Solvolysis of 2-Methylene Bicyclic Bridgehead Derivatives: A Model for Gradual Variation of π-Conjugation in Carbocations

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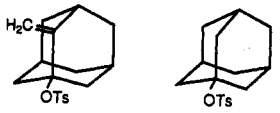
The rates of solvolysis in ethanol or 80% ethanol at 25 °C have been determined on 2-methylenebicyclo-[2.2.2]oct-1-yl triflate (**4a**), 2-methylenebicyclo[3.2.1]oct-1-yl triflate (**5a**), 2-methylenebicyclo[3.2.2]non-1-yl mesylate (**6a**), 2-methylenebicyclo[3.3.1]non-1-yl mesylate (**7a-OMs**) and heptafluorobutyrate (**7a-OHFB**), 1-chloro-2-methylenebicyclo[4.2.2]decane (**8a**), 2-methylenebicyclo[4.3.1]dec-1-yl trifluoroacetate (**9a**), and 4-methylene-3-homoadamantyl heptafluorobutyrate (**10a**) and on their corresponding parent 1-bicycloalkyl and 3-homoadamantyl derivatives **4b–10b** containing the respective leaving group. The rate ratios for **4a/4b**, **5a/5b**, **10a/10b**, **6a/6b**, **7a/7b**, **8a/8b**, and **9a/9b** are $10^{-3.9}$, $10^{-1.9}$, $10^{-1.1}$, $10^{-0.8}$, $10^{0.9}$ (for mesylate), $10^{-0.2}$, and $10^{0.7}$, respectively. A plot of the logarithms of the rate ratios against olefinic strain energies of their corresponding unsubstituted bridgehead olefins shows that the smaller the olefinic strain energy, the greater the rate ratio, providing a methodology to gradually change the conjugative ability of bridgehead carbocations. The enhancement of allylic conjugation with increasing skeletal flexibility has been further verified by the enhanced solvolysis rate of (*E*)-2-ethylidenebicyclo[3.2.2]non-1-yl mesylate ((*E*)-**6e**) relative to **6a** by a factor of 259. A similar study on much more rigid (*E*)-2-ethylidenebicyclo[2.2.2]oct-1-yl triflate ((*E*)-**4e**) gave a (*E*)-**4e**/**4a** rate ratio of 6.3. AM1 semiempirical molecular orbital calculations on pertinent 2-methylene and (*E*)-2-ethylidene bridgehead carbocations and corresponding hydrocarbons (L = hydrogen) also supported the increase in the conjugation with increasing skeletal flexibility. The solvolysis products were solely bridgehead substitution products, no indication for the formation of bridgehead olefin via an S_N1' mechanism having been obtained.

It is well-known that the π-conjugative stabilization of allylic carbocations is highly sensitive to conformation. When the π system is perpendicularly oriented relative to the cationic p orbital, the vinyl group exhibits only the inductive electron-withdrawing effect. In the 2-methylene-1-adamantyl cation the π-system is essentially perpendicular to the developing cationic p orbital. Thus, the rate of acetolysis of 2-methylene-1-adamantyl tosylate (**1a**) relative to 1-adamantyl tosylate (**1b**) is $10^{-4.2}$ at 25 °C.[1]

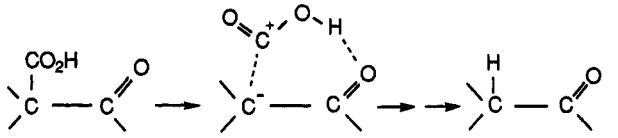


1a **1b**

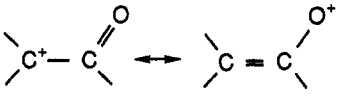
On the other hand, in the compounds where the p orbitals can completely overlap with each other in the incipient carbocations, their rates of solvolysis relative to the corresponding parent compounds are $10^{2-2.8}$.[2,3] Consequently, if we establish a system in which the degree of allylic conjugation can be gradually changed, it will serve as a tool for examining the π-conjugative ability of a group adjacent to the carbocationic center, such as a carbonyl, thiocarbonyl, or imino group.

About three decades ago, Ferris and Miller[4] qualitatively showed that the rates of decarboxylation of various 2-oxobicycloalkane-1-carboxylic acids increase with the increase in the angle between the p orbital of the carbonyl group and the C–C σ bond connecting the bridgehead carbon and the carboxyl group. They interpreted the results to indicate the development of carbanion character in the transition state of decarboxylation (Scheme I).[4]

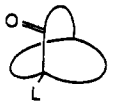
Scheme I



In the course of our study on α-keto cations,[5] we were interested in examining the resonance contribution of a canonical formula **2b**,[6] where the positive charge is delocalized on the carbonyl oxygen. For this purpose, the solvolysis studies of the bridgehead substrates **3** containing the oxo substituent on the 2-position appeared to be appropriate for the reasons that the k_s process and carbonyl participation from the rear side are prohibited. If the conjugation as shown by **2b** is present and can be increased by making the ring system of **3** more and more flexible, the rates of solvolysis relative to the corresponding parent system are expected to rise with increased flexibility owing to concomitantly increased conjugative stabilization of



2a **2b**



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(1) (a) Ree, B. R.; Martin, J. C. *J. Am. Chem. Soc.* **1970**, *92*, 1660. (b) Buss, V.; Gleiter, R.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1971**, *93*, 3927.

(2) These values were derived from the solvolysis of 3-chloro-3-methyl-1-butene (~10^2),[3a] 3-methylene-*endo*-2-norbornyl tosylate ($10^{2.5}$),[3b] and 2-methylenecyclohexyl 3,5-dinitrobenzoate ($10^{2.8}$).[3c]

(3) (a) Young, W. G.; Winstein, S.; Goering, H. L. *J. Am. Chem. Soc.* **1951**, *73*, 1958. (b) Wilcox, C. F.; Jesaitis, R. G. *Chem. Commun.* **1967**, 1046. (c) Tsuji, T.; Moritani, I.; Nishida, S. *Bull. Chem. Soc. Jpn.* **1967**, *40*, 2338.

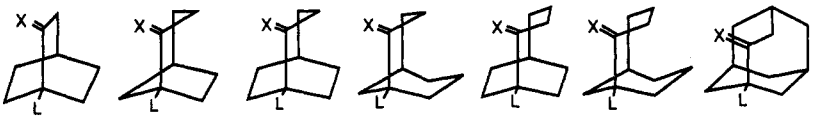
(4) Ferris, P. J.; Miller, N. C. *J. Am. Chem. Soc.* **1966**, *88*, 3522.

(5) (a) Takeuchi, K.; Kitagawa, T.; Okamoto, K. *J. Chem. Soc., Chem. Commun.* **1983**, 7. (b) Takeuchi, K.; Kamata, J.; Shibata, T.; Okamoto, K. In *Studies in Organic Chemistry*, Kobayashi, M., Ed.; Elsevier Science Publishers, B. V.: Amsterdam, 1987; Vol. 31, pp 303–310. (c) Takeuchi, K.; Akiyama, F.; Ikai, K.; Shibata, T.; Kato, M. *Tetrahedron Lett.* **1988**, *29*, 873. (d) Takeuchi, K.; Yoshida, M.; Ohga, Y.; Tsugeno, A.; Kitagawa, T. *J. Org. Chem.* **1990**, *55*, 6063.

(6) For reviews, see: (a) Gassman, P. G.; Tidwell, T. T. *Acc. Chem. Res.* **1983**, *16*, 279. (b) Tidwell, T. T. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 20. (c) Creary, X. *Acc. Chem. Res.* **1985**, *18*, 3. (d) Creary, X.; Hopkinson, A. C.; Lee-Ruff, E. In *Advances in Carbocation Chemistry*; Creary, X., Ed.; Jai Press: Greenwich, CT, 1989; Vol. 1, pp 45–92.

0022-3263/92/1957-0280$03.00/0

Chart I



X=CH_2 L=leaving group	**4a**(L=OTf)	**5a**(L=OTf)	**6a**(L=OMs)	**7a**(L=OMs) (L=OHFB)	**8a**(L=Cl)	**9a**(L=OTFA)	**10a**(L=OHFB)
X=H_2 L=leaving group	**4b**(L=OTf)	**5b**(L=OTf)	**6b**(L=OMs)	**7b**(L=OMs) (L=OHFB)	**8b**(L=Cl)	**9b**(L=OTFA)	**10b**(L=OHFB)
X=CH_2 ; L=OH	**4c**	**5c**	**6c**	**7c**	**8c**	**9c**	**10c**
X=O ; L=OH	**4d**	**5d**	**6d**	**7d**	**8d**	**9d**	**10d**
X=(E)-$CHCH_3$ L=leaving group	(E)-**4e**(L=OTf)		(E)-**6e**(L=OMs)				
X=(Z)-$CHCH_3$ L=OH	(Z)-**4f**		(Z)-**6f**				
X=(E)-$CHCH_3$ L=OH	(E)-**4f**		(E)-**6f**				

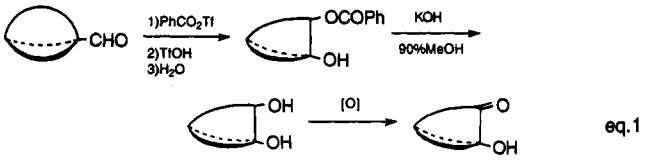
OTf ; CF_3SO_3 OMs ; CH_3SO_3 OHFB ; n-$C_3F_7CO_2$ OTFA ; CF_3CO_2

incipient carbocations.[7] This 2-oxo system **3** has an additional advantage that the steric circumstances around the reaction center are kept essentially constant among a series of 2-oxo substrates. Before undertaking the 2-oxo system, it was required to examine the feasibility of this methodology by using the 2-methylene (or allylic) system.

Fortunately, we previously developed a new route for synthesis of various bicyclic and tricyclic 2-oxo-1-alkanols[8] which can be transformed to corresponding 2-methylene-1-alkanols. This paper describes the solvolysis of various newly prepared 2-methylene bridgehead compounds. The systems employed are bicyclo[2.2.2]oct-1-yl (**4**),[5c] bicyclo[3.2.1]oct-1-yl (**5**), bicyclo[3.2.2]non-1-yl (**6**),[5c] bicyclo[3.3.1]non-1-yl (**7**),[5d] bicyclo[4.2.2]dec-1-yl (**8**), bicyclo[4.3.1]dec-1-yl (**9**), and tricyclo[4.3.1.$1^{3,8}$]undec-3-yl (3-homoadamantyl) (**10**).[5d] The rates of solvolysis of the parent compounds have also been determined and the k(X = CH_2)/k(X = H_2) ratios at 25 °C compared between each system. In order to further substantiate the approach, (*E*)-2-ethylidene derivatives (*E*)-**4e** and (*E*)-**6e** have also been synthesized and subjected to solvolysis.[9,10] The usefulness of the present methodology has been supported by AM1 calculations.

Results

Synthesis of 2-Methylene and Parent Substrates. The intermediate ketols were prepared by acylative ring expansion of bridgehead aldehydes following eq 1,[8] except



eq 1

that 1-hydroxybicyclo[2.2.2]octan-2-one was derived from 1-methoxybicyclo[2.2.2]oct-5-en-2-one which was provided by the Diels–Alder reaction of 1-methoxy-1,3-cyclohexadiene with 2-chloropropenenitrile.[11]

The ketols were subjected to Wittig methylenation,[12] in most cases after protection of the hydroxyl group by trimethyl- or *tert*-butyldimethylsilylation. 2-Methylenebicyclo[3.2.1]octan-1-ol (**5c**) was fortuitously obtained as a major product in the Wittig methylenation of 1-hydroxybicyclo[2.2.2]octan-2-one in DMSO, presumably owing to base-catalyzed ketol rearrangement[13] prior to the Wittig reaction. The parent substrates **4b–10b** were derived from known bridgehead alcohols. All the bridgehead alcohols were converted to the substrates containing an appropriate leaving group which were expected to solvolyze at the rates convenient for measurements.

Synthesis of 2-Ethylidene Substrates. In the beginning, we wished to prepare 2-isopropylidene derivatives, but various efforts to obtain 2-isopropylidenebicyclo[3.2.2]nonan-1-ol failed by using Wittig reaction in DMSO,[12] *i*-PrLi–$SOCl_2$,[14a] and McMurry reaction.[14b] Consequently, we employed 2-ethylidene substrates. Ethylidenation of the *tert*-butyldimethylsilyl (BDMS) ether of **4d** (**4d-OBDMS**) with ethylidenetriphenylphosphorane afforded only one product, which was determined as (*Z*)-2-ethylidenebicyclo[2.2.2]octan-1-ol BDMS ether ((*Z*)-**4f-OBDMS**) by ^{1}H NMR NOE difference experiments; irradiation of the C(3) methylene hydrogens caused significant enhancement of the olefinic hydrogen (13%). To prepare an isomeric alcohol (*E*)-**4f**, (*Z*)-**4f-OBDMS** was subjected to olefin inversion by using the phosphorus betaine method.[15] Application of NOE difference spectroscopy to (*E*)-**4f-OBDMS** showed negligible enhancement of the olefinic hydrogen (<1%) when the C(3) methylene hydrogens were irradiated. Each of the BDMS ethers was converted to (*Z*)-**4f** or (*E*)-**4f** by desilylating with tetrabutylammonium fluoride.[16]

Ethylidenation of **6d** BDMS ether (**6d-OBDMS**) afforded two products in isolated yields of 16% and 22%,

(7) For preliminary communications, see refs 5b–d.

(8) (a) Takeuchi, K.; Kitagawa, I.; Akiyama, F.; Shibata, T.; Kato, M.; Okamoto, K. *Synthesis* **1987**, 612–615. (b) Takeuchi, K.; Ikai, K.; Yoshida, M.; Tsugeno, A. *Tetrahedron* **1988**, *44*, 5681. (c) Takeuchi, K.; Akiyama, F.; Miyazaki, T.; Kitagawa, I.; Okamoto, K. *Tetrahedron* **1987**, *43*, 701.

(9) The solvolysis rate of the *Z* isomer (*Z*)-**4e** was found to be extremely enhanced due to F strain between the methyl group and the leaving group.[10] Consequently, only the *E* isomers (*E*)-**4e** and (*E*)-**6e** were employed for solvolysis studies.

(10) Takeuchi, K.; Ohga, Y.; Kitagawa, T. *J. Org. Chem.* **1991**, *56*, 5007.

(11) Evans, D. A.; Scott, W. L.; Truesdale, L. K. *Tetrahedron Lett.* **1972**, 121.

(12) Greenwald, R.; Chaykovsky, M.; Corey, E. J. *J. Org. Chem.* **1963**, *28*, 1128.

(13) For examples of base-catalyzed rearrangement of bridgehead ketols, see: (a) Nickon, A.; Nishida, T.; Lin, Y. *J. Am. Chem. Soc.* **1969**, *91*, 6860. (b) Paukstelis, J.; Stephens, D. N. *Tetrahedron Lett.* **1971**, 3549.

(14) (a) Olah, G. A.; Wu, A.; Farooq, O. *J. Org. Chem.* **1989**, *54*, 1375. (b) McMurry, J. E.; Krepski, L. R. *J. Org. Chem.* **1976**, *41*, 3929.

(15) Vedejs, E.; Fuchs, P. L. *J. Am. Chem. Soc.* **1973**, *95*, 822.

(16) Collington, E. W.; Finch, H.; Smith, I. J. *Tetrahedron Lett.* **1985**, *26*, 681.

Table I. Rate Data of Solvolysis of 2-Methylene, 2-Ethylidene, or Parent Bridgehead Compounds in Ethanol or 80% Ethanol

compound system	compound L[d]	solvent[a]	temp (°C)	k[b] (s^{-1})	$\Delta H^{\ddagger}$ (kcal/mol)	$\Delta S^{\ddagger}$ (eu)	$k(X = CH_2)/k(X = H_2)$[c]
4a[f]	OTf	EtOH	25.0	2.96×10^{-7} [e,f]	27.1	2.3	$10^{-3.9}$
			50.0	1.09×10^{-5} [f,g]			
			75.0	2.40×10^{-4} [f,g]			
(*E*)-**4e**[h]	OTf	EtOH	25.0	1.86×10^{-6} [g,h]	26.8	5.1	$10^{-3.1}$ [i]
			50.0	6.65×10^{-5} [g,h]			
4b[f]	OTf	EtOH	25.0	2.14×10^{-3} [f,j]	22.4	4.3	
			40.0	1.37×10^{-2} [f,j]			
5a	OTf	EtOH	25.0	1.26×10^{-6} [g]	27.8	7.5	$10^{-1.9}$
			50.0	5.10×10^{-5} [g]			
5b	OTf	EtOH	25.0	1.10×10^{-4} [g]	24.1	4.3	
			0.0	2.43×10^{-6} [g]			
6a[f]	OMs	EtOH	25.0	7.17×10^{-6} [f,g]	24.3	−0.4	$10^{-0.8}$
			50.0	1.86×10^{-4} [f,g]			
(*E*)-**6e**[h]	OMs	EtOH	25.0	1.86×10^{-3} [h,j]	21.6	1.3	$10^{1.6}$ [i]
			40.0	1.11×10^{-2} [h,j]			
6b[f]	OMs	EtOH	25.0	4.75×10^{-5} [f,g]	23.5	0.5	
			0.0	1.15×10^{-6} [f,g]			
7a	OMs	EtOH	25.0	2.83×10^{-3} [j]	20.3	−2.1	$10^{0.9}$
			40.0	1.53×10^{-2} [j]			
7b	OMs	EtOH	25.0	3.28×10^{-4} [j]	22.7	1.7	
			40.0	2.16×10^{-3} [j]			
7a	OHFB	80% EtOH	25.0	1.58×10^{-7} [g]	26.4	−1.2	$10^{0.5}$
			50.0	5.34×10^{-6} [g]			
7b	OHFB	80% EtOH	25.0	5.22×10^{-8} [e]	26.3	−3.8	
			50.0	1.74×10^{-6} [g]			
			75.0	3.50×10^{-5} [g]			
8a	Cl	80% EtOH	25.0	3.14×10^{-4} [j]	22.5	0.7	$10^{-0.2}$
			40.0	2.02×10^{-3} [j]			
8b	Cl	80% EtOH	25.0	4.52×10^{-4} [j]	22.4	1.1	
			40.0	2.89×10^{-3} [j]			
9a	OTFA	80% EtOH	25.0	6.88×10^{-5} [g]	24.5	4.8	$10^{0.7}$
			0.0	1.41×10^{-6} [g]			
9b	OTFA	80% EtOH	25.0	1.46×10^{-5} [g]	24.5	1.7	
			50.0	3.90×10^{-4} [g]			
10a	OHFB	80% EtOH	25.0	1.04×10^{-7} [e]	26.6	−1.4	$10^{-1.1}$
			50.0	3.59×10^{-6} [g]			
			75.0	7.46×10^{-5} [g]			
10b	OHFB	80% EtOH	25.0	1.42×10^{-6} [g,k]	24.9	−2.0	
			50.0	3.93×10^{-5} [g,l]			

[a] Buffered with 0.025 M 2,6-lutidine. [b] Determined by a single run. In all cases the correlation coefficient for the first order plot was greater than 0.999. [c] The rate ratio at 25.0 °C. [d] Leaving group: OTf, trifluoromethanesulfonate; OMs, methanesulfonate; OHFB, heptafluorobutyrate; OTFA, trifluoroacetate. [e] Extrapolated from data at other temperatures. [f] Reference 5c. [g] Determined titrimetrically within an experimental error ±2%. [h] Reference 10. [i] The $k(X = CHCH_3)/k(X = H_2)$ ratio. [j] Determined conductimetrically within an experimental error ±0.5%. [k] A reported value is 2.92×10^{-6} s^{-1} (ref 41). [l] A reported value is 5.54×10^{-5} s^{-1} (ref 41).

which were separated from each other by repeated liquid chromatography on silica gel. These products were assigned as BDMS ethers of (*Z*)-**6f** and (*E*)-**6f**, i.e., (*Z*)-**6f-OBDMS** (minor product) and (*E*)-**6f-OBDMS** (major product), respectively, on the basis of NOE difference spectroscopy. Enhancement of the olefinic hydrogen was 14% or 0.7% for (*Z*)-**6f-OBDMS** or (*E*)-**6f-OBDMS**, respectively, when the C(3) methylene hydrogens were irradiated. Cleavage of the BDMS ethers afforded (*Z*)-**6f** and (*E*)-**6f**.[17]

Examinations of ^1H–^1H coupling constants between the methyl and C(3) methylene hydrogens also supported the above structural assignments. The $J(CH_3CH_2(3))$ values are 1.98 and 1.59 Hz for (*Z*)-**4f** and (*E*)-**4f**, respectively, and 0.90 and 0.66 Hz for (*Z*)-**6f** and (*E*)-**6f**, respectively. (The geometric relation between the methyl and the 3-methylene group is trans in the *Z* isomers and cis in the *E* isomers.) Comparisons of the magnitude of these *J* values with $J(CH_3CH_3)$ values of *trans*-2-butene (1.60 Hz)[18] and *cis*-2-butene (1.18 Hz)[18] are qualitatively consistent with the structural assignments based on the NOE difference experiments. (*E*)-**4f** and (*E*)-**6f** were converted to triflate (*E*)-**4e** and mesylate (*E*)-**6e**, respectively.

Solvolysis Rates. Because of requirement for covering a wide range of reactivity, the leaving group and solvent were appropriately selected as shown in Table I. Most of the substrates were very unstable to water and column chromatography. In such cases, crude substrates were used for solvolysis studies without further purification. Except for **6b**, (*E*)-**6e**, **7a-OMs**, and **7b-OMs**, all the other substrates were essentially pure (>97%) on the basis of ^{13}C NMR spectra. In all the substrates, the sole impurity, if any, was the starting alcohol, which does not influence the solvolysis rates. For the triflates and mesylates, ethanol was used as solvolysis solvent, whereas for the heptafluorobutyrates, trifluoroacetates, and chlorides, 80% ethanol was used.[19] All measurements were conducted in the presence of 0.025 M 2,6-lutidine either titrimetrically or conductimetrically, showing good first-order kinetics over 80–90% reactions. The rate data, activation parameters, and the rates of the 2-methylene or the 2-ethylidene compounds relative to the parent ones $[k(X = CH_2)/k(X$

(17) It was later found that (*Z*)-**4f** and (*E*)-**4f** are more readily separated from each other than their BDMS ethers.

(18) (a) Harris, R. K.; Howes, B. W. *J. Mol. Spectr.* **1968**, *28*, 191. (b) Rummens, F. H. A.; Kaslander, L. W. *Can. J. Chem.* **1972**, *17*, 99.

(19) Tertiary heptafluorobutyrates and trifluoroacetates have been proved to undergo typical S_N1 solvolyses; see: Bentley, T. W.; Roberts, K. *J. Chem. Soc., Perkin Trans. 2* **1989**, 1055, ref 41 and references cited in these papers.

= H_2) or $k(X = CHCH_3)/k(X = H_2)$, respectively] at 25 °C are summarized in Table I.

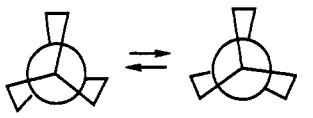
Solvolysis Products. The product(s) of solvolysis was determined only on 2-methylene and 2-ethylidene compounds in the solvent that was used for rate studies: no product studies have been conducted on the parent compounds **4b–10b**. Generally, the solvolysis was carried out on 0.04 M substrate solutions containing 20–50% excess amounts of 2,6-lutidine at convenient temperatures for a period longer than 10 half-lives. ^{13}C NMR analyses of crude products showed that the bridgehead substitution was the sole reaction, no other reactions such as elimination to form bridgehead olefins and allylic rearrangement to give S_N1' products having been detected within experimental errors (±3%).

Discussion

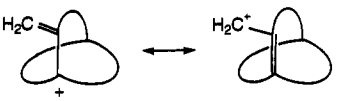
Leaving Group and Solvent. It has been well established that the bridgehead reactivity in solvolysis increases with the decrease in pyramidal strain in the transition state,[20,21] except for extremely strained molecules.[22,23] In the present work the most unreactive alkyl moiety is the 2-methylenebicyclo[2.2.2]oct-1-yl and the most reactive one is the bicyclo[4.2.2]dec-1-yl system. If the kinetic work is done with the same leaving group and the same solvent, the reactivity range would be estimated to be 10^{13} by using relative nucleofugalities of leaving groups[24] and the Y_{Cl} value (−2.5)[25] of ethanol. This extreme reactivity range suggested marked difficulties in both the synthesis and accurate rate measurements of highly reactive substrates even by using recently developed techniques.[26] Consequently, the leaving group and the solvent were appropriately chosen so as to make the synthesis and accurate rate measurements feasible.

These countermeasures may be justified by the data of Table I and hitherto accumulated ones. The rate ratios of ethanolysis at 25 °C of the 1-adamantyl[24,27] to bicyclo[2.2.2]oct-1-yl[28] system are $10^{4.2}$ (= 35.1:2.14 × 10^{-3}) for triflates and $10^{3.9}$ (= 4.4 × 10^{-5}:5 × 10^{-9}) for tosylates (the figures in parentheses are the first-order rate constants (s^{-1}) for 1-adamantyl and bicyclo[2.2.2]oct-1-yl systems). The rate ratios are markedly constant despite an enormous nucleofugality difference of ~10^6 between the TfO– and TsO– leaving groups. In 80% ethanol the tosylate rate ratio for 1-adamantyl/bicyclo[2.2.2]oct-1-yl is $10^{4.0}$ (= 4.03 × 10^{-3}:3.6 × 10^{-7}) at 25 °C,[24,25] again very close to the above value of $10^{3.9}$ in ethanol. Therefore, comparisons of the $k(X = CH_2)/k(X = H_2)$ values between different systems are sound, even if the leaving group and solvent are different between the systems. However, as exemplified by the data of **7a/7b**, i.e., $10^{0.9}$ for mesylates in ethanol and $10^{0.5}$ for heptafluorobutyrates in 80% ethanol, an allowance of $10^{\pm0.2}$–$10^{\pm0.3}$ must be taken into account. The **8a/8b** rate ratio of $10^{-0.2}$ appears to be too small (vide infra). At the present stage we are not in the position to rationalize this value. This might be because of the use of the chlorides, but more probably **8a** and **8b** would be too flexible[29] for simple rate comparisons. In the light of considerably constant OTs/Cl rate ratios ($10^{5.1\pm0.3}$ in 80% ethanol at 70 °C) for various bridgehead compounds,[30] we prefer the latter interpretation for the moment.

Scheme II



Scheme III



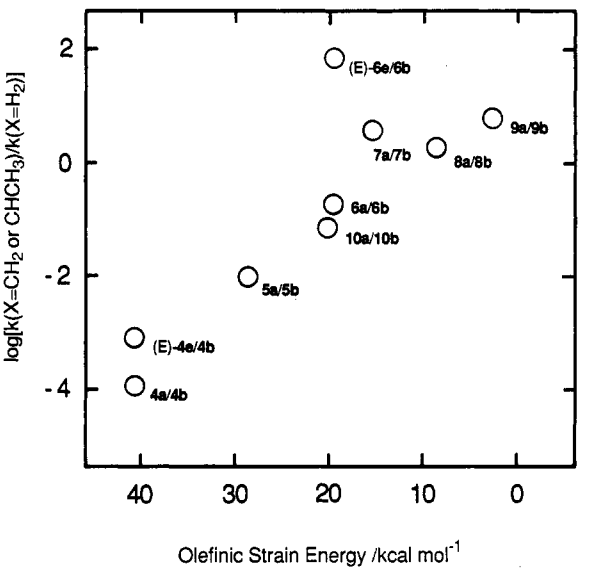


Figure 1. Plot of log [$k(X = CH_2$ or $CHCH_3)/k(X = H_2)$] values against olefinic strain energies of the corresponding unsubstituted bridgehead olefins. For **7a/7b** the data of the mesylates were used. For olefinic strain energies, see ref 33.

Ring Flexibility and Conjugative Ability. The most notable feature of the rate data of Table I is that the k ($X = CH_2$)/$k(X = H_2)$ ratio increases in the order **4a/4b** ($10^{-3.9}$), **5a/5b** ($10^{-1.9}$), **6a/6b** ($10^{-0.8}$), and **7a/7b** ($10^{0.9}$) as has been anticipated from variation of ring flexibility. Since the rate ratio has been shown to increase from 10^{-4} to $10^{2-2.8}$ as the conjugation in the incipient carbocation increases from null to full,[1-3] the rate ratios **6a/6b** and **7a/7b** indicate realization of ~50% and ~80% allylic conjugation[31] in the solvolysis of **6a** and **7a**, respectively.

A measure of ring flexibility of bicyclic compounds would be given by the magnitude of the cross angle at which the twisted conformers show an energy minimum as exemplified by bicyclo[2.2.2]octane (Scheme II). Ac-

(20) (a) Fort, R. C., Jr. In *Carbonium Ions*; Olah, G. A., Schleyer, P. v. R., Eds.; Wiley-Interscience: New York, 1973; Vol. 4, pp 1783–1835. (b) Bingham, R. C.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1971**, *93*, 3189.

(21) (a) Müller, P.; Blanc, J.; Mareda, J. *Helv. Chim. Acta* **1986**, *69*, 635. (b) Müller, P.; Mareda, J. *Helv. Chim. Acta* **1987**, *70*, 1017. (c) Müller, P.; Blanc, J.; Mareda, J. *Chimia* **1987**, *41*, 399. (d) Müller, P.; Mareda, J. In *Cage Hydrocarbons*; Olah, G. A., Ed.; Wiley-Interscience: New York, 1990; pp 189–217.

(22) Della, E. W.; Gill, P. M. W.; Schiesser, C. H. *J. Org. Chem.* **1988**, *53*, 4353.

(23) (a) Eaton, P. E.; Yang, C.-X.; Xiong, Y. *J. Am. Chem. Soc.* **1990**, *112*, 3225. (b) Moriarty, R. M.; Tuladhar, S. M.; Penmasta, R.; Awasthi, A. K. *J. Am. Chem. Soc.* **1990**, *112*, 3228.

(24) Takeuchi, K.; Ikai, K.; Shibata, T.; Tsugeno, A. *J. Org. Chem.* **1988**, *53*, 2852.

(25) Bentley, T. W.; Carter, G. E. *J. Am. Chem. Soc.* **1982**, *104*, 5741.

(26) Bentley, T. W.; Kirmse, W.; Llewellyn, G.; Sollenbohmer, F. *J. Org. Chem.* **1990**, *55*, 1536 and references cited therein.

(27) Kevill, D. N.; Kolwyck, K. C.; Weitl, F. L. *J. Am. Chem. Soc.* **1970**, *92*, 7300.

(28) Bentley, T. W.; Bowen, C. T.; Morten, D. H.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1981**, *103*, 5466.

(29) (a) Dyllick-Brenzinger, R.; Olsen, H. *J. Am. Chem. Soc.* **1981**, *103*, 704. (b) Ōsawa, E. *J. Comput. Chem.* **1982**, *3*, 400.

(30) Bentley, T. W.; Roberts, K. *J. Org. Chem.* **1985**, *50*, 5852.

(31) A reviewer pointed out that the validity of assigning % conjugation depends on what is chosen for the fully conjugated system. We believe that the ratios 10^{-4} and $10^{2-2.8}$ are the best values available at present for null and full conjugation standards for our system, but these figures may undergo minor changes if more appropriate standard rate ratios are established.

Table II. AM1 Calculated Bond Orders and Net Atomic Charges for Carbocations and Corresponding Hydrocarbons (L = Hydrogen)[a]

	bond order[b]						net atomic charge					
	carbocation		hydrocarbon		Δ bond order[c]		carbocation			hydrocarbon		
system	C_α—C_β	C_β=C_γ	C_α—C_β	C_β=C_γ	$\Delta BO(C_\alpha—C_\beta)$	$\Delta BO(C_\beta=C_\gamma)$	C_α	C_β	C_γ	C_α	C_β	C_γ
4a	1.028	1.912	0.972	1.933	0.056	−0.021	0.394	−0.245	−0.077	−0.073	−0.094	−0.232
(*E*)-**4e**	1.034	1.842	0.974	1.889	0.060	−0.047	0.402	−0.281	−0.003	−0.069	−0.104	−0.174
5a	1.048	1.900	0.974	1.932	0.074	−0.032	0.395	−0.241	−0.071	−0.078	−0.093	−0.232
6a	1.087	1.828	0.971	1.932	0.116	−0.104	0.379	−0.231	−0.046	−0.066	−0.088	−0.235
(*E*)-**6a**	1.138	1.722	0.973	1.890	0.165	−0.168	0.353	−0.247	0.045	−0.064	−0.096	−0.177
7a	1.157	1.737	0.972	1.931	0.185	−0.194	0.317	−0.219	0.005	−0.071	−0.090	−0.236
10a	1.026	1.898	0.972	1.930	0.054	−0.032	0.400	−0.232	−0.095	−0.061	−0.083	−0.245

[a] When two conformers are present as in the carbocations from **5a** and **7a**, the calculations were performed for the carbocation corresponding to the more stable conformer of the hydrocarbon. [b] C_α—C_β and C_β=C_γ denote the bonds in the allylic part C_α—C_β=C_γ. [c] The difference in the bond orders of C_α—C_β and C_β=C_γ between a carbocation and a hydrocarbon.

cording to molecular mechanics calculations, bicyclo[2.2.2]octane shows very shallow energy minima at about ±15°, whereas in bicyclo[3.3.2]decane deeper energy minima appear at about ±40°.[32] Although these cross angles indicate that the former is less flexible than the latter, the use of cross angles is too qualitative to evaluate the relation between the structural flexibility and conjugative ability in the present study. A better measure for the conjugative ability would be given by the stability of a bridgehead olefin which corresponds to another resonance structure of the 2-methylene bridgehead carbocation (Scheme III). Therefore, it is expected that the more stable the corresponding bridgehead olefin is, the easier the allylic conjugation will be.

Previously, Maier and Schleyer defined "olefinic strain energy", which is given by the difference between the strain energy of a bridgehead olefin and that of a corresponding saturated hydrocarbon, both being calculated by molecular mechanics for the most stable conformations.[33] A plot of log [k(X = CH_2)/k(X = H_2)] against the olefinic strain energies (Figure 1) shows that the smaller the olefinic strain energy, the easier the allylic conjugation. Although the olefinic strain energies are concerned with the strain in neutral hydrocarbon molecules and the log [k(X = CH_2)/k(X = H_2)] values mainly with the stability of incipient carbocations, the plot of Figure 1 suggests that the olefinic strain energies may be used as an empirical measure of conjugative ability of 2-methylene bicyclic bridgehead carbocations.

Effects of 2-Ethylidene Substituent on Solvolysis Rates. Placement of a methyl substituent on the *E* position in **6a** markedly enhances the solvolysis rate; (*E*)-**6e** solvolyzes 259 times faster than **6a** in ethanol at 25 °C. As described above, the skeletal flexibility of **6a** enables approximately 50% allylic conjugation in the incipient carbocation. Therefore, a major part of this rate enhancement by introducing the methyl substituent is most probably ascribed to enhanced charge delocalization in the transition state, although other factors, in particular the steric strain between the methyl and the 3-methylene group in the ground state and its possible relief in the transition state, may also contribute to the rate acceleration.[34]

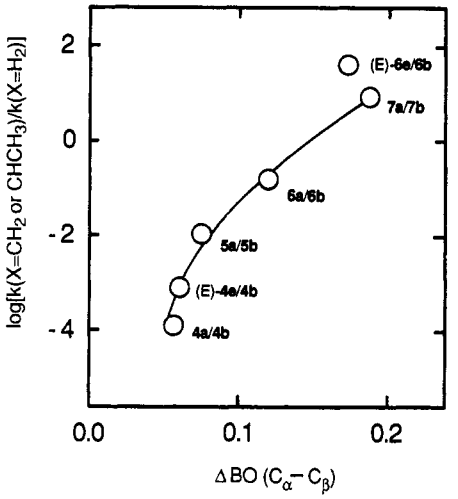


Figure 2. Plot of log [k(X = CH_2 or $CHCH_3$)/k(X = H_2)] values against differences of C_α—C_β bond orders between bridgehead carbocations and the corresponding hydrocarbons. For **7a**/**7b** the data of the mesylates were used.

In contrast to the above methyl substituent effect in the bicyclo[3.2.2]nonyl system, the effect in the much more rigid bicyclo[2.2.2]octyl system is quite small; (*E*)-**4e** solvolyzes only 6.3 times faster than **4a** in ethanol at 25 °C.[36] These results reinforce the notion that the allylic conjugation is enhanced with the increase in the ring flexibility.

Semiempirical MO Calculations on Bridgehead Carbocations. A series of 2-methylene and (*E*)-2-ethylidene bridgehead carbocations and the corresponding hydrocarbons (L; hydrogen in the place of leaving group) were subjected to AM1[37] and MNDO[38] calculations through the AMPAC[39] system. When two conformers are present as in the carbocations from **5a** and **7a**, the calculations were performed for the carbocation corresponding to the more stable conformer of the hydrocarbon (L = hydrogen). **8a** and **9a** were not included in the calculations because of their complex conformations.[29] As indexes for the degree of allylic (C_α—C_β=C_γ) conjugation were employed the difference in C_α—C_β bond orders and that in C_β=C_γ bond orders between the carbocation and the corresponding hydrocarbon (L = hydrogen), denoted, respectively, by $\Delta BO(C_\alpha—C_\beta)$ and $\Delta BO(C_\beta=C_\gamma)$. The results of AM1 and MNDO calculations agreed well with

(32) Ōsawa, E.; Aigami, K.; Inamoto, Y. *J. Chem. Soc., Perkin Trans. 2* **1979**, 172.
(33) Maier, W. F.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1981**, *103*, 1891.
(34) The rate of solvolysis of 1-chloro-2-butene is 3550 times faster than that of 3-chloropropene in formic acid at 44.6 °C: Vernon, C. A. *J. Chem. Soc.* **1954**, 423. On the assumption that these chlorides undergo a limiting S_N1 solvolysis in formic acid and that the cation-stabilizing effect of the methyl group is 50% attained in (*E*)-**6e**, we would expect 60 times acceleration for (*E*)-**6e** in comparison with **6a**. Molecular mechanics (MM2) calculations[35] on (*E*)-**6f** indicated the presence of steric strain of 1.0 kcal/mol between the methyl and the 3-methylene groups, which essentially vanishes in (*E*)-**4f**.
(35) MM2 (87) was obtained from QCPE.
(36) Synthetic and solvolytic studies on the extremely rigid 2-ethylidene-1-adamantyl system are in progress in this laboratory.
(37) Dewar, M. J. S.; Zeobisch, E. G.; Healy, E. F.; Stewart, J. J. P. *J. Am. Chem. Soc.* **1985**, *107*, 3902.
(38) Dewar, M. J. S.; Thiel, W. *J. Am. Chem. Soc.* **1977**, *99*, 4899.
(39) QCPE 527.

each other. In Table II are summarized pertinent bond orders and net atomic charges calculated by AM1. Figure 2 gives the relation between log $[k(X = CH_2$ or $CHCH_3)/k(X = H_2)]$ and $\Delta BO(C_\alpha—C_\beta)$.

A smooth curve in Figure 2 for a homologous series, **4a/4b**, **5a/5b**, **6a/6b**, and **7a/7b**, which shows gradual increases of allylic conjugation in this order, strongly supports the propriety of the present approach. It is also notable that the point for (*E*)-**4e/4b** is accommodated to the curve. However, a marked deviation of **10a/10b** suggests difficulty in applying AM1 (and MNDO) method to 4-methylene-3-homoadamantyl cation. The upward deviation of the point for (*E*)-**6e/6b** by 0.8 logarithmic unit suggests possible rate enhancement in (*E*)-**6e** due to steric origin (vide supra).

Experimental Section

Melting points are uncorrected. IR spectra were recorded on a Hitachi 215 spectrophotometer. ^1H NMR spectra were recorded on a Hitachi R-24 (60 MHz), JEOL FX90A (89.55 MHz), or JEOL GSX270 (270.05 MHz) spectrometer. ^{13}C NMR spectra were obtained on a JEOL FX90A (22.5 MHz), JEOL FX100 (25.0 MHz), or JEOL GSX270 (67.8 MHz) spectrometer. In all NMR measurements TMS was used as an internal standard. Elemental analyses were performed by the Microanalytical Center, Kyoto University, Kyoto. Ketols **7d**,[8b] **8d**,[8b] **9d**,[8b] and **10d**[8d,40] and 3-homoadamantyl heptafluorobutyrate[41] (**10b**) were described previously. The purities of the unstable substrates for rate studies were generally higher than 97% on the basis of their ^{13}C NMR spectra even when a crude product was used. Exceptions were **6b**, (*E*)-**6e**, **7a-OMs**, and **7b-OMs**, whose purities were approximately 85, 70, 37, and 80 mol %, respectively, being contaminated by the respective bridgehead alcohols. Absolute ethanol as a solvolysis solvent was distilled from magnesium ethoxide. All the anhydrous solvents used for synthetic work were purified by standard procedures. *tert*-Butyldimethylsilyl trifluoromethanesulfonate (triflate) was prepared following a literature procedure.[42] Commercially available methyl- and ethyltriphenylphosphonium bromides were dried at 95–100 °C in vacuo for 1 h before use. Other commercially available reagents were of a reagent-grade quality and used as received. Medium-pressure liquid chromatography (MPLC) and conventional liquid chromatography were conducted on Merck silica gel 60 (230–400 mesh) and Nacalai Tesque silica gel No. I (60–200 mesh), respectively.

1-Hydroxybicyclo[2.2.2]octan-2-one (4d). A procedure described for the cleavage of methoxycyclohexane[43] was followed. To a solution of 1-methoxybicyclo[2.2.2]octan-2-one[44] (4.00 g, 25.9 mmol) and pyridine (0.83 g, 10 mmol) in $CHCl_3$ (8 mL) was added iodotrimethylsilane (6.8 g, 34 mmol) with stirring at room temperature. After 65 h at 60 °C, methanol (3.5 mL) was added and then volatile substances were evaporated with a rotary evaporator. The residue was subjected to MPLC (SiO_2, hexane–ether (4:1)) to afford **4d** (1.45 g, 40%): mp 187.5–188.0 °C (from hexane); IR (CCl_4) 3510, 2940, 2860, 1720, 1450, 1400, 1230, 1145, 1090, 960 cm^{-1}; ^1H NMR (89.55 MHz, $CDCl_3$) δ 1.49–2.26 (m, 9 H), 2.42 (d, 2 H, J = 2.7 Hz), 3.46 (s, 1 H, OH); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 74.3 (C), 27.3 (CH), 25.9, 30.1, 43.1 (CH_2), 215.7 (C=O). Analytical data were unsatisfactory probably due to the hygroscopic nature. Anal. Calcd for $C_8H_{12}O_2$: C, 68.55; H, 8.63. Found: C, 67.73; H, 8.59. However, the *p*-nitrobenzoate gave satisfactory analytical data: mp 114.5–115.5 °C (from hexane–benzene). Anal. Calcd for $C_{15}H_{15}NO_5$: C, 62.28; H, 5.23. Found: C, 62.15; H, 5.29.

Protection of 4d by *tert*-Butyldimethylsilylation. To a solution of **4d** (1.45 g, 10.3 mmol) and 2,6-lutidine (2.4 mL) in CH_2Cl_2 (11 mL) was added *tert*-butyldimethylsilyl triflate[42] at 0 °C over 4 min. After being stirred for 1 h, the reaction mixture was diluted with CH_2Cl_2 (15 mL), washed with water (2 × 15 mL), 10% aqueous HCl (2 × 15 mL), saturated aqueous $NaHCO_3$ (2 × 15 mL), and saturated aqueous NaCl (15 mL), and dried ($MgSO_4$). Evaporation of solvent, followed by MPLC (SiO_2, hexane–ether (9:1)) afforded *tert*-butyldimethylsilyl ether **4d-OBDMS** (1.89 g, 71%) as a colorless oil: ^1H NMR (60 MHz, CCl_4) δ 0.1 (s, 6 H), 0.90 (s, 9 H), 1.6–2.4 (m, 11 H); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 18.2, 77.5 (C), 27.3 (CH), 26.2, 31.7, 44.5 (CH_2), -2.7, 25.8 (CH_3), 213.6 (C=O).

2-Methylenebicyclo[2.2.2]octan-1-ol (4c). Following a literature procedure,[12] *tert*-butyldimethylsilyl ether **4d-OBDMS** (0.383 g, 1.51 mmol) was treated in DMSO (6 mL) under N_2 with methylenetriphenylphosphorane, which was generated from methyltriphenylphosphonium bromide (1.62 g, 4.53 mmol) and NaH (60% dispersion 0.182 g, 4.53 mmol) in DMSO at 70 °C for 30 h. The reaction mixture was poured into ice–water (20 mL) and extracted with ether (4 × 15 mL). The combined extracts were washed with water (3 × 15 mL) and saturated aqueous NaCl (2 × 15 mL) and dried ($MgSO_4$). After evaporation of solvent, the crude product was subjected to MPLC (SiO_2, hexane) to give the *tert*-butyldimethylsilyl ether of **4c** (**4c-OBDMS**) (0.322 g), whose purity was estimated to be 86% from the ^1H NMR spectrum. The impure **4c-OBDMS** (0.322 g) was dissolved in THF (6 mL). To this was added a 1.0 M solution of *n*-Bu_4NF in THF (2.6 mL), and the resulting solution refluxed for 46 h under N_2. The reaction mixture was stirred with 4% aqueous NH_4Cl (10 mL) and extracted with ether (3 × 10 mL). The combined extracts were washed with water (2 × 10 mL) and 10% aqueous NaCl (2 × 10 mL) and dried ($MgSO_4$). Evaporation of the ether followed by MPLC (SiO_2, hexane–ether (4:1)) afforded **4c** (0.136 g, 46% based on **4d**): mp 56.5–57.0 °C (from hexane); IR (CCl_4) 3610, 3475 br, 3080, 1650, 880 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.5–1.8 (m, 10 H), 2.38 (br s, 2 H, OH and H-4), 4.60 (br s, 1 H, =CH), 4.95 (br s, 1 H, =CH); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 71.7, 153.1 (C), 26.0 (CH), 26.8, 33.7, 35.9, 102.3 (CH_2). Analytical data were unsatisfactory probably due to the hygroscopic nature. Anal. Calcd for $C_9H_{14}O$: C, 78.21; H, 10.21. Found: C, 75.75; H, 10.21. However, the *p*-nitrobenzoate gave satisfactory analytical data: mp 77.5–78.5 °C (from hexane). Anal. Calcd for $C_{16}H_{17}NO_4$: C, 66.89; H, 5.96. Found: C, 66.85; H, 5.98.

2-Methylenebicyclo[2.2.2]oct-1-yl Triflate (4a). To a solution of **4c** (0.143 g, 1.03 mmol) and pyridine (0.163 g, 2.06 mmol) in CH_2Cl_2 (2 mL) was added a solution of triflic anhydride (0.387 g, 1.37 mmol) in CH_2Cl_2 (1.2 mL) with stirring at 0 °C over 5 min, and then stirring continued for 45 min. After having been stored in a freezer overnight, the reaction mixture was diluted with CH_2Cl_2 (16 mL), washed at 0 °C with 10% aqueous HCl (30 mL), saturated aqueous $NaHCO_3$ (15 mL), and 10% aqueous NaCl (2 × 15 mL), and dried ($MgSO_4$). Evaporation of solvent with a rotary evaporator afforded **4a** (0.226 g, 81%) as an unstable oil, which was used for solvolysis studies without further purification: IR (CCl_4) 3100, 1650, 1405, 1250, 1215, 1145, 930, 890 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.7–2.6 (m, 11 H), 4.81 (t, 1 H, J = 2.2 Hz), 5.10 (t, 1 H, J = 2.2 Hz); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 100.7, 146.0 (C), 25.3 (CH), 27.4, 31.4, 36.8, 106.0 (CH_2), 118.1 (q, CF_3, J = 319 Hz).

(*Z*)-2-Ethylidenebicyclo[2.2.2]octan-1-ol ((*Z*)-4f). Following a literature method for Wittig methylenation,[12] **4d-OBDMS** (1.89 g, 7.43 mmol) was treated in DMSO (34 mL) under N_2 with ethylidenetriphenylphosphorane, which was generated from ethyltriphenylphosphonium bromide (8.28 g, 22.3 mmol) and NaH (60% dispersion 0.892 g, 22.3 mmol) in DMSO at 70 °C for 3.5 h. The reaction mixture was poured into ice (120 g) and extracted with ether (4 × 70 mL). The combined extracts were washed with water (3 × 70 mL) and saturated aqueous NaCl (3 × 70 mL) and dried ($MgSO_4$). When most of the ether was removed with a rotary evaporator, hexane (10 mL) was added and insoluble solid was removed by filtration. Evaporation of solvent followed by MPLC (SiO_2, hexane) afforded a colorless liquid (1.69 g, 85%) whose ^{13}C NMR spectra and ^1H NMR NOE difference experiments showed the formation of (*Z*)-**4f-OBDMS**, the *E* isomer being present in 5%: ^1H NMR (270.05 MHz, $CDCl_3$) δ 0.12 (s, 6 H), 0.88 (s, 9 H), 1.52–1.81 (m, 9 H), 1.84 (dt, 3 H, J = 7.1, 2.0 Hz), 2.27 (br s, 2 H), 5.14 (qt, 1 H, J = 7.1, 2.0 Hz); ^{13}C NMR (22.5 MHz, $CDCl_3$)

(40) Takeuchi, K.; Yoshida, M.; Nishida, M.; Kohama, A.; Kitagawa, T. *Synthesis* **1991**, 37.
(41) Fărcaşiu, D.; Jähme, J.; Rüchardt, C. *J. Am. Chem. Soc.* **1985**, *107*, 5717.
(42) Corey, E. J.; Cho, H.; Rucker, C.; Hua, D. H. *Tetrahedron Lett.* **1981**, *22*, 3455.
(43) Jung, M. E.; Lyster, M. A. *Org. Synth.* **1980**, *59*, 35.
(44) Alfaro, I.; Ashton, W.; Rabone, K. L.; Rogers, N. A. J. *Tetrahedron* **1974**, *30*, 559.

δ 18.3, 77.2, 140.9 (C), 26.2, 116.9 (CH), 26.2, 27.2, 34.6, 38.9 (CH_2), -1.3, 14.3 (CH_3).

The cleavage of (*Z*)-**4f-OBDMS** (0.660 g, 2.48 mmol) was conducted as described for **4c** by refluxing with *n*-Bu_4NF (5.0 mmol) in THF (10 mL) for 19 h under N_2. After usual workup, MPLC (SiO_2, hexane–ether (9:1)) of the crude product afforded (*Z*)-**4f** (0.32 g, 84%): mp 92.0–92.5 °C (from pentane); IR (CCl_4) 3610, 3490 br, 2940, 2860, 1450, 1310, 1100, 1060, 960, 850 cm^{-1}; ^1H NMR (89.55 MHz, $CDCl_3$) δ 1.34–1.80 (m, 10 H), 1.88 (dt, 3 H, *J* = 7.3, 2.0 Hz), 2.28 (br s, 2 H), 5.17 (qt, 1 H, *J* = 7.3, 2.0 Hz); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 74.5, 140.6 (C), 26.3, 116.3 (CH), 26.9, 34.7, 38.2 (CH_2), 13.5 (CH_3). Anal. Calcd for $C_{10}H_{16}O$: C, 78.90; H, 10.59. Found: C, 78.73; H, 10.80.

(*E*)-2-Ethylidenebicyclo[2.2.2]octan-1-ol (*E*)-4f). Following a literature procedure,[15] (*Z*)-**4f-OBDMS** was subjected to olefin inversion via an epoxide and phosphorus betaine. To a stirred solution of *m*-chloroperbenzoic acid (70% pure, 0.300 g, 1.22 mmol) in CH_2Cl_2 (2.7 mL) was added (*Z*)-**4f-OBDMS** (0.300 g, 1.13 mmol) in CH_2Cl_2 (1.7 mL) at 0 °C over 3 min. During the addition *m*-chlorobenzoic acid precipitated. After the solution was stirred for 10 min, cold 10% aqueous NaOH (2.4 mL) was added. The organic layer was washed with 10% aqueous NaCl (2 × 15 mL) and dried ($MgSO_4$). Evaporation of solvent followed by MPLC (SiO_2, hexane–ether (9:1)) afforded (*Z*)-**4f-OBDMS** epoxide (0.177 g, 56%): colorless oil; IR (CCl_4) 2930, 2860, 1470, 1460, 1260, 1150, 1125, 910, 835 cm^{-1}; ^1H NMR (89.55 MHz, $CDCl_3$) δ 0.08 (s, 3 H), 0.10 (s, 3 H), 0.85 (s, 9 H), 1.54 (d, 3 H, *J* = 5.8 Hz), 1.60–2.07 (m, 11 H), 2.79 (q, 1 H, *J* = 5.7 Hz); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 18.2, 64.7, 71.8 (C), 25.5, 63.3 (CH), 26.4, 26.8, 31.3, 32.2, 39.4 (CH_2), -1.7, -1.5, 14.5, 26.1 (CH_3).

The epoxide (0.177 g, 0.63 mmol) in THF (1.8 mL) was added under argon to lithium diphenylphosphide[15] (0.59 mmol) in THF (0.65 mL) with stirring at 25 °C over 2 min. After the solution was stirred at 25 °C for 2 h, iodomethane (0.137 g, 0.96 mmol) was added and stirring continued for 30 min. The reaction mixture was diluted with ether (10 mL), washed with 10% aqueous NaCl (8 mL), and dried ($MgSO_4$). Evaporation of solvent followed by MPLC (SiO_2, hexane) afforded essentially pure (*E*)-**4f-OBDMS** (0.115 g, 69%), the *Z* isomer being present in less than 2%, if any, colorless oil: IR (CCl_4) 2930, 2860, 1670, 1470, 1340, 1255, 1155, 1130, 980, 905 cm^{-1}; ^1H NMR (89.55 MHz, $CDCl_3$) δ 0.08 (s, 6 H), 0.90 (s, 9 H), 1.54 (dt, 3 H, *J* = 6.8, 1.5 Hz), 1.40–1.83 (m, 9 H), 2.27 (br s, 2 H), 5.38 (qt, 1 H, *J* = 6.8, 2.5 Hz); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 18.4, 74.2, 143.5 (C), 26.0, 111.8 (CH), 27.3, 33.6, 34.8 (CH_2), -1.6, 12.4, 26.0 (CH_3). The *Z* configuration was verified by NOE difference experiments (vide infra).

(*E*)-**4f-OBDMS** (0.409 g, 1.53 mmol) was desilylated as described for the preparation of **4c** by refluxing with *n*-Bu_4NF (3.00 mmol) in THF for 36 h under N_2. Usual workup followed by MPLC (SiO_2, hexane–ether (9:1)) afforded (*E*)-**4f** (0.214 g, 92%): mp 100.5–101.0 °C (from hexane); IR (CCl_4) 3600, 3475 br, 2940, 2865, 1675, 1455, 1335, 1105, 1060, 955, 890 cm^{-1}; ^1H NMR (89.55 MHz, $CDCl_3$) δ 1.14–1.74 (m, 10 H), 1.56 (dt, 3 H, *J* = 6.7, 1.59 Hz), 2.29 (br s, 2 H), 5.47 (qt, 1 H, *J* = 6.7, 2.7 Hz); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 71.6, 143.7 (C), 26.1, 110.7 (CH), 27.0, 33.4, 34.3 (CH_2), 12.2 (CH_3). Anal. Calcd for $C_{10}H_{16}O$: C, 78.90; H, 10.59. Found: C, 78.58; H, 10.78.

(*E*)-2-Ethylidenebicyclo[2.2.2]oct-1-yl Triflate ((*E*)-4e). Following the procedure described for the preparation of **4a**, treatment of (*E*)-**4f** (0.080 g, 0.53 mmol) with triflic anhydride (0.193 g, 0.65 mmol) in pyridine (0.083 g, 1.11 mmol) in CH_2Cl_2 (0.7 mL) at 0 °C for 2.5 h followed by usual workup at 0 °C afforded (*E*)-**4e** as a pale brown unstable oil (0.132 g), which was used for solvolysis studies without further purification: ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 101.6, 136.9 (C), 25.2, 114.6 (CH), 27.5, 31.8, 34.2 (CH_2), 12.4 (CH_3), 118.1 (q, CF_3, *J* = 319 Hz).

Bicyclo[2.2.2]oct-1-yl Triflate (4b). Bicyclo[2.2.2]octan-1-ol (mp 211.5–213.0 °C (lit.[45] mp 214–214.5 °C)) (0.170 g, 1.35 mmol), which was derived from bicyclo[2.2.1]hept-1-ylmethyl tosylate,[46] was treated with triflic anhydride (0.478 g, 1.69 mmol) and pyridine (0.225 g, 2.85 mmol) in CH_2Cl_2 (4.0 mL) at 0 °C for 14 h. Workup as described for the preparation of **4a** afforded an unstable oil which was used for rate studies without further purification: ^{13}C NMR (25 MHz, $CDCl_3$) δ 103.3 (C), 23.2 (CH), 27.7, 31.5 (CH_2), 118.1 (q, CF_3, *J* = 319 Hz).

2-Methylenebicyclo[3.2.1]octan-1-ol (5c). This was obtained as a major product on Wittig methylenation of **4d** following a literature method.[12] Treatment of **4d** (0.140 g, 1.00 mmol) in DMSO (5.3 mL) with methylenetriphenylphosphorane, which was generated from methyltriphenylphosphonium bromide (0.89 g, 2.5 mmol) and NaH (60% dispersion 0.10 g, 2.5 mmol) in DMSO, at 35 °C for 18 h followed by usual workup as described for the preparation of **4c** afforded a mixture of **4c** and **5c** in an approximate ratio of 1:3, respectively, as determined by GLC. The separation of **4c** and **5c** by MPLC failed, but it was achieved by converting them to acetates. A mixture of **4c** and **5c** (1:3) (1.05 g, 7.60 mmol) from a scaled up reaction was dissolved in triethylamine (1.16 g, 11.5 mmol) containing acetic anhydride (1.17 g, 11.5 mmol). To this was added 4-(dimethylamino)pyridine (0.074 g, 0.61 mmol) with stirring. After 20 h at room temperature, the reaction mixture was poured into ice and extracted with ether (2 × 20 mL). The combined extracts were washed with 10% aqueous HCl (2 × 15 mL), saturated aqueous $NaHCO_3$ (2 × 15 mL), saturated aqueous NaCl (20 mL), and dried ($MgSO_4$). Evaporation of solvent followed by MPLC (SiO_2, hexane–ether (9:1)) afforded 2-methylenebicyclo[2.2.2]oct-1-yl acetate (0.275 g, 20%) and 2-methylenebicyclo[3.2.1]oct-1-yl acetate (0.844 g, 62%) in this sequence as colorless oils. 2-Methylenebicyclo[2.2.2]oct-1-yl acetate: IR (CCl_4) 3090, 2950, 2860, 1740, 1650, 1430, 1365, 1240, 1070, 885 cm^{-1}; ^1H NMR (60 MHz, $CDCl_3$) δ 1.6–2.5 (m, 11 H), 1.97 (s, 3 H, CH_3), 4.62 (br s, 1 H, =CH), 4.80 (br s, 1 H, =CH); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 81.6, 148.0 (C), 25.7 (CH), 26.5, 29.7, 36.2, 103.9 (CH_2), 22.0 (CH_3), 169.3 (C=O). Anal. Calcd for $C_{11}H_{16}O_2$: C, 73.30; H, 8.95. Found: C, 73.31; H, 9.16. 2-Methylenebicyclo[3.2.1]oct-1-yl acetate: IR (CCl_4) 3090, 2950, 2870, 1745, 1645, 1450, 1365, 1240, 1080, 895 cm^{-1}; ^1H NMR (60 MHz, $CDCl_3$) δ 1.23–2.46 (m, 11 H), 2.00 (s, 3 H), 4.27 (br s, 1 H, =CH), 4.48 (br s, 1 H, =CH); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 88.2, 149.3 (C), 34.1 (CH), 27.7, 29.8, 33.0, 34.5, 45.2, 102.1 (CH_2), 21.4 (CH_3), 169.4 (C=O).

2-Methylenebicyclo[3.2.1]oct-1-yl acetate (0.671 g, 3.72 mmol) was reduced with $LiAlH_4$ in ether to give **5c** (0.482 g, 94%): mp 69.0–70.0 °C (from pentane); IR (CCl_4) 3630, 3400 br, 2950, 2870, 1650, 1455, 1110, 990, 900 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.13–2.47 (m, 11 H), 2.70 (s, 1 H, OH), 4.47 (s, 1 H, =CH), 4.77 (s, 1 H, =CH); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 80.6, 154.4 (C), 35.4 (CH), 27.8, 29.2, 32.8, 36.8, 46.5, 100.9 (CH_2). Analytical data were unsatisfactory probably due to its hygroscopic nature. Anal. Calcd for $C_9H_{14}O$: C, 78.21; H, 10.21. Found: C, 77.55; H, 10.06. However, the *p*-nitrobenzoate prepared by the use of *p*-nitrobenzoyl chloride, triethylamine, and 4-(dimethylamino)pyridine gave satisfactory analytical data: mp 91.0–92.0 °C (from hexane). Anal. Calcd for $C_{16}H_{17}NO_4$: C, 66.89; H, 5.96. Found: C, 67.01; H, 5.96.

2-Methylenebicyclo[3.2.1]oct-1-yl Triflate (5a). Following the procedure described for the preparation of **4a**, treatment of **5c** (0.304 g, 2.20 mmol) with triflic anhydride (0.759 g, 2.69 mmol) and pyridine (0.349 g, 4.40 mmol) in CH_2Cl_2 (5.2 mL) at 0 °C for 12 h followed by usual workup at 0 °C afforded **5a** as a pale brown unstable liquid, which was used for solvolysis studies without further purification: IR (CCl_4) 2960, 2880, 1820, 1660, 1460, 1410, 1220, 1155, 1025, 905, 890 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.32–2.67 (m, 11 H), 4.70 (s, 1 H, =CH), 4.97 (s, 1 H, =CH); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 103.9, 148.4 (C), 34.7 (CH), 26.7, 29.8, 32.0, 34.6, 44.7, 104.4 (CH_2), 118.2 (q, CF_3, *J* = 319 Hz).

Bicyclo[3.2.1]oct-1-yl Triflate (5b). Bicyclo[3.2.1]octan-1-ol was prepared by Baeyer–Villiger oxidation of bicyclo[3.2.1]octane-1-carboxylic acid[47] following a literature procedure.[48] To H_2SO_4 (18.5 mL) was added bicyclo[3.2.1]octane-1-carboxylic acid (3.00 g, 19.5 mmol) at 0 °C, and then the yellowish mixture was

(45) Grob, C. A.; Ohta, M.; Renk, E.; Weiss, A. *Helv. Chim. Acta* **1958**, *41*, 1191.

(46) (a) Bixler, R. L.; Niemann, C. *J. Org. Chem.* **1958**, *23*, 742. (b) Wiberg, K. B.; Lowry, B. R. *J. Am. Chem. Soc.* **1963**, *85*, 3188.

(47) (a) Chow, A. W.; Jakas, D. R.; Hoover, J. R. E. *Tetrahedron Lett.* **1966**, 5427. (b) Vaughan, W. R.; Caple, R.; Csapilla, J.; Scheiner, P. *J. Am. Chem. Soc.* **1965**, *87*, 2204.

(48) (a) Luong, T. M.; Lefort, D. *Bull. Soc. Chim. Fr.* **1962**, *29*, 827. (b) Beak, P.; Trancik, R. J.; Simpson, D. A. *J. Am. Chem. Soc.* **1969**, *91*, 5073.

further stirred at 0 °C for 30 min. To the magnetically stirred mixture was added 30% H_2O_2 (3.75 mL) at 0–8 °C over 1.5 h, and then stirring continued for 4 h. The reaction mixture was poured into ice (80 g) and extracted with ether (3 × 25 mL). The combined extracts were washed with 10% aqueous NaOH (3 × 20 mL) and 10% aqueous NaCl (2 × 20 mL) and dried ($MgSO_4$). Evaporation of the ether afforded a slightly pink solid (0.80 g) which was then recrystallized from hexane to give bicyclo[3.2.1]octan-1-ol (0.50 g, 20%): mp 180.5–181.5 °C (from hexane);[49] IR (CCl_4) 3620, 3330 br, 2940, 2870, 1455, 1340, 1100, 1025 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.1–2.3 (m, 13 H), 2.60 (s, 1 H, OH); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 78.5 (C), 35.1 (CH), 20.0, 27.5, 31.1, 35.7, 39.8, 45.7 (CH_2). Analytical data were unsatisfactory presumably because of the hygroscopic nature. Anal. Calcd for $C_8H_{14}O$: C, 76.14; H, 11.18. Found: C, 74.78, 11.43. *p*-Nitrobenzoate gave satisfactory analytical data: mp 136.5–137.5 °C. Anal. Calcd for $C_{15}H_{17}NO_4$: C, 65.44; H, 6.22. Found: C, 65.41; H, 6.22.

The triflate **5b** was prepared by using bicyclo[3.2.1]octan-1-ol (0.278 g, 2.20 mmol), pyridine (0.349 g, 4.40 mmol), and CH_2Cl_2 (5.2 mL) as described for the preparation of **4a**, as a yellowish liquid (0.489 g, 86%), which was used for solvolysis studies without further purification: ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 105.0 (C), 34.5 (CH), 20.2, 26.4, 30.3, 33.9, 37.7, 43.8 (CH_2), 118.1 (q, CF_3, J = 318 Hz).

1-Hydroxybicyclo[3.2.2]nonan-2-one (6d). Oxidation of bicyclo[3.2.2]nonane-1,2-diol with Ag_2CO_3 on Celite was conducted as described in the literature.[50] To a suspension of Ag_2CO_3 on Celite[50] (161 g) in benzene (850 mL), from which contaminating water had been removed by azeotropic distillation, was added bicyclo[3.2.2]nonane-1,2-diol[8a] (5.32 g, 34.0 mmol) and then the mixture magnetically stirred vigorously at 80 °C for 1 h, during which period the suspension turned black. The reaction mixture was filtered and then the benzene evaporated to afford a semisolid (5.3 g), which on column chromatography (SiO_2; hexane–ether (4:1, 1:1)) gave **6d** (3.41 g, 65%): mp 150.5–151.5 °C (from hexane); IR (CCl_4) 3480 br, 2930, 2860, 1700, 1455, 1380, 1255, 1110, 1080 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.5–2.1 (m, 11 H), 2.50 (t, 2 H, J = 7.0 Hz), 3.60 (s, 1 H, OH); ^{13}C NMR (25 MHz, $CDCl_3$) δ 76.4 (C), 26.8 (CH), 24.9, 27.5, 29.7, 35.7 (CH_2), 214.9 (C=O). Anal. Calcd for $C_9H_{14}O_2$: C, 70.10; H, 9.15. Found: C, 69.90; H, 9.37.

2-Methylenebicyclo[3.2.2]nonan-1-ol (6c). The hydroxyl group of **6d** was first protected by trimethylsilylation. To a solution of **6d** (0.763 g, 4.95 mmol) in acetonitrile (7 mL) was added bis(trimethylsilyl)acetamide (1.21 g, 5.96 mmol) and then the mixture refluxed with stirring under N_2 for 3.5 h. Removal of solvent gave a colorless liquid, which on column chromatography (SiO_2, hexane–ether (4:1)) afforded **6d** trimethylsilyl ether (0.85 g, 76%) as colorless needles.

The trimethylsilyl ether (0.927 g, 4.10 mmol) was subjected to Wittig methylenation[12] in DMSO (10 mL) by treatment with methylenetriphenylphosphorane, which was generated by using methyltriphenylphosphonium bromide (1.61 g, 4.51 mmol) and NaH (60% dispersion, 0.180 g, 4.51 mmol) in DMSO, at 65 °C for 15 h under N_2. The reaction mixture was worked up as described for the preparation of **4c**, and then the crude product was subjected to column chromatography (SiO_2, CH_2Cl_2, ether) to give **6c** trimethylsilyl ether (0.210 g, 23%) and **6c** (0.370 g, 59%). The latter was presumably formed by hydrolysis on SiO_2 during chromatography. The crude **6c** was recrystallized from hexane: mp 72.0–73.0 °C (from hexane); IR (CCl_4) 3600, 3400 br, 2940, 1635, 1450, 1060, 910 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.3–2.1 (m, 13 H), 1.40 (s, 1 H, OH), 2.33 (t, 2 H, J = 6.5 Hz), 4.70 (br s, 1 H, =CH), 5.03 (br s, 1 H, =CH); ^{13}C NMR (25 MHz, $CDCl_3$) δ 73.8, 158.1 (C), 27.8 (CH), 25.9, 31.4, 35.2, 35.4, 107.4 (CH_2). Despite a purity of higher than 99% as estimated from ^{13}C NMR, analytical data of **6c** were unsatisfactory, presumably because of its hygroscopic nature. Anal. Calcd for $C_{10}H_{16}O$: C, 78.90; H, 10.59. Found: C, 76.50; H, 10.81. Satisfactory analytical data were obtained for the mesylate **6a** as described below.

2-Methylenebicyclo[3.2.2]non-1-yl Mesylate (6a). The procedure in the literature[51] was followed. To a solution of **6c** (0.116 g, 0.76 mmol) and triethylamine (0.20 mL, 1.45 mmol) in CH_2Cl_2 was added methanesulfonyl chloride (0.090 mL, 1.1 mmol) at −5 °C over 6 min, and then the mixture stirred at −5 °C for 20 min. The reaction mixture was diluted with CH_2Cl_2 (10 mL) and then washed at 0 °C with water (3 × 10 mL), 10% aqueous HCl (3 × 10 mL), saturated aqueous $NaHCO_3$ (3 × 10 mL), and saturated aqueous NaCl (10 mL), and dried ($MgSO_4$). Evaporation of solvent afforded colorless crystals (0.156 g, 63%): mp 62.5–63.5 °C (from pentane); IR (CCl_4) 3080, 1640, 1455, 1450, 1355, 1175, 920, 885 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.4–2.5 (m, 13 H), 2.85 (s, 3 H, CH_3), 4.92 (br s, 1 H, =CH), 5.10 (br s, 1 H, =CH); ^{13}C NMR ($CDCl_3$) δ 93.6, 151.5 (C), 27.1 (CH), 25.5, 30.6, 32.9, 35.6, 110.4 (CH_2), 41.2 (CH_3). Anal. Calcd for $C_{11}H_{18}O_3S$: C, 57.36; H, 7.88. Found: C, 57.26; H, 8.01.

(*Z*)- and (*E*)-2-Ethylidenebicyclo[3.2.2]nonan-1-ol ((*Z*)- and (*E*)-6f). The hydroxyl group of **6d** was protected by *tert*-butyldimethylsilylation as described for the preparation of **4d-OBDMS** by adding *tert*-butyldimethylsilyl triflate (1.72 g, 6.48 mmol) to a mixture of **6d** (1.00 g, 6.48 mmol) and 2,6-lutidine (1.4 g, 13 mmol) in CH_2Cl_2 (7 mL) at −78 °C and then stirring at room temperature for 2 h under N_2. Usual workup followed by MPLC (SiO_2, hexane–ether (9:1)) of the crude product afforded **6d-OBDMS** (1.20 g, 69%): mp 40.5–42.0 °C. Further elution with hexane–ether (1:1) afforded unchanged **6d** (0.235 g, 24%).

Following a literature method for Wittig methylenation,[12] the above **6d-OBDMS** (1.20 g, 4.48 mmol) was treated in DMSO (31 mL) under N_2 with ethylidenetriphenylphosphorane, which was generated from ethyltriphenylphosphonium bromide (4.99 g, 13.4 mmol) and NaH (60% dispersion 0.537 g, 13.4 mmol) in DMSO, at 70 °C for 21 h. The reaction mixture was worked up as described for the preparation of (*Z*)-**4f** to give a pale yellow liquid (1.49 g). The crude product was subjected to MPLC (SiO_2, hexane) to give a mixture (0.495 g) of two components with R_f 0.52 and 0.60 on TLC (SiO_2, hexane). The mixture was separated to three fractions by MPLC (500 × 20 mm SiO_2, hexane), the first being a pure component (0.050 g), the second (0.415 g) a mixture of two components, and the third (0.004 g). The second fraction was again subjected to MPLC and separated to three fractions. This procedure was repeated five more times, finally affording (*Z*)-**6f-OBDMS** (0.201 g, 16%) as the first and (*E*)-**6f-OBDMS** (0.273 g, 22%) as the third fraction.[17] The assignments of the configurations are based on NOE difference spectroscopy (vide infra). (*Z*)-**6f-OBDMS**: liquid; ^1H NMR (270.05 MHz, $CDCl_3$) δ 0.07 (s, 6 H), 0.87 (s, 9 H), 1.43–1.59 (m, 6 H), 1.81 (d, 3 H, J = 7.3 Hz), 1.86–1.89 (m, 3 H), 2.00–2.10 (m, 2 H), 2.18 (t, 2 H, J = 6.7 Hz), 5.27 (q, 1 H, J = 7.3 Hz); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 18.3, 77.3, 144.5 (C), 28.3, 121.8 (CH), 26.5, 33.9, 35.1, 38.2 (CH_2), −1.8, 15.6, 26.2 (CH_3). (*E*)-**6f-OBDMS**: liquid; ^1H NMR (270.05 MHz, $CDCl_3$) δ 0.01 (s, 6 H), 0.85 (s, 9 H), 1.39–1.89 (m, 11 H), 1.60 (d, 3 H, J = 7.0 Hz), 2.27 (t, 2 H, J = 7.0 Hz), 5.68 (q, 1 H, J = 7.0 Hz); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 18.2, 76.8, 146.5 (C), 28.1, 117.1 (CH), 23.4, 26.2, 35.8, 36.4 (CH_2), −1.9, 12.8, 26.0 (CH_3). A similar synthesis was repeated and the products were combined with each of the above isomers.

The cleavage of (*Z*)-**6f-OBDMS** (0.486 g, 1.73 mmol) was carried out as described for the preparation of (*Z*)-**4f** by treatment with *n*-Bu_4NF (3.5 mmol) in THF (10 mL) at 60 °C for 12 h and then at 70 °C for 72 h under N_2, while the progress of reaction was monitored by TLC. The reaction mixture was worked up in the usual manner and the crude product subjected to MPLC (SiO_2, hexane–ether (9:1)) to give (*Z*)-**6f** (0.243 g, 84%) as colorless crystals: mp 90.0–90.5 °C (from pentane); IR (CCl_4) 3610, 3480 br, 2930, 2855, 1640, 1450, 1380, 1055, 925, 900 cm^{-1}; ^1H NMR (89.55 MHz, $CDCl_3$) δ 1.33–1.96 (m, 11 H), 1.85 (dt, 3 H, J = 7.2, 0.9 Hz), 2.02–2.31 (m, 3 H), 5.33 (qt, 1 H, J = 7.2, 0.9 Hz); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 74.8, 145.2 (C), 28.3, 121.4 (CH), 26.2, 33.7, 34.7, 37.7 (CH_2), 14.6 (CH_3). Anal. Calcd for $C_{11}H_{18}O$: C, 79.47; H, 10.91. Found: C, 79.28; H, 11.15.

The cleavage of (*E*)-**6f-OBDMS** (0.273 g, 0.97 mmol) was similarly carried out, but it reacted much faster than the *Z* isomer,

(49) The rates of acetolysis of bicyclo[3.2.1]oct-1-yl tosylate are found in ref 20b, but the physical properties of bicyclo[3.2.1]octan-1-ol have never been reported.

(50) (a) Fetizon, M.; Golfier, M. *Comp. Rend.* **1968**, *267*, 900. (b) Fieser, M.; Fieser, L. In *Reagents for Organic Synthesis*; John Wiley & Sons: New York, 1969; Vol. 2, p 363.

(51) Crossland, R. K.; Servis, K. L. *J. Org. Chem.* **1970**, *35*, 3195.

taking only 2 h for completion. Workup followed by MPLC afforded (*E*)-**6f** (0.140 g, 86%) as colorless crystals: mp 59.5–60.0 °C (from pentane); IR (CCl_4) 3610, 3470 br, 2950, 2860, 1655, 1460, 1060, 1010, 930 cm^{-1}; ^1H NMR (89.55 MHz, $CDCl_3$) δ 1.18–1.88 (m, 12 H), 1.63 (d, 3 H, J = 6.8 Hz), 2.32 (t, 2 H, J = 6.9 Hz), 5.72 (q, 1 H, J = 6.8 Hz); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 73.9, 147.8 (C), 27.9, 115.7 (CH), 23.3, 25.9, 33.4, 35.1 (CH_2), 12.8 (CH_3). Anal. Calcd for $C_{11}H_{18}O$: C, 79.47; H, 10.91. Found: C, 79.32; H, 11.04.

(*E*)-2-Ethylidenebicyclo[3.2.2]non-1-yl Mesylate ((*E*)-6e). The procedure is similar to that employed for the preparation of **6a**. (*E*)-**6f** (0.050 g, 0.301 mmol) was treated with methanesulfonyl chloride (0.039 g, 0.34 mmol) and triethylamine (0.046 g, 0.46 mmol) in CH_2Cl_2 (1.4 mL) at −20 °C for 50 min, and then the reaction mixture was worked up at 0 °C. The resulting wet CH_2Cl_2 solution was stabilized by 2,6-lutidine (9 mg) and dried ($MgSO_4$). Evaporation of the solvent afforded (*E*)-**6e** (0.057 g) contaminated by 30 mol % of (*E*)-**6f** as a colorless liquid. The crude product was used for solvolysis studies without further purification: ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 95.2, 141.9 (C), 27.6, 119.4 (CH), 23.1, 25.9, 33.4, 35.3 (CH_2), 12.9, 41.3 (CH_3).

Bicyclo[3.2.2]non-1-yl Mesylate (6b). To a solution of bicyclo[3.2.2]nonan-1-ol[45] (mp 195.0–196.5 °C (lit.[45] mp 199–201 °C)) (0.300 g, 2.14 mmol) and triethylamine (0.32 g, 3.2 mmol) in CH_2Cl_2 (10 mL) was added methanesulfonyl chloride (0.27 g, 2.4 mmol) at −5 °C over 5 min and then stirring continued for 20 min. The reaction mixture was diluted with CH_2Cl_2 (10 mL), washed at 0 °C with water (3 × 10 mL), 10% aqueous HCl (3 × 10 mL), saturated aqueous $NaHCO_3$ (3 × 10 mL), and saturated aqueous NaCl (10 mL), and dried ($MgSO_4$). Evaporation of solvent afforded **6b** (0.352 g, 75%) as a colorless liquid whose purity was estimated to be 85% from the ^{13}C NMR spectrum: IR (CCl_4) 2920, 2860, 1460, 1340, 1170, 935, 905, 890 cm^{-1}; ^1H NMR (60 MHz, $CDCl_3$) δ 1.5–2.3 (m, 15 H), 2.79 (s, 3 H, CH_3); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 96.5 (C), 27.2 (CH), 19.8, 25.2, 31.9, 34.4, 40.6 (CH_2), 40.8 (CH_3).

2-Methylenebicyclo[3.3.1]nonan-1-ol (7c). The hydroxyl group of 1-hydroxybicyclo[3.3.1]nonan-2-one[8b] (**7d**) was protected by *tert*-butyldimethylsilylation as described for the preparation of **4d-OBDMS** by treating **7d** (0.600 g, 3.89 mmol) with *tert*-butyldimethylsilyl triflate (1.56 g, 5.90 mmol) and 2,6-lutidine (0.844 g, 7.88 mmol) in CH_2Cl_2 (4.0 mL) for 1 h. Usual workup followed by MPLC (SiO_2, hexane–ether (9:1)) afforded **7d-OBDMS** (0.496 g, 48%) as colorless crystals: mp 53.5–55.0 °C; ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 18.2, 78.6 (C), 30.5 (CH), 21.7, 29.3, 30.6, 37.7, 39.7, 42.6 (CH_2), −2.6, 25.8 (CH_3), 212.1 (C=O).

In a manner similar to that described for the preparation of **4c**, **7d-OBDMS** (0.878 g, 3.27 mmol) was treated in DMSO (14 mL) with methylenetriphenylphosphorane, which was generated from methyltriphenylphosphonium bromide (3.505 g, 9.81 mmol) and NaH (60% dispersion 0.392 g, 9.81 mmol) in DMSO, at 70 °C for 19 h. Usual workup followed by MPLC (SiO_2, hexane) afforded **7c-OBDMS** (0.677 g, 78%) as a colorless liquid: ^1H NMR (60 MHz, $CDCl_3$) δ 0.10 (s, 6 H), 0.87 (s, 9 H), 1.27–2.62 (m, 13 H), 4.70 (m, 1 H, =CH), 5.10 (m, 1 H, =CH).

To **7c-OBDMS** (0.640 g, 2.40 mmol) in THF (10 mL) was added 1.0 M *n*-Bu_4NF in THF (6.0 mL) and the reaction mixture heated at reflux for 45 h with stirring under N_2. Usual workup as described for the preparation of **4c** followed by MPLC (SiO_2, hexane–ether (4:1)) afforded **7c** (0.320 g, 87%) as colorless crystals: mp 44.5–45.5 °C (from pentane); IR (CCl_4) 3610, 3470 br, 3090, 1640, 1460, 1100, 905 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.30–2.87 (m, 14 H), 4.60 (m, 1 H, =CH), 4.93 (m, 1 H, =CH); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 72.0, 154.5 (C), 31.2 (CH), 22.1, 30.3, 30.4, 32.4, 39.9, 43.3, 105.8 (CH_2). Anal. Calcd for $C_{10}H_{16}O$: C, 78.90; 10.59. Found: C, 78.46; H, 10.61.

2-Methylenebicyclo[3.3.1]non-1-yl Mesylate (7a-OMs). The procedure is similar to that employed for the preparation of **6a**. Treatment of **7c** (0.120 g, 0.789 mmol) with methanesulfonyl chloride (0.099 g, 0.86 mmol) and triethylamine (0.120 g, 1.19 mmol) in CH_2Cl_2 (4 mL) at −12 °C for 30 min followed by workup at 0 °C afforded a mixture (0.10 g) of **7a-OMs** and **7c**, the latter being present in as much as 63% based on the ^1H NMR spectrum. ^1H NMR (60 MHz, CCl_4) δ 2.85 (s, 3 H, CH_3), 5.13 (m, 1 H, =CH), 5.27 (m, 1 H, =CH). The crude product was used for rate studies without further purification.

2-Methylenebicyclo[3.3.1]non-1-yl Heptafluorobutyrate (7a-OHFB). Following a literature method,[41] to a solution of **7c** (0.249 g, 1.64 mmol) in pyridine (2.3 mL) was added *n*-C_3F_7COCl (0.657 g, 2.83 mmol) in CH_2Cl_2 (1.6 mL) at 0 °C and then the mixture stirred at 0 °C for 6 h. The reaction mixture was diluted with CH_2Cl_2, washed with 10% aqueous HCl (3 × 20 mL), saturated aqueous $NaHCO_3$ (2 × 20 mL), and 10% aqueous NaCl (2 × 20 mL), and dried ($MgSO_4$). Evaporation of solvent afforded **7a-OHFB** (0.515 g, 90%) as a pale yellow liquid, which was used for solvolysis studies without further purification: IR (CCl_4) 2935, 1765, 1635, 1450, 1300, 1220, 1140, 1080, 950, 905 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 0.87–3.08 (m, 13 H), 4.97 (m, 2 H, =CH_2); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 87.5, 149.3 (C), 28.7 (CH), 19.5, 26.0, 30.4, 31.9, 34.0, 39.2, 110.2 (CH_2).

Bicyclo[3.3.1]non-1-yl Mesylate (7b-OMs). Bicyclo[3.3.1]nonan-1-ol was prepared by hydrolysis of 1-bromobicyclo[3.3.1]nonane in 60% acetone at reflux for 2 h in the presence of excess amounts of $NaHCO_3$ followed by purification of the crude product by sublimation. 1-Bromobicyclo[3.3.1]nonane[52] was derived from bicyclo[3.3.1]nonane, which was prepared by Wolff–Kishner reduction of bicyclo[3.3.1]nonan-9-one.[53] Mesylate **7b** was prepared in a manner similar to that employed for the preparation of **6a**. Treatment of bicyclo[3.3.1]nonan-1-ol (mp 185.0–186.0 °C (lit.[54] mp 182.5–184.0 °C)) (0.302 g, 2.15 mmol) with methanesulfonyl chloride (0.26 g, 2.3 mmol) and triethylamine (0.32 g, 3.2 mmol) in CH_2Cl_2 (11 mL) at −12 °C for 20 min followed by workup at 0 °C afforded colorless crystals (0.349 g). The product was found by ^{13}C NMR to be a mixture of **7b-OMs** (80 mol %) and bicyclo[3.3.1]nonan-1-ol (20 mol %). The mixture was used for rate studies without purification: ^1H NMR (60 MHz, CCl_4) δ 1.3–2.5 (m, 15 H), 2.82 (s, 3 H, CH_3); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 94.2 (C), 31.9 (CH), 22.4, 28.9, 36.3, 40.2 (CH_2), 40.5 (CH_3).

Bicyclo[3.3.1]non-1-yl Heptafluorobutyrate (7b-OHFB). Bicyclo[3.3.1]nonan-1-ol (mp 185.0–186.0 °C (lit.[54] mp 182.5–184.0 °C)) (0.202 g, 1.44 mmol) was treated with *n*-C_3F_7COCl (0.575 g, 2.47 mmol) and pyridine (2.0 mL) in CH_2Cl_2 at 0 °C for 6 h. Usual workup as described for the preparation of **7a-OHFB** afforded a pale yellow liquid (0.451 g, 93%), which was used for solvolysis studies without further purification: IR (CCl_4) 2925, 1770, 1450, 1235, 1215, 1150, 1120, 1085, 965, 905 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.22–2.83 (m, 15 H); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 90.0 (C), 32.0 (CH), 22.5, 29.7, 34.7, 39.4 (CH_2).

2-Methylenebicyclo[4.2.2]decan-1-ol (8c). The hydroxyl group of **8d** was first protected by *tert*-butyldimethylsilylation. To a solution of **8d**[8b] (1.325 g, 7.88 mmol) and 2,6-lutidine (1.69 g, 15.8 mmol) in CH_2Cl_2 (8 mL) was added *tert*-butyldimethylsilyl triflate (2.08 g, 7.88 mmol) at −78 °C over 6 min. The reaction was allowed to warm to −30 °C over 30 min and then to 0 °C over 1 h. The reaction mixture was diluted with CH_2Cl_2, washed with water (2 × 30 mL), 10% aqueous HCl (3 × 30 mL), saturated aqueous $NaHCO_3$ (30 mL), and 10% aqueous NaCl (30 mL), and dried ($MgSO_4$). Evaporation of solvent followed by MPLC (SiO_2, hexane–ether (4:1)) afforded unchanged **8d** (0.460 g, 35%) and **8d-OBDMS** (0.984 g, 44%): IR (CCl_4) 2940, 2860, 1700, 1465, 1360, 1255, 1120, 960, 840 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 0.10 (s, 6 H), 0.90 (s, 9 H), 1.28–2.82 (m, 15 H).

In a manner similar to that described for the preparation **4c**, **8d-OBDMS** (0.984 g, 3.48 mmol) was treated in DMSO (14.5 mL) with methylenetriphenylphosphorane, which was generated from methyltriphenylphosphonium bromide (3.75 g, 10.5 mmol) and NaH (60% dispersion 0.432 g, 10.5 mmol) in DMSO at 70 °C for 18 h. Usual workup afforded a mixture of a liquid and a solid, from which the liquid was extracted with pentane and hexane. Evaporation of solvent afforded **8c-OBDMS** (0.981 g, 100%) as a yellow liquid: ^1H NMR (60 MHz, CCl_4) δ 0.10 (s, 6 H), 0.93 (s, 9 H), 1.20–2.63 (m, 15 H), 4.90 (d, 1 H, =CH, J = 2.8 Hz), 5.18 (d, 1 H, =CH, J = 2.8 Hz).

Similar to the manner described for the preparation of **4c**, **8c-OBDMS** (0.977 g, 3.48 mmol) was treated with *n*-Bu_4NF (7.0

(52) Schleyer, P. v. R.; Isele, P. R.; Bingham, R. C. *J. Org. Chem.* **1968**, *33*, 1239.
(53) Brown, H. C. In *Organic Syntheses via Boranes*; John Wiley & Sons: New York, 1975; pp 166–168.
(54) Dauben, W. G.; Poulter, C. D. *J. Org. Chem.* **1968**, *33*, 1237.

mmol) in THF (22 mL) at reflux for 38 h under N_2. Usual workup followed by MPLC (SiO_2, hexane–ether (4:1)) afforded **8c** (0.485 g, 84%) as colorless crystals: mp 71.5–72.0 °C (from pentane); IR (CCl_4) 3610, 2930, 2855, 1620, 1470, 1450, 1050, 905 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.00–2.58 (m, 16 H), 4.67 (m, 1 H, =CH), 5.00 (d, 1 H, =CH, J = 2.4 Hz); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 73.5, 159.3 (C), 25.7 (CH), 24.1, 25.7, 34.3, 35.0, 35.6, 110.3 (CH_2). Anal. Calcd for $C_{11}H_{18}O$: C, 79.47; H, 10.91. Found: C, 79.21; H, 10.94.

1-Chloro-2-methylenebicyclo[4.2.2]decane (8a). To a stirred solution of $SOCl_2$ (0.537 g, 4.51 mmol) in benzene (0.8 mL) was added a solution of **8c** (0.150 g, 0.90 mmol) and pyridine (0.450 g, 5.69 mmol) in benzene (1.0 mL) at 0 °C over 5 min. The reaction mixture was stirred at 0 °C for 40 min and at room temperature for 2 h, poured into ice–water (20 mL), and extracted with ether (3 × 20 mL). The combined extracts were washed at 0 °C with 10% aqueous HCl (3 × 20 mL) and saturated $NaHCO_3$ (3 × 20 mL) and dried ($MgSO_4$). Evaporation of solvent gave **8a** (0.141 g, 84%) as a pale yellow liquid, which was used for solvolysis studies without further purification: ^1H NMR (60 MHz, CCl_4) δ 1.10–2.77 (m, 15 H), 5.13 (br s, 1 H, =CH), 5.43 (d, 1 H, =CH, J = 1.6 Hz); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 73.7, 155.6 (C), 24.3 (CH), 24.8, 26.2, 34.3, 34.8, 37.4, 117.6 (CH_2). The purity of **8a** was 99% as estimated from the ^{13}C NMR spectrum.

1-Chlorobicyclo[4.2.2]decane (8b). The precursor bicyclo[4.2.2]decan-1-ol was prepared as follows. Bicyclo[4.2.2]decane[55] (mp 160–162 °C) (1.00 g, 7.23 mmol), which was derived from bicyclo[4.2.2]decan-7-one[56] by Wolf–Kishner reduction,[56b] was brominated with NBS (1.35 g, 7.59 mmol) in the presence of dibenzoyl peroxide (0.05 g) in CCl_4 at reflux for 35 min under N_2. Filtration of succinimide followed by evaporation of CCl_4 afforded a yellow liquid (2.00 g), which was then hydrolyzed in 60% (v/v) aqueous acetone (60 mL) with stirring in the presence of $NaHCO_3$ (1.21 g, 14.4 mmol) at room temperature for 5 min, and then at reflux for 40 min. Evaporation of most of the acetone with a rotary evaporator separated a solid, which was extracted with ether (3 × 30 mL). The combined extracts were washed with water (3 × 50 mL) and saturated aqueous NaCl (50 mL) and dried ($MgSO_4$). Evaporation of the ether gave a yellow semisolid (1.02 g), which on column chromatography (SiO_2, hexane–ether (1:1, 1:4)) afforded unchanged bicyclo[4.2.2]decane (0.17 g, 17%), unidentified liquid (0.14 g), and bicyclo[4.2.2]decan-1-ol (0.39 g, 35%) in this sequence. An analytical sample was provided by sublimation at 58–65 °C (2 mmHg): mp 165–171 °C (lit.[57] mp 73–74 °C)[58]; IR (CCl_4) 3600, 3400 br, 2920, 1470, 1450, 1075, 1060, 1020, 940 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.3–1.8 (m, 17 H), 2.0 (s, 1 H, OH); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 72.6 (C), 27.1 (CH), 24.2, 24.7, 25.1, 34.2, 36.8, 45.5 (CH_2).

Chlorination of the above alcohol (0.154 g, 1.00 mmol) with $SOCl_2$ (1.11 g, 9.35 mmol) at 0 °C for 3 h followed by workup as described for the preparation of **8a** afforded crude **8b**, which was purified by sublimation at 55–60 °C (10 mmHg) to give **8b** as colorless crystals (0.106 g, 61%): mp 99.5–101.0 °C (lit.[57] mp 70–71 °C);[59] ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 76.7 (C), 26.3 (CH), 24.4, 26.0, 26.2, 36.3, 36.8, 47.9 (CH_2).

2-Methylenebicyclo[4.3.1]decan-1-ol (9c). The hydroxyl group of **9d** was protected by trimethylsilylation as described for the preparation of **6c** by treating **9d**[8b] (0.200 g, 1.19 mmol) with bis(trimethylsilyl)acetamide (0.35 mL, 1.4 mmol) in acetonitrile (4 mL) at reflux for 3 h. Usual workup of the reaction mixture followed by column chromatography (SiO_2, hexane) afforded **9d** trimethylsilyl ether (0.265 g, 93%): ^1H NMR (60 MHz, CCl_4) δ 0.10 (s, 9 H), 1.10–2.60 (m, 15 H); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 78.4 (C), 32.3 (CH), 21.8, 22.7, 29.5, 34.7, 36.9, 40.4, 41.1 (CH_2), 214.4 (C=O).

The **9d** trimethylsilyl ether (0.260 g, 1.08 mmol) was subjected to Wittig methylenation[12] in DMSO (4.0 mL) by treatment with methylenetriphenylphosphorane, which was generated by using methyltriphenylphosphonium bromide (0.464 g, 1.30 mmol) and NaH (60% dispersion 0.052 g, 1.30 mmol) in DMSO, at 70 °C for 21 h under N_2. The reaction mixture was worked up as described for the preparation of **4c** and subjected to column chromatography (SiO_2, hexane–ether (7:3, 3:2, 1:1)). The Si–O bond cleavage occurred in the column, giving **9c** (0.093 g, 52%) as colorless crystals: mp 55.0–56.0 °C (from pentane); IR (CCl_4) 3605, 3400 br, 3070, 1620, 1045, 1005 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.4–2.5 (m, 16 H), 4.9 (br s, 1 H, =CH), 5.1 (br s, 1 H, =CH); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 73.7, 157.7 (C), 31.9 (CH), 22.3, 26.9, 30.1, 35.4 (two carbons), 41.2, 41.4, 112.5 (CH_2). Anal. Calcd for $C_{11}H_{18}O$: C, 79.46; H, 10.91. Found: C, 79.42; H, 11.12.

2-Methylenebicyclo[4.3.1]dec-1-yl Trifluoroacetate (9a). To a solution of **9c** (0.200 g, 1.20 mmol) in pyridine (3.0 mL) was added trifluoroacetic anhydride (0.34 mL, 2.4 mmol) with stirring at 0 °C over 10 min and then stirring continued for 1 h. The reaction mixture was poured into ice–water (20 mL) and extracted with ether (30 mL). The extract was washed at 0 °C with water (2 × 10 mL), 10% aqueous HCl (3 × 10 mL), saturated aqueous $NaHCO_3$ (3 × 10 mL), and saturated aqueous NaCl (10 mL), and dried ($MgSO_4$). Evaporation of solvent afforded **9a** as a pale yellow liquid, which was used for solvolysis studies without further purification: IR (CCl_4) 3080, 1775, 1630, 1370, 1220, 1170, 1150, 920, 855 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.4–3.1 (m, 15 H), 5.1 (s, 2 H, =CH_2); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 89.6, 153.1 (C), 31.7 (CH), 21.9, 27.4, 30.0, 36.1, 36.9, 37.2, 40.2, 114.1 (CH_2), 114.4 (q, CF_3, J = 286 Hz), 153.9 (q, C=O, J = 19 Hz).

Bicyclo[4.3.1]dec-1-yl Trifluoroacetate (9b). Bicyclo[4.3.1]decan-1-ol[60] (0.180 g, 1.16 mmol) was treated with trifluoroacetic anhydride (0.49 g, 2.3 mmol) in pyridine (3 mL) at 0 °C for 1.5 h. Workup of the reaction mixture as described for the preparation of **9a** afforded **9b** as a pale yellow liquid (0.267 g, 92%), which was used for solvolysis studies without further purification: IR (CCl_4) 2930, 2860, 1775, 1465, 1450, 1375, 1220, 1170, 1020, 935 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.3–2.7 (m, 17 H); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 92.6 (C), 30.7 (CH), 20.9, 24.6, 27.0, 30.5, 34.6, 36.8, 38.0, 38.7 (CH_2), 114.5 (q, CF_3, J = 286 Hz), 156.0 (q, C=O, J = 42 Hz).

4-Methylene-3-homoadamantanol (10c). The hydroxyl group of **10d** was protected by treating **10d** (2.00 g, 11.1 mmol) with *tert*-butyldimethylsilyl triflate (3.64 g, 13.8 mmol) and 2,6-lutidine (2.39 g, 22.3 mmol) in CH_2Cl_2 (12 mL) at room temperature for 1 h, giving **10d-OBDMS** (2.62 g, 90%): mp 105.5–107.0 °C; ^1H NMR (60 MHz, CCl_4) δ 0.10 (s, 6 H), 0.82 (s, 9 H), 1.33–2.60 (m, 15 H). Wittig methylenation[12] of **10d-OBDMS** (2.36 g, 8.00 mmol) was conducted in DMSO (34 mL) by treatment with methylenetriphenylphosphorane, which was generated from methyltriphenylphosphonium bromide (8.57 g, 24.0 mmol) and NaH (60% dispersion 0.950 g, 24.0 mmol) in DMSO, at 70 °C for 20 h under N_2. Workup of the reaction mixture as described for the preparation of **4c** afforded crude **10c-OBDMS** (2.24 g, 96%). The crude **10c-OBDMS** (2.24 g, 7.66 mmol) was treated with *n*-Bu_4NF (19.1 mmol) in refluxing THF (50 mL) for 47 h, and then the reaction mixture was worked up in a usual manner. The crude product was subjected to MPLC (SiO_2, hexane–ether (4:1)), giving **10c** (1.30 g, 95%): mp 117.0–118.0 °C (from pentane); IR (CCl_4) 3600, 3460 br, 2910, 2850, 1620, 1440, 1050, 945, 910, 890 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.3–2.3 (m, 13 H), 1.43 (s, 1 H, OH), 4.63 (m, 1 H, =CH), 5.13 (m, 1 H, =CH); ^{13}C NMR (25 MHz, $CDCl_3$) δ 74.5, 157.4 (C), 28.1, 29.5 (CH), 35.5, 36.8, 40.8, 46.2, 107.5 (CH_2). Analytical data were unsatisfactory, presumably because of hygroscopic nature. Anal. Calcd for $C_{12}H_{18}O$: C, 80.85; H, 10.18. Found: C, 80.38; H, 10.16. The *p*-nitrobenzoate showed satisfactory analytical data: mp 150.5–152.0 °C. Anal. Calcd

(55) ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 28.2 (CH), 24.5, 26.1, 37.8 (CH_2). Five experimental articles, including refs 29a, 56b, and 56c, dealing with bicyclo[4.2.2]decane have appeared so far, but no melting point data have been reported. The ^{13}C NMR spectra agreed with reported data.[56c]

(56) (a) Antkowiak, T. A.; Sander, D. C.; Trimitsis, G. B.; Press, J. B.; Schechter, H. *J. Am. Chem. Soc.* **1972**, *94*, 5366. (b) Jones, M., Jr.; Scott, L. T. *J. Am. Chem. Soc.* **1967**, *89*, 150. (c) Zagorski, M. G.; Allan, D. S.; Salomon, R. G. *J. Org. Chem.* **1985**, *50*, 4484.

(57) Sasaki, Y.; Toyotani, S.; Ohtani, M.; Matsumoto, M.; Tobe, Y.; Odaira, Y. *Bull. Chem. Soc. Jpn.* **1981**, *54*, 1474.

(58) In spite of the wide melting point range (6 °C) of our sample and a marked difference of the melting point from that reported by Sasaki et al.,[57] the alcohol prepared by our hands showed ^{13}C NMR spectra consistent with the structure, with a purity of higher than 95%. The ^{13}C NMR spectrum completely coincided with that kindly provided by Dr. Yoshito Tobe of Osaka University.

(59) Although the melting point was higher than that reported[57] by ca. 20 °C, the ^{13}C NMR spectra of **8b** were consistent with the structure.

(60) Graham, S. H.; Jonas, D. A. *J. Chem. Soc. C* **1969**, 188.

for $C_{19}H_{21}NO_4$: C, 69.71; H, 6.47. Found: C, 69.41; H, 6.43.

4-Methylene-3-homoadamantyl Heptafluorobutyrate (10a). To a mixture of **10c** (0.248 g, 1.39 mmol) and pyridine (1.9 mL, 23 mmol) was added n-C_3F_7COCl (0.556 g, 2.39 mmol) in CH_2Cl_2 (1.7 mL) at 0 °C over 1 min, and the resulting solution was stirred for 6 h. The reaction mixture was diluted with CH_2Cl_2 and washed at 0 °C with 5% aqueous HCl (3 × 20 mL), water (2 × 20 mL), saturated aqueous $NaHCO_3$ (2 × 20 mL), and 10% aqueous NaCl (20 mL), and dried ($MgSO_4$). Evaporation of solvent afforded **10b** as a pale yellow liquid, which was used for solvolysis studies without further purification: IR (CCl_4) 2910, 1780, 1450, 1300, 1265, 1240, 1210, 1190, 1080, 970, 940, 900, 840 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.3–2.7 (m, 15 H), 4.60 (s, 2 H, $=CH_2$); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 90.8, 150.8 (C), 27.9, 28.7 (CH), 35.5, 36.2, 40.9, 42.9, 109.7 (CH_2).

3-Homoadamantyl Heptafluorobutyrate (10b). The above procedure for **10a** and that described in the literature[41] were followed. To a mixture of 3-homoadamantanol[61] (0.333 g, 2.00 mmol) and pyridine (3.0 mL, 37 mmol) was added n-C_3F_7COCl (0.770 g, 3.32 mmol) in CH_2Cl_2 (2.4 mL) at 0 °C, and the resulting mixture stirred at 0 °C for 12 h. Usual workup afforded crude **10b** (0.682 g, 94%), which was used for solvolysis studies without further purification: liquid; ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 93.5 (C), 27.4, 30.7 (CH), 28.8, 35.0, 36.2, 37.0, 42.9 (CH_2).

Product of Solvolysis of 4a in Ethanol: A Typical Procedure. A solution of **4a** (0.164 g, 0.610 mmol) in 0.075 M 2,6-lutidine in ethanol (12.0 mL) was heated in a constant temperature bath (75.0 °C) for 20 h (25 half-lives). Analyses of the reaction mixture by GLC (PEG 20M, 3 mm × 2 m) exhibited the formation of a single product. After most of the ethanol had been removed with a rotary evaporator, the residue was dissolved in ether (20 mL) and the ether solution washed with water (10 mL), cold 2% aqueous HCl (10 mL), saturated aqueous $NaHCO_3$ (10 mL), and saturated aqueous NaCl (10 mL), and dried ($MgSO_4$). Evaporation of the ether afforded 1-ethoxy-2-methylenebicyclo[2.2.2]octane (0.072 g, 71%) as a colorless liquid: IR (CCl_4) 3080, 2950, 2860, 1645, 1430, 1395, 1120, 890 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.13 (t, 3 H, J = 7.0 Hz), 1.67 (br s, 10 H), 2.30 (br s, 1 H), 3.33 (q, 2 H, J = 7.0 Hz), 4.63 (q, 1 H, =CH, J = 2.0 Hz), 4.85 (q, 1 H, =CH, J = 2.0 Hz); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 76.2, 149.8 (C), 26.0 (CH), 26.7, 30.6, 36.5, 57.4, 104.0 (CH_2), 15.8 (CH_3).

Product of Solvolysis of (E)-4e in Ethanol. From **(E)-4e** (0.060 g, 0.211 mmol) in 0.050 M 2,6-lutidine in ethanol (5.3 mL) for 35 h (12 half-lives) was obtained 1-ethoxy-(*E*)-2-ethylidenebicyclo[2.2.2]octane (0.035 g, 92%) as a pale yellow oil: IR (CCl_4) 2950, 2865, 1670, 1455, 1380, 1120, 1045, 910 cm^{-1}; ^1H NMR (89.55 MHz, $CDCl_3$) δ 1.19 (t, 3 H, J = 7.0 Hz), 1.40–1.86 (m, 9 H), 1.56 (dt, 3 H, J = 6.7, 1.5 Hz), 2.27 (br s, 2 H), 3.44 (q, 2 H, J = 7.0 Hz), 5.40 (qt, 1 H, J = 6.9, 2.6 Hz); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 75.8, 140.3 (C), 26.0, 112.3 (CH), 26.9, 30.8, 33.3, 57.3 (CH_2), 12.3, 15.9 (CH_3).

Product of Solvolysis of 5a in Ethanol. From **5a** (0.151 g, 0.559 mmol) in 0.051 M 2,6-lutidine in ethanol (14.0 mL) at 50.0 °C for 50.3 h (13.3 half-lives) was obtained 1-ethoxy-2-methylenebicyclo[3.2.1]octane (0.070 g, 75%) as a pale yellow liquid: IR (CCl_4) 3090, 2940, 2860, 1640, 1450, 1120, 1050, 910 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.00–2.57 (m, 11 H), 1.20 (t, 3 H, J = 7.0 Hz), 3.55 (q, 2 H, J = 7.0 Hz), 4.63 (m, 1 H, =CH), 4.77 (m, 1 H, =CH); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 85.9, 151.8 (C), 35.1 (CH), 27.7, 29.9, 33.4, 33.5, 45.0, 59.8, 102.2 (CH_2), 15.7 (CH_3).

Product of Solvolysis of 6a in Ethanol. From **6a** (0.025 g, 0.109 mmol) in 0.075 M 2,6-lutidine in ethanol (2.0 mL) at 75.0 °C for 18 h (300 half-lives) was obtained 1-ethoxy-2-methylenebicyclo[3.2.2]octane (0.017 g, 87%) as a colorless liquid: IR (CCl_4) 3075, 2920, 2850, 1635, 1450, 1390, 1085, 905 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 1.05 (t, 3 H, J = 7.0 Hz), 1.2–1.4 (m, 13 H), 3.20 (q, 2 H, J = 7.0 Hz), 4.80 (m, 1 H, =CH), 4.93 (d, 1 H, =CH, J = 2.0 Hz); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 78.6, 152.5 (C), 28.1 (CH), 25.7, 32.2, 32.8, 36.3, 56.5, 108.8 (CH_2), 15.9 (CH_3).

Product of Solvolysis of (E)-6e in Ethanol. From a mixture (0.042 g) of **(E)-6e** and **(E)-6f** (70:30 in mol) in 0.050 M 2,6-lutidine in ethanol (6.0 mL) at 25.0 °C for 1 h was obtained a pale yellow liquid, which on MPLC (SiO_2, hexane–ether (9:1, 7:3)) gave 1-ethoxy-(*E*)-2-ethylidenebicyclo[3.2.2]octane (**(E)-6f-OEt**) (0.022 g, 100% based on **(E)-6e**) as a colorless liquid and **(E)-6f** (0.008 g) in this sequence. **(E)-6f-OEt**: IR (CCl_4) 2910, 2860, 1655, 1460, 1390, 1130, 1085, 920 cm^{-1}; ^1H NMR (89.55 MHz, $CDCl_3$) δ 1.09 (t, 3 H, J = 7.0 Hz), 1.66 (dt, 3 H, J = 6.9, 0.9 Hz), 1.23–2.00 (m, 11 H), 2.27 (t, 2 H, J = 6.8 Hz), 3.25 (q, 2 H, J = 7.0 Hz), 5.67 (qt, 1 H, J = 6.9, 1.0 Hz); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 78.8, 142.1 (C), 28.4, 116.9 (CH), 24.2, 25.8, 33.2, 35.9, 56.2 (CH_2), 12.9, 15.9 (CH_3).

Product of Solvolysis of 7a-OHFB in 80% Ethanol: A Typical Procedure. A solution of **7a-OHFB** (0.300 g, 0.86 mmol) in 0.050 M 2,6-lutidine in 80% ethanol (21.5 mL) was heated in a constant temperature bath (75.0 °C) for 21.5 h (12.1 half-lives). To the reaction mixture was added ether (200 mL), and the ether solution was washed with water (5 × 50 mL), saturated aqueous NaCl (50 mL), and dried ($MgSO_4$). Analyses of the ether solution by GLC (PEG 20M, 3 mm × 2 m) exhibited the formation of two products. Removal of the ether with a rotary evaporator afforded a yellow liquid, which on MPLC (SiO_2, hexane–ether (3:2, 1:4)) gave 1-ethoxy-2-methylenebicyclo[3.3.1]nonane (**7c-OEt**) (0.090 g, 56%) and **7c** (0.059 g, 44%) in this sequence. The ^1H NMR spectrum of **7c** obtained was in complete agreement with that of the specimen. **7c-OEt**: IR (CCl_4) 3080, 2930, 2850, 1630, 1450, 1390, 1090, 900 cm^{-1}; ^1H NMR (60 MHz, CCl_4) δ 0.90–2.57 (m, 16 H), 1.07 (t, 3 H, J = 7.1 Hz), 3.30 (q, 2 H, J = 7.1 Hz), 4.52 (m, 1 H, =CH), 4.63 (m, 1 H, =CH); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 76.4, 150.8 (C), 29.2 (CH), 20.7, 27.9, 31.9, 35.3, 40.7, 56.4, 108.6 (CH_2), 16.0 (CH_3).

Product of Solvolysis of 8a in 80% Ethanol. From **8a** (0.115 g, 0.623 mmol) in 0.050 M 2,6-lutidine in 80% ethanol (16 mL) at 25.0 °C for 6 h (10 half-lives) was obtained a pale yellow oil (0.108 g), which on MPLC (SiO_2, hexane–ether (9:1, 1:1)) afforded 1-ethoxy-2-methylenebicyclo[4.2.2]decane (**8c-OEt**) (0.030 g, 25%) and **8c** (0.040 g, 39%) in this sequence. **8c-OEt**: IR (CCl_4) 2920, 1625, 1465, 1450, 1390, 1110, 1080, 905 cm^{-1}; ^1H NMR (89.55 MHz, $CDCl_3$) δ 1.09 (t, 3 H, J = 7.0 Hz), 1.20–2.36 (m, 15 H), 3.27 (q, 2 H, J = 7.0 Hz), 5.08 (d, 1 H, J = 2.4 Hz), 5.16 (d, 1 H, J = 2.5 Hz); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 78.5, 154.9 (C), 25.4 (CH), 23.3, 26.5, 32.1, 34.9, 35.8, 56.0, 113.7 (CH_2), 15.9 (CH_3).

Product of Solvolysis of 9a in 80% Ethanol. From **9a** (0.210 g, 0.801 mmol) in 0.075 M 2,6-lutidine in 80% ethanol (20 mL) at 25.0 °C for 24 h (8.6 half-lives) was obtained a mixture (0.198 g) of 1-ethoxy-2-methylenebicyclo[4.3.1]decane (**9c-OEt**) and **9c**, their ratio having been determined to be 54:46, respectively, based on the ^{13}C NMR spectrum. An attempt to separate the two products of MPLC (SiO_2) failed owing to hydrolysis of the ether on SiO_2. **9c-OEt**: ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 78.1, 153.2 (C), 31.7 (CH), 21.9, 27.3, 30.6, 36.2, 37.1, 37.5, 40.8, 56.0, 113.5 (CH_2), 16.0 (CH_3).

Product of Solvolysis of 10a in 80% Ethanol. From **10a** (0.391 g, 1.04 mmol) in 0.050 M 2,6-lutidine in 80% ethanol (26 mL) at 75.0 °C for 42.3 h (16.4 half-lives) was obtained a liquid (0.219 g), which on MPLC (SiO_2, hexane–ether (9:1, 4:1)) afforded 3-ethoxy-4-methylenehomoadamantane (**10c-OEt**) (0.090 g, 41%) and **10c** (0.108 g, 59%) in this sequence. **10c-OEt**: IR (CCl_4) 2930, 2850, 1630, 1450, 1395, 1125, 1070, 890 cm^{-1}; ^1H NMR (60 MHz, $CDCl_3$) δ 0.86–2.57 (m, 15 H), 1.12 (t, 3 H, J = 7.0 Hz), 3.37 (q, 2 H, J = 7.0 Hz), 4.80 (m, 1 H, =CH), 5.00 (m, 1 H, =CH); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 79.2, 152.5 (C), 27.9, 29.2 (CH), 36.0, 36.6, 42.0, 43.9, 56.1, 109.5 (CH_2), 15.7 (CH_3).

Kinetic Studies. The preparation of 80% ethanol and kinetic methods were described previously.[24] All measurements were conducted in the presence of 0.025 M 2,6-lutidine with 0.02 M or (1–2) × 10^{-4} M substrate concentrations for titrimetric or conductimetric measurements, respectively. The first-order rate constants were calculated by the least-squares method on a microcomputer. The results are summarized in Table I.

NOE Difference Experiments. Nuclear Overhauser enhancement of the olefinic proton of **(Z)-4f-OBDMS**, **(E)-4f-OBDMS**, **(Z)-6f-OBDMS**, and **(E)-6f-OBDMS** on irradiation of the C(3) methylene protons was determined at 270 MHz by the gated decoupling method using $CDCl_3$ solutions degassed under vacuum. An irradiation period of 3.5 times the T_1's of the C(3) methylene protons was employed for NOE generation, followed by a 90° pulse. For spin relaxation, a pulse interval of

(61) Nordlander, J. E.; Jindal, S. P.; Schleyer, P. v. R.; Fort, R. C., Jr.; Harper, J. J.; Nichols, R. D. *J. Am. Chem. Soc.* **1966**, *88*, 4475.

3.5 times the T_1's of the olefinic proton was taken before the next pulse. The T_1 values for (*Z*)-**4f-OBDMS**, (*E*)-**4f-OBDMS**, (*Z*)-**6f-OBDMS**, and (*E*)-**6f-OBDMS** were determined by the inversion recovery method: C(3) methylene protons, 2.6, 1.9, 1.8, and 1.9 s, respectively; olefinic protons, 8.5, 7.9, 6.5, and 6.5 s, respectively.

Calculations. Semiempirical molecular orbital calculations and molecular mechanics calculations were performed through the AMPAC[39] system and MM2,[35] respectively, on FACOM M-780/30, FACOM VP-400E, and FACOM VP-200 computers.

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Registry No. **4a**, 137494-86-1; **4b**, 137494-88-3; **4c**, 116760-09-9; **4c**-OBDMS, 137494-96-3; **4c** *p*-nitrobenzoate, 137494-97-4; **4d**, 116760-07-7; **4d**-OBDMS, 135107-28-7; **4d** *p*-nitrobenzoate, 137494-95-2; (*E*)-**4e**, 137494-87-2; (*E*)-**4f**, 135107-35-6; (*E*)-**4f**-OBDMS, 135107-37-8; (*Z*)-**4f**, 135107-34-5; (*Z*)-**4f**-OBDMS, 135107-36-7; (*Z*)-**4f**-OBDMS epoxide, 137494-98-5; **5a**, 137494-89-4; **5b**, 137494-90-7; **5b** *p*-nitrobenzoate, 137495-03-5; **5c**, 137494-99-6; **5c** *p*-nitrobenzoate, 137495-02-4; **6a**, 116759-95-6; **6b**, 116759-97-8; **6c**, 137495-04-6; **6c** trimethylsilyl ether, 137495-06-8; **6d**, 116760-08-8; **6d**-OBDMS, 135107-29-8; **6d** trimethylsilyl ether, 137495-05-7; (*E*)-**6e**, 137494-91-8; (*E*)-**6f**, 135107-41-4; (*E*)-**6f**-OBDMS, 135144-13-7; (*E*)-**6f**-OEt, 137515-44-7; (*Z*)-**6f**, 135107-40-3; (*Z*)-**6f**-OBDMS, 135107-44-7; **7a**-OHFB, 137494-92-9; **7a**-OMs, 130829-59-3; **7b**-OHFB, 137494-93-0; **7b**-OMs, 130829-60-6; **7c**, 130829-56-0; **7c**-OBDMS, 137495-08-0; **7c**-OEt, 130829-67-3; **7d**, 121455-49-0; **7d**-OBDMS, 137495-07-9; **8a**, 137494-94-1; **8b**, 28054-89-9; **8c**, 137495-09-1; **8c**-OBDMS, 137495-11-5; **8c**-OEt, 137495-20-6; **8d**, 121455-53-6; **8d**-OBDMS, 137495-10-4; **9a**, 137515-53-8; **9b**, 137515-54-9; **9c**, 137495-13-7; **9c**-OEt, 137495-21-7; **9d**, 121455-48-9; **9d** trimethylsilyl ether, 137495-14-8; **10a**, 130829-58-2; **10b**, 97654-82-5; **10c**, 130829-57-1; **10c**-OBDMS, 137515-55-0; **10c**-OEt, 137495-22-8; **10d**, 97382-24-6; **10d**-OBDMS, 137495-15-9; C_3F_7COCl, 375-16-6; 1-methoxybicyclo[2.2.2]octan-2-one, 53921-93-0; ethylidenetriphenylphosphorane, 1754-88-7; bicyclo[2.2.2]octan-1-ol, 20534-58-1; 2-methylenebicyclo[2.2.2]-oct-1-yl acetate, 137495-00-2; 2-methylenebicyclo[3.2.1]oct-1-yl acetate, 137495-01-3; bicyclo[3.2.1]octan-1-ol, 134654-98-1; bicyclo[3.2.1]octane-1-carboxylic acid, 2534-83-0; bicyclo[3.2.2]nonane-1,2-diol, 110977-44-1; bicyclo[3.2.2]nonan-1-ol, 28054-86-6; bicyclo[3.3.1]nonan-1-ol, 15158-56-2; 1-bromobicyclo[3.3.1]nonane, 15292-76-9; bicyclo[4.2.2]decane, 284-26-4; 1-bromobicyclo-[4.2.2]decane, 137495-12-6; bicyclo[4.2.2]decan-1-ol, 79312-80-4; bicyclo[4.3.1]decan-1-ol, 22516-95-6; 3-homoadamantan-1-ol, 14504-80-4; 1-ethoxy-2-methylenebicyclo[2.2.2]octane, 137495-16-0; 1-ethoxy-(*E*)-2-ethylidenebicyclo[2.2.2]octane, 137495-17-1; 1-ethoxy-2-methylenebicyclo[3.2.1]octane, 137495-18-2; 1-ethoxy-2-methylenebicyclo[3.2.2]nonane, 137495-19-3.

Supplementary Material Available: ^{13}C NMR spectra for substrates and precursor alcohols (28 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

Conformations of Oxocane

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Conformational analysis of oxocane (oxacyclooctane) has been examined by molecular mechanics (MM2), variable-temperature ^{13}C NMR, and lanthanide-induced shift (LIS) ^1H and ^{13}C NMR. MM2 calculations find the BC-3 conformer and its enantiomer BC-7 to be favored, with the four next best forms and their energies relative to BC-3 being BC-1 (1.1 kcal/mol), TBC-1 (1.1), BC-4 (1.5), and TCC-1 (1.6). Barriers to pseudorotational interconversion of BC-3 and BC-7 are calculated to be 5.0 kcal/mol through BC-5 and 6.7 kcal/mol through BC-1. The former would allow fast BC-3/BC-7 equilibration even at −170 °C, which would leave reported low-temperature ^1H NMR spectra compatible with a BC-3 structure as well as BC-1. Calculated barriers for BC ring inversion and interconversion of the BC family with the crown family (TCC-1) are 8.2 and 8.5 kcal/mol, respectively. A new two-step synthesis of oxocane and its 2,2,7,7-d_4 analogue is reported, the latter allowing unequivocal assignment of chemical shifts. ^{13}C NMR spectra of oxocane between 138 and 290 K show BC-family/crown-family interconversion in the vicinity of 215 K ($\Delta G^* = 10.0 \pm 0.3$ kcal/mol), with the crown family comprising 4% of the equilibrium at 174 K ($\Delta G° = 1.1 \pm 0.1$ kcal/mol). The ^1H and ^{13}C LIS induced by Yb(fod)$_3$ on oxocane agree well with BC-3 and BC-7 being the predominant conformers at room temperature but do not acceptably fit a BC-1 structure. Thus, all available data from calculation and experiment are in accord with BC-3 being the favored conformation of oxocane.

The conformational properties of cyclooctane are well understood.[2] Both experiment (NMR,[3] electron diffraction,[4] vibrational analysis[5]) and theory (MM2,[4,6,7] MM2′,[8] ab initio 4-21G,[6] etc.[9]) are in complete agreement that at room temperature the major conformer (94%) is the boat-chair (BC; see Figure 1[10]), which undergoes rapid pseudorotation through the TBC with a barrier too low to detect by NMR[3c] (calculated by MM to be 2.8–3.4

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(2) For reviews, see: (a) Anet, F. A. L. *Top. Curr. Chem.* **1974**, *45*, 169. (b) Anet, F. A. L.; Anet, R. In *Dynamic Nuclear Magnetic Resonance Spectroscopy*; Jackman, L. M., Cotton, F. A., Eds.; Academic: New York, 1975; pp 543–619. (c) Anet, F. A. L. In *Conformational Analysis of Medium-Sized Heterocycles*; Glass, R. S., Ed.; VCH: New York, 1988; pp 35–95.

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