energy of the hydrogen bond in vacuo ranges from -3.1 to -19 kcal·mol^{-1}; whereas hydrogen bond energies in an enzyme–substrate complex range from -0.5 to -1.5 kcal·mol^{-1} for uncharged donors and acceptors. The smaller energies in solutions are believed to be due in large part to the effect of water.[25] The association constant of a diamidepyridine receptor with a barbiturate decreases from 3000 M^{-1} in CCl_4 to 155 M^{-1} in $CDCl_3$.[26] Therefore, the large binding constants we observed in the presence of water (in the magnitude of 100 M^{-1}) may be attributed to unique features of the air–water interface. As mentioned in the Introduction, the monolayer of a resorcinol cyclotetramer (**8**) binds monosaccharides structure-selectively.[8] A diaminotriazine functionalized monolayer (**9**) effectively binds barbituric acids[9] and nucleic acid bases[10] by complementary hydrogen bonding. Strong solvation of these polar substrates by water does not prohibit their efficient hydrogen bonding with the functional monolayers on water. This unique feature may arise from rigid alignment of the receptor site on water and/or anisotropic microenvironments near the interface, as discussed before.[8] We do not know the exact answer yet.

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Registry No. 1, 79410-29-0; **2b**, 135365-30-9; **2c**, 65972-30-7; **3a**, 128208-38-8; **3b**, 135365-33-2; **3c**, 135365-34-3; **4a**, 135365-31-0; **4b**, 135365-32-1; 3-(acetylamino)phenol, 621-42-1; octadecyl bromide, 112-89-0; 4-(acetylamino)phenol, 103-90-2; 4-(octadecyloxy)acetanilide, 73722-04-0; 4-(octadecyloxy)aniline, 4105-89-9; octadecylamine, 124-30-1; pyridine, 110-86-1; pyridazine, 289-80-5; pyrimidine, 289-95-2; pyrazine, 290-37-9; quinoline, 91-22-5; isoquinoline, 119-65-3; phthalazine, 253-52-1; quinazoline, 253-82-7; quinoxaline, 91-19-0; imidazole, 288-32-4; benzimidazole, 51-17-2; alanine, 56-41-7; leucine, 61-90-5; phenylalanine, 63-91-2; histidine, 71-00-1; tryptophan, 73-22-3; octadecanoic acid, 57-11-4.

Intramolecular Palladium-Catalyzed Trimethylenemethane Cycloadditions: Initial Studies

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Abstract: The potential application of [3 + 2] cycloadditions to polycarbocycle construction is considerably enhanced by the ability to perform such reactions intramolecularly. The feasibility of such processes is explored in the context of Pd-catalyzed cycloadditions of 2-[(trimethylsilyl)methyl]allyl carboxylates, wherein trimethylenemethane (TMM) precursor fragment (donor) and the electron-deficient olefin (acceptor) is joined by a tether of simple methylene groups of 3, 4, 5, and 8 members. Several versatile synthetic routes to these substrates were developed. 2-Bromo-3-(trimethylsilyl)propene proves to be a key reagent for construction of the donor portion. Acceptors bearing esters, cyano groups, and especially sulfones have been examined. The diastereoselectivity of the reaction has been explored both in terms of ring juncture and the diastereofacial selectivity with respect to an oxygen substituent at the allylic position of the acceptor. Excellent cycloadditions to give the bicyclo[3.3.0]octyl and bicyclo[4.3.0]nonyl systems are observed, whereas larger rings cannot be obtained in this series. The choice of catalyst proves critical, the most useful being either tetrakis(triphenylphosphine)palladium and DPPE or, more generally, triisopropyl phosphite and palladium acetate. The first cycloaddition of a 1,1-dialkylated TMM precursor, which fails in intermolecular cases, has been observed in this intramolecular series to give a bridgehead-substituted bicycle. A rationale for the observed diastereoselectivity is presented.

Ring construction constitutes a continuing major challenge in synthetic organic chemistry. Processes that involve forming more than one bond enhance synthetic efficiency. The tremendous success of the Diels–Alder reaction attests to this fact. New dimensions of selectivity evolve by extending these intermolecular processes to intramolecular ones. In the case of Diels–Alder reactions, questions of regio-, diastereo-, and enantioselectivity have been of particular interest.[1] Much less work has been done in the related 1,3-dipolar cycloadditions; nevertheless, the growing body of literature on their intramolecular versions reveal many unique aspects associated with tethering the two reaction partners.[2]

Carbocyclic versions of the [3 + 2] cycloaddition have emerged largely within the recent past.[3-13] Their intramolecular versions have remained virtually untapped. Of the few studies that exist, the intramolecular cycloadditions of allyl cations,[4] 1,3-diyls,[9] and methylenecyclopropanes[11] stand out.

Our development of a [3 + 2] cycloaddition via the intermediacy of trimethylenemethane palladium complexes (TMM–PdL_2)[12] demands an exploration of the feasibility of an intramolecular version. The geometrical constraints established by the tether may lead to competing reactions, notably protodesilylation. To the extent that cycloaddition will occur, the question of regioselectivity arises. In this paper, we report our initial studies that establish the feasibility of intramolecular [3 + 2] cycloadditions via TMM–PdL_2 intermediates.[14]

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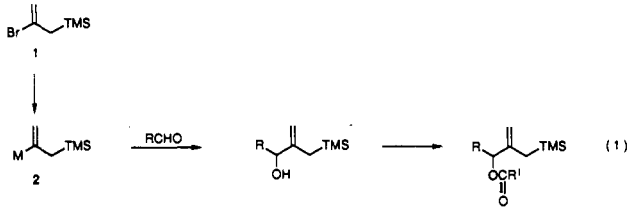
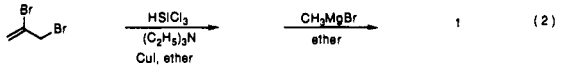
Preparation of Substrates

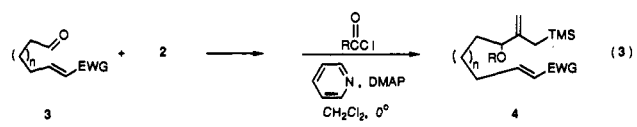
For the preparation of substituted bifunctional conjunctive reagents leading to substrates for intramolecular cycloadditions, we adopted a strategy summarized in eq 1. The synthesis of the



requisite reagent **1**[14-16] entailed coupling of 2,3-dibromopropene with a trimethylsilyl organocopper reagent generated by addition of 1.5 equiv of cuprous cyanide to (trimethylsilyl)lithium in a 3:1 THF–HMPA mixture at 0 °C. Alternatively, the bromosilane was conveniently prepared according to eq 2 in 71% yield. This



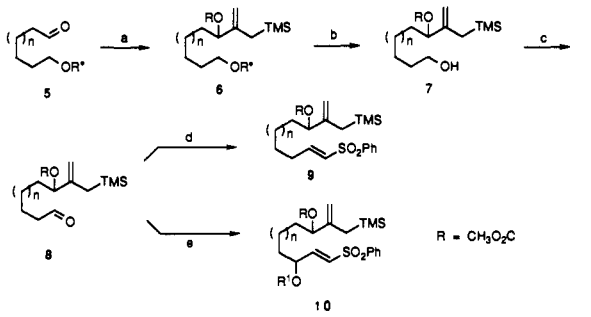
method has the advantage of avoiding the use of HMPA. The resulting bromosilane **1** can be distilled and stored in the dark for prolonged periods. While the Grignard reagent may be formed in the normal manner, metal–halogen exchange with *tert*-butyllithium proved more convenient, especially on smaller scales. Initially, our synthesis of the cyclization substrates focused on addition of the organometallic **2** (M = Li or MgBr) to an aldehyde **3** already possessing the acceptor unit (eq 3). Use of the or-



a) n = 1, EWG = $CO_2C_2H_5$ b) n = 1, EWG = SO_2Ph c) n = 2, EWG = SO_2Ph d) n = 6, EWG = SO_2Ph

ganolithium reagent in such cases led to very poor yields of the desired substrates **4** (R = CH_3CO), whereas variable yields (normally <50%) were obtained in the case of the magnesium reagents, which were generated directly from the bromide with magnesium or generated indirectly by addition of magnesium bromide to the lithium reagent. Attempts to improve the yields by further variation of the metal were not promising.

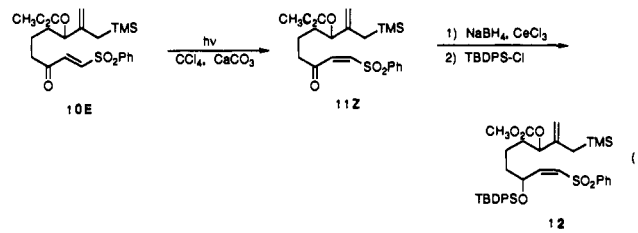
Scheme I. Synthesis of Cyclization Substrates[a]



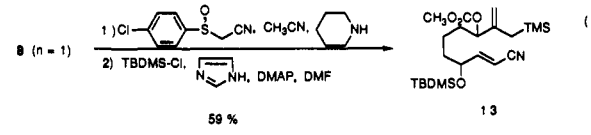
[a] (a) **2** (M = Li), ether, 0 °C, then $ClCO_2CH_3$, room temperature. (b) For R″ = PMB, DDQ, CH_2Cl_2, H_2O, room temperature, for R″ = TBDMS, H_2SO_4, H_2O, THF, room temperature. Overall yield for *n* = 1 R″ = PMB 75%, R″ = TBDMS 64%; *n* = 2 R″ = PMB 42%. (c) PCC, Celite, CH_2Cl_2, room temperature, *n* = 1 81%, *n* = 2 75%. (d) $PhSO_2CH_2PO(OC_2H_5)_2$, $NaN(TMS)_2$, THF, −78 °C, *n* = 1 78%, *n* = 2 94%. (e) *p*-$ClC_6H_4S(O)CH_2SO_2Ph$, $C_5H_{11}N$, CH_3CN, room temperature, then R_3SiCl, $C_3H_4N_2$, DMAP, DMF, 64–72%; *n* = 2, 42%.

Perceiving that the problem lay with electron transfer from the organometallic reagent to the electron-deficient acceptor moiety of **3**, we inverted the order of introduction of the two reaction partners i.e., we incorporated the bifunctional conjunctive portion first and then the acceptor moiety. Construction of the carbonate analogue of **9** (R = CO_2CH_3) from aldehyde **5** illustrates the success of this approach (see Scheme I). In order to probe the effect of a γ-hydroxyl group on the acceptor in terms of reactivity and stereochemistry the aldehydes **8** (R = CH_3O_2C) were condensed with an α-sulfinyl sulfone[17] to provide the hydroxylative Knoevenagel condensation[18] product **10** (R = CH_3O_2C, R′ = TBDMS and TBDPS) after silylation. It is interesting to note that under both olefination conditions only the *E* isomers were observed.[19]

Examination of the effect of olefin geometry required the obtention of the *Z* isomer. An extremely simple solution emerged when we observed double-bond isomerization during thin-layer chromatography of the readily accessible ketone **11E** utilizing ultraviolet detection. Consequently, photolysis of a solution of the *E* enone **11E** gave a 67% yield of *Z* enone **11Z** at 85% conversion (eq 4).[20] Longer irradiation times led to substantial decomposition. Reduction and silylation gave a 65% yield of the *Z* acceptor **12**.



Varying the electron-withdrawing group of the acceptor via the route outlined in Scheme I simply required different olefinating agents. Thus, the cyano acceptor **13** was readily derived from aldehyde **8** (*n* = 1, R = CH_3O_2C) by the hydroxylative Knoevenagel condensation (eq 5).[21]



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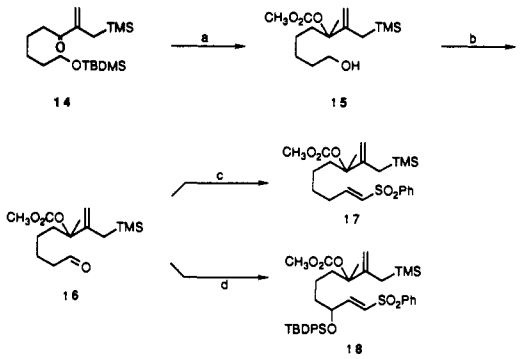
Scheme II. Synthesis of Methyl-Substituted Donor Substrates[a]



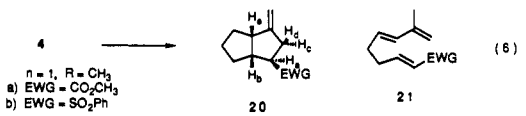
[a] (a) CH_3Li, ether, 0 °C, then $ClCO_2CH_3$, room temperature, then H_2SO_4, H_2O, THF, room temperature; 65%. (b) PCC, Celite, CH_2Cl_2, room temperature. (c) $PhSO_2CH_2PO(OC_2H_5)_2$, $NaN(TMS)_2$, THF, −78 °C; 78%. (d) *p*-$ClC_6H_4S(O)CH_2SO_2Ph$, $C_5H_{11}N$, CH_3CN, then TBDPS-Cl, $C_3H_4N_2$, C_5H_5N, DMAP, DMF, 49%.

The common presence of bridgehead substituents, particularly methyl groups, in fused polycycles led us to synthesize the acceptors **17** and **18**. The intermediates of Scheme I again proved quite versatile since the allyl alcohol **6** (R = H, R″ = TBDMS) is readily oxidized to the enone **14** in 72% yield under Moffatt–Swern conditions[22] (Scheme II). Addition of methyllithium in ether and quenching the formed alkoxide with methyl chlorocarbonate gave the desired tertiary allylic carbonate. Following the route of Scheme I then provides the desired substrates **17** and **18**.

It is important to note that in the above sequences, oxidations frequently employed Moffatt–Swern conditions. Subsequent work shows that trace impurities undetectable by spectroscopy or combustion analysis introduced in this step sometimes affect the subsequent palladium-catalyzed reactions. For this reason, we recommend minimizing the use of this method of oxidation. Chromium-based oxidants and the Dess–Martin reagent appear to be free of this complication.

Cycloadditions

Our cyclization studies began with the very simple substrates **4a** and **4b** (R = CH_3). By using $(Ph_3P)_4Pd$ (**19**) in conjunction with 1,2-bis(diphenylphosphino)ethane (DPPE) as the catalyst system in refluxing THF, a mixture of the desired bicyclo[3.3.0]octanes **20** and the elimination products **21** was obtained. Using only DPPE or only Ph_3P ligands increased the amount of the elimination products **21**. On the other hand, addition of



(6)

N,*O*-bis(trimethylsilyl)acetamide (BSA) minimized the elimination product. In this way, the ester **20a** and sulfone **20b** were isolated in 51% and 45% yields, respectively. In the case of the sulfone, the reaction was also performed in refluxing 1,2-dimethoxyethane (DME), which increased the yield of cycloadduct to 65%. Separation of the trienes **21b** was facilitated by addition of maleic anhydride to the crude mixture to effect cycloaddition, followed by chromatographic purification.

NMR studies provide the initial evidence for support of the structural assignments. The appearance of H_a of **20a** at δ 2.34 as a dt J = 9.6, 7.0 Hz rules out the alternative regioisomer **22** since it has only two vicinal protons. Further, desulfonylation[23]

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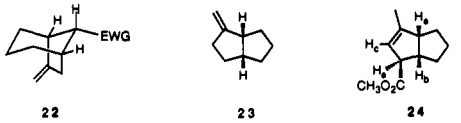
Table I. Eu(fod)$_3$-Induced NMR Shifts (Hertz)

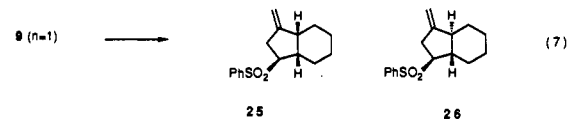
compd	H_a	H_b	H_c	H_d	H_e
20b	441	355	221	362	105
24	444	388	268		121

of **20b** [Na(Hg), Na_2HPO_4, CH_3OH, 47%] produced the known hydrocarbon **23**, whose properties were identical with those of an authentic sample.[24] The exo stereochemistry of the ester and



sulfone functional groups derives from NMR comparisons to model compounds.[25] Thus, J_{ab} of 9.6 Hz agrees with the 9–10.5 Hz coupling for similarly disposed trans hydrogens compared to the 7–8 Hz observed when these protons are cis. Further, isomerization of **20a** to the endocyclic isomer **24** (TsOH, $CDCl_3$, 50 °C, 90%) flattens the ring conformation such that J_{ab} becomes small, 3.6 Hz, in excellent accord with the approximately 4 Hz for model compounds bearing such a trans relationship, but considerably at odds with the 9-Hz coupling for analogues of **24** having these hydrogens cis. Eu(fod)$_3$-induced shifts further support these assignments (see Table I). The large shifts for H_b and H_d in **20b** and H_b in **24** relative to the other observed shifts are consistent with these protons being cis to the coordination site for the europium.

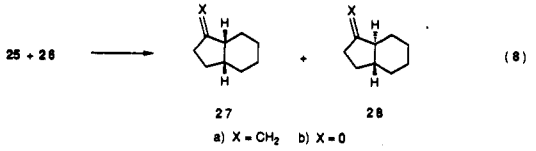
Increasing the tether length by one with substrate **9** (n = 1, R = Ac), led to 43–70% yields of the perhydroindans **25** and **26** as a 2/1 isomeric mixture (eq 7) with only minor amounts of elimination products. Use of the carbonate leaving group **9** (n



(7)

= 1, R = CH_3O_2C) and a switch to triisopropyl phosphite–palladium acetate (cat. G) as the catalyst in the presence of BSA resulted in further improvement, and the bicycles were routinely available in 73% yield.

That the two isomers obtained in the cyclization differed in the stereochemistry of the ring juncture and not the stereochemistry of the sulfone was clearly established upon reductive desulfonylation to a 2/1 olefin mixture. Oxidative cleavage to the known[26] perhydroindanones **27b** and **28b** allows the major isomer to be assigned as cis and the minor as trans (eq 8). Changing the



(8)

acceptor to the γ-siloxy-α,β-unsaturated sulfone **10** (R = Ac, R′ = TBDMS) under conditions identical with those used above gave a 56% yield of four isomeric cycloadducts contaminated with protodesilylated elimination products. Use of the carbonate substrate **10** (n = 1, R = CH_3O_2C, R′ = TBDMS) with the same catalyst gave only elimination products. Gratifyingly, the carbonate substrate using catalyst G gave a 76–82% yield of the

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(26) Larock, R. C.; Dertte, K.; Potter, G. F. *J. Am. Chem. Soc.* **1980**, *102*, 190. We thank Prof. Larock for an authentic sample as well as copies of spectra. The cis:trans equilibrium ratio is 3:1, see: House, H. O.; Rasmusson, A. H. *J. Org. Chem.* **1963**, *28*, 31.

Table II. ^{1}H NMR Chemical Shifts for **29–32** (R = H, ppm)[a]

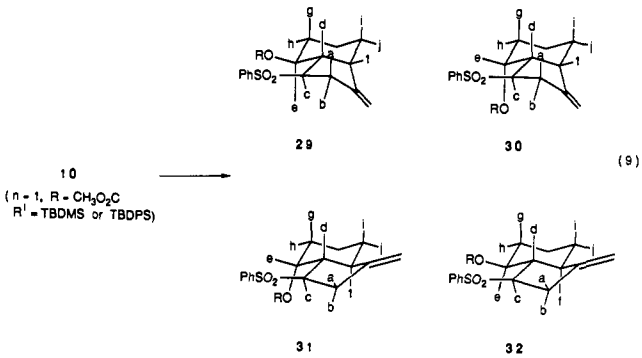
δ	H_a	H_b	H_c	H_d	H_e	H_f
29	2.19	2.97	3.65	2.46	2.77	3.18
30	2.38	2.72	3.71	2.57	3.66	2.84
31	2.08	2.62	3.56	2.03	4.47	2.30
32	2.11	2.44	2.92	1.81	3.46	1.35

[a] Chemical shifts in C_6D_6.

Table III. ^{1}H NMR Coupling Constants for **29–32** (R = H, Hertz)

J	a–b	a–c	b–c	c–d	d–e	d–f	e–g	e–h	f–i	f–j
29	18.0	10.0	4.0	1.8	8.3	6.1	10.4	4.2	small	
30	18.0	10.0	5.7	5.7	7.5	5.6	3.4	4.5	5.7	6.8
31	17.6	10.9	9.1	9.2	2.1	12.2	small		12.0	small
32	17.5	10.0	9.4	9.4	9.6	12.4	9.5	4.5	obscured	

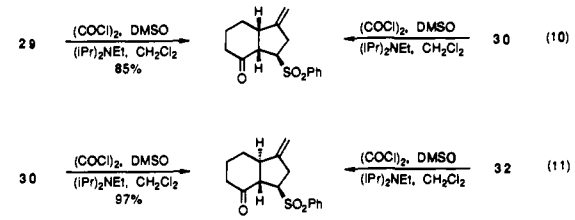
cycloadducts **29–32.** Desilylation with TBAF allowed separation of four product alcohols in 95% yield and a ratio of 4.4:3.0:1.6:1 (eq 9). Use of the TBDPS ether in the substrate led to a somewhat enhanced diastereoselectivity of 9.4:3.5:1.6:1.0 after desilylation.



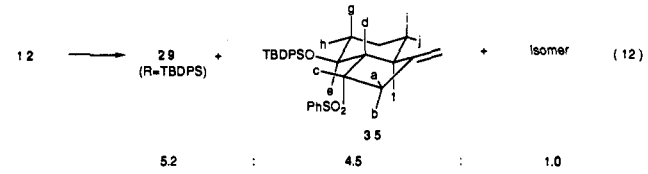
(9)

The dramatic ligand effect on this reaction is surprising. Alkyl- or arylphosphines and aryl phosphites or fluoroalkyl phosphites all resulted in either no reaction or elimination. Other trialkyl phosphites and bis(diphenylphosphino)ferrocene were effective ligands but diastereoselectivities were less than or equal to that with triisopropyl phosphite. Variation of solvent, temperature, and palladium source similarly provided no improvement. Although some cycloadduct could be isolated without the use of BSA, the best results still required the addition of 1 equiv to the reaction mixture, as well as pretreatment of the substrate and reaction vessel with BSA. High pressure and sonication were not effective in promoting cycloaddition.

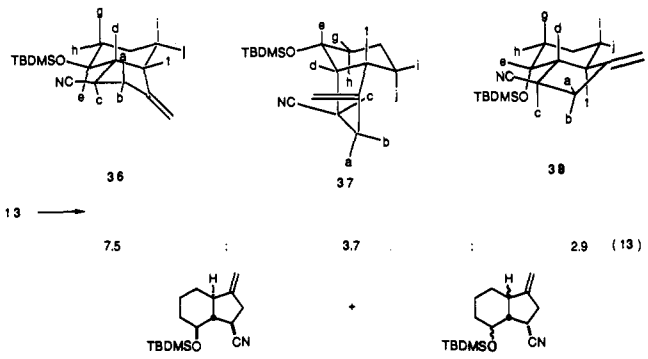
The relative stereochemistry of products **29–32** was determined by ^{1}H NMR spectroscopy, with assignments deriving from decoupling experiments. Chemical shifts and coupling constants for the stereochemically significant signals are displayed in Tables II and III. Starting material olefin stereochemistry was assumed to be maintained, in accord with literature precedent for intermolecular cycloaddition.[27] Coupling constants of 12.2 Hz and 12.4 Hz for H_d–H_f in **31** and **32**, respectively, indicate a trans ring fusion. The values of 6.1 Hz and 5.6 Hz observed for **29** and **30** are more appropriate for cis ring-fused isomers. The relative stereochemistry of the hydroxyl center follows from examination of the chair conformation of the six-membered ring of the product. For conformationally fixed adducts **31** and **32**, only the latter exhibits a coupling constant for H_e (9.5 Hz) that is consistent with a trans diaxial relationship. For adduct **29**, the small coupling constants exhibited by H_f indicate that it must maintain primarily an equatorial orientation. By the same token, two large coupling constants for H_e indicate an axial location, mandating a trans H_e–H_f relationship. Consistent with these assignments is a downfield shift of approximately 1 ppm observed for H_e in **30** and **31**. The phenylsulfonyl unit presumably exerts a deshielding anisotropic effect on H_e when they are placed in a syn orientation. Similar effects have been noted in studies of cyclohexenyl phenyl sulfones.[28] Further confirmation for the stereochemical assignments was obtained by oxidation of the individual alcohols to ketones **33** and **34** (eqs 10 and 11), whose coupling constants of 0.0 Hz and 13.4 Hz for the ring-juncture protons, respectively, suggest the indicated stereochemistry.



Cycloaddition of the cis analogue **12** under conditions similar to those above resulted in a 5.2/4.5/1 mixture of isomers in 67% yield (based on recovered starting material) (eq 12). Surprisingly, the major product was again **29** (R = TBDPS), inseparable from the minor isomer but identified by comparison with spectral data from cycloadditions of **10**. Adduct **35** was separable, and its



stereochemistry was determined from ^{1}H NMR spectral data. A 13.0-Hz coupling constant for H_f–H_d indicates a trans ring juncture, and the two large vicinal couplings for H_e require that it occupy the axial position. Finally, the large downfield shift for H_e (4.95 ppm) and the process of elimination, based on the stereochemistry of **29–32**, require its orientation syn to the vinyl sulfone.[28] The choice of electron-withdrawing group plays no obvious role in these cycloadditions. The cyano analogue **13** underwent cycloaddition in 68% yield to give a 7.5/3.7/2.9/1/1 mixture of diastereomeric products (eq 13), based upon the relative intensities of the *tert*-butyl signals in the ^{1}H NMR spectrum of the initial mixture. The structure of the major cycloadduct **36**

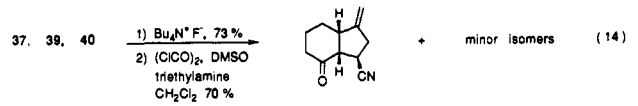


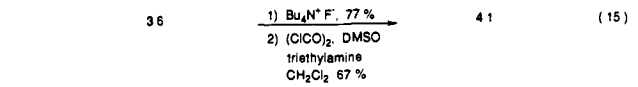
derives from comparison to the major sulfone cycloadduct **29**, specifically (1) a H_d–H_f coupling constant of 6.1 Hz indicating a cis ring fusion, (2) the assumption that the *E* olefin stereochemistry of the starting material is translated to the major products (vide supra), (3) two large (8.2 Hz) coupling constants to H_e, suggesting that this proton is primarily axial and trans diaxial with H_g and H_d, and (4) the absence of large coupling constants to H_f requiring an equatorial assignment, thereby establishing a trans relationship with H_e. Similarly, the structure of **38** derives from analogy to that of **31**: (1) the 12.5-Hz H_d–H_f coupling constant, indicating a trans ring fusion, (2) no large couplings to H_e, consistent with an equatorial designation, (3) a 12.5-Hz H_f–H_i coupling constant requiring a trans diaxial relationship, and thereby establishing a trans relationship between H_f and H_e.

(27) Trost, B. M.; Miller, M. L. *J. Am. Chem. Soc.* **1988**, *110*, 3687.

(28) Schmuff, N. R. Ph.D. Thesis, University of Wisconsin, Madison, WI, 1982.

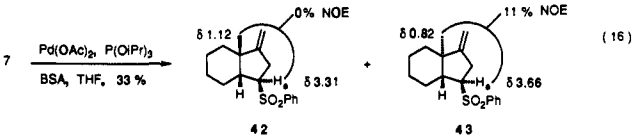
The remaining three isomers could not be separated and were therefore subjected to desilylation and oxidation to provide ketone **41** and a mixture of two other ketones (eq 14). The structure





of **41** was deduced from the 8.0-Hz coupling constant for ^{1}H NMR signals at δ 3.69 and δ 3.09 assigned to the bridgehead protons, and the analogous conversion of **36** into **41** (eq 15). Cycloadduct **37** differs then, from **36**, only in the stereochemistry of the silyloxy group. Additional support for this assignment comes from the single large coupling constant (10 Hz) to H_e for the major isomer in the ^{1}H NMR spectrum of the inseparable mixture of **37**, **39**, and **40**. This implies an axial orientation for H_e, cis to H_d, and with the single large coupling to H_h, further validating the assignment for **36** (vide supra). The remaining cycloadducts could not be fully characterized; however, one is assumed to be **39** by analogy with the sulfone system, and the other must represent a small amount of randomization of the starting olefin geometry or product isomerization.

Incorporating an additional alkyl substituent on the donor fragment of the substrate pushes the system to its limits since intermolecular reactions of 1,1-dialkyl-substituted TMM precursors failed. Tethering such a donor fragment to the acceptor reverses this observation although the cycloadducts were obtained in a more modest 33% yield with substantial production of olefinic byproducts (eq 16). Use of dioxane as solvent and/or higher

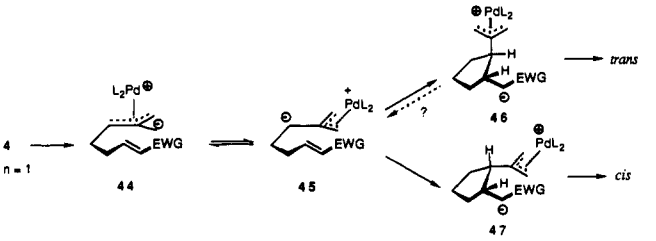


temperatures provided no yield improvement. The stereochemistry of the cycloadducts was deduced from nuclear Overhauser enhancement difference spectroscopy (NOEDS) experiments. Irradiation of the methyl signal at δ 0.82 in the ^{1}H NMR corresponding to the major isomer resulted in an 11% enhancement of the signal at δ 3.31 (dt), assigned therefore as H_a in the trans-fused isomer. Conversely, irradiation of the methyl signal for the minor isomer at δ 1.12 resulted in no enhancement of the signal at δ 3.66 (q), assigned therefore as H_a in the cis isomer. These assignments are again dependent upon the assumption that starting olefin geometry is translated faithfully into product stereochemistry. The 0.30-ppm upfield shift for the angular methyl signal in the ^{1}H NMR of the trans isomer is in qualitative agreement with that observed for the methylhydrindanone system (trans isomer 0.15 ppm upfield),[29] further corroborating the assignment.

Attempted cycloadditions using tethers longer than four methylene groups gave only elimination products. The delicate balance between cycloaddition and elimination becomes evident with the 1,1-disubstituted donor system (cf. eq 16). Extending the use of this donor for reaction with the γ-hydroxy-α,β-unsaturated sulfone led only to trace amounts of cycloadducts. The slight increase in steric hindrance of the acceptor effectively suppressed the cycloaddition.

Discussion

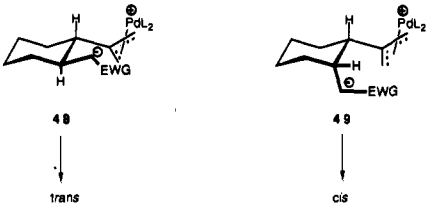
The results of the cyclization studies are in good agreement with the mechanism previously proposed. α,ω-Bifunctional molecules can indeed serve as precursors for the intramolecular trapping of TMM–Pd complexes. Consider the cycloaddition to the bicyclo[3.3.0] system (eq 17). The absence of bridged bicyclic



products indicates that the nucleophilic attack by the TMM–Pd moiety is initiated by the carbon bearing the electron-releasing alkyl side chain. As expected, the equilibration of TMM intermediates, **44** and **45**, precedes the intramolecular cycloaddition. These observations are in accord with the earlier work on the substituted TMM–Pd systems.[30a,b]

The best explanation for the successful cyclization to a bicyclo[3.3.0]octane system is that the initial Michael addition gives a cis-1,2-disubstituted cyclopentane intermediate **47**, which then cyclizes to the observed cis-fused product. The unfavorable 1,2 eclipsing interaction developed in this system is apparently offset by the minimization of charge separation, since this step does involve the conversion of a β-zwitterionic species (the TMM complex) into one with a greater separation of charge (the π-allyl complex and the incipient anion). Collapse of the zwitterionic intermediates should be faster than bond rotation to account for the translation of olefin geometry of the substrates to the ring stereochemistry of the products.[30c] The other interpretation invokes the reversibility of the initial C–C bond formation. Since the ring closure of the corresponding trans intermediate **46** would produce a highly strained product,[31] the process may become so slow that **46** reverses back to the starting material, which eventually forms the more stable cis-fused system via **47**. This seems quite unlikely since carbon leaving groups in retro-Michael additions are rare and often require relief of strain and/or formation of a highly stabilized anion.

The formation of both cis- and trans-fused isomers in the bicyclo[4.3.0]nonane system supports the former explanation. In the intermediate **48** that leads to the trans hydrindan product, placing the π-allyl–Pd complex and the stabilized anion in a diequatorial arrangement minimizes the charge separation and relieves the unfavorable skew interaction that exists in the corresponding cis intermediate **49**. The ratio of the cis to trans hydrindan products (1.5/1 to 2.0/1) suggests that both intermediates are formed in almost equal proportions.[32]



The failure to form bicyclo[5.3.0]decanes and bicyclo[8.3.0]tridecanes also supports the proposed stepwise mechanism, since the initial Michael addition requires the generation of the less favorable seven- and unfavorable ten-membered rings.

The competing formation of trienes and allylic acetates can be attributed to the basicity of the same TMM–Pd intermediates

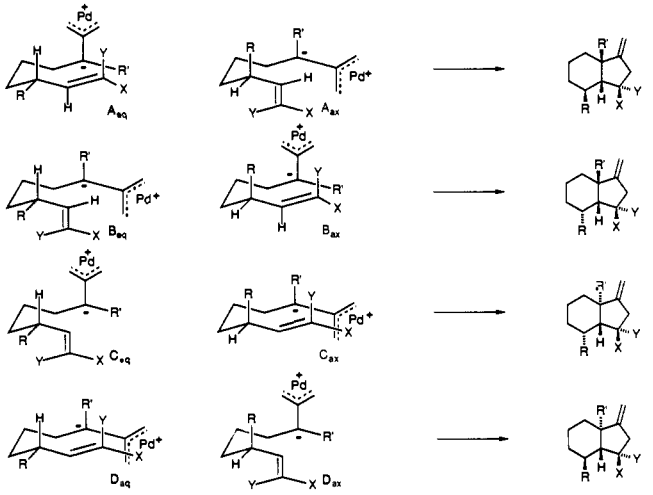
(29) Lansbury, P. T.; Briggs, P. C.; Demmin, T. R.; DuBois, G. E. *J. Am. Chem. Soc.* **1971**, *93*, 1311.

(30) (a) Trost, B. M.; Chan, D. M. T. *J. Am. Chem. Soc.* **1981**, *103*, 5972. (b) Trosi, B. M.; Nanninga, T. N.; Satoh, T. *J. Am. Chem. Soc.* **1985**, *107*, 721. (c) Trost, B. M.; Miller, M. L. *J. Am. Chem. Soc.* **1988**, *110*, 3687.

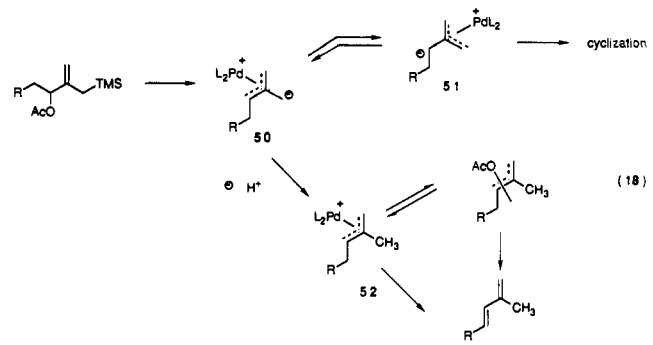
(31) Baneth, J. W.; Linstead, R. P. *J. Chem. Soc.* **1935**, 436. Engler, E. M.; Andose, J. D.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1973**, *95*, 8005. Bailey, W. F.; Khanolkar, A. D. *Tetrahedron Lett.* **1990**, *31*, 5993.

(32) For a discussion of the stereochemistry of intramolecular Michael additions, see: Stork, G.; Winkler, J. D.; Saccomano, N. A. *Tetrahedron Lett.* **1983**, *24*, 465. Stork, G.; Winkler, J.; Shiner, C. *J. Am. Chem. Soc.* **1982**, *104*, 3767. Stork, G.; Shiner, C.; Winkler, J. *J. Am. Chem. Soc.* **1982**, *104*, 310.

Scheme III. Transition States for Cycloaddition of Hydrindan Substrates



50 that produce the cyclized products (eq 18). Instead of equilibrating to the more reactive isomer **51**, this initially formed TMM–Pd complex is protonated to give the π-allyl complex **52**, which then forms the trienes directly or is trapped by the acetate anion.[33] The proton-transfer reaction is very facile since no



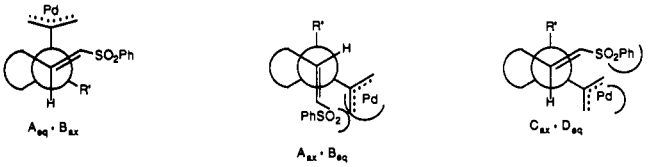
(18)

product derivable from the other TMM–Pd isomer **51** was detected. Thus the proton source must be a relatively acidic one. The facts that the cyclization experiments show a sensitivity toward the purity of substrates and that freshly purified precursors frequently give better yields of the bicyclic products indicate an adventitious proton source may be responsible for the disruption of the cyclization process. This assumption is further supported by the observation that the formation of the triene is suppressed by pretreatment and/or addition of a proton sponge such as BSA. Thus, the apparent inconsistency of the cyclization results could be an artifact of reaction conditions due to the extreme sensitivity of the cycloaddition toward extraneous proton sources.

The characterization of the palladium-catalyzed TMM cycloaddition as a stepwise, but "concerted-like" reaction also provides a framework for rationalizing stereochemical results.[27] The observed stereochemical preferences in the hydrindan series can be explained by the arrangement of the tether in a chairlike conformation (Scheme III). The possibility that the initial cyclization is reversible cannot be ruled out. Under such circumstances, the kinetic conformation preferences are not necessarily dominant. Preference for such retro-Michael reactions involving carbon leaving groups is scant, however, especially in unactivated, strain-free systems.[34] Moreover, the stereochemical outcome does not appear to be based on thermodynamic preferences.

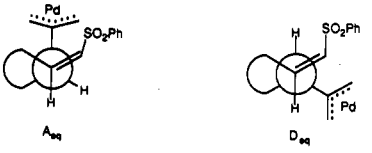
For *E* acceptors in which the olefin geometry is conserved, the relative configurations of all four stereocenters are determined by the initial cyclization. The eight possible chairlike transition states for cycloadditions of substrates leading to the hydrindans are designated as A, B, C, or D and subscripted ax or eq depending upon the orientation of the substitutent R. For **9** (n = 1), R is hydrogen and only four of the transition states are unique.

A cisoid geometry of approach has been implicated in intermolecular TMM cycloadditions,[27,35] and application here serves to disfavor transition states C_{eq} and D_{ax}. For reactions of the (*E*)-vinyl sulfones, Newman projections indicate a destabilizing torsional interaction between the TMM unit and the phenyl sulfone in four of the remaining six transition states. The alternative

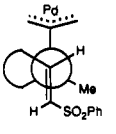


exo arrangement can be utilized to explain the tendency for formation of *cis*-hydrindans through transition states A_{eq} and B_{ax}. Increasing substitution on the tether increases the rigidity of the system, thereby decreasing its ability to relieve the torsional interaction through deformation of the chairlike array, and thereby enhancing the exo preference. The ratio of A adducts to B adducts may then be ascribed to the relative inclination of R to be equatorial. The ratio of C adducts to D adducts is difficult to explain, but if transition states C_{ax} and D_{eq} are completely inhibited, then C_{eq} would predominate over D_{ax} due to the equatorial group R. Alternatively, certain Diels–Alder reactions, in similarly substituted systems, show a preference for axial disposition of the substituent R in endo-selective reactions and equatorial disposition in exo-selective reactions.[1,36] Although the effect is not well-understood, a similar phenomenon may be occurring here.

For the *Z* acceptor **12**, the decreased preference for *cis*-hydrindan formation is understandable since the exo–endo nature of the transition state is reversed. Transition states B and C all encounter severe $A^{1,3}$ interactions between Y and either R or the carbon tether, and products arising from them are minor at best. In view of the above results, it is surprising that transition state A_{eq} competes favorably with D_{eq}. Since the olefin geometry is



scrambled during the reaction, the possibility of isomerization preceding cycloaddition cannot be ignored. Starting material isolated from the reaction mixture was exclusively cis, but since reaction of the trans substrate appears to be considerably more facile, this is not unexpected. The lack of significant quantities of other products from the trans substrate, however, undermines this hypothesis. That there may be additional factors favoring *cis*-hydrindan formation in the absence of the torsional effect is consistent with the cis selectivity, albeit reduced, in the nitrile case where steric effects should be less pronounced. On the other hand, the reversal of selectivity encountered for the bridgehead methyl system implies that steric interactions can overcome this preference. The low yield of this reaction, however, may imply an alternative transition state such as the transoid system.



The reactions outlined herein demonstrate that the intramolecular palladium-catalyzed TMM cycloaddition can be an effective method for the formation of various pentalene and hy-

(33) Cf. Trost, B. M.; Chan, D. M. T. *J. Am. Chem. Soc.* **1983**, *105*, 2326.
(34) Cf. Burgess, K. *J. Org. Chem.* **1987**, *52*, 2046. Shimizu, I.; Ohashi, Y.; Tsuji, J. *Tetrahedron Lett.* **1985**, *26*, 3825.
(35) Trosi, B. M.; Nanninga, T. N. *J. Am. Chem. Soc.* **1985**, *107*, 1075.
(36) Marshall, J. A.; Audia, J. E.; Grote, J.; Shearer, B. J. *Tetrahedron* **1986**, *42*, 2893. Funk, R. L.; Zeller, W. E. *J. Org. Chem.* **1982**, *47*, 180.
(37) Aurich, H. G.; Boutahar, M.; Köbius, K.-D.; Ruiz, L. *Chem. Ber.* **1990**, *123*, 1999.

drindan systems. The ability to achieve moderate ring-juncture selectivity (up to 5:1) with *E* acceptors and good diastereofacial selectivity with *Z* acceptors (9.7 to 1) may have further application. Specifically, the preparation of more highly substituted systems for natural product synthesis would be expected to demonstrate still higher levels of stereocontrol, as is often the case for intramolecular Diels–Alder[1] and diyl-trapping reactions.[9]

Experimental Section

General. All reactions were run under a nitrogen atmosphere in flame-dried glassware unless otherwise indicated. Anhydrous solvents or reaction mixtures were transferred via oven-dried syringe or cannula. The following solvents and reagents were distilled prior to use: ethereal solvents from sodium benzophenone ketyl; toluene and benzene from LAH or sodium metal; DMF from barium oxide; dichloromethane, acid chlorides, *N,O*-bis(trimethylsilyl)acetamide (BSA), amines, triisopropyl phosphite, and triethyl phosphite from calcium hydride. Other solvents were utilized at their commercial level of purity. Palladium acetate was used as provided by the Aldrich Chemical Company. Tris(dibenzylideneacetone)dipalladium, monochloroform complex ($Pd_2dba_3 \cdot CHCl_3$) was prepared by the procedure of Ibers.[38] Flash chromatography, following the method of Still,[39] employed E. Merck silica gel (Kieselgel 60, 200–400 mesh). Analytical thin-layer chromatography was performed with 0.2-mm coated commercial silica gel plates (E. Merck, DC-Plastikfolien, Kieselgel 60 F_{254}). Melting points were obtained on a Thomas-Hoover apparatus in open capillary tubes and are uncorrected. Boiling points are also uncorrected. Kugelrohr distillation was performed in a Büchi GKR-50 glass tube oven. High-pressure reactions were carried out with the assistance of Ms Angela Marquart in facilities located at the University of California-Berkeley.

Proton nuclear magnetic resonance (^1H NMR) data were obtained at 200 MHz on a Bruker WP-200 or a Varian GEM-200, at 300 MHz on a Nicolet NC-300 or a Varian GEM-300, or at 400 MHz on a Varian XL-400 spectrometer. Chemical shifts are reported in delta (δ) units, parts per million (ppm) downfield from tetramethylsilane, or in ppm relative to the singlet at 7.24 ppm for chloroform-d_1. Splitting patterns are designated as: s, singlet; d, doublet; t, triplet, q, quartet; p, pentet; m, multiplet; b, broad. Coupling constants are reported in hertz (Hz). Nuclear Overhauser enhancement difference spectra (NOE) were recorded on a Varian GEM-300 spectrometer. Carbon-13 nuclear magnetic resonance (^{13}C NMR) were obtained at 50 MHz on a JEOL FX-200, at 75 MHz on a Varian GEM-300, at 100 MHz on a Varian XL-400, or at 125 MHz on a Bruker WP-500 spectrometer and are reported in ppm relative to the center line of a triplet at 77.00 ppm for chloroform-d_1. Routine ^{13}C NMR spectra were fully decoupled by broad-band decoupling.

Infrared data were recorded in 0.1-mm path length sodium chloride cavity cells on a Perkin-Elmer 1420 spectrophotometer, and Fourier transform infrared data were obtained on a Nicolet 205 spectrophotometer. Absorbance frequencies are reported in reciprocal centimeters (cm^{-1}), and intensities are designed as (s), strong; (m) medium; (w), weak; (b), broad. Elemental analyses were performed by Spang Microlabs, Eagle Harbor, MI; Galbraith Laboratories, Knoxville, TN; Desert Analytics, Tucson, AZ; or Robertson Laboratories, Madison, NJ. High-resolution mass spectral data (MS) were obtained from the Mass Spectrometry Center, Department of Chemistry, University of Wisconsin–Madison on AE1-MS902, Kratos MS25, or Kratos MS80 spectrometers, or from the Mass Spectrometry Resource, School of Pharmacy, University of California—San Francisco on a Kratos MS9 spectrometer at an ionizing current of 98 mA and an ionizing voltage of 70 eV, and are reported as *m/e* (relative intensity), with accurate mass reported for the molecular ion (M^+) or suitable fragment ions.

2-Bromo-3-(trimethylsllyl)-1-propene. Method A. A solution of methyllithium (lithium bromide complex in ether, 1.25 M, 133 mL, 166 mmol) was added over 10 min at 0 °C to 100 mL of HMPA containing 42 mL (210 mmol) of hexamethyldisilane, and the light yellowish orange-brown solution was stirred for an additional 20 min. THF (330 mL) was added and the reaction mixture turned orange-red in color. Cuprous cyanide (22 g, 246 mmol) was added all at once under a positive pressure of nitrogen. The dark solution was stirred for 45 min at 0 °C and 2,3-dibromopropene (distilled from potassium carbonate, 9.7 mL, 93.5 mmol) was added via a syringe as rapidly as possible. The resultant mixture was stirred for 1 h, diluted with 1.2 L of pentane, and washed with saturated ammonium chloride (500 mL). The aqueous phase (with dark gray gummy solid) was extracted with pentane (300 mL). The combined organic extracts were washed successively with 15% aqueous ammonia (300 mL) and water (5 × 500 mL), and dried over magnesium sulfate. The bulk of the solvent was removed by atmospheric distillation until the pot temperature reached 100 °C. The residue was distilled carefully by using a 15-cm Vigreux column to give unreacted hexamethyldisilane (4.5 g) as a forerun (room temperature to 70 °C, 50 mmHg) and 11.4 g (63% based on dibromopropene) of (2-bromopropenyl)trimethylsilane (bp 82–85 °C, 50–60 mmHg): IR (neat) 1630, 1415, 860 cm^{-1}; NMR (270 MHz, $CDCl_3$) δ 5.41 (m, 1 H), 5.32 (bd, J = 1.5 Hz, 1 H), 2.21 (m, 2 H), 0.22 (s, 9 H); MW calcd for $C_6H_{13}BrSi$ 191.9967, found 191.9960.

Method B. A mixture of 2,3-dibromopropene (61.9 g, 32 mL, 310 mmol) and trichlorosilane (distilled from calcium hydride, 47.4 g, 35.3 mL, 350 mmol) was added dropwise to a mechanically stirred suspension of copper(I) chloride (1.5 g, 15 mmol) in 150 mL of ether containing triethylamine (31.4 g, 43.2 mL, 310 mmol), at a rate-maintaining gentle reflux. A voluminous white precipitate formed, and when addition was complete, the slurry was stirred an additional 6 h. After the mixture was cooled to 0 °C, 467 mL of a 3.0 M solution of methylmagnesium bromide (1.4 mol, 4.5 equiv) in ether was added dropwise, and stirring was continued over a 12-h period. The reaction was quenched carefully with 1 L of saturated aqueous ammonium chloride, the mixture was poured into a mixture of 500 mL of ether and 500 mL of water, and the layers were separated. The organic layer was washed with two 200-mL portions of water and the combined aqueous layers were extracted with two 200-mL portions of ether. The combined organic layers were washed with 500 mL of saturated aqueous sodium chloride, dried over magnesium sulfate, filtered, and concentrated at atmospheric pressure. Distillation of the residue at 46–50 °C (20 mmHg) provided 42.6 g (71%) of the title compound as a clear colorless oil.

[1-[(Trimethylsilyl)methyl]vinyl]magnesium Bromide in THF. Chlorotrimethylsilane (0.25 mL) was added to 2.0 g (82 mg-atom) of magnesium turnings covered by 3 mL of THF. The reaction, initiated by a few crystals of iodine and heating, was allowed to proceed for 1 min. The activated magnesium was washed with THF (5 × 6 mL), and 3 mL of THF was then added. Approximately 0.7 mL of neat (2-bromopropenyl)trimethylsilane and a crystal of iodine were added to initiate the reaction. The rest of the vinyl bromide (4.9 g total, 25 mmol) in 15 mL of THF was added at a rate to maintain a gentle exothermic reaction. The reaction mixture was then heated at reflux for an additional 15 min, cooled, and the supernatant liquid was cannulated into a graduated bottle under nitrogen and diluted to 60 mL. The concentration of this vinylmagnesium solution, determined by titration with *sec*-butyl alcohol/xylene using 2,2'-bipyridyl as an indicator, was found to be 0.325 M; hence the amount of active Grignard reagent was 19.5 mmol (80%). This solution was either used immediately or could be stored in the refrigerator.

Ethyl (*E*)-7-Acetoxy-8-methylene-9-(trimethylsilyl)-2-nonenoate (4a). *tert*-Butyllithium (2.2 M in pentane, 23 mL, 51 mmol) was added to a solution of 4.7 g (24 mmol) of 2-bromo-3-(trimethylsilyl)propene in 52 mL of THF at −78 °C, and the resulting yellow solution was stirred for 45 min and then at −20 °C for 30 min. A solution of magnesium bromide (1.86 M in ether with ca. 5% benzene, 13 mL, 24 mmol) was added and the cloudy mixture was allowed to warm to room temperature over 2 h, after which a homogeneous solution resulted. This Grignard solution was cooled to 0 °C and cannulated into a solution of ethyl (*E*)-7-oxo-2-heptenoate (**3a**, 3.35 g, 19.7 mmol) in 15 mL of THF at −85 °C (liquid nitrogen/THF bath) over a period of 30 min. The reaction mixture was warmed to −70 °C and then inverse quenched into a stirred mixture of ether (600 mL) and 15% aqueous sodium dihydrogen phosphate (200 mL). The organic layer was washed with brine (50 mL) and dried over potassium carbonate. Removal of the solvent under vacuum gave 4.5 g of crude allylic alcohol, which was acetylated without further purification.

To a solution of the crude allylic alcohol, pyridine (7.5 mL, 92 mmol), and DMAP (0.6 g, 5 mmol) in 30 mL of methylene chloride at 0 °C was added acetyl chloride (5.5 mL, 76 mmol). The white cloudy mixture was stirred for 1 h and diluted with 700 mL of ether, washed with saturated sodium bicarbonate (200 mL), water (200 mL), saturated copper sulfate (3 × 200 mL), and water (200 mL), and dried over potassium carbonate. After removal of the solvent in vacuo, the residue was purified by preparative HPLC (10% ether in pentane) to give 2.5 g (40% for the two steps) of the title compound: IR (neat) 1732, 1720, 1651, 1368, 850 cm^{-1}; NMR (270 MHz, $CDCl_3$) δ 6.93 (dt, J = 15.8, 7 Hz, 1 H), 5.81 (dt, J = 15.8, 1.4 Hz, 1 H), 5.10 (t, J = 6.1 Hz, 1 H), 4.85 (m, 1 H), 4.68 (bs, 1 H), 4.18 (q, J = 7.2 Hz, 2 H), 2.21 (bq, J = 7.0 Hz, 2 H), 2.06 (s, 3 H), 1.71–1.39 (m, 4 H), 1.55 (bd of AB, J = 14.2 Hz, 1 H), 1.40 (bd of AB, J = 14.2 Hz, 1 H), 1.28 (t, J = 7.2 Hz, 3 H), 0.04 (s, 9 H); MW calcd for $C_{17}H_{30}O_4Si$ 326.1905, found 326.1902.

(*E*)-3-Acetoxy-8-(phenylsulfonyl)-2-methylene-1-(trimethylsilyl)-7-octene (4b, R = Ac). To a solution of DMSO (2.9 mL, 41 mmol) in 84

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mL of methylene chloride was added oxalyl chloride (1.7 mL, 19 mmol) at −78 °C, followed by a solution of (*E*)-1-(phenylsulfonyl)-1-hexen-6-ol (containing <6% *Z* isomer, 3.6 g, 15 mmol) in 28 mL of methylene chloride. After 40 min of stirring, triethylamine (6.3 mL, 45 mmol) was added and the cloudy mixture was warmed to room temperature over 45 min. Methylene chloride (400 mL) was then added and the solution was washed with water (3 × 150 mL), dried over magnesium sulfate, and concentrated to give 3.6 g of the crude aldehyde **3b**. This sensitive material was carried on to the next step without further purification.

The vinyl sulfone aldehyde was dissolved in 10 mL of THF at −78 °C. A solution of [1-[(trimethylsilyl)methyl]vinyl]magnesium bromide (0.28 M in THF, 75 mL, 21 mmol) was added dropwise over 40 min and the mixture was stirred for 10 min. The reaction was quenched with 150 mL of 5% sodium dihydrogen phosphate at −78 °C and then diluted with 600 mL of ether. The aqueous phase was extracted with ether (100 mL), and the combined ether layers were dried over potassium carbonate and concentrated to give 6.0 g of crude alcohol, which was acetylated without purification.

Acetyl chloride (6.0 mL, 83 mmol) was added dropwise to a solution of the crude alcohol and 0.6 g (5 mmol) of DMAP in 9 mL of pyridine and 35 mL of methylene chloride at ice-bath temperature. The cloudy mixture was stirred for 40 min and diluted with 700 mL of ether, washed with saturated sodium bicarbonate (200 mL), saturated copper sulfate (3 × 150 mL) and water (100 mL), and dried over magnesium sulfate. The crude material after solvent removal was purified by flash chromatography (25% ethyl acetate in hexane) to give 1.3 g (23% overall for the three steps) of the title compound as a viscous oil: IR (neat) 1739, 1642, 1452, 1381, 1154, 1094, 859 cm^{-1}; NMR (270 MHz, $CDCl_3$) δ 7.88 (m, 2 H), 7.65–7.51 (m, 3 H), 6.97 (dt, J = 15.0, 6.8 Hz, 1 H), 6.33 (dt, J = 15.0, 1.4 Hz, 1 H), 5.08 (bt, J = 6.4 Hz, 1 H), 4.83 (bt, J = 1.1 Hz, 1 H), 4.68 (m, 1 H), 2.26 (m, 2 H), 2.06 (s, 3 H), 1.67–1.43 (m, 4 H), 1.53 (dd of AB, J = 14.1, 1 Hz, 1 H), 1.37 (dd of AB, J = 14.1, 1 Hz, 1 H), 0.04 (s, 9 H). Anal. Calcd for $C_{20}H_{30}O_4SSi$: C, 61.72; H, 7.89; MW, 394.1626. Found: C, 61.63; H, 7.92; MW, 394.1635.

(*E*)-3-Acetoxy-9-(phenylsulfonyl)-2-methylene-1-(trimethylsilyl)-8-nonene (4c). To a solution of (*E*)-7-(phenylsulfonyl)-6-hepten-7-al (**3c**, 4.0 g, 15.8 mmol) in 17 mL of THF at −78 °C was added [1-[(trimethylsilyl)methyl]vinyl]magnesium bromide (0.325 M in THF, 58 mL, 18 mmol) dropwise over 35 min. The mixture was stirred for 40 min, quenched with 200 mL of 5% sodium dihydrogen phosphate, and then diluted with 600 mL of ether. The aqueous phase was extracted with ether (100 mL) and the combined organic layers were dried over potassium carbonate and concentrated to give 5.6 g of the crude allylic alcohol, which was not purified.

The alcohol was added to a solution of pyridine (8.0 mL, 98 mmol) and DMAP (0.6 g, 5 mmol) in 35 mL of methylene chloride. Acetyl chloride (5.7 mL, 79 mmol) was then added at 0 °C and the reaction was allowed to proceed for 40 min. Ether (700 mL) was then added and the mixture was washed with saturated sodium bicarbonate (200 mL), saturated copper sulfate (3 × 150 mL) and water (100 mL), and dried over magnesium sulfate. The crude product, obtained on removal of the solvent in vacuo was purified by flash chromatography (25% ethyl acetate in hexane). A total of 1.37 g (22% for two steps) of the title compound was obtained: IR (neat) 1739, 1642, 1452, 1380, 1327, 1153, 1094, 855 cm^{-1}; NMR (270 MHz, $CDCl_3$) δ 7.88 (m, 2 H), 7.64–7.51 (m, 3 H), 6.99 (dt, J = 15.4, 6.7 Hz, 1 H), 6.33 (dt, J = 15.4, 1.4 Hz, 1 H), 5.05 (t, J = 6.6 Hz, 1 H), 4.83 (t, J = 1 Hz, 1 H), 4.67 (m, 1 H), 2.24 (m, 2 H), 2.05 (s, 3 H), 1.68–1.43 (m, 4 H), 1.53 (dd of AB, J = 14.3, 0.8 Hz, 1 H), 1.38 (dd of AB, J = 14.3, 0.8 Hz, 1 H), 1.31 (m, 2 H), 0.04 (s, 9 H). Anal. Calcd for $C_{21}H_{32}O_4SSi$: C, 60.87; H, 7.66; MW, 408.1782. Found: C, 60.98; H, 7.62; MW, 408.1791.

6-[(4-Methoxyphenyl)methoxy]hexanal (5, n = 1, R″ = PMB). A suspension of potassium hydride (24.4 g of 25 wt % suspension, 151 mmol, washed with three 40-mL portions of hexane) in 600 mL of dry THF was treated with a 0.1 M solution of iodine in THF until the yellow color persisted for at least 5 min. 1,6-Hexanediol (15.6 g, 132 mmol) in 200 mL of THF was then added dropwise at 0 °C and the mixture was allowed to warm to room temperature over a period of 40 min. To the resultant slurry, tetrabutylammonium iodide was added (2.3 g, 6.3 mmol), followed by dropwise addition of freshly prepared 4-methoxybenzyl bromide (39.8 g, 198 mmol) in 200 mL of THF. The reaction mixture was stirred overnight, and then quenched carefully with 150 mL of water and diluted with 250 mL of ether. The aqueous layer was separated and washed with two 200-mL portions of ether, the combined organic layers were washed with 100 mL of saturated aqueous sodium chloride, dried over magnesium sulfate, and filtered, and the solvents were removed in vacuo. Flash chromatography (silica gel, 4:1 hexane/ethyl acetate followed by ether) provided 10 g of 6-[(4-methoxyphenyl)methoxy]hexan-1-ol and 5 g of mixed products, which upon rechromatography gave a total of 12.4 g (39%) of the monoprotected alcohol as a yellow oil: IR ($CDCl_3$) 3620, 3460, 1620, 1510 (s), 1300 (s) cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 7.28 (d, J = 9.0 Hz, 2 H), 6.90 (d, J = 9.0 Hz, 2 H), 4.41 (s, 2 H), 3.78 (s, 3 H), 3.61 (t, J = 6.0 Hz, 2 H), 3.42 (t, J = 6.0 Hz, 2 H), 1.25–1.75 (m, 9 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 159.1, 130.7, 129.1, 113.8, 72.4, 70.0, 62.7, 55.2, 32.6, 29.7, 26.0, 25.6; MW calcd for $C_{14}H_{22}O_3$ (M^+) 238.1573, found 238.1569.

Pyridinium chlorochromate (PCC) (15.5 g, 72 mmol) was added to a magnetically stirred slurry of the above alcohol (11.5 g, 48 mmol) and Celite (23.3 g) in 120 mL of methylene chloride, and the brown mixture was stirred at room temperature for 1.5 h. Addition of 100 mL of ether led to the precipitation of a brown material, which was removed by filtration through Celite. The filtrate was dried over magnesium sulfate, filtered, and the solvents were removed in vacuo. Flash chromatography (silica gel, 3:1 hexane/ethyl acetate) gave 8.2 g (72%) of **5** (n = 1, R″ = PMB) as a clear, colorless oil: IR ($CDCl_3$) 2800 (s), 1720 (s), 1610 (s), 1510 (s), 1250 (s) cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 9.73 (t, J = 1.6 Hz, 1 H), 7.28 (d, J = 8.4 Hz, 2 H), 6.90 (d, J = 8.4 Hz, 2 H), 4.40 (s, 2 H), 3.78 (s, 3 H), 3.42 (t, J = 6.4 Hz, 2 H), 2.41 (td, J = 7.2, 1.6 Hz, 2 H), 1.38–1.66 (m, 6 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 202.3, 159.1, 130.6, 129.1, 113.7, 72.5, 69.6, 55.1, 43.7, 29.4, 25.8, 21.8. Anal. Calcd for $C_{14}H_{20}O_3$: C, 71.15; H, 8.53. Found: C, 70.96; H, 8.47.

8-[(4-Methoxyphenyl)methoxy]-3-[(methoxycarbonyl)oxy]-2-[(trimethylsilyl)methyl]-1-octene (6, n = 1, R = CH_3O_2C, R″ = PMB). A 1.63 M solution of *tert*-butyllithium (16.1 mL, 26.2 mmol) was added via syringe to a solution of bromide **1** (3.5 g, 18.3 mmol) in 40 mL of ether at −78 °C. The mixture was stirred at that temperature for 45 min, and then at 0 °C for 1 h. The above aldehyde (3.1 g, 13.1 mmol) was added slowly and stirring was continued at 0 °C for an additional 1 h. The reaction was then quenched with methyl chloroformate (2.5 g, 2.0 mL, 26.2 mmol) while warming to room temperature over a period of 1.5 h. After addition of 200 mL of ether, the mixture was washed carefully with 100 mL of saturated aqueous sodium bicarbonate. The aqueous layer was extracted with two 50-mL portions of ether, the combined organic layers were washed with 50 mL of saturated aqueous sodium chloride, dried over sodium sulfate, and filtered, and the solvents were removed in vacuo. Flash chromatography (silica gel, 10:1 hexane/ether) gave 4.26 g (80%) of the title compound as a clear, colorless oil: IR ($CDCl_3$) 1750, 1730, 1610, 1510, 1440, 1270 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 7.23 (d, J = 8.7 Hz, 2 H), 6.85 (d, J = 8.7 Hz, 2 H), 4.88–4.92 (m, 2 H), 4.69 (d, J = 0.7 Hz, 1 H), 4.40 (s, 2 H), 3.78 (s, 3 H), 3.74 (s, 3 H), 3.40 (t, J = 6.4 Hz, 2 H), 1.33–1.65 (m, 10 H), 0.03 (s, 9 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 159.1, 155.3, 144.7, 130.8, 129.1, 113.8, 109.5, 81.4, 72.5, 70.0, 55.2, 54.5, 33.0, 29.6, 26.0, 25.2, 22.2, −1.2. Anal. Calcd for $C_{22}H_{36}O_5Si$: C, 64.66; H, 8.88. Found: C, 64.66; H, 8.91.

3-Acetoxy-2-[(trimethylsilyl)methyl]-1-octen-8-ol (7, n = 1, R = Ac). Dichlorodicyanobenzoquinone (DDQ) (3.5 g, 15.4 mmol) was added to a solution of **6** (R = CH_3O_2C, R″ = PMB) (5.5 g, 14 mmol) in 70 mL of methylene chloride containing 3.7 mL of water. The mixture was stirred for 45 min. When the starting material was consumed as shown by TLC, 150 mL of ether was added and the mixture washed with 100 mL of water. The aqueous layer was extracted with two 40-mL portions of ether, and the combined organic layers were washed with sodium bisulfite solution (35 g of $NaHSO_3$, 90 mL of water, 33 mL of ethanol) followed by 100 mL of saturated aqueous sodium chloride. After drying over potassium carbonate and filtration, the solvents were removed in vacuo. Flash chromatography (silica gel, 3:1 hexane/ether, 1% triethylamine, followed by ether) gave 3.5 g of the title compound (92%) as a clear, colorless oil: IR ($CDCl_3$) 3610, 3460, 1740, 1370, 1250 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 5.06 (t, J = 6.3 Hz, 1 H), 4.81 (t, J = 1.1 Hz, 1 H), 4.64 (s, 1 H), 3.58 (t, J = 6.4 Hz, 2 H), 2.02 (s, 3 H), 1.26–1.67 (m, 11 H), 0.03 (s, 9 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 170.2, 145.1, 109.0, 77.0, 62.6, 32.9, 32.5, 25.4, 25.2, 22.5, 21.2, −1.2. Anal. Calcd for $C_{14}H_{28}O_3Si$: C, 61.71; H, 10.36. Found: C, 61.42; H, 10.23.

3-[(Methoxycarbonyl)oxy]-2-[(trimethylsilyl)methyl]-1-octen-8-ol (7, n = 1, R = CH_3O_2C). Method A. The title alcohol was prepared from **6** (R = CH_3O_2C, R″ = PMB) by the procedure described above on a 10.3-mmol scale. Flash chromatography (silica gel, 2:1 hexane/ether) gave 2.8 g (94%) of the alcohol as a light pink oil: IR ($CDCl_3$) 3610, 1740, 1450, 1270 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 4.90 (t, J = 5.5 Hz, 1 H), 4.87 (t, J = 1 Hz, 1 H), 4.68 (d, J = 0.9 Hz, 1 H), 3.79 (s, 3 H), 3.60 (t, J = 6.1 Hz, 2 H), 1.3–1.7 (m, 11 H), 0.02 (s, 9 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 155.4, 144.8, 109.6, 81.4, 62.8, 54.5, 33.1, 32.6, 25.5, 25.1, 22.2, −1.2; MW calcd for $C_{12}H_{25}OSi$ $(M - OCO_2CH_3)^+$ 213.1675, found 213.1655.

Method B. Silyl ether **6** (R = CH_3O_2C, R″ = TBDMS) was prepared from aldehyde **5** (R″ = TBMDS) by the procedure described for **6** (R = CH_3O_2C, R″ = PMB) on a 39-mmol scale. Crude adduct (39 mmol) was dissolved in 200 mL of THF and treated with 52 mL of 1 N sulfuric acid. After 2 h, the mixture was diluted with 300 mL of ether and washed with 100 mL of water. The aqueous layer was washed with two

50-mL portions of ether and the combined organic extracts were dried over magnesium sulfate, filtered, and the solvents removed in vacuo to yield 7.15 g of the title compound (64%).

3-[(Methoxycarbonyl)oxy]-2-[(trimethylsilyl)methyl]-1-octen-8-al (8, n = 1, R = CH_3O_2C). Method A. A solution of DMSO (0.86 g, 0.75 mL, 11 mmol) in 33 mL of methylene chloride was cooled to −78 °C and treated dropwise with oxalyl chloride (0.75 g, 516 μL, 5.9 mmol). After the solution was stirred for 10 min at this temperature, alcohol **7** (n = 1, R = CH_3O_2C) (1.54 g, 4.9 mmol) was added slowly. The alcohol dissolved only very slowly at this temperature, and vigorous stirring was required. When dissolution was complete, the mixture was stirred an additional 15 min and triethylamine (1.4 g, 1.9 mL, 13.7 mmol) was added. The mixture was allowed to warm to room temperature, diluted with 200 mL of ether, and washed successively with 150 mL of water, 150 mL of saturated aqueous copper(II) sulfate, and 100 mL of water. After drying over potassium carbonate and filtration, the solvents were removed in vacuo. Flash chromatography (silica gel, 5:1 hexane/ether) gave 1.18 g (84%) of the title compound as a clear, colorless oil: IR ($CDCl_3$) 2740, 1750, 1730, 1450, 1280 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 9.71 (t, J = 1.6 Hz, 1 H), 4.88 (t, J = 6.3 Hz, 1 H), 4.86 (d, J = 0.9 Hz, 1 H), 3.72 (s, 3 H), 2.40 (td, J = 7.4, 1.6 Hz, 2 H), 1.3–1.7 (m, 8 H), 0.01 (s, 9 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 202.2, 155.2, 144.4, 109.6, 81.0, 54.6, 43.7, 32.7, 24.9, 22.1, 21.8, −1.3. Anal. Calcd for $C_{14}H_{26}O_4Si$: C, 58.70; H, 9.15. Found: C, 58.79; H, 9.08.

Method B. PCC (259 mg, 1.2 mmol) was added to a slurry of alcohol **7** (n = 1, R = CH_3O_2C) (200 mg, 0.69 mmol) and Celite (390 mg) in 6 mL of wet methylene chloride. The orange slurry rapidly darkened and was stirred vigorously until the reaction was complete as shown by TLC. A 6-mL portion of ether and powdered sodium sulfate was added and the slurry was stirred an additional 15 min. The mixture was filtered through a plug of silica gel eluting with ether, and the eluents were dried over sodium sulfate, filtered, and the solvent removed in vacuo to yield 159 mg of the title compound (81%).

(*E*)-1-(Phenylsulfonyl)-7-[(methoxycarbonyl)oxy]-8-[(trimethylsilyl)methyl]-1,8-nonadiene (9, n = 1, R = CH_3O_2C). Diethyl (phenylsulfonyl)methylphosphonate[19] (178 mg, 0.61 mmol) in 1.0 mL of THF was added slowly to a solution of sodium bis(trimethylsilyl)amide (103 mg, 0.56 mmol) in 4.5 mL of THF at −78 °C. The mixture was stirred at that temperature for 1 h and aldehyde **8** (R = CH_3O_2C) (159 mg, 0.56 mmol) in 1.0 mL of THF was added slowly. After an additional 45 min at −78 °C, the mixture was diluted with 15 mL of ether and quenched with 5 mL of saturated aqueous ammonium chloride. The organic layer was washed with 5 mL of water, and the aqueous layers were extracted with 5 mL of ether. The combined organic extracts were dried over sodium sulfate and filtered, and the solvents were removed in vacuo. Flash chromatography (silica gel, 2:1 hexane/ether) gave 173 mg (73%) of the title compound as a clear, colorless oil: IR ($CDCl_3$) 1740, 1630, 1490, 1420, 1310, 1080, 850 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.84 (dd, J = 7.0, 1.5 Hz, 2 H), 7.59 (tt, J = 7.4, 1.3 Hz, 1 H), 7.51 (td, J = 7.1, 1.5 Hz, 2 H), 6.95 (dt, J = 15.1, 6.9 Hz, 1 H), 6.28 (dt, J = 15.1, 1.5 Hz, 1 H), 4.86 (t, J = 6.1 Hz, 1 H), 4.85 (s, 1 H), 4.67 (d, J = 0.9 Hz, 1 H), 3.73 (s, 3 H), 2.21 (qd, J = 7.3, 1.4 Hz, 2 H), 1.62 (q, J = 7.5 Hz, 2 H), 1.4–1.5 (m, 2 H), 1.52 (d, J = 15.1 Hz, 1 H), 1.35 (d, J = 15.1 Hz, 1 H), 1.2–1.4 (m, 2 H), 0.01 (s, 9 H); ^{13}C NMR (100 Hz, $CDCl_3$) δ 155.2, 146.7, 144.4, 140.6, 133.2, 130.4, 129.2, 127.5, 109.5, 80.9, 54.6, 32.5, 31.3, 27.3, 24.7, 22.0, −1.3; MW calcd for $C_{20}H_{29}O_5SSi$ $(M - CH_3)^+$ 409.1505, found 409.1490. Anal. Calcd for $C_{21}H_{32}O_5SSi$: C, 59.39; H, 7.61. Found: C, 59.73; H, 7.80.

(*E*)-1-(Phenylsulfonyl)-3-[(*tert*-butyldimethylsilyl)oxy]-7-acetoxy-8-[(trimethylsilyl)methyl]-1,8-nonadiene (10, n = 1, R = Ac, R′ = TBDMS). Aldehyde **8** (n = 1, R = Ac) (600 mg, 2.2 mmol) in 1 mL of acetonitrile was added slowly to a solution of [(*p*-chlorophenyl)sulfinyl](phenylsulfonyl)methane (692 mg, 2.2 mmol) and piperidine (187 mg, 218 μL, 2.2 mmol) in 4 mL of acetonitrile. The mixture was stirred at room temperature until reaction was complete (1 h), and then diluted with 40 mL of ether and washed with 20 mL of water. The aqueous layer was extracted with an additional 10 mL of ether, and the combined organic layers were washed with 10 mL of 10% aqueous sodium hydroxide. After drying over magnesium sulfate and filtration, the solvents were removed in vacuo.

The crude alcohol was dissolved in 5 mL of DMF and treated sequentially with imidazole (300 mg, 4.4 mmol), DMAP (49 mg, 0.4 mmol), and *tert*-butyldimethylsilyl chloride (663 mg, 4.4 mmol). After stirring for 2 h, the reaction was quenched with 20 mL of water and extracted with 20 mL of ether. The aqueous layer was extracted with an additional 10 mL of ether and the combined organic layers were washed with 10 mL of saturated aqueous sodium chloride. After drying over sodium sulfate and filtration, the solvent was removed in vacuo. Flash chromatography (silica gel, 4:1 hexane/ether, 1% triethylamine) followed by rechromatography of the mixed fractions (5:1 hexane/ether) gave a viscous oil that was contaminated with *tert*-butyldimethylsilyl chloride. Treatment under high vacuum (<0.05 mmHg) overnight yielded 1.01 g (85%) of pure title compound as a mixture of diastereomers: IR ($CDCl_3$) 1720, 1630, 1370, 1310, 1240 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 7.48–7.87 (m, 5 H), 6.93 (dd, J = 14.8, 4.0 Hz, 1 H), 6.46 (dd, J = 14.8, 1.7 Hz, 1 H), 5.04 (t, J = 6.2 Hz, 1 H), 4.80 (s, 1 H), 4.65 (s, 1 H), 4.31 (m, 1 H), 2.02 (s, 3 H), 1.23–1.60 (m, 8 H), 0.81 (s, 9 H), 0.02 (s, 9 H), −0.02 (s, 3 H), −0.12 (s, 3 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 170.0 (2), 148.6 (2), 144.8 (2), 140.5 (2), 133.2, 129.8, 129.7, 127.4 (2), 129.1, 109.2, 109.1, 76.6 (2), 70.7 (2), 36.6, 36.5, 32.8, 32.6, 25.7, 22.5, 22.4, 21.2, 20.8 (2), 18.1, −1.2, −4.8, −5.0. Anal. Calcd for $C_{27}H_{46}O_5SSi_2$: C, 60.17; H, 8.60; S, 5.95. Found: C, 60.11; H, 8.65; S, 5.91.

(*E*)-1-(Phenylsulfonyl)-3-[(*tert*-butyldimethylsilyl)oxy]-7-[(methoxycarbonyl)oxy]-8-[(trimethylsilyl)methyl]-1,8-nonadiene (10, n = 1, R = CH_3O_2C, R′ = TBMDS). The title compound was prepared on a 4.1-mmol scale from aldehyde **8** (R = CH_3O_2C) by the method described above. Flash chromatography (silica gel, 6:1 hexane/ether, two passes) gave 1.46 g (64%) of the product mixture of diastereomers as a viscous yellow oil: IR ($CDCl_3$) 1750, 1630, 1450, 1280 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 7.2–7.9 (m, 5 H), 6.91 (dd, J = 14.8, 4 Hz, 1 H), 6.45 (dd, J = 14.8, 1.6 Hz, 1 H), 4.86 (t, J = 6 Hz, 1 H), 4.84 (s, 1 H), 4.67 (s, 1 H), 4.30 (m, 1 H), 3.72 (s, 3 H), 1.3–1.7 (m, 8 H), 0.79 (s, 9 H), 0.01 (s, 9 H), −0.04 (d, J = 1.3 Hz, 3 H), −0.13 (s, 3 H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 154.9, 148.3, 144.2 (2), 140.4, 133.0, 129.7, 129.0, 127.2, 109.4, 109.3, 80.6, 70.5 (2), 54.3, 36.3 (2), 32.6, 32.5, 25.5, 22.0, 21.9, 20.5, 20.4, 17.8, −1.4, −5.0, −5.2. Anal. Calcd for $C_{27}H_{46}O_6SSi_2$: C, 58.44; H, 8.36; S, 5.78. Found: C, 58.27; H, 8.35; S, 5.68.

(*E*)-1-(Phenylsulfonyl)-3-[(*tert*-butyldiphenylsilyl)oxy]-7-[(methoxycarbonyl)oxy]-8-[(trimethylsilyl)methyl]-1,8-nonadiene (10, n = 1, R = CH_3O_2C, R′ = TBDPS). Crude alcohol **10** (R = CH_3O_2C, R′ = H) (365 mg, 0.83 mmol) was dissolved in 1 mL of DMF and treated sequentially with imidazole (136 mg, 2.0 mmol), *tert*-butyldiphenylsilyl chloride (275 mg, 260 μL, 1.0 mmol), and DMAP (12.7 mg, 0.1 mmol). The resulting solution was stirred at 40 °C for 4 h, diluted with 10 mL of ether, and washed with 10 mL of water. The aqueous layer was extracted with 10 mL of ether, the combined organic layers were washed with 10 mL of saturated aqueous sodium chloride, dried over sodium sulfate, and filtered, and the solvent was removed in vacuo. Flash chromatography (silica gel, 4:1 hexane/ether) gave 403 mg (72%) of the title compound mixture of diastereomers as a clear, colorless oil: IR ($CDCl_3$) 1740, 1630, 1440, 1420, 1270, 1140, 1110, 1080 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.27–7.8 (m, 15 H), 6.84 (2 dd, J = 14.8, 5.1 Hz, 1 H), 6.29 (2 dd, J = 14.8, 1.4 Hz, 1 H), 4.81 (s, 1 H), 4.79 (t, J = 6.2 Hz, 1 H), 4.66 (s, 1 H), 4.28 (p, J = 6 Hz, 1 H), 3.74 (2 s, 3 H), 1.11–1.70 (m, 8 H), 1.00 (s, 9 H), 0.06 (s, 9 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 155.4, 147.9, 147.8, 144.6, 144.5, 140.7, 135.9, 135.8, 133.4, 133.2, 130.4, 130.1, 130.0, 129.4, 127.8, 127.7, 109.8, 80.9, 80.8, 71.7 (2), 54.5, 36.1, 36.0, 32.5 (2), 26.7, 21.8, 19.8, 19.7, 19.0, −1.6. Anal. Calcd for $C_{37}H_{50}O_6SSi_2$: C, 65.43; H, 7.44; MW, 678.2867. Found: C, 65.87; H, 7.51; MW, 678.2848.

(*E*)-1-(Phenylsulfonyl)-7-[(methoxycarbonyl)oxy]-8-[(trimethylsilyl)methyl]-1,8-nonadien-3-one (11E). A solution of DMSO (562 mg, 505 μL, 7.2 mmol) in 23 mL of methylene chloride was cooled to −78 °C and treated dropwise with oxalyl chloride (520 mg, 358 μL, 4.1 mmol). After 10 min of stirring at this temperature, alcohol **9** (R = CH_3O_2C, R′ = H) (1.5 g, 3.4 mmol) in 2 mL of methylene chloride was added slowly. When addition was complete, the mixture was stirred an additional 15 min and triethylamine (995 mg, 1.38 mL, 4.9 mmol) was added. The mixture was allowed to warm to room temperature, diluted with 70 mL of ether, and washed successively with 70 mL of water, 70 mL of saturated aqueous copper(II) sulfate, and 70 mL of water. After drying over potassium carbonate and filtration, the solvents were removed in vacuo to yield 1.32 g (94%) of a yellow oil that was used without further purification. Analytical samples and samples for palladium reactions were purified by flash chromatography (silica gel, 2:1 hexane/ether): IR ($CDCl_3$) 1740, 1700, 1630, 1440, 1320, 1270, 1150, 1080, 850 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.90 (d, = 7.0 Hz, 2 H), 7.67 (t, J = 7.0 Hz, 1 H), 7.57 (t, J = 7.8 Hz, 2 H), 7.14 (d, J = 14.0 Hz, 1 H), 6.92 (d, J = 14.0 Hz, 1 H), 4.90 (m, 1 H), 4.89 (s, 1 H), 3.75 (s, 3 H), 2.64 (m, 2 H), 1.67 (m, 4 H), 1.54 (d, J = 14.0 Hz, 1 H), 1.36 (d, J = 14.0 Hz, 1 H), 0.3 and 0.6 (2 s, 9 H); MW calcd for $C_{19}H_{26}O_3SSi$ (M = $HOCO_2CH_3)^+$ 362.1372, found 362.1377.

(*Z*)-(1-Phenylsulfonyl)-7-[(methoxycarbonyl)oxy]-8-[(trimethylsilyl)methyl]-1,8-nonadien-3-one (11Z). A water-cooled, quartz immersion well-reaction vessel was charged with a solution of the above *E* ketone **10** (857 mg, 2.0 mmol) in 40 mL of carbon tetrachloride containing calcium carbonate (100 mg). The stirred solution was photolyzed for 2 h with a 450-W Hanovia immersion lamp, and the entire system was cooled with a room temperature water bath. The solvent was removed

in vacuo and the residue was subjected to flash chromatography (silica gel, 1:1 hexane/ether) to give 487 mg of *Z* ketone **11Z** (67%) and 128 mg of recovered *E* enone **11E**: IR ($CDCl_3$) 1740, 1710, 1440, 1320, 1310, 1270, 1150, 1080, 890 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.92 (d, J = 7.8 Hz, 2 H), 7.64 (t, J = 7.4 Hz, 1 H), 7.55 (t, J = 7.6 Hz, 2 H), 6.58 (dd, J = 11.7, 1.4 Hz, 1 H), 6.37 (d, J = 11.7 Hz, 1 H), 4.94 (m, 1 H), 4.91 (s, 1 H), 4.71 (s, 1 H), 3.75 (s, 3 H), 2.79 (m, 2 H), 1.74 (m, 4 H), 1.56 (d, J = 14.2 Hz, 1 H), 1.42 (d, J = 14.2 Hz, 1 H), 0.03 (s, 9 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 202.2, 155.2, 144.3, 141.3, 139.2, 134.0, 132.5, 129.4, 128.2, 109.6, 80.9, 54.6, 42.8, 32.0, 22.1, 18.7, −1.3; MW calcd for $C_{21}H_{30}O_6SSi$ (M^+) 438.1532, found 438.1488.

(*Z*)-1-(Phenylsulfonyl)-3-[(*tert*-butyldiphenylsilyl)oxy]-7-[(methoxycarbonyl)oxy]-8-[(trimethylsilyl)methyl]-1,8-nonadiene (12). A stirred solution of *Z* enone **11Z** (462 mg, 1.05 mmol) in 5 mL of methanol containing cerium(III) chloride heptahydrate (391 mg, 1.05 mmol) was treated with sodium borohydride (39.9 mg, 1.05 mmol) and the mixture was stirred for 10 min. The reaction was quenched with 5 mL of water, and the mixture was extracted with three 5-mL portions of ether. The combined organic layers were dried over sodium sulfate and filtered, and the solvents were removed in vacuo to give 443 mg (96%) of the crude alcohol.

The crude product was dissolved in 5 mL of DMF and treated sequentially with imidazole (218 mg, 3.2 mmol), DMAP (25.4 mg, 0.2 mmol), and *tert*-butyldiphenylsilyl chloride (440 mg, 416 μL, 1.6 mmol). The reaction was heated at 50 °C for 12 h and then quenched with 25 mL of water. The aqueous mixture was extracted with 40 mL of ether, followed by 25 mL of ether, the combined organic layers were dried over sodium sulfate and filtered, and the solvent was removed in vacuo. Flash chromatography (silica gel, 4:1 hexane/ether) yielded 461 mg of the title compound (65% overall) as a 1/1 mixture of diastereomers as a viscous oil: IR ($CDCl_3$) 1740, 1630, 1480, 1270, 1140, 1100, 1080 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.2–7.7 (m, 15 H), 6.16 (2, dd, J = 8.5, 3.5 Hz, 1 H), 5.87 (dd, J = 8.5, 3.5 Hz, 1 H), 5.49 (m, 1 H), 4.89 (m, 1 H), 4.88 (s, 1 H), 4.68 (s, 1 H), 3.74 (s, 1.5 H), 3.73 (s, 1.5 H), 1.2–1.7 (m, 8 H), 1.00 (s, 9 H), 0.03 (s, 9 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 155.3, 149.0, 144.6, 144.5, 140.6, 135.8, 135.7, 135.6, 133.7, 133.3, 129.8, 129.7, 129.1, 127.7, 127.5, 127.3, 127.1, 109.6, 109.5, 81.3, 81.2, 68.4, 54.5, 38.1, 38.0, 33.0, 32.9, 26.9, 22.0, 20.6, 20.4, 19.2, −1.3. Anal. Calcd for $C_{37}H_{50}O_6SSi_2$: C, 65.43; H, 7.94. Found: 65.34; H, 7.67.

(*E*)-1-Cyano-3-[(*tert*-butyldimethylsilyl)oxy]-7-[(methoxycarbonyl)oxy]-8-[(trimethylsilyl)methyl]-1,8-nonadiene (13). Aldehyde **8** (n = 1) (584 mg, 2.0 mmol) in 2 mL of acetonitrile was added slowly to a solution of [(*p*-chlorophenyl)sulfinyl]acetonitrile (461 mg, 2.1 mmol) and piperidine (182 mg, 213 μL, 2.1 mmol) in 8 mL of acetonitrile. The mixture was stirred at room temperature until the reaction was complete (1 h), and then diluted with 50 mL of ether and washed with 25 mL of water. The aqueous layer was extracted with an additional 75 mL of ether, and the combined organic layers were washed with 15 mL of 10% aqueous sodium hydroxide. After drying over magnesium sulfate and filtration, the solvents were removed in vacuo.

The crude alcohol was dissolved in 3 mL of DMF and treated sequentially with imidazole (317 mg, 4.7 mmol), DMAP (38.2 mg, 0.3 mmol), and *tert*-butyldimethylsilyl chloride (467 mg, 3.1 mmol). The mixture was heated at 60 °C for 4.25 h, with the addition of more portions of imidazole (317 mg, 4.7 mmol) and *tert*-butyldimethylsilyl chloride (467 mg, 3.1 mmol) after each 2-h period. The reaction was quenched with 50 mL of water, and the aqueous layer was extracted with two 50-mL portions of ether. The combined organic layers were washed with 25 mL of saturated aqueous sodium chloride, dried over sodium sulfate, treated with activated carbon, and filtered through Celite. The solvents were removed in vacuo and the residue was purified by flash chromatography (silica gel, 20:1 hexane/ether) to give 525 mg (59%) of the title compound as a 1/1 mixture of diastereomers: IR ($CDCl_3$) 2220, 1740, 1630, 1440 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 6.71 (dd, J = 16.0, 3.7 Hz, 1 H), 5.56 (d, J = 16.1 Hz, 1 H), 4.88 (m, 2 H), 4.70 (s, 1 H), 4.26 (m, 1 H), 3.75 (s, 3 H), 1.2–1.7 (m, 8 H), 0.87 (s, 9 H), 0.02 (s, 12 H), 0.00 (s, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.1, 155.3, 144.3, 117.5, 109.8, 109.7, 98.6, 80.9, 71.3, 54.6, 36.5, 36.4, 32.8 (2), 25.7, 22.2, 22.1, 20.6, 20.4, 18.1, −1.3, −4.8, −5.0; MW calcd for $C_{22}H_{41}NO_4Si_2$ (M^+) 439.2574, found 439.2587. Anal. Calcd for $C_{22}H_{41}NO_4Si_2$: C, 60.07; H, 9.42; N, 3.19. Found: C, 60.33; H, 9.54; N, 3.24.

8-[(*tert*-Butyldimethylsilyl)oxy]-2-[(trimethylsilyl)methyl]-1-octen-3-one (14). A solution of DMSO (15.4 g, 1.41 mL, 19.8 mmol) in 52 mL of methylene chloride was cooled to −78 °C, treated with oxalyl chloride (1.36 g, 0.94 mL, 10.8 mmol), and stirred for 10 min. A solution of crude alcohol **6** (R = H, R″ = TBDMS) (3.0 g, 8.5 mmol) in 8 mL of methylene chloride was added slowly and, after an additional 15 min, triethylamine (2.55 g, 3.51 mL, 25.2 mmol) was added. The mixture was allowed to warm to room temperature, diluted with 250 mL of ether, and washed with 150 mL of water, 150 mL of saturated aqueous copper(II) sulfate, and 100 mL of water. The organic layer was dried over potassium carbonate, filtered, and the solvents were removed in vacuo. Flash chromatography (silica gel, 50:1 hexane/ether) yielded 2.1 g (72%) of the title compound as a yellow oil: IR ($CDCl_3$) 1680, 1620, 1470, 1410, 1370 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.82 (s, 1 H), 5.53 (s, 1 H), 3.57 (t, J = 6.5 Hz, 2 H), 2.66 (t, J = 7.5 Hz, 2 H), 1.77 (s, 2 H), 1.59 (p, J = 7.6 Hz, 2 H), 1.51 (p, J = 7.4 Hz, 2 H), 0.86 (s, 9 H), 0.01 (s, 6 H), −0.07 (s, 9 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 201.8, 147.0, 121.0, 63.0, 37.2, 32.7, 26.0, 25.6, 24.7, 21.0, 18.3, −1.6, −5.3; MW calcd for $C_{18}H_{38}O_2Si_2$ (M^+) 342.2411, found 342.2399.

3-[(Methoxycarbonyl)oxy]-3-methyl-2-[(trimethylsilyl)methyl]-1-octen-8-ol (15). A 1.5 M solution of methyllithium–lithium bromide complex in ether (10.7 mL, 16 mmol) was added via syringe to ketone **14** (2.72 g, 8.0 mmol) stirring in 13 mL of ether at 0 °C. After 30 min at this temperature, the reaction was quenched with methyl chloroformate (3.41 g, 2.86 mL, 28.8 mmol) and the mixture was allowed to warm to room temperature over 1.5 h. A 75-mL portion of ether was added, and the mixture was washed with 50 mL of water. The aqueous layer was extracted with two 25-mL portions of ether, the combined organic layers were dried over sodium sulfate and filtered, and the solvents were removed in vacuo.

The crude carbonate was dissolved in 40 mL of THF and treated with 1 N sulfuric acid (10 mL) for 2 h. The mixture was diluted with 80 mL of ether and washed with 50 mL of water. The aqueous layer was extracted with two 50-mL portions of ether, the combined organic layers were dried over sodium sulfate and filtered, and the solvents were removed in vacuo. Flash chromatography (silica gel, 1:1 hexane/ether) yielded 1.57 g (65%) of the title compound as a clear colorless oil: IR ($CDCl_3$) 3600, 1740, 1630, 1440, 1370 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 4.91 (s, 1 H), 4.81 (s, 1 H), 3.69 (s, 3 H), 3.61 (q, J = 6.6 Hz, 2 H), 1.7–1.9 (m, 2 H), 1.56 (s, 3 H), 1.54 (d, J = 10.7 Hz, 2 H), 1.50 (d, J = 16.0 Hz, 1 H), 1.44 (d, J = 16.0 Hz, 1 H), 1.2–1.4 (m, 4 H), 1.17 (t, J = 7 Hz, 1 H), 0.05 (s, 3 H), 0.04 (s, 6 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 153.7, 148.1, 109.5, 87.2, 62.8, 54.0, 38.4, 32.6, 25.9, 23.5, 22.7, 19.9, 1.0, −0.7; MW calcd for $C_{13}H_{26}OSi$ ($M - CH_3OCO_2H$)$^+$ 226.1752, found 226.1759.

3-[(Methoxycarbonyl)oxy]-3-methyl-2-[(trimethylsilyl)methyl]-1-octen-8-al (16). Aldehyde **16** was prepared from the above alcohol **15** on a 2.5-mmol scale by method B described for aldehyde **8** (n = 1, R′ = CH_3O_2C). Flash chromatography (silica gel, ether) gave 666 mg (88%) of the title compound as a clear, colorless oil: IR ($CDCl_3$) 1780, 1740, 1440 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 9.73 (s, 1 H), 4.89 (s, 1 H), 4.80 (s, 1 H), 3.68 (s, 3 H), 2.41 (t, J = 7.3 Hz, 2 H), 1.7–1.9 (m, 2 H), 1.5–1.7 (m, 2 H), 1.54 (s, 3 H), 1.46 (s, 1 H), 1.44 (s, 1 H), 1.2–1.4 (m, 2 H), 0.04 (s, 9 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 202.4, 153.6, 147.9, 109.6, 87.0, 54.0, 43.7, 38.1, 23.3, 22.7, 22.1, 20.0, 1.0, −0.7; MW calcd for $C_{15}H_{28}O_4Si$ (M^+) 300.1783, found 300.1770.

(*E*)-1-(Phenylsulfonyl)-7-methyl-8-[(trimethylsilyl)methyl]-1,8-nonadiene (17). Substrate **17** was prepared from the above aldehyde **16** on a 2.2-mmol scale by the method described for **4** (n = 1, R = CH_3O_2C, EWG = $PhSO_2$). Flash chromatography (silica gel, two elutions, 1:1 hexane/ether, then 2:1 hexane/ether) gave 750 mg (78%) of the title compound as a clear, colorless oil: IR ($CDCl_3$) 1740, 1620, 1440, 1370, 1310, 1140, 1080, 850 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.84 (dd, J = 7.0, 1.5 Hz, 2 H), 7.58 (t, J = 7.3 Hz, 1 H), 7.50 (t, J = 7.5 Hz, 2 H), 6.94 (dt, J = 15.1, 6.9 Hz, 1 H), 6.28 (td, J = 15.1, 1.5 Hz, 1 H), 4.86 (s, 1 H), 4.77 (s, 1 H), 3.67 (s, 3 H), 2.21 (qd, J = 6.8, 1.4 Hz, 2 H), 1.7–1.9 (m, 2 H), 1.51 (s, 3 H), 1.3–1.5 (m, 4 H), 1.2–1.3 (m, 2 H), 0.02 (s, 9 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 153.6, 147.9, 146.7, 140.7, 133.2, 130.5, 129.2, 127.5, 109.6, 86.9, 54.0, 37.9, 31.3, 27.7, 23.2, 22.7, 20.0, −0.7; MW calcd for $C_{20}H_{31}O_3SSi$ ($M - CH_3OCO_2$)$^+$ 379.1763, found 379.1770. Anal. Calcd for $C_{22}H_{34}O_5SSi$: C, 60.23; H, 7.83. Found: C, 60.24; H, 8.03.

(*E*)-1-(Phenylsulfonyl)-3-[(*tert*-butyldiphenylsilyl)oxy]-7-[(methoxycarbonyl)oxy]-7-methyl-8-[(trimethylsilyl)methyl]-1,8-nonadiene (18). Substrate **18** was prepared from aldehyde **16** on a 1.19-mmol scale by the method described for **9** (R = CH_3O_2C, R′ = TBDPS). Flash chromatography (silica gel, 4:1 hexane/ether) gave 402 mg (49%) of the title compound, a 1/1 mixture of diastereomers, as a light yellow oil, which crystallized upon standing to give a white crystalline solid: mp 73–83 °C; IR ($CDCl_3$) 1740, 1630, 1460, 1440, 1430, 1390, 1370, 1360, 1310, 1140, 1110, 1080, 850 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.72 (2 d, J = 7.3, 6.7 Hz, 2 H), 7.61 (t, J = 7.5 Hz, 1 H), 7.49 (t, J = 7.9 Hz, 6 H), 7.37 (m, 2 H), 7.26 (t, J = 7.4 Hz, 4 H), 6.88 (dd, J = 14.9, 5.2 Hz, 1 H), 6.34 (d, J = 15.0 Hz, 1 H), 4.85 (s, 0.5 H), 4.84 (s, 0.5 H), 4.77 (2 s, 1 H), 4.32 (m, 1 H), 3.68 (s, 3 H), 1.5–1.8 (m, 2 H), 1.47 (2 s, 3 H), 1.3–1.5 (m, 4 H), 1.1–1.3 (m, 2 H), 1.00 (s, 9 H), 0.04 (s, 9 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 153.5, 147.6, 140.3, 135.6, 135.5, 133.1, 132.8, 130.1, 129.8, 129.2, 127.4, 109.5, 86.8, 71.7, 53.9, 38.0, 37.9, 36.4,

26.8, 22.6, 22.5, 19.8, 19.2, 18.5, -0.7; MW calcd for $C_{32}H_{39}O_3SSi_2$ (M - C_4H_9, CH_3OCO_2H)$^+$ 559.2158, found 559.2158.

3-*exo*-Carbomethoxy-1-methylenebicyclo[3.3.0]octane (20a). A solution of substrate **4a** (n = 1, R = CH_3) (185 mg, 0.58 mmol) and BSA (14 mg, 0.069 mmol) in 8 mL of THF was stirred at room temperature for 1.5 h. The solution, followed by a 1-mL rinse of the flask, was cannulated into a 25-mL flask containing tetrakis(triphenylphosphine)-palladium (55 mg, 0.047 mmol) and bis(diphenylphosphino)ethane (10 mg, 0.025 mmol) and refluxed for 42 h under nitrogen. After concentration under a stream of air, the residue was purified by preparative TLC (2 × 10% ether in pentane) to yield 57 mg (51%) of the cycloadduct **20a**. An analytical sample was obtained by preparative VPC, t_R = 8.5 min (a 3 m × 0.6 cm OV-101 column, T = 160 °C, flow rate = 70 mL/min): IR (neat) 1738, 1658 cm^{-1}; ^{1}H NMR (270 MHz, $CDCl_3$) δ 4.89 (bs, 1 H), 4.78 (bs, 1 H), 4.14 (q, J = 7.1 Hz, 2 H), 2.97 (bt, J = 8.6 Hz, 1 H), 2.74 (m, 1 H), 2.59 (m, 2 H), 2.34 (d of t, J = 9.7, 7.3 Hz, 1 H), 1.83–1.43 (m, 6 H), 1.25 (t, J = 7.1 Hz, 3 H); ^{13}C NMR (50.1 MHz) δ 175.4, 155.6, 105.1, 60.21, 49.44, 48.28, 47.61, 38.91, 33.34, 32.79, 25.61, 14.3; MW calcd for $C_{12}H_{18}O_2$ 194.1302, found 194.1303. Irradiation at δ 2.34 collapses the multiplets at δ 2.59 (broad singlet) and δ 2.74 (bt, J = 8 Hz), but does not affect the resonance at δ 2.97.

A more polar band (R_f = 0.05–0.10) was also isolated to give 21 mg (18%) of the triene **21a**: IR (neat) 1723, 1656 cm^{-1}; ^{1}H NMR (270 MHz, $CDCl_3$) δ 6.97 (bd of t, J = 15.4, 6.6 Hz, 1 H), 6.18 (bd, J = 15.4 Hz, 1 H), 5.84 (bd, J = 15.4 Hz, 1 H), 5.62 (bd of t, J = 15.4, 6.6 Hz, 1 H), 4.89 (ns, 2 H), 4.19 (q, J = 7.3 Hz, 2 H), 2.30 (m, 4 H), 1.83 (bs, 3 H), 1.29 (t, J = 7.3 Hz, 3 H); MW calcd for $C_{12}H_{18}O_2$ 194.1302, found 194.1307.

4-*exo*-(Phenylsulfonyl)-2-methylenebicyclo[3.3.0]octane (20b). A solution of (*E*)-3-acetoxy-8-(phenylsulfonyl)-2-methylene-1-(trimethylsilyl)-7-octene (**4b**) (n = 1, R = CH_3) (138 mg, 0.35 mmol) and BSA (38 mg, 0.19 mmol) in 0.5 mL of DME was stirred at 65 °C for 1.5 h. The solution was kept under vacuum (ca. 0.05 mmHg) at 70 °C for 20 min. DME (8 mL initially, then 1 mL for rinsing) was added and the solution was cannulated into a 25-mL flask containing tetrakis(triphenylphosphine)palladium (37 mg, 0.032 mmol), 1,2-bis(diphenylphosphino)ethane (16 mg, 0.040 mmol), and BSA (10 μL, 3.9 μmol). The resulting yellow solution was heated at 90 °C under argon. After 20 h of heating, a precipitate of palladium black was observed. The bulk of the solvent was removed under a stream of air and the residue was filtered through a short column of silica gel. Elution with ether (100 mL) gave 115 mg of yellow oil. Analysis of the crude mixture by 270-MHz NMR revealed a mixture of cyclized product **20b** and trienes in the ratio of 1.1:0.9:0.15. The ratio of products was estimated by integration of resonances at δ 6.9 (dt, J = 16, 6.5 Hz), 6.3 (bd, J = 16, 6.5 Hz), and δ 3.86 (d, J = 7.5 Hz) and 3.75 (d, J = 5 Hz) for trienes, and 2.86 and 2.55 for **20b**. The mixture was heated with maleic anhydride (130 mg, 1.3 mmol) in 1 mL of chloroform at 60 °C for 12 h. The crude reaction mixture was purified by preparative TLC (R_f = 0.5) (30% ethyl acetate in hexane) to give 60 mg (60–63%) of the title compound.

Combined cyclized products from several runs were purified by preparative TLC (3 × 30% ethyl acetate in hexane) and flash chromatography (30% ether in pentane) to give a white solid (mp 62–66 °C) after solvent removal: IR ($CHCl_3$) 1668, 1142, 1083, 889 cm^{-1}; ^{1}H NMR (270 MHz, $CDCl_3$) δ 7.88 (m, 2 H), 7.64–7.51 (m, 3 H), 4.88 (bs, 1 H), 4.80 (bs, 1 H), 3.04 (m, 3 H), 2.81 (d of AB of d of t, J = 14.9, 9.6, 2.5 Hz, 1 H), 2.55 (d of AB of d, J = 14.9, 7.0 Hz, 1 H); ^{13}C NMR (50.1 MHz) δ 152.3, 138.8, 133.6, 129.2, 128.6, 106.6, 69.23, 47.97, 44.50, 36.76, 33.26, 32.94, 25.78; MW calcd for $C_{15}H_{18}O_2S$ 262.1023, found 262.1028.

2-Methylenebicyclo[3.3.0]octane (23) by Desulfonylation of 20b. A mixture of 4-*exo*-(phenylsulfonyl)-2-methylenebicyclo[3.3.0]octane (**20b**) (67 mg, 0.25 mmol) and anhydrous disodium hydrogen phosphate (170 mg, 1.20 mmol) in 2.5 mL of methanol was stirred vigorously at room temperature. Granulated 6% sodium amalgam (600 mg, 1.57 mmol) was added in small portions over 3 h. The mixture was stirred for another 2 h, diluted with pentane (30 mL), washed with water (2 × 10 mL), and dried over magnesium sulfate. The solvent was removed by distillation at atmospheric pressure and the residue was carefully Kugelrohr distilled (70–80 °C, 20 mmHg) to give 14 mg (47%) of the title compound as an extremely volatile colorless liquid: IR (neat) 1660, 877 cm^{-1}; ^{1}H NMR (270 MHz, $CDCl_3$) δ 4.82 (m, 1 H), 4.74 (m, 1 H), 2.81 (bt, J = 8.2 Hz, 1 H), 2.52 (m, 1 H), 2.33 (m, 1 H), 2.20 (d of AB of d of t, J = 14.7, 7.4, 1.7 Hz, 1 H), 1.88–1.65 (m, 3 H), 1.52 (m, 3 H), 1.32 (m, 2 H); MW calcd for C_9H_{14} 122.1092, found 122.1096. This material was identical by ^{13}C NMR spectroscopy with the same compound reported in the literature by Gassman.[24]

Isomerization of 20a to 4-*exo*-Carbomethoxy-2-methylbicyclo[3.3.0]-oct-2-ene (24). A solution of 3-*exo*-carbomethoxy-1-methylenebicyclo-[3.3.0]octane (**20a**) (44 mg, 23 mmol, containing 10–13% of another isomer) in ca. 0.5 mL of chloroform-*d* (in an NMR tube) with a few crystals of *p*-toluenesulfonic acid monohydrate was heated at 55 °C. Analysis by 270-MHz NMR indicated essentially complete rearrangement after 1 h and no further change after 5 h. The solution was filtered through a very short column of silica gel eluting with ether. The eluent was concentrated in vacuo carefully to give 40 mg (90%) of the title compound: IR (neat) 1737, 1438, 1370 cm^{-1}; ^{1}H NMR (270 MHz, $CDCl_3$) δ 5.19 (m, 1 H), 4.12 (q, J = 7.3 Hz, 2 H), 3.11 (m, 1 H), 3.04 (bt, J = 8.0 Hz, 1 H), 2.94 (tt, J = 8.0, 3.6 Hz, 1 H), 1.79 (m, 1 H), 1.69 (m, 3 H), 1.66–1.36 (m, 5 H), 1.26 (t, J = 7.3 Hz); ^{13}C NMR (50.1 MHz) δ 175.3, 145.8, 121.4, 76.37, 60.27, 58.27, 53.59, 45.59, 34.74, 30.07, 25.44, 17.17, 14.29; MW calcd for $C_{12}H_{18}O_2$ 194.1302; found 194.1035. Irradiation at δ 5.19 (olefinic signal) changes the multiplicity pattern at δ 3.11 (width at half-height decreased by 0.6 Hz), but has no effect on resonances at δ 3.04 and 2.94.

3β-(Phenylsulfonyl)-1-methylene-3aβ,4,5,6,7,7aβ-hexahydroindan (25) and 3β-(Phenylsulfonyl)-1-methylene-3aβ,4,5,6,7,7aα-hexahydroindan (26). A mixture of 3-acetoxy-9-(phenylsulfonyl)-2-methylene-1-(trimethylsilyl)-8-nonene (**4c**) (250 mg, 0.62 mmol) and BSA (100 μL, 0.39 mmol) was heated for 5 h under nitrogen at 50 °C, and then kept under high vacuum (0.05 mmHg) for 3 h at 70 °C to remove any volatiles. Tetrakis(triphenylphosphine)palladium (54 mg, 0.074 mmol) and bis-(diphenylphosphino)ethane were added under nitrogen. THF (7 mL) and BSA (5 μL, 20 μmol) were added, and the yellow solution was refluxed under nitrogen for 40 h. TLC (30% ether in pentane) indicated the essentially complete reaction after 24 h. The solution was concentrated under a stream of air and filtered through a short column of silica gel to give 200 mg of a crude yellow oil after elution with ether (100 mL). Analysis by 270-MHz NMR indicated a mixture of cyclized product, triene, desilylated acetates, and allylic sulfone. The presence of these side products was inferred by absorptions at δ 7.0 (dt, J = 15, 7.5 Hz), 6.3 (bd, J = 15 Hz), 6.1 (bd, J = 16 Hz), and 5.6 (dt, J = 16, 7.5 Hz) for triene; 3.9 (d, J = 7.5 Hz) and 3.8 (d, J = 7.5 Hz) for allylic sulfone; and 2.10 (s) and 2.05 (s) for desilylated acetates. (The ratio of products could not be determined accurately.) The crude mixture was heated with maleic anhydride (130 mg, 1.3 mmol) in 1.7 mL of chloroform at 55–60 °C for 15 h. The reaction mixture was purified by flash chromatography (30% ether in pentane) to give 120 mg (70%) of a mixture of **25** and **26** in the ratio of 67:33 based on the integration of olefinic multiplets at δ 4.90 and 4.82 for **25**, and 4.76 and 4.73 for **26**. Combined product mixtures from several reactions were further purified by flash chromatography (30% ether in pentane) to give a thick oil: IR ($CHCl_3$) 1679, 1449, 1305, 1146, 1090, 890 cm^{-1}; ^{1}H NMR (270 MHz, $CDCl_3$) δ 7.90 (m, 2 H), 7.67–7.52 (m, 3 H), 4.90, 4.82 and 4.76, 4.73 (two pairs of multiplets, 2 H), 3.29 (m, 1 H), 2.89–2.43 (m, ~3.3 H), 2.07 (m, ~0.7 H), 1.87–1.04 (m, 8 H); ^{13}C NMR (50.1 MHz, c = **25**, t = **26**) δ 149.3 (c), 148.9 (t), 139.5 (t), 138.9 (c), 133.5 (c, t), 129.2 (c, t), 128.5 (c, t), 128.4 (c, t), 106.1 (c), 104.2 (t), 66.54 (t), 65.81 (c), 50.31 (t), 46.37 (t), 42.92 (c), 40.15 (c), 33.35 (t), 32.18 (c), 31.21 (t), 28.56 (t), 28.12 (c), 25.67 (c), 25.27 (t), 24.00 (c), 21.75 (c). (^{13}C assignments were based on relative peak intensity.) Anal. Calcd for $C_{16}H_{20}O_2S$: C, 69.53; H, 7.29; MW, 276.1179. Found: C, 69.70; H, 7.26; MW, 276.1185.

***cis*- and *trans*-1-Hexahydroindanone (27b, 28b) by Desulfonylation–Ozonolysis of 25 and 26.** To a vigorously stirred mixture of isomeric sulfones **25** and **26** (130 mg, 0.47 mmol) in 5 mL of methanol and anhydrous disodium hydrogen phosphate (256 mg, 1.8 mmol) was added granulated 6% sodium amalgam (905 mg, 2.4 mmol) in small portions over 3 h. The mixture was stirred for 2 h, diluted with 35 mL of pentane, washed with water (2 × 10 mL), and dried over magnesium sulfate. Solvent was removed by distillation at atmospheric pressure. Analysis of the crude olefins by 270-MHz NMR spectroscopy indicated two pairs of olefinic multiplets at δ 4.82, 4.74 and δ 4.68, 4.64 in the ratio of 2:1. The mixture was then subjected to ozonolysis without purification.

The olefinic isomers were dissolved in 1.5 mL of methanol and 1.5 mL of methylene chloride at −78 °C. Ozone was then bubbled through to a blue end point. After nitrogen purging, the ozonides were quenched with 0.8 mL of dimethyl sulfide and allowed to warm to room temperature. Pentane (30 mL) was added and the solution was washed with water (2 × 10 mL) and dried over magnesium sulfate. The solvent was removed by atmospheric distillation and the residue was carefully Kugelrohr distilled (bp 85 °C, 10–12 mmHg) [lit.[26] bp 80 °C (10 Torr)] to give 62 mg (95% for the two steps) of the isomeric hydroindanones. The product was identical with an authentic sample[26] by ^{13}C NMR and analytical HPLC (Radial PAK B, 2% ethyl acetate in hexane, 3.0 mL/min). By comparing with the authentic sample (cis/trans mixture, 27:73), the product had a cis:trans (**27b**:**28b**) ratio of 68:32.

Preparation of Standard Catalyst Solution (cat. G). A standard catalyst solution was prepared on a scale 1–5 times that required for the reaction. Palladium acetate was dissolved in the appropriate solvent (THF or dioxane) to a concentration of 5 × 10^{-3} M. Six equivalents of

triisopropyl phosphite and 20 equiv of BSA were then added via syringe, and the mixture was stirred for 10 min. An aliquot of this solution was then added via syringe to the substrate, so that the substrate concentration was 0.1 M. The reaction mixture thus produced contained 5 mol % palladium acetate, 30 mol % triisopropyl phosphite, and 1 equiv of BSA relative to the substrate.

Cycloaddition of 9 (R = CH_3O_2C, n = 1). Substrate **9** (n = 1, R = CH_3O_2C) (68.5 mg, 0.16 mmol) was pretreated with BSA (79 μL, 0.32 mmol) in 300 μL of THF. After evaporation, the residue was treated with 1.6 mL of the catalyst solution prepared above in THF. The solution was heated at 60 °C for 12 h, the solvent was removed in vacuo, and the residue was purified by flash chromatography (silica gel, 4:1 hexane/ether). The cyclized products **25** and **26** (32.8 mg, 73%), a 1.5/1 mixture of diastereomers, was isolated as a clear, colorless oil whose ^1H NMR spectral characteristics were identical with those above.

(1*S,9*R**)-9-(Phenylsulfonyl)-7-methylene-2-hydroxybicyclo[4.3.0]-nonanes 29–32 (R = H).** From **10** (n = 1, R = CH_3O_2C, R′ = TBDMS). The substrate (279 mg, 0.5 mmol) was dissolved in 1.0 mL of THF and treated with BSA (250 μL, 1.0 mmol) at 60 °C under nitrogen for 3 h. The volatile materials were then removed under high vacuum (<0.2 mmHg) at that temperature for 30 min, and the residue was treated with 12.5 mL of the catalyst solution prepared above in THF. The resulting solution was heated to 60 °C for 1 h and the solvent was removed in vacuo. Flash chromatography of the products (silica gel, 6:1 hexane/ether) gave 154 mg (76%) of a mixture of **29–32**. The product ratio was estimated to be 6.3:3.3:1.8:1.0 (3.4:1 cis/trans ring juncture) from the intensities of ^1H NMR peaks at δ 0.75, 0.79, 0.89, and 0.95 ppm.

This product mixture (146 mg, 0.36 mmol) was dissolved in 2 mL of THF and treated with 0.72 mL of a 1.0 M solution of TBAF (0.72 mmol) in THF and stirred at room temperature overnight. The resulting solution was diluted with 20 mL of ether and washed with 5 mL of water. The aqueous layer was extracted with two 5-mL portions of ether, the combined organic extracts were dried over magnesium sulfate and filtered, and the solvent was removed in vacuo. The products were subjected to flash chromatography (silica gel, 1:1:1 hexane/ether/methylene chloride) to give 10.1 mg of **32**, 29.8 mg of **30**, 15.8 mg of **31**, and 44.3 mg of **29** (100 mg total, 95%, 1.9:1 cis/trans ring juncture).

29: white solid, mp 67–69 °C (hexane/ether); IR ($CDCl_3$) 3570, 1440, 1300, 1140, 1080, 1050 cm^{-1}; ^1H NMR (300 MHz, C_6D_6) δ 7.81 (d, J = 8.0 Hz, 2 H), 6.90 (m, 3 H), 4.72 (m, 1 H), 4.61 (m, 1 H), 3.65 (ddd, J = 10.0, 4.0, 1.9 Hz, 1 H), 3.18 (bs, 1 H), 2.97 (dm, J = 18.2, 2.3 Hz, 1 H), 2.77 (tdd, J = 10.4, 7.9, 4.2 Hz, 1 H), 2.46 (ddd, J = 8.5, 6.1, 1.7 Hz, 1 H), 2.19 (ddd, J = 18.0, 10.0, 1.8 Hz, 1 H), 1.4–1.6 (m, 2 H), 1.15 (m, 2 H), 0.75–0.9 (m, 2 H), 0.79 (d, J = 10.0 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 148.1, 133.6, 129.2, 128.5, 105.6, 70.0, 63.1, 48.9, 42.3, 34.7, 31.6, 23.4, 19.6. Anal. Calcd for $C_{16}H_{20}O_3S$: C, 65.71; H, 6.91. Found: C, 65.98; H, 6.96.

30: yellow oil; IR ($CDCl_3$) 3470, 1450, 1290, 1140, 1090, 1070 cm^{-1}; ^1H NMR (300 MHz, C_6D_6) δ 7.75 (d, J = 7.0 Hz, 2 H), 6.97 (m, J = 7.0 Hz, 3 H), 4.60 (m, J = 2.0 Hz, 2 H), 3.71 (dt, J = 10.0, 5.7 Hz, 1 H), 3.66 (tdd, J = 7.7, 4.5, 3.4 Hz, 1 H), 2.84 (dt, J = 7.4, 5.6 Hz, 1 H), 2.72 (ddt, J = 18.0, 5.7, 2.0 Hz, 1 H), 2.57 (dt, J = 6.8, 5.7 Hz, 1 H), 2.49 (d, J = 7.9 Hz, 1 H), 2.38 (ddd, J = 18.0, 10.0, 2.0 Hz, 1 H), 1.2–1.4 (m, 3 H), 1.16 (q, J = 6.3 Hz, 1 H), 0.8–1.0 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 150.5, 133.8, 129.3, 128.6, 104.8, 69.3, 63.1, 44.7, 43.0, 33.6, 31.2, 25.1, 17.4. Anal. Calcd for $C_{16}H_{20}O_3S$: C, 65.71; H, 6.91. Found: C, 65.92; H, 7.09.

31: white solid, mp 72 °C (hexane/ether); IR ($CDCl_3$) 3220, 1280, 1180 cm^{-1}; ^1H NMR (300 MHz, C_6D_6) δ 7.76 (dd, J = 10.0, 2.0 Hz, 2 H), 6.90 (m, 3 H), 4.68 (m, 2 H), 4.47 (bs, 1 H), 3.56 (dt, J = 10.8, 9.2 Hz, 1 H), 2.62 (ddq, J = 17.6, 11.1, 1 H), 2.03 (ddd, J = 12.5, 9.3, 2.1 Hz, 1 H), 1.76 (dd, J = 12.0, 3.3 Hz, 1 H), 0.8–1.6 (m, 6 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 148.8, 133.7, 129.2, 128.2, 104.9, 65.9, 61.3, 49.5, 42.4, 33.0, 32.8, 28.3, 19.3; MW calcd for $C_{16}H_{18}O_2S$ $(M - H_2O)^+$ 274.1028, found 274.1020.

32: white solid, mp 96–98 °C (hexane/ether); IR ($CDCl_3$) 3460, 1440, 1270, 1140 cm^{-1}; ^1H NMR (400 MHz, C_6D_6) δ 7.77 (d, J = 7.0 Hz, 2 H), 6.87 (m, J = 6.7 Hz, 3 H), 4.57 (m, J = 1.9 Hz, 2 H), 3.46 (td, J = 9.8, 4.5 Hz, 1 H), 2.92 (dt, J = 10.0, 9.4 Hz, 1 H), 2.44 (ddq, J = 17.4, 9.4, 2.0 Hz, 1 H), 2.21 (dq, J = 12.6, 4.1 Hz, 1 H), 2.11 (dd, J = 17.6, 10.0 Hz, 1 H), 1.81 (ddd, J = 12.4, 9.7, 9.6, Hz, 1 H), 1.50 (dm, J = 12.0 Hz, 2 H), 1.2–1.4 (m, 2 H), 0.98 (m, 1 H), 0.86 (m, J = 6.4 Hz, 1 H), 0.66 (m, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 147.2, 134.1, 129.3, 128.0, 105.2, 73.2, 67.3, 53.0, 49.0, 34.3, 34.2, 27.2, 23.8; MW calcd for $C_{16}H_{18}O_2S$ $(M - H_2O)^+$ 274.1028, found 274.1026.

From **10** (n = 1, R = CH_3O_2C, R′ = TBDPS). The substrate (137 mg, 0.20 mmol) was dissolved in 0.6 mL of THF and treated with BSA (100 μL, 0.4 mmol) for 3 h at 60 °C. Volatile materials were then removed under high vacuum (<0.2 mmHg) at that temperature for 30 min. The residue was then treated with 2 mL of the catalyst solution prepared above in THF and heated to 60 °C for 6 h. The solvent was removed in vacuo, and the residue was purified by flash chromatography (silica gel, 6:1 hexane:ether) to give 85.8 mg (80%) of **29–32**. The diastereomeric ratio was determined to be 10.7:6.1:2.1:1 (5.4:1 cis/trans ring juncture) from the ratio of intensities of the ^1H NMR peaks at δ 0.98, 0.99, 1.10, and 1.12.

The above product mixture (93.9 mg, 0.18 mmol) was treated with 1 mL of 1.0 M TBAF in THF and stirred at room temperature overnight, and then at 40 °C for 2 h. The mixture was diluted with 2 mL of ether and washed with 1 mL of water, and the aqueous layer was extracted with two 1-mL portions of ether. The combined organic layers were dried over magnesium sulfate and filtered, and the solvent was removed in vacuo. Flash chromatography (silica gel, 1:1:1 hexane/ether/methylene chloride) gave 3.1 mg of **32**, 10.8 mg of **30**, 4.9 mg of **31**, and 29.2 mg of **29** (48.0 mg total, 93%, 5:1 cis/trans ring juncture).

(1*S,6*S**,9*R**)-9-(Phenylsulfonyl)-7-methylenebicyclo[4.3.0]nonan-2-one (33).** DMSO (11.1 mg, 10.1 μL, 0.14 mmol) was dissolved in 0.5 mL of methylene chloride, cooled to −78 °C, and treated with oxalyl chloride (9.5 mg, 6.5 μL, 0.075 mmol). The mixture was stirred at this temperature for 10 min and alcohol **29** (20 mg, 0.068 mmol) was added. After an additional 15 min, diisopropylethylamine (24.7 mg, 37.3 μL, 0.19 mmol) was added and the mixture was allowed to warm to room temperature. The mixture was diluted with 3 mL of ether, extracted with 2 mL of water, dried over magnesium sulfate, and filtered, and the solvent was removed in vacuo. Flash chromatography (silica gel, 1:1:1 hexane/ether/methylene chloride) gave 16.8 mg (85%) of the title compound as a white solid: mp 107–108 °C dec (hexane/ether); IR ($CDCl_3$) 1710, 1450, 1310, 1240, 1150 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, J = 7.0 Hz, 2 H), 7.64 (t, J = 7.4 Hz, 1 H), 7.56 (d, J = 7.5 Hz, 2 H), 4.92 (q, J = 2.2 Hz, 1 H), 4.79 (q, J = 2.4 Hz, 1 H), 4.34 (ddd, J = 9.4, 4.3, 1.5 Hz, 1 H), 3.47 (m, 1 H), 3.39 (d, J = 9.2 Hz, 1 H), 2.84 (d, J = 17.7 Hz, 1 H), 2.50 (ddd, J = 17.7, 9.5, 1.3 Hz, 1 H), 2.34 (d, J = 10.6 Hz, 1 H), 2.32 (d, J = 10.6 Hz, 1 H), 1.7–2.1 (m, 4 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 207.4, 146.5, 133.5, 130.8, 129.0, 128.1, 106.3, 59.7, 52.8, 45.5, 41.0, 31.7, 22.2; MW calcd for $C_{10}H_{13}O$ $(M - C_6H_5SO_2)^+$ 149.0966, found 149.0958.

(1*S,6*R**,9*R**)-9-(Phenylsulfonyl)-7-methylenebicyclo[4.3.0]nonan-2-one (34).** Ketone **34** was prepared from alcohol **31** by the procedure described above on a 0.035-mmol scale. Flash chromatography (silica gel, 1:1:1 hexane/ether/methylene chloride) gave 9.8 mg (97%) of the title compound as a white solid: mp 165 °C dec (hexane/ether); IR ($CDCl_3$) 1740, 1450, 1440, 1380, 1030, 900 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.87 (dd, J = 7.1, 1.4 Hz, 2 H), 7.63 (t, J = 7.5 Hz, 1 H), 7.53 (t, J = 7.1 Hz, 2 H), 4.92 (dd, J = 4.0, 2.4 Hz, 1 H), 4.86 (dd, J = 4.3, 1.8 Hz, 1 H), 3.98 (ddd, J = 10.7, 9.9, 6.5 Hz, 1 H), 2.98 (ddd, J = 17.5, 6.5, 1.5 Hz, 1 H), 2.92 (dd, J = 13.4, 9.9 Hz, 1 H), 2.70 (dd, J = 17.5, 10.8 Hz, 1 H), 2.1–2.3 (m, 5 H), 1.5–1.7 (m, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.9, 147.3, 133.8, 129.1, 128.6, 128.5, 106.1, 58.9, 57.2, 53.5, 41.4, 31.5, 27.6, 27.4; MW calcd for $C_{10}H_{12}O$ $(M - C_6H_5SO_2H)^+$ 148.0888, found 148.0891.

Cycloaddition of *Z* Acceptor 12: Preparation of (1*S,2*S**,6*R**,9*S**)-9-(Phenylsulfonyl)-7-methylene-2-[(*tert*-butyldiphenylsilyl)oxy]bicyclo[4.3.0]nonane (35) and (1*S**,2*S**,6*S**,9*R**)-9-(Phenylsulfonyl)-7-methylene-2-[(*tert*-butyldiphenylsilyl)oxy]bicyclo-[4.3.0]nonane (29c).** The substrate (247.6 mg, 0.365 mmol) was pretreated with BSA (180 μL, 0.73 mmol) in 1.2 mL of THF in the usual manner above. After evaporation, the residue was treated with 3.7 mL of the catalyst solution prepared above in THF. The solution was heated at 60 °C for 12 h, and then at 68 °C for 55 h. The solvent was removed under a stream of N_2 and the residue subjected to flash chromatography (silica gel, 4:1 hexane/ether) to yield 110.2 mg (66%) of cycloadducts and 33.8 mg of starting materials (86% conversion). The diastereomeric ratio of the major cyclized products was assigned as 5.2:4.5:1 (**29c**:**35**:minor isomer) from the relative intensities of the ^1H NMR ($CDCl_3$) peaks at δ 0.98, 1.08, and 1.05.

Products from several runs were combined and subjected to flash chromatography (silica gel, 10:1 hexane/ether followed by 4:1 hexane/ether) to yield pure **35** and a mixture of other isomers. The major isomer was assigned as **29c** on the basis of comparison with the ^1H NMR spectrum of **29–32**. The new cycloadduct was isolated as a white crystalline solid: mp 138–140 °C (hexane/ether); IR ($CDCl_3$) 1660, 1440, 1420, 1300, 1140, 1110, 1080 cm^{-1}; ^1H NMR (400 MHz, C_6D_6) δ 8.15 (dd, J = 8.1, 1.5 Hz, 2 H), 8.05 (dd, J = 8.0, 1.6 Hz, 2 H), 7.79 (dd, J = 7.3, 1.6 Hz, 2 H), 7.30 (m, 6 H), 6.93 (m, 3 H), 4.95 (td, J = 10.4, 4.8 Hz, 1 H), 4.79 (2 s, 2 H), 3.81 (t, J = 7.1 Hz, 1 H), 2.98 (t, J = 12.0 Hz, 1 H), 2.63 (d, J = 18.2 Hz, 1 H), 2.02 (ddq, J = 18.3, 8.0, 2.2 Hz, 1 H), 1.84 (m, J = 12.4 Hz, 1 H), 1.77 (ddd, J = 14.0, 10.2, 6.2 Hz, 1 H), 1.60 (dm, J = 12.0, 3.2 Hz, 1 H), 1.36 (s, 9 H), 0.7–1.3 (m, 3 H), 0.60 (qd, J = 12.0, 3.2 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 150.3,

140.0, 136.0, 135.5, 134.4, 133.2, 129.3, 129.2, 129.1, 128.3, 127.4, 127.2, 105.3, 72.3, 62.4, 57.9, 44.6, 36.9, 34.3, 29.0, 27.2, 23.9, 19.4; MW calcd for $C_{31}H_{35}O_3SSi$ $(M - CH_3)^+$ 515.2076, found 515.2075. Anal. Calcd for $C_{32}H_{38}O_3SSi$: C, 72.40; H, 7.23. Found: C, 72.59; H, 7.51.

Cycloaddition of 13: Preparation of (1*R,9*R**)-9-Cyano-7-methylene-2-[(*tert*-butyldimethylsilyl)oxy]bicyclo[4.3.0]nonane (36–40).** The substrate (471 mg, 1.02 mmol) was pretreated with BSA (529 μL, 2.1 mmol) in 1.2 mL of THF in the usual manner. After evaporation, the residue was treated with 10.7 mL of the catalyst solution prepared above in THF. After heating at 68 °C for 12 h, the solvent was removed in vacuo and the residue was submitted to flash chromatography (silica gel, 50:1 hexane/ether) to yield 211.8 mg (68%) of the product as a mixture of five isomers. The diastereomeric ratio was assigned to be 7.5:3.7:2.9:1:1 on the basis of the relative intensities of ^1H NMR ($CDCl_3$) resonances at δ 0.87, 0.90, 0.88, 0.89, and 0.91. Combined products from several runs were further purified by flash chromatography (silica gel, 50:1 hexane/ether) to give **36**, **38** and **37**, **39**, and **40** as a mixture of isomers.

36: IR ($CDCl_3$) 2200, 1660, 1250 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 4.94 (q, *J* = 2.2 Hz, 1 H), 4.86 (q, *J* = 2.4 Hz, 1 H), 3.27 (td, *J* = 8.2, 4.0 Hz, 1 H), 2.95 (ddd, *J* = 8.5, 5.2, 3.4 Hz, 1 H), 2.89 (bs, 1 H), 2.73 (m, 2 H), 2.20 (ddd, *J* = 7.9, 6.1, 3.4 Hz, 1 H), 1.67 (m, 2 H), 1.56 (m, 2 H), 1.33 (m, 2 H), 0.86 (s, 9 H), 0.02 (2 s, 6 H); ^{13}C NMR (100 MHz, CDC_3) δ 148.3, 123.0, 106.6, 68.9, 52.8, 42.0, 34.6, 33.4, 27.8, 25.7, 25.0, 19.4, 17.9, −4.1, −4.8; MW calcd for $C_{16}H_{26}NOSi$ $(M - CH_3)^+$ 276.1784, found 276.1777. Anal. Calcd for $C_{17}H_{29}NOSi$: C, 70.02; H, 10.05; N, 4.81. Found: C, 69.96; H, 10.15; N, 4.81.

38: IR ($CDCl_3$) 2240, 1650 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 4.83 (dt, *J* = 2.5, 2.0 Hz, 1 H), 4.78 (q, *J* = 2.4 Hz, 1 H), 4.24 (d, *J* = 2.7 Hz, 1 H), 2.85 (ddd, *J* = 15.6, 8.8, 1.1 Hz, 1 H), 2.62 (dt, *J* = 11.3, 8.8 Hz, 1 H), 2.54 (ddq, *J* = 15.9, 11.6, 1.9 Hz, 1 H), 2.20 (t, *J* = 12.5 Hz, 1 H), 1.91 (dd, *J* = 12.6, 3.1 Hz, 1 H), 1.78 (dd, *J* = 13.7, 3.1 Hz, 1 H), 1.55 (m, 3 H), 1.34 (tdd, *J* = 13.7, 5.1, 2.2 Hz, 1 H), 1.04 (qd, *J* = 12.2, 4.5 Hz, 1 H), 0.88 (s, 9 H), 0.09 (s, 3 H), 0.07 (s, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 149.8, 121.7, 104.9, 65.5, 54.5, 41.6, 34.9, 33.1, 28.2, 25.8, 26.8, 19.3, 18.0, −4.6, −5.1; MW calcd for $C_{17}H_{29}NOSi$ (M^+) 291.2019, found 291.2033.

37, **39**, and **40**: IR ($CDCl_3$) 2250, 1660, 1460 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) major isomer δ 4.83 (s, 1 H), 4.77 (s, 1 H), 3.95 (dt, *J* = 10.0, 4.8 Hz, 1 H), 2.95 (m, 1 H), 2.60 (dt, *J* = 8.9, 1.9 Hz, 1 H), 2.54 (m, 1 H), 1.95 (m, 1 H), 1.67 (m, 2 H), 1.0–1.4 (m, 5 H), 0.90 (s, 9 H), 0.09 (s, 3 H), 0.07 (s, 3 H); minor isomers (partial) δ 4.96 (q, *J* = 5.8 Hz, 1 H), 4.86 (q, *J* = 5.8 Hz, 1 H), 3.71 (ddd, *J* = 11.9, 8.0, 3.9 Hz, 1 H), 3.47 (td, *J* = 9.6, 4.5 Hz, 1 H), 2.82 (dm, *J* = 8.7 Hz, 1 H), 2.71 (q, *J* = 6.4 Hz, 1 H), 0.91 (s, 9 H), 0.13 (s, 3 H), 0.08 (s, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) major isomer δ 155.1, 123.4, 106.0, 70.0, 50.1, 45.1, 35.7, 30.4, 27.8, 26.0, 25.4, 22.1, 18.3, −4.8, −4.9; minor isomers δ 149.0, 122.3, 105.0, 68.2, 56.4, 48.1, 36.3, 29.7, 28.8, 26.1, 25.9, 24.3, 19.1, −3.7, −4.7; MW calcd for $C_{17}H_{28}NOSi$ $(M - H)^+$ 290.1940, found 290.1952.

(1*R,6*S**,9*R**)-9-Cyano-7-methylene-2-oxobicyclo[4.3.0]nonane (41).** From **37**, **39**, and **40**. The cycloadducts (65.9 mg, 0.23 mmol) were treated with 1 mL of a 1.0 M solution of TBAF (1.0 mmol) in THF and stirred at room temperature for 2 h. After workup in the usual way, the products were purified via flash chromatography (silica gel, 1:1:1 hexane/ether/methylene chloride) to give 29.8 mg (73%) of a mixture of three alcohols.

The alcohols obtained above (24.5 mg, 0.14 mmol) were oxidized under Moffatt–Swern conditions with DMSO (24.2 mg, 21.9 μL, 0.31 mmol), oxalyl chloride (21.6 mg, 14.8 μL, 0.17 mmol), and triethylamine (39.4 mg, 54.2 μL, 0.39 mmol) in a total of 800 μL of methylene chloride. The normal workup followed by flash chromatography (silica gel, 4:1 hexane/ether) yielded 12.1 mg of **41** and 5.1 mg of isomers (70%) as clear colorless oils.

41: IR ($CDCl_3$) 2260, 1720 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.02 (m, 1 H), 4.89 (m, 1 H), 3.69 (ddd, *J* = 7.8, 5.5, 1.7 Hz, 1 H), 3.40 (m, 1 H), 3.09 (d, *J* = 8.2 Hz, 1 H), 2.55 (m, 2 H), 2.75 (m, 2 H), 2.05 (m, 2 H), 1.7–2.0 (m, 2 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 208.0, 146.3, 122.6, 108.1, 56.4, 45.5, 40.9, 35.4, 26.0, 24.5, 22.4; MW calcd for $C_{11}H_{13}NO$ (M^+) 175.0998, found 175.0990.

From **36**. The cycloadduct (80 mg, 0.28 mmol) was treated with 1 mL of a 1.0 M solution of TBAF (91.0 mmol) in THF as above. After the same workup, the crude product was subjected to flash chromatography (silica gel, 2:1 hexane/ethyl acetate) to give 37.4 mg (77%) of alcohol as a clear colorless oil: IR ($CDCl_3$) 3620, 3500, 2260, 1660, 1460, 1450 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 4.97 (q, *J* = 2.4 Hz, 1 H), 4.86 (q, *J* = 2.5 Hz, 1 H), 3.2 (m, 2 H), 2.87 (m, 1 H), 2.69 (m, *J* = 2.2 Hz, 2 H), 2.16 (ddd, *J* = 9.0, 6.8, 2.5 Hz, 1 H), 1.8 (m, 2 H), 1.5–1.7 (m, 2 H), 1.2–1.5 (m, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 147.8, 123.2, 106.8, 68.5, 52.4, 42.1, 34.3, 33.9, 27.6, 24.2, 19.2; MW calcd for $C_{11}H_{15}NO$ (M^+) 177.1154, found 177.1153.

Pyridinium chlorochromate (52 mg, 0.24 mmol) was added to a slurry of the above alcohol (27.5 mg, 0.16 mmol) and Celite (78 mg) in 1.4 mL of methylene chloride. After 12 h of stirring at room temperature, 1.5 mL of ether and magnesium sulfate were added, and the mixture was stirred an additional 10 min. Filtration through a pad of silica gel and eluting with hexane yielded 18.1 mg (67%) of ketone **41**, whose spectral characteristics were identical with those reported above.

Cycloaddition of 17: Preparation of (1*R,9*R**)-9-(Phenylsulfonyl)-7-methylene-6-methylbicyclo[4.3.0]nonanes (42, 43).** The substrate **17** (175 mg, 0.40 mmol) was pretreated with BSA (198 μL, 0.08 mmol) in 500 μL of THF in the usual manner. After evaporation, the residue was dissolved in 1 mL of THF and added to a solution of palladium(II) acetate (4.49 mg, 0.02 mmol), triisopropyl phosphite (19.9 mg, 23.6 μL, 0.12 mmol), and BSA (99 μL, 0.4 mmol) in 4 mL of THF. The residue from the substrate flask was rinsed into the reaction mixture with two 0.5-mL portions of THF and the solution was heated to 60 °C. After 2 h, maleic anhydride (98.0 mg, 1.0 mmol) was added and the mixture was stirred at 60 °C overnight. The solvent was removed under a stream of N_2, and the residue was subjected to flash chromatography (silica gel, 6:1 hexane/ether) to give 38.8 mg (33%) of the title compounds, an inseparable 1.5/1 mixture of diastereomers, as a white solid: IR ($CDCl_3$) 1650, 1460, 1440, 1300, 1140, 1080 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.88 (d, *J* = 7.9 Hz, 2 H), 7.63 (t, *J* = 7.4 Hz, 1 H), 7.55 (t, *J* = 7.5 Hz, 2 H), 4.70 (m, 0.8 H), 4.67 (m, 1.2 H), 3.66 (q, *J* = 10.4 Hz, 0.4 H, 0% NOE with irradiation at 1.12 ppm), 3.31 (dt, *J* = 10.6, 8.8 Hz, 0.6 H, 11% NOE with irradiation at 0.82 ppm), 2.5–2.8 (m, 1.4 H), 2.18 (dm, *J* = 10.8 Hz, 0.4 H), 1.1–2.0 (m, 9.2 H), 1.12 (s, 1.2 H), 0.82 (s, 1.8 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 156.2, 155.3, 139.2, 139.0, 133.6, 129.2, 128.4, 128.3, 104.6, 103.19, 68.8, 64.3, 61.9, 48.3, 45.3, 34.0, 35.8, 34.9, 32.9, 32.3, 29.7, 25.8, 24.5, 22.9, 21.9, 20.9, 20.5; MW calcd for $C_{11}H_{16}$ $(M - C_6H_5SO_2H)^+$ 148.1252, found 148.1255.

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Supplementary Material Available: Experimental procedures and analytical data for substrates **3a–c** (8 pages). Ordering information is given on any current masthead page.