the vitamin K-dependent carboxylation of glutamic acid residues of prothrombin.[24] Furthermore, the reaction of $O_2^{\bullet-}$ with phosphates offer some suggestion about the mechanism of nucleic acid damage by active oxygen species. The biological roles of these peroxy species are under investigation.

Experimental Section

Equipment. The Shimadzu 6-AM PEG 6000 GC system and the Shimadzu LC-3A Nucleosil $_5C_{18}$ system were used to separate and identify reaction products. A Yanaco Model P-1000 voltammetric analyzer and Model FG-121B, N F Circuit Design Block Co., Ltd., were used to measure cyclic voltammograms. Raman Spectra were obtained with a Jasco R-800 laser raman spectrophotometer. A JEOL DX-300 GC-MS system was used to determine the incorporation ratio of ^{18}O into reaction products. A Nikko Keisoku potential sweeper NPS-2, dual potentiogalvanostat DGPS-1, motor speed controller SC-5, rotating ring-disk electrodes RRDE-1 rotator, and glassy carbon or platinum ring-disk electrodes were used for the kinetic measurements.

Chemicals and Reagents. Potassium superoxide (KO_2) was prepared according to the method of Rosenthal,[21] and 18-crown-6-ether was purchased from Tokyo Kasei. Tetraethylammonium perchlorate (TEAP) was purchased from Wako Pure Chemical Industries, Ltd. Carbon dioxide (CO_2) gas was obtained from Suzuki Shokan Inc. Other reagents and substrates were of analytical grade or of the highest purity available and generally were used without further purification.

Methods. Oxidation of Various Substrates in the System of KO_2 and Polyhalides. Finely powdered KO_2 (3.0 mmol) was added to an acetonitrile solution (18 mL) containing the substrates (0.3 mmol) and 18-crown-6-ether (0.3 mmol). Then polyhalide (15 mmol) was added dropwise to the solution. The resulting heterogeneous mixture was vigorously stirred at 10-15 °C for 4-24 h with protection from moisture. After the reaction was finished, the mixture was filtered to remove unreacted KO_2. The product yields were determined by HPLC and GC.

Cyclic Voltammetry of O_2 in the Absence or Presence of Polyhalides. The reactivities of polyhalides with $O_2^{\bullet-}$ were monitored by measurement of cyclic voltammetry of dioxygen in the absence or presence of polyhalides using platinum for the electrode and dimethylformamide as the solvent. All the solutions were prepared at 1.0 mM and contained 0.1 M tetraethylammonium perchlorate (TEAP) as a supporting electrolyte.

Oxidation of Substrates in the System of KO_2 and CO_2. The substrate (0.3 mmol) and 18-crown-6-ether (0.3 mmol) were dissolved in dimethylformamide (18 mL) with bubbling of CO_2 gas for 5 min, followed by addition of finely powdered KO_2 (3.0 mmol). The reaction mixture was vigorously stirred at 15-20 °C under a CO_2 atmosphere for 20 h. The reaction mixture was filtered and the product yield was determined by HPLC and GC.

Oxidation of Substrates in the System of KO_2 and Phosphates. Finely powdered KO_2 (3.0 mmol) was added to a dimethylformamide solution (18 mL) containing the substrates (0.3 mmol), 18-crown-6-ether (0.3 mmol), and phosphate (0.45 mmol). The reaction mixture was vigorously stirred at 15-20 °C for 1-5 h with protection from moisture. The reaction mixture was filtered and the product yields were determined by HPLC or GC.

Experiments Incorporating ^{18}O into Reaction Products. Ar, air, or $^{16}O_2$ gas was bubbled into the reaction mixture of substrate, 18-crown-6-ether and $K^{18}O_2$ for 30 min before the reaction was started in a flask with a serum rubber stopper. This was done to examine the oxygen atom source incorporated into the reaction products under various $^{16}O_2$ concentration conditions. Next, the additive compound in a solvent prebubbled with the same gas was added to the reaction mixture via a gas-tight syringe. The resulting reaction mixture was vigorously stirred with bubbling of the same gas. The reaction was quenched by the addition of prebubbled H_2O. The incorporation ratio of $^{18}O_2$ into the reaction products was determined by GC-MS.

Kinetic Measurements by Ring-Disk Voltammetry. The rate of reactions of various additive compounds with $O_2^{\bullet-}$ was measured with a rotating ring-disk electrode under pseudo-first-order conditions. A rotating (900 rpm) platinum ring-glassy carbon disk was used for the measurement in air-saturated 0.1 M tetraethylammonium perchlorate (TEAP) in dimethylformamide. The bulk O_2 concentration was ca. 1 mM. The data were analyzed by the procedures described by Albery and Hitchman to obtain the pseudo-first-order rate constant, k_1.[25]

Acknowledgment. This work was supported by a research grant from the Ministry of Education, Science, and Culture of Japan. We thank Professor Y. Moro-oka and Dr. H. Suzuki, Tokyo Institute of Technology, for the $K^{18}O_2$ preparation, and Dr. Y. Nishimura, University of Tokyo, for the measurement of the Raman spectra.

(24) (a) Stah, D. V.; Suttie, J. W. *Biochem. Biophys. Res. Commun.* **1974**, *60*, 1397-1402. (b) Esnouf, M. P.; Green, M. R.; Hill, H. A. O.; Irvine, G. B.; Walter, S. J. *Biochem. J.* **1978**, *174*, 345-348. (c) Esnouf, M. P.; Fainey, A. I.; Green, M. R.; Hill, H. A. O.; Okolow-Zubkouska, M. J.; Walter, S. J. In *Biological and Clinical Aspects of Superoxide and Superoxide Dismutase*; Bannister, W. H., Bannister, J. V., Eds.; Elsevier/North-Holland: New York, 1980, pp 72-83.

(25) Albery, W. J.; Hitchman, M. L. In *Ring-Disk Electrodes*; Clarendon Press: Oxford, 1971.

1-Oxabicyclobutonium Ions Can Intervene in Epoxycarbinyl and 3-Oxetanyl Solvolyses

Michelle M. Francl,* Gerry Hansell, Bomi P. Patel, and Charles S. Swindell*

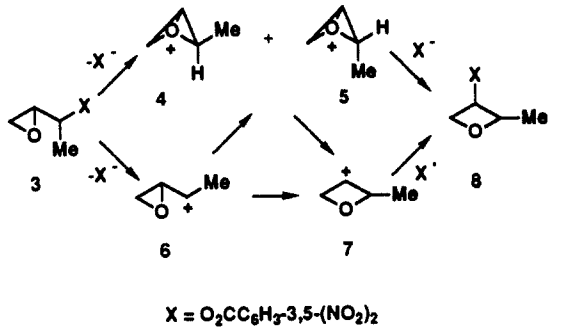
Contribution from the Department of Chemistry, Bryn Mawr College, Bryn Mawr, Pennsylvania 19010. *Received July 13, 1989. Revised Manuscript Received December 19, 1989*

Abstract: The solvolytic reactions of **9** and **12** have been investigated with a view toward probing the possible stereospecific involvement of 1-oxabicyclobutonium ions **4** and **5**, respectively. Solvolysis of **9** in aqueous acetone led to the detection of **10** and **11** as products. A similar experiment on **12** led to **13** and **14** identified by independent synthesis from **15**. Oxetanyl ester **13** was demonstrated to lead to **14** under the solvolytic conditions employed. These results are compatible only with mechanisms requiring the stereospecific, rate-determining, and anchimerically assisted formation of **4** in the reactions of **9** and **10**, and of **5** in the reactions of **12** and **13**. Ions **6** and **7** are not intermediates. Ab initio molecular orbital theory calculations at the MP2/6-31G*//HF/6-31G* level confirmed that of ions **4-7** likely to intervene, **4** and **5** are least energetic. This is the first unequivocal demonstration of the involvement of 1-oxabicyclobutonium ions in epoxycarbinyl and 3-oxetanyl solvolytic processes and of the ability of epoxides to act as conventional neighboring group participators toward adjacent electrophilic sites.

Although the solvolytic chemistry of epoxycarbinyl systems has been investigated repeatedly over the last 20 years, consistent and compelling evidence that the epoxide substructure can play a participatory role in the ionization step and that 1-oxabicyclobutonium ions can mediate these and related reactions remains lacking. Thus while Richey's[1] epoxycarbinyl solvolytic rear-

0002-7863/90/1512-3535$02.50/0

Scheme I



rangement product and rate studies appear to support these contentions, Whalen's[2] refute them. Other investigations,[3] considered in toto, have proven equally equivocal. Indeed an attempt by one of us[4] to show that an epoxide-assisted solvolytic rearrangement might connect biogenetically taxane diterpenes of C-ring type **1** with those of type **2** (cf. taxol[5]) ended in yet another

mechanistic ambiguity. In a search for evidence that such a mechanism applies in *any* related transformation, we focused our attention on the rearrangement of **3** to **8** reported originally by Richey[1] in stereochemically undefined form and which could be envisioned to involve the cationic intermediates and pathways depicted in Scheme I. In particular since the detection of stereospecificity in the conversion of the individual diastereomers of **3** into diastereomers of **8** would rule out the intervention of cations **6** and **7**, and since epoxide participation in the single-step formation from **3** of 1-oxabicyclobutonium ions **4** and **5** could have predictable stereochemical consequences manifested in **8**, we elected to probe the stereochemical details[6] of this transformation. In addition, we expected the computational investigation[7] of cations **4**–**7** to illuminate their relative energies as well as their structural and bonding characteristics. Herein we show that expoxides can behave as conventional neighboring group participators in epoxycarbinyl solvolytic processes and that 1-oxabicyclobutonium ions can intervene in these and 3-oxetanyl solvolyses.

Richey's diastereomeric mixture of epoxy esters **3** could be resolved chromatographically to provide *anti*(*erythro*)-**9** and *syn*(*threo*)-**12** (see Scheme II). The latter were identified by comparison with the 80:20 mixture of 3,5-dinitrobenzoate diastereomers produced from the 80:20 anti/syn, respectively, mixture of epoxy alcohols from the $VO(acac)_2$-catalyzed epoxidation of 3-buten-2-ol.[8] The reactions of **9** and **12** (approximately 0.03

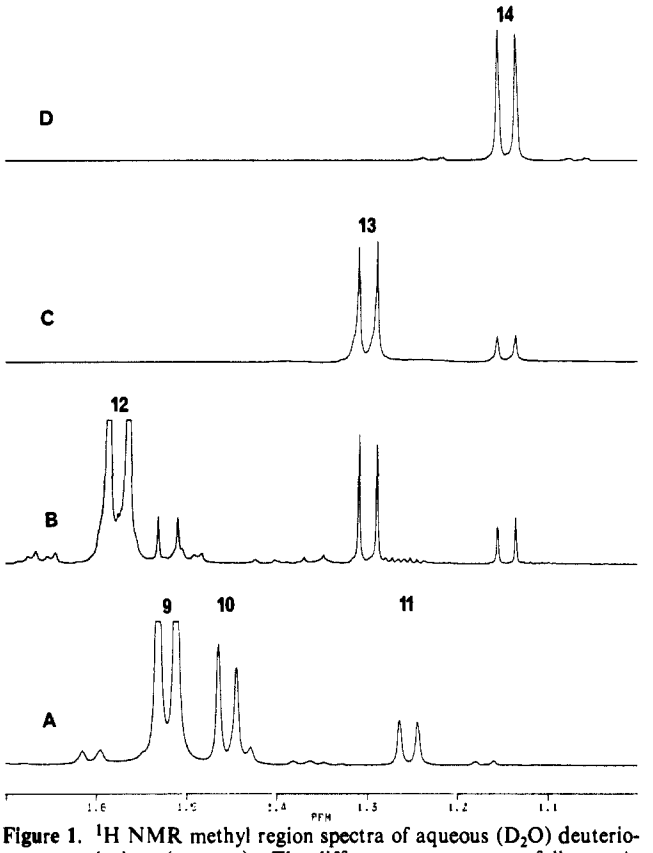


Figure 1. ^1H NMR methyl region spectra of aqueous (D_2O) deuterioacetone solutions (see text). The different spectra are as follows: A, partially converted **9**; B, partially converted **12**; C, partially converted authentic **13**; D, authentic **14**.

M) at 100 °C in 2,6-lutidine-buffered 80% aqueous (D_2O) deuterioacetone[1] were followed by observing the region of the ^1H NMR spectrum containing their methyl doublets as well as those of their derived products (see Figure 1). At high conversions, product mixtures were somewhat complicated, but at moderate conversions (no more than 25%), product mixtures were straightforward. The mass balances observed indicated that in each solvolysis *at least* 97% of the material remaining at approximately 25% conversion could be attributed to the epoxy ester and the products mentioned below.

Under these conditions, **9** led to two products (Figure 1). The one more rapidly formed was identified tentatively as **10** (Scheme II); its ^1H NMR spectrum was consistent with data reported earlier.[9] Less rapidly generated was a substance which possessed a methyl doublet resonating at higher field than either **9** or **10** and remaining ^1H NMR spectral features which suggested structure **11**.[9] Epoxide **12** behaved analogously in producing respective products **13** and **14**, similar spectroscopically to their counterparts above but clearly different stereochemically. Thus these solvolytic rearrangements and solvolyses are stereospecific within the limits of our analytical procedures, ruling out their mediation by cations **6** and **7**.

To authenticate the structures, stereochemistries, and mechanistic rationales depicted in Scheme II, we scrutinized more closely the products and processes emanating from **12**. The structure of oxetanol **14** was confirmed through its independent synthesis from **15**[10] as outlined. In particular, the stereochemistry of **14** incorporated at the stage of **16** was evident in the latter from the ^1H NMR coupling constants involving the benzyloxy methine proton (ddd, J = 1.9, 2.3, 2.9 Hz). These were consistent with

(1) Richey, H. G., Jr.; Kinsman, D. V. *Tetrahedron Lett.* **1969**, 2505.
(2) Whalen, D. L.; Brown, S.; Ross, A. M.; Russell, H. M. *J. Org. Chem.* **1978**, *43*, 428. Whalen, D. L.; Cooper, J. D. *J. Org. Chem.* **1978**, *43*, 432.
(3) Morita, H.; Oae, S. *Tetrahedron Lett.* **1969**, 1347. Thomas, A. F.; Pawlak, W. *Helv. Chim. Acta* **1971**, *54*, 1822. Kagan, J.; Przybytek, J. T. *Tetrahedron* **1973**, *29*, 1163. Peters, E. N. *J. Org. Chem.* **1978**, *43*, 4006. Whalen, D. L. *Tetrahedron Lett.* **1978**, 4973. Santelli, M.; Viala, J. *Tetrahedron* **1979**, *34*, 2327. Clark, G. R. *Tetrahedron Lett.* **1984**, *25*, 2839.
(4) Swindell, C. S.; Britcher, S. F. *J. Org. Chem.* **1986**, *51*, 793.
(5) Wani, M. C.; Taylor, H. L.; Wall, M. E.; Coggon, P.; McPhail, A. T. *J. Am. Chem. Soc.* **1971**, *93*, 2325.
(6) We also assumed that the kinetic detection of epoxide participation in the formation of cations like **4** and **5** would be clouded by the questionable appropriateness of any model-unassisted solvolysis which might be chosen. This point aside, however, participation meeting the usual stereochemical criterion need not at the same time meet the usual kinetic criterion. See, for example: Schleyer, P. v. R.; Bentley, T. W.; Koch, W.; Kos, A. J.; Schwarz, H. *J. Am. Chem. Soc.* **1987**, *109*, 6953 and references cited therein.
(7) For a previous computational investigation of the epoxycarbinyl cation, see: Danen, W. C. *J. Am. Chem. Soc.* **1972**, *94*, 4835.
(8) Rossiter, B. E.; Verhoeven, T. R.; Sharpless, K. B. *Tetrahedron Lett.* **1979**, 4733.
(9) Kinsman, D. V. Ph.D. Dissertation, The Pennsylvania State University, 1969.
(10) Araki, Y.; Nagasawa, J.; Ishido, Y. *J. Chem. Soc., Perkin Trans 1* **1981**, 12.

Scheme II

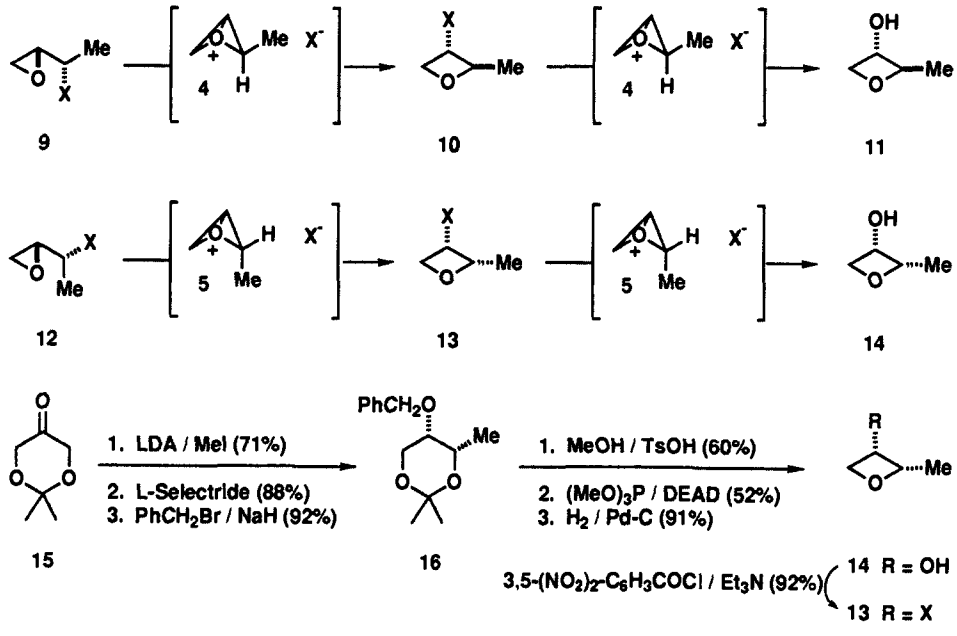


Table I. Relative Energies of 4–7[a]

structure	HF/6-31G*// HF/6-31G*	MP2/6-31G*// HF/6-31G*[b]
4	4.7	−3.7
5	7.6	−1.0
6	0.0	0.0
7	13.5	20.8

[a] All values in kilocalories mole^{-1}. [b] Corrected to 373 K (the temperature of the solvolytic experiments) and for zero-point vibrational energy. See text for details.

an equatorial disposition of the oxygenated methine proton which would only be true for the cis diastereomer shown.[11] The oxetane ring charcteristic of **14** could be closed through the Mitsunobu reaction,[12] and its further conversion to solvolytic rearrangement product **13** verified the structure of the latter. Furthermore with **13** in hand, its solvolysis under the conditions applied to **12** could be investigated whereupon it was observed to return **14** (Figure 1). These observations are fully consistent with the chemistry for **12** depicted in Scheme II and point to the intervention in it of 1-oxabicyclobutonium ion **5**; it is extremely likely that **9** behaves analogously.

The structures and relative energies of the potential intermediates **4–7** were obtained from searches of energy surfaces from ab initio molecular orbital theory in order to corroborate the above observations. The GAUSSIAN82[13] suite of programs was used throughout. No symmetry constraints were imposed on any of the structures. Initially, each of the ions was optimized at the HF/3-21G[14] level, and normal mode analyses were performed to confirm that each of the structures corresponded to a minimum of the 3-21G potential energy surface. Subsequently, optimal HF/6-31G*[15] structures were obtained. Energy differences were derived from single-point energies computed for each intermediate at the MP2/6-31G*//HF/6-31G* level, and then corrected for the zero-point vibrational energy and effects of temperature.[16] The results, which are compatible with the above determination that epoxide participation intervenes in the ionization step of Richey's rearrangement, are shown in Table I.

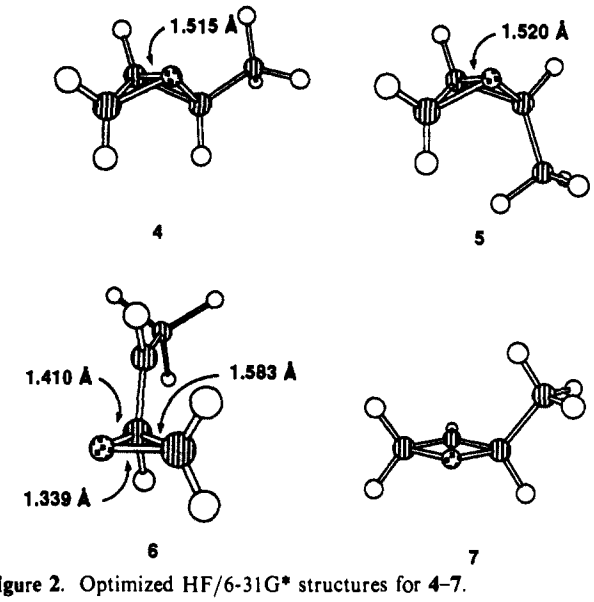


Figure 2. Optimized HF/6-31G* structures for **4–7**.

The exo bicyclic ion **4** proved to be the most stable of the proposed structures at the MP2/6-31G*//HF/6-31G* level of theory. It is slightly less than 4.0 kcal/mol more stable than the isomeric epoxycarbinyl ion **6**. This is in accord with recent results[17] that show the bicyclic isomer of the hydrocarbon analogue $C_4H_7^+$ to be favored over bisected cyclopropylcarbinyl cation by less than 2 kcal/mol at the same level of theory. Saunders et al. did not find that higher level (MP4SDTQ/6-31G*//MP2/6-31G*) calculations on the $C_4H_7^+$ isomers changed the ordering of the cyclopropylcarbinyl cation and the bicyclic structure, though the

(11) The trans benzyl ether diastereomer related to **16** exhibited ^{1}H NMR coupling constants involving the oxygenated methine consistent with it being axial: ddd, J = 2.7, 10.1, 10.4 Hz.

(12) Mitsunobu, O. *Synthesis* **1981**, 1. Berkowitz, W. F.; Marasekara, A. S.; Perumattam, J. J. *J. Org. Chem.* **1987**, *52*, 1119. Bhagwat, S. S.; Hamann, P. R.; Still, W. C. *J. Am. Chem. Soc.* **1985**, *107*, 6372.

(13) Binkley, J. S.; Frisch, M.; Krishnan, R.; DeFrees, D. J.; Schlegel, H. B.; Whiteside, R.; Fluder, E.; Seeger, R.; Pople, J. A. GAUSSIAN82, release H Carnegie-Mellon University: Pittsburgh, PA, ca. 1982.

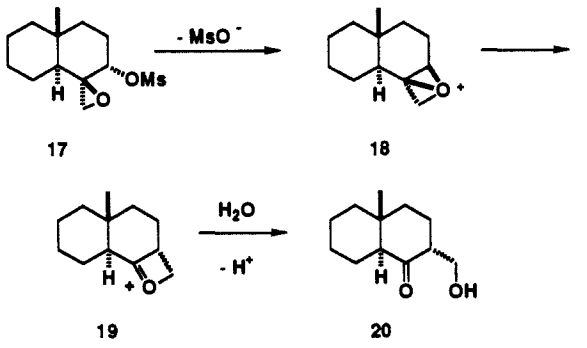
(14) Binkley, J. S.; Pople, J. A.; Hehre, W. J. *J. Am. Chem. Soc.* **1980**, *102*, 9393.

(15) Hahriharan, P. C.; Pople, J. A. *Theor. Chim. Acta* **1973**, *28*, 213.

(16) Corrected as follows to 373 K and for the zero-point energy: $E_{zero\ point} = {}^1/_2 \Sigma h\nu_i$; $H(T) = H_{vib} + H_{rot} + H_{trans}$; $H_{vib} = N\Sigma h\nu_i/[\exp(h\nu_i/kT) - 1] + RT$; $H_{rot} = {}^3/_2RT$; $H_{trans} = {}^3/_2RT$. Vibrational modes less than 400 cm^{-1} were treated as rotations in the calculation of H_{vib}; HF/3-21G normal mode frequencies were used after scaling by 0.85.

(17) Koch, W.; Liu, B.; DeFrees, D. J. *J. Am. Chem. Soc.* **1988**, *110*, 7325. Saunders, M.; Laidig, K. E.; Wiberg, K. B.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1988**, *110*, 7652.

Scheme III



gap between them was narrowed by slightly more than 9 kcal/mol. On the basis of their findings, we would not expect more sophisticated theoretical treatments to change our prediction that **4** is significantly more stable than **6**. Cation **7** is more than 20 kcal/mol less stable than any of the other ions considered. Again, the analogous structure on the $C_4H_7^+$ surface has been shown to be substantially less stable than either the cyclopropylcarbinyl or bicyclic ions.

The structural parameters determined for 1-oxabicyclobutonium ions **4** and **5** support the orthodox bonding arrangements shown for them in Figure 2. The bridging carbon–oxygen bond lengths are somewhat longer than those typical for carbon–oxygen single bonds (1.34–1.47 Å). These results parallel those for bicyclic $C_4H_7^+$ in which the carbon–carbon bridge bond is found to be 1.686 Å in length,[17] thus longer than the "normal" carbon–carbon single bond length of 1.54 Å. Charge density difference plots[18] of **4** reveal a significant buildup of electron density between the bridgehead atoms similar to that seen in bicyclobutane.[19] The cyclopropylcarbinyl analogue **6** possesses a somewhat distorted bisected structure in which the p orbital centered on the formally cationic carbon is canted toward alignment with the ring carbon–carbon bond. The carbon–oxygen bond opposite the exocyclic carbon–carbon bond is significantly shorter (by 0.071 Å) than the adjacent carbon–oxygen bond. On the other hand, the ring carbon–carbon bond is lengthened (1.583 Å) relative to that in oxirane (1.474 Å).[20] These structural features can be attributed to donation into the above p orbital of electron density from an orbital on the three-membered ring analogous to the anti symmetric Walsh cyclopropane HOMO.[21] The skewing of the empty p orbital on the cationic center is a result of the asymmetry of this orbital fragment. As expected, then, rotation about the exocyclic carbon–carbon bond in **6** destroying this stabilization is costly, being characterized by a barrier of approximately 45 kcal/mol at HF/3-21G. Finally, cation **7** differs principally from **4** and **5** in that its four-membered ring is planar rather than puckered.

In conclusion, the involvement of 1-oxabicyclobutonium ions in at least some epoxycarbinyl and 3-oxetanyl solvolytic processes and the capacity of epoxides to engage in conventional neighboring group participation have been demonstrated unequivocally. Given Whalen's previous observations[2] and the relatively narrow range of energies spanned by ions **4–6**, it is likely that the involvement of anchimerically assisted chemistry of this type will be a sensitive function of the structural and electronic details of the system in question. Nevertheless, a mechanistic sequence of events similar to that described herein offers an attractive explanation for our own previous observation[4] of the anomalous transformation of **17** into **20** (Scheme III).[22]

(18) Jackson, N.; Haydock, K.; Francl, M. M.; Lim, K. T.; Poetl, H. A.; Fisher, A.; Peters, N. CDIFF82, unpublished computer code.
(19) Francl, M. M.; Hansell, G. Unpublished results.
(20) Hehre, W. J.; Radom, L.; Schleyer, P. v. R.; Pople, J. A. *Ab Initio Molecular Orbital Theory*; Wiley-Interscience: New York, 1986.
(21) Levi, B. A.; Blurock, E. S.; Hehre, W. J. *J. Am. Chem. Soc.* **1979**, *101*, 5537.
(22) The reasonable possibility that the Richey rearrangement provides the biogenetic connection which might exist between the taxane C-ring structure of type **1** and that of type **2** associated with taxol therefore persists.

Experimental Section

Reactions requiring anhydrous conditions and inert atmospheres were performed in flame-dried glassware under nitrogen with anhydrous solvents distilled under nitrogen. Melting points were determined on a Thomas Hoover capillary apparatus and are uncorrected. ^{1}H NMR spectra (300 MHz) of deuterated chloroform solutions (unless otherwise indicated) were recorded on an IBM NR/AF-300 spectrometer using tetramethylsilane (δ = 0 ppm) as the internal standard. ^{13}C NMR spectra (75 MHz) of deuterated chloroform solutions were determined on the same spectrometer with solvent acting as the internal standard (δ = 77 ppm); degrees of proton substitution were assigned with the aid of 1D DEPT experiments. Infrared spectra of carbon tetrachloride solutions were determined by using a Perkin-Elmer 283 spectrophotometer. Gas chromatographic–mass spectral analyses were carried out on a Hewlett-Packard 5890A/5970 instrument.

***anti*(*erythro*)- and *syn*(*threo*)-3,4-Epoxybut-2-yl 3,5-Dinitrobenzoates (9 and 12).** To a solution of 23.1 g (0.1 mol) of 3,5-dinitrobenzoyl chloride and 13.9 mL (0.1 mol) of triethylamine in 200 mL of methylene chloride at room temperature was added 8.67 mL (0.1 mol) of 3-buten-2-ol. After being stirred for 1 h, the reaction mixture was washed with water, 10% aqueous hydrochloric acid, and saturated aqueous sodium bicarbonate and dried (sodium sulfate), and the solvent was removed to give 23 g (86%) of 3-buten-2-yl 3,5-dinitrobenzoate, mp 144–145 °C (hexane). A solution of 15.6 g (ca 0.07 mol) of 3-chloroperoxybenzoic acid (80–85%) and 18.6 g (0.07 mol) of 3-buten–2-yl 3,5-dinitrobenzoate in 100 mL of methylene chloride at room temperature was stirred overnight. The reaction mixture was then filtered, aand the filtrate was washed with saturated aqueous sodium bicarbonate and dried (sodium sulfate), and the solvent was removed to give 17.1 g (87%) of a 58:42 mixture of epoxide diastereomers **9** and **12**, respectively. Flash chromatography, eluting with hexane/ethyl acetate, gave first 8.0 g of **12** followed by 7.8 g of **9**.

Alternatively, **9** and **12** could be prepared in the following way. To a solution of 0.5 g (6.9 mmol) of 3-buten-2-ol and 22 mg (1 mol %) of vanadyl acetoacetonate in 5 mL of methylene chloride at 0 °C was added 2.9 mL (8.7 mmol) of *tert*-butyl hydroperoxide solution (3.0 M in 2,2,4-trimethylpentane). After being stirred for 6.5 h, the reaction mixture was filtered and shown by GC/MS analysis to contain a 78:22 mixture of anti(erythro) and syn(threo) epoxy alcohols, respectively, with less than 5% unreacted 3-buten-2-ol. To this crude reaction mixture at 0 °C was added 2 g (8.7 mmol) of 3,5-dinitrobenzoyl chloride and 1.61 mL (12 mmol) of triethylamine. After being stirred overnight, the reaction mixture was washed with water, saturated aqueous sodium bicarbonate, saturated aqueous sodium chloride, and dried (sodium sulfate), and the solvent was removed to give 1.54 g (79%) of a mixture of epoxy esters shown by GC/MS and ^{1}H NMR analysis to consist of an 80:20 ratio of **9** and **12**, respectively.

***anti*(*erythro*)-3,4-Epoxybut-2-yl 3,5-dinitrobenzoate (9)**: mp 80–82 °C (hexane/ethyl acetate); ^{1}H NMR (80% deuterated acetone, 20% deuterium oxide; $\delta_{\text{lutidine-Me}}$ = 2.50 ppm) δ 1.52 (3 H, d, J = 6.6 Hz, CH_3), 2.7–2.9 (2 H, m, CH_2), 3.29 (1 H, dt, J = 2.6, 4.5 Hz, epoxy CH), 5.29 (1 H, dq, J = 4.5, 6.6 Hz, CHOR), 9.0–9.2 (3 H, m, aromatic H); ^{13}C NMR ($CDCl_3$) δ 161.07, 148.42, 137.91 (quaternaries), 129.95, 117.54, 72.34, 52.54 (CH), 45.11 (CH_2), 15.83 (CH_3); IR (CCl_4) 1730 cm^{-1}; mass spectrum, m/z (relative intensity) 282 (M^+, 13), 195 (100).

Anal. Calcd for $C_{11}H_{10}N_2O_7$: C, 46.82; H, 3.57; N, 9.93. Found: C, 46.69; H, 3.83; N, 9.93.

***syn*(*threo*)-3,4-Epoxybut-2-yl 3,5-dinitrobenzoate (12)**: mp 86–87 °C (hexane/ethyl acetate); ^{1}H NMR (80% deuterated acetone, 20% deuterium oxide; $\delta_{\text{lutidine-Me}}$ = 2.50 ppm) δ 1.58 (3 H, d, J = 6.5 Hz, CH_3), 2.77 (1 H, dd, J = 2.5, 4.5 Hz, CH_2), 2.89 (1 H, app t, J = 4.5 Hz, CH_2), 3.33 (1 H, ddd, J = 2.5, 4.5, 6.5 Hz, epoxy CH), 4.93 (1 H, app quintet, J = 6.5 Hz, CHOR), 9.0–9.1 (2 H, m, aromatic H), 9.1–9.2 (1 H, m, aromatic H); ^{13}C NMR ($CDCl_3$) δ 161.74, 148.47, 133.78 (quaternaries), 129.47, 122.44, 74.87, 53.20 (CH), 44.77 (CH_2), 16.56 (CH_3); IR (CCl_4) 1730 cm^{-1}; mass spectrum, m/z (relative intensity) 282 (M^+, 9), 195 (100).

Anal. Calcd for $C_{11}H_{10}N_2O_7$: C, 46.82; H, 3.57; N, 9.93. Found: C, 47.08; H, 3.64; N, 9.80.

***cis*-2,2,4-Trimethyl-5-(benzyloxy)-1,3-dioxane (16).** To 1.24 mL (8.8 mmol) of diisopropylamine in 10 mL tetrahydrofuran at −78 °C was added 3.38 mL (8.5 mmol) of *n*-butyllithium solution(2.5 M in hexanes). To this solution after a period of 15 min was added dropwise a solution of 1 g (7.7 mmol) of keto acetonide **15** in 10 mL of tetrahydrofuran. The reaction mixture was stirred for 30 min at −78 °C at which point 1.67 g (11.8 mmol) of freshly distilled methyl iodide was added. After being warmed slowly to room temperature, the solvent was removed and the residue taken up in methylene chloride, washed with saturated aqueous sodium chloride, and dried (sodium sulfate). Solvent removal gave an oil which could be Kugelrohr distilled at 71 °C (14 Torr) to yield 0.786

g (71%) of 2,2,4-trimethyl-5-oxo-1,3-dioxane: ^{1}H NMR δ 1.41 (3 H, s, CH_3), 1.49 (3 H, s, CH_3), 1.54 (3 H, d, J = 4 Hz, CH_3), 4.01 (1 H, q, J = 4 Hz, CH), 4.14 (2 H, app s, CH_2); ^{13}C NMR δ 205.53, 98.85 (quaternaries), 64.94 (CH), 64.40 (CH_2), 27.06, 23.59, 23.28 (CH_3); IR 1710 cm^{-1}; mass spectrum, m/z (relative intensity) 144 (M^+, 16), 71 (100).

To a solution of 1 g (6.9 mmol) of 2,2,4-trimethyl-5-oxo-1,3-dioxane in 10 mL tetrahydrofuran at −78 °C was added dropwise 7 mL (7 mmol) of L-Selectride solution (1 M in tetrahydrofuran). After being stirred for 4 h, the reaction mixture was warmed to 0 °C and 8 mL of 15% aqueous sodium hydroxide followed by 6 mL of 30% hydrogen peroxide was added dropwise. The mixture was stirred for an additional 15 min, water was added, and the mixture was extracted with methylene chloride. The organic layer was washed with aqueous sodium bisulfite and water and dried (sodium sulfate), and the solvent was removed to give an oil which could be Kugelrohr distilled at 80 °C (14 Torr) to yield 0.892 g (88%) of *cis*-2,2,4-trimethyl-5-hydroxy-1,3-dioxane: ^{1}H NMR δ 1.29 (3 H, s, CH_3), 1.34 (3 H, s, CH_3), 1.50 (3 H, d, J = 4 Hz, CH_3), 2.68 (1 H, s, OH), 3.37–3.38 (1 H, m, C*H*OH), 4.03 (1 H, dd, J = 3, 14 Hz, CH_2), 4.13 (1 H, ovlp dq, J = 4, 8 Hz, CH), 4.26 (1 H, dd, J = 6, 14 Hz, CH_2); ^{13}C NMR δ 98.36 (quaternary), 64.30, 62.12 (CH), 61.46 (CH_2), 29.38, 24.86, 24.40 (CH_3); IR 3445 cm^{-1}; mass spectrum, m/z (relative intensity) 146 (M^+, 7), 71 (100).

To a mixture of 2 g (13.7 mmol) of *cis*-2,2,4-trimethyl-5-hydroxy-1,3-dioxane and 0.329 g (13.7 mmol) of sodium hydride in 25 mL tetrahydrofuran at room temperature was added dropwise 1.77 mL (14.9 mmol) of benzyl bromide. After being stirred for 3 h, the reaction mixture was warmed to room temperature, the solvent was removed, and the residue was taken up in methylene chloride, washed with water, saturated aqueous sodium bicarbonate, and saturated aqueous sodium chloride, and dried (sodium sulfate), and the solvent was removed to give 2.97 g (92%) of *cis*-2,2,4-trimethyl-5-(benzyloxy)-1,3-dioxane (**16**): mp 114–116 °C (hexane/ethyl acetate); ^{1}H NMR δ 1.17 (3 H, s, CH_3), 1.45 (3 H, s, CH_3), 1.87 (3 H, d, J = 4 Hz, CH_3), 4.10 (1 H, dd, J = 1.9, 14 Hz, CH_2), 4.19 (1 H, dd, J = 2.9, 14 Hz, CH_2), 4.50 (1 H, dq, J = 2.3, 4 Hz, CH), 4.73 (1 H, ovlp ddd, J = 1.9, 2.3, 2.9 Hz, CHOR), 4.91 (2 H, app s, CH_2), 7.7–7.8 (5 H, m, aromatic H); ^{13}C NMR δ 146.41, 99.10 (quaternaries), 149.63, 148.71 (double signal), 141.37 (double signal), 66.22, 64.91 (CH), 69.48, 61.03 (CH_2), 28.56, 24.28, 23.94 (CH_3); mass spectrum, m/z (relative intensity) 236 (M^+, 9), 145 (100).

***cis*-2-Methyl-3-hydroxyoxetane (14).** To a solution of 1.4 g (5.9 mmol) of *cis*-2,2,4-trimethyl-5-(benzyloxy)-1,3-dioxane (**16**) in 5 mL of methanol at room temperature was added 0.342 g (1.8 mmol) of *p*-toluenesulfonic acid hydrate. After being stirred for 6 h, the mixture was diluted with water and extracted thrice with ether, and the ether layer was washed with saturated aqueous sodium chloride and dried (sodium sulfate). Removal of solvent gave 0.697 g (60%) of *syn*(*threo*)-1,3-dihydroxy-2-(benzyloxy)butane as an oil which could be Kugelrohr distilled at 67 °C (0.05 Torr): ^{1}H NMR δ 1.62 (3 H, d, J = 6 Hz, CH_3), 3.69 (1 H, dd, J = 4, 7 Hz, CH_2), 3.78 (1 H, dd, J = 6, 7 Hz, CH_2), 4.24 (1 H, dq, J = 2, 6 Hz, CH), 4.86 (2 H, app s, CH_2), 5.75 (1 H, ovlp ddd, J = 2, 4, 6 Hz, CHOR), 7.5–7.7 (5 H, m, aromatic H); ^{13}C NMR δ 148.23 (quaternary), 149.82, 146.54 (double signal), 139.98 (double signal), 61.47, 59.79 (CH), 68.83, 59.02 (CH_2), 26.44 (CH_3); mass spectrum, m/z (relative intensity) 178 (M^+, 16), 91 (100).

To a solution of 2.14 mL (18.2 mmol) of trimethyl phosphite in 10 mL of methylene chloride at 0 °C was added 2.08 mL (13.2 mmol) of diethyl azodicarboxylate. After the solution had been stirred for 5 min at room temperature, the resulting solution was added to the above *syn*(*threo*)-1,3-dihydroxy-2-(benzyloxy)butane in 20 mL of dry methylene chloride at 0 °C. After being stirred for 45 min, the solvent was removed from the reaction mixture and the residue was chromatographed on silica gel, eluting with ether, to give 0.325 g (52%) of *cis*-2-methyl-3-(benzyloxy)oxetane as an oil which could be Kugelrohr distilled at 106–107 °C (0.1 Torr). To a suspension of 2 g of 10% palladium/carbon in 120 mL of ethanol was added 1.14 g (6.4 mmol) of *cis*-2-methyl-3-(benzyloxy)oxetane in 30 mL of ethanol. The reaction mixture was stirred for 4 h under an atmosphere of hydrogen at room temperature, filtered, diluted with methylene chloride, and washed successively with saturated aqueous sodium carbonate, water, and saturated aqueous sodium chloride. After being dried (sodium sulfate), solvent removal gave an oil which could be distilled at 89–91 °C (760 Torr) to yield 0.512 g (91%) of *cis*-2-methyl-3-hydroxyoxetane (**14**): ^{1}H NMR (80% deuterated acetone, 20% deuterium oxide; $\delta_{\text{lutidine-Me}}$ = 2.50 ppm) δ 1.14 (3 H, d, J = 6 Hz, CH_3), 3.45 (1 H, dd, J = 6, 7 Hz, CH_2), 3.69 (1 H, dd, J = 5, 7 Hz, CH_2), 4.05 (1 H, ddd, J = 5, 5.5, 6 Hz, C*H*OH), 4.34 (1 H, dq, J = 5.5, 6 Hz, CH); ^{13}C NMR ($CDCl_3$) δ 58.47, 56.81 (CH), 59.46 (CH_2), 24.50 (CH_3); IR (CCl_4) 3490 cm^{-1}.

Anal. Calcd for $C_4H_8O_2$: C, 54.52; H, 9.15. Found: C, 54.32; H, 9.35.

***cis*-2-Methyloxetan-3-yl 3,5-Dinitrobenzoate (13).** To a solution of 0.250 g (1.08 mmol) of 3,5-dinitrobenzoyl chloride and 0.174 mL (1.25 mmol) of triethylamine in 10 mL of methylene chloride was added 0.088 g (1 mmol) of *cis*-2-methyl-3-hydroxyoxetane (**14**) at 20 °C. After being stirred for 1 h at room temperature, the reaction mixture was washed with water, 10% aqueous hydrochloric acid, and saturated aqueous sodium bicarbonate, and dried (sodium sulfate), and the solvent was removed to give 0.259 g (92%) of *cis*-2-methyloxetan-3-yl 3,5-dinitrobenzoate (**13**): mp 80–83 °C (hexane/ethyl acetate); ^{1}H NMR (80% deuterated acetone, 20% deuterium oxide; $\delta_{\text{lutidine-Me}}$ = 2.50 ppm) δ 1.30 (3 H, d, J = 6 Hz, CH_3), 3.52 (1 H, dd, J = 6, 7 Hz, CH_2), 3.92 (1 H, dd, J = 4, 7 Hz, CH_2), 4.54 (1 H, dq, J = 4.7, 6 Hz, CH), 5.37 (1 H, ddd, J = 4, 4.7, 6 Hz, CHOR), 9.2–9.3 (3 H, m, aromatic H); ^{13}C NMR ($CDCl_3$) δ 161.18, 148.27, 132.36 (quaternaries), 131.37, 129.38, 72.73, 58.82 (CH), 60.80 (CH_2), 25.03 (CH_3); IR (CCl_4) 1715 cm^{-1}; mass spectrum, m/z (relative intensity) 282 (M^+, 8), 91 (100).

Anal. Calcd for $C_{11}H_{10}N_2O_7$: C, 46.82; H, 3.57; N, 9.93. Found: C, 46.96; H, 3.68; N, 9.81.

Solvolysis Experiments. To standard 5-mm NMR tubes were added 4 mg (ca. 15 μmol) of **9**, **12**, or **13**, or in the case of the relative rate experiment 2 mg (ca. 7 μmol) each of **9** and **12**, 1 μL of 2,6-lutidine (buffer and internal standard), 400 μL of acetone-d_6, and 100 μL of deuterium oxide. The tubes were then sealed and immersed in a sand bath heated to 100 °C. Periodically the tubes were cooled to room temperature and ^{1}H NMR spectra recorded with the 2,6-lutidine resonances and the methyl doublet region intergrated manually at least twice. NMR experiments included sufficient accumulation of FID's such that product detection was not limited unduly by sensitivity. Conversions and product yields were calculated from the destruction and growth, respectively, of the appropriate methyl doublets relative to the 2,6-lutidine resonances. As an indication of the typical mass balances observed, solvolysis of **9** for 16 h led to 22.0% conversion with 18.2% of **10** and 3.8% of **11** produced, and solvolysis of **12** for 48 h led to 25.9% conversion with 16.0% of **13** and 6.9% of **14** produced. The first order rate constant for the conversion of **9** could be estimated from a single run with four data points to be $k_{obs} = 4.3 \times 10^{-6}$ s^{-1} while the first-order rate constant for the conversion of **12** could be estimated from a single run with six data points to be $k_{obs} = 1.8 \times 10^{-6}$ s^{-1}. In a separate competitive experiment, the rate of disappearance of **9** relative to that of **12** was determined to be $k_9/k_{12} = 2.1$.

Acknowledgment. Acknowledgement is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for the partial support (to C.S.S.) of this research. The acquisition of a GC/MS system was made possible by grants from the Camille and Henry Dreyfus Foundation and the PQ Corp., and of a high-field NMR spectrometer by grants from the W. M. Keck Foundation and Merck & Co., Inc.

Supplementary Material Available: Tables of Cartesian coordinates for the HF/6-31G*//HF/6-31G* structures of **4–7** (2 pages). Ordering information is given on any current masthead page.