tation transition state, the $^3A''$ global minimum, and the $^3A_2'$ planar minimum. The energies (hartrees), relative to that of the $^1A'$ global minimum (−164.4594), were as follows: $^1A'$ pseudorotation transition state (0.0419), $^3A''$ global minimum (0.0226), $^3A_2'$ planar triplet minimum (0.0424). The agreement between these results and those obtained with the STO-3G basis is very good; the largest discrepancy between relative energies is less than 0.005 hartree (3 kcal/mol). The extremely close correspondence between the two sets of calculations is actually somewhat surprising, since the STO-3G basis set overestimates the barrier to inversion in ammonia by about 5 kcal/mol[40] and this failing is apparently accentuated when CI is included.[41]

Acknowledgment is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, and to the National Science Foundation for support of this work.

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(40) See, for instance, the tabulation in: Carlsen, N. R.; Radom, L.; Riggs, N. V.; Rodwell, W. R. *J. Am. Chem. Soc.* **1979**, *101*, 2233.

(41) Stevens, R. M. *J. Chem. Phys.* **1974**, *61*, 2086.

The Region of Mechanistic Transition in Acid-Catalyzed Epoxide Ring Opening. A Mechanistic Switch Mediated by Salt in Aqueous Media[1]

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Abstract: The mechanism of the acid-catalyzed ring opening of tetramethylethylene oxide has been explored through ^{1}H NMR and UV spectrophotometric product analysis in aqueous media. In dilute aqueous media below pH 4 the hydrolysis proceeds to the extent of 99.92% forming pinacol; no detectable amount of pinacolone is formed from a possible rearrangement pathway. With increasing amounts of $NaClO_4$ at constant acid concentration there is a dramatic change in the products; rearrangement products appear even at 2.0 M aqueous $NaClO_4$, and rise to the extent of 10% at 6.0 M $NaClO_4$. Formate buffers in these salt solutions lead to the formation of pinacol monoformate ester concurrent with pinacolone and pinacol; however, limitations in the solubility of the epoxide substrate prohibited rate measurements. The dramatic product change arising from a novel salt effect in aqueous media reveals a mechanistic pathway switch for this acid-catalyzed epoxide ring opening. The initiating step in the mechanism with or without salt is the same, the formation of the protonated epoxide as an intermediate. Nucleophile-assisted opening of the intermediate by water or formate buffer uniquely excludes products derived from skeletal rearrangement. Howerver, high salt concentrations can provide the necessary electrostatic stabilization required for charged intermediates as well as reduce the probability of nucleophilic attack by water. The switch to a carbonium ion intermediate (a species isomeric with the protonated epoxide) is signaled by pinacolone formation.

The exploration and identification of the consequences of adding electrolyte to reaction media have received intensive exploration.[3a] Ingold and co-workers[3b] in an extensive series of studies showed that observations such as rate enhancement or retardation could be used to diagnose charge distribution in transition states in solvolytic reactions of organic halides and other substrates. Because of the low dielectric constant associated with many of the media in these studies, the exact state of the electrolyte remained in doubt. Winstein and co-workers[4] developed the ion-aggregate hypothesis for solvolytic reactions building on the results of data from Kolthoff et al.[5a] In media such as ethanol, acetic acid, formic acid, and acetone, as pure solvents, and when mixed with small quantities of water most salts are found in highly associated form. Certain salts, however, induce very interesting chemical effects arising from a low driving force for aggregate formation or because of selective solvation of one of the ions. Such salts give rise to the "special salt effect" characterized by Winstein et al.[4,5b,6] and to the phenomenon of "electrostatic catalysis" examined by Pocker et al.[7]

These effects are not generally observed in the study of organic reactions in purely aqueous media, as the extent of ionic aggregation is small even at modest concentrations of salt.[8] Indeed salts are often added to reaction systems in order to maintain a constant ionic strength in buffer catalysis studies. Recent examination of the acid-catalyzed epoxide ring-opening step shows that it proceeds with a significant contribution from mechanisms with S_N2 character.[9] We sought then a means of taking advantage of this unusual result by modifying the transition-state environment in an effort to observe a contribution to the ring opening from the S_N1 mode and the immediate consequences thereof. Transition-state environment can be altered by the addition of massive amounts of salt. The salt, however, must not interfere in the reaction by capturing any intermediates that might be formed; neither should it have significant nucleophilic character toward epoxide substrates; nor should the cation selectively complex with the substrate. Sodium perchlorate was selected because it seemed to meet all of these requirements, and thus its effect upon the products of epoxide ring opening was examined.

Experimental Section

Chemicals. Tetramethylethylene oxide (TMEO) was synthesized and

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(1) Support of this work by grants from the National Institutes of Health of the U.S. Public Health Service and the National Science Foundation is gratefully acknowledged. Part 4 of the continuing study devoted to the examination of the role of epoxides in vicinal diol dehydration. Part 3: Y Pocker and B. P. Ronald, *J. Am. Chem. Soc.*, **100**, 3122–3127 (1978).

(2) Visiting Scholar in the Department of Chemistry, University of Washington, during the period 1978–1979 while on sabbatical leave from the Department of Chemistry, Idaho State University, Pocatello, Idaho.

(3) (a) F. A. Long and W. F. McDevit, *Chem. Rev.*, **51**, 119 (1952); W. F. McDevit and F. A. Long, *J. Am. Chem. Soc.*, **74**, 1773 (1952); (b) C. K. Ingold, "Structure and Mechanism in Organic Chemistry", 2nd ed., Cornell University Press, Ithaca, N.Y., 1969, Chapters 7 and 9.

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(8) R. A Robinson and R. H. Stokes, "Electrolyte Solutions", 2nd revised ed., Butterworths, London, 1959, Chapter 14.

(9) Y. Pocker and B. P. Ronald, *J. Am. Chem. Soc.*, **100**, 3122–3127 (1978).

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purified as previously described.[9] The amount of pinacolone contaminant in freshly prepared samples was shown to be less than 0.35% by UV spectrometric analysis.

Anhydrous formic acid for buffer preparation and pinacolone and pinacol for NMR and UV spectrometric reference probes were all prepared as previously described and had spectral properties in accord with literature values.[9-12]

All salts were dried for 24 h in vacuo prior to use. The water of hydration was removed from sodium perchlorate (Fischer Scientific Chemicals purified reagent grade) at 130 °C (10^{-3} Torr) over a period of 24 h. Additional drying for extended periods resulted in only a 0.05% weight loss. A 2.0 M solution of this salt in distilled deionized water had a pH of 6.8 at 25 °C. Perchloric acid solutions were made from Mallinckrodt analytical reagent 70% perchloric acid by dilution with distilled deionized water. All diluted, as well as stock, acid solutions were titrated acidometrically to establish concentrations. The D_2O for NMR solvent and selected product studies was from Stohler Isotope Chemicals Co. and assayed to be 99.8% deuterium.

Kinetic Measurements. The kinetic measurements of TMEO hydration were followed by NMR as previously described.[9] UV spectrometric rate measurements were made as described previously.[13] Rate coefficients were determined graphically from observation of the initial portion of the reaction up to a maximum of 7% reaction. Calculations used the theoretical infinity based upon the substrate weight and the extinction coefficient determined in the medium in question. Usually 10–20 separate points were taken for slow rates (half-lives of from 30 to 100 days) and continuous recording methods were used for faster rates. Duplicate runs with reproducibility error of 3% or less were considered acceptable.

Product Studies. The products of TMEO hydration were determined by absorbance measurement and by NMR spectroscopic measurement. The solutions used for product studies were made up by weight in volumetric apparatus so that the concentrations of all the components were known exactly. The two sets of solutions were 0.24 and 0.0024 M in perchloric acid, respectively, and contained sodium perchlorate ranging from 1.5 up to 6.0 M. Formic acid–sodium formate buffer solutions of ionic strength 2–6 were also used for product studies.

The perchloric acid–sodium perchlorate solution was placed in a vial immersed in a thermostated bath set at 25.0 ± 0.2 °C. The TMEO was added dropwise to the agitated solution. Rapid addition caused the solution to become heterogeneous, whereas very slow addition assured homogeneous conditions. The temperature could not be controlled during the course of rapid addition and moved as much as 15–20 °C from that of the bath. In fact, if addition was too rapid, the reaction became violent. During slow addition the temperature of the reaction sample was the same as that of the bath as measured by an internal thermometer. Within a few minutes after completion of the reaction the solutions were analyzed for pinacolone by absorbance measurement and for pinacol by NMR. Pinacol monoformate formed when buffered media were used was analyzed similarly. All products were stable during the course of the measurements as was shown by duplicate analysis several hours later. In the solutions of the highest ionic strength there are very slow transformations that occur and these have been measured by both NMR and UV spectroscopic methods. Pinacol undergoes slow rearrangement in 0.24 M H^+–6.0 M $NaClO_4$ at 25 °C, $t_{1/2}$ = 19 days. Pinacol monoformate undergoes slow hydrolysis to pinacol at pH 3.9 and 25.0 ± 0.2 °C with a $t_{1/2}$ = 21 days.

Pinacolone was analyzed spectrophotometrically at 278 nm. Since the λ_{max} shifted gradually to shorter wavelength as a function of the sodium perchlorate concentration a calibration curve was constructed for the molar absorptivity at 278 nm. The broad absorption envelope produces only a small change in the molar absorptivity with increasing salt concentration, e.g., $\epsilon^{278}([ClO_4^-] = 0.24\ M) = 28.9 \pm 0.3$ and $\epsilon^{278}([ClO_4^-] = 6.24\ M) = 25.1 \pm 0.3$. Pinacol and pinacolone were analyzed by NMR spectroscopy using a Varian Model T-60 nuclear magnetic resonance spectrometer. Spectra of the clear reaction solutions along with that of a calibration sample were recorded and integrated a minimum of five times. The integrations were recorded over the entire spectral region of interest, from below δ 2.4 to above δ 0.2. This range (>130 Hz) was scanned in 13 s and included the spinning sidebands and the ^{13}C satellite resonances. Prior to commencing the analysis the instrument was optimized for resolution (0.8–1.3 Hz) and for spectral display through adjustment of spinning rate, radio-frequency power, amplifier gain, noise and pen response, and integral amplitude. Integral pen drift and phasing were the most critical adjustments and were reoptimized as required before each integral trace. Thus conditions were established where near ideal integrals were obtained with pen drift less than 2% (corresponding to 0.10–0.14 small chart unit/s) of the total integral height in the data acquisition region. The pinacol concentrations of the reaction samples were determined from a calibration curve constructed from calibration samples analyzed at the same time as the reaction mixtures.

The final product percentages were derived from duplicate analyses and represent combined results from UV and NMR spectrometric analyses. The reproducibility error in these results was 5% based upon results obtained at different times. (We are inclined to attach a larger error of about 7–10% to such results because of their combined nature, but this inclination has no foundation other than our conservative feelings.)

Measurements. pH measurements were made on the reaction media using a Beckman Research Model pH meter fitted with an Orion Model 90-02 double junction reference electrode and a Beckman glass electrode. The outer cavity of the double junction reference electrode was refilled daily with a saturated solution of sodium nitrate analytical reagent. All pH measurements were made at 23 °C and checked by standardization of the meter before and after each duplicate measurement. Beckman standard buffer solutions and titrated dilute perchloric acid solutions in the range 10^{-3}, 10^{-2}, and 10^{-1} M were used for standardization. The pH recorded was the average of two to three measurements which agreed to within 0.007 pH units. The pH observed was corrected for nonlinearity in the electrode response as determined by measurement of the standard perchloric acid solutions as compared to standard buffer solutions.

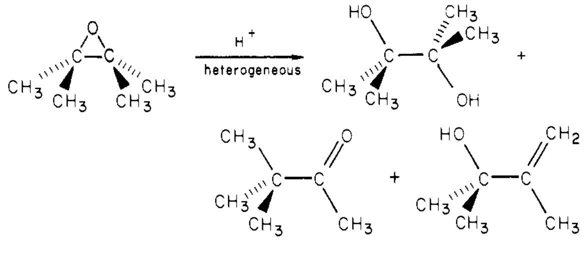
^{13}C NMR measurements were made on a Varian CFT-20 nuclear magnetic resonance spectrometer using standard settings for the instrumental parameters and proton noise decoupling. The lock mode was established using concentric sample tubes such that the D_2O was in the annulus and the sample in the center. The various resonances were identified by comparison with authentic samples run under identical conditions.

Results

Product Studies. Characterization of the Reaction Type. Tetramethylethylene oxide undergoes hydrolysis to form pinacol to the extent of 99.92 ± 0.005% in aqueous media in the pH range between 2 and 8.[9] A detailed NMR and UV-vis spectrometric examination of these solutions demonstrates that no other products are formed. When a sample of TMEO (enough to make the solution about 0.27 M) is added to an aqueous solution of pH ≃3.6, hydrolysis takes place very quickly ($t_{1/2} < 70$ s). The absorbance change, ΔOD, that occurs during the course of this reaction is 0.006 ± 0.0002 ODU, and, if this is attributed to pinacolone, then this corresponds to the formation of 2.1×10^{-4} M pinacolone. Such small optical density changes are at the limit of experimental reliability with our instrumentation. These facts indicate that this hydrolysis reaction has only one significant product under these conditions.

In the pH range from 3 to 5 at constant ionic strength, μ = 2, it was possible to study the effects of varying the buffer concentration on both the rate and products of hydrolysis. Both nucleophilic and general catalysis were detected and the isotope effect for each component was determined.[9] Although a buffer component was incorporated into the product, no other products as, for example, pinacolone or allylic alcohol were observed. These findings describe a background against which the effect of added massive salt can be compared and contrasted, Figures 1a and 1b.

The reactions of TMEO in aqueous sodium perchlorate solutions containing catalytic amounts of perchloric acid or containing various amounts of formic acid–formate buffer can be divided into two distinct types easily characterized by the products which are



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(10) A. H. Blatt, "Organic Syntheses", Collect. Vol. I, Wiley, New York, 1941, pp 462–463.

(11) Reference 10, pp 459–462.

(12) B. Prager and P. Jacobson, Ed., "Beilsteins Handbuch der Organischen Chemie", Vol. I, Hauptwerk, Julius Springer, Berlin, 1920, pp 487–488.

(13) Y. Pocker and B. P. Ronald, *J. Am. Chem. Soc.*, **92**, 3385–3392 (1970); *J. Org. Chem.*, **35**, 3362–3367 (1970).

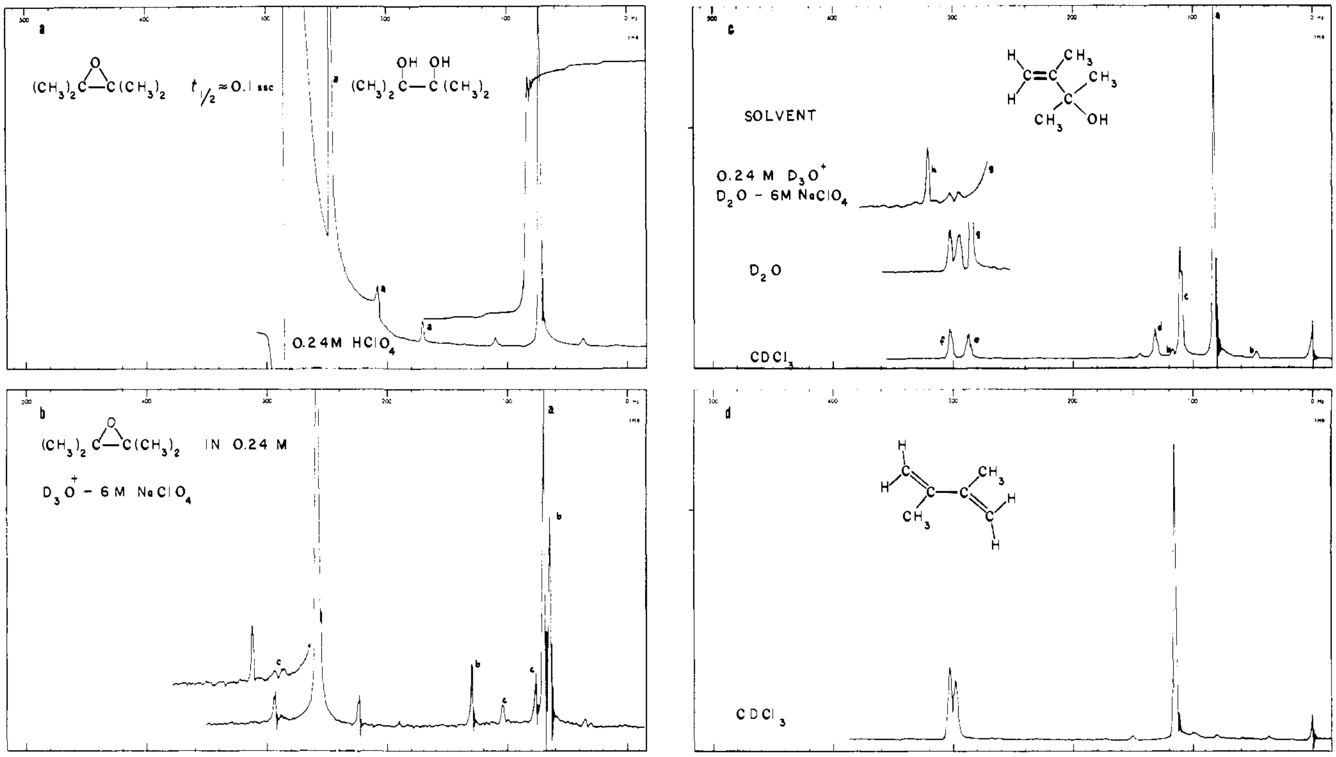

Figure 1. (a) The NMR spectrum of tetramethylethylene oxide (TMEO) in 0.24 M aqueous perchloric acid. The reaction is complete in about 1-2 s after mixing since the half-life is about 0.1 s as determined from a pH-rate profile extrapolation. The upfield resonance with the integral (displaced downfield 10 Hz for clarity) is pinacol. The large resonance is water showing multiple sidebands labeled a. These were conclusively identified by changing the sample spinning rate. (b) An NMR spectrum of tetramethylethylene oxide in 0.24 M D_3O^+–6 M $NaClO_4$ under heterogeneous reaction conditions (fast TMEO addition). Note the multiple resonances upfield from the HOD singlet. The largest resonance is due to pinacol, a; the upfield and low-field singlets, b, arise from pinacolone; the resonances labeled c correspond to those of the allylic alcohol, 2,3-dimethyl-3-buten-2-ol. The hydroxyl protons of both the allylic alcohol and of pinacol are rapidly exchanging and appear as the HOD peak in deuterated media. (c) Spectra of the allylic alcohol, 2,3-dimethyl-3-buten-2-ol, showing a differential solvent effect upon the chemical shift of the olefinic protons. The large upfield singlet, a, corresponds to the methyl resonances of the tertiary alcohol portion of the molecule, with spinning sidebands, b. The allylic methyl group, c, shows evidence of coupling to the cis olefinic proton, e. The resonance, d, is that due to the hydroxyl proton. Rapid exchange causes this resonance to shift downfield to the HOD peak upon addition of D_2O. The remaining olefinic resonance, f, is located downfield due to its proximity to the bulky tertiary alcohol group. The resonance, g, is the HOD peak in D_2O media. When the HOD resonance is large and the spectral amplitude is high, a spinning sideband, h, appears. (d) A spectrum of 2,3-dimethyl-1,3-butadiene for comparison. Its lack of significant water solubility coupled with its distinct spectral features permitted its exclusion as a possible reaction product in the ring opening of TMEO in aqueous acidic sodium perchlorate solutions.

Table I. Heterogeneous Reaction of TMEO with Sodium Perchlorate–Perchloric Acid[a]

acid	$[NaClO_4]$[b]	% addition	% isomerization			$[A/(A + P)]$ (100)
			pinacolone, P	allylic alcohol, A[e]	total	
0.24 M $HClO_4$[c]	0.0	99+[d]	0.06 ± 0.08	0	0	
	2.0	99	0.7 ± 0.7	0.3	1.0	31 ± 10
	3.0	87.6	8.7 ± 2	3.7 ± 1	12.4	30 ± 2
	6.0	46.7	35.5 ± 1	17.9 ± 1	53.3	34 ± 2

[a] All reactions were run at a bath temperature of 25.0 ± 0.5 °C. Product percentages were determined by NMR spectroscopy after a time lapse corresponding to greater than 10 half-lives of reaction. Independent confirmation of the accuracy of the NMR method was shown on test samples by correspondence with values determined by UV spectroscopy at the pinacolone λ_{max} (278 nm). All products were stable during the course of these measurements. [b] Solutions made by weighing anhydrous $NaClO_4$. Anhydrous $NaClO_4$ was prepared by drying in vacuo at 130 °C until no further water could be collected. See ref 1. Rapid addition of TMEO precluded homogeneity in samples with $NaClO_4$. [c] Perchloric acid was determined by acidimetric titration. [d] Identified by NMR and through isolation as pinacol. [e] Identified by NMR spectroscopy and by comparison with an authentic sample.

generated. Pinacol is a product common to both types. In the first type, eq 1, not only rearrangement to pinacolone but also isomerization to an allylic alcohol occurs. The nature of these products, the ratios of the components, the heterogeneous conditions, and the temperature fluctuations all taken together with the results from the literature suggest that the first reaction type is a thermal surface-catalyzed reaction.[14] It appears to occur at the interface when TMEO is added too rapidly to the reaction medium and when there is insufficient means for maintaining constant temperature. Table I shows the various product ratios as a function of the sodium perchlorate concentration. The rapidity of this reaction appears to exclude it from the category of a pure thermal reaction[15] while the olefinic product seems to support the suggestion of a surface-catalyzed reaction.

The allylic alcohol was identified in the reaction mixture by comparison of the chemical shifts of the methyl groups with those of an authentic sample and by spiking the reaction mixtures and noting an increase in the signal height and the integral step height while signal multiplicity remained unaltered. Additional confirmatory data for the identity of the allylic alcohol was derived from examination of the olefinic region of the spectrum in D_2O solvent, and from the behavior of the chemical shift upon the

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(14) Kazushi Arata, Susumu Akutagawa, and Kozo Tanabe, *Bull. Chem. Soc. Jpn.*, **48**, 1097–1101 (1975); G. H. Posner and D. Z. Rogers, *J. Am. Chem. Soc.*, **99**, 8208–8214, 8214–8218 (1977).

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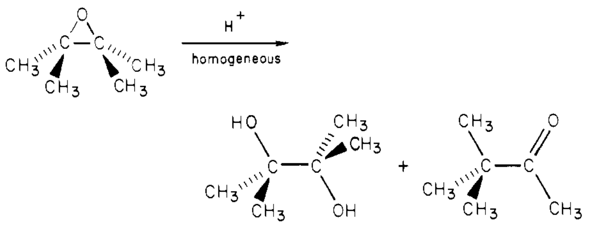
Table II. Homogeneous Reaction of TMEO with Sodium Perchlorate–Perchloric Acid[a]

$[NaClO_4]$	% pinacolone[b]	% pinacol[c]	pH cor[d]	Δδ,[e] Hz
		I. $[HClO_4]$ = 0.24 M		
0.00	<0.08 ± 0.005	>99.92 ± 0.005	0.76 ± 0.01	213.3 ± 0.5
1.51	0.46 ± 0.07	99.54 ± 0.07	0.59 ± 0.01	200.3 ± 1.0
2.00	1.0 ± 0.1	99.0 ± 0.1	0.52 ± 0.01	196.5 ± 1.3
2.50	1.8 ± 0.1	98.2 ± 0.1	0.47 ± 0.01	193.6 ± 0.5
3.00	1.9 ± 0.4	98.1 ± 0.4	0.36 ± 0.01	189.5 ± 0.4
3.50	3.0 ± 0.2	97.0 ± 0.2	0.25 ± 0.01	186.3 ± 1.2
4.00	4.1 ± 0.2	95.9 ± 0.2	0.22 ± 0.01	181.5 ± 0.8
4.50	4.4 ± 0.3	95.6 ± 0.3	0.07 ± 0.01	179.8 ± 1.0
5.00	7.6 ± 0.7	92.4 ± 0.7	−0.04 ± 0.01	178.0 ± 1.1
6.00	10.0 ± 0.8	90.0 ± 0.8	−0.26 ± 0.03	171.0 ± 0.7
		II. $[HClO_4]$ = 0.0024 M		
0.00	<0.08 ± 0.005	>99.92 ± 0.005	2.65 ± 0.01	209.6 ± 0.9
2.00	<0.14 ± 0.05	>99.86 ± 0.05	2.26 ± 0.01	190.5 ± 0.1
4.00	0.24 ± 0.1	99.76 ± 0.1	1.95 ± 0.01	176.0 ± 0.0
6.00	2.6 ± 0.4	97.4 ± 0.4	1.61 ± 0.01	163.3 ± 0.5

$[NaClO_4]$	buffer[f] ratio	total[f] buffer, M	% pinacolone[b]	% pinacol monoformate[g]	% pinacol[c]	pH cor[b]	Δδ, Hz[e]
0.00	2.0	3.0	0.0	14.3 ± 0.9	85.7 ± 0.9	3.93 ± 0.1	
4.00	2.0	3.0	0.9 ± 0.7	20.9 ± 0.3	78.2 ± 0.6	3.89 ± 0.1	187.2 ± 1.1
4.00	1.0	4.0	1.8 ± 0.6	24.4 ± 0.6	13.6 ± 0.9	3.52 ± 0.1	194.8 ± 1.6

[a] Temperatures of samples in a thermostat at 25.0 ± 0.5 °C. [b] Pinacolone determined by UV spectrophotometric analysis at λ 278 nm. [c] Pinacol determined by NMR spectrometric analysis from calibration standards. [d] The pH as read at 23 ± 2 °C corrected for double junction electrode response. [e] The chemical-shift difference between the water resonance and the pinacol methyl resonance in hertz. The spectra were obtained at 60 MHz. [f] Sodium formate–formic acid buffer. The ratio is defined as $[NaO_2CH]/[HCO_2H]$. [g] Pinacol monoformate determined by NMR spectrometric analysis.

addition of salt. The olefinic protons are clearly visible between the lower spinning sideband and the main peak for HOD, Figure 1c; however, spectral overlap prevented quantitative measurement of integrals for intensity comparison purposes. The NMR evidence in conjunction with the modest solubility of the allylic alcohol in water and salt solutions provides confidence in our identification of 2,3-dimethyl-3-buten-2-ol as the allylic alcohol. Other conceivable products including the isomeric allylic alcohol, 2,3-dimethyl-2-buten-1-ol, and 2,3-dimethyl-1,3-butadiene[16] have been excluded because of their insolubility (the latter) and because of the lack of appreciable spectral changes over the course of several days after the completion of the reaction (the former), Figures 1c and 1d. The one possibility that cannot be excluded is that an equilibrium mixture of the two allylic alcohols is formed. This, however, does not alter the conclusion that isomerization and rearrangement products are formed.[17]



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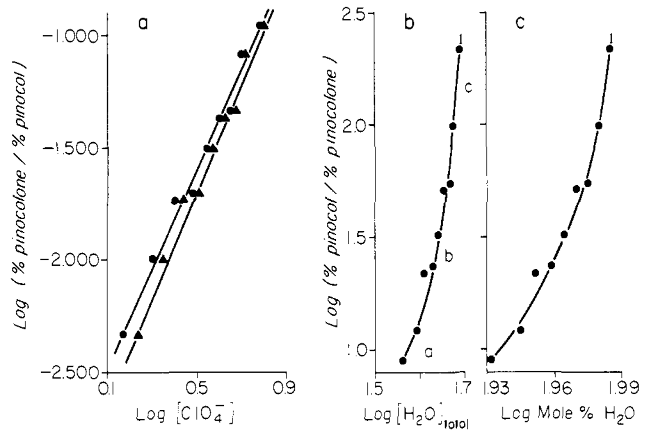

Figure 2. (a) A plot of the logarithm of the product ratio, log (% pinacolone/% pinacol) vs. log $[ClO_4^-]$ for the reaction of tetramethylethylene oxide with aqueous sodium perchlorate solutions containing 0.24 M perchloric acid at 25 °C. The line defined by the triangles, ▲, has as its abscissa the total perchlorate concentration, $[ClO_4^-] = [NaClO_4] + [HClO_4]$. The least-squares slope is 2.40 ± 0.12 with the correction coefficient of 0.991. The line defined by the solid circles, ●, has as its abscissa the perchlorate concentration, $[ClO_4^-] = [NaClO_4]$. The least-squares slope is 2.21 ± 0.11 with correlation coefficient 0.992. (b) A plot of the logarithm of the product ratio, log (% pinacol/% pinacolone), vs. log $[H_2O]_{total}$ in aqueous 0.24 M perchloric acid with varying amounts of sodium perchlorate. The slope in region a is 4, that in region b is 9, and that in region c is 18. (c) A plot of the logarithm of the product ratio, log (% pinacol/% pinacolone), vs. log (mol % H_2O) in aqueous 0.24 M perchloric acid with varying amounts of sodium perchlorate.

The product ratios from the second type reaction, eq 2, the purely homogeneous reaction, as a function of the sodium perchlorate concentration are presented in Table II. Two features of the data are especially noteworthy: firstly, the allylic alcohol is entirely absent as a product at all concentrations of sodium perchlorate; secondly, in the absence of sodium perchlorate the amount of rearrangement is less than 0.08%—the same value found for dilute solutions in the pH region from 3 to 5. With increasing sodium perchlorate concentration the rearrangement process, although small, makes an ever-increasing contribution to the products. During the course of this study TMEO was added very slowly to the thermostated, vigorously stirred solution of $NaClO_4$–$HClO_4$. The absence of two phases and the transparency

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(16) H. von Brachel and U. Bahr in "Houben-Weyl Methoden der Organischen Chemie", Vol. V/1c, Part 3, 4th ed., E. Muller, Ed., Georg Thieme Verlag, Stuttgart, 1970, pp 219–234; C. F. H. Allen and A. Bell, "Organic Syntheses", Collect. Vol. III, Wiley, New York, 1943, pp 312–316.

(17) It is attractive to suggest that the diene might be formed in this reaction since by analogy it is formed from thermal acid-catalyzed dehydration of pinacol.[16] Under kinetic conditions and under the reaction conditions employed here this diene does not form. However, when the allylic alcohol was added to very strong acid or when the epoxide was added to perchloric acid 5 M or stronger a violent reaction ensued in which an insoluble oil was generated in addition to pinacolone and pinacol. This oil (possibly polymeric) has the same appearance as that generated from the acid-catalyzed polymerization of 2,3-dimethyl-1,3-butadiene. The ^1H NMR spectrum of the oil is ill defined with a large, broad band of resonances between about δ 0.8 and 2.2. The diene behaves similarly in both formic acid and TFA. The sensitivity of this diene to acid-catalyzed polymerization has been well documented.[18]

(18) A. S. Onishchenko, "Diene Synthesis", Daniel Davy and Co., New York, 1964, pp 602–603.

Table III. Activation Parameters

*E*a, kcal/mol^{-1}	no. of points	ΔT, °C	$\Delta S^{\ddagger}$, eu	$\Delta V^{\ddagger}$, cm^3 mol^{-1}	ref
34.1 ± 0.7	7	29	24.7 ± 2.3		this study
36.1 ± 0.4	3	10	22.3 ± 1.0	5.9 ± 0.3	*a*
34.7 ± 2.6	5	46	18.5 ± 8.7		*b*
33.7 ± 1.0	2	27	16.8 ± 3.4		*c*

[a] *Rev. Phys. Chem. Jpn.*, 40, 48 (1970). [b] *J. Chem. Soc.*, 3512, 3519, 3674 (1956). [c] *Ibid.*, 403 (1958).

of the reaction mixtures during the course of addition assured that these products arose from a purely homogeneous reaction system. The rate of addition could be increased up to a critical point above which the solution would become heterogeneous and products characteristic of reaction type one, eq 1, would begin to apear. Care was taken to ensure that the rate of addition was well below this threshold level for inception of reaction type one. Normal addition times ranged from 7 to 10 min.

Addition of formate buffers changes the product ratio suppressing the rearrangement process, Table II. The formation of a monoformate ester in an amount which is a function of the buffer ratio and the total buffer concentration indicates the capacity of the formate ion to act as a nucleophilic species. This same ester was previously identified in earlier buffer studies[9,19a] and was here fully confirmed by its ^{13}C NMR spectrum. In this medium it is kinetically unstable with respect to hydrolysis to pinacol and formic acid, no other products being generated as deduced from NMR spectral analysis ($t_{1/2}$ = 9.7 days at pH 3.5, μ = 6.0 at 25 °C).

Pinacol is kinetically unstable in solutions containing high concentrations of sodium perchlorate and 0.24 M perchloric acid; however, the very slow rate of its conversion to pinacolone, vide ante, has absolutely no effect upon the results presented for the ring opening of TMEO.

A plot of log (% pinacolone/% pinacol) against log [$NaClO_4$] is linear with a slope of 2.2–2.4, Figure 2a. This suggests that pinacolone formation requires an order in sodium perchlorate larger by two than pinacol formation. Water is obligatory for pinacol formation and yet no unique natural relationship could be found for the product ratio and the water concentration. Plots of log (% pinacol/% pinacolone) against log [H_2O] and against log (mol % H_2O) are parabolic, Figures 2b and 2c. Although surprising, this is not without precedent as other workers have observed similar behavior albeit in hydroxylic solvents other than water.[21]

Three measurements were made to explore properties of this aqueous sodium perchlorate–perchloric acid medium. Changes in pH with ionic strength, although bearing no formal relationship to concentration at these high ionic strengths, reveal changes in hydronium ion solvation indicating increasing effective acidity (at constant acid concentration). The chemical shift of water in the NMR is a function of salt concentration[22] and the changes observed here reflect solvation changes in the dissolved species. Interestingly, the activation parameters for the conversion of pinacol to pinacolone, a carbonium ion rearrangement reaction, show no significant differences except in the entropy, Table III, Figure 3 . Increases in activation entropies with ionic strength have been previously recorded.[7]

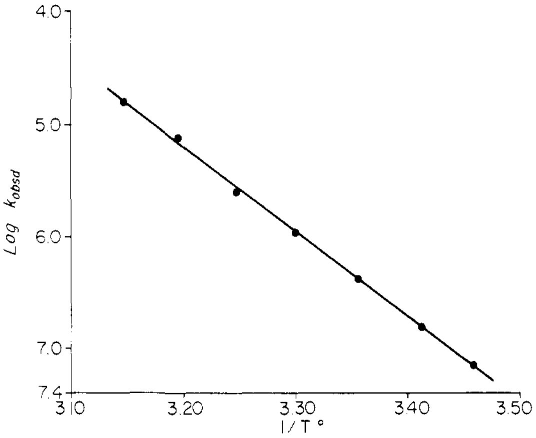


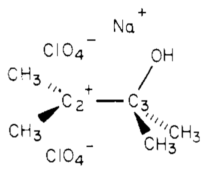
Figure 3. A plot of log k_{obsd} vs. $1/T°$ for the rearrangement of pinacol in 0.24 M perchloric acid with 6 M sodium perchlorate. The Arrhenius activation energy is 34.1 ± 0.7 kcal mol^{-1} with a correlation coefficient of 0.999. Each point represents the average rate coefficient for duplicate rates run on different days.

Discussion

Reaction Type One (eq 1). The inception of this reaction as a function of the TMEO addition rate, mixing rate, and the absence of isothermal control is a line of evidence supporting the conclusion that this is a heterogeneous reaction. The above factors cause undissolved colloidal droplets of TMEO to form. A vigorous reaction occurs at the interface with the salt solution.

The rearranged nature of one of the products, pinacolone, suggests that this heterogeneous reaction involves at least in part a carbonium ion intermediate. This is consistent with acid catalysis, for the epoxide after protonation could ring open to a carbonium ion. The details of its microenvironment would direct the carbonium ion toward elimination and rearrangement paths.

Reaction Type Two (eq 2). The homogeneous reaction of TMEO in media containing perchloric acid and sodium perchlorate produces some rearranged product, but no elimination product. The amount of rearranged product increases with the salt concentration. The similarity of this reaction to the pinacolic rearrangement suggests at least a similarity in mechanistic steps. In the pinacolic rearrangement the 2,3-dimethyl-3-hydroxy-2-butyl cation has been identified as an intermediate.[23] The existence



I

of this intermediate, encumbered with two perchlorate counterions, I, would account for the products arising from TMEO.[24] Both rearrangement and solvent capture products can arise from I, the former by a slight rotation of the 2,3 carbon–carbon bond and

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(19) (a) It has been reported that pinacol rearranges to pinacolone in pure formic acid with the formation of an intermediate: S. Wold, *Acta Chem. Scand.*, **23**, 1266–1274 (1969). TMEO was tentatively identified as the intermediate because it was thought to have the same chemical shift as an unidentified resonance observed during the course of rearrangement. The critical test of adding TMEO to formic acid was not performed. In our hands TMEO is unstable in formic acid and reacts instantly to produce pinacolone and pinacol monoformate. Pinacol monoformate possesses two resonances, one upfield which has the same chemical shift as pinacol and thus overlaps with pinacol when the two compounds are present, and one downfield which is even below the shift of where one would expect the epoxide to be. This latter resonance is what was mistakenly ascribed to TMEO. This same pinacol monoformate is observed as a product when TMEO undergoes acid-catalyzed hydrolysis in formic acid–formate buffer solutions. The ^{13}C NMR spectrum has been observed under these same conditions and conforms to the structure of the ester.[19b] Pinacol monotrifluoroacetate has been similarly identified from TMEO ring opening in trifluoroacetic acid.[19b] This ester has been independently synthesized and its behavior studied.[19c] Although pinacol monoformate is stable for several hours under the conditions of these experiments, it undergoes slow rearrangement in formic acid, $t_{1/2}$ = 47 h at 35 °C. In aqueous media this same ester undergoes hydrolysis to pinacol as the only product. The rate of this hydrolysis is pH dependent. It is unfortunate that this claim of the intermediacy of TMEO has been seized upon purporting to show that certain aliphatic pinacols behave as their aromatic analogues and rearrange via several intermediates including epoxides.[20] (b) Y. Pocker and B. P. Ronald, unpublished observations. (c) J. Hine, D. Rieard, and R. Perz, *J. Org. Chem.*, **38**, 110 (1973).

(20) F. A. Carey and R. J. Sundberg "Advanced Organic Chemistry", Part B, "Reactions and Synthesis", Plenum Press, New York, 1977, pp 336–337.

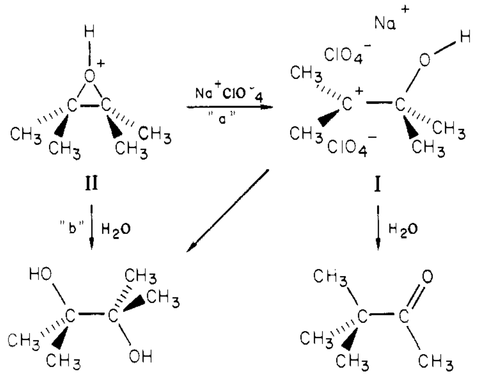
(21) E. D. Hughes, C. K. Ingold, S. F. Mok, S. Patai, and Y. Pocker, *J. Chem. Soc.*, 1220–1230 (1957); E. D. Hughes, C. K. Ingold, S. F. Mok, and Y. Pocker, *ibid.*, 1238–1255 (1957).

(22) Reference 8, Chaper 1.

(23) C. A. Bunton, T. Hadwick, D. R. Lelewellyn, and Y. Pocker, *J. Chem. Soc.*, 403–408 (1957); Y. Pocker, *Chem. Ind. (London)*, 332–333 (1959).

the latter by attack by water. The perchlorate counterions which account for the second-order dependence with salt would easily be pushed aside during the bond rotation and migration step.

A comprehensive mechanistic description of the reaction of TMEO unites the results found in dilute buffer solutions with those found in high-salt media.[9] The protonated epoxide, II, plays a pivotal role in this mechanism in that it can be transformed to products by two paths. One path (path a) is the spontaneous ring opening to a carbonium ion; the other (path b) is an S_N2-like process involving a water molecule. A change in mechanism from path b to path a is observable in solutions with high salt content. Greater transition-state stabilization due to ionic aggregation may make path a more favorable than path b. It is also possible that the acidity dependence of path a may be greater than that for path b.[25] In either case, an effect of this nature observable in water is striking. It is analogous to the effects found in acetic acid and in aqueous acetone solvolysis studies where the ion-pair mechanistic schemes were first developed. Most studies in aqueous media, however, have not been designed to exceed the "limiting laws" for solution behavior, and thus have not uncovered unusual effects of salts as has been done here. Even with the knowledge that salt effects of this type could be observed the choice of the substrate is probably a critical factor in revealing them. Tetramethylethylene oxide is very unusual in that its modes of reaction lie so near the mechanistic demarcation between S_N1 and S_N2 processes.



The phenomenon of mechanistic switching as explored here is very interesting and is under active investigation with a number of epoxides. Whether the epoxide ring itself imparts intrinsic sensitivity to the reaction environment or whether the extent of substitution engenders such sensitivity are questions currently being addressed.

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(24) A consequence of the existence of I could be its collapse with perchlorate ion to produce a covalent ester. The stability of this ester is anticipated to be very low owing to the leaving-group characteristics of perchlorate ion and because the ester would be tertiary. Even methyl perchlorate has very limited stability in aqueous solution: D. N. Kevill and G. M. L. Lin, *Tetrahedron Lett.*, 949–952 (1978). The NMR spectra of our reaction solutions do not show any resonances in addition to pinacolone and pinacol. If such an ester is formed, it must be below the detectable level.

(25) We are indebted to the referees for directing our attention to the possibility that a differential acidity dependence may be the origin of the mechanistic switch.

Relationship between the Gas-Phase Entropies of Molecules and Their Entropies of Solvation in Water and 1-Octanol

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Abstract: The entropies of solvation of ammonia, methane, and water in water are almost identical, yet their enthalpies of solvation are quite different. This suggests that, despite differences in the solute–solvent interactions, all molecules, including water, lose the same fraction of their entropy upon going from the gas phase into water and that changes in the entropy of water contribute little to the entropy of solvation. An equation containing no adjustable parameters is derived from these assumptions and found to reproduce the entropies of solvation of the hydrocarbons, alcohols, aromatic compounds, primary amines, and inert gases in water. These ideas are successfully extended to the water/1-octanol partition coefficients of the hydrocarbons. Our ideas are in conflict with prevailing ideas of the origin of entropies of solvation in water. Reasons for their validity and success are discussed.

Introduction and Results

Solutions and solute–solvent interactions play an important role in chemistry. One aspect of this subject that has received much attention is the so-called "hydrophobic interaction". The hydrophobic interaction refers to the low solubilities of nonpolar molecules (e.g., hydrocarbons) in water and to the tendency of molecules containing both highly water soluble groups and nonpolar groups to form micelles when dissolved in water.

Most discussions of the origins of the hydrophobic interaction are in terms of the "structured-water" hypothesis of Frank and Evans.[1] The low solubility of nonpolar groups in water is due to a negative entropy of solvation which overcomes a favorable enthalpy of solvation. The structured-water hypothesis rationalizes these facts by saying that water in the vicinity of nonpolar solutes is more structured than bulk water. The nature of this structured water is not specified, but it is assumed that it has more hydrogen bonds per water molecule than the bulk water and that these additional hydrogen bonds restrict the mobility of the water molecules, resulting in a lower entropy for such water molecules.[2,3] The additional hydrogen bonds are believed to account for the favorable enthalpy of solvation.

The structure of water and how solutes affect it have been the subject of a variety of experimental studies. Most of the experimental results have been interpreted as showing that nonpolar solutes increase the number of hydrogen bonds,[4,5] but some studies have been interpreted as showing that nonpolar solutes decrease the number of hydrogen bonds.[6,7]

We were led to reexamine the idea that hydrogen bonds and changes in the structure of water made the dominant contributions to the entropies of solvation by some seemingly anomalous data. As Table I shows, adding a methyl group to a compound makes it, at best, slightly less soluble in water and often makes it slightly

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(2) F. Franks and D. S. Reid in "Water, a Comprehensive Treatise", Vol. 2, F. Franks, Ed., Plenum Press, New York, 1973, Chapter 5.

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