Cine Substitution in 2-Oxabicyclo[4.2.0]octanones and Subsequent Unusual Rearrangements[1]

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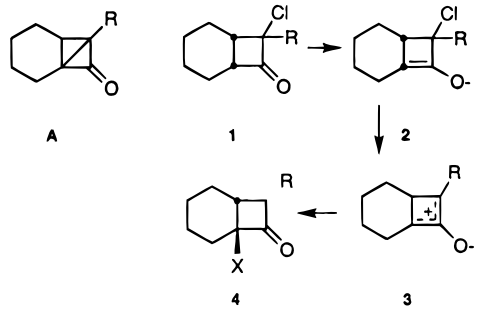
Reaction of 2-chlorooxabicyclo[4.2.0]octanone **5** with several nucleophiles was examined and found to differ significantly from those of carbon analog **1**. MeO^- and PhS^- led either to products of cine substitution **9** or of ring opening to cyclobutenones **8**. With most enolates cine substitution occured via C-alkylation of the intermediate oxidoallyl cation in spite of formation of a new C−C bond between two quaternary carbons; with nitroalkanes O-alkylation was preferred. With azide as a nucleophile, further transformations occurred, among them an oxy-promoted electrocyclic cyclobutane opening, with incorporation of a phenyl triazole unit and final formation of the unusual product **19a**. Evidence for a mechanism explaining formation of **19a** was obtained by isolation of intermediates. Thermolysis or photolysis of **8e** or **9b** led via electrocyclic ring opening to a vinyl ketene which was trapped by MeOH, alkenes, dienes, or oxygen to produce polyfunctional unsaturated esters **29** and **30** or 8-membered ring lactone **31**, fused cyclobutanones **33** and **34**, pyranone **38**, or γ-lactone **39**, respectively.

Introduction

α-Halo ketones can react with nucleophiles to afford either Favorskii products (via cyclopropanones) or α-substitution or α′-substitution products (cine substitution).[2] Among these ketones, α-halocyclobutanones have found wide application in the synthesis of tropolones,[3] cyclopropanes,[4] cyclopentanone derivatives,[5] and α-methylene γ-lactones.[6] In α-chlorobicyclo[4.2.0]octanones **1**, cine substitution is the only mode of reaction with a variety of nucleophiles,[7] presumably because the high energy pathway via the strained cyclopropanone **A** is disfavored.

We have postulated[7] that cine substitution in **1** occurs via enolization to **2** followed by loss of chloride ion to produce an oxido-stabilized allyl cation **3**.[8] The latter is trapped by a nucleophile preferentially at the α′-position to afford the cine substitution product **4**. In monocyclic halocyclobutanones, electronic as well as steric influences of the second α-substituent were given as the governing factors in the substitution preference (namely α or α′),[9] but in our bicyclic systems **3** (R = Ph) the formation of a more stable enol (a styrene *vs* bridgehead double bond) probably determines the site of the nucleophilic attack. We decided to study the chemistry of the analog **5**, where the presence of an oxygen function may change the course of reaction of enolate **6** and lead instead of or in addition to **9** to formation of cyclobutenones (**7** or **8**), useful intermediates for generation of vinyl ketenes.



Reaction of 5 with O-, S-, C and N-Nucleophiles

The reaction of α-chloro ketone **5** at room temperature with several O-, S-, C-, and N-nucleophiles led to a variety of substitution products, some of rather unexpected structure. The primary products were usually those of cine substitution, i.e., **9** or the derived isomeric cyclobutenones **8**.[10] Thus, exposure of **5** to methanol in the

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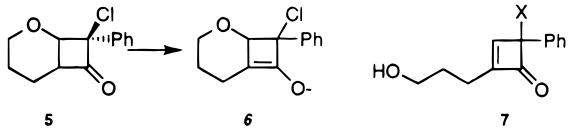
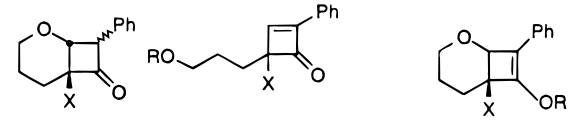
Table 1. Products in the Reaction of 5 with Nucleophile at 20 °C

nucleophile	conditions	products, yield
MeO^-	MeOH, H_2O 9:1, TEA, 15 min	**8a**, quantitative
PhS^-	1.1 equiv PhSH :TEA, 3h, acetone	**9b** *(cis trans)*, 90%
$^-CH(CO_2Et)_2$	diethyl malonate 1.1 equiv t-BuOK ,crown ether, THF, 30 min	**9c**, 70%
	dimedone 1.1 equiv t-BuOK ,crown ether, THF, 20 min	**11+12**, 60%
N_3^-	2 equiv NaN_3. acetone, $LiClO_4$, 30 min	**19a** + isomers
$^-CH_2NO_2$	tBuOK, CH_3NO_2, THF , 0.6 equiv of crown ether,15 min.	**15a,16**, 40%, 10%
$O_2\overset{-}{N}CH(CH_3)_2$	tBuOK ,($CH_3)_2CHNO_2$, THF , 0.6 equiv of crown ether, 15 min.	**15b**, 60%

presence of TEA afforded solely cyclobutenone **8a**, while PhSH and TEA led to **9b** as a mixture of *cis*−*trans* isomers (Table 1). Acetylation of **8a** furnished **8e** as well as cyclized enol acetate **10a.** That an equilibrium between the fused cyclobutanone **9** and the ring-opened cyclobutenone **8** can exist was demonstrated by (phenylthio)cyclobutanone (**9b**), which at 20 °C in acetonitrile−water solution, in the presence of *p*-toluenesulfonic acid or TEA was shown by NMR to exist as a mixture of **9b** and **8b** in a ratio of 11:9. Attempts to trap the cyclobutenone alcohol **8b** from this equilibrium by reaction with Ac_2O or $tBuSiMe_2Cl$ led to **10b** or **10c**, the enol derivatives, respectively, of **9b**. The cyclobutenone **8b** exhibited a singlet at 8.0 ppm for the vinylic hydrogen and a characteristic triplet at 3.65 for the CH_2OH of the side chain; by contrast, the CH_2O of **9b** appeared near 4.0 ppm as a multiplet. In the ^{13}C NMR the β-vinylic carbon of the unsaturated ketone **8b** appeared at 165.5 ppm.



5 **6** **7**



9 **8** **10**

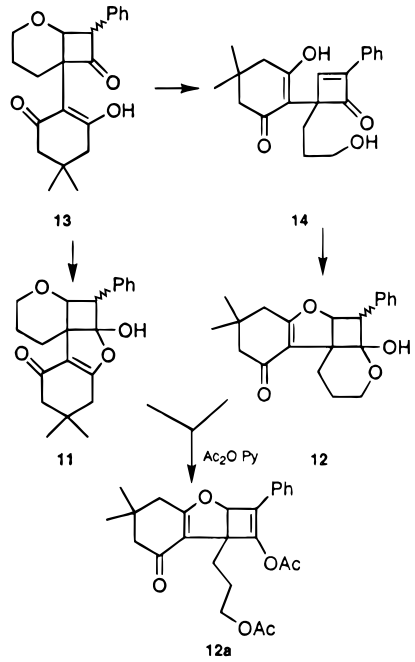
a; X=OMe
b; X=SPh
c; X=$CH(CO_2Et)_2$
d; X=N_3
e; X=CH_2COMe

a; X=OMe; R=H
b; X=SPh; R=H
c; X=$CH(CO_2Et)_2$; R=H
d; X=N_3; R=H
e: X=OMe; R=Ac

a; R=Ac; X=OMe
b; R=Ac; X=SPh
c; R=TBDMS; X=SPh

An initial attempt at cine substitution of **5** with a carbon nucleophile (i.e., dimethyl malonate in the presence of TEA) was unsuccessful. However, reaction of chloro ketone **5** with preformed diethyl potassium malonate in THF afforded the C-alkylation product **9c**. The potassium enolate of dimedone also reacted with **5** to generate in 60% yield an equilibrium mixture of the unusual hemiketals **11** and **12** (Table 1). This mixture on reaction with Ac_2O−Pyr was converted to **12a**, the diacetate derived from **12**. Both **11** and **12** are the result of cine substitution at the oxidoallyl cation (analog of **3**) leading to C- rather than O-alkylation of the dimedone enolate and resulting in formation of a C−C bond between two quaternary centers (see **13**). A similar phenomenon of hindered C−C bond formation had been observed in the isolation of dimers from reaction of **1** or **5** with hydroxide ion (water−TEA) and can be interpreted as involving electron transfer between the enolate and the oxidoallyl cation followed by C−C bond formation.[7,11] Structures **11** and **12** were assigned with the aid of 2D-NMR experiments on the equilibrium mixture. In the rearranged product **12** the hemiketal carbon appeared at 96.2 ppm and the α,β-unsaturated carbonyl system absorbed at 197.1, 118.6, and 178.3 ppm in the ^{13}C NMR. The formation of **12** can be explained by ring opening of an initial adduct **13** to a cyclobutenone **14** to which the enol of the dimedone unit adds by an intramolecular Michael addition, followed by hemiketalization.

Reaction of **5** with the enolate of acetone (from Bu_4NOH) proceeded analogously to the reaction of malonate (as indicated by NMR); however, the product **9e** was unstable and was not further characterized.



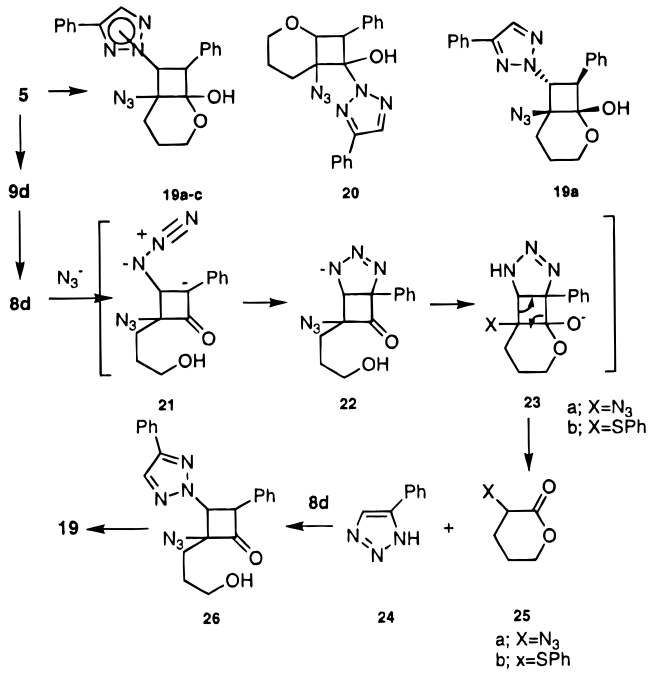
13 **14** **11** **12** **12a**

Nitromethane in the presence of tBuOK and 18-crown-6-ether reacted with **5** mainly via O-alkylation to produce the unusual γ-lactone formaldoxime ether **15a**, in 40% yield, as well as a second product **16** (10%). 2-Nitropropane also reacted via O-alkylation to afford the acetone oxime-derived γ-lactone **15b** (Table 1). The structures of ketal lactones **15a** and **15b** were apparent from ^1H and ^{13}C NMR which exhibited the lactone carbonyl at 169.1 and 169.4 ppm, the β carbon at 144.2 and 145.4 ppm, and the quaternary (ketal) carbon at 108.8 and 109.6 ppm for **15a** and **15b**, respectively. In ^1H NMR the vinylic proton appeared at 7.32 and 7.34 ppm, respectively. The formation of **15** can be explained by initial generation of the nitronate **17** followed by hemiketal formation **18**, ring opening with rearrangement to the oxime ether, and finally base-catalyzed opening of the pyran ring with elimination of the alcohol chain to yield **15**.

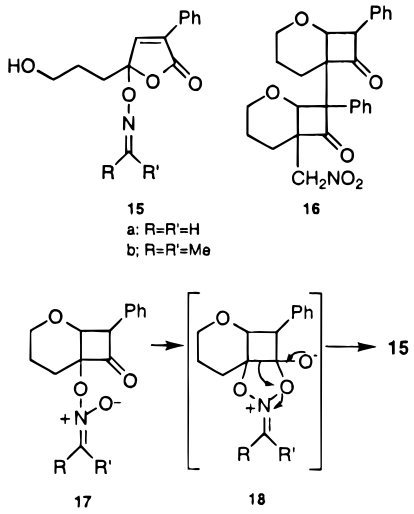
Dimer **16** exhibited two carbonyl carbons at 208.2 and 205.7 ppm. The nitro methylene appeared as an AB quartet at 5.18 ppm and at 76.7 ppm in the ^{13}C NMR. One of the hydrogens at the 4′-carbon absorbed at very high field 0.01ppm (q, J = 14, 4 Hz), which is very characteristic of such dimeric compounds.[11] Dimer **16**

(11) Hassner, A.; Naidorf-Meir, S.; Gottlieb, H. E.; Goldberg, I. *J. Org. Chem.* **1992**, *57*, 2442.

Scheme 1

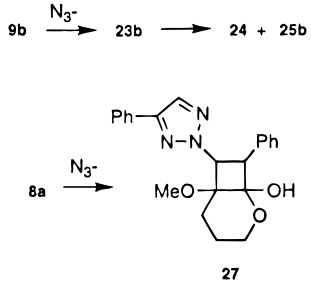


is the result of cine substitution by nitromethide anion on the primarily formed oxidoallyl cation, with C−C bond formation followed by an attack of the derived enolate similar to the dimer formation observed with OH^-.[11]



An unexpected transformation was observed when **5** was treated with an excess of NaN_3 in acetone at room temperature.[10] The major product formed in 40% yield (see **19a**, Scheme 1) together with two minor isomers analyzed for **5** (−Cl + N_6 + a styrene unit). IR indicated the presence of an azide function and absence of the ketone carbonyl. NMR showed the presence of two phenyl groups and what could be a triazole unit. On the basis of the hetero COSY experiments two structures **19** and **20** fit all the data, and **19a** proved to be correct for the major isomer, with the stereochemistry ultimately confirmed by the X-ray diffraction data.[10] The ^{1}H NMR and ^{13}C NMR spectra of **19b** and **19c** suggest them to be isomers of **19a**. Examination of the NMR absorptions for the triazole unit in the three isomers reveals a great similarity in the chemical shifts of **19a** and **19b** which were different from those of **19c**. Spectral comparison with those of known 4-phenyltriazole derivatives[12] led to the tentative conclusion that isomers **19a** and **19b** are epimers with the triazole unit connected via the central nitrogen, while isomer **19c** is a 1-substituted triazole. The stereochemistry of **19b** and **19c** remains unassigned. To explain the isolation of **19,** it was necessary to postulate formation of 4-phenyl-1,2,3-triazole (**24**) during reaction. The following mechanism appears plausible (Scheme 1). The first steps follow the general pattern shown above, namely, formation of **9d** by cine substitution of **5** with azide ion, followed by ring opening to cyclobutenone **8d**. Addition of NaN_3 to this conjugated ketone produced the β-azido ketone enolate **21**, which underwent cycloaddition to afford triazoline **22**. The latter, after proton exchange, exists in equilibrium with the hemiketal **23**. The next step appears to be an oxy-promoted electrocyclic opening of the cyclobutane ring taking place at room temperature. The driving force for this interesting ring opening probably comes from formation of the aromatic triazole ring **24** as well as of the enol form of lactone **25**. Next, it is postulated that phenyltriazole **24** added, in a Michael addition, to the conjugated ketone of **8d**, followed by hemiketalization of **26** to **19**. As already shown above, hemiketal formation appears to be favored in these fused cyclobutanones.

To obtain further evidence for this unusual pathway, and since intermediates **8d** and **9d** could not be isolated, the analogous thioether **9b** was subjected to NaN_3. Unlike in the formation of **19**, where neither products **24** nor **25a** could be found, the reaction of **9b** with NaN_3 led to isolation of the phenylthio lactone **25b** and of 4-phenyl-1,2,3-triazole (**24**), products of the decomposition of **23b**. Apparently, here **8b** was consumed before Michael addition of phenyltriazole **24** to yield an analog of **26** could take place. We also showed that the methoxycyclobutenone **8a** underwent reaction with azide ions to produce **27** an analog of **19a** (via the pathway analogous to Scheme 1). On the other hand, **8e**, the acetate ester of **8a**, remained unchanged under these conditions, consistant with the requirements of a free OH group for steps **22** → **23** → **24**.



Preferential addition of phenyltriazole **24** to the unsaturated ketone **8a** or **8d** via the central nitrogen rather than via N-1 has analogy in the formation of a hemiaminal via N-2 in the reaction of 4-vinyltriazole and acetone.[12]

Transformations via Vinylketenes

When cyclobutanone **9b** was refluxed in dry MeOH for 4 h a mixture of unsaturated esters **29** and **30** as well as the 8-membered ring lactone **31** were obtained in a ratio of 1:3:1.2. When the solvent was changed from MeOH

(12) Toppet, S.; Woutes, G.; Smeto, G. *Org. Magn. Reson.* **1978**, *11*, 578.

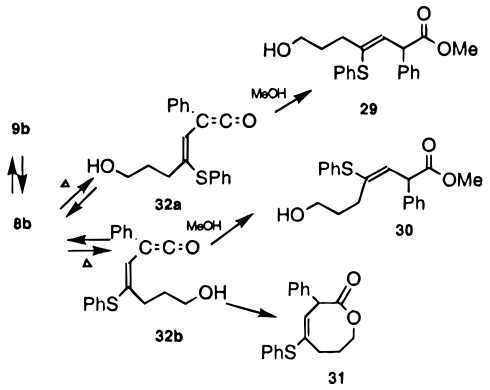
Table 2. Products in the Thermolysis[a] of 9b or 8e (via Vinylketenes)

condns	products, yield (%)
9b in MeOH reflux, 4 h	**29** + **30** + **31** (1:3:1.2), 90
9b in PhH reflux, 18 h	**31**, 70
8e + dihydrofuran in PhH reflux, 2 h	**33**, 65
8e 1,3-cyclohexadiene in PhH reflux, 14 h	**34**, 55
8e + **35** in PhH reflux, 4 h	**36**, 46 → **38**
8e in $CHCl_3$ reflux, 14 h	**39**, 70
8e in PhH + O_2 photolysis 20 °C, 24 h	**39**, 60

[a] Except for photolysis of **8e**.

to benzene, **31** was isolated as the only product in 70% yield (Table 2).

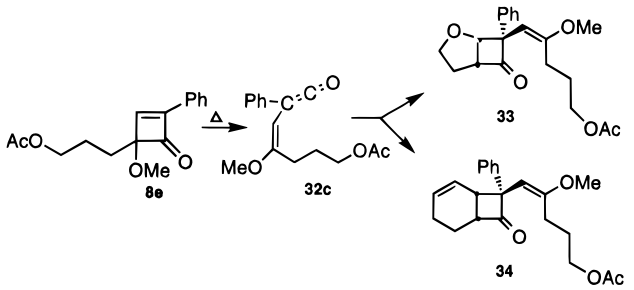
Esters **29** and **30** were inseparable by chromatography, and their assignment as the *Z* and *E* isomers of methyl 2-phenyl-4-(phenylthio)-7-hydroxy-3-heptenoate is based on elemental analysis as well as ^{1}H NMR of the mixture which showed two vinylic protons at 6.37 and 6.22 and two benzylic doublets at 5.13 and 4.70 ppm. The ester carbonyl was indicated by IR (1730 cm^{-1}) and ^{13}C NMR (172.5 and 172.9 ppm). The structure of lactone **31** was suggested by HRMS as well as by a carbonyl signal at 174.8 ppm and the vinylic doublet at 5.88 ppm.



These results suggest that in this system *β*-elimination (**9** → **8**) as well as electrocyclic ring opening (**8** → **32**) had occurred under mild conditions (neutral, 65 °C). Such a thermochemical ring opening of the cyclobutene should take place in an equilibrating conrotatory mode,[13] and since the two substituents in the 4-position of **8** are different, two modes of conrotatory ring opening can take place forming two different vinylketenes, **32a** and **32b**. Reaction of MeOH with **32a** results in the minor *Z* isomer **29**, while **32b** leads to the major *E* isomer **30**. Alternatively, ketene **32b** can react intramolecularly with the side chain hydroxy group to produce the 8-membered ring lactone **31**. In the absence of an external ketenophile, lactone **31** is the only product. The preferred mode of ring opening of cyclobutenone **8b** is in agreement with computational studies[13] on cyclobutene ring opening which concluded that electron-donating groups on C_3 and C_4 (OMe and SPh in our case) preferentially rotate outward in order to minimize repulsive four-electron interactions between the donor nonbonding electron pair on the substituent with the C_3-C_4 σ orbital and to maximize the stabilizing two-electron interaction between the same donor and the C_3-C_4 σ^* orbital.

In order to further verify the existence of vinyl ketene **32**, we decided to trap it by cycloaddition with olefins or dienes. For this purpose we blocked the alcohol function of the side chain as the acetate **8e** to prevent it from competing with an external ketenophile. Reaction of **8e** with dihydrofuran in refluxing benzene for 2 h gave the cycloadduct **33** in 65% yield; see Table 2 (a byproduct in 10% yield was also obtained). Cyclobutanone acetate **33** showed two carbonyl absorptions at 209.0 and 170.0 ppm for C-6 and the ester carbonyl, respectively. In the ^{1}H NMR the H-1 methine α to the oxygen appeared as a doublet (J = 5.5 Hz) at 4.47 ppm. The CH_2O hydrogens of the side chain appeared as a dt at 3.62 and 3.78 ppm. We know that the methoxy group is cis to the olefinic hydrogen since there is a 21% enhancement of the latter on irradiation of the methoxy frequency. The same NOE experiment provided unambiguous proof for the stereochemistry of the cyclobutanone ring substituents. Important mutual interactions were observed between the olefinic hydrogen and H-1 (12%, 14%) and between H-1 and H-5 (7% and 4%), showing that all three (H-1, H-5, and the unsaturated side chain) are located on the exo face of the bicyclic system. The minor product is assumed to be the C-7 exo phenyl isomer indicated by an NOE of (5% and 4%) between the aromatic hydrogens and H-1.

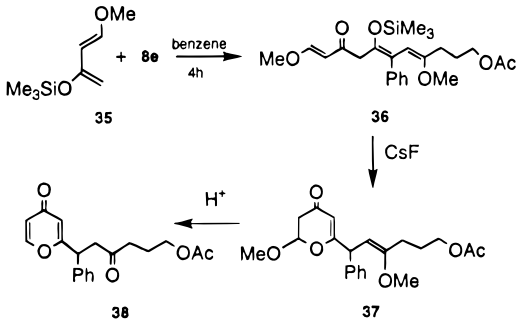
Heating **8e** with 1,3-cyclohexadiene in refluxing benzene overnight provided the unsaturated cyclobutanone **34** as a single isomer in 55% yield. Structure assignment is based on elemental analysis, as well as on NMR data. ^{13}C NMR showed two carbonyl absorptions at 208.5 (C-7) and 170.9 (ester) and the enol ether double bond at 102.5 and 162.6 ppm. In a 2D hetero COSY experiment, three-bond correlations were observed between the enol ether proton and the allylic bridgehead carbon, as well as with the side chain methylene carbons. Cyclobutanones **33** and **34** are the result of a (2 + 2)-cycloaddition of vinylketene **32c**, generated from **8e**, with dihydrofuran and cyclohexadiene, respectively.



Trapping of vinyl ketene **32** also was possible with Danishefsky diene **35.** Thus, reaction of acetate **8e** with **35** in dry benzene for 4 h produced the open chain siloxy product **36** in 46% yield (Table 2); a *trans* α,*β*-unsaturated carbonyl system was indicated by the two doublets (J = 12.5 Hz) at 7.67 and 5.76 ppm and by ^{13}C peaks at 195.1 and 163.5 ppm. The second enol ether proton appeared at 5.23 ppm. In the ^{13}C NMR the enol ether signals were at 160.2 and 98.4 ppm and the silyl enol ether signals at 145.1 and 119.7 ppm.

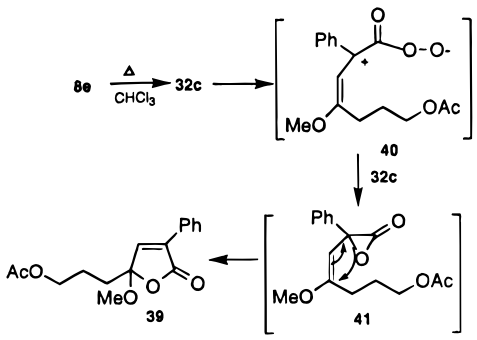
Formation of **36** can be explained by a stepwise addition of the siloxy diene to the vinyl ketene **32** generated *in situ*. Formation of a dipolar intermediate is followed by silyl transfer to the ketene oxygen. Hydrolysis of the siloxy enone **36** with fluoride ions afforded an unstable 1,3-diketone which underwent cyclization to a dihydropyranone **37** followed by conversion to 4-pyranone **38** only after addition of a catalytic amount of *p*-toluenesulfonic acid. Pyranone **38** showed characteristic absorption in the ^{13}C NMR at 178.4, 117.1, and 156.3

(13) Rondan, N. E.; Hauk, K. N. *J. Am. Chem. Soc.* **1985**, *107*, 2099.



ppm and the side chain carbonyl at 206.9 ppm. In the ^{1}H NMR the pyranone hydrogens appeared at 7.96, 6.21, and 6.13 ppm.

An unexpected product was obtained when **8e** was refluxed for 4 h in a dilute solution of $CDCl_3$ in the absence of a trapping agent (Table 2). The product, obtained in 70% yield, analyzed for **8e** and an additional oxygen. The ^{1}H NMR spectrum showed a vinylic singlet at 7.21 and the CH_2OAc side chain triplet at 4.07 but in the ^{13}C NMR the carbonyl appeared at 160.7 ppm, which suggested a carboxylic acid derivative rather than an α,β-unsaturated ketone. COSY experiments showed three-bond correlations between the vinylic hydrogen and the carbonyl as well as the aromatic ipso carbon and a two-bond correlation to the quaternary carbon. On the basis of the spectral data the structure was assigned as lactone **39**.



The transformation of **8e** to lactone **39** is apparently an oxidation process. Since on heating or irradiation cyclobutenone **8e** is expected to undergo electrocyclic ring opening, one can assume that the species undergoing the oxidation is the vinyl ketene **32c**. This oxidation has analogy in the work of Turro[14] and Bartlett,[15] who found that arylketenes underwent autoxidation at room temperature, and the interesting feature of this reaction is that it appears to be initiated spontaneously. A plausible mechanism for the formation of **39** is an electrophilic attack by oxygen on the vinylketene **32c** to form first a dioxetanone, which opens to a zwitterionic intermediate **40**.[16] Epoxidation of another molecule of the vinyl ketene **32c** by **40** can leads to α-lactone **41**, which rearranges to γ-lactone **39** (vinyl epoxide rearrangement). The oxidation of **8e** to **39** apparently required the thermal generation of vinylketene **32c**. In order to obtain further evidence for this oxidation process, it was desirable to examine the electrocyclic opening of **8e** in the presence of oxygen *at room temperature*; indeed photolysis of 8e at 20 °C in the presence of oxygen led to lactone **39** in 60% yield.

Conclusions

In conclusion, the introduction of an ether oxygen into the chlorobicyclooctanone **1** (see **5**) has important consequences for the reaction of **5** with O-, N-, S-, and C-nucleophiles. Thus, the initial cine substitution products **9** can equilibrate to cyclobutenones **8**, and from there can undergo unusual transformations. For instance, cine substitution of **5** by azide ions is followed by several conversions including an oxy-promoted electrocyclic cyclobutanol opening. Support for the latter process comes among others from isolation of intermediates **24** and **25** as well as from reaction of **8a** with NaN_3 which led to **27**. Reaction of **5** with enolates leads to C−C bond formation between quaternary carbons (see **9c**, **9e**, **11**, **12**) except with nitronates which react via O to produce rearranged oxime ether lactones **15**. Thermolysis or photolysis of cyclobutenone **8a** or **8e** leads to vinyl ketenes which can be trapped by MeOH, alkenes, dienes, or oxygen.

Experimental Section

General. For general experimental techniques and analytical measurements see ref 17.

4-Methoxy-4-(3-hydroxypropyl)-2-phenyl-2-cyclobutenone (8a). To a solution of 0.1 g (0.43 mmol) of **5** in 10 mL of 9:1 MeOH:H_2O was added 70 μL (1.1 equiv) of TEA. The mixture was stirred for 15 min, and solvent was removed under reduced pressure. The residue was dissolved in CH_2Cl_2 and washed successively with 5% aqueous HCl, 5% aqueous $NaHCO_3$, and saturated NaCl and dried ($MgSO_4$). Removal of solvent afforded **8a** in quantitative yield: ^{1}H NMR δ 8.47 (s, 1H), 7.65 (m, 2H), 7.35 (m, 3H), 3.60 (t, J = 7 Hz, 2H), 3.27 (s, 3H), 2.0 (m, 2H), 1.73 (m, 2H); ^{13}C NMR δ 195.1 (s), 160.7 (d), 130.5, 128,8, 127.6, 99.5 (s), 62.7 (t), 53.1 (q), 30.9 (t), 28.0 (t); IR 3400, 2960, 1750 cm^{-1}; MS CI *m/e* 232 (MH^+), 201 (MH^+ − MeOH).

Acetylation of 8a. A solution of 0.2 g (0.86 mmol) of **8a** in 1 mL of acetic anhydride and 0.5 mL of pyridine was stirred overnight, and the solvent was removed under reduced pressure. The residue was dissolved in CH_2Cl_2 and washed successively with 5% aqueous HCl, 5% aqueous $NaHCO_3$, and saturated NaCl and dried ($MgSO_4$). Removal of solvent left a mixture of **8e** and **10a** which was separated by chromatography (eluent 1:4 EtOAc:hexane) to produce 115 mg of **8e** and 54 mg of **10a**.

4-Methoxy-4-(3′-acetoxypropyl)-2-phenyl-2-cyclobutenone (8e). Cyclobutenone **8e** was obtained as an oil in 60% yield: ^{1}H NMR δ 8.54 (s, 1H), 7.78 (m, 2H), 7.45 (m, 3H), 4.09 (t, J = 7 Hz, 2H), 3.34 (s, 3H), 2.03 (s, 3H), 1.9 (m, 4H); ^{13}C NMR δ 195.1 (s), 171.1 (s), 160.7 (d), 133.6, 130.6, 128.9, 128.6 (s), 127.7, 99.3 (s), 64.3 (t), 53.1 (q), 30.8 (t), 24.0 (t), 20.3 (q); IR 1751, 1730, 1280 cm^{-1}; MS CI *m/e* 274 (MH^+), 243 (MH^+ − MeO,), 232 (MH^+ − CH_3CO); HRMS calcd for $C_{16}H_{18}O_4$ 274.1205, found 274.1233.

7-Acetoxy-6-methoxy-8-phenyl-2-oxa-*cis*-bicyclo[4.2.0]-7-octene (10a). The enolacetate **10a** was obtained as an oil in 23% in yield; ^{1}H NMR δ 7.58 (m, 2H), 7.37 (m 3H), 4.72 (s, 1H), 3.71 (m, 2H), 3.32 (s, 3H), 2.4−1.4 (m, 4H); ^{13}C NMR δ 166.1 (s), 141.8 (s), 131.2, 128.6, 128.6, 128.4, 127.4, 126.0 (s),

(14) Turro, N. J.; Chaw, M. F.; Ito, Y. *J. Am. Chem. Soc.* **1978**, *100*, 5580.

(15) (a) Bartlett, P. D.; McCluney, R. E. *J. Org. Chem.* **1983**, *48*, 4165. (b) Schmid, G. H.; Garratt, D. *J. Org. Chem.* **1983**, *48*, 4109.

(16) Although the autoxidation of ketenes has been well documented,[14, 15] one of the reviewers has suggested an alternate pathway, namely, a Baeyer−Villiger oxidation of **8e** to **39** in the presence of peroxides. While such a mechanism might be plausible in ether the use of $CDCl_3$ or benzene as solvents makes the presence of peroxides less likely.

(17) Ghera, E.; Yechezkel, T.; Hassner, A. *J. Org. Chem.* **1990**, *55*, 5977.

(18) Woerner, F. P.; Reimlinger, H. *Chem. Ber.* **1970**, *103*, 1908.

86.1 (s), 72.6 (d), 60.1 (t), 51.8 (q), 27.6 (t), 20.8 (q), 19.9 (t); IR (neat) 1770, 1660 cm^{-1}; MS CI *m/e* 274 (MH^+), 243 (MH^+ − MeOH); HRMS calcd for $C_{16}H_{18}O_4$ 274.1205, found 274.1209.

6-(Phenylthio)-8-phenyl-2-oxa-*cis*-bicyclo[4.2.0]octan-7-one (9b). To a solution of 0.1 g (0.43mmol) of **5** in 10 mL of acetone was added 1.1 equiv of PhSH and 1.1 equiv of TEA. The mixture was stirred for 3 h, and the acetone was removed in vacuum. The residue was dissolved in CH_2Cl_2, washed successively with 5% aqueous HCl, 5% aqueous $NaHCO_3$, and brine, and dried over $MgSO_4$. Removal of the solvent left an oil **9b** (120 mg 90%) as a mixture of cis and trans isomers in a ratio of 2:1. Purification by chromatography was not possible since partial ring opening to **8b** took place. Major isomer: ^{1}H NMR δ 7.30 (m, 10H), 4.66 (d, J = 7 Hz, 1H), 4.31 (d, J = 7 Hz, 1H), 3.95 (ddd, J = 12, 8, 5 Hz, 1H), 3.85 (dt, J = 11, 2 Hz, 1H), 2.3−1.5 (m, 4H); ^{13}C NMR δ 204.5 (s), 136.3, 135.9, 135.2 134.5, 132.6, 132.0, 129.5, 129.4, 129.3, 129.2, 129.1, 129.1, 128.6, 128.1, 127.4, 127.2, 127.1, 73.6 (d), 64.4 (t), 64.1 (d), 63.9 (s), 24.5 (t), 19.5 (t). Minor isomer: ^{1}H NMR δ 7.30 (m, 10H), 5.23 (d, J = 6.5 Hz, 1H), 4.39 (d, J = 6 Hz, 1H), 3.83 (m, 1H), 3.38 (ddd, J = 13, 10, 2 Hz, 1H), 2.3−1.5 (m, 4H); ^{13}C NMR δ 203.8 (s) 72.1 (d), 66.5 (d), 66.5 (s), 62.1 (t), 26.5 (t), 22.2 (t); IR (neat) 1770 cm^{-1}. **9b** mixture (*cis trans*): MS CI *m/e* 311 (MH^+), 283 (M − CO), 201 (M − PhSH); HRMS calcd for $C_{19}H_{18}O_2S$ 310.1027, found 310.1094.

7-Acetoxy-8-phenyl-6-(phenylthio)-2-oxa-*cis*-bicyclo-[4.2.0]-7-octene (10b). Treatment of 0.1 g (0.32 mmol) of **9b** with acetic anhydride pyridine produced an oil which was purified by chromatography (1:4 EtOAc:hexane) to afford 90 mg of **10b** as an oil in 76% yield: ^{1}H NMR δ 7.50 (m, 2H), 7.30 (m, 3H), 4.36 (s, 1H), 3.75 (m, 2H), 2.43 (ddd, J = 13.5, 6, 5.5 Hz, 1H), 2.26 (s, 3H), 2.23 (ddd, J = 13.5, 9.5, 6 Hz, 1H), 1.8 (m, 2H); ^{13}C NMR δ 166.4 (s), 143.3 (s), 135.8, 131.2, 131.1, 128.7, 128.5, 128.5, 128.1, 128.0, 125.4 (s), 74.4 (d), 61.3 (s), 60.8 (t), 29.1 (t), 20.7 (q), 20.1 (t); IR 1770, 1680 cm^{-1}; MS CI *m/e* 352 (MH^+), 243 (M − PhS), 310 (M − CH_3CO), 201.

6-(Phenylthio)-7-[(*tert*-butyldimethylsilyl)oxy]-8-phenyl-2-oxabicyclo[4.2.0]-7-octene (10c). To a solution of 260 mg (0.85mmol) of **9b** in 5 mL of dry THF under Ar were added 130 mg (1.1 equiv) of *tert*-butyldimethylsilyl chloride and 240 μL of TEA (2 equiv). The solution was stirred overnight and filtered. The residue after evaporation was purified by chromatography (eluent 1:20 EtOAc:petroleum ether) to afford 250 mg of **10c** in 70% yield: ^{1}H NMR δ 7.50 (m, 2H), 7.42(m, 2H), 7.25 (m, 5H), 7.15 (m, 1H), 4.30 (s, 1H), 3.74 (m, 2H), 2.08 (m, 2H), 1.75 (m, 2H), 1.16 (s, 9H), 0.26 (s, 3H), 0.32 (s, 3H); ^{13}CNMR δ 148.0 (s)134.9 (s), 132.7, 131.6, 128.5, 128.2, 127.9, 126.7, 126.0, 118.2 (s), 74.3 (d), 60.1 (t), 60.0 (s), 27.7 (t), 25.3 (q), 20.3 (t), 18.3 (s), −3.0 (q), −3.3(q); MS CI *m/e* 424 (M − 1), 315 (M − PhS).

6-[Bis(ethoxycarbonyl)methyl]-8-phenyl-2-oxa-*cis*-bicyclo[4.2.0]octan-7-one (9c). Reaction of 0.2 g (0.85 mmol) of **5** with 1.1 equiv of the potassium salt of diethyl malonate and 0.1 equiv of 18-crown-6 ether in THF for 0.5 h gave an oil which was purified by chromatography (eluent 1:4 EtOAc: hexane) and recrystallized from EtOAc−hexane to give 210 mg of **9c** as white crystals in 70% yield: mp 60−61 °C; ^{1}H NMR δ 7.35 (m, 5H), 5.20 (d, J = 7.5 Hz, 1H), 5.03 (d, J = 7.5 Hz,1H), 4.24 (q, J = 7 Hz, 2H), 4.13 (dq, J = 7, 2 Hz, 2H), 3.88 (m, 2H), 3.71 (s, 1H), 2.11 (m, 2H), 1.56 (m, 2H), 1.28 (t, J = 7 Hz, 3H), 1.17 (t, J = 7 Hz, 3H); ^{13}C NMR δ 204.9 (s), 167.1, 167.0 (s), 135.0 (s), 128.5, 127.2, 127.0, 71.1 (d), 61.7 (d), 61.7, 61.8 (t), 60.8 (t), 56.2 (s), 56.0 (d), 25.1 (t), 21.1 (t), 14.0 (q), 14.0 (q); IR (KBr) 1780, 1730 cm^{-1}; MS CI *m/e* 361 (MH^+), 343 (MH^+ − H_2O), 315 (MH^+ − EtOH), 269 (MH^+ − 2EtOH); HRMS calcd for (M − EtOH) $C_{18}H_{18}O_5$ 315.1228, found 315.1324. Anal. Calcd for $C_{20}H_{24}O_6$: C, 66.65; H, 6.71. Found: C, 66.41; H, 6.64.

Reaction of 5 with Dimedone. Treatment of 0.1 g (0.43 mmol) of **5** with 1.1 equiv of the potassium salt of dimedone in THF and 0.1 equiv of 18-crown-6 ether for 20 min gave a mixture of two products. Purification by chromatography (eluent 1:4 to 1:2 EtOAc:hexane) gave 85 mg of an oil (60% yield) that contained **11** and **12** in a ratio of 6:10 (by NMR).

2-Phenyl-4-(3-hydroxypropyl)-1-oxocyclobutano[3,4-*b*]-4-oxo-6,6-dimethyl-2,3,4,5,6,7-hexahydrobenzofuran Hemiketal (12) and 6-(5′,5′-dimethyl-1′-hydroxy-3′-oxo-1′-cyclohexen-2′-yl)-8-phenyl-2-oxa-*cis*-bicyclo[4.2.0]octan-7-one Hemiketal (11). The hemiketals **11** + **12** (mixture) were obtained as an oil: ^{1}H NMR δ 7.25 (m, 10H), 5.06 (OH), 5.04 (d, J = 5.5 Hz, 1H), 4.28 (d, J = 4 Hz, 1H), 4.01 (d, J = 4 Hz, 1H), 3.87 (dt, J = 11, 4 Hz, 1H), 3.75 (d, J = 5.5 Hz, 1H), 3.70 (m, 3H), 2.43, 2.31 (ABq, J = 18 Hz, 4H), 2.39, 2.30 (ABq, J = 16 Hz, 4H), 2.2-1.9 (m, 8H), 1.14, 1.11 (s, 3H), 1.00, 0.86 (s, 3H); ^{13}C NMR δ 197.1* (s), 194.2 (s), 178.3* (s), 175.3 (s), 135.7, 135.2 (s), 128.1, 128.0, 127.9, 127.8, 126.5, 126.2, 118.6* (s), 118.0 (s), 112.1 (s), 96.2 *(s), 83.7* (d), 74.6 (d), 63.5 (t), 60.5* (t), 60.5 (d), 59.7* (d), 54.9* (s), 51.4 (t), 49.23* (t), 38.1* (t), 37.3 (t), 34.7* (s), 33.4 (s), 28.6, 28.4* (q), 24.0 *(t), 22.2 (t), 21.5 (t), 20.1 (t); *these absorptions belong to compound **12**. IR (neat) 2249, 1780, 1705, 1605 cm^{-1}; MS CI *m/e* 341 (MH^+) 323 (MH^+ − H_2O).

2-Phenyl-4-(3-acetoxypropyl)-1-acetoxy-1-cyclobutено-[3,4-*b*]-4-oxo-6,6-dimethyl-2,3,4,5,6,7-hexahydrobenzofuran (12a). A solution of 0.2 g (0.86 mmol) of **11** and **12** in 1 mL of acetic anhydride and 0.5 mL of pyridine was stirred overnight, and the solvent was removed under reduced pressure. The residue was chromatographed (eluent: 1:3 EtOAc: hexane), affording 325 mg (90% yield): ^{1}H NMR δ 7.38 (m, 5H), 5.29 (s, 1H), 4.07 (t, J = 5 Hz), 2.27 (s, 3H), 2.26 (m, 3H), 2.21 (m, 2H), 2.03 (s, 3H), 1.93 (m, 3H), 1.65 (m, 2H),1.09 (s, 3H), 1.08 (s, 3H). ^{13}C NMR δ 194.6 (s), 178.5 (s), 171.0 (s), 166.5 (s), 130.3 (s), 128.6, 128.2, 126.8, 125.9 (s), 115.6 (s), 82.5 (d), 64.3 (t), 63.0 (s), 51.5 (t), 38.8 (t), 33.9 (s), 28.9 (q), 28.3 (q), 26.4 (t), 25.0 (t), 20.9 (q), 20.6 (q); MS CI *m/e* 425 (MH^+); HRMS calcd for $C_{25}H_{29}O_6$ MH^+ 425.1964, found 425.1974.

Reaction of 5 with Nitroalkanes. To a solution of 2 equiv of the nitroalkane in 5 mL of dry THF under Ar were added 2 equiv of tBuOK and 0.6 equiv of 18-crown-6 ether. The solution was stirred for 5 min, and 0.25 mL (1 mmol) of **5** was added. After 15 min the reaction was stopped by addition of 1 mL of 5% HCl. The solvent was evaporated, and methylene chloride was added to the residue which was washed with brine, dried, and evaporated. The products were purified by chomatography. In the reaction with CH_3NO_2 **15a** and **16** were obtained after chromatography (eluent 1:5 to 1:1 EtOAc: petroleum ether).

2-Phenyl-4-(3′-hydroxypropyl)-4-(*O*-formaldoximino)-2-buten-4-olide (15a). The title compound was obtained as an oil in 40% yield (110 mg); ^{1}H NMR 7.85 (m, 2H), 7.42 (m, 3H), 7.32 (s, 1H), 7.12 (d, J = 8 Hz, 1H), 6.56 (d, J = 8 Hz, 1H), 3.70 (t, J = 7 Hz,2H), 2.18 (dd, J = 10,1.5 Hz, 1H), 2.16 (d, J = 10 Hz, 1H), 1.77 (m, 2H); ^{13}C NMR δ 169.1 (s), 144.2 (d), 140.5 (t), 134.3 (s), 129.8, 128.8, 128.6, 127.5, 108.8 (s), 62.2 (t), 32.2 (t), 26.4 (t); MS CI *m/e* 245 (M + C_2H_5), 216 (MH^+); HRMS calcd for $C_{14}H_{15}O_4N$ 261.1001, found 261.1006. The compound loses formaldoxime upon heating in the mass spectrometer and shows a molecular peak of MH^+ 216 (unsaturated compound).

6-(Nitromethylene)-8-phenyl-8-(8′-phenyl-7′-oxo-2′-oxabicyclo[4.2.0]octan-6′-yl)-2-oxabicyclo[4.2.0]octan-7-one (16). Dimer **16** was obtained as an oil in 10% yield: ^{1}H NMR δ 7.40 (m, 10H), 5.18 (AB, J = 8 Hz, 2H), 4.86 (d, J = 12 Hz, 1H), 4.67(d, J = 12 Hz, 1H), 4.67 (d, J = 12 Hz, 1H), 4.58 (s, 1H), 3.60 (dm, J = 12 Hz, 1H), 3.74 (td, J = 12, 2 Hz, 1H), 3.42 (dtm, J = 11, 4 Hz, 1H), 2.92 (m, 1H), 2.56 (dm, J = 15 Hz, 1H), 2.08 (dtm, J = 15, 3.5 Hz, 1H), 1.95−1.65 (m, 3H), 1.05 (dm, J = 14 Hz, 1H), 0.85 (m, 2H), 0.01 (qt, (J = 14,4 Hz, 1H); ^{13}C NMR δ 208.2 (s), 205.7 (s), 134.0, 133.0, 129.0, 128.7, 128.2, 127.6, 126.9, 76.7(t), 75.1 (s), 72.2 (d), 70.2 (d), 62.3 (t), 60.3 (t), 60.0 (s), 59.6(d), 57.4 (s), 23.5 (t), 22.8 (t), 20.3 (t), 19.2(t); MS CI *m/e* 462 (MH^+), 445 (MH^+ − H_2O), 415 (M − NO_2).

2-Phenyl-4-(3′-hydroxypropyl)-4-(*O*-acetoximino)-2-buten-4-olide (15b). This butenolide was prepared from **5** and 2-nitropropane and was obtained as an oil in 60% yield (175 mg): ^{1}H NMR δ 7.80 (m, 2H), 7.40 (m, 3H), 7.34 (s, 1H), 3.69 (t, J = 7 Hz, 2H), 1.97 (m, 2H), 1.89 (s, 3H), 1.80 (s, 3H), 1.75 (m, 2H); ^{13}C NMR δ 169.4 (s), 158.5 (s), 145.4 (d), 133.6 (s), 129.5, 129.1, 128.5, 127.4, 109.6 (s), 62.2 (t), 32.5 (t), 26.6 (t), 21.8 (q), 16.0 (q); MS CI ($C_{16}H_{19}O_4N$) (NH_3) *m/e* 289 (M^+), 307

(MNH_4^+); HRMS calcd for $C_{13}H_{12}O_3N$ (M − C_3H_7NO) 216.0792, found 216.0786.

Reaction of 5 with NaN_3. Treatment of 0.2 g (0.85 mmol) of **5** with 110 mg (2 equiv) of NaN_3 and 0.1 g of $LiClO_4$ in 10 mL of acetone for 0.5 h gave in 70% overall yield a mixture of three products **19** in a ratio of 4:1:2.1 The products were separated by chromatography (eluent 1:4 to 1:1 EtOAc: hexane).

2-Phenyl-3-*trans*-(4″-phenyl-2″-triazolyl)-4-*cis*-azido-4-(3′-hydroxypropyl)cyclobutanone Hemiketal (19a). Recrystallization from EtOAc−hexane gave 70 mg of white crystals: mp 142 °C; ^{1}H NMR δ 7.90 (s, 1H), 7.80 (m, 2H), 7.38 (m, 8H), 5.48 (d, J = 10 Hz, 1H), 4.78 (d, J = 10 Hz, 1H), 4.05 (dt, J = 12, 6 Hz, 1H), 3.91 (dt, J = 12, 7 Hz, 1H), 3.02 (OH), 2.04 (dt, J = 14, 9 Hz, 1H), 1.71 (m, 1H), 1.62 (dt, J = 14, 3 Hz, 2H); ^{13}C NMR δ 148.4 (s), 133.6 (s), 131.7 (d), 129.9 (s), 128.9, 128.7, 128.2, 127.60, 126.0, 96.8 (s), 66.2 (s), 63.7 (d), 62.1 (t), 48.9 (d), 23.9 (t), 19.2 (t); IR (neat) 3351, 2110 cm^{-1}; MS CI *m/e* 389 (MH^+), 361 ($MH^+ - N_2$), 346 ($MH^+ - HN_3$), 146 (phenyltriazole). Anal. Calcd for $C_{21}H_{20}O_2N_6$: C, 64.93; H, 5.19; N, 21.64. Found: C, 64.6; H, 5.15; N, 21.16. X-ray diffraction crystal data:[10] $C_{21}H_{20}O_2N_6$ transparent, prismatic, 0.4 × 6.3 × 0.3 mm, triclinic, P_1 (NO, 2), a = 11.300(2) Å, b = 14.750(2) Å, c = 5.605(1) Å, è, a = 91.19(2)°, b = 99.25-(2)°, c = 81.54(2)°, from 25 reflections, T − 90 K, V = 914.5(3) A^3, Z = 2 Fw = 388.428, D_c = 1.41 g/mL, $\hat{E}$ = 0.892 cm^{-1}.

4-Azido-4-(3′-hydroxypropyl)-2-phenyl-3-(4″-phenyl-2″-triazolyl)cyclobutanone Hemiketal (19b). Recrystallized from EtOAc−hexane: mp 155 °C; ^{1}H NMR δ 7.95 (s, 1H), 7.80 (m, 2H), 7.35 (m, 8H), 5.36 (d, J = 10 Hz, 1H), 4.81 (d, J = 10 Hz, 1H), 3.77 (m, 2H), 3.40 (OH), 2.45 (m, 2H), 2.2−1.9 (m, 2H); ^{13}C NMR δ 148.7 (s), 134.0 (s), 131.8, (d), 130.1 (s), 128.8, 128.3, 128.0, 127.4, 94.9 (s), 69.4 (s), 61.1 (t), 59.8 (d), 54.4 (d), 25.3 (t), 22.1 (t); IR (neat) 2100 cm^{-1}; MS CI *m/e* 361 ($MH^+ - N_2$), 146 (phenyltriazole).

4-Azido-4-(3′-hydroxypropyl)-2-phenyl-3-(4″-phenyl-1″-triazolyl)cyclobutanone Hemiketal (19c). Recrystallized from EtOAc−hexane: mp 152 °C; ^{1}H NMR (acetone-d_6), δ 8.62 (s, 1H), 7.92 (m, 10H), 5.49 (d, J = 11 Hz, 1H), 4.63 (d, J = 11 Hz, 1H), 3.82 (td, J = 11, 1.5 Hz, 1H), 3.72 (dm, J = 11 Hz, 1H), 2.22 (m, 2H), 1.92 (m, 2H); ^{13}C NMR δ 147.4 (s), 135.0 (s), 129.2 129.0, 128.5, 128.3, 127.6, 1259, 121.1 (d), 96.6 (s), 68.6 (s), 61.0 (t), 56.0 (d), 55.3 (d), 25.1 (t), 22.7 (t); IR (neat) 2100 cm^{-1}; MS CI *m/e* 361 ($MH^+ - N_2$), 146 (phenytriazole).

Reaction of 8a with NaN_3. 4-Methoxy-2-phenyl-3-(4′-phenyl-2′-triazolyl)-4-(3′-hydroxypropyl)cyclobutanone Hemiketal (27). Treatment of 50 mg (0.13 mmol) of **8a** with 28 mg (2 equiv) of NaN_3 and 0.1 g of $LiClO_4$ in acetone for 3 h afforded after workup a mixture of products. Chromatography with 1:4 EtOAc:hexane afforded 15 mg of the major product **27** in 30% yield: mp 139−140 °C; ^{1}H NMR δ 7.89 (s, 1H), 7.79 (m, 2H), 7.35 (m, 8H), 5.27 (d, J = 10 Hz, 1H), 4.70 (d, J = 10 Hz, 1H), 4.02 (s, OH), 3.95 (m, 2H), 3.60 (s, 3H), 2.0−1.6 (m, 4H); ^{13}C NMR δ 148.0 (s), 134.1 (s), 131.3 (d), 128.9, 128.7, 128.4, 127.92, 127.1, 125.9, 94.7 (s), 79.7 (s), 65.9 (d), 60.9 (t), 52.0 (q), 48.3 (d), 19.1 (t), 18.5 (t); IR 3344, 1597, 1463; MS CI *m/e* 378 (MH^+), 346 (MH^+ − MeOH), 146 (phenyltriazole).

Reaction of 9b with NaN_3. 2-(Phenylthio)-5-pentanolide (25b). Treatment of 0.1 g (0.32 mmol) of **9b** with 65 mg (3 equiv) of NaN_3 and 0.1 g of $LiClO_4$ in acetone for 3 h afforded a mixture of two products: phenyltriazole (**24**) identical to authentic **24** prepared according to ref 18 (mp 141 °C (lit.[18] 143−145 °C)) and lactone **25b** in a 1:1 ratio. Chromatography of the mixture (eluent EtOAc:hexane 1:6) gave 30 mg of **25b** in 45% yield (oil): ^{1}H NMR δ 7.45 (m, 2H), 7.34 (m, 3H), 4.40 (m, 2H), 3.92 (t, J = 7 Hz, 1H), 2.4−1.8 (m, 4H); ^{13}C NMR δ 169.5 (s), 133.4, 132.8 (s), 129.2, 127.6, 68.9 (t), 46.7 (d), 26.7 (t), 21.2 (t); IR 1730 cm^{-1}; MS CI *m/e* 209 (MH^+), 236 ($MC_2H_5^+$), 181(MH^+ − CO).

Thermolysis of Cyclobutenone 9b. A solution of 0.2 g (0.6 mmol) of **9b** in 5 mL of dry MeOH was refluxed for 4 h. Removal of the solvent left an oil. Chromatography of the residue (eluent 1:4 to 1:2 EtOAc:hexane) afforded 70 mg of lactone **31** (35%) and 120 mg of a mixture of *Z*/*E* hydroxy esters **29**, **30** (55%).

2-Phenyl-4-(phenylthio)-3-hepten-7-olide (31): mp 122 °C (CH_2Cl_2:petroleum ether); ^{1}H NMR δ 7.30 (m, 5H), 5.88 (d, J = 6.5 Hz, 1H), 4.68 (d, J = 6.5 Hz, 1H), 4.51 (m, 2H), 2.48 (m, 2H), 1.93 (m, 2H); ^{13}C NMR δ 174.8 (s), 136.8, 136.6 (s), 123., 129.3, 128.7, 128.6, 127.8, 127.6 (d), 67.9 (t), 51.7 (d), 29.1 (t), 28.2 (t); IR (neat) 1730, 1610 cm^{-1}; MS CI *m/e* 311 (MH^+), 283 (MH^+ − CO), 201 (M − PhSH); HRMS calcd for $C_{19}H_{18}O_2S$ 310.10256, found 310.10263.

(*Z*)- and (*E*)-Methyl 7-hydroxy-2-phenyl-4-(phenylthio)-3-heptenoate (29 and 30). This mixture was obtained as an oil: ^{1}H NMR δ 7.30 (m, 10H)*, 6.37 (dt, J = 10, 0.5 Hz, 1H), 6.22 (d, J = 11 Hz, 1H), 5.13 (d, J = 10 Hz, 1H), 4.70 (d, J = 10 Hz, 1H), 3.68 (s, 3H)*, 3.54 (t, J = 7 Hz, 2H), 3.52 (t, J = 7 Hz, 2H), 2.33 (m, 2H)*, 1.7 (m, 2H)* absorbance of the two isomers; ^{13}C NMR δ 173.5 (s), 172.9 (s), 138.6, 138.0, 136.4, 133.8 (s), 132.6, 131.6, 130.4, 130.1, 129.1, 129.0, 128.9, 127.9, 127.8, 127.4, 127.3, 126.7, 61.7 (t), 61.3 (t), 52.4 (q), 52.3 (q), 51.8 (d), 50.9 (d), 33.4 (t), 31.1 (t), 30.9 (t), 27.4 (t); IR (neat) 1730 cm^{-1}; MS CI *m/e* 343 (MH^+, 10), 311 (MH^+ − MeOH, 5), 283 (MH^+ − CO_2Me, 100), 325 (MH^+ − H_2O, 23). Anal. Calcd for $C_{20}H_{22}O_3S$: C, 70.16; H, 6.48. Found: C, 69.87; H, 6.70.

7-*syn*-Phenyl-7-*anti*-[2′-methoxy-5′-(acetyloxy)-1′(*Z*)-pentenyl]-2-oxa-*cis*-bicyclo[3.2.0]heptan-6-one (33). Refluxing 0.2 g (0.73 mmol) of **8e** in 2 mL of dry benzene for 2 h in the presence of 160 mg (3 equiv) of 4,5-dihydrofuran for 2 h followed by removal of the solvent left a brown residue. Purification by chromatography (eluent 1:6 EtOAc:petroleum ether) afforded 143 mg of **33** as an oil in 65% yield: ^{1}H NMR (benzene-d_6) δ 7.50 (m 2H), 7.20 (m, 3H), 4.52 (s, 1H), 4.47 (dd, J = 5.5, 0.5 Hz, 1H), 3.86 (dt, J = 11, 6.5 Hz, 1H), 3.78 (dt, J = 11, 7 Hz, 1H), 3.62 (ddd, J = 9, 5.5, 12 Hz, 1H), 3.50 (ddd, J = 9, 8, 2.5 Hz, 1H), 3.38 (td, J = 9.5, 6 Hz, 1H), 3.15 (s, 3H), 2.33 (m, 2H), 1.91 (ddm, J = 12.5, 6 Hz, 1H), 1.66 (s, 3H), 1.60 (m, 1H), 1.40 (m, 2H); ^{13}C NMR δ 209.0 (s), 170.0 (s), 163.2 (s), 139.8 (s), 128.4, 127.8, 126.9, 98.8 (d), 83.2 (d), 71.5 (s), 69.7 (t), 62.2 (d), 54.3 (q), 28.7 (t), 28.6(t), 26.1 (t), 20.5 (q); MS CI *m/e* 345 (MH^+), 313 (M − MeOH), 285 (M − AcOH); HRMS calcd for $C_{20}H_{24}O_5$ 344.1628, found 344.1537.

8-*trans*-Phenyl-8-[2′-methoxy-5′-(acetyloxy)-1′(*E*)-pentenyl]-*cis*-bicyclo[4.2.0]oct-2-en-7-one (34). Refluxing 0.2 g (0.73 mmol) of **8e** in 10 mL of dry benzene, in the presence of 175 mg (3 equiv) of 1,3-cyclohexadiene overnight, gave after removal of the solvent a brown residue. Purification by chromatography, eluent EtOAc:hexane 1:6, afforded 143 mg of **34** as an oil in 55% yield: ^{1}H NMR δ 7.30 (m, 5H), 5.72 (dddd, J = 10.5, 5.5, 2.5, 1 Hz, 1H), 5.21 (dm, J = 10.5 Hz, 1H), 4.95 (s, 1H), 3.93 (m, 1H), 3.76, 3.69 (dt, J = 11, 6.5 Hz, 2H), 3.59 (s, 3H), 2.96 (ddt, J = 9.5, 4, 2 Hz, 1H), 2.12* (m, 1H), 2.02 (m, 1H), 1.96 (s, 3H), 1.95 (m, 1H), 2.01 (m, 2H), 1.54 (m, 1H), 1.51, 1.28 (ddq, J = 13.5, 9, 7 Hz, 2H); ^{13}C NMR δ 208.5 (s), 170.9 (s), 162.6 (s), 140.5 (s), 129.5 (d), 127.7, 127.5, 126.6 (d), 126.3, 102.5 (d), 69.7 (s), 64.1 (t), 54.6 (q), 53.8 (d), 40.4 (d), 25.3 (t), 21.3 (t), 20.8 (q), 18.6(t); IR (neat) 2930, 1763, 1736, 1641, 1239 cm^{-1}; MS CI *m/e* 355 (MH^+), 323 (MH^+ − MeOH). Anal. Calcd for $C_{22}H_{26}O_4$: C, 74.54; H, 7.39. Found: C, 74.23; H, 7.30. *The chemical shift was obtained from a hetero COSY NMR experiment.

11-Acetoxy-1,8-dimethoxy-6-phenyl-5-(trimethylsiloxy)-1,5,7(*E*,*Z*,*Z*)-undectrien-3-one (36). Ketone **36** was obtained from **8e** (0.22 g, 0.8 mmol) and 1.25 equiv of **35** by refluxing in 1 mL of dry benzene for 4 h (46%) and chromatography (eluent 1:4 to 1:2 EtOAc:hexane): ^{1}H NMR (acetone-d_6) δ 7.67 (d, J = 12.5 Hz, 1H), 7.40 (m, 2H), 7.27 (m, 3H), 5.76 (d, J = 12.5 Hz, 1H), 5.23 (s, 1H), 3.87 (t, J = 7.5 Hz, 2H), 3.46 (s, 2H), 3.75 (s, 3H), 3.60 (s, 3H), 2.09 (m, 2H), 1.93 (s, 3H), 1.67 (dt, J = 7.5,6.5 Hz, 2H); ^{13}C NMR δ 195.1 (s), 170.8 (s),163.5 (d), 160.2 (s), 145.1 (s), 130.7, 128.4, 126.7, 119.7 (s), 98.4 (d), 64.5 (t), 58.0(q), 54.9 (q), 48.5 (t), 28.5 (t), 26.6 (t), 20.7 (q), 0.7 (q).

6-Methoxy-2′-[6′-acetoxy-3′(*Z*)-methoxy-1′-phenyl-2′-hexen-1′-yl]-5,5-dihydro-4-pyranone (37). Hydrolysis of **36** with 1.2 equiv of CsF in CH_2Cl_2 followed by chromatography (eluent 1:3 EtOAc:hexane) afforded dihydropyranone **37** in 45% yield. The product is a mixture of diastereomers (two chiral centers): ^{1}H NMR δ 7.42 (m, 2H), 7.34 (m, 2H), 7.26 (m, 1H), 5.57, 5.48 (each d, J = 0.5 Hz, 1H), 5.46, 5.48 (dd, J = 3, 2 Hz,

dd, J = 4, 2.5 Hz, 1H), 5.06, 5.01 (each d, J = 10 Hz, 1H), 4.56, 4.61 (each d, J = 10 Hz, 1H), 4.09, 4.07 (each t, J = 7 Hz, 2H), 3.76, 3.68 (s, 3H), 3.33, 3.28 (s, 3H), 2.83, 2.90 (dd, J = 12, 4 Hz, 1H), 2.46 (m 3H), 2.08, 2.06 (s, 3H), 1.90 (m, 2H); ^{13}C NMR δ 190.6, 190.4 (s), 170.9 (s), 159.2, 159.0 (s), 142.8, 142.2 (s), 129.8, 129.3, 128.8, 128.7, 127.7, 105.2, 105.0 (d), 103.7, 103.5 (d), 97.2, 96.7 (d), 64.1(t), 56.7, 56.6 (q), 54.8 (q), 49.1, 49.0 (d), 42.4 (t), 27.6 (t), 27.3 (t), 20.8 (q); MS CI *m/e* 375 (MH^+), 341 (M − MeOH).

2-(6′-Acetoxy-1′phenyl-3′-oxohexyl)-4-pyranone (38). Stirring of 0.1 g of **37** in CH_2Cl_2 with a catalytic amount of *p*-TsOH for 2 h afforded after chromatography (eluent 1:3 to 2:1 EtOAc:hexane) **38** in 40% yield: ^{1}H NMR (acetone-d_6) δ 7.96 (d, J = 6 Hz, 1H), 7.35 (m, 5H), 6.21 (dt, J = 2, 0.5 Hz, 1H), 6.13 (dd, J = 6, 2 Hz, 1H), 4.40 (dd, J = 8, 6.5 Hz, 1H), 3.97(t, J = 7 Hz, 2H), 3.42 (dd, J = 17, 8 Hz, 1H), 3.18 (dd, J = 17, 6.5 Hz, 1H), 2.62, 2.58 (each dt, J = 18, 7 Hz, 2H), 1.96 (s, 3H), 1.82 (quintet, J = 7Hz, 2H); ^{13}C NMR δ 206.9 (s), 178.4 (s), 170.5 (s), 156.3 (d), 140.8 (s), 128.7, 128.6, 128.2, 117.1 (d), 114.8 (d), 63.5 (t), 45.6 (t), 45.3 (t), 39.5 (t), 23.5 (t), 20.7 (q); MS CI *m/e* 329 (MH^+), 270 (M − OAc); HRMS calcd for $C_{19}H_{20}O_5$ 328.1310, found 328.1309.

2-Phenyl-4-methoxy-4-[3-(acetyloxy)propyl]-2-buten-4-olide (39). a. Thermolysis of Cyclobutenone 8e. A solution of 0.2 g (0.73 mmol) of **8e** was refluxed in 5 mL of chloroform overnight, the solvent was removed in vacuum, and the residue was purified by chromatography (eluent EtOAc: hexane 1:5) to afford 150 mg of **39** as an oil (70%): ^{1}H NMR δ 7.87 (m, 2H), 7.42 (m, 3H), 7.21 (s, 1H), 4.07 (t, J = 6.5 Hz, 2H), 3.25 (s, 3H), 2.00 (m, 2H), 1.83 (m, 2H), 2.02 (s, 3H); ^{13}C NMR δ 170.8 (s), 168.7 (s), 144.0 (d), 135.1, 129.9, 128.7, 128.5 (s), 127.3, 107.6 (s), 63.7 (t), 54.0 (q), 34.2 (t), 22.8 (t), 20.8 (q); IR (neat) 1766, 1737, 1226 cm^{-1}; MS CI *m/e* 259 (MH^+ − MeOH); Anal. Calcd for $C_{16}H_{18}O_5$: C, 66.19; H, 6.25. Found: C, 66.01; H, 6.36.

b. Photolysis of 8e. The same product resulted from photolysis (Rayonet photochemical reactor at 300 nm) of **8e** in benzene saturated with oxygen for 24 h the presence of oxygen at 20 °C.

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Supporting Information Available: Copies of 17 ^{13}C NMR spectra (17 pages). This material is available in 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.

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