rate Constants for Catalyzed Hydrolysis of **1** and **2** at 30 °C

catalyst	pK_a' [a] of catalyst conjugate acid	k^1, s^{-1} M^{-1}	k^2, s^{-1} M^{-1}
hydrogen ion		47	110
hydroxide ion	15.57	165	770
trifluoroethylamine	6.14	$1.6_8 \times 10^{-3}$	$8.7_1 \times 10^{-3}$
hydrogen phosphate	6.83	$5.0_0 \times 10^{-3}$	$1.8_7 \times 10^{-2}$
2-cyanoethylamine	8.13	$5.5_0 \times 10^{-2}$	$2.2_8 \times 10^{-1}$
Tris	8.57	$6.0_9 \times 10^{-2}$	$3.6_6 \times 10^{-1}$
hexafluoro-2-propanol	9.59	$2.7_4 \times 10^{-1}$	1.1_8
glycine	9.98	1.2_3	3.0_8

[a] Buffer pK_a's were determined by half-neutralization under the appropriate conditions.

Table II. Solvent Deuterium Isotope Effect for the Specific-Acid-Catalyzed Hydrolysis of **1** at 30 °C

acid	concn, M [a]	k_{obsd}, s^{-1}	$k_{H(D)}$, s^{-1} M^{-1}	k_H/k_D
DCl	0.096	0.096	0.98_4	
	0.096	0.093		1.2_4
HCl	0.096	0.11_8	1.2_2	
	0.096	0.11_6		

[a] Determined by titration against standard potassium hydroxide solution.

for hydrolysis at a particular pH were obtained by extrapolation of the observed rate constants in buffered solution to zero buffer concentration. The spontaneous hydrolysis rate constants thus obtained are presented as a pH-rate profile in Figure 2 (solid line). The hydrolysis appears to be both specific acid and specific base catalyzed since the slopes of the plot at pHs above and below the rate minimum around pH 6.5 are drawn to be +1 and −1, respectively, and obviously fit the data well. Second-order rate constants for the specific acid (k^1_H) and base (k^1_{OH}) catalyzed hydrolyses are reported in Table I. Curve fitting about the rate minimum of the profile suggests that, within experimental uncertainty, no pH-independent component is needed to fit the data, i.e., spontaneous water-catalyzed hydrolysis does not occur to any significant extent.

The specific-acid-catalyzed reaction was characterized further by measurement of its deuterium solvent isotope effect and the activation parameters $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$. For the former, rates were measured in hydrochloric acid solutions using the stopped-flow method, and the resulting rate constants are given in Table II. From these data a $k_{H_3O^+}/k_{D_3O^+}$ value of 1.24 is obtained. The measurements used to determine the activation parameters were carried out in acetate buffers at pH 4.00 and the results are reported in Table III. It is clear from this table (and from the further results discussed below) that acetate does not catalyze the hydrolysis at this pH. A plot of ln (k_{obsd}/T) vs. $1/T$ (where k_{obsd} is the observed first-order rate constant at temperature T) from this data (not shown) yields $\Delta H^{\ddagger} = +9.2$ kcal/mol and $\Delta S^{\ddagger} = -39$ cal deg^{-1} mol^{-1}.

Both of the above parameters are more in accord with an associative A-2 type mechanism

$$\mathrm{PhSi(OR)_3 + H^+ \overset{fast}{\rightleftharpoons} PhSi(OH^+R)(OR)_2 \xrightarrow[slow]{H_2O} PhSi(OH)(OR)_2 + ROH} \quad (2)$$

than a dissociative A-1 type mechanism. The large negative entropy of activation suggests a highly ordered A-2 type transition state, with probably more than one water molecule associated with it,[8] either of the S_N2^{**}-Si or S_N2^{*}-Si type if a pentacoordinate intermediate is involved, or of the S_N2-Si type if not.[9] Similar values to these parameters have been observed previously in some studies of R_3SiOR systems,[10,11] but it is not clear, in view of the different types of silanes and the quite different solvent systems used, to what extent this agreement is significant rather than fortuitous. It certainly seems possible, however, that a similar mechanism is involved in all of these cases.

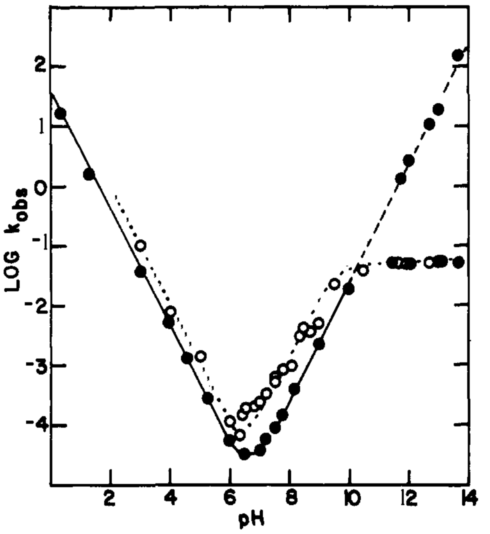


Figure 2. pH-rate profiles for the hydrolysis of **1** (●) and of **2** (○) under the conditions described in the text. The lines are theoretical and derived from the parameters of Table I in the manner described in the text.

Table III. Rates of Hydrolysis of **1** in Acetate Buffers at pH 4.00 as a Function of Temperature

acetate concn, M	temp, °C	$k_{obsd} \times 10^3$, s^{-1} [a]
0.01	6.46	1.02 ± 0.03
0.02	8.00	1.17 ± 0.03
0.04	8.26	1.27 ± 0.10
0.01	12.30	1.72 ± 0.13
0.02	12.30	1.71 ± 0.03
0.01	20.81	2.49 ± 0.09
0.02	20.81	2.43 ± 0.06
0.04	20.81	2.50 ± 0.07
0.02	29.50	4.50 ± 0.20
0.04	29.50	3.93 ± 0.05
0.01	37.40	6.55 ± 0.07
0.02	37.61	6.27 ± 0.1
0.04	37.63	6.45 ± 0.03
0.01	48.80	10.2 ± 0.1
0.02	49.50	11.0 ± 0.4
0.04	49.50	10.6 ± 0.1

[a] Mean and standard deviation of three determinations.

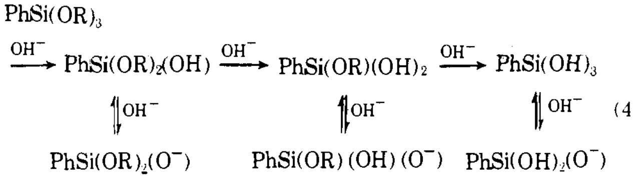
Comparison with the acid-catalyzed hydrolysis of the carbon analogues of **1**, carboxylic acid ortho esters, which hydrolyze by an A-1 mechanism through an oxocarbonium ion intermediate,[12,13] suggests that oxygen is no more successful than carbon[4,14,15] at stabilizing a siliconium ion, i.e., that oxosiliconium ions are not significantly more stable than alkyl/aryl siliconium ions with respect to their carbon analogues. The acid-catalyzed hydrolysis of **1** occurs at a rate some seven times slower at a given pH than that of triethyl orthobenzoate[16] and consequently the siliconium ion must really be at a considerably higher energy with respect to starting materials than the carbonium ion and not just hidden under a very facile A-2 mechanism.

The change at high pH from a specific-base-catalyzed reaction to one whose rate is pH independent (Figure 2) indicates that the hydrolysis may not be as simple as first appeared and that at high pH a change in rate-determining step occurs. A stopped-flow investigation at high pH revealed that under these conditions there were in fact two stages to the reaction, a slow second stage whose rate was pH independent, as described above, and a fast first stage whose rate was found to be first order in hydroxide ion concentration. Furthermore, the second-order rate constant for the fast hydroxide ion catalyzed reaction was the same as that found for the specific-base-catalyzed reaction at lower pH. This is made clear by the dashed line in Figure 2, where the points taken from the fast stage at high pH are plotted. Hence there appear to be two steps to the reaction at high pH and, since the two steps are of quite different rate, an intermediate must not only exist but accumulate.

There are two obvious possibilities for the nature of the intermediate. It could either be one of the probable intermediate species, **2** or **3** (eq 1), or it could be a pentacoordinate intermediate, **5**:

$$\mathrm{PhSi(OR)_3} \overset{\mathrm{OH^-}}{\rightleftharpoons} \underset{\mathbf{5}}{\mathrm{PhSi^-(OR)_3(OH)}} \rightarrow \mathrm{PhSi(OR)_2(OH)} \rightarrow \mathrm{PhSi(OH)_3} \qquad (3)$$

In the latter scheme the rate-determining pH-independent step at high pH would be breakdown of the pentacoordinate intermediate while in the former it would be hydrolysis of **2** or **3**. The pH independence from eq 1 can be obtained if it is assumed that **2** or **3** is converted at high pH into the corresponding anion **2a** or **3a** and that this anion is inert to hydroxide ion attack (eq 4).



$$\begin{tikzcd}
\mathrm{PhSi(OR)_3} \arrow[r, "\mathrm{OH^-}"] & \mathrm{PhSi(OR)_2(OH)} \arrow[r, "\mathrm{OH^-}"] \arrow[d, shift left, "\mathrm{OH^-}"] & \mathrm{PhSi(OR)(OH)_2} \arrow[r, "\mathrm{OH^-}"] \arrow[d, shift left, "\mathrm{OH^-}"] & \mathrm{PhSi(OH)_3} \arrow[d, shift left, "\mathrm{OH^-}"] \\
 & \mathrm{PhSi(OR)_2(O^-)} \arrow[u, shift left] & \mathrm{PhSi(OR)(OH)(O^-)} \arrow[u, shift left] & \mathrm{PhSi(OH)_2(O^-)} \arrow[u, shift left]
\end{tikzcd} \qquad (4)$$

2a **3a** **4a**

The correct scheme was determined by quenching experiments. It was shown spectrophotometrically that at 2.5 °C the fast and slow phases could be conveniently separated if the reaction in 0.01 M potassium hydroxide solution was stopped after 1 min. This quenching was achieved by the addition of 1 equiv (to the potassium hydroxide) of hydrochloric acid and sufficient potassium phosphate to give a final solution 5 mM in phosphate with a pH between 6.5 and 7. The quenched solution contained material whose hydrolysis in situ could be followed spectrophotometrically at 220 nm yielding a first-order rate constant (at pH 6.5) of $1.64 \times 10^{-4}\ \mathrm{s^{-1}}$ (cf. about $4 \times 10^{-5}\ \mathrm{s^{-1}}$ for **1** under the same conditions). Furthermore, when the quenched solution was subject to 0.05 M potassium hydroxide solution in the stopped-flow spectrophotometer, only the slow phase of hydrolysis was observed, with a rate constant identical with that previously obtained. These observations suggest that the intermediate has been trapped at neutral pH. This suggests that eq 4 is probably correct since the potential intermediate of eq 3 should revert to **1** at neutral pH.

The quenching experiment was also carried out under the above conditions on a preparative scale (3 L of 0.113 mM **1**) and the product isolated as an involatile, colorless oil by chloroform extraction. A ^{1}H NMR spectrum of this material in $\mathrm{C^2HCl_3}$ was very similar to that of **1** but the ratio of phenyl to methoxyethoxy groups was 1:2 rather than 1:3. A mass spectrum showed significant peaks at *m/e* 449 ($\mathrm{PhSi^+(OR)OSi(OR)_2Ph}$) and 451 ($\mathrm{Si^+(OR)_2OSi(OR)_2Ph}$). This data is taken to indicate that the isolated product is the disiloxane $\mathrm{[PhSi(OR)_2]_2O}$ which would be the expected product from evaporation of a dilute solution of the silanol **2**. It is unlikely that **2–4** would be extensively associated in solution at the concentrations employed in this work (<0.2 mM). Even silicic acid itself, which should associate more readily than the silanols here, is believed to be essentially monomeric at concentrations less than 1 mM.[17] Also, preliminary measurements on the rate of hydrolysis of $\mathrm{[PhSi(OR)_2]_2O}$ suggest it to be several times smaller than that of **1** under the same conditions and followed at 220 nm, presumably because of steric hindrance. $\mathrm{[PhSi(OR)_2]_2O}$ was thus not present in significant amounts in the solutions of **2** used since this slower hydrolysis was not observed. This experiment is thus also in accord with **2** as the observed intermediate and hence eq 4.

Hydrolysis of Bis(2-methoxyethoxy)phenylsilanol. As a result of the stability of **2** at high pH relative to that of **1**, the former compound could be trapped from an alkaline hydrolysis mixture of **1** by rapid neutralization of the solution. Consequently the kinetics of the hydrolysis of **2** could be independently studied. Neutral solutions of **2**, 0.1–1 mM, were prepared as described above and stored frozen at −70 °C. Combinations of aliquots of these solutions with appropriate buffers allowed a study of the kinetics of hydrolysis of **2**, followed spectrophotometrically at 220 nm as for **1**. Again it was evident that the hydrolysis was buffer catalyzed (discussed below in detail) so that spontaneous hydrolysis rate constants at a particular pH were obtained by extrapolation of the observed pseudo-first-order rate constants in buffered solution to zero buffer concentration. These spontaneous hydrolysis rate constants are presented as a pH-rate profile also in Figure 2 (dotted line). The hydrolysis of **2**, like that of **1**, is specific acid and base catalyzed. At high pH the rate of hydrolysis becomes pH independent with a first-order rate constant the same as that obtained for the slow stage of the hydrolysis of **1**, as would be expected on the basis of the above-described experiments and discussion. The dotted line of Figure 2 fits eq 5, which relates the observed pseudo-first-order rate constant, k_{obsd}, to the hydrogen ion activity, a_{H}:

$$k_{\mathrm{obsd}} = k^2{}_{\mathrm{H}} a_{\mathrm{H}} + k^2{}_{\mathrm{OH}} K_{\mathrm{w}} / (K_{\mathrm{a}} + a_{\mathrm{H}}) \qquad (5)$$

where $k^2{}_{\mathrm{H}}$ and $k^2{}_{\mathrm{OH}}$ are second-order rate constants for the specific acid and base catalyzed hydrolysis of **2**, respectively, and K_{a} is an apparent dissociation constant which, in terms of eq 4, can be equated with the acid dissociation constant of **2**. Values of the rate constants yielding the dotted line of Figure 2 are given in Table I. The pK_{a} value for this fit to the data is 9.5. This is certainly a reasonable value for such a pK_{a}. The first pK_{a} of silicic acid itself is close to 9.5 under comparable conditions[17] and the first pK_{a} of phenylsilanetriol has been determined as described in the Experimental Section to be 9.85 ± 0.05.

The second-order rate constants for specific acid and base catalysis of the hydrolysis of **2** are somewhat larger (two to three times) than those of **1** (Table I), but this difference can be readily ascribed to the lesser steric hindrance to nucleophilic attack in **2** than in **1**. Nucleophilic displacements at silicon are known to be significantly susceptible to steric hindrance.[3,18] The mechanisms of hydrolysis of **1** and **2** are then probably the same, presumably the expected bimolecular displacements either without ($\mathrm{S_N2}$-Si) or with ($\mathrm{S_N2^*}$-Si or $\mathrm{S_N2^{**}}$-Si) a pentacoordinate intermediate. The absence of any appearance of unusual reactivity of **2** by comparison with **1** precludes any requirement for a facile unimolecular decomposition path for alkoxysilanols such as are seen in phosphate, sulfate, and carbonate monoesters and in tetrahedral carbonyl adduct anions. This reflects again the reluctance of silicon to form stable tricoordinate species by (3p–2p) π bonding with oxygen.

In view of the fact that both hydrolyses are followed at 220 nm it may not be apparent how good first-order kinetics can

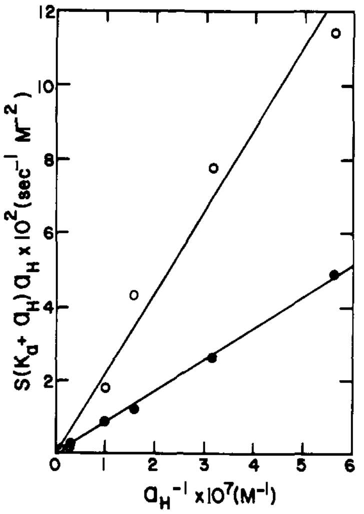


Figure 3. Plots to differentiate between general acid and general base catalysis of the hydrolysis of **1** (●) and of **2** (○) in phosphate buffers as described in the text.

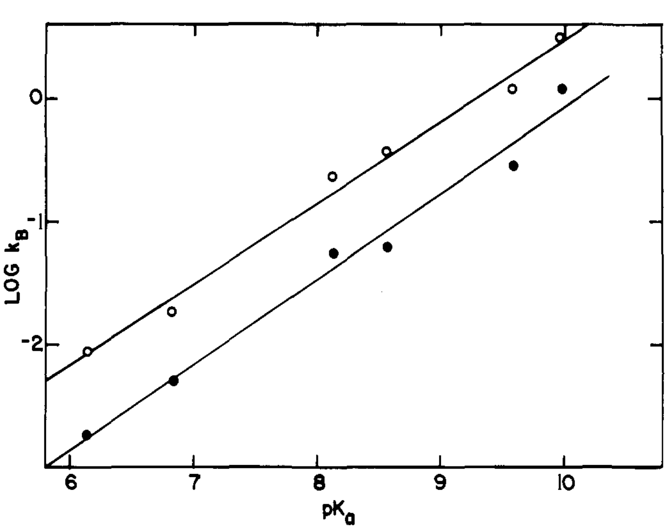


Figure 4. Brønsted plots for general base catalysis of the hydrolysis of **1** (●) and of **2** (○).

be obtained spectrophotometrically for the hydrolyses of **1** at any given pH. This is apparently possible here because of a fortuitous combination of the greater rate of hydrolysis of **1** and the smaller extinction coefficient change on hydrolysis of **2**. That the apparent first-order constants obtained at pHs between 7 and 9 for the hydrolysis of **1** are good approximations is shown by the excellent collinearity of the pH-rate profile in this region with that above pH 11 where the hydrolysis of **2** is much slower and can be readily dissected out (Figure 2).

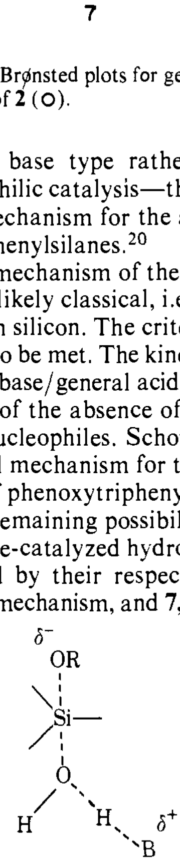
No indication is present at any pH for the existence of **3**, which thus presumably hydrolyzes more rapidly than **2**. At very high pH (>13[17]), **3** should be converted into a dianion, which, if inert, should lead to the rate of hydrolysis of **3** and hence of **1** and **2** apparently decreasing with pH increase in this region. This decrease is not observed, which must reflect one or more of the following: the significantly greater reactivity of **3** than **2**, the higher pK_a of **3** than would be estimated by the available data (i.e., $\gg$13), or the small spectral difference between **3** and **4** under these conditions.

Buffer Catalysis. The hydrolyses of both **1** and **2** are buffer catalyzed at pHs between 6 and 9. Plots of the observed pseudo-first-order rate constants vs. total buffer concentration at a particular pH are linear with slope S. At pHs below 6 buffer catalysis becomes impossible to detect (acetate and chloroacetate buffers). The above suggests that general base catalysis obtains. This conclusion is confirmed by the data shown in Figure 3, where an appropriate function of S[19] ($S(K_a' + a_H)/a_H$ where K_a' is the acid dissociation constant of the buffer) is plotted against a_H^{-1} for the phosphate-catalyzed hydrolyses of **1** and **2**. The intercepts of such plots represent k_{HA}, the second-order rate constant for general acid (i.e., $H_2PO_4^-$) catalysis, and from the slope, k_B, the corresponding constant for general base (i.e., HPO_4^{2-}) catalysis can be obtained.[19] Clearly in both cases phosphate is behaving as a general base catalyst (zero intercept, nonzero slope).

In a similar way k_B values were obtained for a variety of buffer species. The results are given in Table II and as a Brønsted plot in Figure 4. Clearly the β values of **1** and **2** (the slopes of the respective straight lines of Figure 4) are very similar, being, from a least-squares treatment, 0.69 and 0.66, respectively. That the β values for the hydrolyses of **1** and **2** are the same within experimental uncertainty is further evidence of mechanistic identity in these reactions. Further, the accommodation of a variety of oxygen and nitrogen bases on the same Brønsted line suggests that the catalysis is indeed of the general base type rather than the kinetically equivalent nucleophilic catalysis—the latter has been proposed as a possible mechanism for the amine-catalyzed hydrolysis of aryloxytriphenylsilanes.[20]

The mechanism of these general-base-catalyzed reactions is most likely classical, i.e., general-base-catalyzed attack of water on silicon. The criteria for a n-f class reaction[21] would appear to be met. The kinetically indistinguishable alternative specific base/general acid catalysis mechanism seems unlikely in view of the absence of general acid catalysis of attack of other nucleophiles. Schowen and Latham[22] also prefer the classical mechanism for the general-base-catalyzed methanolysis of phenoxytriphenylsilane.

The remaining possibilities for the mechanism of the general-base-catalyzed hydrolyses would appear to be those represented by their respective transition states below: **6**, an S_N2-Si mechanism, and **7**, an S_N2^{**}-Si mechanism, where the



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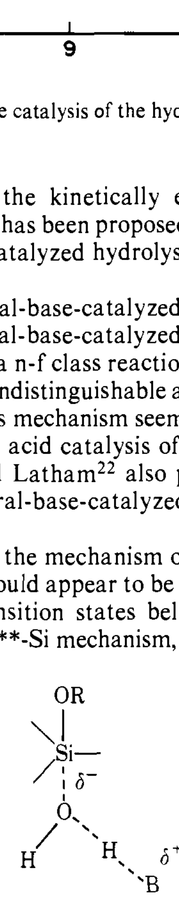

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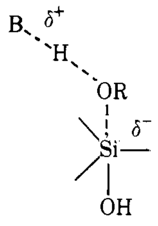
latter involves formation of a pentacoordinate intermediate. The Brønsted β value of 0.7 would suggest that proton transfer is reasonably well advanced in whichever of these transition states obtains but the exact position of the proton cannot be defined with the available data because of the other bond-making and -breaking processes probably occurring concerted with proton transfer.

As represented here the transition state **6** would seem to be incomplete. This conclusion arises from the following argument. The formation of the pentacoordinate intermediate is represented in **7** as general base catalyzed and hence the reverse reaction, breakdown of the intermediate to starting materials, must be, by microscopic reversibility, general acid catalyzed. Since water and methoxyethanol have very similar acidity[23] it would seem likely that departure of RO^- should also be general acid catalyzed, i.e., the transition state for breakdown of the pentacoordinate intermediate to products should be **8**. By similar reasoning and stemming from the very similar nature of entering and leaving groups it would seem plausible that the transition state for the S_N2-Si mechanism



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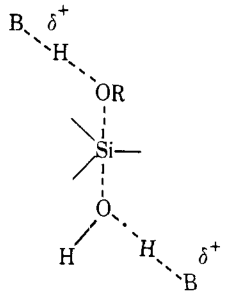

9

should be **9** rather than **6.** This would predict for the S_N2-Si mechanism a termolecular rate expression of the type

$$\text{rate} = k[\mathbf{1}][B][BH^+]$$

Since such a rate expression is not observed—all k_{obsd} vs. buffer concentration plots were strictly linear up to 0.1 M—this general-base-catalyzed hydrolysis must proceed by a stepwise mechanism involving formation of a pentacoordinate intermediate rather than by a concerted S_N2-Si mechanism.

One can speculate that the considerable translational entropy loss involved in assembling a transition state bimolecular in catalyst vs. one unimolecular[24] so destabilizes **9** that transient formation of a pentacoordinate intermediate is enforced. A similar state of affairs presumably occurs with respect to tetrahedral intermediate formation in nucleophilic substitution reactions of carboxylic acid derivatives where concerted catalysis of both bond making and bond breaking is required, e.g., general-base-catalyzed hydrolysis of alkyl esters. Conversely, since nucleophilic displacement reactions at saturated carbon cannot involve an intermediate one might predict that analogous cases of this type should show bimolecular kinetics in catalyst; they should thus be very slow and hence perhaps seldom seen. The latter at least seems true.[25] A "working generalization" then might be that all catalyzed substitution reactions where two catalyst molecules would be required to effect a concerted[21] reaction will prefer to proceed stepwise by way of metastable intermediates where these are available.

If the base-catalyzed hydrolysis of **1** does indeed involve a pentacoordinate intermediate as argued above, then because of the presumably similar leaving-group abilities of RO^- and HO^- neither formation (S_N2^{**}-Si) nor breakdown (S_N2^*-Si) of the intermediate should be decisively rate determining; kinetically the two are indistinguishable since the partitioning of the intermediate is symmetrically catalyzed.

It is interesting to note in passing that an argument such as that presented above to distinguish between concerted and stepwise general-base-catalysis mechanisms could also be applied, although to our knowledge it has not been, to comparable nucleophilic displacements at phosphorus, in phosphate esters, for example, where this distinction is often and usually inconclusively discussed. One reason for its nonapplication is probably the absence of analogous studies because of the low reactivity to nucleophilic attack at phosphorus of phosphate esters with poor alkoxide leaving groups. One notable example, however, is the hydrolysis of methyl ethylenephosphate, which proceeds rapidly because of the cyclic structure of this compound and where classical general base catalysis has been observed.[26] From the absence of termolecular rate equations in this case also one would conclude, as above, that the reaction proceeds via a pentacoordinate phosphorus intermediate. This conclusion is of course quite in accord with that reached from other evidence obtained for this hydrolysis.[27]

Other relevant examples in phosphorus chemistry involve intramolecular nucleophilic displacements at phosphorus by hydroxyl groups, i.e., cyclization reactions. One such example is the cyclization of ribonucleotides as the first step in the base- (and ribonuclease-) catalyzed hydrolysis of these compounds. It is interesting to note that the termolecular transition state analogous to **9** is similar to that originally proposed for the ribonuclease mechanism by Findlay et al.[28] and employed in many subsequent variants.[29] In the case of the enzymic mechanism the entropic disadvantage of supplying a second separate catalyst molecule is absent so that in this case a concerted mechanism might well be more likely than in the model systems. Certainly the available evidence at present is not inconsistent with a concerted displacement ribonuclease mechanism.

To conclude, the results described above are consistent with the proposal that the hydrolysis of **1** proceeds sequentially via the route described by eq 4. It is clear from the data presented that compounds **1, 2,** and presumably **3** hydrolyze readily, apparently to completion, in aqueous solution at ambient temperatures and at around neutral pH and hence simple acyclic alkoxysilanes are unlikely to exist in natural aqueous solutions. The hydrolyses, even at neutral pH, are largely hydrogen ion and hydroxide ion catalyzed and hence the observed rates of hydrolysis are quite pH sensitive throughout the region of biological interest. Below neutral pH only specific acid catalysis, i.e., no general acid catalysis of hydrolysis, is observed, whereas at and above neutral pH general base catalysis by buffer species is observed. From this it seems likely that all Si-O-C bond-making and bond-breaking reactions in aqueous solution are acid/base catalyzed and thus their reaction rates will be strongly dependent on the composition of the solution.

These observations are in good qualitative agreement with previous investigations of the Si-O-C functional group in $R_3/Ar_3SiOR/Ar$ systems.[3,18,22,30] In this work we have extended these previous observations into a $-Si(OR)_3/Si(OH)(OR)_2/Si(OH)_2(OR)$ system and established a general reaction scheme and a framework of rate constants. These results will be employed in future work where the interactions of simple and more complex silicates with biological macromolecules will be investigated.

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On the Structure of Cyclopropylcarbinyl and Cyclobutyl Cations. The 2,8-Dimethyl-8,9-dehydro-2-adamantyl and 4-Phenyl-2,5-dehydro-4-protoadamantyl Cations[1]

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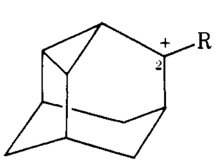
Abstract: The 2,8-dimethyl-8,9-dehydro-2-adamantyl cation (**7**) and the 4-phenyl-2,5-dehydro-4-protoadamantyl cation (**12**) have been prepared under stable ion conditions from the corresponding alcohols. The ^{1}H and ^{13}C NMR spectra of **7** show that, although it is static at −128 °C, upon warming to −26 °C it undergoes a degenerate cyclopropylcarbinyl-cyclopropylcarbinyl rearrangement which apparently proceeds either by way of the 3,5-dimethyl-2,5-dehydro-4-protoadamantyl cation (**8**) or via the degenerate 2,3-dimethyl-2,5-dehydro-4-protoadamantyl cation (**9**) and the 8,9-dimethyl-8,9-dehydro-2-adamantyl cation (**10**). The ^{13}C NMR spectra of **12** indicate that, while it is static at −135 °C, upon warming to −40 °C it undergoes a threefold degenerate cyclobutyl-cyclobutyl rearrangement. This process seems to occur via the 1-phenyl-8,9-dehydro-2-adamantyl cation (**13**). From the temperature-dependent NMR behavior of **7** and **12**, an approximate energy barrier of $\Delta G^{\ddagger} = 7.4 \pm 0.5$ kcal/mol can be calculated for **7** → **8** or **9** or **10** and $\Delta G^{\ddagger} = 6.9 \pm 0.5$ kcal/mol for **12** → **13**.

Introduction

The rapid interconversion of cyclopropylcarbinyl, cyclobutyl, and homoallyl derivatives in carbocationic reactions has attracted considerable attention.[5] Several reports have appeared concerning the direct observation by NMR spectroscopy of a series of cyclopropylcarbinyl cations under stable ion conditions.[6] This work has also been extended to the study of cyclopropylcarbinyl cations with rigid carbon skeletons.[7] The parent 8,9-dehydro-2-adamantyl cation (**1**, R = H) has been shown by NMR spectroscopy to be a carbenium ion that is undergoing a threefold degenerate cyclopropylcarbinyl-cyclopropylcarbinyl rearrangement which is fast on the NMR time scale at −120 °C.[7a] This rearrangement is believed to proceed via the 2,5-dehydro-4-protoadamantyl cation (**2**, R = H). Introduction of an electron-releasing substituent at C-2 in **1** significantly increases the energy barrier for this process. Thus, cations **1**, R = CH_3, C_6H_5, and c-C_3H_5, all have been demonstrated by NMR spectroscopy to be static carbocations with varying degrees of charge delocalization into the rigid cyclopropane ring.[7a] On the other hand, three precursors which potentially could have afforded the 1-methyl-8,9-dehydro-2-adamantyl cation (**3**) were shown by NMR spectroscopy to give under stable ion conditions the 4-methyl-2,5-dehydro-4-protoadamantyl cation (**2**, R = CH_3) which undergoes a threefold degenerate cyclobutyl-cyclobutyl rearrangement that is fast on the NMR time scale even at −120 °C.[7a] It is proposed that this rearrangement occurs via **3**. We now wish to report the preparation and temperature-dependent behavior of suitably substituted derivatives of **1** and **2** which permit an experimental determination of the approximate energy barriers for **1** → **2** and **2** → **1**.



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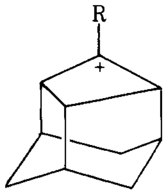

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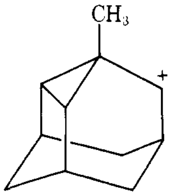

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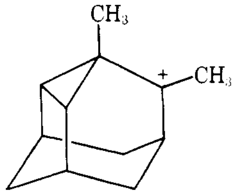
Results and Discussion

The 2,8-Dimethyl-8,9-dehydro-2-adamantyl Cation. Two identical groups can be substituted in the cyclopropylcarbinyl moiety of parent ion **1** in two different ways. Previously we have shown that under stable ion conditions the 1,2-dimethyl-8,9-dehydro-2-adamantyl cation (**4**) is a static carbenium ion from −95 to −10 °C.[7a] No contribution of the 3,4-dimethyl-2,5-dehydro-4-protoadamantyl cation (**5**) to the NMR parameters of **4** was observed. Of course, a degenerate rearrangement in **4** is not possible. However, such behavior could occur in the 2,8-dimethyl-8,9-dehydro-2-adamantyl cation (**7**). In order to explore this possibility, 2,8-dimethyl-8,9-dehydro-2-adamantanol (**6**) was added to a solution of fluorosul-



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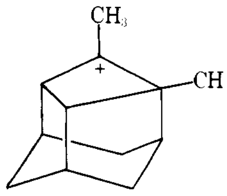

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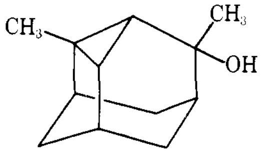

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