Preparation and Photosensitized Oxidation of Isopropylidenecyclobutanes and -cyclobutenes

Aryeh A. Frimer,* Joseph Weiss, Hugo E. Gottlieb, and Joel L. Wolk

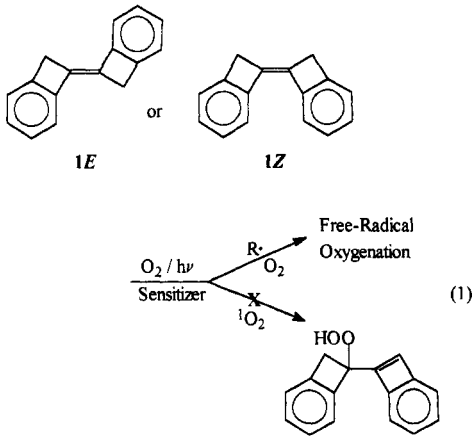
The Ethel and David Resnick Chair in Active Oxygen Chemistry, The Department of Chemistry, Bar-Ilan University, Ramat Gan 52900, Israel

Received June 10, 1993®

Isopropylidenecyclobutanes **2–5** underwent facile ene reaction with singlet dioxygen, yielding (upon Ph_3P reduction) the corresponding pairs of epimeric allylic alcohols **9** and **10**, **11** and **12**, **13** and **14**, and **15** and **16**, respectively. A combination of spectral evidence and molecular modeling studies were utilized in the structural assignment of the epimers. The data clearly indicate that steric considerations play an important role in determining the face of the ring which $^1O_2$ approaches. Isopropylidenecyclobutenes **6** and **7** reacted with singlet oxygen more slowly than their monoolefinic analogs, yielding upon reduction allylic alcohols **21b** and **22**, respectively. Benzo analog **7** also generated a small and solvent-dependent amount of isomeric aldehydes **23** and **24**, presumably via a free-radical mechanism. *n*-Butyl diene **8** underwent rapid photosensitized oxygenation producing allylic alcohol **35** (as the $^1O_2$ ene product) and dione **37** (the Hock-cleavage product of allylic hydroperoxide **39**, formed in turn via a free-radical route) in a 1:9 ratio. *Ab initio* (STO-3G) calculations confirm that, in their lowest energy conformations, compounds **2–8** are planar with the methylene ring hydrogens displaced ca. 36° from the perpendicular. As a result, only exocyclic ene product is formed, since $^1O_2$ strongly prefers axial or pseudoaxial allylic hydrogens. These calculations combined with the relative rate data suggest that the initial interaction between the electrophilic $^1O_2$ and alkylidenecyclobutenes involves both ends of the singlet dioxygen molecule, in which the "front" end attacks the reactive exocyclic double bond while the "back" end obtains stabilization by interacting with the more electron rich but unreactive endocyclic olefin linkage. Because of this added, and presumably substantial, stabilization, the relative rates *within* this system are determined in part by the orbital coefficients at the latter olefinic center.

Introduction

As part of our study of the photooxidation of ring-strained olefins,[1] we described the preparation[2] and photosensitized oxidation[3] of the *E* and *Z* isomers of 1,1′-bi(benzocyclobutenylidene) (**1*E*** and **1*Z***; eq 1). We re-



ported[3] that these substituted stilbenes undergo *E*/*Z* isomerization (upon both direct and sensitized irradiation) as well as oxygenation by free-radical processes. Lacking was any hint of a singlet oxygen ene reaction which should have led to the generation of a benzocyclobutadiene moiety. The absence of such a reaction mode may reflect the increased activation energy required to generate an anti-aromatic product. Alternatively, the inability of the ring methylene hydrogens to attain a pseudoaxial conformation may actually be the controlling factor in inhibiting the ene process. In order to obtain greater insight into the role played by the alignment of the allylic ring hydrogen in four-membered ring systems, we decided to study the reactions of alkylidenecyclobutanes and -cyclobutenes with singlet dioxygen ($^1O_2$).

Results and Discussion

(A) Synthesis of the Starting Olefins. For this study, olefins **2–8** were conveniently prepared either via a Wittig condensation[4] of isopropylphosporane with the corresponding cyclobutanones (for olefins **2–6**) or by a Grignard reaction (for **7** and **8**) of these ketones with isopropylmagnesium bromide followed by dehydration (eq 2).[5] With the exception of benzocyclobutenone,[6] the required ketones were prepared by cycloadding dichloroketene to the appropriately substituted ethylene or acetylene, followed by reductive dechlorination.[7]

(B) Photosensitized Oxidation and Product Identification—General Comments. Olefins **2–8** were photooxygenated as previously described[8] using $CHCl_3$ as

® Abstract published in *Advance ACS Abstracts*, February 1, 1994.

(1) (a) Frimer, A. A.; Roth, D.; Sprecher, M. *Tetrahedron Lett.* **1977**, 1927–1930. (b) Frimer, A. A.; Farkash, T.; Sprecher, M. *J. Org. Chem.* **1979**, *44*, 989–995. (c) Frimer, A. A.; Roth, D. *J. Org. Chem.* **1979**, *44*, 3882–3887. (d) Frimer, A. A.; Antebi, A. *J. Org. Chem.* **1980**, *45*, 2334–2340. (e) Frimer, A. A. *Isr. J. Chem.* **1981**, *21*, 194–202. (f) Frimer, A. A. *J. Photochem.* **1984**, *25*, 211–226. (g) Frimer, A. A. In *The Chemistry of Peroxides*; Patai, S., Ed.; Wiley: New York, 1983; pp 201–234. (h) Frimer, A. A.; Stephenson, L. M. In Singlet O_2 Reaction Modes and Products–Part I, Frimer, A. A., Ed.; Chemical Rubber Co.: Boca Raton, FL, 1985; Vol. II, pp 67–91.

(2) Frimer, A. A.; Weiss, J.; Rosental, Z. *J. Org. Chem.*, in press.

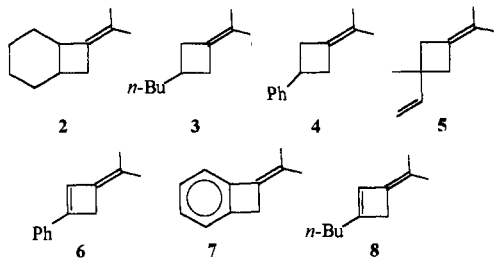
(3) Frimer, A. A.; Weiss, J. *J. Org. Chem.* **1993**, *58*, 3660–3667.

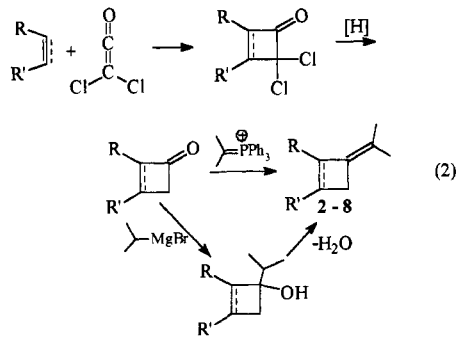
(4) For a review, see: Maercker, A. *Org. React.* **1965**, *14*, 270–490.

(5) Newsoroff, G. P.; Stenhell, S. *Aust. J. Chem.* **1972**, *25*, 1669–1693.

(6) Durr, H.; Nickels, H.; Philippi, W. *Tetrahedron Lett.* **1978**, 4387–4390.

0022-3263/94/1959-0780$04.50/0



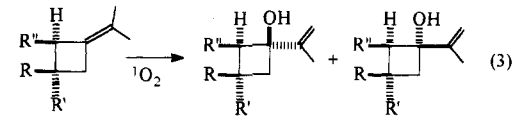


(2)

solvent and polymer-based Rose Bengal (p-RB) as sensitizer. The irradiation was stopped when oxygen uptake had essentially ceased, which generally occurred when >90% of an equivalent of O_2 had been absorbed and little if any starting material could be detected via TLC. A 10% excess of triphenylphosphine was then added, in order to reduce the labile allylic hydroperoxides to the corresponding alcohols. For the purpose of our later discussion, we note that the Ph_3P reduction of hydroperoxides is typically a very exothermic process. Indeed, instances where release of heat is not observed indicate that either hydroperoxides are not formed at all or if formed are so labile that they rearrange to nonperoxidic products prior to Ph_3P treatment.[1b,d,f,g] Products were separated by column or preparative thin-layer chromatography and identified by their spectral data.

(C) Singlet Oxygenation of Alkylidenecyclobutanes 2–5. The photosensitized oxygenation of olefins **2–5** is undoubtedly a singlet oxygen process: no reaction occurs in the absence of oxygen, sensitizer, or light or in the presence of the $^1O_2$ quencher DABCO,[1f,9] nor are the rate or mode of reaction affected by the addition of the radical inhibitor 2,6-di-*tert*-butylphenol (DTBP).[1f,10] As outlined in eq 3, each of these olefins reacts via a $^1O_2$-ene mode, involving the abstraction of an allylic hydrogen from the isopropylidene methyl groups, and yields a pair of geometric isomers.[11]

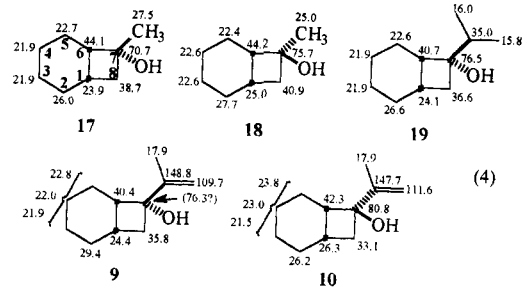
In the photooxidation of **2**, a mixture of epimeric alcohols **9** and **10** was obtained in a 1:6 ratio, but the determination



(3)

2:R=R"=-$(CH_2)_4$-; R'=H	**9** (15%)	**10** (85%)
3:R=*n*-C_4H_9; R'=R"=H	**11** (40%)	**12** (60%)
4:R=Ph; R'=R"=H	**13** (40%)	**14** (60%)
5:R=Me; R'=vinyl; R"=H	**15** (40%)	**16** (60%)

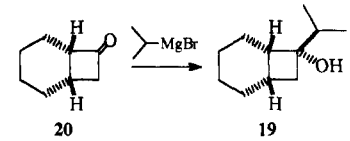
of the stereochemistry of the two isomers was far from trivial. The ^{13}C NMR data of the 7-methyl analogs **17** and **18** (see eq 4 below)[12] indicate that the primary differences



(4)

between the two epimers should be observed at C_7, with the epimer in which the hydroxyl group is *cis* to the bridgehead hydrogens shifted downfield by approximately 5 ppm. Turning to the ^{13}C spectrum of the mixture of **9** and **10**, we note that except for the $CDCl_3$ triplet at 77.5, 77.1, and 76.7 ppm, only one other absorption in the 70–90 ppm region is present: a peak at 80.8 ppm corresponding to C_7 of the major epimer **10**. With no peak observed above 81 ppm, we reasoned that minor epimer C_7 peak must be under the $CDCl_3$ absorptions.

Our suggestion that the C_7 absorption of **9** occurs at ca. 77 ppm is in fact well founded. In our exploratory work on the preparation of olefin **2**, we synthesized 7-isopropylbicyclo[4.2.0]octan-7-ol (**19**), the saturated analog of **9**, via the addition of isopropylmagnesium bromide to bicyclo[4.2.0]octan-7-one (**20**, eq 5). The stereochemistry



(5)

of the isopropyl group in **19** is expected to be *cis* to the bridgehead hydrogens because of Cram's rule[13] which predicts a preferred addition of the Grignard reagent from the less hindered face. Compounds **9** and **19** are, therefore, expected to have the same stereochemistry. In light of the fact that the introduction of a double bond has only a very small effect on the ^{13}C chemical shifts of the neighboring carbons in a molecule,[14a] **19** should be an excellent model compound for **9**. Indeed, a comparison

(7) (a) Krepski, L. R.; Hassner, A. *J. Org. Chem.* **1978**, *43*, 2879–2882. (b) Hassner, A.; Dillon, Jr., J. L. *J. Org. Chem.* **1983**, *48*, 3382–3386. (c) Mori, K.; Uematsu, T.; Minobe, M.; Yanagi, K. *Tetrahedron* **1983**, *39*, 1735–1743. See also: *Tetrahedron Lett.* **1982**, *23*, 1921–1924. (d) Ammann, A. A.; Rey, M.; Dreiding, A.S. *Helv. Chim. Acta* **1987**, *70*, 321–328. (e) Danheiser, R. L.; Savariar, S. *Tetrahedron Lett.* **1987**, *28*, 3299–3302. (f) Danheiser, R. L.; Savariar, S.; Cha, D.D. *Org. Synth.* **1989**, *68*, 32–39. (g) Dillon, J. L., Jr. Ph.D. Dissertation, SUNY Binghamton, 1983. (h) Naidorf-Meir, S. Ph.D. Dissertation, Bar-Ilan University, Ramat Gan, Israel, 1991.

(8) Frimer, A. A.; Bartlett, P. D.; Boschung, A. F.; Jewett, J. G. *J. Am. Chem. Soc.* **1977**, *99*, 7977–7986.

(9) (a) Ouannes, C.; Wilson, T. *J. Am. Chem. Soc.* **1968**, *90*, 6527–6528. (b) Davidson, R. S.; Trethewey, K. R. *J. Am. Chem. Soc.* **1976**, *98*, 4008–4009. (c) Davidson, R. S.; Trethewey, K. R. *J. Chem. Soc., Perkin Trans. 2* **1977**, 178–182. (d) Monroe, B. M. *J. Phys.. Chem.* **1977**, *81*, 1861–1864. (e) Deneke, C. F.; Krinsky, N. I. *Photochem. Photobiol.* **1977**, *25*, 299–304.

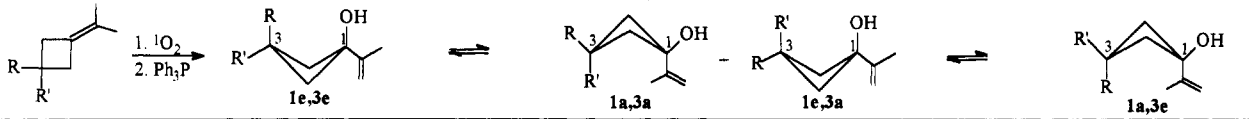
(10) Cf. Foote, C. S. In *Free Radicals in Biology*; Pryor, W. A., Ed.; Academic Press: New York, 1977; Vol. II, pp 85, 101.

(11) This is in contradistinction to the case of achiral dienes **6–8** discussed below, in which singlet oxygenation is expected to produce, subsequent to Ph_3P reduction, a racemic mixture of allylic alcohols. This is because $^1O_2$ addition to olefins **6–8** occurs *perpendicular* to the plane of symmetry and the addition of the achiral oxygen to the different enantiotopic faces will result in a racemic mixture of products. On the other hand, $^1O_2$-addition to olefins **2–5** occurs in the plane of symmetry and, hence, yields two achiral geometric isomers. See: March, J. *Advanced Organic Chemistry—Reactions, Mechanisms and Structure*, 3rd ed.; McGraw-Hill: New York, 1985; p 118.

(12) Bouquant, J.; Churche, J.; Convert, O.; Furth, B. *Org. Magn. Res.* **1979**, *12*, 5–11.

(13) See ref 11, p 103.

Table 1. Molecular Mechanics Calculations of Configuration Energies (kcal/mol) for Compounds 11–16[a]



	1e,3e		1a,3a	1e,3a		1a,3e
3: R = H, R′ = *n*-Bu	32.73	12	35.37	33.91	11	34.76
4: R = H, R′ = Ph	41.37	14	45.71	43.52	13	43.38
5: R = (CH=CH$_2$), R′ = CH$_3$	35.46	16	37.41	36.12	15	37.44

[a] The designations a (axial) and e (equatorial) refer to the C_1-isopropenyl and C_3-R′ groups, respectively.

of the spectral data confirms this point, with C_7 of **19** absorbing at 76.5 ppm. Reexamining the ^{13}C of **9** we observe a small peak riding on the $CDCl_3$ triplet at 76.3 ppm, which we have tentatively assigned as the absorption of C_7 in **9**.

We conclude, therefore, that the predominant isomer **10** is the downfield epimer in which the hydroxyl group is *cis* to the bridgehead hydrogens. The preferential formation of **10** is indeed consistent with singlet dioxygen's well-known propensity to undergo ene attack from the less sterically encumbered face of a substrate.[1gh,15]

Turning now to the photooxidations of **3–5**, here, too, epimeric mixtures are observed, and in all three cases, in a 3:2 ratio. Since the less sterically encumbered face of **3** and **4** is presumably the one opposite to the substituent at C_3 (*n*-butyl or phenyl group), our chemical intuition would predict that the predominant isomer in these cases should be **12** and **14**, respectively, in which the hydroxyl group is *trans* to the C_3-substituent. In the case of **5**, Eliel and Manoharan[16] report that vinyl has a slightly smaller steric effect than methyl; hence, **16** should predominate in the photooxidation reaction mixture. Let us turn now to the spectral data and see whether our predictions are confirmed.

In order to simplify the discussion, let us focus first on the phenylcyclobutyl system **4**. As shown in Table 1, molecular modeling calculations (PC Model, Serena Software, Bloomington, IN) indicate that the preferred conformation of oxygenation product **14** places the bulky isopropenyl and phenyl groups on the bottom face of the puckered cyclobutane ring in pseudoequatorial positions. This *e,e*-configuration for the isopropenyl and phenyl groups in **14** is preferred over the corresponding *a,a* analog by almost 4.5 kcal/mol; it also requires that both the hydroxy group at C_1 and the proton at C_3 be on the top face in pseudoaxial positions. Razin and others[17] have reported deshielding effects on H_3 in such situations of ca. 0.5 ppm. For epimer **13**, on the other hand, in which the isopropenyl and phenyl groups must lie on opposite faces, our molecular mechanics calculations are less decisive and give a small 0.14 kcal preference to a configuration in which the phenyl is equatorial and the isopropenyl is axial. However, irrespective of whether the 1-isopropenyl and 3-phenyl groups in **13** are configured 1*a*,3*e* or 1*e*,3*a*, H_3 and the hydroxyl group are *trans* to each other and H_3 is not expected to be substantially *deshielded*.

In short, then, if the major photooxidation product of **4** is **14**, we expect to see a large downfield shift of H_3 in its ^1H NMR spectrum as compared to the minor product. This is indeed observed: the H_3 peaks appear at 3.82 ppm in the major product but only at 3.00 ppm in the minor isomer. We note that the 0.8 ppm H_3 shift is somewhat larger than the 0.5 ppm reported by Razin and others.[17] This seems to confirm the molecular modeling calculation that **13** will be configured 1*a*,3*e* so that the double bond of the axial isopropenyl moiety at C_1 actually has a small (ca 0.3 ppm) *shielding* effect on the axial H_3 proton.

The identification of **14** as the major product is also consistent with the absorption of the four H_2 and H_4 protons as two 2H multiplets separated by 0.5 ppm in the case of the minor product, but as a single 4H multiplet in the major. In **13**, the OH and Ph lie on the same face; thus, the protons fall into two sets—with the downfield protons being those which are *cis* to and, hence, deshielded by *both* the OH and the Ph groups. In the case of **14**, however, the OH and Ph groups lie on opposite faces; hence, all four hydrogens are deshielded, presumably almost equally.

Alkylidenecyclobutane **5** lacks a hydrogen at C_3; nevertheless, ^1H NMR arguments similar to that used in phenyl system **4** allow us to determine that **16** is the major $^1O_2$ product. As seen from Table 1, the isopropenyl group strongly prefers being equatorial. It follows, therefore, that in **15**, where the hydroxy group and the methyl are both axial on the same face of the ring, a deshielding of the methyl hydrogens should be observed. Indeed, the C_3-methyl of the minor fraction is shifted downfield by 0.24 ppm. On the other hand, a deshielding of the vinyl hydrogens is expected in epimer **16**, and indeed in the major product each of the three vinyl hydrogens is shifted 0.22 ppm downfield. This evidence clearly indicates that, as predicted, oxygen attack occurs preferentially from the vinyl group face of the cyclobutane ring, yielding **16** as the major product.

Unfortunately, in the case of **3** we have no analogous hard evidence to confirm our "chemical intuition". Both in the major and minor products, H_3 appears as a multiplet at ca. 2.5 ppm. Molecular mechanics calculations (Table 1) again assist us in rationalizing these results. These calculations indicate that, for isomer **12**, in which the isopropenyl and *n*-butyl groups are *cis* to each other, an *e,e*-configuration is preferred over the corresponding *a,a*-analog by more than 2.5 kcal. As in phenyl analog **14**, we would expect a hydroxy group induced 0.5 ppm deshielding of H_3. However, for the *trans* analog **11**, in contradistinction to the phenyl analog **13**, a 1*e*,3*a*-configuration is preferred. As a result, H_3, which is axial in **12**, is now equatorial in **11**. Since equatorial hydrogens are deshielded with respect to axial ones by about 0.5 ppm,[14b] it should not be surprising that the chemical shifts of the H_3 proton in both **11** and **12** coincide.

(14) Silverstein, R. M.; Bassler, G. C.; Morril, T. C. *Spectrometric Identification of Organic Compounds*, 4th ed.; Wiley: New York, 1981; (a) p 261; (b) p 189.

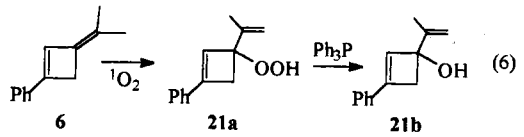
(15) (a) Frimer, A. A. *Chem. Rev.* **1979**, *79*, 359–387. (b) Frimer, A. A. In *The Chemistry of Enones*; Patai, S., Rappoport, Z., Eds.; Wiley, New York, 1989; Part 2, pp 781–921.

(16) Eliel, E. L.; Manoharan, M. *J. Org. Chem.* **1981**, *46*, 1959–1962.

(17) (a) Razin, V. V.; Eremenko, M. V.; Ogloblin, K. A. *Zh. Org. Khim.* **1977**, *13*, 1003–1009; **1981**, *17*, 953. (b) Livneh, M. Ph.D. Dissertation, Bar Ilan University, July 1985; see especially pp 81 and 84. (c) Azran, C. Ph.D. Dissertation, Bar Ilan University, March 1991; see especially p 164.

(D) Singlet Oxygenation of Alkylidenecyclobutenes 6–8. Before turning to a discussion of the photooxidation of the title olefins, one general comment is in order. In contradistinction to olefins **2–5**, the unsaturated analogs **6–8** undergo facile autoxidation at room temperature. The resulting oxidized products include, according to mass spectral analysis, the corresponding epoxides and hydroperoxides. Hence, it was imperative to store the freshly synthesized olefin in the freezer under argon until photooxidation. As will be seen from the discussion below, care was taken to ensure that a mode identified as a $^1O_2$ reaction was indeed so.

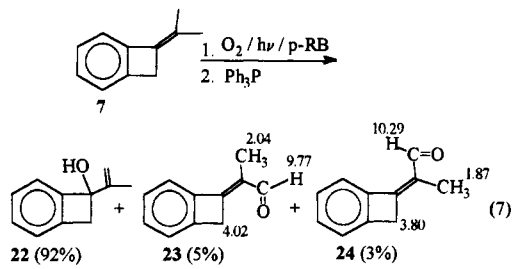
In this regard, the photosensitized oxygenation of diene **6** is clearly a singlet oxygen process, as determined by the aforementioned DABCO and DTBP tests. $^1O_2$ attack occurs, as expected,[1g,h,15a] exclusively at the tetrasubstituted exocyclic double bond yielding hydroperoxide **21a**, and upon Ph_3P reduction allylic alcohol **21b**, as the sole product (eq 6). The latter undergoes facile rearrangement



6 21a 21b (6)

at room temperature to as yet undetermined products. Cyclobutanol **21b** was independently synthesized by reacting isopropenylmagnesium bromide with 3-phenyl-2-cyclobuten-1-one according to the procedure of Sammes and coworkers.[25]

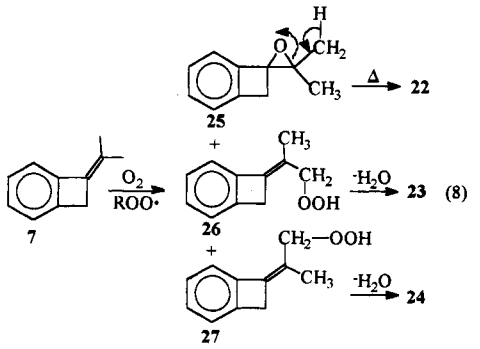
In the case of isopropylidenebenzocyclobutene (**7**), photosensitized oxygenation in $CHCl_3$ followed by Ph_3P reduction yielded three products: allylic alcohol **22** (92%) and isomeric enals **23** (5%) and **24** (3%) (eq 7). The ratio



22 (92%) 23 (5%) 24 (3%) (7)

of photooxidation products **22:23:24** was 96:2:2 in benzene, while only negligible amounts of the enals (<1%) could be observed in CH_3OH or CH_3CN. ^1H NMR spectroscopy readily permits the determination of the stereochemistry of these two enals. In **23**, both the allylic methyl group, which is *syn* to the aromatic ring, and the cyclobutyl methylene, which is *syn* to the aldehydic carbonyl, undergo anisotropic deshielding as compared to their counterparts in **24**. On the other hand, in isomer **24** the aldehydic proton now lies *syn* to aromatic ring and is shifted 0.5 ppm downfield as compared to its counterpart in **23**.

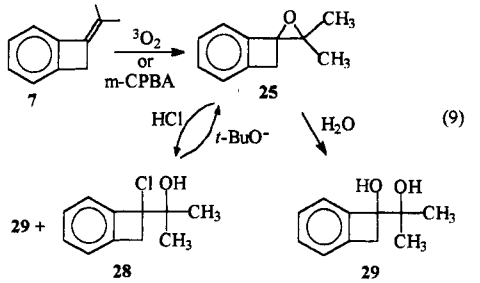
Of the three products, only **22** would seem to be a $^1O_2$ product, since only in **22** is the double bond shifted, with respect to the substrate, to a vicinal position—as is required by a bona fide singlet oxygen "ene" reaction.[1g,h,15a] This would seem to be confirmed by the fact that allylic alcohol **22** is the sole product observed when $^1O_2$ is generated chemically using triphenyl phosphite ozonide.[1d,18] One possible scenario (eq 8) is that under the photochemical conditions we are not observing a $^1O_2$ process at all. Rather, facile free radical autoxidation is occurring generating



(8)

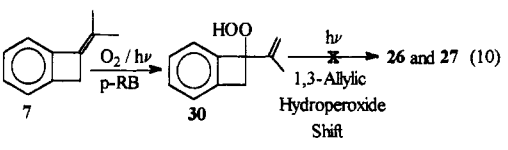
epoxide **25** (via short chain polyperoxidation[19]) and allylic hydroperoxides **26** and **27** (from a competing autoxidative hydroperoxidation processes[19]). Rearrangement of **25** and thermal or photochemically induced Hock-dehydration[1f–h,15a] of hydroperoxides **26** and **27** would yield the desired products (eq 8).

While such a scheme is intriguing and well precedented,[1,15] it is easily ruled out by several observations. Firstly, the oxygenation was slowed dramatically by DABCO but not by the radical inhibitor DTBP, nor did either have an effect on the product distribution—a clear indication that a singlet oxygenation is occurring. Furthermore, the sole product of room temperature thermal autoxidation is epoxide **25** (independently synthesized with *m*-CPBA), and it is totally stable to the photooxidation reaction conditions. When reacted with aqueous acid (concentrated HCl), **25** does not rearrange to **22**, but rather generates chlorohydrin **28**, along with a lesser amount of diol **29**. The latter is the sole product when the epoxide is stirred overnight with water. Chlorohydrin **28** can be recyclized back to epoxide **25** under basic conditions (*tert*-butoxide/*tert*-butyl alcohol) (eq 9).



(9)

Another possible scenario is that initial "ene" reaction leads to the expected allylic hydroperoxide **30**, which then undergoes a 1,3-allylic hydroperoxide shift with subsequent dehydration (eq 10).[1g,1,15] But this, too, is easily ruled out.



(10)

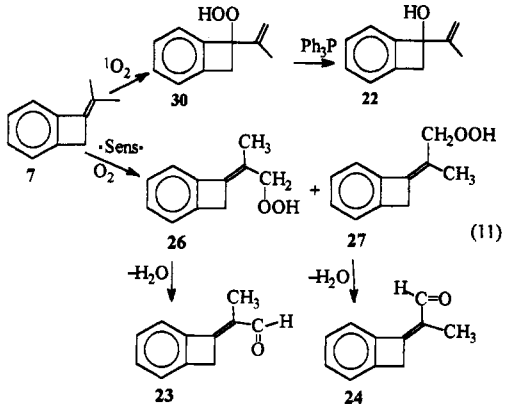
Hydroperoxide **30** (accompanied by small amounts of **22–24**) was the primary product observed in photooxidized

(18) Cf. Murray, R. W.; Kaplan, M. L. *J. Am. Chem. Soc.* **1969**, *91*, 5358–5364.

(19) (a) Mayo, F. R. *J. Am. Chem. Soc.* **1958**, *80*, 2465–2480. (b) Mayo, F. R.; Miller, A.A.; Russell, G. A. *J. Am. Chem. Soc.* **1958**, *80*, 2500–2507. (c) Van Sickle, D.E.; Mayo, F. R.; Gould, E. S.; Arluck, R. M. *J. Am. Chem. Soc.* **1967**, *89*, 977-984. (d) Mayo, F. R. *Acc. Chem. Res.* **1968**, *7*, 193–201. (e) Howard, J. A. In *Free Radicals*; Kochi, J. K., Ed.; Wiley: New York, 1973; Vol. II, pp 3–62; see especially p 25ff. (f) Filippova, T. V.; Blyumberg E. A. *Russ. Chem. Rev.* **1982**, *51*, 582–591.

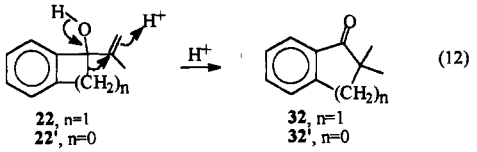
reaction mixtures not reduced with Ph_3P; it remained stable under further irradiation (2 h) or when standing for at least 2 weeks at room temperature.

Having excluded the above scenarios, it is likely that we are observing two competing modes of action. Cyclobutanol **22** is the Ph_3P reduction product of allylic hydroperoxide **30** formed in a $^1O_2$ process, which is the predominant reaction in this system. At the same time, however, there is a solvent-dependent sensitizer-induced free radical process leading to **23** and **24** via the Hock-dehydration products of hydroperoxides **26** and **27** (eq 11). In the latter case, the sensitizer triplet abstracts one



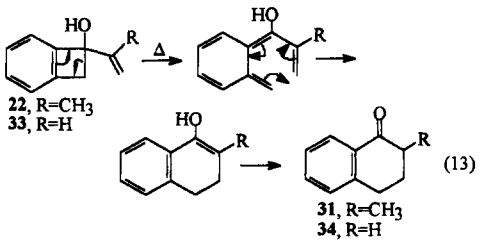
of the allylic isopropylidene methyl hydrogens initiating autoxidation. Indeed, the literature is replete with examples in which Rose Bengal, the sensitizer in the present study, initiates "type I" hydrogen or electron-transfer processes.[20] These processes are often accompanied by rapid bleaching of the sensitizing dye, as indeed occurs in our system, and are frequently inhibited by DABCO which quenches the triplet sensitizer. The radical process suggested is most likely not a chain reaction, which explains why it was not inhibited by DTBP.

Before closing our discussion on the photooxidation of **7**, we would like to note that upon standing for 2 months at room temperature, a $CHCl_3$ solution of ene product **22** gave white crystals identified as 2-methyl--tetralone (**31**). Were this an acid-catalyzed rearrangement, we would have expected it to generate cyclopentanone **32** (eq 12, $n = 1$),



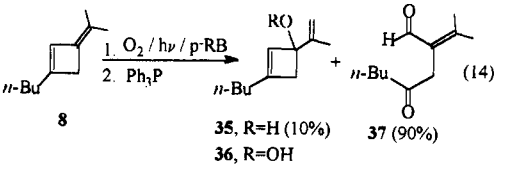
i.e., a five—not a six—membered ring. Indeed, the related acid-catalyzed ring expansion reaction of vinylcyclopropanol (**22'**, $n = 0$) to cyclobutanone (**32'**) is well documented,[21] though all previous attempts to carry out an acid catalyzed transformations in the next higher homolog have thus far proven unsuccessful.[21a] Furthermore, there must be something unique about the benzocyclobutanol system of **22** since in none of the other vinylcyclobutanols reported in this paper or by others[22-24] was such a transformation to a cyclohexanone observed.

The answer would seem to lie in a report of Sammes and co-workers[25] who have noted that 1-vinylbenzocyclobuten-1-ol (**33**) *thermally* and rapidly rearranges in refluxing toluene to -tetralone (**34**). These workers invoke the intermediacy of a vinyl o-quinone dimethide (eq 13).



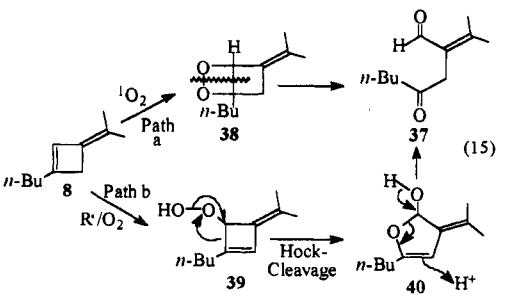
Electrocyclic closure of this hexatriene generates the observed product (**34**). It is probable that a similar process is occurring slowly in our system as well.

Let us now turn to the final olefin in this study, 3-*n*-butyl-1-isopropylidenecyclobutene (**8**). Photosensitized oxidation was carried out under standard conditions; surprisingly, however, the subsequent Ph_3P reduction was not accompanied by the evolution of heat. Inspection of the reaction mixture revealed the presence of two products in a 9:1 ratio. The minor product was cyclobutanol **35** (eq 14), presumably formed as in the case of olefins **2–7**, via



the $^1O_2$ ene reaction product allylic hydroperoxide **36**. These products were identified by their spectral data. In addition, cyclobutanol **35** was independently synthesized by reacting isopropenylmagnesium bromide with 3-*n*-butyl-2-cyclobuten-1-one[7f] according to the procedure of Sammes and co-workers.[25]

The generation of keto aldehyde **37** as the major product was somewhat surprising, and two mechanisms can be invoked to rationalize its formation. One possibility (eq 15, path a) is that keto aldehyde **37** is simply the oxidative cleavage product of dioxetane **38**. Indeed, the absence of



(20) For a review of Rose Bengal and its derivatives as photosensitizers, see: (a) Lamberts, J. J. M.; Neckers, D. C. *Tetrahedron* **1985**, *41*, 2183–2190; see also refs 17–23 cited therein for examples of "type I" initiation. (b) Zakrzewski, A.; Neckers, D. C. *Tetrahedron* **1987**, *43*, 4507–4512. (c) Reference 20 *supra*.

(21) (a) Johnson, C. R.; Herr, R. W. *J. Org. Chem.* **1973**, *38*, 3153–3159. (b) Wasserman, H. H.; Hearn, M. J.; Cochoy, R. E. *J. Org. Chem.* **1980**, *45*, 2874–2880.

(22) Frimer, A. A.; Farkash, T. Unpublished results.

(23) Bee, L. K.; Everett, J. W.; Garatt, P. J. *Tetrahedron* **1977**, *33*, 2143–2150.

(24) (a) Rousseau, G.; Le Perchec, P.; Conia, J. M. *Tetrahedron Lett.* **1977**, 2517–2520. (b) Rousseau, G.; Le Perchec, P.; Conia, J. M. *Tetrahedron* **1976**, *34*, 3475–3482. (c) Rousseau, G.; Le Perchec, P.; Conia, J. M. *Tetrahedron* **1976**, *34*, 3483–3494. (d) Rousseau, G. Ph.D. Thesis, L'Universite de Paris-Sud–Centre d'Orsay, 1977.

(25) (a) Arnold, B. J.; Sammes, P. G. *J. Chem. Soc., Chem. Commun.* **1972**, 1034–1035. (b) Arnold, B. J.; Sammes, P. G.; Wallace, T. W. *J. Chem. Soc., Perkin Trans. 1* **1974**, 415–420.

hydroperoxide formation seems to be consistent with the lack of an exothermic reaction upon the addition of Ph_3P. Nevertheless, the intermediacy of a dioxetane is immediately suspect, in light of the fact that the analogous olefins **6** and **7** gave hydroperoxides exclusively; nor is **8** particularly electron rich or sterically strained—the usual prerequisite for dioxetane formation.[1g,h,15]

Indeed, several simple experiments were carried out which demonstrate that keto aldehyde **37** is formed neither via dioxetane **38** nor even in a $^1O_2$ process. Firstly, the $^1O_2$ quencher DABCO had little effect on the rate of reaction. Secondly, radical inhibitor DTBP (in an equimolar ratio with the substrate) completely changed the course of the reaction yielding cyclobutenol **35** and keto aldehyde **37** in a ratio of 2:1. Thirdly, when the dioxetane trap diphenyl sulfide[1f-h,15] was added, there was essentially no change in the course of the reaction.

The above data lead us to conclude that, as in the case of olefins **6** and **7**, isopropenylcyclobutenol (**35**) is the true singlet oxygen product. However, in the absence of a radical inhibitor, a very facile free-radical chain process occurs to generate hydroperoxide **39**. The latter undergoes rapid Hock cleavage[1f-h,15] primarily to alkylidene keto aldehyde **37** (eq 15, path b). It has been well documented that small rings are particularly susceptible to this mode of rearrangement.[1f] Interestingly, in these photoinduced free-radical processes, no epoxide **41** is observed, though the latter is the predominant product observed in room-temperature thermal autoxidation (eq 16).

8 **41** (16)

(E) Product Analysis. As stated in the Introduction, we embarked upon this research in order to get better insight into the role played by the alignment of the allylic ring hydrogen in four-membered ring systems. We note that in the singlet oxygenation of the alkylidenecyclobutanes and -cyclobutenes **2–8** no allylic *ring* hydrogen abstraction is observed; the "ene" reaction products stem exclusively from removal of an allylic hydrogen from the isopropylidene moiety. These results are consistent with previous observations[26] that, in the ene reaction, $^1O_2$ shows a strong preference for those allylic hydrogens aligned in a 90° dihedral angle with respect to the plane of the double bond *in the low energy conformations* of the olefin. Similarly, in cyclic systems, the abstraction of pseudoaxial hydrogens are greatly preferred over pseudoequatorial ones. Considering that the low-energy conformation of methylenecyclobutane is almost planar, with at most a 3.8° pucker,[27] the allylic ring hydrogens are not likely to attain the proper alignment in the low-energy conformations. This is in sharp contrast to the allylic methyl hydrogens of the isopropylidene groups in our substrates which can rotate into proper orientation and, hence, are preferably abstracted. Although there are a few examples in the literature[1e] (e.g., methylenecyclobutane,[22] bicyclobutylidene,[23] cyclopropylmethylenecyclobutane[24]) in which the ring hydrogens of alkylidenecyclobutanes undergo $^1O_2$ ene reaction, they are generally instances in which the ring hydrogens are the only ones available or more preferably aligned.[28] In these systems, there is presumably enough flexibility remaining to permit even a normally equatorial hydrogen to attain a pseudoaxial position (via "flipping" or "puckering"), if necessary.

The situation is even more clear cut in the case of alkylidenecyclobutenes **6–8**. Here, we are dealing with cyclobutyl rings containing three trigonal carbons which are constrained to be planar. The remaining ring methylene hydrogens—the only available allylic hydrogens on the ring—are displaced ca. 36° from the perpendicular,[29] and there is no way these allylic ring hydrogens can attain anything even approximating a pseudoaxial position. That these hydrogens lack of $^1O_2$ ene reactivity should, therefore, not be surprising. A similar rationale has been suggested[3] for the absence of ene reactivity in the case of alkylidenecyclopropanes[30] and cyclopropenes[31] (whose ring hydrogens are displaced ca. 33° from the perpendicular) and bi(benzocyclobutylidene).[3]

(F) Reaction Kinetics and Theoretical Calculations. We conclude this paper with a discussion of the relative rates of reaction (k_r) of olefins **2–8** (Table 2). Table 2 indicates that, generally speaking, alkylidenecyclobutane systems **2–5** react at approximately the same rate (k_r varies only by a factor of 2—from 0.20 to 0.39) and substantially faster than the corresponding alkylidenecyclobutene systems **6–8**. In the latter case, however, there were large differences in rate between the various dienes (k_r varies by a factor of 13—from 0.027 to 0.38). In order to obtain some insight into the possible electronic and orbital factors that might be involved in these reactions, we carried out Gaussian 90 *ab initio* (STO-3G basis set) calculations[32] on olefins **1–8**.

These calculations confirm that the cyclobutyl ring for all these systems is essentially planar in the lowest energy conformation, with the ring methylene hydrogens—the only available allylic hydrogens on the ring—displaced 35.5–35.9° from the perpendicular (*vide supra* section E).[29] More interesting, however, is the fact that, in the lowest energy conformation of **2–8**, one of the three hydrogens on each of the alkylidene allylic methyl groups is properly aligned for ene abstraction. Little wonder, then, that $^1O_2$ exclusively abstracts these methyl hydrogens, while **1*E*** and **1*Z***, lacking any such allylic hydrogens, prove unreactive to $^1O_2$.[3]

Turning now to the rates of reaction, we explored several factors that have been reported to control these reactions. $^1O_2$ is a "soft" electrophile, whose reactions should be dominated by HOMO(olefin)–LUMO($^1O_2$) interactions.[33] In such a situation the energy of orbital overlap becomes (eq 17):

(26) (a) Denny, R. W.; Nickon, A. *Org. React.* **1973**, *20*, 133–336. (b) Gollnick, K.; Kuhn, H. J. In *Singlet Oxygen*; Wasserman, A. A., Murray, R. W., Eds.; Academic Press: New York, 1979; pp 287–427; see especially pp 318–327. (c) See also refs 1e,g,h and 15a. (d) References 1c and 3 describe interesting applications of this rule.

(27) (a) Malloy, T. B., Jr.; Fisher, F.; Hedges, R. M. *J. Chem. Phys.* **1970**, *52*, 5325–5333. (b) Cole, K. C.; Gilson, D. F. R. *Can. J. Chem.*, **1976**, *54*, 657–664.

(28) Conia and co-workers[24] report that cyclohexylidenecyclobutane and diisopropylmethylenecyclobutane give >50% of cyclobutyl ring abstraction. While we have no clear rationale for this behavior, we believe that conformational analysis will reveal that the other allylic hydrogens are improperly aligned. For a related discussion see ref 1d, especially p 3884.

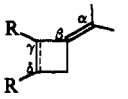
(29) (a) Lebedev, V. L.; Bagatur'yants, A. A.; Taber, A. M.; Kalechits, I. V. *Russ. J. Phys. Chem.* **1978**, *58*, 633–635. (b) Goldish, E. *J. Chem. Educ.* **1959**, *36*, 408–416.

(30) Laurie, V. W.; Stiglani, W. M. *J. Am. Chem. Soc.* **1970**, *92*, 1485–1488.

(31) Allen, F. H. *Tetrahedron* **1982**, *38*, 645–655.

(32) Frisch, M. J.; Head-Gordon, M.; Trucks, G. W.; Foresman, J. B.; Schlegel, H. B.; Raghavachari, K.; Robb, M.; Binkeley, J. S.; Gonzalez, C.; Defrees, D. J.; Fox, D. J.; Whiteside, R. A.; Seeger, R.; Melius, C. F.; Baker, J.; Martin, R. L.; Kahn, L. R.; Stewart, J. J. P.; Topiol, S.; Pople, J. A. Gaussian 90, Revision I, Gaussian Inc., Pittsburgh, PA, 1990.

Table 2. Relative Rate and Theoretical (STO-3G) Results



class	compd	rel rate (k_r)[a]	HOMO energy (eV)	$\sum c_{\alpha,\beta}$	$\sum c_{\alpha-\delta}$	$\Delta E'_{\alpha,\beta}$[b]	$\Delta E'_{\alpha-\delta}$[b]	charges[c] $\sum_{\alpha,\beta}$	charges[c] $\sum_{\gamma,\delta}$
Cyclobutanes	**2**	0.21	−7.3984	1.1770		−0.1988		−0.007 764	
	3	0.39	−7.4718	1.1894		−0.2009		−0.000 211	
	4	0.23	−7.5616[d]	1.1899		−0.1985		+0.000 140	
	5	0.20	−7.5181	1.1899		−0.1998		−0.001 189	
Cyclobutenes	**6**	0.096	−5.9296	0.7371	1.5545	−0.0988	−0.4394	+0.002 786	−0.012 803
	7	0.027	−6.4029	0.7990	1.5209	−0.1069	−0.3873	+0.013 041	−0.011 631
	8	0.38[e]	−6.4164	0.8781	1.8253	−0.1288	−0.5565	+0.005 932	−0.072 643
	1*E*	*f*	−5.9840	0.7693	1.3092	−0.1066	−0.3086	−0.006 622	−0.006 974
	1*Z*	*f*	−5.9976	0.7717	1.3104	−0.1070	−0.3084	−0.006 257	−0.005 837

[a] Relative rate of reaction with $^1O_2$ as compared to tetramethylethylene (k_r = 1.00). [b] See eq 18. For $\Delta E'_{\alpha,\beta}$, based on $\sum c_{\alpha,\beta}$; for $\Delta E'_{\alpha-\delta}$, based on $\sum c_{\alpha-\delta}$. [c] Sum of the Mulliken atomic charges on the olefinic carbons. [d] Sub-HOMO value. The HOMO is essentially localized on the phenyl ring. [e] For the formation of **35**; photooxidation in the presence of DTBP. [f] Photooxidation proceeds via a free-radical mechanism.[3]

$$\Delta E = \frac{c^2_{(O\text{-}LU)}[\sum c]^2_{(olefin\text{-}HO)}\beta^2_{CO}}{E_{(olefin\text{-}HO)} - E_{(O\text{-}LU)}} \qquad (17)$$

$c_{(O\text{-}LU)}$ and $E_{(O\text{-}LU)}$ represent the coefficient on the front oxygen[34b] of $^1O_2$ in its LUMO and its LUMO energy, respectively; $[\sum c]_{(olefin\text{-}HO)}$ and $E_{(olefin\text{-}HO)}$ represent the sum of the coefficients on the double bond in the HOMO interacting with the front oxygen of $^1O_2$ and the olefin's HOMO energy, respectively; and β_{CO} is the carbon oxygen resonance integral. Since $c_{(O\text{-}LU)}$ and β_{CO} can be taken as constant, we will divide through by this quantity. Furthermore, $E_{(O\text{-}LU)}$ can be equated with the electron affinity of molecular oxygen, which is −0.43 eV.[34a] This yields (eq 18):

$$\Delta E' = \frac{[\sum c]^2_{(olefin\text{-}HO)}}{E_{(olefin\text{-}HO)} + 0.43} \qquad (18)$$

Assuming the variation in the olefinic coefficients to be minor, several authors have found a good general correlation between olefin HOMO energies (or ionization potentials) and the relative rates of $^1O_2$ ene reaction,[35] i.e., the higher $E_{(olefin\text{-}HO)}$ (or the lower the IP) the greater the rate. The STO-3G calculations for compounds **2**–**8** reveal that the HOMO energy of the exocyclic α,β bond (see Table 2) in the cyclobutane system is lower than that of the corresponding cyclobutenes. This is what one would expect considering that the latter are conjugated dienes. In any case this would predict that cyclobutenes should react *faster* than the related monoolefins, which (as Table 2 indicates) is simply not the case.

In search of other factors that might play a role in these systems, we looked at a possible correlation between the reaction rate and $\Delta E'_{\alpha,\beta}$, which takes into account the size of the coefficients on the reactive α,β-olefinic carbons. Indeed, the sum of the coefficients for the α,β double bond ($\sum c_{\alpha,\beta}$; see Table 2) is substantially larger in the case of the monoolefins **2**–**5** than dienes **6**–**8**, resulting in turn in larger $\Delta E'_{\alpha,\beta}$ values for the former. This might well have explained the relative reactivities between the two groups, were it not for the fact that there is no correlation between the relative rates and the corresponding $\Delta E'$ values *within* each group.

What is fascinating is that, in the case of cyclobutenes **6**–**8**, there is an definite logarithmic correlation (correlation coefficient = 0.96) between the rate of reaction and $\Delta E'$ [ln k_r vs $\Delta E'$; see Figure 1) if in our summing of the coefficients we also include those of the unreactive γ,δ-double bond [$\sum c_{\alpha-\delta}$].[36] A logarithmic relationship between energy and rate is of course typical of linear free energy relationships and has been recently reconfirmed for some HOMO–LUMO systems by Houk and Munchausen.[37] However, that the rate should be determined in great part by the *unreactive* γ,δ-double bond is a surprising observation. This result motivated us to check the relative electron densities of the α,β- and γ,δ-double bonds. The sum of the Mulliken atomic charges for the carbon atoms of these double bonds indicate that the latter is the more electron rich of the two. This result is also counterintuitive since the α,β-double bond is tetrasubstituted while the γ,δ-double bond is only trisubstituted.

Combined together, these pieces of evidence allow us to resolve the discrepancies raised at the opening of this section. The STO-3G data suggest that the reaction scenario in the case of alkylidenecyclobutanes **2**–**5** differs from that of the unsaturated analogs **6**–**8**. In the former, singlet oxygen attack occurs end-on[34b] at the α,β-double bond (eq 19) with the overall rate of reaction presumably controlled by $\Delta E'_{\alpha,\beta}$, whose value is essentially the same for olefins **2**–**5**. This overall rate is then fine-tuned, by

(33) Fleming, I. *Frontier Orbitals and Organic Chemical Reactions*; Wiley: Chichester, 1976. $^1O_2$ is briefly referred to on pp 120–121. (c)See ref 33, p 27 and top of p 88. We have assumed that the coulombic term is minimal. We have also assumed that the overlap integral in the evaluation of the cross term involving the coefficients of the two carbons—which are almost equal—would slightly shift the absolute values in the $\Delta E'$ column of Table 2, but would otherwise leave the relative picture substantially unchanged.

(34) (a) Paquette, L. A.; Liotta, D. C.; Baker A. D. *Tetrahedron Lett.* **1976**, 2681–2684. (b) van den Heuvel, C. J. M.; Verhoeven, J. W.; de Boer, Th. *Recl. Trav. Chim. Pays-Bas* **1980**, 99, 280–284. (c) Our equation differs slightly from that of Paquette et al.[34a] in that we have assumed an initial perepoxide-type of interaction (as is now commonly accepted for simple olefins)[1h] in which the front oxygen attacks both olefinic carbons. In addition, the sum of the coefficients is squared, i.e., $[\sum c]^2$ rather than $\sum c$.

(35) (a) Kearns, D. R. *J. Am. Chem. Soc.* **1969**, *91*, 6554–6563. (b) Reference 34. (c) Adam, W.; Carballiera, N.; Cheng, C.-C.; Sakanishi, K.; Gleiter, R. *J. Org. Chem.* **1979**, *44*, 851–853. (d) Hurst, J. R.; Schuster *J. Am. Chem. Soc.* **1982**, *104*, 6854–6856. (e) Reference 26b, Table 2, pp 291–295 and 298ff. (f) Monroe, B. M. In *Singlet O_2. Physical-Chemical Aspects*, Frimer, A. A., Ed.; Chemical Rubber Co.: Boca Raton, Florida, 1985; Vol. I, pp 177–224; see especially pp 201–206. (g) Reference 1h, p 71. (h) We note, however, that the IP/rate correlation is far from perfect,[35d-g] primarily because ionization potential is by no means the sole determinant of reaction rate.

(36) We note that in the diene HOMO, the orbital coefficients of the γ,δ-double bond are of opposite sign to those of the α,β-linkage, but the same is true of the relative sign of the orbitals in the dioxygen LUMO (see eq 19). Hence, we have summed the absolute values of these coefficients.

(37) (a) Houk, K. N.; Munchausen, L. L. *J. Am. Chem. Soc.* **1976**, 98, 937–946. (b) Houk, K. N. In *Pericyclic Reactions*; Marchand, A. P., Lehr, R. E., Eds.; Academic Press: New York, 1977; Vol. II, pp 181–271.

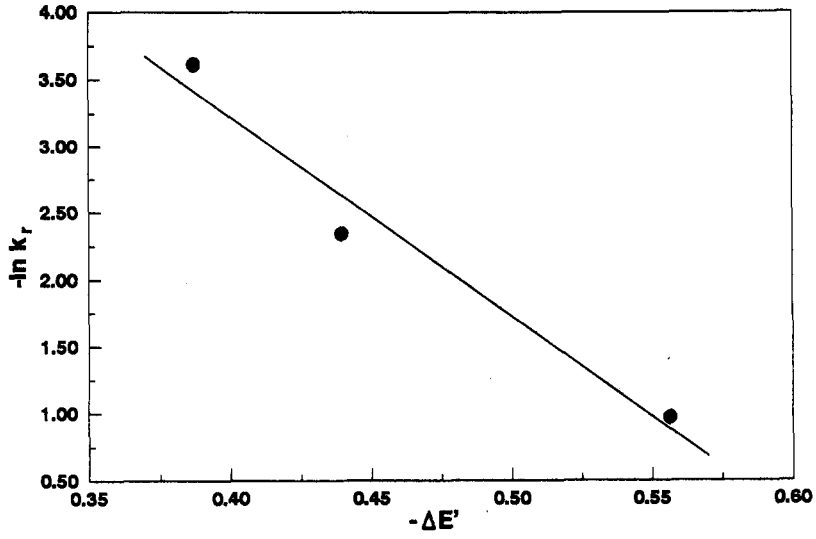
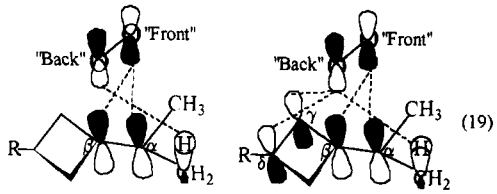


Figure 1. Plot of $-\ln k_{rel}$ vs $-\Delta E'$.



Transition State for **2-5** Transition State for **6-8** (19)

steric considerations, in which the order of increasing steric hindrance is *n*-butyl < phenyl < hexahydrobenzo < 3-methyl-3-vinyl (the latter blocking both faces of the ring).

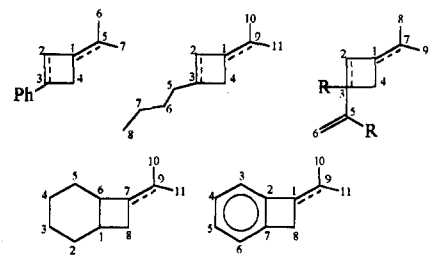
By contrast, the initial interaction between the electrophilic $^1O_2$ and alkylidenecyclobutenes involves both ends of the singlet dioxygen molecule, in which one end (arbitrarily dubbed the "front" end in equation 19) attacks the reactive α,β-double bond while the other end (referred to in eq 19 as the "back" end) obtains stabilization by interacting with the more electron rich but unreactive γ,δ-double bond (eq 19). Indeed, in view of the electrophilicity[1g,h] of $^1O_2$, it is possible—if not likely—that the $^1O_2/\gamma,\delta$-double bond interaction is the initiatory and more dominant of the two. Because of this added substantial stabilization, the relative rates *within* this system are determined in part by the coefficients at this γ,δ-olefinic center. Regarding steric factors, we expect them to be minimal, since substituents at C_2 and C_3 will lie in the plane of the ring.

Secondary orbital interactions have been previously invoked by several authors to explain product distribution.[38] This would seem to be the first instance where such stabilization is utilized to *quantitatively* explain the overall reaction rate.

Experimental Section

^1H NMR (300 MHz) and ^{13}C NMR (75 MHz) spectra were obtained on a Bruker AM 300 Fourier transform spectrometer. Assignments were facilitated by correlating proton and carbon chemical shifts through analysis of residual couplings in off-resonance decoupled spectra. In all cases, TMS served as the internal standard. In the case of known compounds, the previously published NMR spectral data were often obtained on a 60-MHz instrument and/or lacking the corresponding ^{13}C data and are, therefore, recorded below. IR spectrometers used were generally Perkin-Elmer models 457 and 621, though spectra designated FTIR were taken with the Nicolet 60 SXB FTIR. EI and CI mass spectra were run on a Finnigan-4000 GC/MS machine, except where exact mass data are given. In the latter instance, the EI data reported are based on the high-resolution mass spectra (HRMS), performed by the Mass Spectroscopy Center at the Technion, Haifa. UV–vis spectra were taken with a Varian DMS-100 spectrometer. Analytical thin-layer chromatography (TLC) was performed using Riedel-De Haen silica gel microcards. Preparative runs (PTLC) were carried out on Merck silica gel F_{254} precoated plates, and the products were extracted from the silica by stirring overnight in a solution of 10% CH_3OH in $CHCl_3$. The retention times given are for the analytical runs. Column chromatography was performed on Fluka neutral alumina (type 507C). Preparative gas chromatography (GC) was carried out on a 30-in. × 0.25-in. copper column packed with 10% SE-30 on Chromosorb W AW DMCS with a flow rate of 75 mL/min. Activated zinc was generally prepared as described by Danheiser and co-workers.[7f]

The numbering of the carbons in the NMR spectra of the various cyclobutyl, benzocyclobutenyl, and *cis*-bicyclo[4.2.0]octyl derivatives is as shown below.



Preparation of 1-Isopropylidene-*cis*-bicyclo[4.2.0]octane (2), 7-Isopropyl-*cis*-bicyclo[4.2.0]octan-7-ol (19), and *cis*-Bicyclo[4.2.0]octan-7-one (20). A 250 mL round-bottom flask was charged with 8,8-dichloro-*cis*-bicyclo[4.2.0]octan-7-one[39] (**41**, 7 g, 36 mmol), zinc (10 g), and glacial acetic acid (40 mL). The mixture was refluxed for 16 h, cooled, and filtered through a

(38) (a) Inagaki, S.; Fujimoto, H.; Fukui, K. *Chem. Lett.* **1976**, 749–752. (b) Rousseau, G.; Le Perchec, P.; Conia, J. M. *Tetrahedron Lett.* **1977**, 2517–2520. (c) Lerdal, D.; Foote, C. S. *Tetrahedron Lett.* **1978**, 3227–3230. (d) Stephenson, L. M.; Grdina, M. J.; Orfanopoulos, M. *Acc. Chem. Res.* **1980**, *13*, 419–425. (e) Stephenson, L. M. *Tetrahedron Lett.* **1980**, *21*, 1005–1008. (f) References 1h and 35d. (g) Clennan, E.L.; L'Esperance, R. P. *J. Am. Chem. Soc.* **1985**, *107*, 5178–5182. (h) Clennan, E. L.; Lewis, K. K. *J. Am. Chem. Soc.* **1987**, *109*, 2475–2478. (i) Clennan, E. L.; Nagraba, K. *J. Am. Chem. Soc.* **1988**, *110*, 4312–4318. (j) Matusch, R.; Schmidt, G. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 717–718.

(39) (a) Reference 7g, p 92, which is a slight modification of ref 39b. For alternate methods and spectral data see refs 39c,d and 40. (b) Bak, D. A.; Brady, W.T. *J. Org. Chem.* **1979**, *44*, 107–110. (c) Harding, K. E.; Trotter, J. W.; May, L.M. *J. Org. Chem.* **1977**, *42*, 2715–2719. (d) Brady, W. T.; Waters, O. H. *J. Org. Chem.* **1967**, *32*, 3703–3705.

Celite pad on a glass sinter, and the filtrate was taken up in 50 mL of ether. The ether solution was washed successively with water, saturated $NaHCO_3$ (carefully and several times), and saturated NaCl and then dried over $MgSO_4$. Removal of the ether *in vacuo* and distillation (42 °C/1 Torr) yielded 1.6 g (13 mmol, 36% yield) of a sweet smelling colorless oil, whose spectral data corresponded to that of the known ketone **20**.[40] Its higher field ^1H (300 MHz) and ^{13}C (75 MHz) NMR spectra are given below.

A flame-dried three-necked flask, fitted with a septum, a pressure-equalizing dropping funnel, and an efficient reflux condenser topped with a nitrogen bubbler, was charged with a magnetically stirred suspension of isopropyltriphenylphosphonium bromide[41] (10 g, 25 mmol) in dry THF (125 mL). *n*-Butyllithium (15.6 mL of a 1.6 M solution in hexane, 0.025 mol) was then injected through the septum yielding a red ylide solution which was allowed to stir at room temperature for another 15 min until all the salt dissolved. From the dropping funnel, ketone **20** (2.4 g, 0.02 mmol) in dry THF (70 mL) was added dropwise over 40 min. The reaction mixture was stirred for another 0.5 h at room temperature and then overnight at 60–65 °C. The reaction mixture was then cooled to room temperature, diluted with CH_2Cl_2 (200 mL), and extracted five times with 100-mL portions of H_2O. After the organic phase was dried ($MgSO_4$) and rotary evaporated, the resulting crude product (1.98 g) was chromatographed on an alumina column eluting with hexane yielding pure olefin **2** (0.315 g, 2.1 mmol, 10% yield). An analytical sample was obtained via preparative GC (T_{col} = 105 °C; R_f = 31 min).

In exploratory studies, we attempted to prepare olefin **2** via the addition of isopropylmagnesium bromide to ketone **20** and dehydration of the resulting 7-isopropyl-*cis*-bicyclo[4.2.0]octan-7-ol (**19**). This approach had proven successful for the preparation of isopropylidinebenzocyclobutene (**7**) (*vide infra*). While alcohol (**19**) was obtained in good yield, the dehydration resulted in a mixture of products, and this route was abandoned.

2: R_f (5% acetone in hexane) 0.357; ^1H NMR ($CDCl_3$) 2.92–2.78 (m, 1H, H_6), 2.56–2.44 (m, 1H, H_8), 2.37–2.18 (m, 2H, $H_{8'}$ and H_1), 1.80–1.32 (m, 7H), 1.545 (d, J = 1.5 Hz, 3H, isopropylidene CH_3), 1.498 (d, J = 1 Hz, 3H, isopropylidene CH_3), 1.28–1.18 (m, 1H); ^{13}C NMR ($CDCl_3$) δ 135.22 (C_7), 120.97 (C_9), 39.89 (C_6), 32.77 (C_8), 28.06 (C_1), 26.95 and 26.44 (C_2 and C_5), 21.85 and 21.60 (C_3 and C_4), 18.88 and 18.54 (C_{10} and C_{11}); MS (CI, 70 eV) m/z 151 (MH^+, 100), 135 (M – CH_3, 0.69), 109 (MH^+ – $[CH_3]_2C$, 1.98), 95 (MH^+ – C_4H_8, 58.95), 81 (MH^+ – C_4H_8 – CH_2, 11.51). Anal. Calcd ($C_{11}H_{18}$): C, 87.93; H 12.07. Found: C, 88.30; H, 12.34.

19: ^1H NMR ($CDCl_3$) 2.25–2.16 (1H), 2.08–1.89 (2.5H), 1.89–1.74 (2.5H) 1.74–1.33 (5H), 1.28–1.05 (1H), 0.92 and 0.89 (each d, J = 7 Hz, each 3H, diastereotopic isopropyl methyls); ^{13}C NMR ($CDCl_3$) 76.50 (C_7), 40.68 (C_6), 36.59 (C_8), 35.00 (C_9), 26.63 (C_2), 24.07 (C_1), 22.62 (C_5), 21.87 (C_3 and C_4), 15.96 (C_{10}), 15.76 (C_{11}); MS (EI, 70 eV) 168 (M^+, 12.69), 150 (M – H_2O, 10.87), 135 (M – H_2O – CH_3, 13.40), 125 (M – $(CH_3)_2CH_2$, 62.30), 97 (M – $(CH_3)_2CH_2CO$, 95.95), 93 (M – $C_4H_{11}O$, 14.92), 87 (M – C_6H_9 [cyclohexenyl], 100), 81 (C_6H_9, 40.53), 79 (M – C_6H_7, 44.50); HRMS calcd ($C_{11}H_{20}O$, M^+) 168.1514, obsd 168.1514.

20: ^1H NMR ($CDCl_3$) 3.28 (m, 1H, H_6), 3.14 (ddd, J = 17, 9, 2 Hz, 1H, H_8), 2.52 and 2.44 (overlapping m, each 1H, H_1 and $H_{8'}$), 2.16 and 1.96 (each m, each 1H, H_5 and $H_{5'}$), 1.57 (m, 2H), 1.43 (m, 1H), 1.16 (m, 3H); ^{13}C NMR ($CDCl_3$) δ 209.68 (C_7), 56.69 (C_6), 52.16 (C_8), 29.54 (C_2), 22.66 (C_1), 22.55 and 22.42 (C_3 and C_4), 21.27 (C_5).

Preparation of 1-Isopropylidene-3-*n*-butylcyclobutane (3), 2,2-Dichloro-3-*n*-butylcyclobutanone (42), and 3-*n*-Butylcyclobutanone (43). Dichlorobutanone **42** was prepared from 1-hexene (5 g; 59 mmol) according to the procedure of Krepski and Hassner[7a] and identified by its spectral data. The crude product (7.9 g; 40 mmol; 69% yield) is yellow-brown and can be used in the subsequent reduction without further purification. Pure colorless **42**, however, could be obtained via bulb-to-bulb distillation.

A three-necked 500 mL round-bottom flask, fitted with a reflux condenser topped with a N_2-inlet, a pressure-equalizing dropping funnel, and a magnetic stirrer, was charged with zinc powder (15.8 g; 0.241 mol) and glacial acetic acid (45 mL). From the dropping funnel, ketone **42** (7.9 g; 40 mmol) in glacial acetic acid (45 mL) was added, and an exothermic reaction occurred. After the reaction subsided, the reaction temperature was maintained at 60 °C for 1 h. The reaction mixture was cooled to room temperature, diluted with 100 mL of ether, filtered through Celite, washed successively with water, saturated $NaHCO_3$ solution, and saturated NaCl solution, dried over $MgSO_4$, and concentrated by rotary evaporation. Vacuum distillation (42 °C/3 Torr) gave a 55% yield of pure **43** (2.8 g; 22 mmol).

Wittig reaction between ketone **43** and isopropyltriphenylphosphonium bromide (essentially as described above for the preparation of compound **2**), followed by alumina column chromatography eluting with hexane, yielded olefin **3** in an 11% yield. An analytical sample was obtained via preparative GC (T_{col} = 120 °C; R_f = 11 min).

3: ^1H NMR ($CDCl_3$) 2.76–2.60 (m, 2H, H_2 and H_4), 2.20–2.08 (m, 3H, $H_{2'}$, H_3 and $H_{4'}$), 1.48 and 1.49 (each s, each 3H, isopropylidene methyls), 1.41 (sept, J = 7 Hz, 2H, H_5), 1.33–1.18 (m, 4H, H_6 and H_7), 0.89 (t with virtual coupling, J = 7 Hz, 3H, CH_3, H_8); ^{13}C NMR ($CDCl_3$) δ 129.47 (C_1), 122.28 (C_9), 37.13 (C_2 and C_4), 34.43 (C_3), 30.07 (C_5), 29.38 (C_6), 22.71 (C_7), 18.2 (C_{10} and C_{11}), 14.13 (C_8); MS (CI, 70 eV) m/z 177 (MH^+, 2.04) 123 (MH – $[CH_3]_2C$=C], 17.22), 109 (MH – $[CH_3]_2C$=C – CH_2], 100). Anal. Calcd ($C_{11}H_{20}$): C, 86.76; H, 13.24. Found: C, 87.11; H, 13.45.

42: ^1H NMR ($CDCl_3$) δ 3.35 (distorted dd, A of ABC pattern, J_{gem} = 17 Hz; $J_{3,4}$ = 9 Hz, 1H, H_4), 2.95 (highly distorted dd, B of ABC pattern, J_{gem} = 17 Hz; $J_{3,4'}$ = 9 Hz, 1H, $H_{4'}$), 2.85 (highly distorted t with second order splitting, C of ABC pattern, $J_{3,4}$ = $J_{3,4'}$ = 9 Hz, 1H, H_3), 1.98–1.86 (m, 1H, H_5), 1.66–1.54 (m, 1H, $H_{5'}$), 1.48–1.34 (m, 4H, H_6 and H_7), 0.94 (bt with virtual coupling, J = 7 Hz, 3H, CH_3, H_8); ^{13}C NMR ($CDCl_3$) δ 192.49 (C_1), 88.88 (C_2), 47.75 (C_4), 45.96 (C_3), 31.00 (C_5), 29.50 (C_6), 22.40 (C_7), 13.82 (C_8); FTIR (neat) 1811.9 (s, CO)[7a] cm^{-1}; MS (EI, 31 eV) m/z 198 (M + 4, 2.26), (M + 2, 7.72), 194 (M^+, 13.27), 159 (M – Cl, 15.73), 154 (M – C_3H_8, 43.35), 152 (M – CH_2CO, 57.19), 122 (M – HCl – Cl, 40.86), 116 (M – HCl – CH_2CO, 20.83), 111 (Cl_2CHCO), 95 (Cl_2CCH, 74), 81 (C_4H_9CC, 100), 69 (C_4H_9C, 70.70). Anal. Calcd ($C_8H_{12}OCl_2$): C, 49.25; H, 6.20. Found: C, 49.40; H, 6.35.

43: ^1H NMR ($CDCl_3$) δ 3.20–3.06 (m, 2H, H_2 and H_4), 2.74–2.60 (m, 2H, $H_{2'}$ and $H_{4'}$), 2.35 (sept with second order splitting, $J_{2,3}$ = $J_{2',3}$ = $J_{3,4}$ = $J_{3,4'}$ = $J_{3,5}$ = 7 Hz, 1H, H_3), 1.62–1.54 (q with virtual coupling, $J_{3,4}$ = $J_{4,5}$ = 7 Hz, 2H, H_4), 1.44–1.26 (m, 4H, H_6 and H_7), 1.01 (bt with virtual coupling, J = 6 Hz, 3H, CH_3, H_8); ^{13}C NMR ($CDCl_3$) δ 208.67 (C_1), 52.37 (C_2 and C_4), 23.72 (C_3), 35.91 (C_5), 30.33 (C_6), 22.36 (C_7), 13.88 (C_8); FTIR (neat) 1774.8 (s, CO)[14b] cm^{-1}; UV ($CDCl_3$) $_{max}$ = 286.8 nm; MS (CI, 70 eV) m/z 127 (MH^+, 100), 125 (M – 1, 51.52), 109 (M – OH, 87.62), 98 (M – CO, 30.29), 83 (M – C_3H_7, 41.91), 69 (M – C_4H_9, 45.33); MS (EI, 70 eV) m/z 127 (M^+ + 1, 67.27), 125 (M – 1, 22.08), 109 (M – OH, 69.39), 98 (M – CO, 100), 83 (M – C_3H_7, 90.45), 69 (M – C_4H_9, 100). Anal. Calcd (C_8H_4O): C, 76.14; H, 11.18. Found: C, 76.02; H, 10.90.

Preparation of 1-Isopropylidene-3-phenylcyclobutane (4), 2,2-Dichloro-3-phenylcyclobutanone (44), and 3-Phenylcyclobutanone (45). Dichlorobutanone **44** was prepared from in 80% yield from styrene according to the procedure of Krepski and Hassner[7a] as modified by Dillon[7g] and identified by its melting point (66–67 °C from ligroine)[7g] and spectral data.[7a,g,18d] The higher field ^1H and ^{13}C NMR data are given below.

Zinc/acetic acid reduction[7b,g] of **44**, followed by alumina column chromatography (eluting with 25% ethyl acetate in hexane), gave a 33% yield of colorless cinnamon-scented liquid, which was identified as cyclobutanone **45** by its spectral data. The ^1H NMR (60 MHz) data reported by Hassner and Dillon[7b,g] are clearly in error and should be shifted downfield by ca. 0.35 ppm, as is clear from the unequivocal higher field ^1H and ^{13}C NMR data reported below.

Wittig reaction between ketone **45** and isopropyltriphenylphosphonium bromide (essentially as described above for the

(40) Ghosez, L.; Montaigne, R; Roussel, A.; Vanlierde, H.; Mollet, P. *Tetrahedron* **1971**, *27*, 615–633.

(41) (a) Fagerlund, U. H. M.; Idler, D. R. *J. Am. Chem. Soc.* **1957**, *79*, 6473–6475. The product was recrystallized from ethanol–ether and dried in a vacuum oven at 100 °C before use. (b) Isopropyltriphenylphosphonium bromide can also prepared by heating Ph_3P (0.1 mol) and isopropyl bromide (0.14 mol) in 80 mL of refluxing xylene overnight. The product is washed with hot ligroine and recrystallized from 80 mL of boiling water.

preparation of compound 2), followed by alumina column chromatography eluting with hexane, yielded olefin 4 in an 20% yield.

4: ^{1}H NMR ($CDCl_3$) δ 7.34–7.14 (m, 5H, aromatic), 3.46 (tt, J = 9, 7.5 Hz, 1H, H_3), 3.16–3.00 (m, 2H, H_2 and H_4), 2.78–2.66 (m, 2H, $H_{2'}$ and $H_{4'}$), 1.56 (quint, J = 1.7, 6H, isopropylidene methyls); ^{13}C NMR ($CDCl_3$) 146.44 (C_{ipso}), 128.20(C_{meta}), 127.63 (C_1), 126.43 (C_{ortho}), 125.70 (C_{para}), 122.64 (C_5), 37.07 (C_2 and C_4), 18.39 (C_6 and C_7); MS (EI, 70 eV) m/z 172 (M^+, 32.85), 157 (M – CH_3, 27.94), 129 (M – $(CH_3)_2C$, 47.35), 104 (M – $PhCHCH_2$, 100), 91 ($PhCH_2$, 31.29); HRMS calcd ($C_{13}H_{16}O$, M^+) 172.1253, obsd 172.1253.

44: ^{1}H NMR ($CDCl_3$) δ 7.47–7.35 (m, 3H, aryl), 7.34–7.28 (m, 2H, aryl), 4.25 (t, $J_{3,4} = J_{3,4'}$ = 10 Hz, 1H, H_3), 3.64 (dd, $J_{4,4'}$ = 17.5 Hz, $J_{3,4}$ = 10 Hz, 1H, H_4), 3.55 (dd, $J_{4,4'}$ = 17.5 Hz, $J_{3,4'}$ = 10 Hz, 1H, $H_{4'}$); ^{13}C NMR ($CDCl_3$) δ 191.88 (C_1), 134.44 (C_{ipso}), 128.62 (C_{meta}), 128.31 (C_{para}), 128.04 (C_{ortho}), 89.56 (C_2), 50.57 (C_3), 45.77 (C_4).

45: ^{1}H NMR ($CDCl_3$) δ 7.40–7.22 (m, 5H, aromatic), 3.68 (quint, J = 8 Hz, 1H, H_3), 3.56–3.43 (m, 2H, H_2 and H_3), 3.32–3.20 (m, 2H, $H_{2'}$ and $H_{3'}$); ^{13}C NMR ($CDCl_3$) δ 206.56 (C_1), 143.53 (C_{ipso}), 128.65 (C_{meta}), 126.60 (C_{para}), 126.45 (C_{ortho}), 54.67 (C_2 and C_4), 28.44 (C_3); MS (CI, 70 eV) m/z 147 (MH^+, 100), 129 (MH – H_2O, 6.47), 119 (MH – CO, 8.91), 104 (MH – CH_2COH, 41.72).

Preparation of 1-Isopropylidene-3-methyl-3-vinylcyclobutane (5), 2,2-Dichloro-3-methyl-3-vinylcyclobutanone (46), 2,2-Dichloro-3-isopropenycyclobutanone (47), 3-Methyl-3-vinylcyclobutanone (48) and 3-Isopropenycyclobutanone (49). Dichlorobutanone **46** was prepared from isoprene (5 g; 73 mmol) according to the procedure of Krepski and Hassner[7a,c] with the following modifications: the reaction vessel was cooled in an ice bath during the 1-h addition of the ether solution of Cl_3CCOCl and $POCl_3$ and then stirred overnight at room temperature prior to workup. Spectral analysis[7c] of the crude product (11.2 g; 63 mmol; 85% yield) indicated it to be a mixture of **46** and **47** in a ratio of approximately 3:1. The 60 MHz NMR spectrum of the mixture has been reported,[7c] but the 300 MHz instrument permits a more definitive assignment. As has been previously noted, the product mixture is an unstable oil and was used in the next reduction step without further purification.

Zinc/acetic acid reduction of the above dichloride mixture, essentially as described above for **42**, followed by vacuum distillation (ca. 60 °C/10 Torr) gave a 59% yield (4.1 g; 37 mmol) of product which proved to be an isomeric mixture of **48** and **49** in a ratio of approximately 3:1. Compound **49** was also isolated from the reduction of the unsaturated analog of **47**, 4,4-dichloro-3-isopropenyl-2-cyclobuten-1-one.[7b,g] Spectral data for these two compounds have also been reported previously.[7c] The higher field ^{1}H and ^{13}C NMR spectra are given below.

Wittig reaction between the **48**/**49** ketone mixture and isopropyltriphenylphosphonium bromide (essentially as described above for the preparation of compound **2**), followed by alumina column chromatography eluting with hexane, yielded two major fractions. The first [R_f (hexane) 0.50] contained the desired olefin **5** (25% isolated yield based on **48**). The second fraction was analyzed by GC–MS and proved to be a mixture of five compounds, four with molecular weights of 136 [including **5** and 1-isopropylidene-3-isopropenylcyclobutane (**50**)] and one with a MW of 134. This latter fraction was not further investigated. An analytical sample of **5** was obtained via preparative GC (T_{col} = 92 °C; R_f = 10 min).

5: ^{1}H NMR ($CDCl_3$) δ 6.04 (ddd, J_{trans} = 17 Hz, J_{cis} = 10 Hz, J_{gem} = 2 Hz, 1H, H_5), 4.96 (dd, J_{trans} = 17 Hz, J_{gem} = 2 Hz, 1H, $H_{6(trans)}$), 4.88 (dd, J_{cis} = 10 Hz, J_{gem} = 2 Hz, 1H, $H_{6(cis)}$), 2.58 and 2.35 (broad AB quartet, J = 15 Hz, 4H, H_2 and H_4), 1.51 (quint, $J_{allylic}$ = 1.5 Hz, 6H, C_{10} and C_{11} methyls), 1.16 (s, 3H, C_3-methyl); ^{13}C NMR ($CDCl_3$) δ 147.35 (C_5), 125.82 (C_1), 123.90 (C_9), 109.61 (C_6), 41.20 (C_2 and C_4), 35.58 (C_3), 26.38 (C_3-methyl), 18.40 (C_{10} and C_{11}); MS (EI, 70 eV) m/z 136 (M^+, 11.73), 121 (M – CH_3, 37.41), 107 (M – CH_3 – CH_2, 10.38), 93 (M – $[CH_3]_2CH$, 39.14), 91 (M – 3 × CH_3, 13.41), 79 (M – CH_3 – $[CH_3]_2C$, 14.62), 67 (M – CH_3 – $[CH_3]_2C{=}C$, 35.41), 53 (M – CH_3–$[CH_3]_2C{=}C$ – CH_2, 11.38), 40 ($CH_2{=}CHCH$, 100); MS (CI, 70 eV) m/z 137 (MH^+, 35.67), 135 (M – 1, 50.88), 121 (M – CH_3, 14.33), 109 (M – CH_2CH, 14.62), 95 (MH – CH_3 – $CH_2{=}CH$, 100), 81 (M – CH_3 – $[CH_3]_2$-CH, 47.08), 69 (M – CH_3 – $[CH_3]_2C{=}CH$, 17.84). Anal. Calcd ($C_{10}H_{16}$): C, 88.16; H, 11.84. Found: C, 87.89; H, 12.04.

46: ^{1}H NMR ($CDCl_3$) δ 6.145 (dd, $J_{5-6(trans)}$ = 17 Hz, $J_{5-6(cis)}$ = 11 Hz, 1H, H_5), 5.365 (d, $J_{5-6(cis)}$ = 11 Hz, 1H, H_6), 5.23 (d, $J_{5-6(trans)}$ = 17 Hz, 1H, $H_{6'}$), 3.54 (d, J_{gem} = 17Hz, 1H, H_4), 2.96 (d, J_{gem} = 17Hz, 1H, $H_{4'}$), 1.48 (s, 3H, C_3-methyl); ^{13}C NMR ($CDCl_3$) δ 192.58 (C_1), 138.15 (C_5), 116.49 (C_6), 92.99 (C_2), 52.61 (C_4), 47.27 (C_3), 23.79 (C_4-methyl).

47: ^{1}H NMR ($CDCl_3$) δ 5.18–5.15 (m, 1H, H_6), 4.92–4.88 (m, 1H, $H_{6'}$), 3.54-3.40 (m, 2H, H_4, second order effects due to ABC system), 3.28–3.15 (m, 1H, H_3, second order effects due to ABC system), 1.98–1.96 (m, 3H, C_5-methyl); ^{13}C NMR ($CDCl_3$) δ 191.88 (C_1), 139.58 (C_5), 114.18 (C_6), 90.07 (C_2), 51.90 (C_4), 44.30 (C_4), 22.09 (C_5-methyl).

48: ^{1}H NMR ($CDCl_3$) δ 6.14 (dd, $J_{5-6(trans)}$ = 17 Hz, $J_{5-6(cis)}$ = 11 Hz, 1H, H_5), 5.11 (d, $J_{5-6(trans)}$ = 17 Hz, 1H, $H_{6'}$), 5.09 (d, $J_{5-6(cis)}$ = 11 Hz, 1H, H_6), 3.20–2.95 (m, 2H, H_2 and H_4), 2.89–2.72 (m, 2H, $H_{2'}$ and $H_{4'}$), 1.42 (s, 3H, C_3-methyl); ^{13}C NMR ($CDCl_3$) δ 206.71 (C_1), 144.67 (C_5), 111.95 (C_6), 58.16 (C_2 and C_4), 31.39 (C_3), 25.95 (C_4-methyl).

49: ^{1}H NMR ($CDCl_3$) δ 4.88 (bs, 1H, H_6), 4.84 (bs, 1H, $H_{6'}$), 3.26–3.10 (m, 2H, H_2 and H_4), 3.09–2.97 (m, 3H, $H_{2'}$ H_3 and $H_{4'}$), 1.81 (s, 3H, C_5-methyl); ^{13}C NMR ($CDCl_3$) δ 206.59 (C_1), 145.72 (C_5), 109.99 (C_6), 51.32 (C_2 and C_4), 30.01 (C_3), 20.53 (C_5-methyl).

Preparation of 1-Isopropylidene-3-phenyl-2-cyclobutene (6), 4,4-Dichloro-3-phenyl-2-cyclobuten-1-one (50), and 3-Phenyl-2-cyclobuten-1-one (51). Dichlorobutanone **50** was prepared in a 77% yield according to Hassner and Dillon.[7b,g] Although our ^{13}C NMR spectrum of **50** matched exactly with that reported by Hassner and Dillon,[7b,g] their 60-MHz ^{1}H NMR data are clearly in error and should be shifted downfield by ca. 0.2 ppm. The unequivocal 300-MHz ^{1}H data is reported below.

Activated zinc/acetic acid–pyridine reduction of **50** as described by Dreiding[7d] led to extensive reduction of the desired cyclobutenone **51** to the saturated analog **45**. On the other hand, Danheiser's[7f] TMEDA/zinc dust procedure proved totally ineffective in this instance. The Dreiding[7d] procedure was, therefore, modified as follows: the activated zinc[7a,g] was added under N_2 to an *ice bath chilled* glacial HOAc–pyridine solution of dichloride **50** over a 20 min period, and the reaction mixture was then allowed to stir at room temperature for another 20 min. Following workup, neutral alumina column chromatography (eluting with 25% ethyl acetate in hexane) gave, in addition to a 15% yield of cyclobutanone **45**, a 60% yield of the desired unsaturated analog **51**. The latter was identified by its spectral data and melting point (52 °C from ethyl acetate–hexane).[7a,g,h]

Wittig reaction between ketone **51** and isopropyltriphenylphosphonium bromide (essentially as described above for the preparation of compound **2**), followed by alumina column chromatography eluting with hexane, yielded olefin **6** in an 40% yield as a white solid (mp 63 °C). The product undergoes facile autoxidation at room temperature and was, therefore, stored in the freezer under argon or photooxidized immediately upon isolation. Solutions of **6** have a purple fluorescence.

6: ^{1}H NMR ($CDCl_3$) δ 7.50–7.17 (m, 5H, aryl), 6.67 (s, 1H, H_3), 3.12 (s, 2H, H_4), 1.78 and 1.71 (each s, each 3H, C_6 and C_7 methyls); ^{13}C NMR ($CDCl_3$) δ 144.77 (C_3), 134.60 (ipso), 131.41 (C_1) 128.30 (meta), 127.43 (para), 126.53 (C_2), 124.87 (ortho), 117.39 (C_5), 34.30 (C_4), 19.19 and 18.84 (C_6 and C_7); MS (EI, 70 eV) m/z 170 (M^+, 51.15), 155 (M – CH_3, 100), 128 (M – $[CH_3]_2C$, 23.38), 115 (M – $[CH_3]_2CCH$, 22.76), 102 (M – $[CH_3]_2CCCH_2$, 20.51). HRMS calcd ($C_{13}H_{14}$, M^+) 170.1096, obsd 170.1095.

50: ^{1}H NMR ($CDCl_3$) δ 7.94 (d with second order splitting, J = 8, 1.5 Hz, 1H, ortho), 7.92 (d with second order splitting, J = 8, 1.5 Hz, 1H, ortho'), 7.68–7.55 (m, 3H, meta and para), 6.67 (s, 1H, H_2),

51: ^{1}H NMR ($CDCl_3$) δ 7.66–7.60 (m, 2H, aryl), 7.54–7.48 (m, 3H, aryl), 6.38 (s, 1H, H_2), 3.55 (s, 2H, H_4); ^{13}C NMR ($CDCl_3$) δ 187.31 (C_1), 170.94 (C_3), 131.92 (C_2), 131.36 (ipso), 129.72, 128.93, 128.79, 48.55 (C_4).

Preparation of Isopropylidenebenzocyclobutene (7) and 1-Isopropybenzocyclobuten-1-ol (52). Benzocyclobutanone[6] (4.1 g; 0.034 mol) in 50 mL of ether was slowly added to an ether solution (50 mL) of isopropylmagnesium bromide, prepared from 2 g (0.082 mol) of magnesium and 9.2 g (0.075 mol) of 2-bromopropane, at a rate which maintained a gentle reflux.[5,42] After

(42) Horner, L.; Subramaniam, P. V.; Eiben, K. *Leibigs Ann. Chem.* 1968, *714*, 91–111.

spontaneous boiling ceased, the reaction mixture was further refluxed for 0.5 h and cooled to room temperature, and 100 mL of a cold aqueous saturated NH_4Cl solution was added to the reaction vessel. The aqueous layer was extracted twice with ether. The ether layer and washings were combined, dried over $MgSO_4$, and concentrated to a yellowish oil (4.49 g, 0.027 mol, 82% yield). The product was identified as benzocyclobutenol **52** by its spectral data which were similar to that of the 1-ethyl[5] and 1-prop-2'-enyl analogs.[43] Alcohol **52** was generally suitable for further use without further purification; however, an analytical sample was obtained by distilling (80–80 °C/5 Torr) the crude product and then chromatographing the colorless distillate on an alumina column eluting with 10% acetone in hexane.

Alcohol **52** (7.84 g; 0.048 mol) and a few crystals of I_2 were distilled (95 °C/25 Torr) through a Vigreux column to yield 5.07 g of a mixture of water, iodine, and oily product. TLC revealed the latter to be a mixture of substrate and product. Column chromatography on alumina yielded 2.5 g (0.017 mol, 36% yield) of olefin **7** which solidified on storing in the freezer. Alternatively, alcohol **40** (2.75 g; 0.017 mol) can be dehydrated by refluxing it under N_2 in anhydrous ether (100 mL) for 7 h with boron trifluoride etherate (10 mL). Water (100 mL) was then added to the cooled reaction mixture, and the aqueous layer was extracted thrice with ether. The combined ether layer and washings were combined, washed with water and a saturated NaCl solution, dried over $MgSO_4$, and concentrated to an oil (2.2 g). Column chromatography as before yielded 0.8 g (0.0054 mol; 32% yield) of the desired isopropylidenebenzocyclobutene (**7**).[44] Because of the olefin's tendency to autoxidize to the corresponding epoxide **25**, it was stored under argon in the freezer until use. An analytical sample was obtained via preparative GC (T_{col} = 100 °C; R_f = 54 min.). The spectral data were similar to that reported for ethylidenebenzocyclobutene.[45]

7: R_f (5% acetone in hexane) 0.53; ^1H NMR ($CDCl_3$) 7.12 (m, 4H, aryl), 3.48 (s, 2H, ring CH_2), 1.95 (s, 3H, isopropyl CH_3 *cis* to aromatic ring), 1.75 (s, 3H, isopropyl CH_3 *trans* to aromatic ring); ^{13}C NMR ($CDCl_3$) 145.46 (C_2), 143.19 (C_7), 131.16 (C_1), 126.95 and 126.88 (C_4 and C_5), 124.38 (C_9), 122.37 and 118.66 (C_3 and C_6), 36.60 (C_8), 20.57 and 19.77 (C_{10} and C_{11}); MS (CI, 70 eV) *m/z* 145 (MH^+, 100), 91 ($C_7H_7^+$, 3.98); UV ($CHCl_3$)$_{max}$ = 306 nm. Anal. Calcd ($C_{11}H_{12}$): C, 91.56; H, 8.34. Found: C, 91.82; H, 8.07.

52: R_f (10% acetone in hexane) 0.46; R_f (5% acetone in hexane) 0.17; ^1H NMR ($CDCl_3$) δ 7.13–7.02 (m, 4H, aryl), 3.37 and 3.03 (ABq, *J* = 14 Hz, 2H, ring CH_2), 2.20 (bs, 1H, OH), 2.02 (sept, *J* = 7 Hz, 1H, isopropyl methyne), 1.03 and 1.08 (each d, *J* = 7 Hz, each 3H, isopropyl methyls); ^{13}C NMR ($CDCl_3$) δ 149.81 (C_2), 141.90 (C_7), 129.05 and 126.91 (C_4 and C_5), 123.77 and 121.45 (C_3 and C_6), 83.93 (C_1), 44.81 (C_8), 35.34 (C_9), 17.30 and 17.20 (C_{10} and C_{11}); FTIR ($CDCl_3$) 3400 (s, br, OH) cm^{-1}; MS (CI, 70 eV) *m/z* 163 (MH^+, 4.03), 161 (M – H, 7.89), 145 (MH – H_2O, 100), 119 (M – C_3H_7, 11.24); MS (EI, 70 eV) *m/z* 162 (M^+, 0.2), 145 (M – OH, 0.2), 129 (M – H_2O – CH_3, 1.94), 119 (M – C_3H_7, 100), 91 ($C_7H_7^+$, 23.82). Anal. Calcd ($C_{11}H_{14}O$): C, 81.44; H 8.70. Found: C, 81.18; H, 8.86.

Preparation of 1-Isopropylidene-3-*n*-butyl-2-cyclobutene (8) and 3-*n*-Butyl-1-isopropyl-2-cyclobuten-1-ol (53). Alcohol **53** was prepared in 95% yield from 3-*n*-butyl-2-cyclobuten-1-one (**54**)[7f,46] and isopropylmagnesium bromide and subsequently dehydrated to olefin **8** in a 30% yield with BF_3 etherate (essentially as described for the preparation of cyclobutene **7**). Alternatively, a Wittig reaction between ketone **54** and isopropyltriphenylphosphonium bromide (as described above for the preparation of compound **2**), followed by alumina column chromatography eluting with hexane, yielded olefin **8** in a 40% yield. The product undergoes facile autoxidation at room temperature and was, therefore, stored in the freezer under argon or photooxidized immediately upon isolation.

8: ^1H NMR ($CDCl_3$) δ 6.12 (bt, *J* = 0.5, 1H, H_3), 2.74 (s, 2H, H_4), 2.22 (bt with virtual coupling, *J* = 6 Hz, 2H, H_5), 1.69 (d, *J* = 0.5 Hz, 3H, isopropylidene CH_3), 1.61 (s, 3H, isopropylidene CH_3), 1.54–1.20 (m, 4H, H_6 and H_7), 0.91 (t with virtual coupling, *J* = 7 Hz, 3H, H_8); ^{13}C NMR ($CDCl_3$) δ 151.55 (C_3), 127.84 (C_2), 131.92 (C_1), 113.12 (C_9), 36.68 (C_4), 30.61 (C_5), 29.28 (C_6), 22.58 (C_7), 18.94 and 18.52 (C_{10} and C_{11}), 13.95 (C_8); MS (EI, 70 eV) *m/z* 150 (M^+, 100), 135 (M – CH_3, 20.16), 121 (M – C_2H_5, 46.57), 107 (M – C_3H_7, 72.31), 93 (M – C_4H_9, 68.62), ($C_4H_9CHCH_2$, 87.37). Anal. Calcd ($C_{11}H_{18}$): C, 87.93; H, 12.07. Found: C, 88.22; H, 11.71.

53: ^1H NMR ($CDCl_3$) δ 5.82 (s, 1H, H_2), 2.49 and 2.21 (AB q, *J* = 13 Hz, 2H, H_3), 2.05 (t with virtual coupling, *J* = 8 Hz, 2H, H_5), 1.80 (sept, *J* = 6 Hz, 1H, H_9), 1.50–1.20 (m, 4H, H_6 and H_7), 0.96 (d, *J* = 7 Hz, 6H, H_{10} and H_{11}), 0.90 (t with virtual coupling, *J* = 7 Hz, 3H, H_8); ^{13}C NMR ($CDCl_3$) δ 152.43 (C_3), 131.74 (C_2), 79.32 (C_1), 44.33 (C_4), 35.09 (C_9), 30.46 (C_5), 28.65 (C_6), 22.47 (C_7), 17.45 and 17.26 (C_{10} and C_{11}), 13.92 (C_8); MS (CI, 70 eV) *m/z* 169 (MH^+, 10.81), 151 (MH – H_2O, 100), 125 (MH – $[CH_3]_2CH_2$, 5.13); MS (EI, 70 eV) *m/z* 168 (M^+, 1.28), 150 (M – H_2O, 37.30), 135 (M – CH_3 – H_2O, 17.32), 125 (M – C_3H_7, 31.75), 121 (M – C_2H_5 – H_2O, 56.35), 107 (M – C_3H_7 – H_2O, 63.12), 93 (M – C_4H_9 – H_2O, 100) HRMS calcd ($C_{11}H_{20}O$, M^+) 168.1514, obsd 168.1513.

General Photooxidation Procedure. The previously described photooxidation apparatus[10] was flushed with oxygen and charged with pure olefin (ca. 250 mg) dissolved in 2 mL of $CHCl_3$ to which a spatula tipful of polymer-based Rose Bengal (p-RB, Dye Tel Inc., POB 23, Perrysburg, OH) was added. The sample was irradiated (λ > 360 nm) until oxygen uptake essentially ceased (ca. 2 h), which generally occurred at 90–100% of the theoretical oxygen uptake (ca. 22.4 mL per mmol of substrate). A 10% excess of Ph_3P (1.1 equiv as compared to substrate) was then added to the chilled reaction mixture, with the reduction of the hydroperoxide reaction product(s) usually accompanied by an exothermic reaction and at times vigorous bubbling of the solvent. The polymer-based sensitizer was removed by filtering the reaction solution through a cotton plug, and the products were isolated by GC, PTLC, or column chromatography, as appropriate, and characterized by their spectral data. In the photooxidation of olefins **2–5**, the product proved to be a mixture of epimers in a ratio shown in eq 3; the ^1H and ^{13}C NMR data were extracted from this mixture. The reason for the assignment of **10, 12, 14,** and **16** as the major products is discussed in the text. DABCO (10^{-5}–10^{-3} M) and DTBP (0.4 M) were added to the photooxidation solution to determine, respectively, whether $^1O_2$ or free-radical processes were involved. Competition studies to determine the k_r of the various substrates as compared to TME were carried out by NMR.[1c] The experimental error for these measurements was <10%.

Singlet Oxygenation of 2. The crude reduced product was loaded on to an alumina column and eluted with 5% acetone in hexane.

9: ^1H NMR ($CDCl_3$) δ 5.02 (bd, 1H, vinyl H), 4.90 (1H, under downfield vinyl H of **10**, vinyl H), 1.82 (dd, 3H, CH_3), the remaining absorptions are too small and/or are hidden under **10**; ^{13}C NMR ($CDCl_3$) 148.18 (C_9), 109.71 (C_{10}), ca. 77 (presumably under $CDCl_3$ peaks, see Discussion, C_7), 40.44 (C_6), 35.80 (C_8), 29.41 (C_1), 24.42 (C_2), 22.80, 21.98, and 21.91 (C_3, C_4 and C_5), 17.94 (C_{11}).

10: ^1H NMR ($CDCl_3$) δ 4.90 (quint, $J_{allylic}$ = J_{gem} = 1.3 Hz, 1H, vinyl H *trans* to CH_3), 4.82 (bd, J_{gem} = 1.3 Hz, $J_{allylic}$ = 0.7 Hz, 1H, vinyl H *cis* to CH_3), 2.88–2.74 (m, 1H, H_1), 2.32 (t, J_{vic} = J_{gem} = 11 Hz, 1H, H_8), 2.26–2.13 (m, 1H), 1.72 (ddd, *J* = 11.5, 8 and 5 Hz, 1H, H_6), 1.69 (dd, $J_{allylic}$ = 1.3 Hz, $J_{allylic}$ = 0.75 Hz, 3H, CH_3), 1.60–1.36 and 1.36–0.93 (overlapping m, 6H, H_{eq} and H_{ax}); ^{13}C NMR ($CDCl_3$) δ 147.70 (C_9), 111.58 (C_{10}), 80.77 (C_7), 42.28 (C_6), 33.09 (C_8), 26.34 (C_1), 26.16 (C_2), 23.76, 22.99, and 21.46 (C_3, C_4 and C_5), 17.94 (C_{11}).

Epimeric mixture of 9 and 10: MS (EI, 70 eV) *m/z* 166 (M^+, 4.97), 151 (M – CH_3, 4.89), 148 (M – H_2O, 6.53), 133 (M – H_2O – CH_3, 8.09), 124 (M – C_3H_6, 6.05), 123 (M – C_3H_7, 6.02), 119 (M – C_2H_5 – H_2O, 6.92), 105 (M – C_3H_7 – H_2O, 21.37), 97 (M – C_5H_9, 11.6), 91 (M – C_4H_9 – H_2O, 25.68), 84 (M – C_6H_{10}, 100), 79 (M – C_5H_9 – H_2O, 26.01) HRMS calcd ($C_{11}H_{18}O$, M^+) 166.1358, obsd 166.1370.

(43) Adam, G.; Andrieux, J.; Plat, M. *Tetrahedron Lett.* **1981**, *22*, 3181–3184.

(44) (a) The preparation of this olefin has been reported in the literature, but no experimental or spectral data are given. (b) Tsushima, K.; Matsuo, N.; Itaya, N.; Yano, T.; Hatakoshi, M. In *Pesticide Chemistry: Human Welfare and the Environment*; Proceedings of the Fifth International Congress Of Pesticide Chemistry, Kyoto, 1982, Miyamoto, J., Kearney, P., Eds.; Pergamon: Oxford, 1982; pp 91–94.

(45) See ref 5 and Table 1 (p 1672), entries 15 and 16.

(46) For alternate preparations and spectral data of this compound, see also refs 7b,d,e.

Singlet Oxygenation of 3. The crude reduced product mixture was purified by preparative TLC, eluting three times with 10% acetone in hexane. The ^{1}H NMR assignments were assisted by resolution enhancement and a COSY experiment.

11: ^{1}H NMR ($CDCl_3$) δ 5.01 (bdq, J_{gem} = 1.5 Hz, $J_{allylic}$ = 0.8 Hz, 1H, vinyl), 4.87 (quint, $J_{allylic}$ = J_{gem} = 1.5 Hz, 1H, vinyl), 2.53–2.46 (m, 1H, H_3), 1.82 (dd, $J_{allylic}$ = 1.5 and 0.8 Hz, 3H, allylic CH_3), 1.80–1.50 (m, 4H, H_2, $H_{2'}$, H_4 and $H_{4'}$), 1.50–1.16 (m, 6H, H_5, H_6 and H_7), 0.89 (t with virtual coupling, J = 7 Hz, 3H, CH_3, H_8); ^{13}C NMR ($CDCl_3$) δ 147.47 (C_9), 109.59 (C_{10}), 73.89 (C_1), 41.05 (C_2 and C_4), 37.02 (C_5), 29.64 (C_6), 25.84 (C_3), 22.63 (C_7), 17.59 (C_{11}), 14.07 (C_8).

12: ^{1}H NMR ($CDCl_3$) δ 4.88 (dq, J_{gem} = 1.5 Hz, $J_{allylic}$ = 0.8 Hz, 1H, vinyl), 4.79 (quint, $J_{allylic}$ = J_{gem} = 1.5 Hz, 1H, vinyl), 2.45 (sept, J = 8 Hz, 1H, H_3), 2.18–2.08 (m, 2H, H_2 and H_4), 1.93–1.83 (m, 2H, $H_{2'}$ and $H_{4'}$), 1.75 (dd, $J_{allylic}$ = 1.5 and 0.8 Hz, 3H, allylic CH_3), 1.50–1.16 (m, 6H, H_5, H_6 and H_7), 0.88 (t with virtual coupling, J = 7 Hz, 6H, CH_3, H_8); ^{13}C NMR ($CDCl_3$) δ 149.90 (C_9), 109.29 (C_{10}), 76.39 (C_1), 39.76 (C_2 and C_4), 36.51 (C_5), 29.64 (C_6), 27.96 (C_3), 22.63 (C_7), 17.31 (C_{11}), 14.07 (C_8).

Epimeric mixture of 11 and 12: MS (EI, 70 eV) m/z 168 (M^+, 0.41), 153 (M – CH_3, 2.84), 150 (M – H_2O, 2.74), 125 (M – C_3H_7, 2.19), 121 (M – C_2H_5 – H_2O, 1.76), 111 (M – C_4H_9, 18.97), 107 (M – C_3H_7 – H_2O, 8.74), 93 (M – C_4H_9 – H_2O, 29.95), 84 ($C_4H_9CHCH_2$, 100); HRMS calcd ($C_{11}H_{12}O$, M^+) 168.1515, obsd 168.1535.

Singlet Oxygenation of 4. The crude reduced product was loaded on to a preparative TLC and eluted three times with 10% acetone in hexane.

13: ^{1}H NMR ($CDCl_3$) δ 5.15 (bdq, $J_{allylic}$ = 1.5 Hz, J_{gem} = 1 Hz, 1H, vinyl), 4.99 (quint, J_{gem} = $J_{allylic}$ = 1.5 Hz, 1H, vinyl), 3.00 (quint with second order splitting, J = 4 Hz, 1H, H_3), 2.86–2.76 (m, 2H, H_2 and H_4), 2.34–2.20 (m, 2H, $H_{2'}$ and $H_{4'}$), 1.90 (dd, $J_{allylic}$ = 1.5 Hz and 1 Hz, 3H, CH_3); ^{13}C NMR ($CDCl_3$) δ 147.11 (C_5), 145.31 (C_{ipso}), 128.34 (C_{meta}), 126.46 (C_{ortho}), 125.94 (C_{para}), 109.79 (C_6), 76.19 (C_1), 40.91 (C_2 and C_4), 32.83 (C_3), 17.35 (C_7).

14: ^{1}H NMR ($CDCl_3$) δ 4.91 (dq, $J_{allylic}$ = 1.5 Hz, J_{gem} = 1 Hz, 1H, vinyl), 4.83 (quint, J_{gem} = $J_{allylic}$ = 1.5 Hz, 1H, vinyl), 3.82 (quint with second order splitting, J = 4 Hz, 1H, H_3), 2.52–2.34 (m, 4H, H_2, $H_{2'}$, H_4 and $H_{4'}$), 1.78 (dd, $J_{allylic}$ = 1.5 Hz and 1 Hz, 3H, CH_3); ^{13}C NMR ($CDCl_3$) δ 149.27 (C_5), 144.95 (C_{ipso}), 128.34 (C_{meta}), 126.66 (C_{ortho}), 126.02 (C_{para}), 110.40 (C_6), 73.34 (C_1), 42.33 (C_2 and C_4), 31.95 (C_3), 17.67 (C_7).

Epimeric mixture of 13 and 14: MS (EI, 70 eV) m/z 188 (M^+, 5.22), 173 (M – CH_3, 2.77), 170 (M – H_2O, 5.54), 155 (M – H_2O – CH_3, 7.77), 129 (M – H_2O – CH_2CCH_3, 8.62), 115 (M – HOCC(CH_3)CH_2, 7.85), 110 (M – C_6H_6, 2.22), 104 (M – $PhCHCH_2$, 100), 91 (M – $PhCH_2$, 14.23), 84 (M – $PhCHCH_2$, 50.52); HRMS calcd ($C_{13}H_{16}O$, M^+) 188.1202, obsd 188.1205.

Singlet Oxygenation of 5. The crude reduced product was purified via preparative TLC, eluting twice with 20% acetone in hexane. The desired product had an R_f of 0.17.

15: ^{1}H NMR ($CDCl_3$) δ 5.95 (dd, $J_{5-6(trans)}$ = 17 Hz, $J_{5-6(cis)}$ = 11 Hz, 1H, H_5), 4.93 (bd, J_{gem} = 1.5 Hz, 1H, H_7), 4.91 (dd, $J_{5-6(cis)}$ = 11 Hz, J_{gem} = 2 Hz, 1H, $H_{6(cis)}$), 4.86 (dd, $J_{5-6(trans)}$ = 17 Hz, J_{gem} = 2 Hz, 1H, $H_{6(trans)}$), 4.83 (quint, J_{gem} = $J_{allylic}$ = 1.5 Hz, 1H, $H_{7'}$), 2.46 and 1.96 (AB q with second order splitting, J_{gem} = 13 Hz, 4H, H_2 and H_4), 1.76 (dd, $J_{allylic}$ = 1.5 Hz and 1 Hz, 3H, C_7-methyl), 1.40 (s, 3H, C_4-methyl); ^{13}C NMR ($CDCl_3$) δ 149.29 (C_6), 147.63 (C_5), 109.90 (C_8), 109.81 (C_6), under $CHCl_3$ (C_1), 44.74 (C_2 and C_4), 33.35 (C_3), 27.53 (C_3-methyl), 17.39 (C_9).

16: ^{1}H NMR ($CDCl_3$) δ 6.17 (dd, $J_{5-6(trans)}$ = 17 Hz, $J_{5-6(cis)}$ = 11 Hz, 1H, H_5), 5.03 (dd, $J_{5-6(trans)}$ = 17 Hz, J_{gem} = 2 Hz, 1H, $H_{6(trans)}$), 5.00 (bd, J_{gem} = 1.5 Hz, 1H, H_7), 4.98 (dd, $J_{5-6(cis)}$ = 11 Hz, J_{gem}=2 Hz, 1H, $H_{6(cis)}$), 4.90 (quint, J_{gem} = $J_{allylic}$ = 1.5 Hz, 1H, $H_{7'}$), 2.31 and 2.18 (AB q with second order splitting, J_{gem} = 13 Hz, 4H, H_2 and H_4), 1.80 (dd, $J_{allylic}$ = 1.5 Hz and 1 Hz, 3H, C_7-methyl), 1.16 (s, 3H, C_4-methyl); ^{13}C NMR ($CDCl_3$) δ 149.50 (C_6), 148.25 (C_5), 110.49 (C_8), 110.05 (C_6), under $CHCl_3$ (C_1), 42.21 (C_2 and C_4), 32.35 (C_3), 26.84 (C_3-methyl), 17.34 (C_9).

Epimeric mixture of 15 and 16: MS (EI, 70 eV) 152 (M^+, 0.38), 137 (M – CH_3, 11.11), 134 (M – H_2O, 6.15), 119 (M – CH_3 – H_2O, 20.91), 109 (M – C_2H_3O, 17.50), 84 (M – CH_2=CHC[CH_3]CH_2, 100), 69 (CH_2=C[CH_3]C=O, 91.85); MS (CI, 70 eV) m/z 151 (M – 1, 2.2), 135 (MH^+ – H_2O, 100), 107 (MH^+ – H_2O – C_2H_4, 34.07), 93 (MH^+ – H_2O – CH_2=$CHCH_3$, 49.45), 69 (CH_2=C[CH_3]C=O, 76.92); HRMS calcd ($C_{10}H_{16}O$, M^+) 152.1202, obsd 152.2221; calcd ($C_9H_{13}O$, M^+ – CH_3) 137.0967, obsd 137.0974; calcd ($C_{10}H_{14}$, M^+ – H_2O) 134.1096, obsd 134.1101.

Singlet Oxygenation of 6. The photooxidation was complete and yielded hydroperoxide **21a** as the sole product. The latter could be isolated essentially pure by stripping off the solvent and proved to be relatively stable. Upon Ph_3P reduction, allylic alcohol **21b** was obtained, but undergoes facile rearrangement at room temperature to as yet undetermined products and was, therefore, difficult to purify. Cyclobutanol **21b** was independently synthesized by reacting isopropenylmagnesium bromide with 3-phenyl-2-cyclobuten-1-one (**51**) according to the procedure of Sammes and co-workers.[25] We note that not only the Grignard addition but also preparation of the Grignard reagent itself (from isopropenyl bromide and magnesium with a trace of iodine) was carried out in an ice bath cooled reaction flask.

21a: ^{1}H NMR ($CDCl_3$) δ 8.10 (bs, 1H, OOH), 7.44–7.00 (m, 5H, aryl), 6.48 (s, 1H, H_2), 5.04 (bs, 1H, H_6 vinyl *cis* to CH_3), 4.98 (bq, $J_{allylic}$ = 1.5 Hz, 1H, H_6 vinyl *trans* to CH_3),[40] 2.82 (s, 2H, H_4), 1.81 (bs, 3H, H_7); ^{13}C NMR ($CDCl_3$) δ 149.30 (C_5), 143.75 (C_3), 133.38 (ipso), 128.83 (para), 128.31 (meta), 126.66 (C_2), 125.32 (ortho), 114.07 (C_6), 86.95 (C_1), 38.60 (C_4), 18.37 (C_7); MS (EI, 70 eV) 202 (M^+, 4.09), 186 (M – O, 9.92), 185 (M – OH, 21.93), 184 (M – H_2O, 58.19), 169 (M – OOH, 42.25), 154 (M – OOH – CH_3, 29.99), 145 (M – OH – [CH_3CCH], 13.68), 144 (M – OH – [CH_3CCH_2], 28.23), 141 (M – OOH – C_2H_4, 42.47), 129 (M – OOH – [CH_3CCH], 31.45), 128 (M – OOH – [CH_3CCH_2], 25.22), 115 (M – HOOCHC[CH_3]CH_2), 100); HRMS calcd ($C_{13}H_{14}O_2$, M^+) 202.0994, obsd 202.0986.

21b: ^{1}H NMR ($CDCl_3$) δ 7.55–7.00 (m, 5H, aryl), 6.48 (s, 1H, H_2), 5.10 (bq, J = 1 Hz, 1H, H_6 vinyl *cis* to CH_3), 4.88 (bq, $J_{allylic}$ = 1.5 Hz, 1H, H_6 vinyl *trans* to CH_3),[40] 3.07 and 2.80 (ABq, J = 12 Hz, 2H, H_4), 1.88 (bs, 3H, H_7); ^{13}C NMR ($CDCl_3$) δ 142.30 (C_5), 140.55 (C_3), 133.57 (ipso), 128.32 (para), 127.61 (meta), 125.83 (C_2), 125.05 (ortho), 116.03 (C_6), 77.21 (C_1), 44.42 (C_4), 17.70 (C_7); MS (EI, 70 eV) 186 (M^+, 6.71), 171 (M – CH_3, 28.27), 144 (M – C_2H_2O, 34.69), 143 (M – C_2H_3O, 47.54), 129 (M – OH – [CH_3-CCH], 100), 128 (M – OH – [CH_3CCH_2], 43.5); MS (CI, 70 eV) m/z 187 (MH^+, 100), 169 (MH^+ – H_2O, 82.26), 159 (MH^+ – 28, 32.31); HRMS calcd ($C_{13}H_{14}O$, M^+) 186.1045, obsd 186.1086.

Singlet Oxygenation of 7. The photooxidation of **7** in $CHCl_3$ was rapid, with 90% of the theoretical uptake of oxygen already absorbed within the first hour, and accompanied by sensitizer bleaching. The NMR spectrum of the crude product mixture after Ph_3P reduction revealed the presence of three products corresponding to allylic alcohol **22** (92%) and isomeric enals **23** (5%) and **24** (3%). The ratio of photooxidation products **22**:**23**:**24** was 96:2:2 in benzene, while only negligible amounts of enals (<1%) could be observed with CH_3OH or CH_3CN. Hydroperoxide **30** (accompanied by small amounts of **22**–**24**) was observed in reaction mixtures not reduced with Ph_3P and was stable for at least 2 weeks at room temperature. The oxygenation was slowed dramatically by DABCO but not by DTBP, nor did either have an effect on the product distribution. Products **22**–**24** were separated from the reaction mixture (containing Ph_3P and Ph_3PO) by PTLC, eluting with 5% acetone in hexane. Aldehydes **23** and **24** were obtained as a mixture. Upon standing in $CHCl_3$ solution, **22** rearranges slowly to the commercially available (Aldrich) 2-methyl-1-tetralone (**31**). The ^{1}H NMR spectrum of the vinyl analog of **22**, cyclobutanol **33**, has been reported.[25b]

22: R_f (5% acetone in hexane) 0.10; ^{1}H NMR ($CDCl_3$) 7.35–7.05 (m, 4H, aryl), 5.06 (dq, J_{gem} = 2 Hz, $J_{cis\text{-}allylic}$ = 1 Hz, 1H, vinyl *cis* to CH_3),[47] 4.89 (quint, J_{gem} = 2 Hz, $J_{trans\text{-}allylic}$ = 2 Hz, 1H, vinyl *trans* to CH_3), 3.49 and 3.25 (AB q, J_{gem} = 14 Hz, each 1H, cyclobutyl methylene), 1.85 (dd, $J_{trans\text{-}allylic}$ = 2 Hz, $J_{cis\text{-}allylic}$ = 1 Hz, CH_3); ^{13}C NMR ($CDCl_3$) δ 148.48 (C_2), 145.91 (C_9), 142.09 (C_7), 129.33 (C_5), 127.21 (C_4), 124.01 (C_6), 121.55 (C_3), 111.57 (C_{11}), 82.71 (C_1), 46.55 (C_8), 18.36 (C_{10}); IR ($CHCl_3$) 3580(s, OH), 3430 (m, OH) cm^{-1}; MS (CI, 70 eV) m/z 161 (MH^+, 6.03), 143 (MH^+ – H_2O, 100); HRMS calcd ($C_{11}H_{12}O$, M^+) 160.0888, obsd 160.0920.

Isomeric mixture of 23 and 24: *Rf* (5% acetone in hexane) 0.16; MS (CI, 70 eV) m/z 159 (MH^+, 100), 129 (M – HCO, 1.19), 119 (MH^+ – COC, 3.56).

(47) We have made the assignment of *cis* and *trans* assuming that $J_{trans} > J_{cis}$. See: Gunther, J. *NMR Spectroscopy*; Wiley: Chichester, 1980; p 118.

23: ^{1}H NMR ($CDCl_3$) δ 9.77 (s, 1H, aldehydic), 7.42–7.26 (m, 4H, aryl), 4.02 (s, 2H, cyclobutyl CH_2), 2.04 (s, 3H, CH_3).

24: ^{1}H NMR ($CDCl_3$) δ 10.29 (s, 1H, aldehydic), 7.42–7.26 (m, 4H, aryl), 3.80 (s, 2H, cyclobutyl CH_2), 1.87 (s, 3H, CH_3).

30: ^{1}H NMR ($CDCl_3$) 7.35–7.16 (m, 4H, aryl), 5.11 (dq, J_{gem} = 1.5 Hz, $J_{cis\text{-}allylic}$ = 1 Hz, 1H, vinyl *cis* to CH_3),[40] 5.09 (quint, J_{gem} = 1.5 Hz, $J_{trans\text{-}allylic}$ = 2 Hz, 1H, vinyl *trans* to CH_3), 3.36 and 3.33 (AB q, J_{gem} = 14 Hz, each 1H, cyclobutyl methylene), 1.90 (dd, $J_{trans\text{-}allylic}$ = 1.5 Hz, $J_{cis\text{-}allylic}$ = 1 Hz, CH_3); ^{13}C NMR ($CDCl_3$) δ 144.98 (C_2), 142.69 (C_9), 142.42 (C_7), 129.60 (C_5), 127.02 (C_4), 123.78 (C_6), 122.72 (C_3), 115.17 (C_{11}), 92.55 (C_1), 41.66 (C_8), 18.23 (C_{10}); IR ($CHCl_3$) 3510 (s, OH), 3320 (m, v br, OH) cm^{-1}; MS (CI, 70 eV) *m/z* 175 (M - 1, 0.5), 159 (M – OH, 100), 143 (M – OOH, 13.69), 135 (M – CH_3CCH_2, 16.22), 131 (53.80), 119 (benzocyclobutanone, 9.49).

1,1′-Epoxy-1-(1′-methylethylidene)benzocyclobutene (25). Olefin **7** (200 mg, 1.3 mmol) dissolved in 150 mL of CH_2Cl_2 was added over a 20-min period to a CH_2Cl_2 solution (150 mL) of *m*-CPBA (1.43 mmol). The reaction mixture was stirred overnight washed with 10% Na_2SO_3, 5% $NaHCO_3$, H_2O, and saturated NaCl, and dried over $MgSO_4$. Rotary evaporation gave 280 mg of crude product, containing epoxide and substrate in a 6:1 ratio. PTLC eluting with 5% acetone in hexane gave 100 mg (0.49 mmol; 38% isolated yield) of pure **25**. The same product is obtained when chlorohydrin **28** is treated with *tert*-butoxide in *tert*-butyl alcohol. Irradiation of the epoxide under the standard photooxidation conditions (*vide supra*) left it unchanged.

25: R_f (5% acetone in hexane) 0.28; 7.4–7.1 (m, 4H, aryl), 3.52 and 3.40 (AB q, J = 14 Hz, 2H, ring CH_2), 1.52 (s, 3H, CH_3), 1.44 (s, 3H, CH_3); ^{13}C NMR ($CDCl_3$) δ 145.35 (C_2), 143.64 (C_7), 129.59 and 127.46 (C_4 and C_5), 122.53 and 121.77 (C_3 and C_6), 72.20 (C_1, α-epoxy), 61.90 (C_9), 38.89 (C_8), 22.17 and 21.54 (C_{10} and C_{11}); MS (EI, 70 eV) *m/z* 160 (M^+, 24.81), 145 (M – CH_3, 33), 144 (M – O, 53.86), 129 (M – CH_3 – O, 100), 117 (M – CH_3CO, from pinacol rearrangement, 28.24), 115 (M – CH_3CHOH, 36.52), 102 (M – $(CH_3)_2CO$, 45.53); MS (CI, 70 eV) *m/z* 161 (MH^+, 100) 143 (MH – H_2O, 6.66); HRMS calcd ($C_{11}H_{12}O$, M^+) 160.0888, obsd 160.0889.

1-Chloro-1-(1′-hydroxy-1′-methylethyl)benzocyclobutene (28) and 1-(1′-Hydroxy-1′-methylethyl)benzocyclobuten-1-ol (29). Epoxide **25** (50 mg) was dissolved in ether (10 mL), treated with 2 drops of concd HCl, and stirred overnight. The ether was washed with $NaHCO_3$ solution, dried over $MgSO_4$, and concentrated. PTLC of the resulting oil yielded two fractions, corresponding to clorohydrin **28** (20 mg) and diol **29** (10 mg). The latter could be obtained by stirring the epoxide in water overnight. The product was extracted with ether and purified by PTLC.

28: R_f (5% acetone in hexane) 0.12; ^{1}H NMR ($CDCl_3$) 7.38–7.16 (m, 4H, aryl), 3.81 and 3.47 (AB q, J = 14 Hz, 2H, ring CH_2), 1.41 (s, 3H, CH_3), 1.37 (s, 3H, CH_3); ^{13}C NMR ($CDCl_3$) δ 146.12 (C_2), 141.31 (C_7), 130.22 and 127.92 (C_4 and C_5), 123.49 and 121.73 (C_3 and C_6), 79.23 (C_1), 74.04 (C_9), 45.16 (C_8), 25.34 and 24.92 (C_{10} and C_{11}); MS (CI, 70 eV) *m/z* 197 (MH^+, 0.96); MS (EI, 70 eV) *m/z* 198 (M + 2, 0.19), 196 (M^+, 0.63), 160 (M – HCl [epoxide], 47.39), 145 (M – HCl – CH_3, 44.80), 143 (M – HCl – OH, 18.93), 140 (138+2, 33.49), 138 (M – $[CH_3]_2CO$, 100), 128 (M – HCl – OH – CH_3, 26.40), 119 (M – $[CH_3]_2C$ – Cl, 60.12), 103 (M – $[CH_3]_2CO$ – Cl, 89.67), 91 (C_7H_7, 53.46); HRMS calcd ($C_{11}H_{13}OCl$, M^+) 196.0655, obsd 196.0655.

29: R_f (5% acetone in hexane) 0.30; ^{1}H NMR ($CDCl_3$) δ 7.35–7.15 (m, 4H, aryl), 3.55 and 3.06 (AB q, J = 14 Hz, 2H, ring CH_2), 2.62 (vb s, 2H, OH), 1.31 (s, 3H, CH_3), 1.26 (s, 3H, CH_3); ^{13}C NMR ($CDCl_3$) 147.28 (C_2), 142.53 (C_7), 129.52 and 127.27 (C_4 and C_5), 123.56 and 121.68 (C_3 and C_6), 85.24 (C_1), 73.77 (C_9), 42.70 (C_8), 24.63 and 24.53 (C_{10} and C_{11}); IR (CCl_4) 3560 (br m, OH), 3400 (br m, OH) cm^{-1}; MS (EI, 19 eV) *m/z* 178 (M^+, 69); 162 (M – O, 49.87), 161 (M – OH, 65.16), 145 (M – CH_3 – H_2O, 100), 129 (M – OH – OH – CH_3, 16.10), 117 (benzocyclobutenone – H, 26.86), 102 (benzocyclobutene, 34.72); MS (EI, 70 eV) *m/z* 178 (M^+, 0.61), 145 (M – CH_3 – H_2O, 27.39), 144 (M – OH – OH, 39.82), 129 (M – OH – OH – CH_3, 90.13), 128 (M – H_2O – OH – CH_3, 73.10), 120 (benzocyclobutenol, 100), 119 (120-H, 80.71), 91 (C_7H_7, 95.10); HRMS calcd ($C_{11}H_{14}O_2$, M^+) 178.0994, obsd 178.1021.

Singlet Oxygenation of 8. The photooxidation of **8** in $CHCl_3$ was extremely rapid. The NMR spectrum of the crude product mixture after Ph_3P reduction revealed the presence of two products corresponding to allylic alcohol **35** (10%) and keto aldehyde **37** (90%). DABCO had a minimal effect on the rate of reaction, though in the presence of DTBP (in a 1:1 ratio to substrate) the photooxidation yielded **35** and **37** in a 2:1 ratio. Diphenyl sulfide (in a 1:1 ratio to substrate) had essentially no effect on the course of the reaction. Cyclobutanol **35** was independently synthesized by reacting isopropenylmagnesium bromide with 3-*n*-butyl-2-cyclobuten-1-one (**54**) according to the procedure of Sammes and co-workers for the preparation of allylic alcohol **33**.[25] [As noted above in the case of **21b**, not only the Grignard addition but also preparation of the Grignard reagent itself (from isopropenyl bromide and magnesium with a trace of iodine) was carried out in an ice bath cooled reaction flask.] We had difficulty purifying cyclobutanol **35** since it is thermally labile and rearranges gradually to yet undetermined products. The chromatographic purification of keto aldehyde **37**, on the other hand, presented no unusual difficulty, and the assignment of the isopropylidene methyls in its ^{13}C NMR spectrum is based on the γ-effect. Correlation of the proton and carbon chemical shifts through analysis of residual couplings in the off-resonance decoupled spectrum allowed for the CH_3 assignments in the ^{1}H NMR spectrum.

35: ^{1}H NMR ($CDCl_3$) δ 5.90 (s, H_2), 5.01 (bs, H_{10} vinyl), 4.86 (bs with additional splitting, $H_{10'}$ vinyl), 2.64 and 2.46 (ABq, J_{gem} = 12 Hz, each 1H, H_4 and $H_{4'}$), 2.09 (bt with virtual coupling, J = 7 Hz, 2H, H_5), 1.83 (s, 3H, H_{11} methyl) 1.58–1.10 (m, 4H, H_6 and H_7), 0.90 (t with virtual coupling, J = 7 Hz, 3H, H_8); ^{13}C NMR ($CDCl_3$) δ 152.97 (C_3), 147.64 (C_9), 131.35 (C_2), 109.92 (C_{10}), 77.81 (C_1), 45.99 (C_4), 30.04 (C_5), 28.46 (C_6), 22.37 (C_7), 18.38 (C_{11}), 13.79 (C_8); MS (EI, 70 eV) 166 (M^+, 12.92), 151 (M – CH_3, 12.61), 148 (M – H_2O, 14.93), 137 (M – C_2H_5, 6.10), 133 (M – CH_3 – H_2O, 6.50), 125 (M – C_3H_5, 17.20), 124 (M – C_3H_6, 35.32), 123 (M – C_3H_7, 28.92), 119 (M – C_2H_5 – H_2O, 31.28), 109.0973 (M – C_3H_5O, 23.61), 109.0598 (M – C_4H_9, 100), 105 (M – C_3H_7 – H_2O, 17.31), 95.0882 (M – CH_2=$CH(CH_3)$ – C(OH), 19.71), 95.0520 (M – C_4H_8 – CH_3, 24.41), 91 (M – C_4H_9 – H_2O, 57.93); HRMS calcd ($C_{11}H_{18}O$, M^+) 166.1357, obsd 166.1361.

37: ^{1}H NMR ($CDCl_3$) δ 10.10 (s, 1H, aldehyde), 3.41 (s, 2H, H_4), 2.46 (t, J = 7, 2H, H_5), 2.27 (s, 3H, isopropylidene CH_3 *anti* to aldehyde), 1.92 (s, 3H, isopropylidene CH_3 *syn* to aldehyde), 1.57 (m, 2H, H_6), 1.35 (m, 2H, H_5), 0.90 (t with virtual coupling, J = 7 Hz, H_7); ^{13}C NMR ($CDCl_3$) 207.83 (C_4), 189.90 (C_1), 158.30 (isopropylidene vinyl), 131.02 (C_2), 42.18 (C_5), 39.44 (C_3), 25.97 (C_6), 23.94 (isopropylidene CH_3 *syn* to aldehyde), 22.31 (C_7), 19.58 (isopropylidene CH_3 *anti* to aldehyde), 14.08 (C_8); UV (abs ethanol) $_{max}$ = 244.7 nm; MS (CI, 70 eV) *m/z* 183 (MH^+, 100), 165 (MH – H_2O, 31.86), 155 (MH – CO, 16.69), 137 (MH – HCO – OH, 9.77), 85 (C_4H_9CO, 34.76). Anal. Calcd ($C_{11}H_{18}O_2$): C, 72.49; H, 9.95. Found: C, 72.73; H, 10.15.

3-*n*-Butyl-1,1′-epoxy-1-(1′-methylethylidene)cyclobutene (41). Olefin **8** was epoxidized overnight with *m*-CPBA (as described for epoxide **25**). PTLC eluting with 15% acetone in hexane gave a 20% isolated yield of pure **41**. NMR and mass spectra of other fractions indicated the presence of unreacted starting material and an isomeric epoxide (presumably generated via epoxidation of the endocyclic double bond), but the isolation and characterization of the latter was not pursued.

41: ^{1}H NMR ($CDCl_3$) δ 6.14 (s, 1H), 2.87 and 2.65 (AB q, J = 13 Hz, 2H, H_4), 2.14 (bt with virtual coupling, J = 7 Hz, 2H, H_5), 1.52–1.24 (m, 4H, H_6 and H_7), 1.32 and 1.29 (each s, each 3H, isopropyl methyls), 0.91 (t with virtual coupling, J = 7 Hz, 2H, H_8); ^{13}C NMR ($CDCl_3$) δ 154.76 (C_3), 127.90 (C_2), 89.92 (C_1), 73.41 (C_9), 40.39 (C_4), 30.22 (C_5), 28.33 (C_6), 25.94 and 25.66 (C_{10} and C_{11}), 22.48 (C_7), 13.85 (C_8); MS (CI, 70 eV) *m/z* 167 (MH^+, 100); HRMS calcd ($C_{11}H_{18}O$, M^+) 166.1358, obsd 166.1381.

Supplementary Material Available: 300-MHz ^{1}H NMR spectra of **4**, **6**, **9** and **10** (mixture), **11** and **12** (mixture), **13** and **14** (mixture), **15** and **16** (mixture), **19**, **21a**, **21b**, **22**, **23** and **24** (mixture), **25**, **28**, **29**, **30**, **41**, and **53** as well as a ^{13}C NMR spectrum of **35** (18 pages). This material is contained 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.