Anal. Calcd for $C_{10}H_{10}O_3$: C, 67.41; H, 5.66. Found: C, 67.27; H, 5.73.

Acknowledgment. The financial support of the National Cancer Institute (Grants CA-12115 and CA-24487) is most gratefully acknowledged. L.A.P. is particularly appreciative of helpful exchanges of information with Professor Rolf Gleiter.

Registry No. 5, 6675-72-5; 6, 6675-71-4; 10, 75101-90-5; 11, 75101-91-6; 12, 75171-61-8; 13, 75101-92-7; 14, 75101-93-8; 15, 75171-62-9; 20, 75101-94-9; 21, 75171-63-0.

Supplementary Material Available: Fractional coordinates and thermal parameters (Table I), bond distances (Table II), and bond angles (Table III) for 11 (3 pages). Ordering information is given on any current masthead page.

Electronic Control of Stereoselectivity. 6. Directionality of Singlet Oxygen Addition to 1,4-Dimethoxynaphthalenes Laterally Fused to Bridged Bicyclic Systems[1]

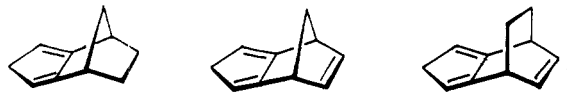
Leo A. Paquette,*[2a] Francois Bellamy,[2a,3] Michael C. Böhm,[2b] and Rolf Gleiter*[2c]

Evans Chemical Laboratories, The Ohio State University, Columbus, Ohio 43210, the Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany, and the Institut für Organische Chemie der Universität Heidelberg, D-6900 Heidelberg, West Germany

Received July 29, 1980

The photooxygenation in methanol solution of 1,4-dimethoxynaphthalene derivatives having bridged bicyclic systems fused at C_2,C_3 with rose bengal as sensitizer leads to formation of stereoisomeric epoxynaphthoquinone monoketals. These products, which are readily hydrolyzed in acid solution to the epoxynaphthoquinones, possess an epoxide oxygen which serves as a stereochemical marker for the directionality of singlet oxygen addition. For the norbornyl and norbornenyl cases, endo bonding by $^1O_2$ is preferred; the reverse is true for the pair of bicyclo[2.2.2]octenyl derivatives studied. This contrasting stereoselection was compared to the stereochemical consequences of alkaline hydroperoxidation of the corresponding naphthoquinones. In each instance, the reaction course was opposite to that observed with singlet oxygenation. Both processes are analyzed from the theoretical viewpoint, use being made of the photoelectron spectra of the substrate molecules, detailed evaluation of frontier orbital effects, and prevailing σ/π interactions. While the alkaline hydroperoxidation results can be interpreted in terms of standard kinetic and steric control, an understanding of the directionality of $^1O_2$ capture appears dependent on our appreciation of the contributions made by the σ electrons of the bicyclic moieties upon the aromatic π orbitals. The tilting caused by such interactions is thought to be the source of the experimentally observed exo/endo ratios.

The intrinsic ability of norbornenes to direct electrophilic additions to their exo surface and of 2-norbornyl cations to capture nucleophiles stereospecifically from the same direction has been a topical issue in physical organic chemistry for a long time. Steric effects have been shown to be of such considerable importance that the possibility of implicating the operation of complementary electronic effects has continued to be elusive.[4,5] We have considered that experimental evidence for significant interaction between norbornyl and norbornenyl σ electrons and proximal π electrons in neutral molecules might be observed at somewhat longer range where steric factors are inconsequential. Indeed, stereochemical identification of the Diels–Alder adducts to **1** (90–100% endo), **2** (100% endo), and **3** (variable) has caused us to develop an appreciation for the existence of directed electronic effects in bridged bicyclic systems.[1,6–8] Theoretical calculations indicate that σ–π mixing in **1** and **2** causes tilting of the diene p orbitals in a manner which is highly conducive to kinetically favored endo dienophile capture; in the case of **3**, this unusual feature is not seen to the same extent.[6]



1 **2** **3**

Where photooxygenation is concerned, the conversion of **1** and **2** to the respective endo peroxides is now recognized not to occur stereospecifically.[1] Evidently, the latter cycloaddition proceeds by a modestly interactive concerted $(4 + 2)\pi$-bonding scheme. To explain the nonconformance of singlet oxygen to the general pattern of endo dienophile capture, we have suggested that the crux of the matter lies in the excited-state nature of $^1O_2$ which reveals itself (a) in virtually complete control of the endoperoxidation process by entropic factors, with atypical disregard for enthalpy changes ($\Delta H^{\ddagger} \approx 0$ kcal/mol),[9,10] and (b) in a loss of that discriminatory ability for exo/endo stereoselection which is characteristic of Diels–Alder reactions because of the quite diverse energies in the π_1(S) levels of the cyclo-

(1) Part 5: Paquette, L. A.; Carr, R. V. C.; Arnold, E.; Clardy, J. *J. Org. Chem.*, previous paper in this issue.
(2) (a) Columbus. (b) Darmstadt. (c) Heidelberg.
(3) NATO Postdoctoral Fellow with financial support provided by the CNRS.
(4) (a) Brown, H. C.; Kawakami, J. H. *J. Am. Chem. Soc.* **1975**, *97*, 5521 and earlier papers in this series. (b) Brown, H. C.; Guedin, B. G.; Takeuchi, K.; Peters, E. N. *Ibid.* **1975**, *97*, 610. (c) Brown, H. C. "The Nonclassical Ion Problem"; Plenum: New York, 1977.
(5) (a) Inagaki, S.; Fujimoto, H.; Fukui, K. *J. Am. Chem. Soc.* **1976**, *98*, 4054. (b) Houk, K. N. In "Reactive Intermediates"; Jones, M., Moss, R. A., Eds.; Wiley: New York, 1978; Vol. 1, pp 326–327.
(6) (a) Paquette, L. A.; Carr, R. V. C.; Böhm, M. C.; Gleiter, R. *J. Am. Chem. Soc.*, **1980**, *102*, 1186. (b) Böhm, M. C.; Carr, R. V. C.; Gleiter, R.; Paquette, L. A. *J. Am. Chem. Soc.*, in press. (c) Paquette, L. A.; Carr, R. V. C.; Charumilind, P.; Blount, J. F. *J. Org. Chem.*, following paper in this issue.
(7) Hardy, M.; Carrupt, P.-A.; Vogel, P. *Helv. Chim. Acta* **1976**, *79*, 1685.
(8) (a) Sugimoto, T.; Kobuke, Y.; Furukawa, J. *J. Org. Chem.* **1976**, *41*, 1457. (b) Alder, K.; Flock, F. H.; Janssen, P. *Chem. Ber.* **1956**, *89*, 2689.
(9) Koch, E. *Tetrahedron* **1968**, *24*, 6295.
(10) Gorman, A. A.; Lovering, G.; Rodgers, M. A. *J. Am. Chem. Soc.* **1979**, *101*, 3050.

0022-3263/80/1945-4913$01.00/0

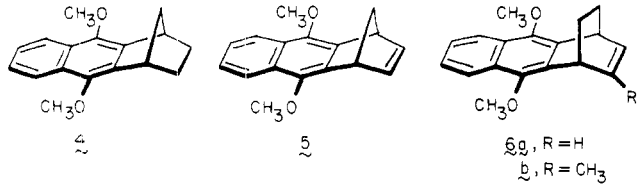
Table I. Epoxynaphthoquinone Product Distributions

	reaction[a]	% endo epoxide 8[b]	% exo epoxide 10
norbornenyl (4)	A	82	0
	B	0	100
norbornadienyl (5)	A	77	7
	B	23	70
bicyclo[2.2.2]octadienyl (6)	A	13.5	77
	B	91.5	6.4

[a] A, sensitized photooxygenation of the 1,4-dimethoxynaphthalene; B, alkaline hydroperoxidation of the naphthoquinone. [b] In the case of 6, endo means syn to the etheno bridge. All values cited are actual isolated yields (unoptimized.)

pentadiene moiety (9.6–10.0 eV) and singlet oxygen (16.12 eV) which diminish the dependence on first-order orbital control.[1]

As a possible further test of this mechanistic thinking, we have now chosen to examine the singlet photooxygenation of 4–6. Two factors were principally responsible for our selection of these substrates: (i) the enhanced ionization potential of 1,4-dimethoxynaphthalene[11] relative to those of norbornene, norbornadiene, and bicyclo[2.2.2]octadiene,[12,13] which was expected to persist when in fused combination, and (ii) resultant attack of singlet oxygen regiospecifically at the substituted aromatic ring, as anticipated on the basis of frontier MO considerations.[14,15] An additional special advantage uncovered with 4–6 is the special facility with which they enter into a previously unknown rearrangement to deliver epoxynaphthoquinone monoketals, the isomeric distributions of which parallel in direction the trends previously uncovered for 1 and 2. In order to ascertain the stereochemistry of the products, we have also examined the course of alkaline hydrogen peroxide addition to the structurally related naphthoquinones.[16]



4 5 6a, R = H; b, R = CH3

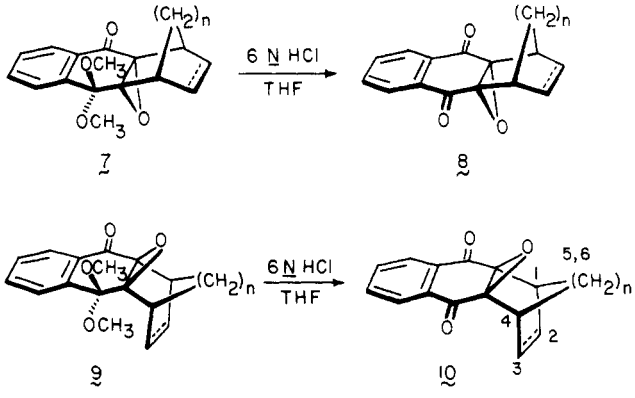
Results

Synthesis and Oxidation Studies. The preparation of 5 and 6 involved Diels–Alder addition of 1,4-naphthoquinone to the appropriate dienes followed by O-methylation. Catalytic hydrogenation of 5 provided 4. The photooxygenation of 4, 5, and 6a proceeded smoothly in purified methanol solution with rose bengal as sensitizer to afford mixtures of 7 and 9. Certain aliquots of these mixtures were subjected directly to chromatographic separation, while others were hydrolyzed to provide 8 and 10 which were comparably purified. Identical exo/endo product distributions were realized from either workup procedure (Table I, reaction A), after suitable correction was made for the fact that 8a and 8b are partially converted to their naphthoquinones in acidic solution.[17] Particularly striking is the fact that the distributions of 8 and 10 arrived at from singlet oxygenation of 4–6 are *opposite* those observed upon alkaline hydroperoxidation of the related naphthoquinones.

Table II. ^{1}H NMR Spectra of 8, 10, and 12[a]

compd	H_1,H_4	H_2,H_3	H_5 (and H_6)
8a	3.20 (m)	2.35–1.40 (series of m)	
10a	3.10 (m)	1.90–0.80 (series of m)	
8b	3.65 (m)	6.05 (t, J = 2 Hz)	2.10 (m)
10b	3.55 (m)	6.50 (t, J = 2 Hz)	1.65 (m)
8c	3.80 (m)	6.0 (dd, J = 4.2, 3.5 Hz)	1.45 (br s)
10c	3.80 (m)	6.45 (dd, J = 4.2, 3.5 Hz)	2.05–0.90 (series of m)
12	3.80–3.45 (m)	6.0 (m)	2.0–0.90 (series of m)

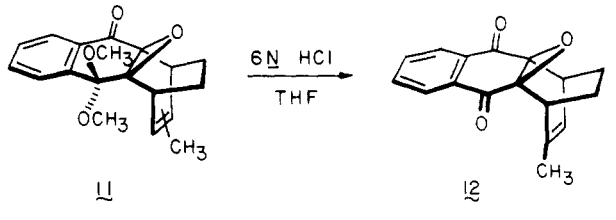
[a] At 60 MHz in $CDCl_3$ solvent; values given in δ units.



7 8 9 10

a, n = 1, saturated; b, n = 1, unsaturated; c, n = 2, unsaturated

Although dimethoxynaphthalene 6b does not possess the level of symmetry enjoyed by the other substrates, this molecule makes available an opportunity for gauging the relative reactivities of the functionalized naphthalene ring and the methyl-substituted norbornene double bond. When subjected to analogous treatment with singlet oxygen, 6b underwent ready conversion in 64% yield to a mixture of the isomeric forms of 11. No evidence was found for operation of an ene reaction, although very low levels of allylic alcohols could have been missed. Acidic hydrolysis of 11 as before resulted exclusively in formation of the homogeneous epoxyquinone 12. Because of the



11 12

(11) (a) Baker, A. D.; May, D. P.; Turner, D. W. *J. Chem. Soc. B* **1968**, 22. (b) Turner, D. W.; Baker, C.; Baker, D. A.; Brundle, C. R. "Molecular Photoelectron Spectroscopy"; Wiley-Interscience: New York, 1970. (c) Rao, C. N. R. *Tetrahedron* **1976**, *32*, 1561.

(12) Bischof, P.; Hashmall, J. A.; Heilbronner, E.; Hornung, V. *Helv. Chim. Acta* **1971**, *54*, 783; **1969**, *52*, 1745.

(13) Bischof, P.; Gleiter, R.; Heilbronner, E. *Helv. Chim. Acta* **1970**, *53*, 1425.

(14) Paquette, L. A.; Liotta, D. C.; Baker, A. D. *Tetrahedron Lett.* **1976**, 2681.

(15) The endoperoxidation of simplet dimethoxynaphthalenes as well as anthracenes is recognized to be regiospecific: (a) Dufraisse, C.; Rigaudy, J.; Basselier, J.-J.; Cuong, N. K. *C. R. Hebd. Seances Acad. Sci.* **1965**, *260*, 5031. (b) Rigaudy, J.; Cohen, N. C.; Cuong, N. K. *Ibid.* **1967**, *264*, 1851. (c) Rigaudy, J.; Deletang, C.; Basselier, J.-J. *Ibid.* **1966**, *263*, 1435. (d) Rigaudy, J.; Deletang, C.; Sparfel, D.; Cuong, N. K. *Ibid.* **1968**, *267*, 1714. (e) Rigaudy, J. *Pure Appl. Chem.* **1968**, *16*, 169.

(16) Paquette, L. A.; Carr, R. V. C.; Bellamy, F. *J. Am. Chem. Soc.* **1978**, *100*, 6764.

(17) The extent of this deoxygenation, etc., was established by independent experimentation.

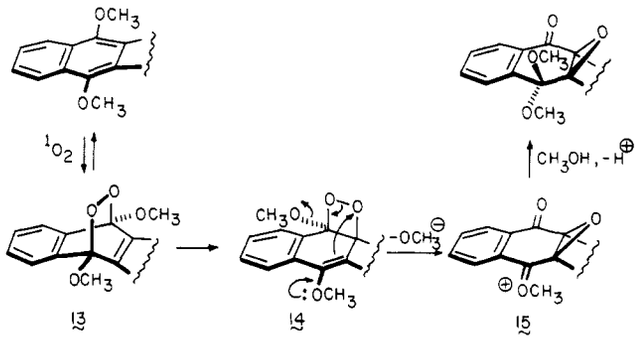
complexities intrinsic to this system, small amounts of the endo isomer could have escaped detection and isolation. However, we are of the opinion that **6b** exhibits a >20:1 preference for capture of $^1O_2$ syn to its ethano bridge.

Structural assignments to **8**, **10**, and **12** follow convincingly from their ^1H (Table II) and ^{13}C NMR spectra and a recent independent X-ray study of a structurally related bromo compound.[18] Comparison of the proton spectra reveals obvious similarities between the exo isomers on the one hand and their endo counterparts on the other. In **8b**, the protons on the methano bridge appear downfield of those in **10b**, a phenomenon which persists, although less clearly so because of overlapping signals, in the saturated analogues **8a** and **10a**. When ethano bridges are present as in **8c**, **10c**, and **12**, a syn epoxide oxygen atom has the effect of causing the proximal and distal hydrogen pairs on this bridge to exhibit widely differing chemical shifts. In the anti arrangement, all four proton resonances are grouped closely together. Tori and co-workers had previously demonstrated the existence of this phenomenon in *exo*-norbornene oxide, *exo*-norbornadiene oxide, *exo*-benzonorbornadiene oxide, and the *exo*- and *endo*-benzobicyclo[2.2.2]octadiene oxides.[19] While caution has been urged in the analysis of anisotropic effects from structurally varied epoxides,[20] the geometries of **8**, **10**, and **12** are sufficiently rigid and closely comparable to those of the model systems[18] that direct ^1H NMR comparison is feasible.

The effect of epoxynorbornane stereochemistry on the ^{13}C chemical shift of the methano bridge carbon has been shown to be quite marked.[1,21,22] In agreement with this earlier work, the methano carbon in **8a** (52.48 ppm) appears significantly downfield of that in **10a** (28.30 ppm). However, the ethano carbons of **8c** (21.33 ppm) are seen slightly upfield of those in **10c** (22.09 ppm) and provide little diagnostic value. Furthermore, we have noted that the oxirane carbon shifts of these isomeric epoxides (60.87 and 72.31 ppm, respectively) are in reverse order to those observed for **8a** (75.78 ppm) and **10a** (63.94 ppm). For **19**, the values are 61.93 and 60.56 ppm. These findings again reveal the possible pitfalls which may arise when comparing ^{13}C spectral data from different series of compounds.

As is to be discussed below, the photoelectron spectra of **3**–**6** reveal the highest occupied MO's to be naphthalenic in character. On this basis, attack by $^1O_2$ to provide initially one of the two stereoisomeric endo 1,4-peroxides of type **13** should be kinetically favored.[14] The conversion of these species to **7** and **9** is the likely result of a subsequent 1,3 oxygen shift to provide the dioxetanes **14** (Scheme I). Such rearrangements are not unprecedented, various endo peroxides having been found to decompose to carbonyl cleavage products, presumably via 1,2-dioxetane intermediates, when treated with Brønsted or Lewis acids.[15d,f,23] Although the reported reaction conditions

Scheme I



usually are too stringent to permit identification and/or isolation of such intermediates,[24] a few cases have been reported where this feat has proven possible.[25-27] Perhaps the closest analogy to the proposed conversion of **13** to **14** is the demonstration by Wilson that 1,4-dimethoxy-9,10-diphenylanthracene endo peroxide chemiluminesces during acid-catalyzed destruction, apparently as a result of transient dioxetane intervention.[28] In the present circumstances, the hypothetical intermediates **15**, which presumably originate from a further electronic reorganization within **14** characterized by release both of steric strain and methoxide ion, constitute the penultimate precursors to the observable oxygenation products.

In Scheme II are summarized the product ratios realized from reaction of the dimethoxynaphthalenes **4**–**6** with singlet oxygen on the one hand and the corresponding 1,4-naphthoquinones **16**–**18** with hydrogen peroxide and base on the other. In both types of reaction, considerable stereoselectivity is observed. In the following paragraphs, we elucidate the electronic structures of the substrate molecules and attempt to identify the factors which give rise to the observed product distributions.

Electronic Structure of the 1,4-Dimethoxynaphthalenes. Our successful rationalization of the stereochemical course of the cycloaddition reactions involving tricyclo[2.2.1.$0^{2,6}$]deca-2,5-diene (**1**) and related compounds with various dienophiles[6] suggested that frontier orbital effects could be equally important in the reactions of **4**–**6** with $^1O_2$, with σ contributions to the frontier orbitals ruling the observed stereoselectivity. For this reason, comparison was initially made of the first bands in the He(I_α) photoelectron spectra in **4**–**6** with the results of molecular orbital calculations. This comparison was considered to be a diagnostic test for the reliability of the calculated orbital sequence, since our previous model studies[6] showed that the shape of the predicted wave function depends critically on the sequence of the canonical orbitals and thus sometimes on the method used.

(a) Photoelectron Spectra of 4–6. The photoelectronic data for **4**–**6** are illustrated in Figure 1 and the vertical ionization potentials, $I_{V,J}$, are listed in Table III. In each case, the spectra exhibit two bands at approximately 8 eV, clearly separated from a series of strongly overlapping bands above 9 eV. On the assumption that Koopmans' theorem ($-\epsilon_J = I_{V,J}$) is valid,[29] the photoelectron spectra can be interpreted by comparison of the measured

(18) Giles, R. G. F.; Green, I. R.; Mitchell, P. R. K.; Ralston, C. L.; White, A. H. *J. Chem. Soc., Perkin Trans. 1* **1979**, 719.
(19) Tori, K.; Kitahonoki, K.; Takano, Y.; Tanida, H.; Tsuji, T. *Tetrahedron Lett.* **1964**, 599.
(20) Paquette, L. A.; Fristad, W. E.; Schuman, C. A.; Beno, M. A.; Christoph, G. G. *J. Am. Chem. Soc.* **1979**, *101*, 4645.
(21) Davies, S. G.; Whitham, G. H. *J. Chem. Soc., Perkin Trans. 2* **1975**, 861.
(22) Zefirov, N. S.; Kasyan, L. I.; Gnedenkov, L. Y.; Shashkov, A. S.; Cherapanova, E. G. *Tetrahedron Lett.* **1979**, 949.
(23) (a) Baldwin, J. E.; Basson, H. H.; Krauss, H. Jr. *J. Chem. Soc., Chem. Commun.* **1968**, 984; (b) LeRoux, J.-P.; Basselier, J.-J. *C. R. Hebd. Seances Acad. Sci.* **1970**, *271*, 461; (c) Rio, G.; Berthelot, J. *Bull. Soc. Chim. Fr.* **1971**, 2938. (e) Basselier, J.-J.; Cherton, J.-C.; Caille, J. C. *R. Hebd. Seances Acad. Sci.* **1971**, *273*, 514. (f) Lundeen, G. W.; Adelman, A. H. *J. Am. Chem. Soc.* **1970**, *92*, 3914.
(24) Wilson, T.; Landis, M. E.; Baumstark, A. L.; Bartlett, P. D. *J. Am. Chem. Soc.* **1973**, *95*, 4765.
(25) LeRoux, J.-P.; Goadsoue, C. *Tetrahedron* **1975**, *31*, 2761.
(26) Griffiths, J.; Chu, K. Y.; Hawkins, C. *J. Chem. Soc., Chem. Commun.* **1976**, 676.
(27) Schaap, A. P.; Burns, P. A.; Zaklika, K. A. *J. Am. Chem. Soc.* **1977**, *99*, 1270.
(28) Wilson, T. *Photochem. Photobiol.* **1969**, *10*, 441.
(29) Koopmans, T. *Physica (Utrecht)* **1934**, *1*, 104.

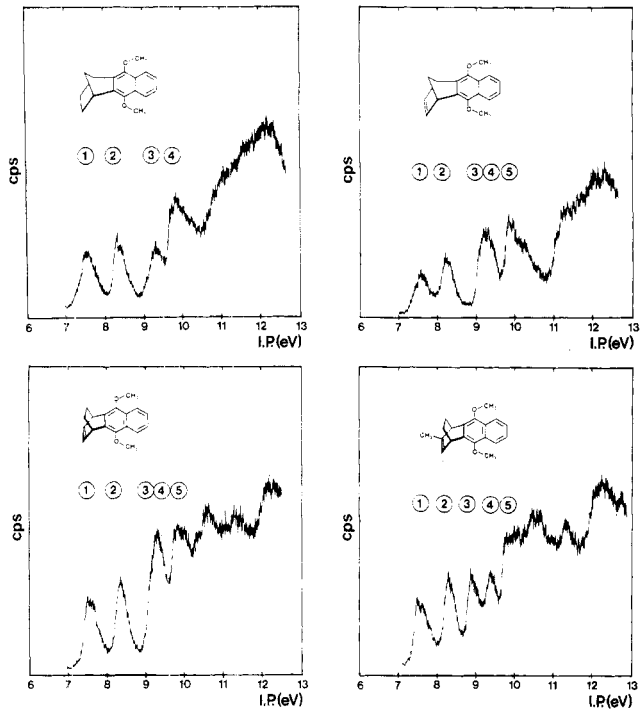


Figure 1. Photoelectron spectra of 4–6.

Table III. Comparison between the Vertical Ionization Potentials of 4–6 and the Calculated Orbital Energies, ϵ_J, for the Corresponding 1,4-Naphthalenediols[a]

compd[b]	band	$I_{V,J}$	assignment	ϵ_J
4 (C_s)	1	7.5	a'' (π)	−7.88 (a'')
	2	8.3	a' (π)	−8.94 (a')
	3	9.3	a'' (n_-)	−9.18 (a'')
	4	9.8	a'' (π)	−9.92 (a'')
5 (C_s)	1	7.55	a'' (π)	−7.85 (a'')
	2	8.2	a' (π)	−8.90 (a')
	3	9.23	a' (π)	−9.05 (a')
	4		a'' (n_-)	−9.27 (a'')
	5	9.8	a'' (π)	−9.89 (a'')
6a (C_s)	1	7.5	a'' (π)	−7.84 (a'')
	2	8.37	a' (π)	−8.96 (a')
	3	9.3	a' (π)	−9.25 (a')
	4		a'' (n_-)	−9.09 (a'')
	5	9.85	a'' (π)	−9.86 (a'')
6b (C_1)	1	7.4	π	
	2	8.2	π	
	3	8.8	π	
	4	9.3	n	
	5	8.7	π	

[a] The calculations were carried out according to the MINDO/3 method. $I_{V,J}$ and ϵ_J values are in electron volts. [b] Symmetry type in parentheses.

vertical ionization potentials with the calculated orbital energies (Table III). This comparison reveals that the molecular orbital sequences predicted by the MINDO/3 method,[30] a modified INDO version (OH instead of OCH_3),[31] and the extended Hückel (EH) technique[32] reproduce orbital patterns which are quite similar to those uncovered by the photoelectron spectroscopy experiments. The first band exhibited by 4–6 is due to ionization from a π orbital localized on the naphthalene rings and related to the $a_u(\pi)$ MO of naphthalene. The calculations predict

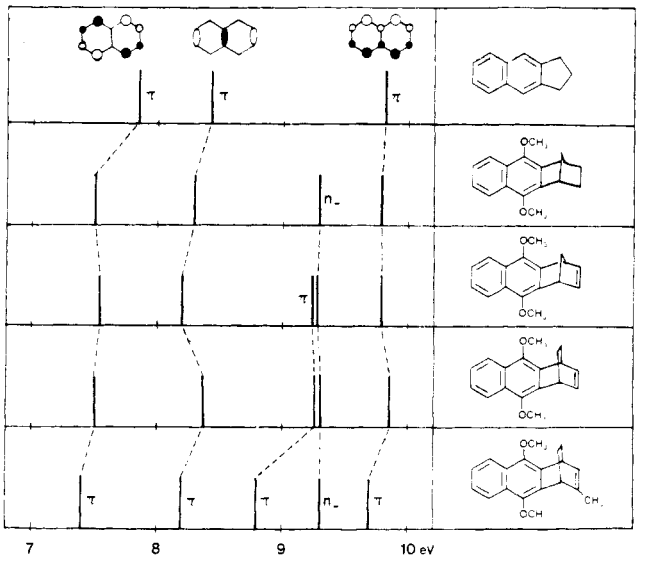


Figure 2. Correlation between the first bands of the photoelectron spectra of 2,3-cyclopentenonaphthalene and 4–6.

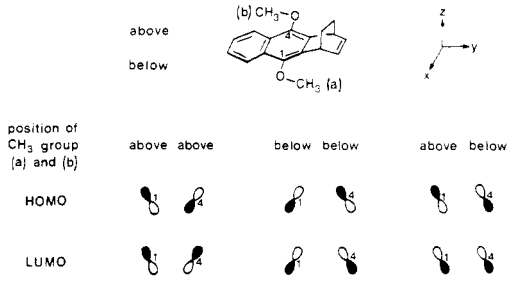
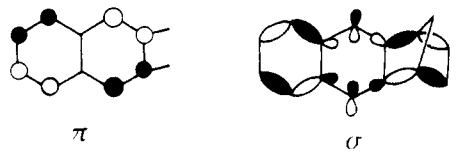


Figure 3. π lobes at positions 1 and 4 of the HOMO of **6a** as a function of the conformation of the methyl substituents a and b viewed along the x-axis.

large coefficients at the methoxy-substituted carbon atoms (see Figure 2). The next bands are due to ionization from a second π orbital localized on the naphthalene ring (related to $b_{1u}(\pi)$ of naphthalene) and a π orbital localized mainly on the double bond in the cases of **5**, **6a**, and **6b**.

The assignments given in Table III and Figure 2 are in line with those given to the photoelectron spectrum of cyclopentenonaphthalene.[33] The first photoelectron bands of this hydrocarbon appear at 7.85 (a_2), 8.44 (b_1), and 9.83 eV (a_2).

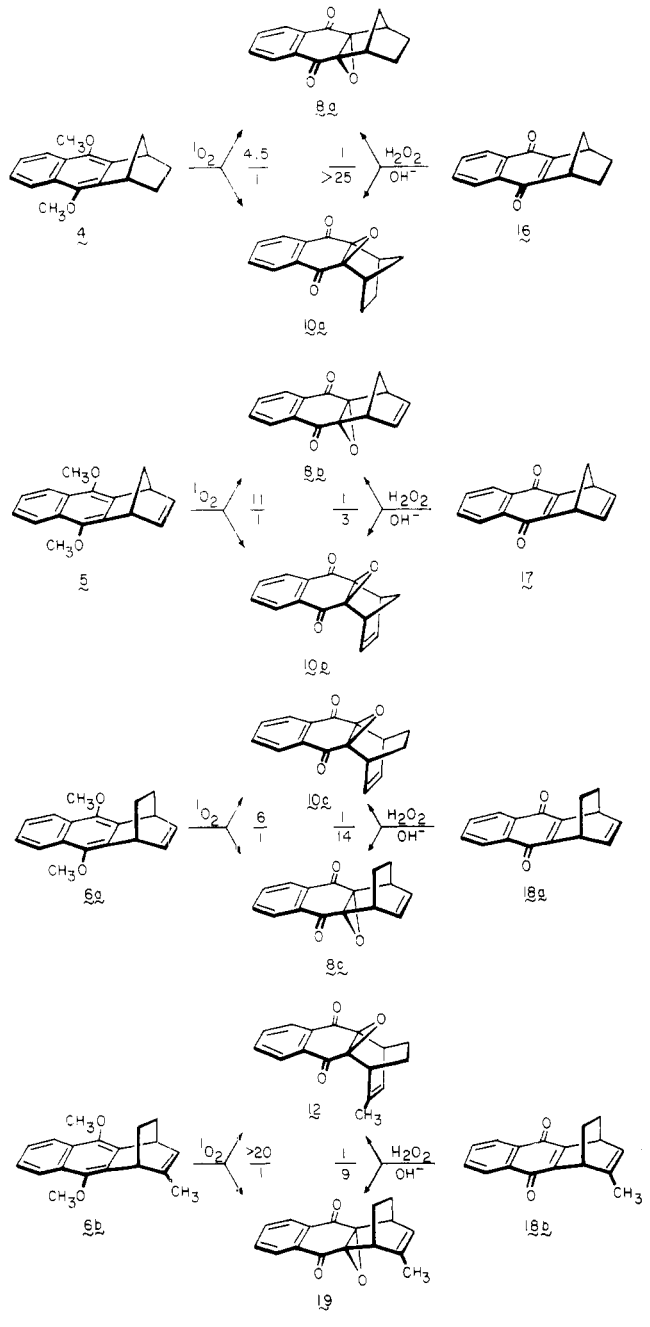
(b) σ/π Interactions in 3–6. The preceding spectroscopic studies indicated that the triad of computational techniques correctly predict the sequencing of the highest occupied molecular orbitals in the dimethoxynaphthalenes. Importantly, there are encountered two σ/π interactions. The first of these involves the HOMO and highest occupied σ orbital. Both relevant precanonical MO's (π and σ) are indicated. The particular conformation adopted by



the methoxy groups is important to this interaction since the p orbitals on the oxygen atoms participate strongly in the σ orbital. In Figure 3 are shown the prevailing σ/π interactions in **6a** for three different out-of-plane confor-

(30) Bingham, R. C.; Dewar, M. J. S.; Lo, D. H. *J. Am. Chem. Soc.* **1975**, *97*, 1285; a program written by P. Bischof (see ref 34).
(31) Böhm, M. C. Dissertation, Technishe Hochschule Darmstadt, Darmstadt, West Germany.
(32) Hoffmann, R. *J. Chem. Phys.* **1963**, *39*, 1397; Hoffmann, R.; Lipscomb, W. N. *Ibid.* **1962**, *36*, 2179, 3489; **1962**, *37*, 2872.
(33) Heilbronner, E.; Hoshi, T.; von Rosenberg, J. L.; Hafner, K. *Nouv. J. Chim.* **1977**, *1*, 105.

Scheme II



mations of its two methyl groups.

If both methyl groups are directed toward the ethano bridge, addition of $^1O_2$ from the same direction should be preferred if steric interactions are neglected for the moment. This statement is founded on the assumption that the repulsive interaction between the HOMO of $^1O_2$ and the HOMO of the naphthalene derivative is smaller for topside approach than for addition from below (see Figure 4). When both methyl groups are directed toward the double bond, $^1O_2$ is predicted to add from the side syn to the double bond. As concerns the third extreme possibility in which the two methyl groups adopt different conformations, no stereospecificity can be predicted. Similar electronic reasons favor the addition of $^1O_2$ to **3** and **4** from the same molecular surface as that to which the CH_3 groups are directed. If steric effects are not introduced, the electronic effects just described appear to be canceled or overruled.

In a manner paralleling observations made in our model studies,[6] the second lowest occupied π orbital interacts

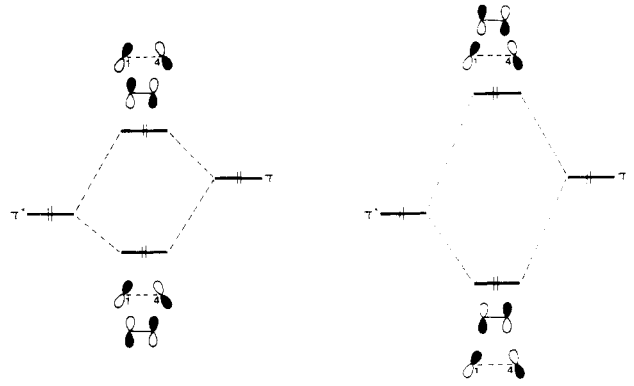


Figure 4. Qualitative diagram of the interaction between centers 1 and 4 of the highest occupied π orbital of the naphthalene system in **3–6** and the HOMO of $^1O_2$: left, approach from the direction syn to the CH_3 groups; right, corresponding anti approach.

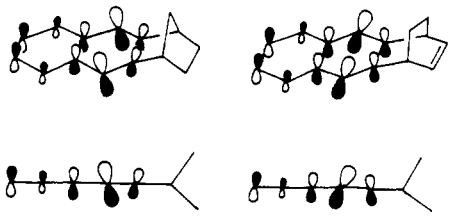
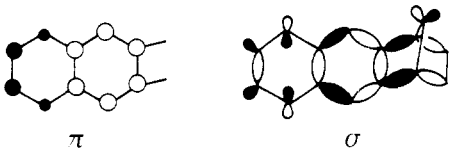


Figure 5. Schematic drawing of the second lowest occupied π orbital of **4** and **5** (left) as well as **6** (right).

Table IV. Heats of Formation of Endo Peroxides 20–25

compd	ΔH_f, kcal/mol	compd	ΔH_f, kcal/mol
20	59.34	**23**	95.94
21	59.06	**24**	61.77
22	95.80	**25**	62.06

considerably with a σ orbital of the same symmetry. Both precanonical orbitals are sketched below for **5**. On this

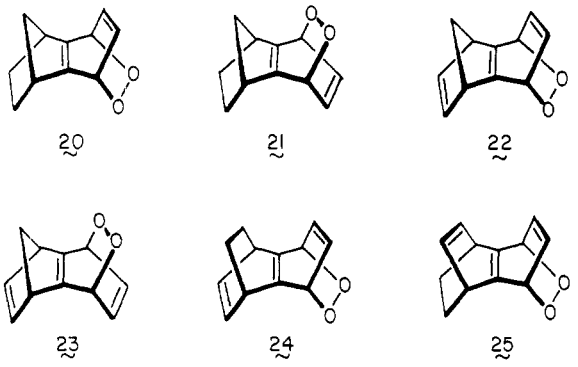


π σ

occasion, the conformation of the methyl groups is *not* influential. This particular σ/π interaction causes a rotation of the terminal p_π lobes away from the methylene group in the cases of **4** and **5** (see Figure 5). The antibonding interaction which develops as the result of $^1O_2$ approach from the side of the methano group will therefore be stronger than that from the surface syn to the C_2H_4 or C_2H_2 bridge. In the case of **6**, σ/π interaction causes an increase of electron density on the side of the double bond. Thus, attack of $^1O_2$ from the direction of the ethano bridge should be preferred, as is observed.

Thermodynamic Considerations. Leaving aside for the moment the electronic considerations just presented, we next turn our attention to MINDO/3 calculations of the heats of formation of **20–25** as models for the presumed primary reaction products. According to the results summarized in Table IV, the endo peroxides **21**, **22**, and **24** should be thermodynamically preferred.

In Table V are collected the calculated heats of formation of epoxyquinones **8** and **10**. Since the geometries of these molecules are also not known, energies were again minimized with respect to geometry through use of a Fletcher–Powell procedure.[34] To the extent that the ΔH_f



20 21 22

23 24 25

values are reliable, the data suggest that alkaline hydroperoxidation of the naphthoquinones leads to the thermodynamically more stable epoxide in each instance. Even the energy difference between **8b** and **10b** is predicted to be larger than that for **8a** and **10a**, in agreement with the experimental data.

The predicted order of thermodynamic stability can be traced back to an antibonding interaction between a σ orbital localized predominantly in the methylene bridge and the 2p lone pair of the epoxide oxygen. This antibonding interaction is more decisive than the antibonding interaction between the 2p lone pair of the oxygen and the π orbital of the ethylene bridge prevailing in **8b**. For **10c** and **8c**, the combined antibonding interactions between the 2p orbital of the oxygen and Walsh orbitals of the three-membered ring with the C–H σ orbitals of the ethano bridge are larger in the former bicyclo[2.2.2]octene than is the antibonding 2p–π interaction present in the latter system (**8c**).

Electronic Structure of the Naphthoquinones. To test the sequence of the highest occupied MO's in **16–18** suggested by semiempirical calculations of the MINDO/3,[30] INDO,[31] and EH types,[32] we have also investigated the photoelectron spectra of these compounds. Our test is again based on the validity of Koopmans' theorem.[29] The measured vertical ionization potentials, $I_{V,J}$, are collected in Table VI and compared with calculated orbital energies, ϵ_J.

The photoelectron spectra of **16–18** are seen to be less instructive for our purposes than are those of **4–6**. In the low-energy region, there appears a broad band at approximately 9.5 eV followed by a region of strongly overlapping bands starting at 11 eV. Comparison between calculation and experiment suggests that the first band be attributed to the states $^2B_2$, $^2A^2$, $^2B_1$, and $^2A_1$. In a first-order approximation, these four states are generated by ionization from the n_- and n_+ combination of the 2p lone pairs ($^2B_2$, $^2A_1$) and by ejection of electrons from the highest occupied π orbitals ($^2A_2$, $^2B_1$). With **17** and **18** there is encountered an additional band which is ascribed to ionization from the olefinic π bond. The interpretations suggested in Table VI are in line with findings culled from the photoelectron PE spectrum of 1,4-naphthoquinone.[35]

Table V. Heats of Formation of Epoxynaphthoquinones 8 and 10

compd	ΔH_f, kcal/mol	compd	ΔH_f, kcal/mol
8a	−0.52	**10b**	−35.50
10a	−0.81	**10c**	−21.36
8b	−36.43	**8c**	−22.13

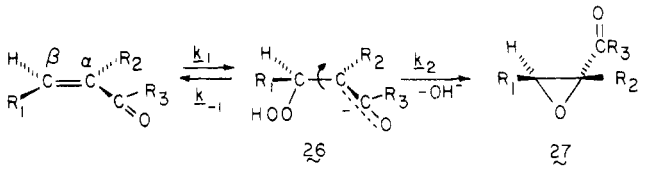
Table VI. Comparison of the First Vertical Ionization Potentials, $I_{V,J}$, with the Calculated Orbital Energies, ϵ_J, of Naphthoquinones 16–18[a]

compd	$I_{V,J}$	assignment	ϵ_J
16	9.22	b_2 (n_-),	−8.98 (b_2)
	9.64	a_2 (π),	−9.47 (a_2)
		b_1 (π),	−9.64 (b_1)
		a_1 (n_+)	−9.79 (a_1)
17	9.0	π (olefin)	−9.30 (π)
	9.5	b_2 (n_-),	−9.03 (b_2)
		a_2 (π),	−9.44 (a_2)
		b_1 (π),	−9.72 (b_1)
		a_1 (n_+)	−9.83 (a_1)
18a	7.8		
	8.5	π	−9.43 (π)
	9.5	b_2 (n_-),	−8.91 (b_2)
		a_2 (π),	−9.59 (a_2)
		b_1 (π),	−9.77 (b_1)
		a_1 (n_+)	−9.87 (a_1)

[a] The calculations were carried out according to the MINDO/3 method. All values are in eV.

Discussion

Stereochemical Course of Naphthoquinone Epoxidations. The ability of alkaline hydrogen peroxide to effect the epoxidation of α,β-unsaturated carbonyl compounds was discovered by Weitz and Scheffer in their classic study of enones.[36] The kinetics of the process were subsequently examined by Bunton and Minkoff.[37] Their findings, in conjunction with more recent observations which show the reaction to be nonstereospecific but highly stereoselective,[38-42] have implicated reversible Michael addition of hydroperoxide anion and C_α–C_β rotational equilibrium during the lifetime of enolate anion **26**. Evidence has also been presented which indicates that the rate-determining step is k_1.[37] Although loss of HOO^- from **26** generally competes favorably with closure to the epoxy ketone **27** ($k_{-1} > k_2$), Pappas and Bao have reported that phenalenone is an exceptional molecule which leads to the epoxy ketone faster (rate constant $>10^5$ s) than proton transfer from water can take place on the intermediate carbanion.[43] At the other end of the scale, Paquette and co-workers have recently described examples where the barriers associated with k_{-1} and k_2 are so high that the β-hydroperoxy ketones are stable to the reaction conditions and isolable.[16]

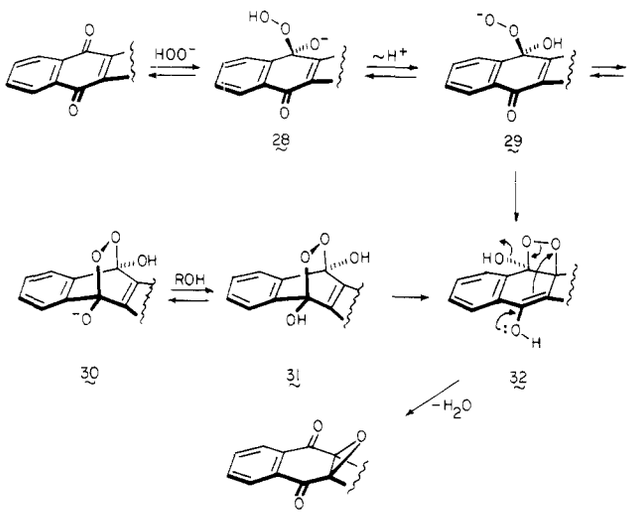


26 27

When addressed to this mechanistic thinking, the stereoselectivities of nucleophilic hydroperoxide anion attack on **16–18** (Scheme II, Table I) can be best understood as being controlled by prevailing kinetic and steric factors.

(34) Bischof, P. *J. Am. Chem. Soc.* **1976**, *98*, 6844.
(35) Lauer, G.; Schäfer, W.; Schweig, A. *Chem. Phys. Lett.* **1975**, *33*, 312.
(36) Weitz, E.; Scheffer, A. *Chem. Ber.* **1921**, *54*, 2327.
(37) Bunton, C. A.; Minkoff, G. J. *J. Chem. Soc.* **1949**, 665.
(38) (a) Black, W. G.; Lutz, R. E. *J. Am. Chem. Soc.* **1953**, *75*, 5990. (b) Bauer, C. R.; Lutz, R. E. *Ibid.* **1953**, *75*, 5995. (c) Lutz, R. E.; Weiss, J. O. *Ibid.* **1955**, *77*, 1814.
(39) Cromwell, N. H.; Setterquist, R. A. *J. Am. Chem. Soc.* **1954**, *76*, 5752.
(40) (a) Wasserman, H. H.; Aubrey, N. E.; Zimmerman, H. E. *J. Am. Chem. Soc.* **1953**, *75*, 96. (b) Wasserman, H. H.; Aubrey, N. E. *Ibid.* **1955**, *77*, 590.
(41) (a) House, H. O.; Reif, D. J. *J. Am. Chem. Soc.* **1955**, *77*, 6525. (b) House, H. O.; Ro, R. S. *Ibid.* **1958**, *80*, 2328.
(42) Zimmerman, H. E.; Singer, L.; Thyagarajan, B. S. *J. Am. Chem. Soc.* **1959**, *81*, 108.
(43) Pappas, S. P.; Bao, L. Q. *J. Am. Chem. Soc.* **1973**, *95*, 7906.

Scheme III



For **16**, epoxidation occurs exclusively from the exo surface. In line with the well-known falloff in stereoselection which accompanies a norbornene–norbornadiene structural change, the level of exo epoxide formation observed in the case of **17** is 75%. For the bicyclo[2.2.2]octadiene derivatives **18a** and **18b**, a crossover in stereoselectivity is encountered, with introduction of the epoxide ring syn to the etheno bridge now being overwhelmingly favored. A similar steric bias has been seen previously in the chemistry of this ring system;[44] certainly, it conforms with the lesser space-filling demands of the unsaturated bridge.

At this point, it is amusing and of some interest to view the epoxidation of 1,4-quinones from a different mechanistic perspective. With the pair of carbonyl groups symmetrically disposed about the double bond, the tendency of the system to function as a Michael acceptor could be substantially reduced. It is therefore not implausible to consider kinetically favored attack of the hydroperoxide anion at one of the carbonyl centers to produce an intermediate such as **28** (Scheme III). In addition to reverting to reactants, **28** is also capable of a prototropic shift to deliver **29**. The subsequent internal collapse of this species would give rise to **30** and then **31**. The close structural relationship of **31** to **13** (Scheme I) is clear. If a comparable rearrangement process is followed by both endo peroxide systems, then a pathway becomes open for conversion via **32** to the observed product.

In view of the well-known accelerative influences of oxy anions on sigmatropic shifts,[45-49] the additional possibility exists that **30** could rearrange to the anionic form of **32** more rapidly than the **31** → **32** change.

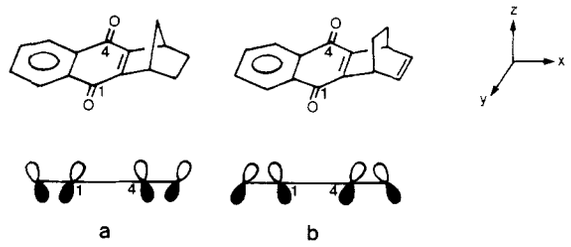


Figure 6. π orbitals at the carbonyl groups of **16** and **18a** as viewed along the x-axis.

Whatever the situation, if HOO^- does add preferentially to one of the carbonyl groups, the effect of σ/π mixing upon the corresponding π and π^* orbitals demands consideration. MINDO/3 and extended Hückel calculations predict no σ/π mixing for the lowest occupied π orbitals. However, one of the π combinations which is heavily localized at the CO groups shows significant σ/π mixing in **16** and **18**; on the other hand, **17** gives no evidence for σ/π mixing. The resulting π orbitals are shown in Figure 6. For **16**, repulsion between the π orbital shown and the lone pair of a nucleophile is less if approach is made from the side of the methylene bridge. In the case of **18a**, the reverse is predicted.

Directionality of Singlet Oxygen Addition to the 1,4-Dimethoxynaphthalenes. It is now appropriate to make inquiry into the dominant forces underlying the stereoselectivity of $^1O_2$ capture by **4–6**. Certainly, consideration of the thermodynamic stabilities of the assumed primary endo peroxide products does not lead to a satisfactory answer. Perhaps the model systems **21–26** are too simple; on the other hand, the singlet oxygen discrimination exhibited by **4** and **5** compares closely to that found for the somewhat less structurally intricate hydrocarbons **1** and **2**.[1] Furthermore, although endo peroxides of general formula **13** are known to be subject to retrocycloaddition,[15] this possibility does not seem to contravene the operation of electronic influences.

Since the prevailing levels of σ/π interaction nicely account for the observed stereoselectivity, these effects are presently considered most influential in determining those *endo*-/*exo*-epoxyquinone ratios derived from the dimethoxynaphthalenes. To the extent that the electronic contributions from the σ-electron networks of bicyclo[2.2.1]-heptyl and bicyclo[2.2.2]octenyl frames exert a comparable influence on neighboring fused cyclopentadiene (e.g., **1–3**)[6] and 1,4-dimethoxynaphthalene ring systems (e.g., **4–6**), our assessment of the phenomenon enjoys a commonality which may see application in a wider range of substrates.

There remains the question of concertedness. In this regard, the dimethoxynaphthalenes must be viewed as less sensitive substrates than the structurally related cyclopentadiene analogues,[1] chiefly because the chemical diagnosis of stereoselection rests upon the operation of a multistep rearrangement sequence whose precise nature is unclear. Despite this drawback, the directionality of $^1O_2$ capture in the two series not only is characterized by nonstereospecificity but has remarkable similarities. In light of the mechanistic considerations advanced in the preceding paper,[1] it would appear most logical to consider 1,4-dimethoxynaphthalene endoperoxidation to be a concerted reaction stereochemically guided by modest levels of orbital interaction. It becomes especially important to emphasize that the influence of a fused norbornane or norbornene ring on the singlet oxygen and alkaline hydroperoxidation reactions, while of contrasting stereose-

(44) See, for example: Müller, E. *Chem. Ber.* **1976**, *109*, 3793.

(45) (a) Evans, D. A.; Golob, A. M. *J. Am. Chem. Soc.* **1975**, *97*, 4765. (b) Evans, D. A.; Raillargeon, D. J. *Tetrahedron Lett.* **1978**, 3315. (c) Evans, D. A.; Raillargeon, D. J. *Ibid.* **1978**, 3319. (d) Steigerwald, M. L.; Goddard, W. A., III; Evans, D. A. *J. Am. Chem. Soc.* **1979**, *101*, 1994. (e) Ahlgren, G. *Tetrahedron Lett.* **1979**, 915. (f) Carpenter, B. K. *Tetrahedron* **1978**, *34*, 1877.

(46) (a) Seebach, D.; Geiss, K.-H.; Pohmakotr, M. *Angew. Chem., Int. Ed. Engl.* **1976**, *15*, 437. (b) Still, W. C. *J. Am. Chem. Soc.* **1977**, *99*, 4186. (c) Miyashi, T.; Hazato, A.; Mukai, T. *Ibid.* **1978**, *100*, 1008. (d) Evans, D. A.; Baillargeon, D. J.; Nelson, J. V. *Ibid.* **1978**, *100*, 2242. (e) Jung, M. E.; Hudspeth, J. P. *Ibid.* **1978**, *100*, 4309. (f) House, H. O.; Sayer, T. S. B.; Yau, C.-C. *J. Org. Chem.* **1978**, *43*, 2153. (g) Marvell, E. N.; Almond, S. W. *Tetrahedron Lett.* **1979**, 2779.

(47) Franzus, B.; Scheinbaum, M. L.; Waters, D. L.; Bowlin, H. B. *J. Am. Chem. Soc.* **1976**, *98*, 1241.

(48) (a) Thies, R. W.; Steiz, E. P. *J. Chem. Soc., Chem. Commun.* **1976**, 846. (b) Wilson, S. R.; Mao, D. T.; Jernberg, K. M.; Ezmirly, S. T. *Tetrahedron Lett.* **1977**, 2559. (c) Wilson, S. R.; Mao, D. T. *J. Chem. Soc., Chem. Commun.* **1978**, 479. (d) Thies, R. W.; Seitz, E. P. *J. Org. Chem.* **1978**, *43*, 1050. (e) Wilson, S. R.; Misra, R. N. *Ibid.* **1978**, *43*, 4903.

(49) (a) Paquette, L. A.; Crouse, G. D., submitted for publication in *J. Am. Chem. Soc.* (b) Paquette, L. A.; Sharma, A. K.; Crouse, G. D. *J. Am. Chem. Soc.* **1980**, *102*, 3972.

lectivity in their own right, is diametrically opposite to that of a fused bicyclo[2.2.2]octene ring.

Experimental Section

Infrared spectra were recorded on a Perkin-Elmer Model 467 spectrophotometer. The ^1H NMR spectra were determined with a Varian T-60 instrument, and apparent splittings are given in all cases. The ^{13}C NMR spectra were recorded on a Bruker WP-80 instrument. Mass spectra were measured on an AEI-MS9 spectrometer at an ionizing energy of 70 eV. Microanalytical determinations were performed at the Scandinavian Microanalytical Laboratory.

1,4-Dihydro-9,10-dimethoxy-1,4-methanoanthracene (5). A solution of purified 1,4-naphthoquinone (14.07 g, 0.089 mol) and freshly prepared cyclopentadiene (6.0 g, 0.091 mol) in ethanol (150 mL) was maintained at 0 °C for 3 h and allowed to warm slowly to room temperature. The precipitated crystals were separated by filtration and air-dried to give 18.0 g (90%) of adduct: ^1H NMR ($CDCl_3$) δ 8.0–7.4 (m, 4 H), 5.92 (m, 2 H), 3.70–3.25 (m, 4 H), 1.55 (br s, 2 H). This material was not further purified.

To a slurry of sodium hydride (7.5 g of a 50% oil dispersion, 0.156 mol) in anhydrous tetrahydrofuran (30 mL) was added dropwise a solution of the adduct (11.2 g, 50 mmol) in 20 mL of the same solvent. When the addition was complete, the reaction mixture was chilled, and methyl iodide (21.5 g, 0.01 mol) was slowly introduced. The flask was allowed to warm to room temperature with continued stirring of the contents for 3 h. Ether and water were added. After the layers were partitioned, the aqueous phase was extracted three times with ether. The combined organic layers were washed with water, dried, and evaporated to leave 12.6 g (100%) of **5** as a tan solid. Recrystallization of this material from ethanol gave colorless crystals: mp 84–84.5 °C; ^1H NMR ($CDCl_3$) δ 8.05–7.75 (m, 2 H), 7.40–7.10 (m, 2 H), 6.55 (m, 2 H), 4.15 (m, 2 H), 3.85 (s, 6 H), 2.10 (br s, 2 H); mass spectrum, m/e calcd 252.1150, obsd 252.1155.

Anal. Calcd for $C_{17}H_{16}O_2$: C, 80.92; H, 6.39. Found: C, 80.88; H, 6.55.

9,10-Dimethoxy-1,4-methano-1,2,3,4-tetrahydroanthracene (4). A solution of **5** (3.35 g, 13.3 mmol) in 200 mL of ethanol was hydrogenated in a Parr apparatus over 350 mg of 5% palladium on charcoal at 30 psi of H_2. After 3 h, the catalyst was removed by filtration through Celite, and the filtrate was evaporated to leave 3.35 g (99%) of **4** as a colorless crystalline solid: mp 76.5–77 °C (from ethanol); ^1H NMR ($CDCl_3$) δ 8.05–7.75 (m, 2 H), 7.40–7.10 (m, 2 H), 3.90 (s, 6 H), 3.67 (br s, 2 H), 2.10–1.10 (series of m, 6 H); mass spectrum, m/e calcd 254.1307, obsd 254.1306.

Anal. Calcd for $C_{17}H_{18}O_2$: C, 80.28; H, 7.13. Found: C, 79.94; H, 7.12.

1,4-Dihydro-9,10-dimethoxy-1,4-ethanoanthracene (6a). To a suspension of purified 1,4-naphthoquinone (23.3 g, 15 mmol) in ethanol (150 mL) was added 12.0 g (15 mmol) of 1,3-cyclohexadiene, and the resulting mixture was heated at reflux for 3 h. During this time, the yellow color of the quinone had disappeared. The reaction mixture was kept at 0 °C overnight, and the deposited crystals were filtered and dried. There was obtained 31.30 g (87.5%) of **6a**: colorless crystals; mp 135 °C (from ethanol) (lit.[50] mp 135 °C); ^1H NMR ($CDCl_3$) δ 8.0–7.40 (m, 4 H), 6.01 (dd, J = 4, 3 Hz, 2 H), 3.40–3.05 (m, 4 H), 1.90–1.15 (m, 4 H).

Treatment of 28.6 g (0.12 mol) of this adduct with 18 g (0.38 mol) of 50% sodium hydride oil dispersion and 51 g (0.36 mol) of methyl iodide in the predescribed manner afforded 32.7 g (100%) of **6a** as a tan-brown solid. After recrystallization from ethanol, there was obtained colorless crystals: mp 124–125 °C; ^1H NMR ($CDCl_3$) δ 8.05–7.75 (m, 2 H), 7.40–7.10 (m, 2 H), 6.40 (m, 2 H), 4.30 (m, 2 H), 3.85 (s, 6 H), 1.55 (br s, 4 H).

Anal. Calcd for $C_{18}H_{18}O_2$: C, 81.17; H, 6.81. Found: C, 81.31; H, 6.89.

1,4-Dihydro-9,10-dimethoxy-1,4-ethano-2-methylanthracene (6b). The adduct of 1,4-naphthoquinone and 2-methyl-1,3-cyclohexadiene was obtained in 85% yield and directly methylated. The ^1H NMR spectrum of the adduct in $CDCl_3$ shows δ 8.0–7.40 (m, 4 H), 5.60 (m, 1 H), 3.30–2.95 (m, 4 H), and 1.85–1.10 (m with d, J = 2 Hz, at 1.55, 6 H).

(50) Diels, O.; Alder, K. *Chem. Ber.* **1929**, *62*, 2337.

Dimethoxynaphthalene derivative **6b** was obtained quantitatively in crude form, but proved quite difficult to purify. After medium-pressure chromatography, molecular distillation, and recrystallization from ethanol at −16 °C there was obtained a colorless crystalline solid: mp 56.5–58.5 °C; ^1H NMR ($CDCl_3$) δ 8.10–7.75 (m, 2 H), 7.40–7.10 (m, 2 H), 6.0 (m, 1 H), 4.35–4.0 (m, 2 H), 3.85 (s, 6 H), 1.85 (d, J = 2 Hz, 3 H), 1.7–1.3 (m, 4 H); mass spectrum, m/e calcd 280.1463, obsd 280.1468.

Anal. Calcd for $C_{19}H_{20}O_2$: C, 81.39; H, 7.19. Found: C, 80.98; H, 7.16.

General Photooxygenation and Ketal Hydrolysis Procedures. All photooxygenations were carried out under identical conditions. Solutions consisting of 10 mg of substrate and 1 mg of rose bengal per milliliter of purified methanol were prepared and irradiated at room temperature with a 600-W Sylvania tungsten lamp. The irradiations were followed by thin-layer chromatography until total disappearance of starting material. The solvent was evaporated in vacuo to leave a solid residue.

An aliquot (usually one-tenth) of this material was hydrolyzed with 1 drop of 6 N hydrochloric acid in 5 mL of refluxing tetrahydrofuran. After cooling, the mixture was poured into water, and the aqueous solution was extracted three times with chloroform. The combined organic extracts were washed with water, dried, and evaporated. The epoxynaphthoquinones were isolated in pure form by preparative layer chromatography on silica gel.

The major portion was purified by column chromatography on silica gel to furnish the ketals for characterization. After suitable spectral analysis, the pure ketals were also hydrolyzed according to the conditions described above.

For **4**, a single ketal identified as **7a** was isolated in 55% yield as a colorless crystalline solid: mp 61–65 °C; ν_{max} (KBr) 1600 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.85–7.10 (m, 4 H), 3.50 (s, 3 H), 3.20–2.90 (m, 2 H), 3.05 (s, 3 H), 2.45–1.30 (series of m, 6 H).

Anal. Calcd for $C_{17}H_{18}O_4$: C, 71.31; H, 6.34. Found: C, 71.41; H, 6.36.

Hydrolysis of **7a** led in 82% yield to **8a**: colorless crystals; mp 103.5–104.5 °C; ν_{max} (KBr) 1690, 1595 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.9–7.4 (m, 4 H), 3.20 (m, 2 H), 2.35–1.40 (series of m, 6 H); ^{13}C NMR ($CDCl_3$) 189.92, 133.85, 133.41, 126.96, 75.78, 52,48, 35.68, 25.29 ppm; mass spectrum, m/e calcd 240.0786, obsd 240.0790.

Anal. Calcd for $C_{15}H_{12}O_3$: C, 74.99; H, 5.03. Found: C, 74.92; H, 5.22.

For **5**, a mixture of ketals consisting chiefly of **7b** (77% containing 7% of **9b**) was isolated in 57.5% yield as a colorless crystalline solid: mp 86–88 °C; ν_{max} (KBr) 1690, 1600 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.9–7.1 (m, 4 H), 6.05 (dd, J = 4, 3 Hz, 2 H), 3.65–3.30 (m, 2 H), 3.50 (s, 3 H), 3.10 (s, 3 H), 2.45–1.85 (series of m, 2 H); mass spectrum, m/e calcd 284.1049, obsd 284.1053.

Anal. Calcd for $C_{17}H_{16}O_4$: C, 71.82; H, 5.67. Found: C, 71.90; H, 5.76.

Hydrolysis of **7b** led in 77% yield to **8b**: colorless crystalline solid; mp 100–101 °C; ν_{max} (KBr) 1690, 1595 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.9–7.4 (m, 4 H), 6.05 (t, J = 1.5 Hz, 2 H), 3.65 (m, 2 H), 2.10 (m, 2 H); mass spectrum, m/e calcd 238.0630, obsd 238.0634.

Anal. Calcd for $C_{15}H_{10}O_3$: C, 75.62; H, 4.23. Found: C, 75.57; H, 4.31.

Hydrolysis of **9b** led in 80% yield to **10b**: colorless crystalline solid; mp 120–121 °C; ν_{max} (KBr) 1690, 1595 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.9–7.4 (m, 4 H), 6.50 (t, J = 1.5 Hz, 2 H), 3.55 (m, 2 H), 1.65 (m, 2 H); mass spectrum, m/e calcd 238.0630, obsd 238.0634.

Anal. Calcd for $C_{15}H_{10}O_3$: C, 75.62; H, 4.23. Found: C, 75.47; H, 4.38.

For **6**, a mixture of ketals consisting chiefly of **9c** (85% with 15% of **7c**) was isolated in 74% yield. The major ketal was isolated as a colorless crystalline solid: mp 118–120 °C (from hexane); ν_{max} (KBr) 1700 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.92–7.35 (m, 4 H), 6.7–6.3 (m, 2 H), 3.75–3.4 (m, 2 H), 3.42 (s, 3 H), 2.96 (s, 3 H), 1.80 (br d, 2 H), 1.10 (br d, 2 H).

Anal. Calcd for $C_{18}H_{18}O_4$: C, 72.46; H, 6.08. Found: C, 72.44; H, 5.99.

Hydrolysis of **9c** led in 90% yield to **10c**: colorless crystalline solid; mp 115–115.5 °C; ν_{max} (KBr) 1690, 1600 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.9–7.4 (m, 4 H), 6.45 (dd, J = 4, 3 Hz, 2 H), 3.80 (m, 2 H), 2.05–0.9 (series of m, 4 H); ^{13}C NMR ($CDCl_3$) 190.40, 136.64,

134.03, 133.05, 127.02, 72.31, 30.40, 22.09 ppm; mass spectrum, m/e calcd 252.0786, obsd 252.0792.

Anal. Calcd for $C_{16}H_{12}O_3$: C, 76.18; H, 4.80. Found: C, 75.82; H, 4.93.

Hydrolysis of **7c** led in 89% yield to **8c**: colorless crystalline solid; mp 144.5–145 °C; ν_{max} (KBr) 1690, 1595 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.95–7.45 (m, 4 H), 6.0 (dd, J = 4, 3 Hz, 2 H), 3.80 (m, 2 H), 1.45 (br s, 4 H); ^{13}C NMR ($CDCl_3$) 190.92, 134.12, 133.66, 129.35, 126.93, 60.87, 29.46, 21.33 ppm; mass spectrum, m/e calcd 252.0786, obsd 252.0791.

Anal. Calcd for $C_{16}H_{12}O_3$: C, 76.18; H, 4.80. Found: C, 75.91; H, 4.97.

For **7**, a mixture of ketals identified as **11** was isolated in 64% yield: ν_{max} (KBr) 1690 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.9–7.15 (m, 4 H), 6.15–5.72 (m, 1 H), 3.7–3.05 (m, 2 H), 3.40 (s, 3 H), 2.90 (s, 3 H), 2.10–0.9 (series of m, 4 H), 1.85 (d, J = 2 Hz, 3 H).

Hydrolysis of this material afforded in 76% yield the single epoxide **12**: colorless solid; mp 112–113 °C (from hexane); ν_{max} (KBr) 1690, 1595 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.9–7.35 (m, 4 H), 6.0 (m, 1 H), 3.8–3.45 (m, 2 H), 1.85 (d, J = 2 Hz, 3 H), 2.0–0.9 (series of m, 4 H); mass spectrum, m/e calcd 266.0943, obsd 266.0948.

Anal. Calcd for $C_{17}H_{14}O_3$: C, 76.67; H, 5.30. Found: C, 76.47; H, 5.54.

Catalytic Hydrogenation of 10b. A solution of **10b** (50 mg, 0.21 mol) in ethanol (10 mL) containing 15 mg of 5% palladium on charcoal was hydrogenated at atmospheric pressure until the uptake of hydrogen ceased (1.5 h). Filtration through Celite to remove the catalyst and solvent evaporation left 52 mg (100%) of **10a**: colorless crystalline solid; mp 152–153 °C (from ethanol); ν_{max} (KBr) 1690, 1595 cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.0–7.5 (m, 4 H), 3.10 (m, 2 H), 1.9–0.8 (series of m, 6 H); ^{13}C NMR ($CDCl_3$) 190.75, 134.04, 126.96, 63.94, 35.63, 28.30, 24.76 ppm; mass spectrum, m/e calcd 240.0786, obsd 240.0792.

Anal. Calcd for $C_{15}H_{12}O_3$: C, 74.99; H, 5.03. Found: C, 74.90; H, 5.15.

1,4-Dihydro-1,4-methano-9,10-anthraquinone (17). A solution of the naphthoquinone–cyclopentadiene adduct (4.94 g, 0.022 mol) in anhydrous tetrahydrofuran (20 mL) was added dropwise to an ice-cold suspension of 50% sodium hydride oil dispersion (1.375 g, 0.029 mol) in 15 mL of the same solvent. The reaction mixture was allowed to warm to room temperature where it was stirred for 2 h. After the mixture was cooled to 0 °C, saturated ammonium chloride solution was added, and the dihydroxynaphthalene was extracted into chloroform.

Oxygen was bubbled through the combined organic layers until one spot could be seen on thin-layer chromatography. After the solution was dried and evaporated, there remained 4.4 g (90%) of the naphthoquinone as a yellow solid: mp 155 °C (from ethanol) (lit.[50] mp 156 °C); ^1H NMR ($CDCl_3$) δ 8.0–7.4 (m, 4 H), 4.2 (m, 2 H), 2.22 (m, 2 H); mass spectrum, m/e calcd 222.0681, obsd 222.0685.

Catalytic Hydrogenation of 17. A solution of **17** (2.5 g, 0.0011 mol) in ethanol (200 mL) containing 300 mg of 5% palladium on charcoal was hydrogenated at atmospheric pressure, filtered through Celite, and evaporated to leave 2.5 g (100%) of **16** as a bright yellow solid: mp 137–138 °C (from methanol) (lit.[50] mp 138 °C); ^1H NMR ($CDCl_3$) δ 8.0–7.4 (m, 4 H), 3.6 (m, 2 H), 2.1–1.0 (series of m, 6 H); mass spectrum, m/e calcd 224.0837, obsd 224.0840.

1,4-Dihydro-1,4-ethano-9,10-anthraquinone (18a). A 2.0-g (8.4 mmol) sample of the naphthoquinone–cyclohexadiene adduct was dissolved in a mixture of 2 N sodium hydroxide (30 mL) and tetrahydrofuran (15 mL), and oxygen was bubbled through this solution with vigorous stirring for 24 h. The reaction mixture was saturated with sodium chloride and the product was extracted into chloroform. The combined organic extracts were dried, filtered, and evaporated to give 1.73 g (87%) of **18a** after recrystallization from ethanol: mp 160–190 °C (gas evolution) (lit.[50] mp 160–180 °C); ^1H NMR ($CDCl_3$) δ 8.0–7.4 (m, 4 H), 6.35 (m, 2 H), 4.45 (m, 2 H), 1.50 (br s, 4 H).

1,4-Dihydro-1,4-ethano-2-methyl-9,10-anthraquinone (18b). Oxidation of 1.50 g (5.95 mmol) of the naphthoquinone–2-methyl-1,3-cyclohexadiene adduct in an identical manner afforded 1.36 g (91%) of **18b**: a yellow solid; mp 143–145 °C (gas evolution); ν_{max} ($CHCl_3$) 1655, 1600 cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.0–7.4 (m, 4 H), 5.85 (m, 1 H), 4.4–4.1 (m, 2 H), 1.90 (d, J = 2 Hz, 3 H), 1.50 (br s, 4 H); mass spectrum, m/e calcd 250.0994, obsd 250.0995.

General Naphthoquinone Epoxidation Procedure. The procedure employed is an adaptation of methodology taken from two earlier reports[51,52] and is exemplified for **18a**.

To a solution of **18a** (1.18 g, 5 mmol) in ethanol (60 mL, some heating required) was added with stirring a solution of 30% hydrogen peroxide (1.3 mL) and sodium carbonate (320 mg) in water (5 mL) at 45–50 °C. After 5 min, the resulting solution was poured into water, and the precipitated white solid was collected by filtration and dried. There was obtained a 15:1 mixture of **8c** and **10c** (1.24 g, 98%). The isomeric epoxynaphthoquinones were separated by high-pressure liquid chromatography (except in the case of **16**) and were identified by direct comparison with the substances characterized earlier.

The only previously unreported epoxynaphthoquinone was **19**: colorless solid; mp 118–119 °C; ^1H NMR ($CDCl_3$) δ 8.0–7.4 (m, 4 H), 5.58 (dt, J = 6, 2 Hz, 1 H), 3.7–3.4 (m, 2 H), 1.81 (d, J = 2 Hz, 3 H), 1.46 (pseudo s, 4 H); ^{13}C NMR ($CDCl_3$) 191,22, 138.52, 134.06, 133.72, 126.89, 121.71, 61.93, 60.56, 34.53, 29.52, 22.12, 21.18, 20.15 ppm.

Anal. Calcd for $C_{17}H_{14}O_3$: C, 76.67; H, 5.30. Found: C, 76.73; H, 5.47.

Acknowledgment. This investigation was made possible by the financial support of the National Cancer Institute, DHEW (Grant CA-12115), the Deutsche Forchungsgemeinschaft, and the Fonds der Chemischen Industrie.

Registry No. 4, 75102-19-1; **5**, 52457-25-7; **6a**, 75102-20-4; **6b**, 75102-21-5; **7a**, 75102-22-6; **7b**, 75102-23-7; **7c**, 75172-25-7; **8a**, 75171-64-1; **8b**, 71127-62-3; **8c**, 75102-24-8; **9b**, 75171-65-2; **9c**, 75102-25-9; **10a**, 75171-66-3; **10b**, 71155-61-8; **10c**, 75171-67-4; **11**, 75102-47-5; **12**, 75102-26-0; **16**, 5821-57-8; **17**, 32745-55-4; **18a**, 32740-61-7; **18b**, 75102-27-1; **19**, 75171-68-5; **20**, 75102-28-2; **21**, 75171-69-6; **22**, 75102-29-3; **23**, 75171-70-9; **24**, 75102-30-6; **25**, 75171-71-0; 1,4-naphthoquinone, 130-15-4; cyclopentadiene, 542-92-7; 1,3-cyclohexadiene, 592-57-4; 2-methyl-1,3-cyclohexadiene, 1489-57-2; 9,10-dihydroxy-1,4-methano-1,2,3,4-tetrahydroanthracene, 75102-31-7; 1,4-dihydro-9,10-dihydroxy-1,4-methanoanthracene, 52457-24-6; 1,4-dihydro-9,10-dihydroxy-1,4-ethanoanthracene, 75102-32-8.

(51) Rashid, A.; Read, G. *J. Chem. Soc. C* **1967**, 1323.
(52) Fieser, L. F.; Campbell, W. P.; Fry, E. M.; Gates, M. D. *J. Am. Chem. Soc.* **1939**, *61*, 3216.