Urazoles **24d** and **2kd** were partially separated on silica gel (elution with 5% ethyl acetate in petroleum ether) with a Waters Prep 500A HPLC chromatograph operating in the recycling mode. The urazole mixture was dissolved in the minimum quantity of dichloromethane and injected onto the HPLC. The leading and trailing edges were independently collected after six recycles. The diastereomeric excess of each fraction was determined by ^{1}H NMR integration of the δ 0.77 and 0.76 singlets.

Hydrolysis–Oxidation of 24d. A sample of **24d** (38 mg, 0.08 mmol, leading edge with 23% diastereomeric excess) in isopropyl alcohol (3 mL) and sodium hydroxide (82 mg, 2.05 mmol) was heated at reflux for 2 h under nitrogen. The cooled reaction mixture was acidified with 2 N hydrochloric acid to pH 1 and neutralized with 3 N ammonium hydroxide to pH 9. Pentane (6 mL) and activated manganese dioxide (60 mg) were added. After being stirred at room temperature for 30 min, the reaction mixture was diluted with more pentane (8 mL). After filtration, the pentane layer in the filtrate was separated. The aqueous phase was extracted with pentane (2 × 8 mL), and the combined organic layers were washed with water, dried, and concentrated. The residue was immediately chromatographed at −30 °C on silica gel. Elution with pentane gave 78 mg (40%) of **5d**, which had no optical rotation.

A similar reaction was performed using the trailing edge urazole (60.4 mg, 0.127 mmol, $[\alpha]_D$ −7.1° (*c* 6.0, $CHCl_3$), 14% diastereomeric excess) and furnished 8.0 mg (26%) of **5d**, which likewise was totally racemic.

Peracid Oxidation of 21. To a mixture of **21** (15.2 mg, 0.06 mmol) and anhydrous sodium bicarbonate (13 mg, 0.16 mmol) in anhydrous dichloromethane (3 mL) was added *m*-chloroperbenzoic acid (18.5 mg of 56% purity, 0.06 mmol) in one portion. The reaction mixture was stirred at ambient temperature for 3 h, diluted with dichloromethane (50 mL), and washed with water (50 mL), saturated sodium bicarbonate solution (50 mL), water (50 mL), and brine (50 mL) prior to drying. After removal of the solvent in vacuo, the residue was chromatographed on silica gel (elution with 2% ethyl acetate in petroleum ether) to give **27** as a colorless oil (4.9 mg, 31%): ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.53 (t, J = 2.2 Hz, 1 H), 6.91 (s, 2 H), 3.99 (d, J = 2.2 Hz, 2 H), 2.82–2.54 (m, 4 H), 2.30 (s, 3 H), 1.94–0.43 (m, 16 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 199.99, 141.92, 136.85, 129.57, 125.77, 44.68, 33.31, 28.30, 26.99, 26.48, 26.43, 21.03.

Procedure for Determining Rates of Racemization for 5c. The sample of **5c** used for the kinetic studies was characterized by $[\alpha]^{20}_D$ +125.3°, $[\alpha]^{20}_{578}$ +132.3°, and $[\alpha]^{20}_{546}$ +160.0° (*c* 0.37, diglyme) and was obtained by oxidation–hydrolysis of a urazole sample that was 33% diastereomerically enriched, $[\alpha]^{20}_D$ +12.04° (*c* 0.49, $CHCl_3$). A 7.5-mg quantity of (+)-**5c** was dissolved in a polarimeter cell thermally equilibrated by means of a circulating constant-temperature bath. The solution was allowed to equilibrate for 4 min at 20.0 °C, an accurate timer was started, and readings were taken at appropriate time intervals. After adequate data were recorded, the solution temperature was then increased to 30.0 and 40.0 °C, respectively, where additional readings were again taken at appropriate time intervals. The resulting −ln α data were plotted vs time and slopes of the straight lines were determined by least-squares methods.

Acknowledgment. This investigation was supported primarily by the National Science Foundation whom we thank. M.P.T. expresses his gratitude to Phillips Petroleum for a fellowship.

Is Pseudorotation the Operational Pathway for Bond Shifting within [8]Annulenes? Probe of Planarization Requirements by 1,3-Annulation of the Cyclooctatetraene Ring. Kinetic Analysis of Racemization and 2-D NMR Quantitation of π-Bond Alternation and Ring Inversion as a Function of Polymethylene Chain Length

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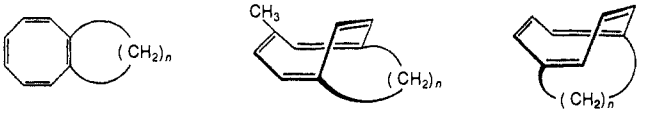
Abstract: The chiral 1,3-bridged cyclooctatetraenes **9a–c** have been prepared in nine steps from the appropriate 2-cycloalkenone precursors. Following annulation with ethyl acetoacetate to give **15**, *trans*-1,2-dichloroethylene was cycloadded photochemically in a [2 + 2] reaction and a cyclobutene ring was ultimately formed. Once reduction to alcohol **19** was accomplished, dehydration was effected and the bicyclo[4.2.0]octatrienes so generated underwent disrotatory ring opening to deliver the [8]annulenes. The rates of this electrocyclic ring opening were determined in two examples. Polarimetric studies provided quantitative measure of the readiness with which planar dianion formation occurs as a function of loop size. Unexpectedly, attempts to resolve these molecules failed to deliver them in optically active condition because of too rapid enantiomerization via ring inversion and/or bond shifting. The rates of these processes were determined by 2-D dynamic NMR methods, the data revealing that both processes are accelerated relative to nonbridged models. These and related findings are interpreted in terms of a pseudorotation scheme leading to flattened saddle and not planar-alternate transition states. The unique features associated with this mechanistic phenomenon are discussed.

As extensive as studies of the dynamic properties of cyclooctatetraenes have been,[1] only recently has attention been paid to bracketing the [8]annulene core for the purpose of probing mechanistic detail. 1,2-Bridging as in **1** is now recognized to accelerate ring inversion rates relative to those of bond shifting.[2]



1 2 3

In contrast, (1,4)cyclooctatetraenophanes such as **2** that carry a short polymethylene chain (e.g., n = 5) are totally impeded from undergoing either process.[3] In the preceding paper,[4a] it was shown

(1) Reviews: (a) Oth, J. F. M. *Pure Appl. Chem.* **1971**, *25*, 573. (b) Paquette, L. A. *Tetrahedron* **1975**, *31*, 2855. (c) Fray, G. I.; Saxton, R. G. *The Chemistry of Cyclooctatetraene and Its Derivatives*; Cambridge University Press: New York, 1978. (d) Paquette, L. A. *Pure Appl. Chem.* **1982**, *54*, 987.

(2) (a) Paquette, L. A.; Wang, T.-Z. *J. Am. Chem. Soc.* **1988**, *110*, 8192. (b) Paquette, L. A.; Wang, T.-Z.; Cottrell, C. *Ibid.* **1987**, *109*, 3730.

(3) (a) Paquette, L. A.; Trova, M. P. *J. Am. Chem. Soc.* **1988**, *110*, 8197. (b) Paquette, L. A.; Trova, M. P. *Tetrahedron Lett.* **1986**, *27*, 1895.

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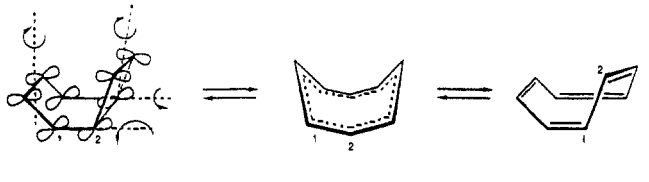
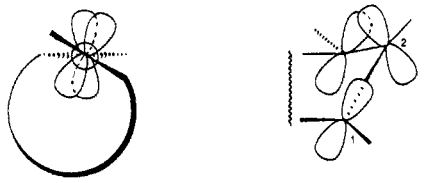
that the 1,5-belting arrangement illustrated by **3** allows for optical resolution when $n = 8$ or less and the subsequent determination of racemization rates. The activation parameters for loss of optical activity in the octamethylene derivative, it was argued, are not in agreement with flexing of a portion of the [8]annulene ring through the loop (i.e., net ring inversion). Rather, the energetic costs were considered to reflect the exclusive operation of bond shifting, although not by means of the "classical" planar-alternate transition-state model. The latter view has been held for many years.[1,5] Rather, the novel proposal was advanced that the favored minimum energy pathway may involve simultaneous pseudorotation at all eight trigonal centers.[4]

We[2-6] and others[7] have come to regard the energetics of bond shifting within cyclooctatetraenes to be insufficiently costly to be mediated by planar delocalized $4n$ antiaromatic transition-state structures. Here we consider the pseudorotation phenomenon in greater detail and show that such a reaction profile is consistent with the kinetic behavior of a series of 1,3-bridged cyclooctatetraenes.

The Nature of Pseudorotation. To understand the concept of pseudorotation as applied to cyclooctatetraene, it is instructive to construct a Dreiding or Flexible Stereochemistry[8] molecular model in which the eight *nonrigidly interlinked*, trigonal carbon atoms are arranged in a cyclic tub conformation. As rotation around the transannularly positioned π bonds commences in the *same* direction (see **4**), twisting sets in about each of the four



4 **5** **6**



7 **8**

original olefinic linkages, much as CC double bonds are forced out of coplanarity in *trans*-cycloalkenes (see **7**).[9] Although the latter systems probably attempt to incorporate some s character into their p orbitals as a means of regaining some of the lost π overlap,[10] comparable hybridization changes are not mandated in **4**. This is because only modest levels of twisting begin to allow overlap with the alternative nearest-neighbor sp^2 center. An attempt to display this unique capability of annulenes is made in **8**. The greater the level of twisting in **4**, the greater is the extent of dismantling the original π bonds and the more advanced is installation of the new set of unsaturated linkages.

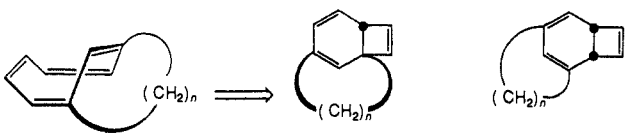
There are several important consequences of this particular bond-shifting (BS) pathway. First and foremost, the cyclooctatetraene core does not at any time become planar and no driving force exists for coercing it to do so. Therefore, the resultant BS transition state takes on the topographical characteristics of a somewhat flattened saddle[7] as in **5**. As a result, bond shifting can be realized within a cyclooctatetraenophane without need of forcing a portion of the [8]annulene ring proximal to the interior of the polymethylene loop.

From the energetic vantage point, the almost concurrent π-disconnection/reestablishment of alternative π overlap can be expected to lower the costs of accomplishing bond alternation. An ability within these systems to bypass delocalized planar-alternate conformations would have the effect of giving rise to lower values of $\Delta H^{\ddagger}$ and $\Delta G^{\ddagger}$ than otherwise expected. Of course, substituent groups originally positioned across a CC single bond in **4** will experience enhanced compression as pseudorotation is initiated. Steric contributions of this type, including buttressing effects,[11] are recognized to impact in a meaningful way on the rates of bond shifting.[6,12]

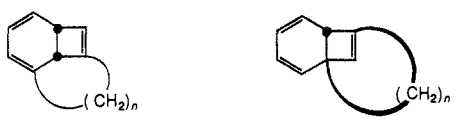
In a broad sense, pseudorotation can be applied in principle to any annulene that has a nonplanar ground state. Aromaticity is presently recognized to be maintained at $p\pi$ distortion angles up to 30 °C and beyond.[13] Were the twisting about C-1/C-2 and C-3/C-4 in **4** to be carried forward to that extreme level, a new π bond would have essentially been formed across C-2/C-3 since the original angle between the C-1/C-2 and C-3/C-4 plane in the ground-state tub conformation is less than 90 °C.

The task then is to develop experiments capable of distinguishing between transition states that differ predominantly in conformation (and, to an extent, electronic character also). This distinction is not trivial. The customary test probes (regiochemistry, stereochemistry, and the like) are unable to deliver the proper level of mechanistic insight. The placement of alkyl and aryl groups around the cyclooctatetraene perimeter has proven useful in a variety of contexts,[6,11,12] but cannot per se provide mechanistic confirmation. It is for these reasons that we have made recourse to annulated derivatives, for the likelihood appeared greatest that molecules of this type might be the source of more convincing evidence.

Preparation of the (1,3)Cyclooctatetraenophanes.[14] Confidence in the reliability of an electrocyclic ring-opening strategy[6,12] led us to consider the suitable construction of **9** from one or the other



9 **10** **11**



12 **13**

(4) (a) Paquette, L. A.; Trova, M. P.; Luo, J.; Clough, A. E.; Anderson, L. B. *J. Am. Chem. Soc.*, preceding article in this issue. (b) Paquette, L. A.; Trova, M. P. *Tetrahedron Lett.* **1987**, *28*, 2795; errata p 4354.

(5) Gardlik, J. M.; Paquette, L. A.; Gleiter, R. *J. Am. Chem. Soc.* **1979**, *101*, 1617, and relevant references cited therein.

(6) (a) Paquette, L. A.; Gardlik, J. M.; Johnson, L. K.; McCullough, K. J. *J. Am. Chem. Soc.* **1980**, *102*, 5026. (b) Paquette, L. A.; Hanzawa, Y.; McCullough, K. J.; Tagle, B.; Swenson, W.; Clardy, J. *Ibid.* **1981**, *103*, 2262. (c) Paquette, L. A.; Hanzawa, Y.; Hefferon, G. J.; Blount, J. F. *J. Org. Chem.* **1982**, *47*, 265. (d) Paquette, L. A.; Gardlik, J. M.; McCullough, K. J.; Hanzawa, Y. *J. Am. Chem. Soc.* **1983**, *105*, 7644. (e) Paquette, L. A.; Gardlik, J. M.; McCullough, K. J.; Samodral, R.; DeLucca, G.; Ouellette, R. J. *Ibid.* **1983**, *105*, 7649.

(7) Ermer, O.; Klärner, F.-G.; Wette, M. *J. Am. Chem. Soc.* **1986**, *108*, 4908, and relevant references cited therein.

(8) These model kits are available from Darling Models, P.O. Box 1818, Stow, OH 44224.

(9) Review: Shea, K. J. *Tetrahedron* **1980**, *36*, 1683.

(10) (a) Allinger, N. L. *J. Am. Chem. Soc.* **1958**, *80*, 1953. (b) Mock, W. L. *Tetrahedron Lett.* **1972**, 475. (c) Radom, L.; Pople, J. A.; Mock, W. L. *Ibid.* **1972**, 479. (d) Allinger, N. L.; Sprague, J. T. *J. Am. Chem. Soc.* **1972**, *94*, 5734. (e) Rogers, D. W.; Voitkenberg, H.; Allinger, N. L. *J. Org. Chem.* **1978**, *43*, 360.

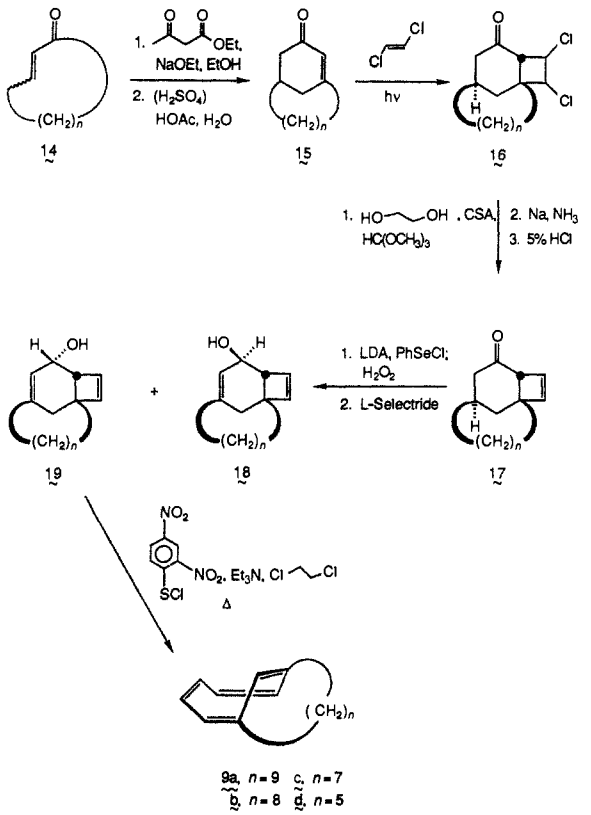
(11) Paquette, L. A.; Gardlik, J. M. *J. Am. Chem. Soc.* **1980**, *102*, 5033.

(12) (a) Paquette, L. A.; Photis, J. M. *J. Am. Chem. Soc.* **1976**, *98*, 4936. (b) Paquette, L. A.; Gardlik, J. M. *Ibid.* **1980**, *102*, 5016. (c) Paquette, L. A.; Gardlik, J. M.; Johnson, L. K.; McCullough, K. J. *Ibid.* **1980**, *102*, 5026. (d) Hanzawa, Y.; Paquette, L. A. *Ibid.* **1981**, *103*, 2269. (e) Paquette, L. A.; Hefferon, G. J.; Samodral, R.; Hanzawa, Y. *J. Org. Chem.* **1983**, *48*, 1262.

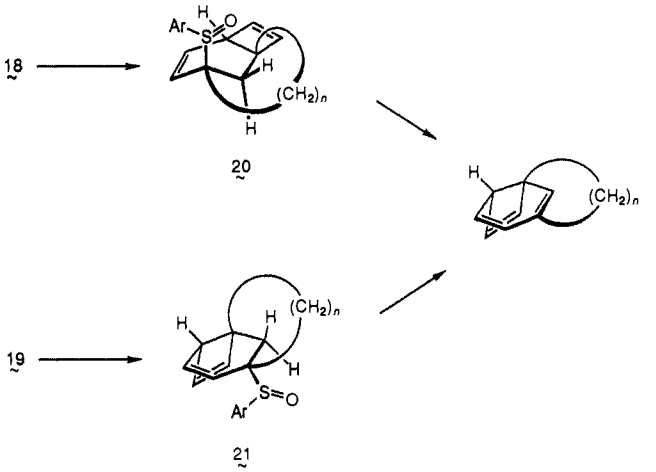
(13) For a recent demonstration of a highly bent aromatic system, see: Blank, N. E.; Haenel, M. W.; Kruger, C.; Tsay, Y.-H.; Wientges, H. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 1064.

(14) Preliminary communication: Wang, T.-Z.; Paquette, L. A. *Tetrahedron Lett.* **1988**, *29*, 41.

Scheme I



Scheme II



of the bicyclo[4.2.0]octatrienes **10–13**. Of these, **11–13** were quickly dismissed as useful penultimate intermediates because the locations of their polymethylene chains caused access to be impractical. On the other hand, triene **10** appeared to lend itself more readily to synthesis since its bridging carbons are so positioned on the cyclohexadiene subunit that utilization of a modestly functionalized macrocycle as starting material appeared feasible.

Since the thrust was to proceed from large to small values of *n*, cyclododecanone was initially transformed into 2-cyclododecenone (**14a**) according to literature precedent.[15] Base-catalyzed Michael addition of ethyl acetoacetate to **14a** followed by cyclizative decarboxylation[16] delivered **15a** quantitatively (Scheme I). The final two carbons were introduced by photochemical [2 + 2] cycloaddition to *trans*-1,2-dichloroethylene. Although some dichloromethane may be used as diluent, the latter olefin was often employed as the reaction solvent because of the need to engage **15a** in cyclobutane formation at a rate faster than deconjugation[17] or intramolecular photocyclization.[16] A 73% yield of **16a** could be routinely realized by this means. Submission of **16a** to sequential ketalization, reductive dechlorination, and acid hydrolysis gave rise efficiently (94%) to **17a**. The necessary cyclohexenone double bond was next introduced by the application of organoselenium chemistry. Reduction with L-Selectride in dichloromethane solution at −78 °C produced the epimeric allylic alcohols **18a** and **19a**. Whereas **19a** is obtained in substantial excess over **18a** under these conditions, the use of diisobutylaluminum hydride provided **19a** in less dominant amounts (ratio 2.5:1). Subsequent treatment of the mixture with 2,4-dinitrobenzenesulfenyl chloride and triethylamine in refluxing 1,2-dichloroethane[18] provided **9a** in 65% yield. When pure samples of **18a** and **19a** were individually submitted to dehydration in this fashion, the cyclooctatetraenophane was produced in yields of 60% and 82%, respectively.

That electrocyclic ring opening of the intermediate bicyclo[4.2.0]octatriene had occurred spontaneously was confirmed by spectral analysis. The high-field 300-MHz ^{1}H NMR spectrum of the hydrocarbon (in $CDCl_3$) revealed six olefinic protons to be present. Of these, two appear as well-separated singlets at δ 5.62 and 5.54, one is seen as a discrete doublet at low field (δ 6.00, J = 11.7 Hz), and the remaining three are displayed as an overlapping multiplet centered at δ 5.75. Furthermore, the ^{13}C NMR spectrum of **9a** is characterized by eight olefinic carbon signals in addition to those arising from the nine distinctive methylene units.

To arrive at the next lower homologue, cycloundecanone was prepared by ring contraction of the inexpensive, readily available cyclododecanone according to Garbisch[19] and subjected to sequential ketalization, bromination, elimination, and hydrolysis as before.[15a] The ensuing six-step conversion of **14b** to **17b** (Scheme I) was similarly realized in 49% overall yield. L-Selectride reduction of the corresponding dienone gave **18b** and **19b** in a 1:2 ratio. Following chromatographic separation, these allylic alcohols were individually subjected to the Reich–Wollowitz procedure.[18] While **19b** delivered **9b** in 70% yield, **18b** showed no signs of undergoing an analogous transformation.

At this point, it becomes relevant to outline the important stereochemical implications of the sulfenate → sulfoxide [2,3] sigmatropic rearrangement in the context of the isomeric allylic alcohols **18** and **19**. Thus, the constraints of orbital symmetry and least motion require that **20** and **21** be formed stereospecifically (Scheme II). In **21**, the geometrical alignment between ArS(O) and the neighboring cis methylene hydrogen remains quite respectable for a wide range of *n* values. Contrastingly, the sulfoxide group in **20** can hope to eclipse an adjacent C–H bond and enter into elimination only when *n* is sufficiently large to permit reasonable conformational flexibility within the six-membered ring. This is possible when n = 9 as shown by the fact that pure **18a** could be transformed into **9a**. The disparity in efficiency relative to **19a** (60% versus 82%) could, however, be a reflection of the pronounced structural differences just noted. Certainly, an *n* value of 8 is adequate to curtail elimination within sulfoxide isomer **20**.

The latter phenomenon is, of course, expected to be exacerbated further in **18c** and **18d**. Increased attention had therefore to be paid to attaining as much stereocontrol as possible in the 1,2-reduction of their precursor dienones.

To arrive at **9c**, we had next to address the acquisition of 2-cyclodecenone in reasonable quantity. Although **22** could be prepared by the further ring contraction of cycloundecanone,[19] this route proved too lengthy and tedious. Moreover, submission of the ethylene ketal of **22** to standard bromination–dehydro-

(15) (a) Shinsaku, F.; Takeyouki, K.; Hitosi, N. *Bull. Chem. Soc. Jpn.* **1970**, *45*, 2596. (b) For an alternate approach, see: Reich, H.; Renga, J. M.; Reich, I. L. *J. Am. Chem. Soc.* **1975**, *97*, 5434.

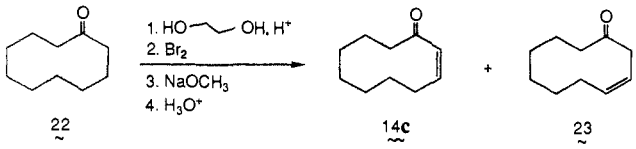
(16) Gioia, B.; Marchesini, A.; Andreeti, G. D.; Bocelli, G.; Sgarabotto, P. *J. Chem. Soc., Perkin Trans. 1* **1977**, 410.

(17) (a) Marchesini, A.; Pagnoni, U. M.; Beccalli, E. M.; Cecchi, R.; Marchesini, A. *J. Chem. Soc., Perkin Trans. 1* **1981**, 560.

(18) (a) Reich, H. J.; Wollowitz, S. *J. Am. Chem. Soc.* **1982**, *104*, 7051. (b) Wang, T.-Z.; Paquette, L. A. *J. Org. Chem.* **1986**, *51*, 5232.

(19) Garbisch, E. W., Jr.; Wohllebe, J. *J. Org. Chem.* **1968**, *33*, 2157.

bromination[20] resulted in the isolation of a difficulty separable mixture of **14c** and **23** in low yield.[21]



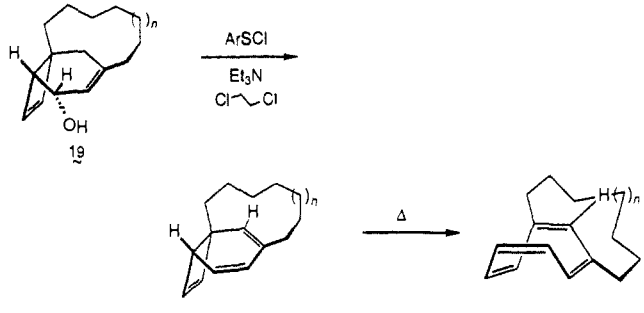
22 14c 23

A much simpler protocol is outlined in Scheme III. Sebacoin (**24**), produced reliably by the acyloin condensation of commercially available dimethyl sebacate,[22] was transformed into its mesylate and subjected to S_N2 reaction with sodium thiophenoxide. Oxidation of **25b** with 1 equiv of *m*-chloroperbenzoic acid and subsequent heating of **26** with calcium carbonate in benzene made pure **14c** available in 56% overall yield from **24**.

The condensation of **14c** with ethyl acetoacetate proved more sluggish than heretofore and required heating. Enone **15c** was formed in good yield and purified by recrystallization. The subsequent elaboration of **17c** proceeded very well. With arrival at the dienone, it was noted that L-Selectride reduction continued to produce the desired α-alcohol predominantly (**19c**:**18c** = 2.2:1). Alcohol **19c** underwent smooth dehydration to **9c**. While reduction in the size of the belt has no significant impact on the carbon shifts of this [8]annulene, changes are manifested in the details of its ^{1}H NMR spectrum. For example, the olefinic proton signals in **9c** at 300 MHz in $CDCl_3$ consists of a five-proton multiplet in the δ 5.96–5.68 region and a broadened singlet at δ 5.52. Similar effects have been noted for 1,2-bridged cyclooctatetraenes during downsize progression from cyclohexyl to cyclopentyl.[2b]

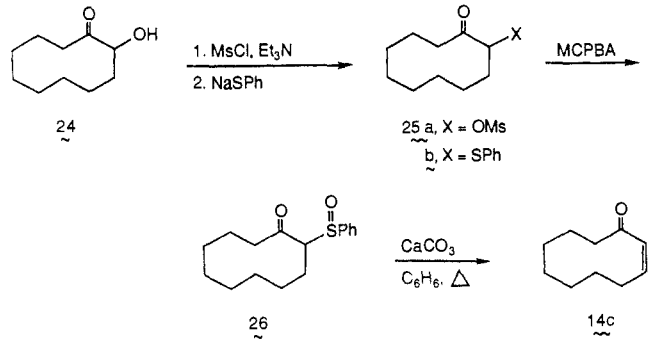
Bicyclic enone **15d** is a well-known and readily available substance[10b,23] that was transformed without event into **17d**. However, all attempts to achieve the conversion of this ketone into **19d** invariably led exclusively to **18d**. In the present instance, the polymethylene chain is sufficiently contracted that a significant steric barrier is now provided to deter hydride attack from the syn direction. Disappointingly, all attempts to invert hydroxyl configuration in **18d** were also to no avail. As expected, submission of **18d** to dehydration in the customary manner gave no **9d**, and this cyclooctatetraenophane was therefore not available for study.

Kinetic Analysis of an Electrocyclic Ring Opening. The conversion of **10** into the target (1,3)cyclooctatetraenophanes **9** must, if orbital symmetry controlled, proceed by disrotatory cleavage of the central bicyclooctatriene σ bond. The principal consequence is that electronic reorganization materializes exclusively within the confines of the original cyclohexadiene subunit. In those examples where the ultimate positioning of the π bonds can be recognized precisely, this mechanistic pathway is clearly followed;[4-6,11,12] that is, the original cyclobutene double bond is not translocated. For **10**, important consequences follow.[24] In this



19 10 9

Scheme III



24 25 a, X = OMs b, X = SPh 26 14c

series, disrotatory opening brings with it the need to force the interior vinylic proton through the polymethylene loop as illustrated. As a result, the kinetic stability of **10** should increase as *n* decreases because of the incrementally enhanced steric screening.

Earlier, the dehydration of **19a–c** had been accomplished by heating during several hours in refluxing 1,2-dichloroethane (bp ~80 °C). In order to permit the isolation of **10** (n = 8 and 7), it became necessary to perform this conversion at reduced temperatures for more limited periods of time. On doing so, **10b** and **10c** were indeed obtained alongside smaller amounts of the corresponding annulated cyclooctatetraenes. Moreover, these trienes were sufficiently stable to survive rapid medium-pressure liquid chromatographic (MPLC) separation from their valence isomers.

With **10b** and **10c** thus available, their ring-opening rate constants were determined on degassed benzene solution in NMR tubes sealed in vacuo. ^{1}H NMR spectra were recorded during appropriate time intervals at three temperatures, and the ratios of **10** to **9** were calculated on the basis of integrals stemming from a one-proton vinyl absorption in each isomer. For **10b**, the $t_{1/2}$ for its first-order isomerization at 30 °C is approximately 90 min. Ring opening of the lower analogue **10c** proceeds yet more slowly as expected and is conveniently amenable to kinetic analysis: $\Delta H_{25°C}^{\ddagger}$ = 24.4 kcal/mol, $\Delta S_{25°C}^{\ddagger}$ = 1.7 eu, $\Delta G_{25°C}^{\ddagger}$ = 23.9 kcal/mol, and E_a = 25.0 kcal/mol. The energy of activation for the latter process is higher by 6.3 kcal/mol than that for ring opening of the parent bicyclo[4.2.0]octa-2,4,7-triene ($t_{1/2}$ = 14 min at 0 °C); E_a = 18.7 kcal/mol).[25]

Therefore, the presence of the heptamethylene chain in **10** clearly has significant consequences. This process is related to that operational in the conformational flipping within [7]metacyclophane and *trans*-cyclononene. Although the aromatic ring in the phane is already planar, the barrier ($\Delta G^{\ddagger}$) associated with its passage through the heptamethylene chain is 11.5 kcal/mol.[26] The free energy of activation ($\Delta G_{-10°C}^{\ddagger}$) for racemization of the *trans*-cycloalkene has been defined as 19.1 kcal/mol.[27]

Reduction Studies. Cyclooctatetraene and a variety of its substituted analogues undergo two one-electron reductions of the eight-membered monocyclic ring.[12a,b,28-31] Comparison of the measured formal reductive potentials for different substituted COTs is a valid method for gaining quantitative understanding of nonbonded steric interactions accompanying the reductive process.

To accomplish this, the effects of changes in solvation, ion pairing, aromaticity, and C–C–C bond angle strain in the ring, which also accompany its reduction, must be virtually constant

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Table I. Formal Reduction Potentials of (1,3)Cyclooctatetraenophanes in 0.1 M TBAP/HMPA[a]

compd	$E_1^{0\prime}$,[b] V (vs SCE)	$E_2^{0\prime}$,[b] V (vs SCE)	$E_{1,2}^{0\prime}$, V	ΔE_{bridge}, V	K_D ($\times 10^{-5}$)
COT	−1.61	−1.92			0.576
9a	−1.87	−2.11	−0.225	−0.045	8.78
9b	−1.89	−2.10	−0.230	−0.050	28.2
9c	−1.96	−2.23	−0.330	−0.150	2.73

[a] TBAP, tetra-*n*-butylammonium perchlorate; HMPA, hexamethylphosphoramide. [b] The $E^{0\prime}$ values were obtained vs Ag/0.1 M $AgClO_4$ in HMPA and corrected to SCE by adding 0.36 V.

from molecule to molecule. This is true if the formal potentials compared are those for reaction of the form

$$RCOT + 2e^- \overset{E_{1,2}^{0\prime}}{\rightleftharpoons} RCOT^{2-} \quad (1)$$

RCOT represents the nonplanar, neutral hydrocarbon and $RCOT^{2-}$ the fully planar, aromatic dianion. In contrast, comparison of the potentials for the one-electron reduction of RCOT to its radical anion, $E_1^{0\prime}$, will be of uncertain validity because the conformations and aromaticity levels of the various radical anions are not well-known and they may vary substantially among molecules experiencing a wide range of nonbonded steric strain.

$E_{1,2}^{0\prime}$ is computed from experimental data as the average of the formal potentials of the two one-electron processes:

$$E_{1,2}^{0\prime} = (E_1^{0\prime} + E_2^{0\prime})/2 \quad (2)$$

or as the formal potential of the two-electron process (1) when the first and second reductions occur at virtually the same potential.[32]

For the 1,3-methylene-bridged COT derivatives studied here, the effects of bond angle strain, changes in aromaticity, solvation, and ion pairing on their reduction potentials are assumed to be similar to those experienced by the parent hydrocarbon. Any additional shifts in $E_{1,2}^{0\prime}$ may then be ascribed to inductive effects of substituents and nonbonded steric effects such as buttressing[11] and interactions of the methylene bridge with itself as well as with the planarized (though not necessarily planar), eight-membered ring.

$$\Delta E_{1,2}^{0\prime} = [E_{1,2\,RCOT}^{0\prime} - E_{1,2\,HCOT}^{0\prime}] = \Delta E_{ind} + \Delta E_{buttress} + \Delta E_{bridge} \quad (3)$$

The bridge effect, ΔE_{bridge}, has been computed for compounds **9a–c** (Table I). In calculating these values, two approximations were made: (a) the inductive effect ($\Delta E_{ind} = -0.150$ V) was the same for all the compounds studied and was equal to twice the magnitude of ΔE_{ind} for monomethylCOT; (b) the buttressing effect ($\Delta E_{buttress} = -0.030$ V) was also the same for all the compounds and equaled that of 1,3-$(CH_3)_2$COT computed from its $E_{1,2}^{0\prime}$ and assuming $\Delta E_{ind} = -0.150$ V. The remaining change in $E_{1,2}^{0\prime}$ for these compounds is attributable to the presence of the bridging group.

As the length of the bridging chain decreases, the bridge effect increases dramatically. In shorter bridges, the methylene groups are constrained to a smaller area and the nonbonded steric interactions between them increase. These interactions, therefore, have a significant influence on the electrochemical behavior of cyclooctatetraenes containing bridging groups.

The methylene bridges in these compounds also decrease the stabilities of the radical anions relative to disproportionation (eq 4). This is reflected in the increase of the equilibrium constant

$$2RCOT^{\bullet-} \overset{K_D}{\rightleftharpoons} RCOT + RCOT^{2-} \quad (4)$$

for disproportionation, K_D. In addition, the cyclic voltammograms indicate that the products of reduction are less stable toward chemical reaction than the radical anion and dianion of the unadorned cyclooctatetraene molecule due to the presence of the bridges.

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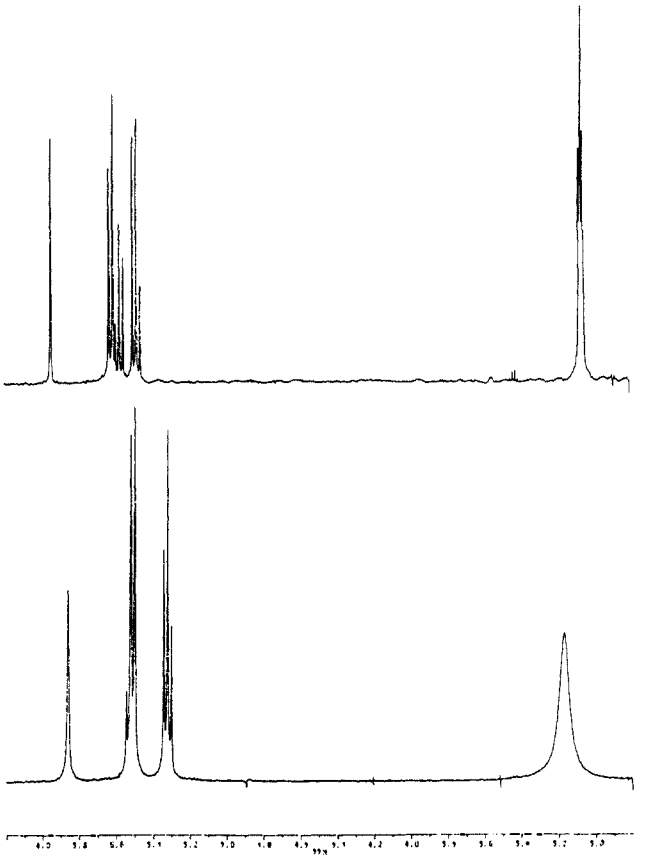
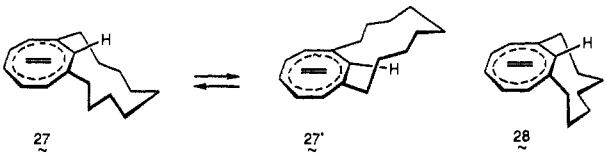


Figure 1. 500-MHz ^1H NMR spectra of the dianions of **9a** (top) and **9c** (bottom) in ND_3 at 213 K.

In a separate study, the dissolving-metal reduction of **9a** and **9c** was undertaken in order to examine their conversion to dianions spectroscopically. These reactions were performed in NMR tubes using potassium metal in ND_3 solution containing trimethylamine as the internal standard.[30,33] The resultant spectra are shown in Figure 1. As concerns **27**, the triplet nature of the δ 3.06

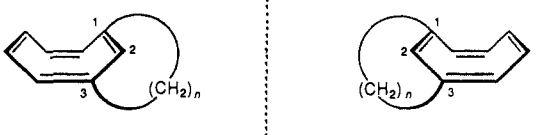


27 **27′** **28**

absorption due to the four allylic protons is taken as an indication that bridge flipping to sites above and below the planar dianion surface, i.e., **27** ⇄ **27′**, is occurring rapidly on the NMR time scale even at −60 °C. For the more strained $(CH_2)_7$ congener **28**, this process is measurably slowed, as reflected in the appearance of the same four-proton signal (now at δ 3.17) as a broadened singlet.

The existence of these dianions was further corroborated by their subsequent oxidation with iodine.[34] In both instances, reconversion to the starting cyclooctatetraenophanes was seen. By comparison, direct quenching in cold methanol led instead to mixtures of dihydro derivatives (GC–MS analysis).

Attempted Resolution of the (1,3)Cyclooctatetraenophanes. As a consequence of their lack of symmetry, the (1,3)-cyclooctatetraenophanes are chiral annulenes. When *n* is even,



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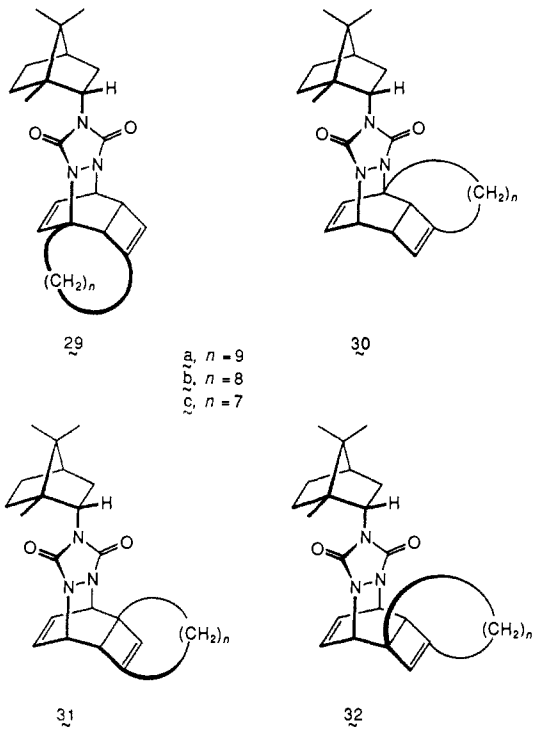
all of the methylene groups along the loop are constituted of a diastereopair of protons. This phenomenon applies equally well to **9a** and **9c** with the exception of the central CH_2 link. One possible scheme for enantiomer interconversion in this series involves the passage of C-2 and its associated hydrogen through the loop, a process that should become progressively impeded as the value of *n* decreases. Since determination of the rates of racemization of **9** would advance our fundamental appreciation of their dynamic capabilities, the direct optical resolution of **9a–c** was next pursued.

Treatment of **9a** with (−)-*endo*-bornyltriazolinedione[35] in refluxing ethyl acetate solution gave rise to the diastereomeric urazoles **29a–32a**. The major pair consisting of **29a** and **30a** could



be separated from the other by MPLC. Following several recrystallizations from ethyl acetate/petroleum ether, a single pure adduct (300-MHz ^{1}H NMR analysis)[36] that exhibited $[\alpha]^{25}_D$ +14.0° was isolated. Its absolute configuration was not determined. Submission of this urazole to standard hydrolysis–oxidation conditions, with careful attention to maintaining reaction temperatures as low as possible,[4,6,12] returned only racemic **9a**. Optical activity had obviously been completely lost during the course of reaction and/or workup, signaling that the nine-membered loop is sufficiently loose to permit rapid enantiomerization by one or more pathways.

Racemic **9b** also entered into Diels–Alder reaction with the same optically pure triazolinedione. In this instance, diastereomer separation was achieved by MPLC on silica gel. Oxidative hydrolysis of either structural isomer under conditions that again precluded the use of excessive temperatures invariably returned samples of **9b** that exhibited $[\alpha]_D$ values of zero. Racemization need therefore be occurring rapidly below 20 °C in this series as well.

When the lower homologue **9c** was studied, efficient trapping likewise occurred with (−)-*endo*-bornyltriazolinedione to give only **29c** and **30c**. No separation of these urazoles was realized by recrystallization, and MPLC met with limited success. By the latter means, a purified sample of **29c** or **30c** could be obtained as a white solid characterized by $[\alpha]^{25}_{436}$ +86°. ^{1}H NMR analysis

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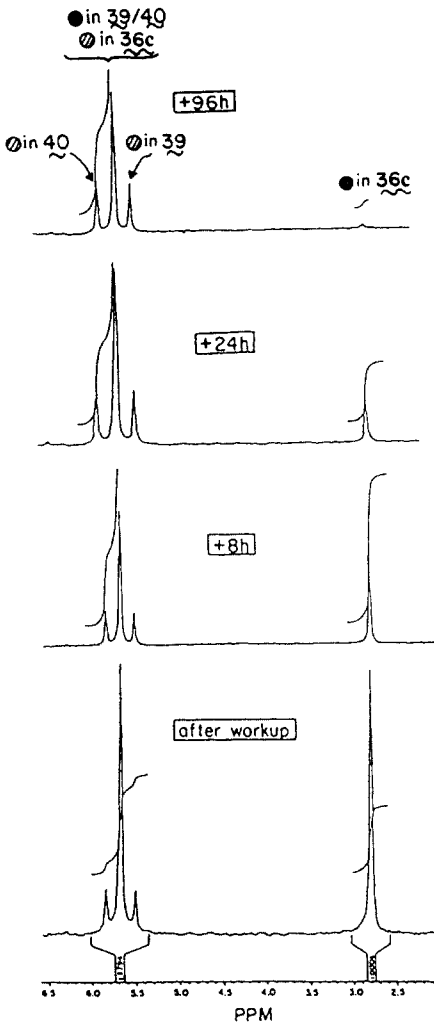
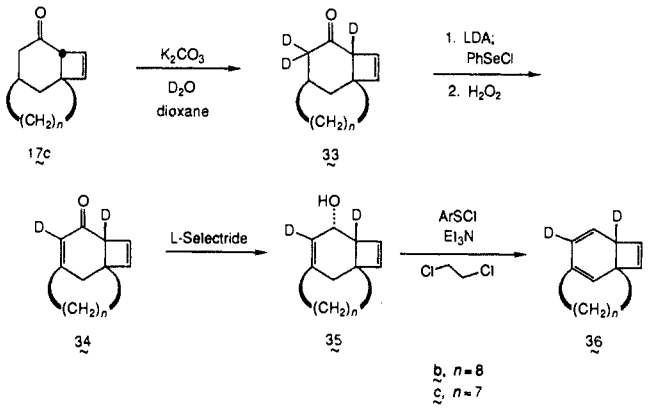


Figure 2. Time-dependent conversion of **36c** to **39** and **40** (500-MHz ^{2}H NMR, C_6H_6 solution, room temperature). Note that the areas of the ● and ○ signals stemming from **36c** decrease in intensity at the same rate.

Scheme IV

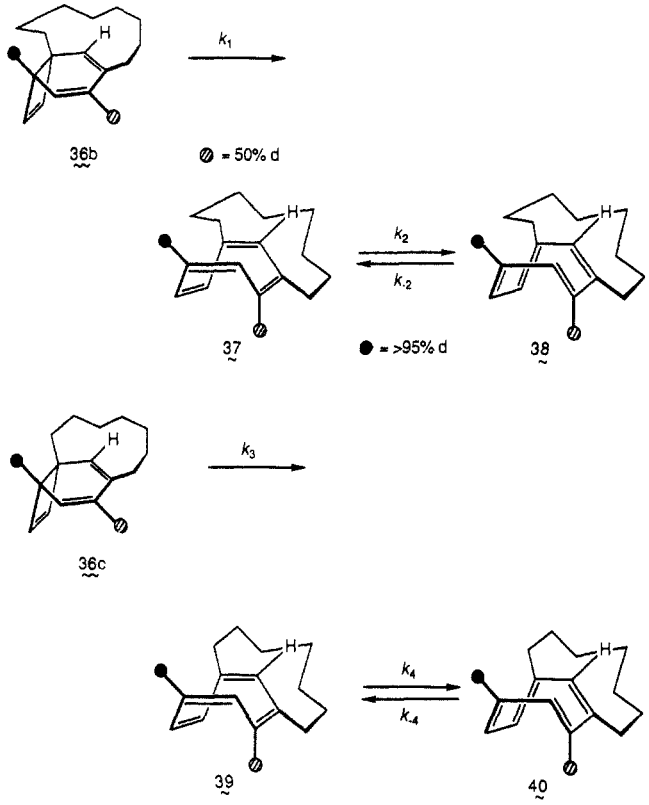


of this material at 300 MHz[36] showed it to be of approximately 90% diastereomeric purity. Once again, however, its hydrolysis–oxidation resulted in delivery of a (1,3)cyclooctatetraenophane that had no optical activity.

Isotopic Labeling as a Probe of Bond Shifting. The manifold inability to resolve **9a–c** can be attributed to a facile bond shifting, ring inversion, or a combination of the two since both processes enantiomerize these molecules. In order to establish whether bond shifting does or does not operate very rapidly under these conditions, ketones **17b** and **17c** were subjected to base-catalyzed H–D exchange and **33b** together with **33c** were independently transformed in the predescribed manner into **36b** and **36c**, respectively (Scheme IV). The ^{1}H NMR spectra of **34b** and **34c** showed that

approximately 50% of their vinyl deuterium had been washed out, presumably as a direct result of the enhanced acidity of the α-proton in the α-phenylselenenyl precursor.

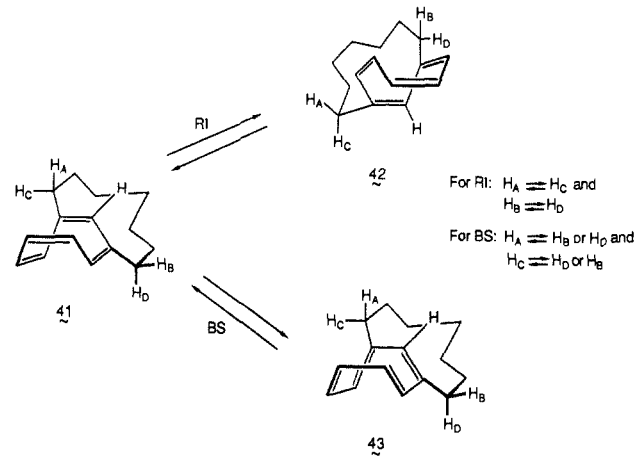
When **36b** was gently warmed to room temperature and the course of its ring opening was monitored by ^{1}H-decoupled ^{2}H NMR, *three new absorptions made their appearance simultaneously.*[37] The pair of equally intense peaks at δ 5.88 and 5.46 were each one-fourth the intensity of the signal at δ 5.69. The latter absorption is due to deuteron ● in both **37** and **38**, which overlap. The pair of smaller area peaks arise from deuterons (◉), which are easily distinguishable because of the differing nature of the substituent positioned alongside them on the double bond. Accordingly, $k_1 \ll k_2$ and k_{-2}.



The behavior of **36c** was entirely analogous, although complete conversion to the isotopically scrambled phane now required approximately 100 h instead of the earlier 40 h (Figure 2). Should the disrotatory opening within **36c** be faster than the bond shifting within **39** and **40**, [8]annulene **39** should accumulate as reaction proceeds such that the concentration of **39** is substantially in excess of that of **40**. This is *not* seen. Therefore, bond alternation must occur with remarkable ease in these molecules.

Dynamic NMR Studies. Under appropriate circumstances, the four allylic protons in a (1,3)cyclooctatetraenophane should each exhibit a distinctively different chemical shift once bond shifting and ring inversion have been arrested by cooling to an adequately low temperature. If these hydrogens are labeled as shown in **41**, ring inversion would have the effect of switching the environment of the geminal protons and bringing on coalescence between H_A/H_C and H_B/H_D (see **42**). In contrast, the consequences of bond shifting are to interchange the environment of the two sets of methylene protons as in **43**.

As matters turned out, the 500-MHz ^{1}H NMR spectra of **9a** and **9c** are uniquely different. Only in the case of **9c** were four well-separated allylic proton signals clearly apparent at 320 K and below. These have been labeled A–D proceeding from low field to high field (see Figure 3). A 2-D C–H correlation experiment and homodecoupling confirmed that the geminal proton



pairs consisted of H_A/H_C and H_B/H_D. Thus, the actual situation corresponds to that given by **41**, although the precise stereochemical relationships are not known. While it is in principle possible to calculate rate constants for bond shifting and ring inversion in these systems by means of NMR line-shape analysis, the problems associated with such an analysis are formidable. An example is the need to include at least eight spins in the calculations. Complications also loom from the fact that a third rate process (vide infra) induces small changes in the chemical shifts of H_A–H_D with alterations in the temperature. Fortunately, it appeared that the rates of immediate interest were slow enough at room temperature that some type of magnetization-transfer experiment might be utilized to determine them. The decision was made to proceed with the 2-D chemical exchange (2-D EXSY) experiment not only because of its capacity for delivering rate constant data, but also to map out the exchange pathways as well. Thus, one sees clearly in Figure 3 that ring inversion (RI) is the sole process operating below 310 K, with BS setting in only above this temperature. On this basis, one can confidently conclude that RI in **9c** must be faster than BS.

The pulse sequence used for 2-D EXSY is the same as used for the 2-D NOESY experiment, viz.: relaxation delay—$\pi/2$–t_1–$\pi/2$–τ_m–$\pi/2$–t_2 (acquisition). Instead of monitoring cross relaxation, however, we are measuring magnetization transfer via chemical exchange. A 2-D spectrum recorded with this sequence (see Experimental Section) is shown in Figure 3. The off-diagonal peaks arise from magnetization that was precessing at one site during the t_1 period and then observed precessing at another site during the t_2 time period. For a symmetrical two-site exchange, the ratio of the diagonal peak intensity (area) to that of a cross peak can be used to calculate a first-order rate constant as in eq 5, should the exchange or more complicated approach need be taken to determine rate constants from the 2-D data.

$$\frac{I_{\text{diag}}}{I_{\text{off-diag}}} \simeq \frac{1 - k\tau_m}{k\tau_m} \tag{5}$$

Several authors have discussed the determination of rate constants from 2-D EXSY data,[38-40] and we have followed the procedure described by Abel et al.[39] An exchange matrix for our system can be written as

$$\mathbf{L} = \begin{vmatrix} -R_a - \sum_{2 \neq a} k_{ai} & k_{ab} & k_{ac} & k_{ad} \\ k_{ab} & -R_b - \sum_{i \neq b} k_{bi} & k_{bc} & k_{bd} \\ k_{ca} & k_{cb} & -R_c - \sum_{i \neq c} k_{ci} & k_{cd} \\ k_{da} & k_{db} & k_{dc} & -R_d - \sum_{i \neq d} k_{di} \end{vmatrix}$$

where R_i is the relaxation state for spin i and k_{ij} is the rate constant for exchange between site i and j. Note should be taken that no

(37) The spectra recorded for the time-dependent ring-opening valence isomerization of **36b** have been illustrated in our preliminary communication on this subject (ref 24).

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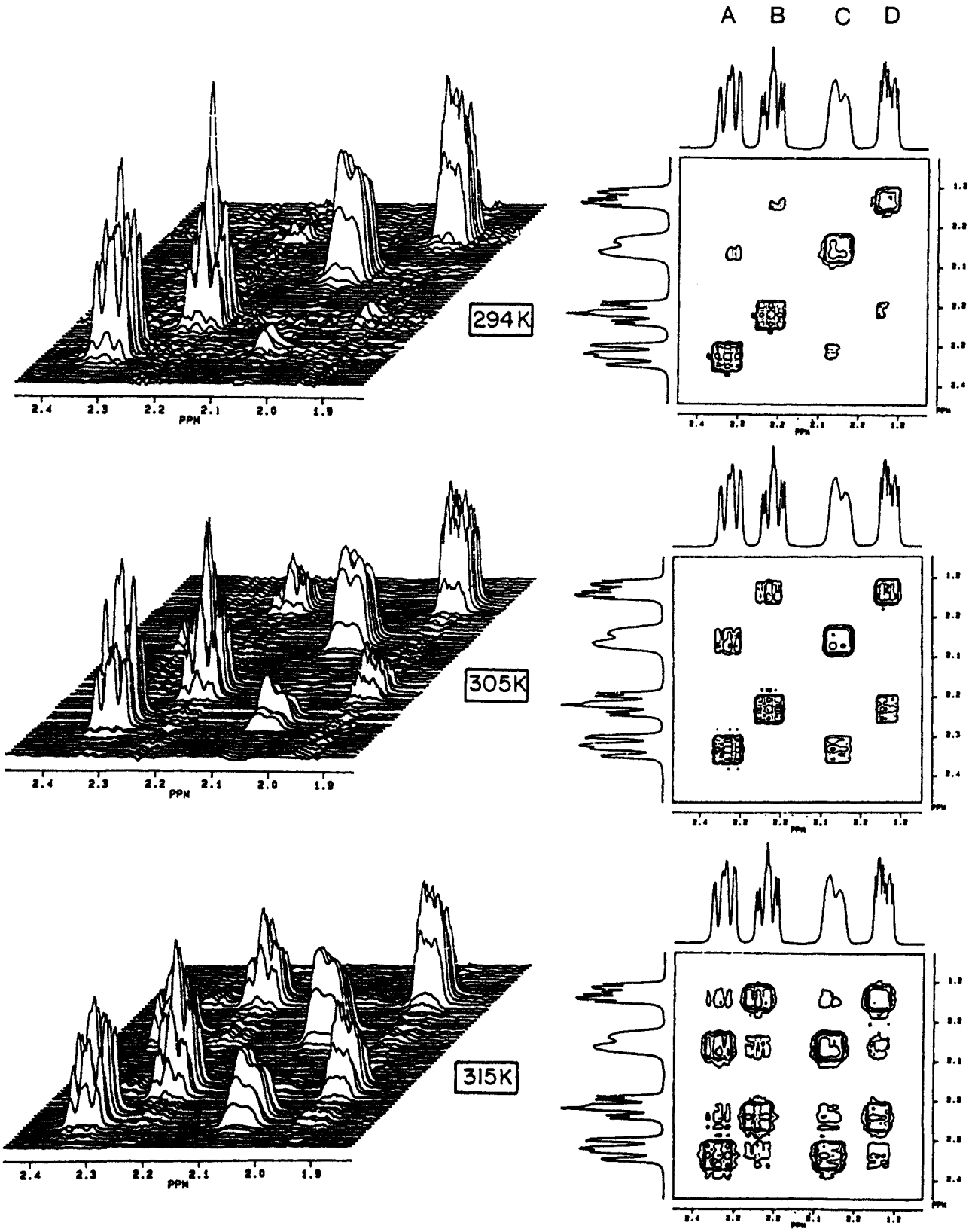


Figure 3. Stack and contour plots of the 500-MHz 2-D EXSY spectra of 9c recorded in CD_2Cl_2 solution at the three temperatures indicated.

consideration is given to cross-relaxation effects.

Matrix **L** is related to matrix **I**, an array of areas measured from the 2-D EXSY spectra, by

$$\mathbf{I} = \mathbf{P} \exp(\mathbf{I}\tau_m)$$

where **P** is a population array and τ_m is the mixing time. If **J** is defined as

$$\mathbf{J} = \mathbf{I}\cdot\mathbf{P}^{-1}$$

then the diagonalization of **J** gives the array $\exp(\Lambda\tau_m)$, which allows determination of the **L** matrix

$$\mathbf{J} = \mathbf{X} \exp(\Lambda\tau_m)\cdot\mathbf{X}^{-1}$$

$$\ln \mathbf{J}/\tau_m = \frac{\mathbf{X} \ln \exp(\Lambda\tau_m)\cdot\mathbf{X}^{-1}}{\tau_m} = \mathbf{X}\cdot\Lambda\cdot\mathbf{X}^{-1} = \mathbf{L}$$

where Λ and **X** are the eigenvalues and eigenvectors of **J**, re-

Table II. Rate Data and Activation Parameters for Ring Inversion and Bond Shifting in **9c**

ring inversion[a]			bond shifting[b]		
t, K	τ_m	rate const, s^{-1}	t, K	τ_m	rate const, s^{-1}
285	1.0	0.080			
294	0.1	0.195	297	0.5	0.016–0.019
300	0.2	0.410	307	0.5	0.058–0.068
305	0.2	0.720	317	0.5	0.19–0.20
310	0.2	1.29	327	0.5	0.59–0.61
315	0.2	2.00			
320	0.2	2.95			
E_{act} = 19.3 kcal/mol			E_{act} = 22.7 kcal/mol		
ln A = 31.4			ln A = 34.4		
$\Delta H^{\ddagger}$ = 18.7 ± 0.4 kcal/mol			$\Delta H^{\ddagger}$ = 22.0 ± 0.4 kcal/mol		
$\Delta S^{\ddagger}$ = 1.9 ± 1.4 eu			$\Delta S^{\ddagger}$ = 7.7 ± 1.4 eu		
$\Delta G_{(298)}^{\ddagger}$ = 18.09 ± 0.03 kcal/mol			$\Delta G_{(298)}^{\ddagger}$ = 19.76 ± 0.03 kcal/mol		

[a] Determined by 2-D ^{1}H NMR in CD_2Cl_2 solution. [b] Determined by 2-D ^{13}C NMR in toluene-d_8 solution. All data were fitted to the Eyring equation.

spectively. A Pascal program was written by one of us (C.E.C.) to solve this problem.

As a direct consequence of geometrical constraints imposed upon the system by the structure of these cyclooctatetraenophanes, certain pairs of k's in the **L** matrix should be zero. The remainder of the rate constants will be equal to k_{BS} or to k_{RI}. However, no a priori assumptions need to be made about the exchange pathway to solve for the **L** matrix. If the reverse procedure is to be carried out, i.e., calculation of the theoretical areas as a function of the exchange matrix, then an exchange pathway must be specified.

An example of the calculation is given for **9c** at 310 K with a mixing time of 0.2 s.

area matrix

$$\mathbf{I} = \begin{array}{c|cccc} & A & B & C & D \\ & 55.8 & 1.4 & 27.4 & 1.6 \\ & 1.4 & 55.2 & 2.3 & 26.5 \\ & 27.5 & 2.3 & 59.8 & 1.4 \\ & 1.6 & 26.3 & 1.4 & 55.8 \end{array}$$

Therefore the **L** matrix is

$$\mathbf{L} = \begin{array}{c|cccc} & A & B & C & D \\ & -2.87 & 0.05 & 2.58 & 0.11 \\ & 0.05 & -2.92 & 0.18 & 2.60 \\ & 2.59 & 0.18 & -2.50 & 0.05 \\ & 0.11 & 2.58 & 0.05 & -2.87 \end{array}$$

The elements L_{ac}, L_{bd}, L_{ca}, and L_{bd} relate only to the geminal proton interchange and must therefore correspond to k_{RI}. These elements must be divided by 2 since the exchange is intramolecular between two equally populated sites. Thus

$$k_{RI} = L_{ac}/2 = 1.29 \pm 0.05 \text{ s (4\% error)}$$

$$k_{BS} = L_{bc}/2 = 0.09 \pm 0.02 \text{ s (22\% error)}$$

where the standard deviations were derived from the fit of all the rate constants to the Eyring equation. The elements L_{ab}, L_{ba}, L_{cd}, and L_{dc} reflect experimental error in measuring the areas of weak cross peaks. As pointed out by Mendz et al.,[41] the variances in rate constants determined from 2-D exchange spectra are related to the signal/rms noise ratio. Consequently, greater error will be found in those rate constants derived from weak signals.

Theoretical areas of cross peaks and diagonal peaks were generated from the above rate constants by using the reverse of the procedure described above for the calculation of rate constants. These calculated areas were then pseudorandomly varied approximately 5%, and the rate constants were recalculated. Matrix elements such as L_{ab} (k = 0) were most sensitive, varying from small negative to just positive. Although the changes in the recomputed rate constants were a complicated function of the variation of each of the area elements, the error in both the large and the small rate constants was ~3%. If, however, the areas of the small off-diagonal peaks were allowed to vary by 10%, then the errors in the computed rates were consistent with our experimental results. The final rate data for **9c** and **9b** are compiled in Tables II and III. Because the rate constant for bond shifting was measured more accurately from the ^{13}C 2-D exchange data, only those results are reported.

Due to the relatively slow rate of bond shifting within **9c** (>310 K) in CD_2Cl_2 (bp 313 K), only a limited set of rate data could be obtained in the accessible temperature range [i.e., k_{BS} = 0.07 (310 K), 0.18 (315 K), and 0.22 (320 K)]. Alternatively, ^{13}C 2-D EXSY spectra were recorded in order to gain an independent measure of k_{BS}. When bond shifting occurs within **9c**, two allylic carbons (37.63 and 35.80 ppm) are interchanged. Hence, rate constants could again be derived from the cross peaks. The data thus obtained (Table II) are in superb agreement with those from the proton 2-D EXSY experiments.

The ^{1}H NMR spectra of **9a** in CD_2Cl_2 within the 263–303 K temperature range of interest showed a pattern of allylic proton signals similar to **9c**, except that the upfield protons H_C and H_D are somewhat overlapped. The rate data for **9a** are collected in Table IV.

The ^{1}H NMR spectrum of **9b** at 303 K shows two signals for the vinylic protons that split on lowering the temperature to 183 K to form a pattern essentially identical with that exhibited by **9c**. This phenomenon was previously attributed to operation of a very fast bond-shifting process.[14] This claim has since been found not to be tenable, as the ^{13}C spectrum shows two distinct signals for the fully substituted vinylic carbons. Furthermore, a CH correlation study confirmed that the AC protons from one allylic carbon overlap with the BD protons from the other, i.e., that A and B are accidentally overlapped, as are C and D. This complex feature was actually not recognized until **9a** was examined by ^{1}H NMR methods in two solvent systems (CD_2Cl_2 and toluene-d_8). In particular, the spectrum of **9a** in toluene-d_8 appeared to be the

Table III. Rate Data and Activation Parameters for Ring Inversion and Bond Shifting in **9b**

ring inversion[a]			bond shifting[b]		
t, K	τ_m	rate const, s^{-1}	t, K	τ_m	rate const, s^{-1}
273	0.5	0.51–0.52			
283	0.1	1.3–1.4	303	0.4	0.28–0.29
288	0.1	2.6–2.8	313	0.25	0.82–0.86
293	0.1	4.6–4.8	323	0.15	1.82–2.06
298	0.2	5.9–6.1	333	0.15	3.10–3.30
303	0.075	9.3–9.9			
E_{act} = 16.2 kcal/mol			E_{act} = 16.2 kcal/mol		
ln A = 29.3			ln A = 25.8		
$\Delta H^{\ddagger}$ = 15.7 ± 0.5 kcal/mol			$\Delta H^{\ddagger}$ = 15.7 ± 0.9 kcal/mol		
$\Delta S^{\ddagger}$ = 2.2 ± 1.7 eu			$\Delta S^{\ddagger}$ = −9.4 ± 2.9 eu		
$\Delta G_{(298)}^{\ddagger}$ = 16.35 ± 0.05 kcal/mol			$\Delta G_{(298)}^{\ddagger}$ = 18.40 ± 0.07 kcal/mol		

[a] Determined by 2-D ^{1}H NMR in CD_2Cl_2 solution. [b] Determined by 2-D ^{13}C NMR in toluene-d_8 solution. All data were fitted to the Eyring equation.

Table IV. Rate Data and Activation Parameters for Ring Inversion and Bond Shifting in **9a**

ring inversion[a]			bond shifting[b]		
t, K	τ_m	rate const, s^{-1}	t, K	τ_m	rate const, s^{-1}
263	0.1	0.51–0.70			
268	0.4	0.61–0.80	303	0.75	0.80–0.82
273	0.1	0.9–1.2	313	0.25	1.83–1.86
278	0.4	1.4–1.5	323	0.10	3.54–3.75
283	0.1	2.8–3.0	333	0.075	10.12–10.79
294	0.1	8.0–8.2			
303	0.1	9.7–10.9			
E_{act} = 12.5 kcal/mol			E_{act} = 16.7 kcal/mol		
ln A = 23.2			ln A = 27.5		
$\Delta H^{\ddagger}$ = 12.0 ± 0.7 kcal/mol			$\Delta H^{\ddagger}$ = 15.9 ± 0.8 kcal/mol		
$\Delta S^{\ddagger}$ = −14.0 ± 2.5 eu			$\Delta S^{\ddagger}$ = −6.7 ± 2.4 eu		
$\Delta G_{(298)}^{\ddagger}$ = 16.22 ± 0.11 kcal/mol			$\Delta G_{(298)}^{\ddagger}$ = 17.87 ± 0.05 kcal/mol		

[a] Determined by 2-D ^{1}H NMR in CD_2Cl_2 solution. [b] Determined by 2-D ^{13}C NMR in toluene-d_8 solution. All data were fitted to the Eyring equation.

(41) Kuchel, P. W.; Bulliman, B. T.; Chapman, B. E.; Mendz, G. L. *J. Magn. Reson.* **1988**, *76*, 136.

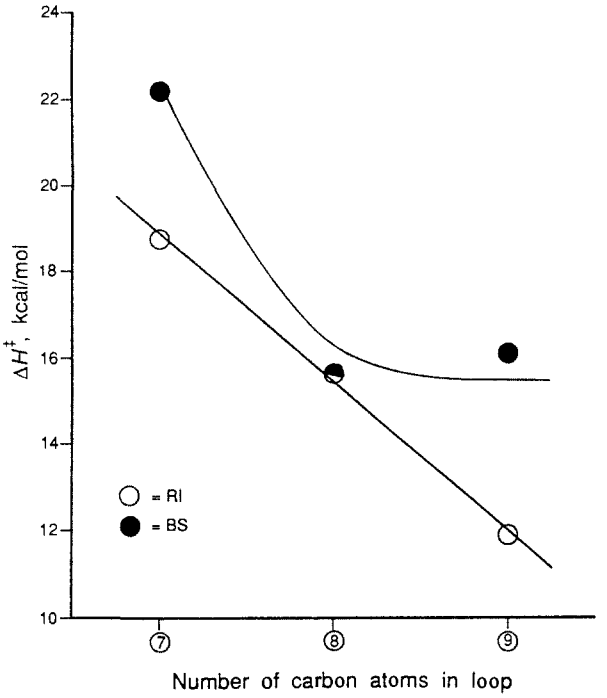
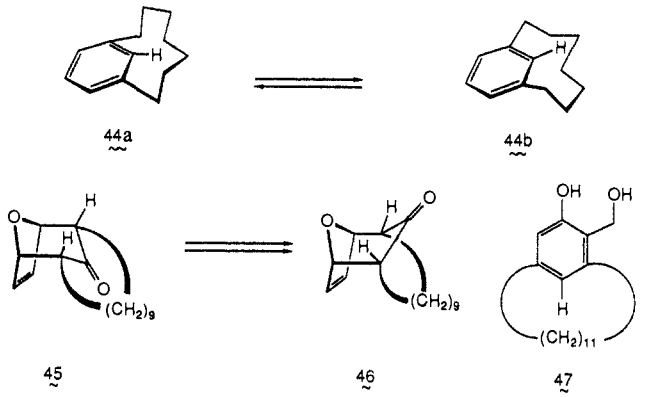


Figure 4. Correlation of ring-inversion and bond-shifting enthalpies with polymethylene chain length in **9a–c**.

same as that recorded for **9b** in the same solvent.

The fast rate being observed here is most likely due to fluctuations within the methylene bridge. Because of the accidental overlap of the proton signals, it was not possible to measure RI and BS simultaneously under these conditions. However, by recording proton 2-D EXSY spectra at sufficiently low temperatures, the BS rate could be neglected. At the highest temperature (303 K) at which ring inversion was measured, the rate constant for RI was approximately 10 s^{-1} while that for BS, determined by means of ^{13}C data, was on the order of 0.3 s^{-1}. Despite these kinetic differences, the activation parameters given in Table III show RI and BS in **9b** to be isoenthalpic (see also Figure 4).

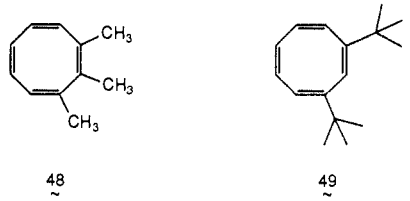
Discussion of Results. To assist in interpreting the preceding results, it is useful to examine the quantitative aspects of jump rope isomerization in other systems that bear some structural resemblance to the (1,3)cyclooctatetraenophanes. Hirano and co-workers have established on the basis of coalescence studies that the energy barriers ($\Delta G^{\ddagger}$) for passage of the internal C–H groups through the loop in [10]$^{-}$, [7]$^{-}$, and [8]metacyclophanes (e.g., **44**) are <8, 11.5 (t_c −28 °C), and 17.4 (t_c −76.5 °C)



kcal/mol, respectively.[26,42] These workers also demonstrated that as the methylene bridge is shortened, the benzene ring is increasingly distorted, diamagnetic character is progressively reduced, and olefinic character increases at the cost of aromaticity. Vinter and Hoffmann also utilized NMR line-shape analysis to deduce the activation parameters for interconversion of **45** with **46**: $\Delta H^{\ddagger}$ = 16.7 kcal/mol, $\Delta S^{\ddagger}$ = 1.5 eu, $\Delta G^{\ddagger}$ = 16.0 and 16.4 kcal/mol, E_{act} = 17.3 kcal/mol, and log A = 13.7.[43] The added steric bulk of the carbonyl oxygen is nicely reflected in suitably increased energy demands. Kang and Chan reported that **47** is capable of resolution, but racemizes completely during 5 min in boiling hexane.[44]

In light of the behavior of **44**, the E_{act} for disrotatory ring opening in **10c** might be expected to be impeded by somewhat more than 10 kcal/mol relative to the parent bicyclo[4.2.0]octatriene. However, the heptamethylene chain in **10c** raises the barrier only ~6 kcal/mol. The major reason for this drop-off may lie in the rather appreciable change in the dihedral angles that link the loop to the π framework under scrutiny. It is therefore important to give proper consideration to such factors during interpolation of rate data between different classes of molecules.

At −2.23 V (Table I), the half-wave potential for the two-electron reduction of **9c** compares closely to that recorded (−2.2 V) for 1,2,3-trimethylcyclooctatetraene.[12b] The previous racemization and deuterium labeling studies on **48** have provided E_{act}



48 49

values of 23.0 and 23.5 kcal/mol for RI and BS in this system. Additional comparison with the 1,3-di-*tert*-butyl derivative **49** is warranted since the latter is nonvicinally substituted, as is **9**. In this instance, the transition-state demands for RI and BS translate into energies of activation amounting to 19.9 and 23.3 kcal/mol, respectively.[6b] There is thus a *net overall decrease* in the E_{act} values for **9a–c** relative to both **48** and **49**. These differences are more magnified for ring inversion than for bond shifting.

Accordingly, even though the tub-to-tub interconversion in **9** requires that a vinyl proton be forced through a polymethylene loop, the barriers are lower than in open-chain analogues. These facts can be reconciled with the dynamic properties of **44–47** if the assumption is made that 1,3-annulation increases the ground-state energy of the bracketed [8]annulene to an extent that reduces in turn the total energy demands placed on the system during conformational flexing. An exact parallel is seen in the properties of **44**. Additionally, this feature is especially evident in 1,2-bridged cyclooctatetraenes where dynamical ring inversion is notably accelerated for this very reason.[2a]

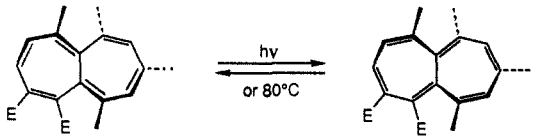
The enthalpies of activation for RI conform regularly to alterations in the length of the methylene chain in **9** (Figure 4). This is as it should be if the process is dependent on passage of a methine unit through the center of this loop. Informatively, bond shifting is not governed by a similar response factor. The $\Delta H^{\ddagger}$ values for bond shifting in **9a** and **9c** reflect the customarily higher enthalpy demands of this process (usually by 3–4 kcal/mol) relative to those for ring inversion.[1–6,12] In contrast, the *two transformations within* **9b** *are isoenthalpic*. Since close correspondence is seen for $\Delta H_{BS}^{\ddagger}$ in **9a** and **9b**, considerable curvature of the BS line materializes in Figure 4. This most striking result appears inconsistent with comparable conformational dynamics relative to the polymethylene chain during ring inversion and π-bond alternation. These unconventional activation parameters provide in our view a basis for distinguishing between a planar-delocalized or saddlelike transition state for bond shifting. Mo-

(42) The conformational mobility of 2,2-dimethyl[7](2,6)pyridinophane offers additional interesting comparison: Fujita, S.; Imamura, K.; Nozaki, H. *Bull. Chem. Soc. Jpn.* **1973**, *46*, 1579. Present views on this subject have developed considerably, though they are still subject to some controversy. See: (a) Rice, J. E.; Lee, T. J.; Remington, R. B.; Allen, W. D.; Clabo, D. A., Jr.; Schaefer, H. F., III. *J. Am. Chem. Soc.* **1987**, *109*, 2902. (b) Bickelhaupt, F.; de Wolf, W. H. *Recl. Trav. Chim. Pays-Bas* **1988**, *107*, 459.

(43) Vinter, J. G.; Hoffmann, H. M. R. *J. Am. Chem. Soc.* **1973**, *95*, 3051.
(44) Kang, G. J.; Chan, T. H. *J. Org. Chem.* **1985**, *50*, 452.

lecular models, constructed in the manner described earlier, show that **9b** and **9c** can pseudorotate in only one screw sense, since to do otherwise would require forcing the central methine group through the loop—a less than desirable alternative. Since the methylene chain in either phane is adequately long to cope with the steric demands of the pseudorotation process, the activation parameters for BS in the two systems correspond closely. When an *n* value of 9 is reached in **9a**, pseudorotation can probably now proceed in either direction, the loop now being adequately flexible to allow internal passage of the central CH group to occur competitively. In mechanistic detail then, **9a** is most similar to alkyl-substituted cyclooctatetraenes in its dynamic behavior.

The rationale just advanced is based primarily on kinetic data and cannot be considered as proof that the pseudorotation process does operate. However, this transition-state model is fully compatible with the observed energetics, conforms nicely to the reactivity profiles of (1,5)cyclooctatetraenophanes,[4] and finds direct analogy in the heptalene series.[45,46] These $4n\ \pi$ systems likewise exist as nonequivalent, thermally interconvertible bond shift isomers. In the case of chiral derivatives, optical resolution is possible. Since bond shifting within resolved substrates, e.g., **50** $\rightleftarrows$ **51**, occurs without racemization, the associated transition states must be chiral, helical, and *nonplanar*.



(-)-50 (-)-51

To summarize, the involvement of planar-alternate transition states to account for bond shifting in [8]annulenes faces explicit problems in rationalizing the universally low energy demands, the dynamics of (1,5)cyclooctatetraenophanes, and the kinetic response of 1,3-bridged analogues. Resolution of the dilemma involves identifying an alternative geometry that permits this class of molecules to circumvent these restrictions. Ermer has identified the flattened saddle as an energy minimum for the delocalized cyclooctatetraene ring,[7] and we advance herein a pseudorotation scheme for conversion of ground-state tub conformations into such species. During this process, nonbonded steric interactions will be manifested on the perimeter of the eight-membered ring and the consequences of annulation can easily be dealt with since planarity is skirted. We caution, however, that the saddle may be deformed to differing degrees depending on ring substitution. These differences will perhaps only be recognized through computation. It now seems probable, however, that saddle transition states are the more readily accessible and that the full expense of true antiaromatic delocalization is never paid.

Experimental Section

Bicyclo[9.3.1]pentadec-14-en-13-one (15a).[16] To a mixture of 2-cyclododecenone (2.3 g, 12.8 mmol) and ethyl acetoacetate (1.84 g, 14.2 mmol) was added a solution of sodium ethoxide in ethanol (prepared from 30 mg of sodium in 1.5 mL of ethanol). Following an initial exothermic reaction, the mixture was stirred at room temperature for 12 h, diluted with dichloromethane, washed with water, and dried. Evaporation afforded 3.73 g of a yellow oil, which was dissolved in 8.6 mL of water, 14.6 mL of acetic acid, and 2.1 mL of concentrated sulfuric acid. This mixture was heated at reflux for 4 h, cooled, treated with water, and extracted with ether/petroleum ether. The combined organic phases were carefully washed with saturated aqueous sodium bicarbonate solution and brine and dried. Concentration gave 2.8 g (~100%) of **15a** as a white solid: mp 116–117 °C (from ethyl acetate/hexane); ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.83 (s, 1 H), 2.62–2.49 (m, 2 H), 2.32–2.08 (m, 5 H), 1.73–0.97 (m, 16 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 198.85, 162.76, 127.88, 45.45, 37.25, 33.49, 29.82, 28.09, 26.49, 26.39, 23.48, 23.34, 22.92, 21.89; MS *m/z* (M^+) calcd 220.1827, obsd 220.1835.

[2 + 2] Photocycloaddition of *trans*-1,2-Dichloroethylene to 15a. Two samples (5 g each) of **15a** were separately dissolved in 50 mL of *trans*-1,2-dichloroethylene and placed in two 70-mL Pyrex tubes. Dichloromethane (5 mL) was added to each tube to increase the solubility of the enone. The solutions were deoxygenated for 30 min with argon and photolyzed for 44 h with a Hanovia 450-W mercury lamp through a uranium filter. Concentration of both solutions left a yellow solid, recrystallization of which from ethyl acetate/hexane yielded 11 g (75.8%) of **16a** as colorless crystals: mp 169.5–170.5 °C; IR (CH_2Cl_2) cm^{-1} 2940, 1700, 1470, 1334, 1237; ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.32 (m, 1 H), 4.03 (d, J = 7.9 Hz, 1 H), 2.72 (m, 1 H), 2.58 (d, J = 8.4 Hz, 1 H), 2.25 (m, 3 H), 1.85 (m, 2 H), 1.65–1.00 (m, 17 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 206.01, 66.88, 59.35, 58.38, 48.03, 45.28, 40.01, 35.48, 34.01, 25.71, 25.19, 25.05, 24.42, 21.47, 20.19, 20.11, 18.52; MS *m/z* (M^+) calcd 316.1362, obsd 316.1354. Anal. Calcd for $C_{17}H_{26}Cl_2O$: C, 64.35; H, 8.26. Found: C, 64.46; H, 8.30.

Ketalization of 16a. A sample of **16a** (20.96 g, 66.1 mmol) was dissolved in 400 mL of dichloromethane. Ethylene glycol (200 g, 3.2 mol) and 42 g (0.40 mol) of trimethyl orthoformate were added, followed by 1.4 g (7.4 mmol) of *p*-toluenesulfonic acid. The mixture was stirred at room temperature overnight and neutralized with 0.8 g of potassium hydroxide before it was washed successively with water to remove excess ethylene glycol prior to drying. Evaporation afforded a quantitative yield of the ketal: mp 95–96 °C (from ethyl acetate/hexane); ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.12 (m, 1 H), 4.03–3.90 (m, 5 H), 2.12–1.82 (m, 5 H), 1.65–1.25 (m, 19 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 107.08, 67.48, 64.73, 64.20, 58.06, 54.77, 44.90, 40.65, 37.90, 32.86, 32.07, 25.55, 24.40, 23.37, 22.10, 21.93, 20.25, 18.26; MS *m/z* (M^+) calcd 360.1622, obsd 360.1596.

Tricyclic Enone 17a. Ammonia (250 mL) was condensed into a 500-mL round-bottomed flask containing 7.5 g (0.33 mol) of sodium. A solution of the preceding dichloro ketal (66.0 mmol) in 100 mL of dry ether was added dropwise at −78 °C, and the blue mixture was stirred for 20 min after addition. A few pipets of isoprene were added to quench the excess sodium, and saturated aqueous ammonium chloride solution was next introduced to neutralize the mixture. After evaporation of the ammonia, the residue was taken up in ether and washed quickly with 5% hydrochloric acid, saturated aqueous sodium bicarbonate solution, and water before drying. Solvent removal yielded 19.48 g (quantitative) of dechlorinated ketal as a pale yellow oil, which was used without further purification: ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.32 (d, J = 2.8 Hz, 1 H), 6.00 (m, 1 H), 3.90 (m, 4 H), 2.51 (s, 1 H), 2.10–1.84 (m, 3 H), 1.7–1.2 (m, 20 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 146.67, 132.67, 111.70, 64.71, 63.86, 56.24, 51.66, 37.31, 37.22, 34.01, 31.88, 29.36, 26.41, 26.30, 25.38, 24.37, 21.40, 21.30, 20.99; MS *m/z* (M^+) calcd 290.2246, obsd 290.2290.

The ketal prepared above was dissolved in 200 mL of ether and 200 mL of tetrahydrofuran. Hydrochloric acid (200 mL of 5%) was added. The mixture was stirred at room temperature for 3 days until complete hydrolysis and diluted with ether. The layers were separated, and the ether phase was washed with saturated aqueous sodium bicarbonate solution and water before drying. Concentration afforded a light brown oil, which was passed down a short silica gel column to give 15.30 g (94% overall from **16a**) of pure **17a** as a very light yellow oil. This enone solidified when deposited in a refrigerator: mp 40–41 °C; IR (neat) cm^{-1} 2920, 1695, 1560, 1470, 1440, 770; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.42 (m, 1 H), 5.97 (m, 1 H), 3.04 (s, 1 H), 2.62 (m, 1 H), 2.15 (m, 2 H), 1.90 (m, 1 H), 1.75–1.20 (m, 20 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 213.27, 148.78, 131.99, 59.89, 52.05, 45.64, 37.65, 34.34, 32.83, 31.56, 27.19, 25.98, 25.30, 23.60, 22.11, 21.87; MS *m/z* (M^+) calcd 246.1984, obsd 246.2004. Anal. Calcd for $C_{17}H_{26}O$: C, 82.87; H, 10.64. Found: C, 82.76; H, 10.66.

Conversion of 17a to Dienone. A solution of diisopropylamine (3.75 g, 37.1 mmol) in 150 mL of tetrahydrofuran was cooled to −78 °C, treated with *n*-butyllithium (1.6 M in hexane, 23 mL, 26.8 mmol), and stirred for 15 min before 7.65 g (31.0 mmol) of **17a** in 50 mL of the same solvent was added dropwise over 30 min. The resulting yellow solution was stirred for 40 min longer. Phenylselenenyl chloride (7.1 g, 37.1 mmol) in 30 mL of tetrahydrofuran was added quickly in one portion. The brown reaction mixture was stirred for 5 min at −78 °C before it was

(45) (a) Hafner, K.; Knaup, G. L.; Lindner, H. J.; Floter, H.-C. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 212. (b) Hafner, K.; Knaup, G. L. *Tetrahedron Lett.* **1986**, *27*, 1665. (c) Hafner, K.; Hock, N.; Knaup, G. L.; Meinhardt, K.-P. *Ibid.* **1986**, *27*, 1669. (d) Hafner, K.; Knaup, G. L. *Ibid.* **1986**, *27*, 1673. (e) Hafner, K.; Knaup, G. L.; Lindner, H. J. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 633. (f) Hafner, K.; Knaup, G. L.; Lindner, H. J. *Bull. Chem. Soc. Jpn.* **1988**, *61*, 155.

(46) (a) Bernhard, W.; Brugger, P.; Daly, J. J.; Schonholzer, O.; Weber, R. H.; Hansen, H.-J. *Helv. Chim. Acta* **1985**, *68*, 415. (b) Bernhard, W.; Brugger, P.; Schonholzer, P.; Weber, R. H.; Hansen, H.-J. *Ibid.* **1985**, *68*, 429. (c) Bernhard, W.; Brugger, P.; Daly, J. J.; Englert, G.; Schonholzer, P.; Hansen, H.-J. *Ibid.* **1985**, *68*, 1010. (d) Weber, R. H.; Brugger, P.; Jenny, T. A.; Hansen, H.-J. *Ibid.* **1987**, *70*, 742. (e) Weber, R. H.; Brugger, P.; Schonholzer, P.; Arnold, W.; Hansen, H.-J. *Ibid.* **1987**, *70*, 1439.

allowed to warm to 0 °C. Water (80 mL) and 3.6 mL of glacial acetic acid were added in sequence, followed by slow addition of 18 mL of 30% hydrogen peroxide. The mixture was warmed to room temperature and stirred for 20 min. After dilution with water, the mixture was extracted with ether. The combined ether phases were washed with saturated aqueous sodium bicarbonate solution and brine before drying. Concentration yielded 9 g of red viscous oil, chromatography of which on silica gel (elution with 10% ethyl acetate in petroleum ether) gave 0.7 g of unreacted **17a** and 3 g of dienone as a colorless oil (43% based on recovered starting material): IR (neat) cm^{-1} 3050, 3030, 2920, 2860, 1650, 1465, 1285; ^1H NMR (300 MHz, $CDCl_3$) δ 6.27 (dd, J = 2.6, 1.6 Hz, 1 H), 6.05 (dd, J = 1.6, 1.2 Hz, 1 H), 5.99 (d, J = 1.4 Hz, 1 H), 3.03 (d, J = 0.8 Hz, 1 H), 2.62 (d, J = 19.3 Hz, 1 H), 2.31–2.17 (m, 3 H), 1.97–1.18 (m, 16 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 199.51, 165.12, 146.58, 127.26, 56.88, 47.87, 37.98, 37.22, 33.27, 26.46, 26.11, 26.08, 25.23, 23.81, 23.35, 22.67; MS m/z (M^+) calcd 244.1827, obsd 244.1833. Anal. Calcd for $C_{17}H_{24}O$: C, 83.55; H, 9.90. Found: C, 83.44; H, 9.90.

Hydride Reduction of the [9]Dienone. A solution of 2.45 g (10 mmol) of the above dienone in 200 mL of dichloromethane was cooled to −78 °C and treated with Dibal-H (1.0 M in hexane, 13 mL, 13 mmol). The mixture was stirred for 15 min, quenched with methanol, warmed to room temperature, diluted with dichloromethane, washed in sequence with 5% hydrochloric acid, saturated sodium bicarbonate solution, and water, and dried. Concentration afforded 2.52 g of yellow viscous oil, chromatography of which on silica gel (elution with 10% ethyl acetate in petroleum ether) yielded 0.63 g (25.7%) of **19a** and 1.3 g (53.1%) of **18a** as pale yellow solids.

For **19a**: mp 90–92 °C (from ethyl acetate/hexane); IR ($CHCl_3$) cm^{-1} 3610, 2930, 1640, 1468; ^1H NMR (300 MHz, $CDCl_3$) δ 6.53 (d, J = 2.7 Hz, 1 H), 6.14 (dd, J = 2.6, 0.7 Hz, 1 H), 5.86 (m, 1 H), 4.43 (t, J = 6.3 Hz, 1 H), 2.62 (d, J = 6.7 Hz, 1 H), 2.36–2.06 (m, 3 H), 1.80–1.00 (m, 18 H); ^{13}C NMR (20 MHz, $CDCl_3$) ppm 147.02, 143.87, 132.31, 126.05, 65.43, 53.70, 49.73, 36.50, 35.86, 30.50, 27.23, 26.43, 24.95, 23.65, 23.26, 22.06, 21.75; MS m/z (M^+) calcd 246.1984, obsd 246.1996.

For **18a**: mp 70–71 °C (from ethyl acetate/hexane); IR ($CHCl_3$) cm^{-1} 3595, 2930; ^1H NMR (300 MHz, $CDCl_3$) δ 6.42 (d, J = 2.7 Hz, 1 H), 6.32 (d, J = 2.6 Hz, 1 H), 5.65 (s, 1 H), 4.02 (m, 1 H), 2.39 (d, J = 14.9 Hz, 1 H), 2.26–2.02 (m, 3 H), 1.82–1.69 (m, 2 H), 1.49–1.01 (m, 16 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 144.90, 141.07, 135.21, 130.42, 72.66, 57.71, 49.57, 36.10, 35.38, 27.54, 26.77, 24.62, 24.56, 22.86, 21.67, 21.46; MS m/z (M^+) calcd 246.1983, obsd 246.1997.

[9](1,3)Cyclooctatetraenophane (9a). A sample of allylic alcohols **18a** and **19a** (2.18 g, 8.8 mmol) was dissolved in 140 mL of 1,2-dichloroethane. The solution was cooled to 0 °C before 2.67 g (26.4 mmol) of triethylamine and 6.19 g (26.4 mmol) of 2,4-dinitrobenzenesulfenyl chloride were added in sequence. The yellow mixture was brought to reflux for 10.5 h. The solvent was removed by evaporation, and the residue was taken up in petroleum ether, washed with water, and dried. Concentration gave 2.1 g of red oil, which was chromatographed on silica gel (elution with petroleum ether) to yield 1.24 g (61.4%) of **9a** as a yellow oil.

When a sample of allylic alcohol **18a** (107 mg, 0.43 mmol) was submitted to the same dehydration conditions, 60 mg of **9a** was obtained (60%). Allylic alcohol **19a** (30 mg) produced 23 mg (82%) of **9a** when treated as described above: IR (neat) cm^{-1} 2920, 1635, 1460, 1438, 1347, 1210, 970, 702, 670; ^1H NMR (300 MHz, $CDCl_3$) δ 6.00 (d, J = 11.7 Hz, 1 H), 5.75 (m, 3 H), 5.62 (s, 1 H), 5.54 (s, 1 H), 2.15 (m, 4 H), 1.55–1.25 (m, 14 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 145.80, 142.28, 133.40, 132.69, 131.38, 130.88, 130.66, 126.09, 38.37, 35.77, 27.62, 25.92, 25.66, 25.47, 24.73, 24.61, 24.50; MS m/z (M^+) calcd 228.1878, obsd 228.1919. Anal. Calcd for $C_{17}H_{24}$: C, 89.44; H, 10.59. Found: C, 89.55; H, 10.55.

Bicyclo[8.3.1]tetradec-13-en-12-one (15b). To a mixture of 2-cycloundecenone (19.52 g, 117 mmol) and ethyl acetoacetate (16.75 g, 128 mmol) at 0 °C was added a solution of sodium ethoxide in ethanol [prepared from 270 mg (11.7 mmol) of sodium and 10 mL of ethanol]. After overnight stirring at room temperature, workup as before gave 35 g of oil, which was dissolved in 150 mL of acetic acid, 108 mL of water, and 21.8 mL of concentrated sulfuric acid. After 6 h of reflux, the reaction mixture was worked up as before. Chromatography on silica gel (elution with 15% ethyl acetate in petroleum ether) gave 18 g (74%) of **15b** as a pale yellow solid: mp 96.5–97.5 °C (from ethyl acetate/petroleum ether); IR ($CHCl_3$) cm^{-1} 3005, 2940, 1655; ^1H NMR (300 MHz, $CDCl_3$) δ 5.84 (dd, J = 2.5, 0.8 Hz, 1 H), 2.63 (dt, J = 18.1, 1.9 Hz, 1 H), 2.52 (dd, J = 16.6, 5.2 Hz, 1 H), 2.30–2.05 (m, 5 H), 1.70 (m, 1 H), 1.63–1.10 (m, 13 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 199.03, 165.04, 127.22, 44.82, 37.28, 33.75, 31.20, 29.64, 27.87, 27.20, 26.12, 25.94, 25.03; MS m/z (M^+) calcd 206.1671, obsd 206.1670. Anal. Calcd for $C_{14}H_{22}O$: C, 81.50; H, 10.75. Found: C, 81.43; H, 10.80.

[2 + 2] Photocycloaddition of *trans*-1,2-Dichloroethylene to 15b. A solution of **15b** (1.2 g, 5.8 mmol) in 25 mL of 1,2-dichloroethylene was degassed and photolyzed as described above. Concentration gave 2 g of viscous oil, chromatography of which on silica gel (elution with 10% ethyl acetate in petroleum ether) produced two dichloro ketone isomers i (1.1 g) and ii (0.46 g), both as white solids (combined yield 89%).

For i: mp 108.5–110 °C (from ethyl acetate); IR ($CHCl_3$) cm^{-1} 2940, 1705; ^1H NMR (300 MHz, $CDCl_3$) δ 4.87 (dd, J = 8.9, 6.2 Hz, 1 H), 4.33 (d, J = 6.2 Hz, 1 H), 2.97 (d, J = 8.9 Hz, 1 H), 2.78 (m, 1 H), 2.44 (d, J = 15.2 Hz, 1 H), 2.27 (d, J = 14.9 Hz, 2 H), 2.00–1.11 (series of m, 17 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 207.29, 67.52, 59.75, 54.09, 47.20, 45.54, 36.70, 35.36, 31.88, 31.42, 27.45, 26.90, 26.25, 24.26, 23.58, 23.31; MS m/z (M^+) calcd 302.1204, obsd 302.1206.

For ii: mp 128–129 °C (from ethyl acetate); ^1H NMR (300 MHz, $CDCl_3$) δ 4.32 (m, 1 H), 4.00 (d, J = 7.9 Hz, 1 H), 2.72 (dd, J = 15.7, 5.8 Hz, 1 H), 2.62 (d, J = 8.7 Hz, 1 H), 2.38–2.04 (m, 3 H), 1.95 (dd, J = 15.7, 4.3 Hz, 1 H), 1.75–1.12 (m, 16 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 206.25, 67.39, 58.35, 58.13, 48.04, 45.68, 40.31, 35.89, 31.44, 27.42, 26.79, 26.67, 25.90, 24.45, 23.39, 22.92; MS m/z (M^+) calcd 302.1204, obsd 302.1207.

Ketalization and Dechlorination of 16b. A mixture of the isomeric dichloro ketones **16b** (1.56 g, 5.14 mmol) was dissolved in 30 mL of methylene chloride. Ethylene glycol (10 g, 161 mmol) and trimethyl orthoformate (2.2 g, 20.7 mmol) were added, followed by 70 mg of *p*-toluenesulfonic acid. After overnight stirring, workup as usual gave an oil, which was used directly in the next step. This oily dichloro ketal mixture was reduced with 0.6 g (26 mmol) of sodium in 120 mL of ammonium as described above. There was isolated 1.3 g (91.5% from **16b**) of unsaturated ketal as a yellow oil, which was essentially pure by TLC: IR (neat) cm^{-1} 3040, 2930, 1475, 1445, 1055, 810, 740; ^1H NMR (300 MHz, C_6D_6) δ 6.32 (d, J = 2.5 Hz, 1 H), 6.10 (m, 1 H), 3.56 (m, 4 H), 2.73 (s, 1 H), 2.05–1.24 (series of m, 21 H); MS m/z (M^+) calcd 276.2089, obsd 276.2073.

Tricyclic Enone 17b. The above ketal (1.3 g, 4.7 mmol) was dissolved in 75 mL of ether and 35 mL of tetrahydrofuran and then treated with 25 mL of 5% hydrochloric acid. The mixture was stirred for 19 h and diluted with ether. The layers were separated, and the organic phase was washed with saturated sodium bicarbonate solution and water and then dried. After concentration, there was isolated 1.08 g (100%) of **17b** as a pale yellow oil: IR (neat) cm^{-1} 3050, 2920, 1700, 1475; ^1H NMR (300 MHz, $CDCl_3$) δ 6.40 (m, 1 H), 5.89 (t, J = 1.2 Hz, 1 H), 3.09 (s, 1 H), 2.78 (dd, J = 14.1, 4.3 Hz, 1 H), 2.05–1.82 (m, 4 H), 1.67–1.09 (m, 16 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 213.19, 151.88, 131.42, 59.63, 52.83, 44.26, 38.50, 37.03, 31.18, 30.52, 28.43, 28.23, 28.09, 25.30, 24.80, 21.60; MS m/z (M^+) calcd 232.1827, obsd 232.1799. Anal. Calcd for $C_{16}H_{24}O$: C, 82.70; H, 10.41. Found: C, 82.75; H, 10.41.

Conversion of 17b to the [8]Dienone. Diisopropylamine (0.43 g, 4.3 mmol) was dissolved in 30 mL of tetrahydrofuran at −78 °C and treated with *n*-butyllithium (4.3 mmol). After 10 min of stirring, 0.83 g (3.6 mmol) of **17b** in 15 mL of the same solvent was added dropwise. The reaction mixture was stirred for 45 min before 0.82 g (4.3 mmol) of phenylselenenyl chloride in 10 mL of the same solvent was added. The resulting mixture was oxidized as before with 10 mL of water, 0.4 mL of acetic acid, and 2 mL of 30% hydrogen peroxide. Chromatography of the residue on silica gel (elution with 10% ethyl acetate in petroleum ether) afforded 0.35 g (42%) of dienone as a viscous oil: IR (neat) cm^{-1} 3045, 2920, 1650, 1463, 1280; ^1H NMR (300 MHz, $CDCl_3$) δ 6.35 (dd, J = 2.5, 1.8 Hz, 1 H), 6.09 (dd, J = 2.5, 1.3 Hz, 1 H), 6.05 (d, J = 1.8 Hz, 1 H), 3.20 (s, 1 H), 2.62 (d, J = 19.2 Hz, 1 H), 2.47–2.24 (m, 3 H) 1.77–1.26 (m, 14 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 199.45, 165.75, 147.34, 132.29, 127.73, 53.71, 48.46, 37.71, 37.17, 36.73, 26.11, 25.27, 25.17, 24.72, 24.57, 23.67; MS m/z (M^+) calcd 230.1671, obsd 230.1675. Anal. Calcd for $C_{16}H_{22}O$: C, 83.43; H, 9.63. Found: C, 83.01; H, 9.65.

Hydride Reduction of the [8]Dienone. A. L-Selectride Reduction. A solution of the preceding dienone (1.75 g, 7.6 mmol) in 75 mL of dichloromethane at −78 °C was treated with L-Selectride (1.0 M in THF, 10 mL). The mixture was warmed to room temperature and stirred for 30 min. Water was added and the resultant mixture was extracted with dichloromethane. The organic phase was washed with water and dried. After concentration, chromatography of the residue on a Waters Prep 500 (elution with 10% ethyl acetate in petroleum ether) afforded 0.75 g (43%) of **19b** as a white solid and 0.40 g (23%) of **18b** as a colorless oil.

B. Lithium Aluminum Hydride Reduction. To a suspension of lithium aluminum hydride (10 mg, 0.24 mmol) in 2 mL of ether was added 20 mg (0.08 mmol) of the dienone dissolved in 2.5 mL of ether at −78 °C. After being warmed to 0 °C, the reaction mixture was quenched with a drop of water, washed with 5% hydrochloric acid and water, and dried. Concentration afforded exclusively the β-alcohol **18b** in almost quantitative yield.

For **19b**: mp 83–84 °C (from ethyl acetate/hexane); IR ($CHCl_3$) cm^{-1} 3600, 3010, 2930, 1650, 1050; ^1H NMR (300 MHz, $CDCl_3$) δ 6.47 (d, J = 2.7 Hz, 1 H), 6.13 (d, J = 2.3 Hz, 1 H), 5.87 (m, 1 H), 4.52 (t, J = 6.3 Hz, 1 H), 2.81 (d, J = 6.6 Hz, 1 H), 2.39 (dd, J = 5.4, 3.0 Hz, 1 H), 2.23–2.03 (m, 3 H), 1.67–1.18 (m, 15 H); MS m/z (M^+) calcd 232.1827, obsd 232.1822.

For **18b**: IR (neat) cm^{-1} 3320, 3040, 2930, 1645, 1470, 1050, 755; ^1H NMR (300 MHz, $CDCl_3$) δ 6.31 (d, J = 2.7 Hz, 1 H), 6.29 (d, J = 2.7 Hz, 1 H), 5.62 (br s, 1 H), 4.01 (dt, J = 7.4, 2.2 Hz, 1 H), 2.31–2.08 (m, 4 H), 1.77–1.16 (m, 16 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 146.01, 141.00, 135.23, 129.84, 73.54, 56.08, 49.87, 37.85, 37.46, 33.36, 26.92, 25.25, 24.79, 24.66, 24.44, 24.05; MS m/z (M^+) calcd 232.1827, obsd 232.1823.

[8](1,3)Cyclooctatetraenophane (9b). Alcohol **19a** (0.29 g, 1.2 mmol) in 30 mL of 1,2-dichloroethane at 0 °C was treated with triethylamine (0.61 g, 6 mmol) and 2,4-dinitrobenzenesulfenyl chloride (1.4 g, 6 mmol). The mixture was refluxed for 3 h and worked up as above. There was isolated 180 mg (67%) of **9b** as a yellow oil; ^1H NMR (300 MHz, $CDCl_3$) δ 5.98 (d, J = 11.1 Hz, 1 H), 5.76 (m, 4 H), 5.5 (br s, 1 H), 2.33 (m, 2 H), 1.94 (m, 2 H), 1.66–1.16 (m, 12 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 147.22, 142.42, 134.32, 132.65, 130.54, 130.49, 124.90, 37.50, 36.63, 27.03, 25.89, 25.82, 25.68, 24.90, 24.70; MS m/z (M^+) calcd 214.1721, obsd 214.1725. Anal. Calcd for $C_{16}H_{22}$: C, 89.66; H, 10.34. Found: C, 89.71; H, 10.41.

2-[(Methylsulfonyl)oxy]cyclodecanone (25a). Sebacoin (**24**; 26.5 g, 157 mmol) was dissolved in 600 mL of dry dichloromethane at 0 °C. Triethylamine (47 g, 471 mmol) and methanesulfonyl chloride (54 g, 471 mmol) were slowly added dropwise. The mixture was stirred for an additional 10 min before water was added. The reaction mixture was washed with 10% hydrochloric acid, saturated sodium bicarbonate solution, and water prior to drying. Concentration gave an almost quantitative yield of mesylate **25a** as a brown oil, which was used without further purification. MPLC (silica gel, elution with 40% ethyl acetate in petroleum ether) of a small sample gave pure **25a** as a low-melting solid: mp 54–55 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 5.10 (dd, J = 3.2, 6.8 Hz, 1 H), 3.13 (s, 3 H), 2.72 (m, 2 H), 2.26 (m, 1 H), 2.13 (m, 1 H), 1.97 (m, 1 H), 1.90–1.63 (m, 2 H), 1.53–1.26 (m, 9 H); MS m/z (M^+) calcd 152.1201, obsd 152.1232.

2-(Phenylthio)cyclododecanone (25b). A suspension of sodium hydride (7.5 g, 0.31 mmol) in 500 mL of dry dimethylformamide was cooled to 0 °C. Thiophenol (34.2 g, 0.31 mmol) was added dropwise. The mixture was warmed to room temperature and stirred until a clear solution was formed. The solution was cooled back to 0 °C and the above sample of **25a** in 50 mL of the same solvent was added. The resulting mixture was warmed to room temperature and stirred for 13 h. Water (1.5 L) was added and the mixture was stirred for 1 h, extracted with petroleum ether, and washed with 5% sodium hydroxide solution and water. Drying and concentration gave 42.5 g of red oil, which was directly oxidized. A small sample was purified by MPLC with 6% ethyl acetate in petroleum ether for spectroscopic analysis: IR (neat) cm^{-1} 3045, 2910, 1685, 1575, 1465; ^1H NMR (300 MHz, $CDCl_3$) δ 7.41–7.27 (m, 5 H), 4.00 (dd, J = 11.6, 3.7 Hz, 1 H), 2.70–2.50 (m, 2 H), 2.08 (m, 1 H), 1.97–1.82 (m, 2 H), 1.76–1.60 (m, 2 H), 1.52–1.21 (m, 9 H); MS m/z (M^+) calcd 262.1391, obsd 262.1408.

***cis*-2-Cyclodecenone (14c).** The sulfide from the last experiment was dissolved in 600 mL of dry dichloromethane and cooled to −78 °C. *m*-Chloroperbenzoic acid (45 g, 0.26 mol) in 300 mL of the same solvent was added while the reaction mixture was stirred mechanically. The mixture was warmed to room temperature and the white solids were filtered off. The filtrate was washed with water and dried. Concentration followed by chromatography on silica gel (elution with 20% ethyl acetate in petroleum ether) gave 26 g of sulfoxide, which was dissolved in 350 mL of benzene. Calcium carbonate (13.7 g, 0.14 mol) was added. The mixture was heated at reflux for 2 h. After filtration, the filtrate was diluted with ether, washed with water, and dried. Evaporation and distillation afforded 13.2 g of **14c** [bp 60–70 °C (0.9 Torr)] (56% overall from **24**). The spectroscopic properties of **14c** are identical with those reported in the literature.[20]

Bicyclo[7.3.1]tridec-12-en-11-one (15c). To a mixture of **14c** (13.5 g, 88.6 mmol) and ethyl acetoacetate (12.7 g, 97.6 mmol) was added a solution of sodium ethoxide in ethanol [prepared from 400 mg (17.4 mmol) of sodium and 8 mL of ethanol]. Reaction was much slower than those involving the *trans*-enones. After being stirred for 24 h, the mixture was diluted with ether and washed with water. Ether was evaporated and the residue was dissolved in 95 mL of acetic acid, 55 mL of water, and 14 mL of concentrated sulfuric acid. The mixture was refluxed for 12 h under argon. Water (500 mL) was added and the product was extracted into ether. The combined extracts were washed with saturated sodium bicarbonate solution and water before drying. Concentration gave 13.5 g of yellow solid, which was chromatographed on silica gel (elution with 15% ethyl acetate in petroleum ether) to yield 9 g (51%) of pure **15c** as a white solid: mp 75–76 °C (from ethyl acetate/petroleum ether); IR ($CHCl_3$) cm^{-1} 2930, 1655; ^1H NMR (300 MHz, $CDCl_3$) δ 5.87 (s, 1 H), 2.77 (m, 1 H), 2.50 (m, 1 H), 2.30 (m, 4 H), 1.90 (m, 1 H), 1.59–1.27 (m, 12 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 199.41, 164.73, 126.54, 46.12, 37.18, 34.52, 31.22, 26.74, 26.28, 24.83, 24.15, 23.42, 23.06; MS m/z (M^+) calcd 192.1514, obsd 192.1498.

[2 + 2] Photocycloaddition of *trans*-1,2-Dichloroethylene to 15c. A solution of **15c** (3.35 g, 17.4 mmol) in 50 mL of *trans*-1,2-dichloroethylene was deoxygenated with argon for 20 min and photolyzed for 42 h as before. Concentration gave an almost quantitative yield of a mixture of the two dichloro ketones i and ii. Separation of small samples by MPLC on silica gel (elution with 10% ethyl acetate in petroleum ether) afforded pure isomers as white solids.

For i: mp 130–131.5 °C (from ethyl acetate); IR ($CHCl_3$) cm^{-1} 2930, 1695; ^1H NMR (300 MHz, $CDCl_3$) δ 4.35 (t, J = 8.0 Hz, 1 H), 4.00 (d, J = 7.8 Hz, 1 H), 2.72 (dd, J = 14.9, 6.4 Hz, 1 H), 2.57 (d, J = 8.6 Hz, 1 H), 2.46–2.29 (m, 3 H), 2.25–2.06 (m, 13 H); MS m/z (M^+) calcd 288.1048, obsd 288.1033.

For ii: mp 115–116 °C (from ethyl acetate); ^1H NMR (300 MHz, $CDCl_3$) δ 4.90 (dd, J = 9.0, 6.3 Hz, 1 H), 4.31 (d, J = 6.3 Hz, 1 H), 2.87 (d, J = 9.0 Hz, 1 H), 2.78 (dd, J = 15.1, 6.4 Hz, 1 H), 2.65 (d, J = 15.6 Hz, 1 H), 2.29 (m, 2 H), 2.05 (m, 1 H), 1.79–1.26 (m, 14 H); MS m/z (M^+) calcd 288.1047, obsd 288.1062.

Ketalization–Dechlorination of 16c. Dichloro ketone **16c** [from the photocycloaddition of 3.35 g (17.4 mmol) of **15c**] was dissolved in 150 mL of dichloromethane. Ethylene glycol (68 g, 1.1 mol) and trimethyl orthoformate (14.5 g, 137 mmol) were added, followed by 0.4 g (2.1 mmol) of *p*-toluenesulfonic acid. The mixture was stirred for 24 h and worked up as before. Concentration gave a yellow oil, which was used without purification.

To a blue solution of sodium (2 g, 87 mmol) in 130 mL of ammonia at −78 °C was added a solution of the above dichloro ketal in 30 mL of dry ether. After 20 min of stirring, workup as before gave 4.4 g of red liquid, which was homogeneous by TLC and ^1H NMR (96% overall from **15c**). A small pure sample was obtained by MPLC on silica gel (elution with 10% ethyl acetate in petroleum ether) as a colorless oil, which solidified in the cold: mp 61.5–63 °C; IR ($CHCl_3$) cm^{-1} 2940, 1486, 1295, 1110, 1045; ^1H NMR (300 MHz, $CDCl_3$) δ 6.40 (dd, J = 2.7 Hz, 1 H), 5.96 (d, J = 2.7 Hz, 1 H), 3.96–3.80 (m, 4 H), 2.50 (s, 1 H), 2.16 (d, J = 14.8 Hz, 1 H), 1.96 (m, 3 H), 1.63–1.15 (m, 15 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 147.49, 131.80, 111.34, 65.34, 63.61, 57.70, 51.88, 38.99, 33.99, 32.49, 30.61, 27.48, 24.64, 23.48, 23.06, 22.14, 19.21; MS m/z (M^+) calcd 262.1932, obsd 262.1966.

Tricyclic Enone 17c. The preceding ketal (4.3 g, 16.4 mmol) was dissolved in 100 mL of tetrahydrofuran and 50 mL of 5% hydrochloric acid was added. The mixture was stirred at room temperature for 6 h and diluted with ether. The organic phase was washed with saturated sodium bicarbonate solution and water and then dried. Concentration gave a quantitative yield of **17c** as a pale yellow oil, which was pure by TLC and solidified when deposited in a refrigerator: mp 62–64 °C; IR (neat) cm^{-1} 3040, 2920, 1700, 1480; ^1H NMR (300 MHz, $CDCl_3$) δ 6.39 (d, J = 1.9 Hz, 1 H), 5.92 (m, 1 H), 3.06 (s, 1 H), 2.63 (dd, J = 14.6, 6.2 Hz, 1 H), 2.33 (d, J = 15.0 Hz, 1 H), 2.06 (m, 1 H), 2.02 (m, 1 H), 1.86 (m, 1 H), 1.64–1.33 (m, 14 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 213.78, 150.76, 131.06, 60.39, 53.10, 45.66, 37.38, 35.53, 32.13, 30.90, 25.13, 24.42, 23.80, 23.68, 23.26; MS m/z (M^+) calcd 218.1670, obsd 218.1692. Anal. Calcd for $C_{15}H_{22}O$: C, 82.52; H, 10.16. Found: C, 82.54; H, 10.23.

Dienone Formation from 17c. To a solution of 1.12 g (11.06 mmol) of diisopropylamine in 70 mL of tetrahydrofuran at −78 °C was added *n*-butyllithium (7 mL, 1.6 M in hexane, 11.05 mmol). The mixture was stirred for 15 min before 2.0 g (9.2 mmol) of **17c** in 30 mL of the same solvent was added over 30 min. The mixture was stirred for 45 min and phenylselenenyl chloride (2.12 g, 11.06 mmol) in 20 mL of tetrahydrofuran was added in one portion. The resulting brown mixture was warmed to 0 °C before 25 mL of water, 1 mL of acetic acid, and 5 mL of 30% hydrogen peroxide were added in sequence. After continued stirring for 20 min at room temperature, workup as before gave a brown oil, chromatography of which on silica gel (elution with 10% ethyl acetate in petroleum ether) yielded 0.2 g of unreacted **17c** and 0.72 g (40% based on recovered starting material) of dienone as a colorless oil that solidified when deposited in the cold: mp 47–48.5 °C; IR (neat) cm^{-1} 3050, 2930, 1655, 1475; ^1H NMR (300 MHz, $CDCl_3$) δ 6.33 (m, 1 H), 6.09 (t, J = 1.3 Hz, 1 H), 6.01 (dd, J = 2.6, 1.1 Hz, 1 H), 3.03 (s, 1 H), 2.57 (d, J = 18.0 Hz, 1 H), 2.29 (m, 3 H), 1.76–1.05 (m, 12 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 199.79, 166.14, 147.11, 131.08, 129.43, 55.52, 50.01, 38.95, 37.55, 33.99, 26.81, 26.23, 21.68, 21.24; MS m/z (M^+) calcd 216.1514, obsd 216.1505. Anal. Calcd for $C_{15}H_{20}O$: C, 83.29; H, 9.32. Found: C, 83.39; H, 9.35.

Hydride Reduction of the [7]Dienone. A sample of the preceding dienone (0.47 g, 2.2 mmol) was dissolved in 60 mL of dichloromethane. L-Selectride (1.0 M in tetrahydrofuran, 3.5 mL) was added at 0 °C. After being stirred for 20 min at room temperature, the reaction mixture was quenched with methanol. Methylene chloride was removed on a rotary evaporator, and the residue was taken up in ether, washed with water, and dried. Ether was evaporated and the residue was purified by MPLC on silica gel (elution with 15% ethyl acetate in petroleum ether) to give 0.22 g (47%) of **19c** as a white solid and 100 mg (21%) of **18c** as a colorless oil.

For **19c**: mp 103–104 °C (from ethyl acetate); IR ($CHCl_3$) cm^{-1} 3600, 3010, 2940, 1475, 1043; ^1H NMR (300 MHz, $CDCl_3$) δ 6.47 (d, J = 2.7 Hz, 1 H), 6.12 (m, 1 H), 5.95 (m, 1 H), 4.54 (t, J = 6.7 Hz, 1 H), 2.74 (dd, J = 7.0, 0.8 Hz, 1 H), 2.34–2.09 (m, 4 H), 1.64–1.21 (m, 13 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 148.87, 144.05, 131.90, 127.43, 65.27, 51.49, 50.74, 40.37, 37.08, 32.71, 26.85, 26.66, 21.87, 21.41, 21.06; MS m/z (M^+) calcd 218.1671, obsd 218.1691.

For **18c**: IR (neat) cm^{-1} 3300, 3020, 2920, 1560, 1468, 1035; ^1H NMR (300 MHz, $CDCl_3$) δ 6.27 (m, 2 H), 5.64 (br s, 1 H), 4.04 (m, 1 H), 2.67 (br s, 1 H), 2.25–2.06 (m, 4 H), 1.78 (d, J = 15.5 Hz, 1 H), 1.66–1.18 (m, 12 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 146.63, 140.57, 135.20, 130.84, 72.86, 55.55, 49.69, 39.77, 36.10, 35.26, 26.88, 26.65, 22.22, 21.82, 21.25; MS m/z (M^+) calcd 218.1670, obsd 218.1640.

[7](1,3)Cyclooctatetraenophane (9c). Allylic alcohol **19c** (177 mg, 0.81 mmol) was dissolved in 30 mL of 1,2-dichloroethane at 0 °C. Triethylamine (0.25 g, 2.43 mmol) and 2,4-dinitrobenzenesulfenyl chloride (0.57 g, 2.43 mmol) were added. The mixture was refluxed for 3 h before it was cooled and diluted with petroleum ether. The yellow precipitate was removed by filtration, and the filtrate was washed with water and dried. Concentration followed by MPLC on silica gel (elution with petroleum ether) produced 113 mg (70%) of pure **9c** as a yellow oil: ^1H NMR (300 MHz, $CDCl_3$) δ 5.96–5.68 (m, 5 H), 5.52 (br s, 1 H), 2.39–2.19 (m, 2 H), 2.08–1.92 (m, 2 H), 1.74–1.28 (m, 10 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 146.84, 142.18, 134.00, 133.79, 131.19, 130.72, 130.08, 124.23, 37.63, 35.80, 26.90, 25.30, 24.98, 24.73, 24.68; MS m/z (M^+) calcd 200.1565, obsd 200.1562. Anal. Calcd for $C_{15}H_{20}$: C, 89.94; H, 10.06. Found: C, 89.90; H, 10.02.

[2 + 2] Photocycloaddition of *trans*-1,2-Dichloroethylene to 15d. Enone **15d**[10b,22] (1.4 g, 8.52 mmol) was dissolved in 60 mL of *trans*-1,2-dichloroethylene. This solution was degassed with argon for 20 min and photolyzed as before for 19 h. Concentration followed by recrystallization from ethyl acetate/petroleum ether gave 2.0 g (90%) of dichloro ketone **16d** as a mixture of four isomers, which were separated by MPLC on silica gel (elution with 10% ethyl acetate in petroleum ether).

Diastereomer A: ^1H NMR (300 MHz, $CDCl_3$) δ 4.82 (t, J = 7.0 Hz, 1 H), 4.35 (d, J = 6.5 Hz, 1 H), 2.83 (d, J = 7.5 Hz, 1 H), 2.62 (dd, J = 16.6, 6.0 Hz, 1 H), 2.35–2.00 (m, 4 H), 1.75–1.05 (m, 10 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 208.11, 68.97, 59.42, 55.07, 45.88, 45.02, 36.32, 35.25, 33.50, 30.55, 28.78, 24.29, 21.65; MS m/z (M^+) calcd 260.0734, obsd 260.0734.

Diastereomer B: ^1H NMR (300 MHz, $CDCl_3$) δ 4.41 (dd, J = 11.2, 7.2 Hz, 1 H), 4.22 (d, J = 7.3 Hz, 1 H), 3.10 (d, J = 11.2 Hz, 1 H), 2.50–2.17 (m, 4 H), 1.92–1.06 (m, 11 H).

Diastereomer C: ^1H NMR (300 MHz, $CDCl_3$) δ 4.27 (t, J = 8.3 Hz, 1 H), 3.97 (d, J = 8.0 Hz, 1 H), 2.70–2.60 (m, 2 H), 2.37–2.25 (m, 2 H), 2.13–1.94 (m. 2 H), 1.77–1.07 (m, 10 H).

Diastereomer D: ^1H NMR (300 MHz, $CDCl_3$) δ 4.75 (dd, J = 8.2, 7.1 Hz, 1 H), 4.37 (d, J = 7.0 Hz, 1 H), 2.98 (d, J = 8.3 Hz, 1 H), 2.71 (dd, J = 17.3, 6.3 Hz, 1 H), 2.47 (dd, J = 15.1, 3.8 Hz, 1 H), 2.37–2.28 (m, 2 H), 2.08–1.93 (m, 2 H), 1.73–1.09 (m, 9 H).

Ketalization–Dechlorination of 15d. A sample (1.82 g, 7.0 mmol) of the mixture of four dichloro ketones **15d** was dissolved in 40 mL of dichloromethane. Ethylene glycol (20 g, 0.3 mol), 4.13 g (39 mmol) of trimethyl orthoformate, and 0.15 g (0.7 mmol) of *p*-toluenesulfonic acid were added. The mixture was stirred at room temperature for 36 h. Workup as before produced a yellow oil, which was dissolved in 30 mL of ether. This solution was added to 0.84 g (36.5 mmol) of sodium in 100 mL of ammonia at −78 °C. After being stirred at −78 °C for 30 min, the reaction mixture was worked up as before. Concentration afforded 1.32 g (81%) of ketal as a yellow oil: IR (neat) cm^{-1} 3030, 2920, 1460, 1285, 950, 795; ^1H NMR (300 MHz, $CDCl_3$) δ 6.24 (d, J = 2.7 Hz, 1 H), 5.92 (m 1 H), 4.01–3.80 (m, 4 H), 2.62 (s, 1 H), 2.30 (m, 1 H), 1.98–1.24 (m, 14 H); ^{13}C NMR (20 MHz, $CDCl_3$) ppm 149.10, 131.00, 111.75, 65.02, 63.92, 54.66, 50.67, 41.12, 36.24, 34.50, 33.03, 32.01, 28.21, 26.83, 25.71; MS m/z (M^+) calcd 234.1620, obsd 234.1617.

Tricyclic Enone 17d. A sample (1.30 g, 5.66 mmol) of the preceding ketal was hydrolyzed with 5% hydrochloric acid as previously described to give 1.0 g (94%) of pure **17d** after filtration through a short silica gel column: IR (neat) cm^{-1} 2915, 1695, 1470, 780; ^1H NMR (300 MHz, $CDCl_3$) δ 6.32 (dd, J = 1.4, 2.6 Hz, 1 H), 5.84 (m, 1 H), 3.07 (s, 1 H), 2.43 (dd, J = 16.6, 4.3 Hz, 1 H), 2.15 (m, 3 H), 1.86–1.22 (m, 11 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 214.16, 150.80, 130.39, 58.35, 49.97, 46.72, 40.47, 35.64, 33.97, 28.17, 25.22, 23.80, 22.69; MS m/z (M^+) calcd 190.1358, obsd 190.1343. Anal. Calcd for $C_{13}H_{18}O$: C, 82.06; H, 9.53. Found: C, 82.06; H, 9.56.

Dienone Formation from 17d. Diisopropylamine (350 mg, 3.48 mmol) dissolved in 20 mL of tetrahydrofuran was cooled to −78 °C and treated with *n*-butyllithium (1.6 M in hexane, 2.3 mL, 3.48 mmol). The mixture was stirred for 20 min before 0.51 g (2.68 mmol) of **17d** in 15 mL of the same solvent was added dropwise. After stirring was continued for 45 min, 0.67 g (3.5 mmol) of phenylselenenyl chloride in 10 mL of the same solvent was added. The mixture was warmed to 0 °C and 7 mL of water, 0.3 mL of glacial acetic acid, and 1.5 mL of 30% hydrogen peroxide were added. After additional stirring at room temperature for 20 min, workup as before followed by MPLC on silica gel (elution with 15% ethyl acetate in petroleum ether) gave 300 mg (60%) of dienone as a colorless oil: IR (neat) cm^{-1} 2920, 1670, 1620, 1550, 1460, 755; ^1H NMR (300 MHz, $CDCl_3$) δ 6.36 (m, 1 H), 6.25 (m, 1 H), 6.00 (d, J = 2.5 Hz, 1 H), 3.06 (s, 1 H), 2.56–2.39 (m, 4 H), 2.23–1.24 (m, 8 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 201.41, 167.61, 145.87, 130.94, 126.14, 57.65, 51.31, 40.49, 40.33, 37.74, 35.19, 27.34, 27.21; MS m/z (M^+) calcd 188.1201, obsd 188.1214. Anal. Calcd for $C_{13}H_{16}O$: C, 82.94; H, 8.57. Found: C, 82.84; H, 8.63.

Hydride Reduction of the [5]Dienone. A sample (110 mg, 0.6 mmol) of the above dienone was dissolved in 5 mL of methylene chloride and cooled to −78 °C. Dibal-H (1.0 M in hexane, 0.9 mL) was added dropwise. Workup as before gave 100 mg (90%) of pure **18d**: mp 76–78 °C (from ethyl acetate/hexane); IR ($CHCl_3$) cm^{-1} 3610, 3460, 2930, 1650, 1560, 1465; ^1H NMR (300 MHz, $CDCl_3$) δ 6.35 (m, 2 H), 5.73 (s, 1 H), 4.04 (d, J = 7.7 Hz, 1 H), 2.42–1.30 (m, 14 H); ^{13}C NMR (20 MHz, $CDCl_3$) ppm 145.94, 143.34, 134.87, 129.83, 74.09, 56.15, 51.91, 40.86, 39.06, 35.67, 32.43, 27.84, 26.97; MS m/z (M^+) calcd 190.1358, obsd 190.1334.

Bicyclooctatriene 10c. A sample of alcohol **19c** (50 mg, 0.23 mmol) in 6 mL of 1,2-dichloroethane was treated at 0 °C with triethylamine (70 mg, 0.69 mmol) and 2,4-dinitrobenzenesulfenyl chloride (162 mg, 0.69 mmol). The yellow reaction mixture was stirred at room temperature for 3 h. The solvent was evaporated and the residue was taken up in petroleum ether, washed with water, and dried. After concentration, MPLC of the residue on silica gel (elution with petroleum ether) afforded 17 mg (37%) of **10c** as a colorless oil and 3 mg of **9c** as a yellow oil. For **10c**: ^1H NMR (300 MHz, C_6D_6) δ 5.97–5.67 (m, 4 H), 5.25 (s, 1 H), 2.84 (s, 1 H), 2.08–1.16 (series of m, 14 H); ^{13}C NMR (75 MHz, benzene-d_6) ppm 142.76, 133.05, 131.95, 127.44, 126.99, 126.10, 50.91, 48.44, 41.02, 36.83, 29.14, 27.03, 26.58, 26.46, 25.29.

Electrochemical Measurements. The cyclic voltammetric studies were carried out in a vacuum-line electrochemical cell[47] that allowed solution preparations and measurements to be completed under strictly anhydrous conditions. Details of the procedure, including techniques for drying and purifying the solvent and background electrolyte, are described elsewhere.[48]

Dianions 27 and 28. A vacuum line was set up and 20 mg (0.5 mmol) of potassium was placed in the reaction vessel (5 mL). The system was dried under high vacuum with gentle flaming and filled with argon. The precondensed deuterated ammonia (ca. 1 mL) and trimethylamine (as an internal standard) were condensed into the reaction vessel by cooling it with liquid nitrogen. When the liquid nitrogen bath was replaced by a dry ice/isopropyl alcohol bath, a blue solution was formed. Cyclooctatetraenophanes **9a** or **9c** (20 mg) were introduced into the vessel. After 25 min of stirring, the blue reaction mixture was solidified with a liquid nitrogen bath, and an NMR tube fitted with a glass wool filter was connected to the reaction vessel through a ground joint. The system was pumped down and flushed with argon before the vessel was turned upside down. The NMR tube was cooled in a dry ice bath. Solids in the vessel began to melt and run down into the filter. The liquid mixture was filtered into the NMR tube by replacing the dry ice bath with liquid nitrogen. The NMR tube was sealed under high vacuum. Solids in the NMR tube remelted to form a blue solution when warmed to −78 °C. The ^1H NMR spectra of the dianions were recorded at 500 MHz and −60 °C. They are displayed in Figure 1.

Reoxidation of 27 and 28. The two solutions of dianions **27** and **28** prepared above were separately poured into two dry hexane solutions containing excess iodine at −78 °C. The mixtures were warmed to room temperature, washed with aqueous sodium thiosulfate solution to remove the excess iodine, and then dried. The recovered hydrocarbons had the

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same spectral properties as authentic **9a** and **9c**, respectively.

Diels–Alder Addition of (−)-*endo*-Bornyltriazolinedione to 9a. A 1.1-g sample (4.8 mmol) of **9a** in 20 mL of ethyl acetate was added to a solution of 1.7 g (7.2 mmol) of (−)-*endo*-bornyltriazolinedione in 20 mL of the same solvent. The red reaction mixture was refluxed for 7 h. Evaporation of the solvent produced a yellow-brown solid, which was chromatographed on silica gel (elution with 6% ethyl acetate in petroleum ether) to remove very polar base-line material. A pale yellow solid (0.76 g, 34%) was obtained. This solid was subjected to MPLC silica gel (elution with 4% ethyl acetate in petroleum ether) in order to separate **29a/30a** from **31a/32a**.

For **29a/30a**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.04 (m, 1 H), 5.86 (m, 1 H), 5.63 (br s, 1 H), 4.85 (m, 1 H), 4.33 (m, 1 H), 3.33 (d, J = 3.8 Hz, 1 H), 3.07 (br s, 1 H), 2.49–2.26 (m, 3 H), 2.02 (m, 1 H), 1.86–1.27 (m, 21 H), 0.94 (s, 3 H), 0.86 (s, 3 H) 0.79 (s, 1.5 H), 0.77 (s, 1.5 H).

For **31a/32a**: mp 191–192 °C (from ethyl acetate/petroleum ether); IR ($CHCl_3$) cm^{-1} 2940, 1755, 1695, 1420, 1395; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.23 (m, 1 H), 5.97 (m, 1 H), 5.64 (s, 1 H), 4.86 (m, 1 H), 4.42 (m, 1 H), 4.23 (m, 1 H), 3.05 (d, J = 4.2 Hz, 1 H), 2.39 (m, 1 H), 2.16 (m, 1 H), 1.95–1.20 (series of m, 23 H), 0.95 (s, 3 H), 0.87 (s, 3 H), 0.78 (s, 3 H); MS m/z (M^+) calcd 463.3200, obsd 463.3222.

The **29a/30a** urazole mixture was recrystallized twice from ethyl acetate/petroleum ether to yield a single diastereomer: mp 183–185 °C; $[\alpha]^{25}_D$ = +14.0°, $[\alpha]^{25}_{436}$ = +21.1° (c 1.05, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.03 (dd, J = 7.9, 5.8 Hz, 1 H), 5.85 (d, J = 7.9 Hz, 1 H), 5.63 (d, J = 1.9 Hz, 1 H), 4.84 (m, 1 H), 4.24 (m, 1 H), 3.34 (d, J = 3.9 Hz, 1 H), 3.07 (m, 1 H), 2.46 (m, 2 H), 2.24 (m, 1 H), 2.03 (m, 1 H), 1.91–1.13 (m, 21 H), 0.94 (s, 3 H), 0.86 (s, 3 H), 0.79 (s, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 158.29, 157.31, 154.13, 131.41, 128.98, 124.71, 67.11, 58.39, 54.25, 51.57, 47.71, 45.42, 41.49, 37.84, 31.95, 30.40, 29.50, 27.14, 26.51, 26.39, 26.08, 24.85, 22.63, 21.54, 20.65, 19.59, 19.18, 18.66, 13.96; MS m/z (M^+) calcd 463.3199, obsd 463.3169. Anal. Calcd for $C_{29}H_{41}N_3O_2$: C, 75.12; H, 8.91. Found: C, 74.87; H, 8.90.

Diastereomer enrichment in the other series could not be accomplished by recrystallization.

Diels–Alder Addition of (−)-*endo*-Bornyltriazolinedione to 9c. A sample (0.55 g, 2.75 mmol) of **9c** in 25 mL of ethyl acetate was heated to reflux under argon while 1.25 g (5.32 mmol) of (−)-*endo*-bornyltriazolinedione in 20 mL of the same solvent was added. The mixture was refluxed for 1 h. After cooling, the solvent was evaporated. MPLC of the residue (silica gel, elution with 10% ethyl acetate in petroleum ether) gave 0.55 g (46%) of a white solid, the ^{1}H NMR of which revealed it to be a 1:1 mixture of **29c** and **30c**. Recrystallization did not enrich either one of them. However, partial separation was achieved by MPLC on silica gel (elution with 3% ethyl acetate in petroleum ether). One fraction, the ^{1}H NMR of which shows a diastereomeric purity of 90%, exhibited the following: $[\alpha]^{25}_{436}$ = +8.6° (c 1.4, $CHCl_3$); mp 177–179 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.05 (dd, J = 7.9, 5.9 Hz, 1 H), 5.80 (d, J = 7.9 Hz, 1 H), 5.66 (s, 1 H), 4.83 (m, 1 H), 4.21 (m, 1 H), 3.50 (d, J = 3.8 Hz, 1 H), 3.13 (br s, 1 H), 2.77 (m, 1 H), 2.41 (dd, J = 12.9, 5.3 Hz, 1 H), 2.12–1.24 (m, 19 H), 0.93 (s, 3 H), 0.85 (s, 3 H), 0.78 (s, 3 H); MS m/z (M^+) calcd 435.2885, obsd 435.2899. Anal. Calcd for $C_{27}H_{37}N_3O_2$: C, 74.45; H, 8.56. Found: C, 74.79; H, 8.68.

Prototypical *endo*-Bornylurazole Hydrolysis–Oxidation. A sample of the preceding urazole (21 mg, 0.048 mmol), $[\alpha]^{25}_{436}$ = +8.6°, was dissolved in 3 mL of isopropyl alcohol. Sodium hydroxide (80 mg, 2 mmol) was added. The mixture was refluxed for 4 h, cooled to room temperature, carefully acidified with 5% hydrochloric acid to pH = 1, and neutralized with 3 N ammonium hydroxide to pH = 9. Petroleum ether (4 mL) and manganese dioxide (60 mg, 0.69 mmol) were added. After being stirred for 15 min, the reaction mixture was diluted with more petroleum ether, washed with water, dried, and concentrated. The residue was chromatographed on silica gel at 0 °C (elution with pentane) to give 7 mg (73%) of **9c**, which exhibited no optical rotation.

Prototypical Hydrogen–Deuterium Exchange Sequence. A mixture of **9c** (5.7 g, 26.1 mmol) and potassium carbonate (18 g, 1.30 mmol) in 20 mL of dioxane and 20 mL of deuterium oxide was refluxed under argon for 26 h. The reaction mixture was cooled and diluted with ether. The ether layer was washed with water until the washing remained neutral and then dried. Concentration gave 5.4 g (94%) of **33c**, which has at least 90% of deuterons incorporated at the three positions α to the carbonyl: ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.43 (d, J = 2.7 Hz, 1 H), 5.96 (d, J = 2.7 Hz, 1 H), 2.35 (dd, J = 5.0, 2.1 Hz, 1 H), 2.17 (m, 1 H), 1.91 (m, 1 H), 1.68–1.33 (m, 14 H).

Diisopropylamine (0.55 g, 5.4 mmol) in 30 mL of tetrahydrofuran at −78 °C was treated with n-butyllithium (1.6 M in hexane, 3.4 mL, 5.4 mmol). After 20 min, **33c** (1.0 g, 4.5 mmol) in 10 mL of the same solvent was added dropwise, and the mixture was stirred for 50 min before phenylselenenyl chloride (1.05 g, 5.4 mmol) in the same solvent (5 mL) was added. The mixture was warmed to 0 °C and 1 mL of deuterium oxide was added to quench the excess base. Oxidation was effected exactly as described earlier. After chromatography (silica gel, elution with 10% ethyl acetate in petroleum ether) of the residue, 0.36 g (36%) of **34c** and 0.1 g of the starting material were obtained. For **34c**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.36 (d, J = 2.6 Hz, 1 H), 6.12 (d, J = 2.6 Hz, 1 H), 6.04 (d, J = 2.6 Hz, 0.5 H), 2.60 (d, J = 18.0 Hz, 1 H), 2.33 (m, 3 H), 1.75–1.08 (m, 13 H).

A solution of **34c** (0.24 g, 1.1 mmol) in 50 mL of dichloromethane was reduced as before with L-Selectride (1.65 mmol). There was isolated 140 mg (58%) of **35c**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.46 (d, J = 2.7 Hz, 1 H), 6.12 (d, J = 2.7 Hz, 1 H), 5.94 (m, 0.5 H), 4.54 (br s, 1 H), 2.33–2.09 (m, 5 H), 1.67–1.17 (m, 12 H).

Allylic alcohol **35c** (100 mg, 0.45 mmol) was dehydrated to give **36c** in exactly the manner described above. There was isolated 30 mg (33%) of **36c**, which was submitted directly to 2-D analysis (Figure 2).

Dynamic NMR Studies. All of the proton 2-D EXSY spectra were acquired at 500 MHz with the Bruker pulse program NOEPHR using TPPI[49] to generate phase-sensitive spectra. The program was slightly modified by adding a π pulse inserted at random position during a fixed mixing time to suppress J cross peaks arising from zero-quantum coherence.[50] The program was also modified to allow setting the receiver phase to any desired value.

By setting the receiver phase so that the zero-order phase correction is zero and adjusting the preacquisition delay to give a first-order phase correction of zero, flat base lines were obtained, which needed only a linear base-line correction to remove a dc offset and/or a linear slope. After the data were transformed into the t_2 domain, a linear correction was applied (ABC) and the data were then transformed into the t_1 domain. Areas of cross peaks and diagonal peaks were measured directly from the 2-D display be selecting a voxel surrounding a peak and integrating over that volume. Typically four scans each of 128 t_1 increments were acquired in 1 K blocks with a relaxation delay of 5–8 s. When the data were processed, an exponential broading equal to the digital resolution was applied. The ^{13}C exchange spectra were acquired in a similar manner except that no π pulse was used during the mixing time.

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