o-Quinone Methides from 4-Allenylcyclobutenones: Synthesis and Chemistry

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Selected 4-allenylcyclobutenones ring expand to the corresponding *o*-quinone methides upon thermolysis in refluxing toluene or benzene. These reactive intermediates were not isolated but trapped to give stable products. The reaction has synthetic potential as a route to highly-substituted phenols, benzofurans, and aryl analogs of hexahydrocannabinol. In addition, a unique rearrangement involving a methyl migration from silicon to carbon of selected 4-[3,3-bis(trimethylsilyl)-1,2-propadienyl]cyclobutenones to give 1,2-benzoxasilols is described. Finally, data are presented that show rapid rotation around the alkylidene bond of *o*-quinone methides at 30 °C and that 2-(1-methylethenyl)phenols are in equilibrium with the corresponding *o*-quinone methides.

Reported here are a number of studies associated with the thermally induced rearrangements of selected 4-allenylcyclobutenones. These rearrangements lead to ring-expanded products and proceed *via o*-quinone methides, a synthetically useful class of reactive intermediates that previously were not readily available by a general route with the control of regiochemistry that is inherent in the method outlined herein.[1−3] This new route to *o*-quinone methides along with the fact that the ring expansions proceed under neutral conditions allows synthetic studies and mechanistic investigations that would be difficult or impossible to approach by other methods. Examples of such studies are presented herein as follows: (1) vinyl quinones, available from *o*-quinone methides bearing at least one alkyl group on the alkylidene terminus, undergo a previously unknown isomerization to benzofurans (Scheme 1); (2) selected *o*-quinone methides bearing a trimethylsilyl group on the alkylidene terminus proceed to benzoxasilols by an unusual reaction involving methyl migration from silicon to carbon (Scheme 3); (3) a tandem ring expansion/intramolecular Diels−Alder cycloaddition route to enantiomerically pure aryl analogs of hexahydrocannabinol is presented (Scheme 4); (4) mechanistic data showing a facile (30 °C) configurational equilibration of *o*-quinone methides bearing two alkyl groups at the alkylidene terminus were obtained; (5) finally, data are provided that establish an equilibrium between selected 2-(1-methylethenyl)-1,4-benzenediols and the corresponding *o*-quinone methides.

Regiospecific Synthesis of Highly-Substituted 2-Alkenylphenols: A New Benzofuran Synthesis. A potentially general regiospecific route to highly-substituted 2-alkenylphenols is outlined in Scheme 1. Here, the starting cyclobutenones **1a**−**d** were prepared as mixtures of diastereomers by the addition of 1-lithio-1-methoxy-3-(trimethylsilyl)-1,2-hexadiene to the corresponding cyclobutenedione at −78 °C in THF.[1,4] Thermolysis of these adducts at 110 °C (toluene) gave 1-(trimethylsilyl)-1(*E*)-butenyl-substituted hydroquinones **3a**−**d** in good yields (75−90%). Such transformations document an efficient route to synthetically useful 2-(1-(trimethylsilyl)ethenyl)phenols and further license regiocontrol in the synthesis of highly-substituted aromatic compounds from cyclobutenones.[5,6] The structures of the phenol derivatives, including the (*E*) stereochemistry of the alkene moiety, were established on the basis of their spectral properties as well as a complete X-ray crystal structure of **3a**.[7]

The above rearrangements are envisaged to involve ring expansion of the cyclobutenones **1** to the corresponding *o*-quinone methides **2**. These, in turn, suffer a 1,5-hydrogen shift thus leading to the 2-ethenylphenols **3**. It is of interest that even though precedents exist for the 1,5-hydrogen shift within *o*-quinone methides, the reaction has not been generally employed as a synthetically viable reaction.[8,9] This is likely due to the fact that until now no general regiospecific route to these intermediates was available.

The ring expansion reaction also provides a useful route to alkyl quinones, i.e., oxidation of the initially formed 2-alkenylphenols (hydroquinones). A synthetically useful and mechanistically interesting reaction of

[⊗] Abstract published in *Advance ACS Abstracts,* December 15, 1995.

(1) For lead references concerning the synthesis of substituted cyclobutenones, see: Schmidt, A. H.; Ried, W. *Synthesis* **1978**, 1. Knorr, H.; Ried, W. *Synthesis* **1978**, 649. Schmidt, A. H.; Ried, W. *Synthesis* **1978**, 869. Reed, M. W.; Pollart, D. J.; Perri, S. T.; Foland, L. D.; Moore, H. W. *J. Org. Chem.* **1988**, *53*, 2477. Liebeskind, L. S.; Fengl, R. W.; Wirtz, K. R.; Shawe, T. T. *J. Org. Chem.* **1988**, *53*, 2482. Liebeskind, L. S.; Fengl, R. W. *J. Org. Chem.* **1990,** *55*, 5359. Liebeskind, L. S.; Wirtz, K. R. *J. Org. Chem.* **1990**, *55*, 5350. Liebeskind, L. S.; Wang, J. *Tetrahedron Lett.* **1990**, 4293.

(2) Excellent reviews of allene chemistry are the following: Moreau, J. L. In *The Chemistry of Ketenes, Allenes and Related Compounds*; Patai, S., Ed.; Wiley: New York, 1980; p 363. Schuster, H. E.; Coppola, G. M. *Allenes In Organic Synthesis*; Wiley: New York, 1984. For a specific reference to 1-lithio-1-methoxyallene, see: Hoff, S.; Brandsma, L.; Arens, J. F. *Recl. Trav. Chim. Pays-Bas* **1968**, *87*, 916. Weiberth, F. J.; Hall, S. S. *J. Org. Chem.* **1985**, *50*, 5308.

(3) For reviews on the chemistry of quinone methides, see: Veciana, J.; Martinez, A. D.; Armet, O. *Rev. Chem. Intermed.* **1988**, *10* (1), 35−70. Volod'kin, A. A.; Ershov, V. V. *Usp. Khim.* **1988**, *57* (4), 595−624. Also see the following and references cited therein; Angle, S. R.; Arnaiz, D. O. *J. Org. Chem.* **1990**, *55*, 3708−10. Angle, S. R.; Turnbull, K. D. *J. Am. Chem. Soc.* **1990**, *112*, 3698−700. Angle, S. R.; Yang, W. *J. Am. Chem. Soc.* **1990**, *112*, 4524−8. Angle, S. R.; Louie, M. S.; Mattson, H. L.; Yang, W. *Tetrahedron Lett.* **1989**, 30, 1193−6. Angle, S. R.; Turnbull, K. D. *J. Am. Chem. Soc.* **1989**, *111*, 1136−8.

(4) Allenes in this series are conveniently prepared from readily available propargyl ethers. See for examples: Corey, E. J.; Terashim, S. *Tetrahedron Lett.* **1972**, 1819. Leroux, Y.; Roman, C. *Tetrahedron Lett.* **1973**, 2585. Mantione, R.; Leroux, Y. *Tetrahedron Lett.* **1971**, 593.

(5) For a recent detailed reviews on related ring expansions of cyclobutenones, see: Moore, H. W.; Yerxa, B. R. *Chemtracts: Org. Chem.* **1992**, *5*, 273. Moore, H. W.; Yerxa, B. R. *Advances in Strain in Organic Chemistry*; JAI: London, 1995; Vol. 4.

(6) For reviews on the synthetic utility of vinylsilanes, see: Fleming, I. *Kem. Kemi* **1982**, *9*(5), 365. Huang, Z. *Huaxue Shiji* **1991**, *13* (1), 32. Overman, L. E. *Lect. Heterocycl. Chem.* **1985**, *8*, 59.

(7) The authors have deposited atomic coordinates for compound **3a** with the Cambridge Crystallographic Data Centre. The coordinates can be obtained, on request, from the Director, Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge, CB2 1EZ, UK.

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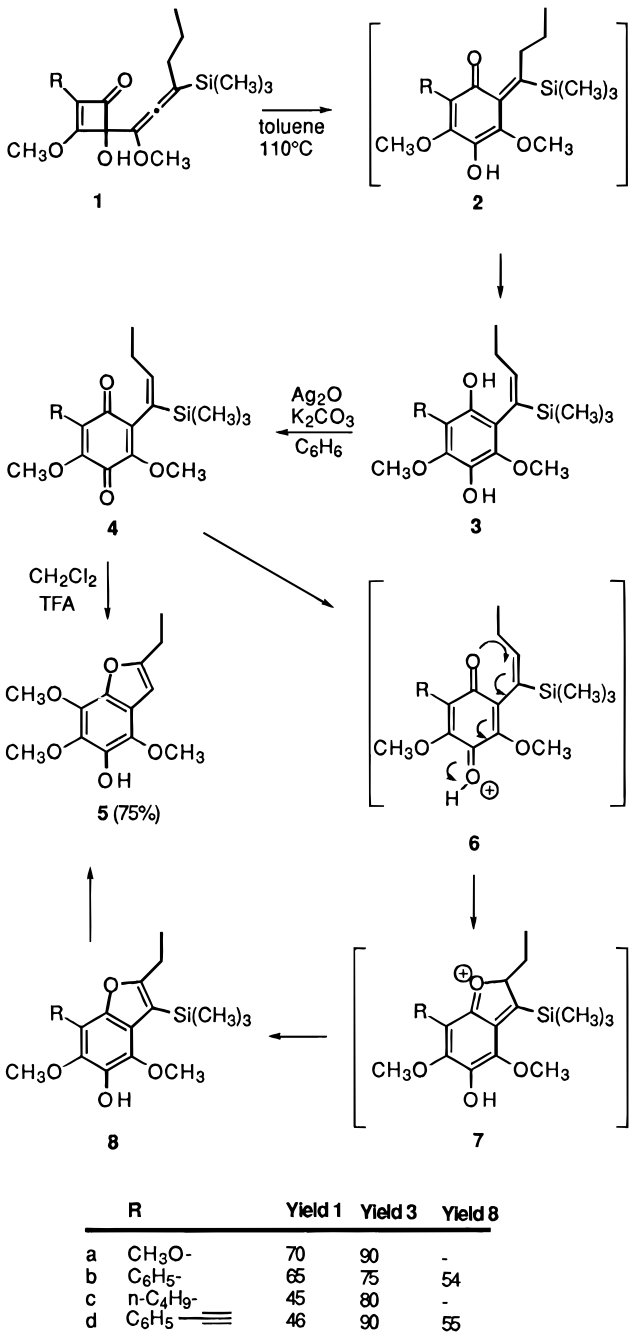
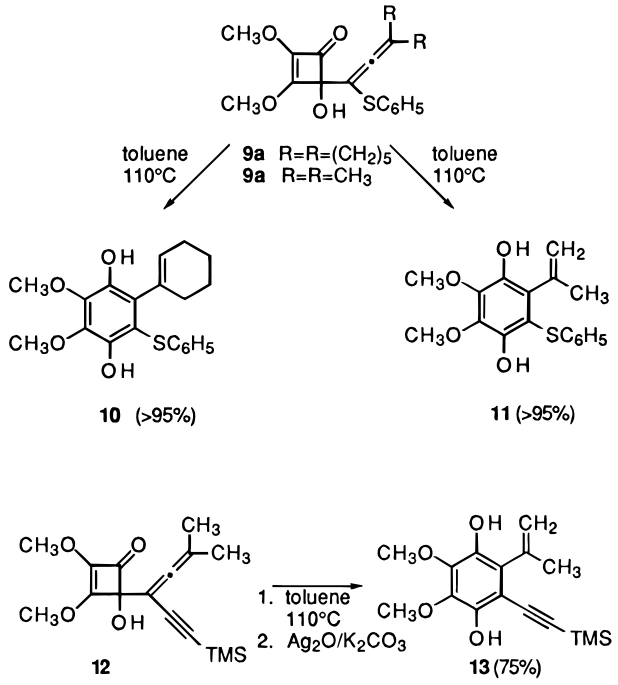
Scheme 1



	R	Yield 1	Yield 3	Yield 8
a	CH_3O-	70	90	-
b	C_6H_5-	65	75	54
c	n-C_4H_9-	45	80	-
d	C_6H_5—≡	46	90	55

such quinones is illustrated by the isomerization of the quinone **4a** to benzofuran **8** and ultimately to the desilylated analog **5**. This was accomplished in 75% overall yield starting from the hydroquinone **3a**, i.e., oxidation (Ag_2O) of **3a** to quinone **4a** (90%) followed by its treatment with trifluoroacetic acid (TFA). The transformation is envisaged to involve formation of cation **6** upon protonation of **4a**, ring closure to **7**, and finally proton loss. The resulting trimethylsilyl-substituted benzofuran **8** then undergoes protiodesilylation to give **5**.

Scheme 2



A modification of the above procedure allows the silylbenzofurans to be prepared in reasonable overall yields from the corresponding vinyl hydroquinones. For example, when the hydroquinones **3b** and **3d** were subjected to oxidation (Ag_2O) and benzene solutions of the resulting crude quinone products **4b** and **4d** were refluxed in the presence of silica gel, the silylbenzofurans **8b** and **8d** were obtained in 54 and 55% yields, respectively.

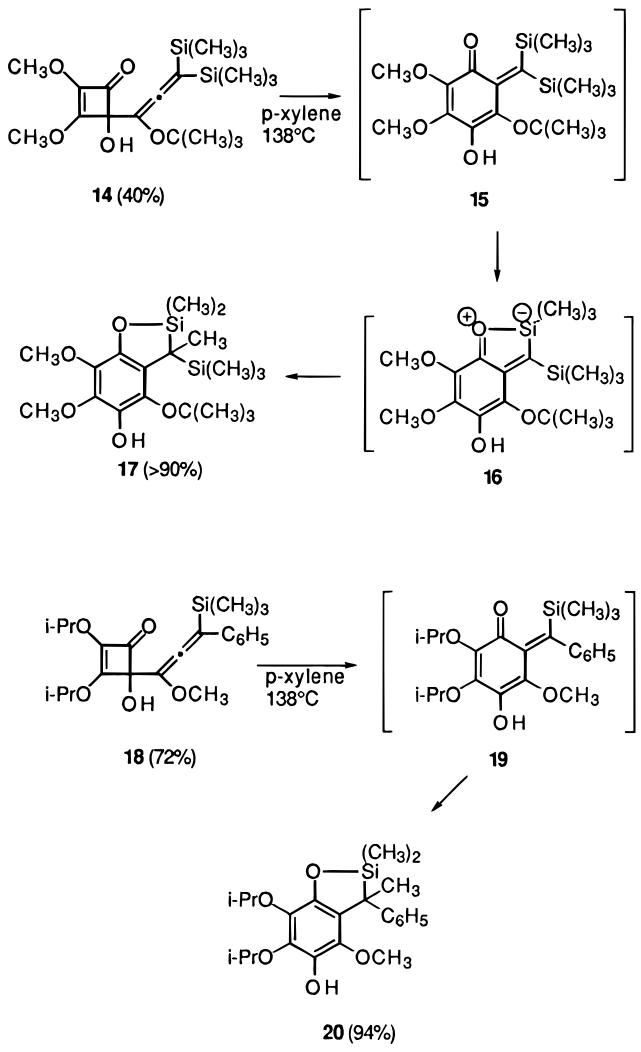
The potential generality of the vinylhydroquinone/vinylquinone/benzofuran synthesis is further illustrated by the observation that the starting vinyl quinones are readily available from 4-allenylcyclobutenones as illustrated by the examples outlined in Scheme 2. Specifically, the cyclobutenones **9a** (70%), **9b** (70%), and **12** (34%) were prepared from dimethyl squarate and the corresponding allenyllithium reagents. The vinyl hydroquinones **10** and **11** were obtained in nearly quantitative yields from **9a** and **9b**, respectively (toluene, 110 °C). In an analogous manner, thermolysis of **12** gave the quinone **13** (75%) after subsequent oxidation of the initially formed hydroquinone.

Generation and Rearrangement of Selected Trimethylsilyl-Substituted *o*-Quinone Methides: Synthesis of Benzoxasilols. The convergent synthesis of 4-allenylcyclobutenones and the propensity of these cyclobutenones to rearrange provide a potentially general route to *o*-quinone methides having unique or unusual structures. In this regard, an example showing interesting chemistry associated with a previously unknown class of *o*-quinone methide is found in a new carbon−carbon bond forming reaction (Scheme 3). Specifically, the cyclobutenone **14** [40% yield from dimethyl squarate and 1-lithio-1-*tert*-butoxy-3,3-bis(trimethylsilyl)propadiene] was initially targeted as a potential precursor to the quinone methide **15**, a sterically hindered and thus possibly isolable example. However, under the thermolysis conditions employed (toluene, 110 °C), **14** undergoes an unusual intramolecular rearrangement to **17** (>90%). In a similar fashion, the analogous phenyl analog **18** gives **20** (94%) *via* the *o*-quinone methide **19**. The spectral and

(8) For examples of 1,5-hydrogen shift involving *o*-quinone methides, see: Yamashita, A.; Toy, A.; Scahill, T. A. *J. Org. Chem.* **1989**, *54*, 3625. Yamashita, A. *J. Am. Chem. Soc.* **1985**, *107*, 5823. Yamashita, A.; Scahill, T. A.; Chidester, C. G. *Tetrahedron Lett.* **1985**, 1159. Arduni, A.; Pochini, A.; Ungaro, R. *Synthesis* **1984**, 950. Jurd, D. *Aust. J. Chem.* **1978**, *31*, 347. Casnati, G.; Pochini, A.; Terenghi, G. M.; Ungaro, R. *J. Org. Chem.* **1983**, *48*, 3783.

(9) Boger, D. L.; Weinreb, S. N. *Hetero Diels−Alder Methodology in Organic Synthesis*; Academic Press Inc.: London, 1987; pp 193−199.

Scheme 3



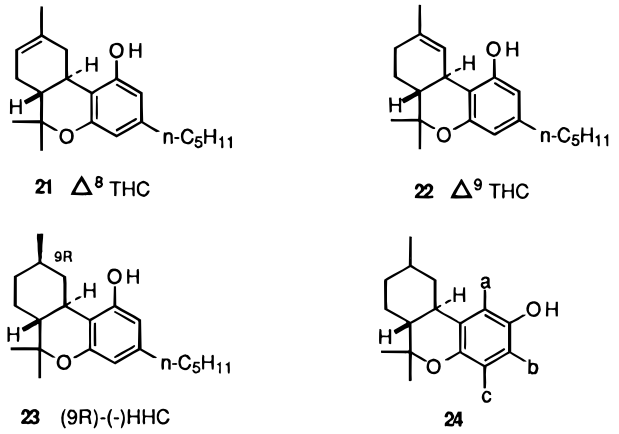
analytical data for **17** and **20** are in accord with their assigned structures; particularly revealing is their ^{1}H NMR spectra which show the C−CH_3 absorption at 1.59 ppm for **17** and 1.85 ppm for **20**.

These rearrangements apparently involve hypervalent silicate intermediates ("ate complex") such as **16** which lead to **17** upon methyl migration from silicon to carbon. Analogies for this rearrangement appear to be rare; one example is the thermal rearrangement of α-acetoxy silanes to the corresponding silyl acetates with concurrent migration of an alkyl or aryl group from silicon to carbon.[10]

For comparison, it is of interest to note that *o*-quinone methides bearing an alkyl group and a trimethylsilyl group (**2a,b**) at the alkylidene terminus undergo the 1,5-hydrogen shift while those such as **15** and **19** undergo methyl migration.

Enantiospecific Synthesis of Aryl Analogs of Hexahydrocannabinol. The cyclobutenone/*o*-quinone methide rearrangement is an attractive method for the synthesis of a variety of annulated ring systems. For example, it is ideally suited for the generation of appropriately substituted *o*-quinone methides that lead to annulated products *via* subsequent intramolecular hetero-Diels−Alder cycloadditions. In this regard, work outlining a potentially general route to enantiomerically pure aryl analogs of hexahydrocannabinol is presented here. Since the cannabinoids have been observed to show marked antinausea activity new routes to analogs are important.

The natural cannabinoids, Δ^8-tetrahydrocannabinol (THC) (**21**) and Δ^9-THC (**22**), are the major psychoactive constituents of marijuana (hashish). These and related analogs have attracted medical interest since they show promising biological activities that include antiemetic, analgesic, and psychotropic effects.[11,12] The enantiomerically pure hexahydrocannabinoid analog **23** [(9*R*)-(−)-HHC] has attracted much attention since clinical evaluations showed it to have psychotropic activity similar to that of natural Δ^8-THC, **21**.[13]



The cyclobutenone/*o*-quinone methide rearrangement is an attractive method for the synthesis of enantiomerically pure aryl analogs of cannabinoids having the general structure **24**. A tandem ring expansion/cycloaddition sequence was employed for the synthesis of the hexahydrocannabinol analogs **33a**, **33b** (Scheme 5), and **38** (Scheme 6). This method is potentially general and could conceivably be used to prepare a large number of HHC analogs. It is particularly attractive for aryl analogs since the aromatic moiety translates to the cyclobutenones' ring, and a variety of methods are now available for their regiospecific synthesis.[1,5]

The synthesis initiates from (*R*)-5,9-dimethyl-3-(trimethylsilyl)-1-decyn-8-ene, **28**, which was prepared in 32% overall yield starting with commercially available (*R*)-(−)-citronellyl bromide (**25**) (Scheme 4). Treatment of this with lithio(trimethylsilyl)ethyne in a mixed solvent system of THF and DMSO gave the alkyne **26** in 70% isolated yield. This was lithiated at the propargylic position using *tert*-butyllithium in THF at −23 °C. Quenching the reaction with chlorotrimethylsilane gave **27** which was immediately deprotected [$AgNO_3$ in C_2H_5-OH(aq) followed by KCN(aq)] to give **28** (45%).

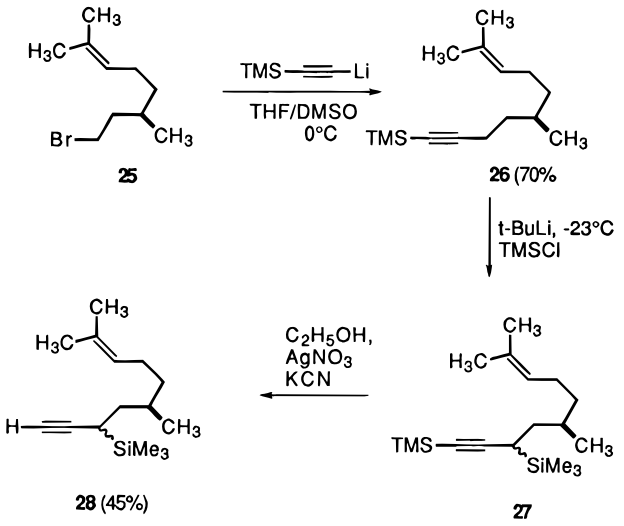
(10) Buynak, J. D.; Strickland, J. B.; Lamb, G. W.; Khasnis, D.; Modi, S.; Williams, D.; Zhang, H. *J. Org. Chem.* **1991**, *56*, 7076. Bassindale, A. R.; Brook, A. G.; Jones, P. F.; Lennon, J. M. *Can. J. Chem.* **1975**, *53*, 332. Reetz, M. T.; Greif, N. *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 712. Tacke, R.; Lange, H. *Chem. Ber.* **1983**, *116*, 3585.

(11) Makriyannis, A; Rapaka, R. S. *Life Sci.* **1990**, *47*, 2173.

(12) (a) *Cannabinoids as Therapeutic Agents*; Mechoulam, R., Ed.; CRC Press, Inc.: Boca Raton, FL, 1986. (b) Little, P. J.; Compton, D. R.; Johnson, M. R.; Melvin, L. S.; Martin, B. R. *J. Pharmacol. Exp. Ther.* **1988**, *247*, 1046. (c) Feigenbaum, J. J.; Richmond, S. A.; Weissman, Y.; Mechoulam, R. *Eur. J. Pharmacol.* **1989**, *169*, 159. (d) Tius, M. A.; Busch-Petersen, J. *Tetrahedron Lett.* **1994**, *35*, 5181. (e) Tius, M. A.; Kannangara, G. S. K. *J. Org. Chem.* **1990**, *55*, 5711. (f) Yan, G.; Yan, G.; Yin, D.; Khanolka, A. D.; Compton, D. R.; Martin, B. R.; Makriyannis, A. *J. Med. Chem.* **1994**, *37*, 2619.

(13) Mechoulam, R.; Lander, N.; Varkony, T. H.; Kimmel, I.; Becker, O.; Ben-Zri, Z. *J. Med. Chem.* **1980**, *23*, 1068.

Scheme 4



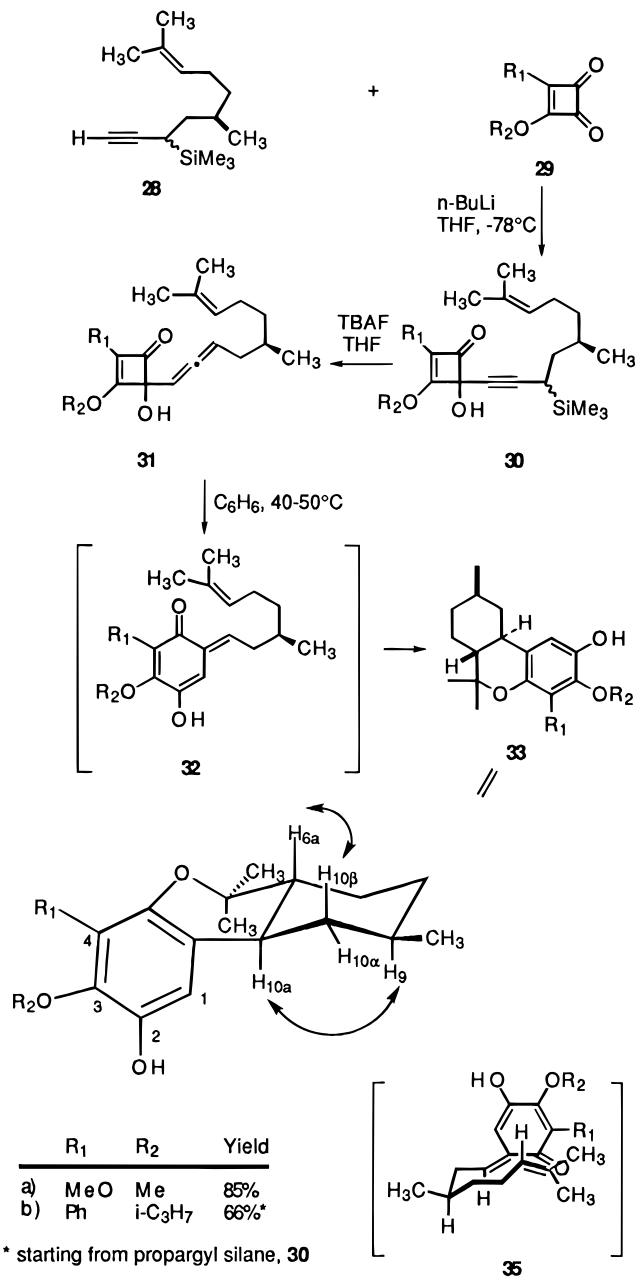
Addition of the lithium salt of **28** to the cyclobutenediones **29a,b** gave the corresponding 4-alkynylcyclobutenones **30a,b** in 71−80% yield. The desired allenylcyclobutenones **31a,b** were then readily obtained (80−84%) upon treatment of **30a,b** with tetra-*n*-butylammonium fluoride (TBAF) in THF. Heating a benzene solution of **31a** at 50 °C for 36 h gave **33a** (85%) *via* the *o*-quinone methide **32a**. In comparison, **31b** rearranged under similar conditions (40 °C, 7 h) to the cannabinoid **33b** in 79% isolated yield.

In a manner analogous to the above, (*S*)-(−)-citronellyl bromide provided the (*S*)-isomer of the propargyl silane **36**, and this led to the (*S*)-enantiomer of hexahydrocannabinol **38** in 67% overall yield (Scheme 6).

The stereochemistry of **33a** was determined by the following spectroscopic experiments. The assignment of the chemical shifts for different protons in the ring system was established by ^{1}H NMR and confirmed by a 2-D COSY experiment. From the analysis of the ^{1}H NMR spectrum, both H_{10a} and H_{6a} appear as a doublet of triplets at δ 2.34 (J = 11.4, 3.7 Hz) and 1.36 (J = 11.7, 2.6 Hz), respectively. The observed coupling constants are the result of *trans*-diaxial coupling between H_{10a} and the adjacent protons ($H_{10\beta}$, H_{6a}) and the axial−equatorial coupling between H_{10a} and $H_{10\alpha}$. Similarly, H_{6a} is coupled to the axial protons (H_{10a}, $H_{7\alpha}$) and the equatorial proton ($H_{7\beta}$).[13] Further evidence of the *trans*-fused juncture was revealed by a NOESY experiment. The appearance of the NOE between H_{10a}−H_9 and H_{6a}−$H_{10\beta}$ confirms the relative 1,3-diaxial positions of those pairs of protons as indicated in the three-dimensional structure of **33a** (Scheme 5). Analogous stereochemistry is assumed for **33b** and **38**.

A mechanism accounting for the above stereostructures is based upon a chair transition state, **35**, having the methyl group at position 9 in an equatorial position. This postulate is in strict agreement with the work of Marino and Dax who reported a related synthesis of hexahydrocannabinol *via* a method utilizing an intramolecular hetero-Diels−Alder cycloaddition to an *o*-quinone methide.[14,15]

Scheme 5

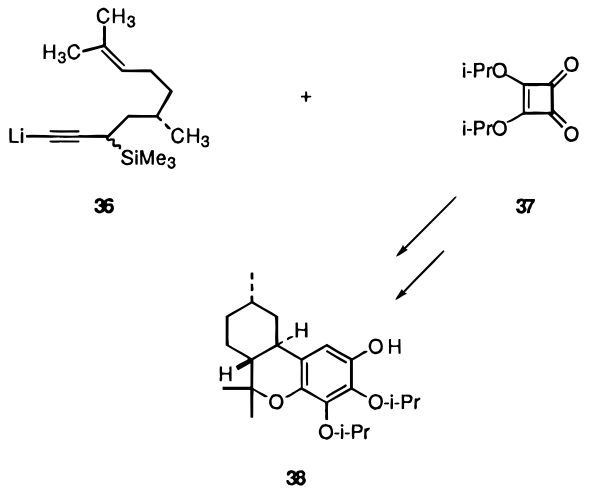


***o*-Quinone Methide Configurational Equilibration and Equilibration between Selected 2-(1-Methylethenyl)-1,4-benzenediols and *o*-Quinone Methides.** The thermally induced 4-allenylcyclobutenone ring expansion as described herein is ideally suited to probe mechanistic questions concerning the reactivity and structure of *o*-quinone methide intermediates. For example, the rearrangement is accomplished under neutral conditions while most other routes to *o*-quinone methides require oxidation or reaction conditions that induce elimination reactions. As a result, reagents are often present that trap the quinone methide intermediates at low concentrations.

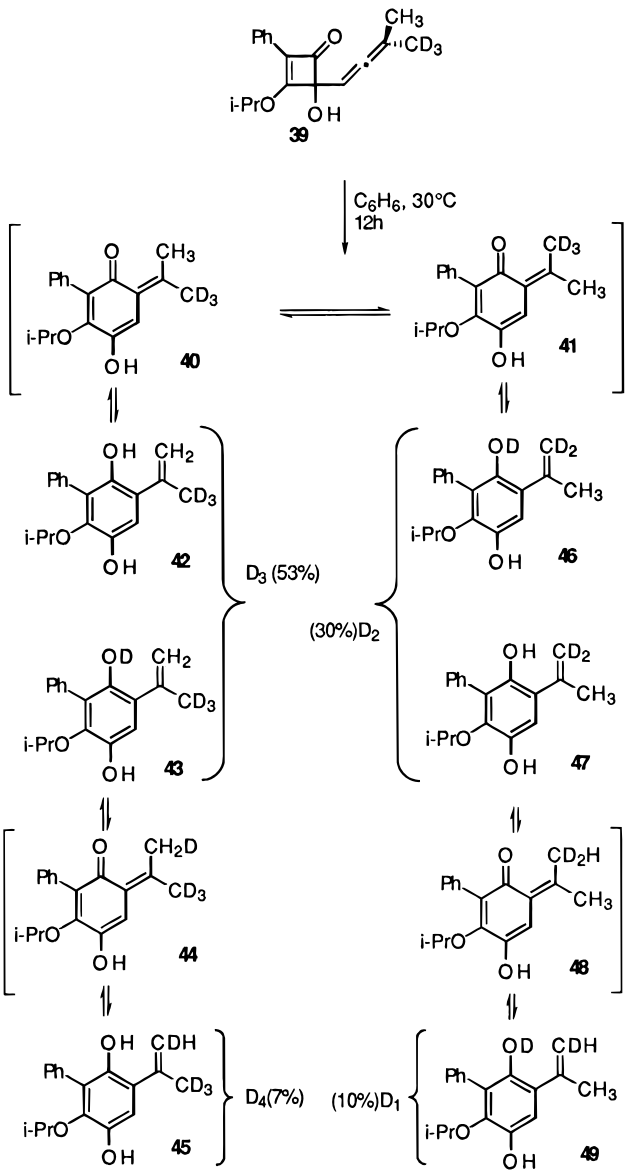
One question of interest, for which no clear answer has previously been reported, concerns the facility of configurational equilibrium around the alkylidene group of *o*-quinone methides. The answer was sought by investigating the thermolysis of **39** and determining the extent of deuterium scrambling (Scheme 7). *This study revealed the presence of an equilibration between the o-quinone*

(14) Marino, J. P.; Dax, S. L. *J. Org. Chem.* **1984**, *49*, 3671.
(15) For a related synthesis of hexahydrocannabanol itself, see: Tietze, L.-F.; Kiedrowski, G.; Harms, K.; Clegg, W.; Sheldrick, G. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 134. Archer, R. A.; Boyd, D. B.; Demarco, P. V.; Tyminski, I. J.; Allinger, N. L. *J. Am. Chem. Soc.* **1990**, *92*, 5200.

Scheme 6



Scheme 7



*methides (**40** and **41**) as well as between quinone methides and 2-ethenylphenols (e.g., **40** and **42**) even at 30 °C.* Specifically, when a benzene solution of **39** (1:1 mixture of diastereomers as revealed by ^{1}H NMR) was allowed to stand at 30 °C for 12 h, it rearranged to a mixture of deuterated 2-ethenylphenols in >95% overall yield. This mixture was observed to be composed of phenols containing one, two, three, and four deuterium atoms. As revealed by mass spectrometric analysis, after correction for the ^{13}C satellite peak, the ratio of the D_1:D_2:D_3:D_4 products was 7 (D_1):30 (D_2):53 (D_3):10 (D_4). [It is noted that none of the deuterium is associated with the exchangeable phenolic hydroxyl group since the mixture of vinylphenols was subjected to chromatographic purification (SiO_2) prior to mass spectral analysis.] Since the size of CH_3 and CD_3 are effectively the same, it is assumed that the *o*-quinone methides **40** and **41** are initially formed in equal amounts. It is also assumed that no significant secondary isotope effect is operative in the electrocyclic ring closure of the ketene intermediates to the corresponding *o*-quinone methides. With these assumptions in mind, the above results provide the foundation for the following conclusions:

1. Since **45** (D_4) and **49** (D_1) are formed in the reaction, an equilibrium between the *o*-quinone methides and the vinylphenols must exist.

2. The fact that **45** and **49** are formed in nearly equal amounts suggests the presence of a significant isotope effect in the 1,5-hydrogen shift reaction leading to the vinylphenols from the quinone methides. That is, a primary isotope effect would significantly reduce the amount of **49** relative to that of **45**, and apparently does to the extent that **45** and **49** are formed in nearly equal amounts. Indeed, if a primary isotope effect was not present, the amount of **49** (D_1) should be significantly greater than that of **45** (D_4) since there are more sources of exchangable protons than deuterons, i.e., proton sources for D_1 (**49**) include **42, 43, 45, 46, 47,** and **49** (nine protons) while deuteron sources for D_4 (**45**) are **43, 46** and **49** (3 deuterons).

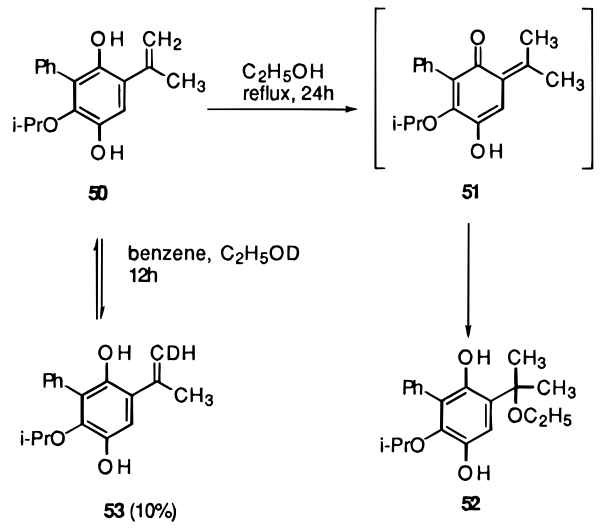
3. The above proposed isotope effect which seemingly reduces the amount of **49** (D_1) along with the observations that D_3 (**42** + **43**) is significantly greater than D_2 (**46** + **47**) shows that the quinone methides, e.g., **40** and **41**, are in equilibrium under the conditions of the reaction.

Trapping experiments that confirm the vinylphenol/*o*-quinone methide equilibration are outlined below. Specifically, when an ethanolic solution of the ethenylphenol **50** was refluxed for 24 h, a mixture composed of approximately 25% starting material and 75% of the ethanol adduct **52** was realized (^{1}H NMR analysis) (Scheme 8). Michael addition of ethanol to the enone of the *o*-quinone methide accounts for the observed product **52**.

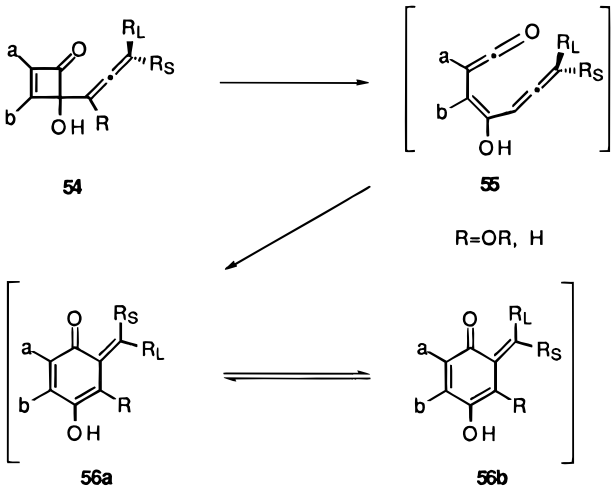
Further evidence was gained from a related experiment showing deuterium incorporation when a benzene solution containing 10 equiv of C_2H_5OD and 1 equiv of ethenylphenol **50** was held at 30 °C for 12 h (Scheme 8). Under these conditions, the ethenylphenol−*O-d* would be generated *in situ* and is apparently in equilibrium with the deuterated quinone methide which leads to the deuterated phenol **53**. The mass spectrum of the product showed a 10% (corrected) enhancement of the m + 1 peak at *m*/*z* 285 associated with the monodeuterated ethenylphenol **53**.

Mechanism. Inspection of the reactions involving *o*-quinone methides as outlined in this paper reveals an apparent common selectivity. Specifically, for those *o*-quinone methides bearing two different groups on the alkylidene terminus, the products appear to arise from the intermediate having the larger group disposed *trans* to the carbonyl moiety, i.e., presumably the countrath-

Scheme 8



Scheme 9



ermodynamic *o*-quinone methide for **2** and **19** and the thermodynamic isomer for **32**. For example, the trimethylsilyl group (A = 2.5 kcal mol^{-1}) in **2** is larger than the propyl (A = approximately 1.79 kcal mol^{-1}), and thus hydrogen transfer is available from the *E*-isomer; likewise, the phenyl group (A = 2.8 kcal mol^{-1}) in the quinone methide **19** is slightly larger than the trimethylsilyl substituent, thus allowing formation of the "ate" complex and ultimate methyl migration to give **20**.[16] Finally, the alkyl group in **32** is significantly larger than the proton, and the indicated *E*-isomer is required to account for the observed stereochemistry in the hexahydrocannabinoids **33a,b** and **38**.

A mechanistic paradigm accounting for the above reactions is outlined in Scheme 9. Here, the cyclobutenone **54** undergoes torquoselective[17] electrocyclic ring opening with outward rotation of the 4-hydroxy group to generate the trienylketene **55**. It is reasonable to assume that an early transition state for the electrocyclic ring closure of the reactive ketene intermediate dictates the structure of the initially formed *o*-quinone methide **56a.** Thus, steric interactions between the substituents (R_S and R_L) and the ketene carbonyl group are more important than analogous interactions involving the ring-based group (*R*). As a result, the alkylidene group in the *o*-quinone methide product would be formed by a rotation mode in which the larger group (R_L) rotates away from the carbonyl group and toward the R group, thus resulting in the quinone methides generally represented by **56a**, even for those cases leading to the countrathermodynamic isomer. This process is further complimented by the configurational equilibration of the *o*-quinone methides (**56a**/**56b**), a process shown herein to be facile for a specific example, i.e., **40**/**41**. Thus, even though the reactions outlined above can be rationalized as being dictated by the "birth" of the specific configurational isomer of the *o*-quinone methide (**56a**), this assumption is not necessarily valid for all cases. Rather, for those transformations experiencing a rapid equilibrium between the *E*- and *Z*-isomers (**56a** and **56b**), product formation would be controlled by subsequent and slower rate events.

Conclusions

In conclusion, the following significant points are noted: 1) the reactions presented here add to the growing importance of the ring expansions of cyclobutenones to a variety of other ring systems including benzo- and naphthoquinones, chlorophenols, benzofurans, methylenebenzofurans, bicyclo[3.2.0]heptenones, indolizines, indolizine-5,8-diones, [3.2.2]cyclazines, 2-alkylidene-1,3-cyclopentenediones, spiroepoxycyclohexadienones, and *p*-quinone methides;[5] (2) the route to *o*-quinone methides presented here is arguably the most versatile method for the generation of highly-substituted examples; (3) utilization of *o*-quinone methides as a regiospecific route to highly-substituted 2-alkenylphenols and benzofurans is presented as a useful synthetic reaction; (4) a new carbon−carbon bond-forming reaction is described which involves an unprecedented reaction of trimethylsilyl-substituted *o*-quinone methides; (5) a potentially general route to highly-substituted aryl analogs of hexahydrocannabinol is presented; (6) data are presented that establish a low barrier to rotation around the alkylidene group of selected *o*-quinone methides; and (7) an equilibrium between 2-(1-methylethenyl)-1,4-benzenediols and the corresponding *o*-quinone methides was established.

Experimental Section

General Procedure. All reactions were carried out in flame-dried glassware under a positive pressure of dry nitrogen. Tetrahydrofuran (THF) was distilled from sodium (benzophenone indicator). Benzene, toluene, and *p*-xylene were distilled from calcium hydride. Solvents were removed by a Buchi rotary evaporator at 15−30 Torr. All reactions were followed by TLC using E. Merck silica gel 60 F-254. Flash column chromatography was performed by using E. Merck silica gel (230−400 mesh).

Many of the cyclobutenone derivatives described here are mixtures of diastereomers. These are generally unstable compounds and tend to readily rearrange *via* the ring expansion pathways outlined in this paper. As a result, it is not possible to purify the individual diastereomers. Thus, spectral properties are presented for the mixtures. When obvious, the ^{1}H NMR absorptions for analogous protons of the individual diastereomers are presented in brackets, and the proton count is recorded for the sum of the peaks within the brackets. When

(16) *A* values were taken from the following reference: Eliel, E. L.; Wilen, S. H. *Stereochemistry of Organic Compounds*; Wiley and Sons, Inc: New York, 1994.

(17) Kirmse, W.; Rondam, N. G.; Houk, K. N. *J. Am. Chem. Soc.* **1989**, *111*, 975. Niwayama, S.; Kallel, E. A.; Houk, K. N. *J. Org. Chem.*, in press.

the mixture shows an enhancement of one isomer over the other, the first peak listed in the brackets is for the major isomer.

2,3-Dimethoxy-4-hydroxy-4-(1-methoxy-3-(trimethylsilyl)-1,2-hexadienyl)-2-cyclobuten-1-one (1a) [Mixture of Diastereomers]. *n*-Butyllithium (0.845 mmol, 1.6 M, 0.5 mL) was added (syringe) to a solution of 1-methoxy-3-(trimethylsilyl)-1,2-hexadiene[18] (0.170 g, 0.922 mmol) in freshly distilled THF (10 mL) at −78 °C. After 30 min (stirring), the resulting yellow solution was transferred *via* cannula to a flask containing a solution of dimethyl squarate (0.100 g, 0.705 mmol) in 20 mL of THF at −78 °C. The resulting solution was stirred for another 10 min followed by the addition of a mixture of distilled water and ether (25 + 20 mL). The aqueous portion was extracted with ether (3 × 10 mL). The combined organic layers were washed with brine (3 × 20 mL) and dried over anhyd $MgSO_4$. Purification was achieved by flash column chromatography (SiO_2, Hexane:EtOAc, 4:1) to afford 0.160 g (70%) of **1a** as a yellow oil (mixture of diastereomers 1:1): R_f 0.12 (Hexane:EtOAc, 4:1); ^{1}H NMR (500 MHz, $CDCl_3$) δ [4.05/4.06] (s, 3H), 3.94 (s, 3H), [3.37/3.38] (s, 3H), [2.84/2.94] (s, 1H), 2.09−2.13 (m, 2H), 1.42−1.53 (m, 2H), 0.90−0.94 (m, 3H), [0.09/0.12] (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 192.9, 192.7, 183.1, 164.3, 164.0, 135.5, 129.6, 129.3, 124.7, 124.4, 85.2, 85.1, 59.6, 59.5, 58.4, 56.4, 56.3, 34.4, 34.3, 22.1, 22.0, 14.0, 13.9, −1.76, −1.86; IR (neat) 3414, 2955, 1931, 1777, 1643 cm^{-1}; MS (CI) *m*/*z* calcd for $C_{16}H_{26}O_5Si$ 326.1549, found 326.1518; 327 (100), 309 (54), 295 (60), 253 (1), 237 (10), 223 (12).

4-Hydroxy-3-methoxy-2-phenyl-4-(1-methoxy-3-(trimethylsilyl)-1,2-hexadienyl)-2-cyclobuten-1-one (1b) [Mixture of Diastereomers]. In a manner analogous to that used for the preparation and purification of **1a**, 1-methoxy-3-(trimethylsilyl)-1,2-hexadiene (120 mg, 0.64 mmol) and 3-methoxy-4-phenyl-3-cyclobutene-1,2-dione (0.100 g, 0.530 mmol) gave 0.13 g (65%) of **1b** as a yellow oil (mixture of diastereomers 6:1): ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.74−7.76 (m, 2H), 7.34 (t, J = 7.50 Hz, 2H), 7.24−7.27 (m, 1H), [4.23/4.21] (s, 3H), [3.41/3.42] (s, 3H), 3.07 (s, 1H), 2.13−2.16 (m, 2H), 1.46−1.51 (m, 2H), 0.93 (t, J = 7.30 Hz, 3H), [0.13/0.12] (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 192.3, 186.5, 178.6, 129.9, 128.7, 128.4, 128.0, 127.1, 126.8, 125.8, 90.4, 59.6, 56.5, 34.5, 22.2, 14.0, −1.80; IR (neat) 3535, 2959, 1927, 1758, 1638 cm^{-1}; MS (CI) *m*/*z* calcd for $C_{21}H_{28}O_4Si$ 372.1757, found 372.1758; 373 (100), 359 (9), 341 (22), 329 (1), 285 (4), 269 (5), 146 (6).

2-*n*-Butyl-4-hydroxy-3-methoxy-4-(1-methoxy-3-(trimethylsilyl)-1,2-hexadienyl)-2-cyclobuten-1-one (1c) [Mixture of Diastereomers]. In a manner similar to the above, 1-methoxy-3-(trimethylsilyl)-1,2-hexadiene (300 mg, 1.60 mmol) and 2-*n*-butyl-3-methoxy-3-cyclobutene-1,2-dione (139 mg, 1.39 mmol) gave 0.22 g (45%) of **1c** as a colorless oil (mixture of diastereomers 3:2): ^{1}H NMR (500 MHz, $CDCl_3$) δ [4.04/4.05] (s, 3H), [3.37/3.36] (s, 3H), [3.06/2.94] (s, 1H), 2.06−2.12 (m, 4H), 1.45−1.49 (m, 4H), 1.30 (sextet, J = 7.7 Hz, 2H), 0.91 (dt, J = 10.3, 7.33 Hz, 3H), 0.86 (t, J = 7.33 Hz, 3H), [0.12/0.08] (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 192.8, 192.6, 189.1, 180.0, 179.9, 140.2, 138.1, 130.5, 130.4, 129.8, 129.4, 124.9, 124.7, 89.4, 89.3, 59.1, 58.9, 56.3, 34.5, 34.4, 29.2, 22.4, 22.1, 21.7, 14.0, 13.9, 13.7, −1.72, −1.84; IR (neat) 3531, 2956, 2872, 1930, 1754, 1619, cm^{-1}; MS (CI) *m*/*z* calcd for $C_{19}H_{32}O_4Si$ 352.2069, found 352.2055; 354 (24), 353 (87), 352 (100), 337 (10), 322 (9), 321 (21), 311 (11), 309 (26).

4-Hydroxy-3-methoxy-2-(phenylethynyl)-4-(1-methoxy-3-(trimethylsilyl)-1,2-hexadienyl)-2-cyclobuten-1-one (1d) (Mixture of Diastereomers). In a manner similar to the above, 1-methoxy-3-(trimethylsilyl)-1,2-hexadiene (0.613 mmol, 0.113 g) and 3-methoxy-4-(phenylethynyl)-3-cyclobutene-1,2-dione (0.111 g, 0.524 mmol) gave 0.1 g (46%) of **1d** as a yellow oil (mixture of diastereomers 3:2): R_f 0.17 (Hexane:EtOAc, 4:1); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.43−7.45 (m, 2H), 7.30−7.33 (m, 3H), [4.36/4.35] (s, 3H), 3.41 (s, 3H), [3.00/2.98] (s, 1H), 2.12−2.16 (m, 2H), 1.49−1.52 (m, 2H), 0.95 (q, J = 7.33 Hz, 3H), [0.15/0.13] (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 192.2, 192.1, 185.9, 185.8, 182.6, 182.4, 131.6, 128.9, 128.5, 128.3, 125.5, 125.4, 122.2, 110.3, 93.6, 93.6, 90.1, 75.7, 60.9, 60.8, 56.5, 56.4, 34.4, 34.3, 22.2, 22.1, 14.1, 14.0, −1.80, −1.73; IR (neat) 3372, 2955, 1933, 1761, 1620 cm^{-1}; MS (CI) *m*/*z* calcd for $C_{23}H_{28}O_4Si$ 396.1757, found 396.1742; 399 (7), 398 (22), 397 (64), 396 (100), 382 (6), 366 (10), 355 (8).

3,5,6-Trimethoxy-2-(1-(trimethylsilyl)-1(*E*)-butenyl)-1,4-benzenediol (3a). A solution of **1a** (56.4 mg, 0.173 mmol) in freshly distilled toluene (50 mL) was heated at reflux for 4 h. The solvent was then removed, and the crude product was purified by flash column chromatography (SiO_2, Hexane:EtOAc, 4:1) to afford 51 mg (90%) of **3a** as a yellow oil: R_f 0.25 (Hexane:EtOAc, 4:1); ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.15 (t, J = 6.9 Hz, 1H), 5.31 (s, 1H), 4.97 (s, 1H), 3.94 (s, 3H), 3.86 (s, 3H), 3.63 (s, 3H), 1.95−2.00 (m, 2H), 0.96 (t, J = 7.3 Hz, 3H), 0.046 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 147.4, 139.6, 138.4, 137.4, 136.1, 135.3, 134.8, 117.1, 61.0, 60.9, 24.4, 13.1, −1.02; IR (neat) 3439, 2959, 2838, 1610 cm^{-1}; MS (EI) *m*/*z* calcd for $C_{16}H_{26}O_5Si$ 326.1549, found 326.1553; 326 (36), 309 (6), 296 (25), 279 (37), 265 (20), 251 (43), 237 (8), 221 (12), 207 (11), 193 (9), 179 (5), 109 (11), 89 (28), 73 (100), 59 (36).

3,5-Dimethoxy-6-phenyl-2-(1-(trimethylsilyl)-1(*E*)-butenyl)-1,4-benzenediol (3b). In a manner similar to the above, **1b** (60.0 mg, 0.161 mmol) gave 45 mg (75%) of **3b** as a yellow oil: R_f 0.28 (Hexane:EtOAc, 6:1); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.42−7.48 (m, 4H), 7.34−7.36 (m, 1H), 6.30 (t, J = 6.97 Hz, 1H), 5.37 (s, 1H), 4.70 (s, 1H), 3.77 (s, 3H), 3.47 (s, 3H), 2.04−2.07 (m, 2H), 1.0 (t, J = 7.7 Hz, 3H), 0.11 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 148.9, 143.6, 143.1, 141.0, 135.8, 135.5, 133.6, 130.5, 128.1, 127.1, 116.9, 60.6, 60.4, 24.5, 13.2, −1.01; IR (neat) 3517, 2960, 2896, 2834, 1614 cm^{-1}; MS (EI) *m*/*z* calcd for $C_{21}H_{28}O_4Si$ 372.1757, found 372.1754; 374 (6), 373 (26), 372 (100), 370 (7), 357 (8), 329 (21), 315 (6), 161 (14).

5-*n*-Butyl-3,5-dimethoxy-2-(1-(trimethylsilyl)-1(*E*)-butenyl)-1,4-benzenediol (3c). In a manner similar to the above, **1c** (59.5 mg, 0.168 mmol) gave 57 mg (95%) of **3c** as a light yellow oil: R_f 0.43 (Hexane:EtOAc, 4:1); ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.31 (t, J = 6.97 Hz, 1H), 5.21 (s, 1H), 4.65 (s, 1H), 3.85 (s, 3H), 3.65 (s, 3H), 2.60 (t, J = 7.7 Hz, 2H), 2.00 (dt, J = 2.57, 7.33 Hz, 2H), 1.50−1.53 (m, 2H), 1.34−1.39 (m, 2H), 0.98 (t, J = 7.33 Hz, 3H), 0.91 (t, J = 7.33 Hz, 3H), 0.06 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 149.1, 144.4, 141.8, 141.6, 136.3, 135.3, 117.6, 115.9, 61.0, 60.4, 32.0, 24.3, 23.9, 22.8, 13.9, 13.1, −1.13; IR (neat) 3531, 2956, 2872, 1619 cm^{-1}; MS (EI) *m*/*z* calcd for $C_{19}H_{32}O_4Si$ 352.2070, found 352.2055; 354 (7), 353 (30), 352 (100), 350 (9), 337 (7), 310 (17), 309 (91), 294 (5), 279 (5), 277 (11).

3,5-Dimethoxy-6-(phenylethynyl)-2-(1-(trimethylsilyl)-1(*E*)-butenyl)-1,4-benzenediol (3d). In a manner similar to the above, **1d** (62.0 mg, 0.156 mmol) gave 58 mg (90%) of **3d** as a slightly red oil: R_f 0.30 (Hexane:EtOAc, 4:1); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.54−7.56 (m, 2H), 7.32−7.36 (m, 3H), 6.23 (t, J = 6.90 Hz, 1H), 5.37 (s, 1H), 5.28 (s, 1H), 4.10 (s, 3H), 3.75 (s, 3H), 1.98−2.02 (m, 2H), 1.00 (t, J = 7.3 Hz, 3H), 0.09 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 148.2, 146.1, 145.7, 145.1, 135.3, 134.9, 131.4, 128.3, 123.1, 116.9, 98.7, 98.2, 81.0, 61.2, 60.4, 24.5, 13.2, −0.95; IR (neat) 3512, 2960, 2207, 1596, 1495 cm^{-1}; MS (CI) 397 (100) *m*/*z* calcd for $C_{23}H_{28}O_4Si$ 396.1757, found 396.1753; MS (EI) *m*/*z* 396 (7), 379 (2), 364 (14), 349 (10), 105 (8), 73 (100).

3,5,6-Trimethoxy-2-(1-(trimethylsilyl)-1(*E*)-butenyl)-2,5-cyclohexadiene-1,4-dione (4a). Compound **1a** (51.8 mg, 0.16 mmol) was converted to **3a** as described above. The crude product was dissolved in anhyd benzene (10 mL), and Ag_2O (0.15 g, 0.65 mmol) and K_2CO_3 (0.10 g, 0.72 mmol) were added. After 3 h of stirring at ambient temperature, the mixture was filtered through a pad of Celite and rinsed with several portions of ether. Purification was achieved by flash column chromatography (hex:EtOAc, 4:1) to afford 47.3 mg (90%) of **4a** as a red oil: R_f 0.33 (hex:EtOAc, 4:1); ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.01 (t, J = 7.0 Hz, 1H), 3.97 (s, 6H), 3.83 (s, 3H), 1.85−1.88 (m, 2H), 0.92 (t, J = 7.5 Hz, 3H), 0.044 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 183.4, 180.1, 151.6, 146.8, 144.1, 142.5, 132.7, 129.1, 61.2, 61.1, 60.6, 25.1, 13.1, −1.06; IR (neat) 2954, 1661, 1614, 1588 cm^{-1}; MS (CI) *m*/*z* calcd for $C_{16}H_{24}O_5Si$ 324.1393, found 324.1382; 325 (83), 324 (53), 310 (32), 309 (65), 295 (20), 294 (100), 285 (13), 279 (24), 95 (10), 79 (10).

(18) (a) Mantione, R.; Leroux, Y. *Tetrahedron Lett.* **1971**, 593. (b) Mantione, R.; Leroux, Y. *J. Organomet. Chem.* **1971**, *31*, 15.

2-Ethyl-5-hydroxy-4,6,7-trimethoxybenzofuran (5). To a solution of quinone **4a** (22.6 mg, 0.07 mmol) in anhyd CH_2Cl_2 (5 mL) was added TFA in excess (approximately 0.4 mL) at 0 °C with stirring. The solution was allowed to stir at ambient temperature for 2 days after which the solvent was removed and the crude product purified by flash chromatography (SiO_2, hex:EtOAc, 4:1) to afford 13.2 mg (75%) of **5a** as a light brown oil: R_f 0.2 (hex:EtOAc, 4:1); ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.41 (s, 1H), 5.50 (s, 1H), 4.10 (s, 3H), 3.98 (s, 3H), 3.96 (s, 3H), 2.76 (q, J = 7.40 Hz, 2H), 1.31 (t, J = 7.50 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 160.4, 140.2, 136.9, 136.4, 133.8, 133.2, 117.9, 98.4, 61.6, 60.9, 60.5, 21.6, 11.8; IR (neat) 3423, 3118, 2974, 2938, 2836, 1610, 1500 cm^{-1}; MS (CI) m/z calcd for $C_{13}H_{16}O_5$ 252.0998, found 252.0970; 253 (61), 252 (100), 238 (24).

2-Ethyl-7-phenyl-5-hydroxy-4,6-dimethoxy-3-(trimethysilyl)benzofuran (8b). Thermolysis of **1b** (45.3 mg, 0.122 mmol) gave quinone **4b** as a red oil after oxidation of the hydroquinone **3b** (Ag_2O). The crude quinone product was dissolved with benzene (30 mL), and silica gel (0.50 g) was added. The mixture was refluxed overnight. The red solution turned yellow in color during the reflux time. After filtration and removal of the solvent, the residue was purified by flash column chromatography (SiO_2, hex:EtOAc, 8:1) to give 24.3 mg (54%) of compound **8b** as a brown oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.72 (d, J = 7.0 Hz, 2H), 7.46−7.49 (m, 2H), 7.26−7.38 (m, 1H), 5.66 (s, 1H), 4.11 (s, 3H), 3.46 (s, 3H), 2.75 (q, J = 7.44 Hz, 2H), 1.22 (t, J = 7.41 Hz, 3H), 0.38 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 165.1, 146.2, 142.6, 139.0, 136.7, 132.9, 130.0, 128.3, 127.3, 122.5, 112.4, 105.9, 61.3, 60.1, 22.3, 14.1, 1.01; IR (neat) 3511, 2937, 1617, 1559 cm^{-1}; HRMS (EI) calcd for $C_{22}H_{26}O_4Si$ 370.1600, found 370.1617; m/z 371 (76), 370 (100), 355 (57), 340 (27), 325 (12), 308 (11), 170 (8), 113 (5), 89 (10).

2-Ethyl-5-hydroxy-4,6-dimethoxy-7-(phenylethynyl)-3-(trimethysilyl)benzofuran (8d). In a manner similar to the preparation of **8b** quinone **4d** (26.5 mg, 0.067 mmol) and silica gel (73 mg) gave 14.6 mg (55%) of **8d** as a yellow oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.59−7.61 (m, 2H), 7.26−7.37 (m, 3H), 5.56 (s, 1H), 4.15 (s, 3H), 4.10 (s, 3H), 2.81 (q, J = 7.49 Hz, 2H), 1.31 (t, J = 7.57 Hz, 3H), 0.35 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 165.1, 149.0, 146.1, 140.8, 140.3, 136.1, 131.4, 128.3, 128.2, 123.5, 122.0, 106.4, 97.0, 94.2, 80.6, 61.9, 60.1, 22.3, 14.2, 1.50; IR (neat) 3510, 2939, 2195, 1507 cm^{-1}; HRMS (EI) calcd for $C_{23}H_{26}O_4Si$ 394.1600, found 394.1598; m/z 396 (9), 395 (31), 394 (100), 379 (17), 364 (12), 349 (8), 190 (3), 175 (6), 159 (3), 73 (32).

1-(Phenylsulfinyl)-3,3-(pentamethylene)allene. Benzenethiol (0.54 mL) was slowly added at ambient temperature to a slurry of *N*-chlorosuccinimide (2.0 g, 15.3 mmol) in freshly distilled methylene chloride (12 mL). Once the reaction initiated, as evidenced by an intense red color, the remaining benzenethiol (a total of 1.65 g, 15 mmol) was added over a period of 5−10 min (caution! exothermic reaction). The resulting red-colored solution was stirred for another 30 min and then transferred in 10 portions over a period of 10 min *via* cannula to a solution of 1-ethynyl-1-cyclohexanol in ether (50 mL) and triethylamine (4 mL) at −78 °C. The reaction mixture was allowed to stir for 2 h at −78 °C and then 1.5 h at ambient temperature. The reaction was quenched with water (30 mL) and then extracted with ether (3 × 20 mL). The combined organic layers were washed with 1 N hydrochloric acid (3 × 20 mL), 10% potassium carbonate solution (3 × 10 mL), and brine and dried over magnesium sulfate. Purification was achieved by flash chromatography (SiO_2, hex:EtOAc, 2:1) to afford 1.85 g (53%) of the title compound as a light yellow oil. It solidified upon refrigeration: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.60−7.70 (m, 2H), 7.45−7.55 (m, 3H), 5.92 (s, 1H), 2.10−2.30 (m, 4H), 1.45−1.65 (m, 6H); IR (neat) 3054, 2931, 2853, 1949 cm^{-1}.

1-(Phenylthio)-3,3-(pentamethylene)allene. Pyridine (0.68 g, 8.6 mmol) followed by P_2S_5 (0.24 g, 1.08 mmol) was added to a solution of (phenylsulfonyl)vinylidenecyclohexane (0.500 g, 2.15 mmol) in freshly distilled methylene chloride (30 mL). The solution was stirred for 2.5 h, the solvent was removed, and the residue was purified by flash column chromatography (SiO_2, Hexanes) to afford 0.276 g (60%) of the allene as a yellow oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.40 (d, J = 7.5 Hz, 2H), 7.30 (t, J = 7.5 Hz, 2H), 7.20 (t, J = 7.5 Hz, 1H), 5.60 (s, 1H), 2.10−2.30 (m, 4H), 1.40−1.70 (m, 6H); IR (neat) 3058, 2929, 2853, 1949, 1582 cm^{-1}.

2,3-Dimethoxy-4-hydroxy-4-(1-(phenylthio)-3,3-(pentamethylene)-1,2-propadienyl)-2-cyclobuten-1-one (9a). In a manner analogous to that used for the preparation of **1a**, dimethyl squarate (0.104 g, 0.703 mmol) and 1-(phenylthio)-3,3-(pentamethylene)allene (0.160 g, 0.738 mmol) gave 0.175 g (70%) of **9a** as a light yellow solid: mp 94−95 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.42−7.48 (m, 2H), 7.22−7.32 (m, 3H), 3.96 (s, 3H), 3.93 (s, 3H), 3.16 (s, 1H), 2.00−2.20 (m, 4H), 1.35−1.60 (m, 6H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 197.4, 183.0, 164.2, 135.9, 134.3, 132.0, 128.8, 127.5, 113.0, 99.5, 87.2, 76.9, 59.6, 58.5, 31.1, 31.0, 27.1, 27.0, 25.5; IR (neat) 3376, 2930, 2853, 1949, 1774, 1629 cm^{-1}; HRMS (EI) calcd for $C_{20}H_{22}O_4S$ 358.1238, found 358.1232; m/z 358 (100), 343 (11), 281 (28), 249 (53). Anal. Calcd: C, 67.02; H, 6.19. Found: C, 67.00; H, 6.32.

6-(1-Cyclohexenyl)-2,3-dimethoxy-5-(phenylthio)-1,4-benzenediol (10). In a manner analogous to that used for the preparation of **2,** the cyclobutenone **9a** (52.9 mg, 0.148 mmol) gave 51.2 mg (97%) of **10** as a light brown oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.19 (t, J = 7.70 Hz, 2H), 7.10 (t, J = 7.70 Hz, 1H), 7.00 (d, J = 7.70 Hz, 2H), 6.30 (s, 1H), 5.39 (s, 1H), 5.34 (s, 1H), 4.02 (s, 3H), 3.95 (s, 3H), 2.00−2.01 (m, 4H), 1.58−1.70 (m, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 145.0, 142.3, 139.6, 138.8, 137.2, 133.2, 130.4, 128.9, 128.8, 126.6, 125.6, 110.2, 61.1, 60.9, 29.2, 25.2, 22.7, 21.8; IR (neat) 3406, 2932, 2831, 1579 cm^{-1}; HRMS (EI) calcd for $C_{20}H_{22}O_4S$ 358.1238, found 358.1248; m/z 358 (100), 343 (12), 281 (31), 250 (11), 249 (61), 234 (10).

6-(1-Cyclohexenyl)-2,3-dimethoxy-5-(phenylthio)-2,5-cyclohexadiene-1,4-dione. To a solution of **10** (46.6 mg, 0.13 mmol) in anhyd benzene (5 mL) were added K_2CO_3 (0.10 g, 0.78 mmol) and Ag_2O (0.12 g, 0.52 mmol). After 10 min of stirring at ambient temperature, the reaction mixture was filtered through a pad of Celite and rinsed with several portions of ether. Purification was achieved by flash column chromatography (hex:EtOAc, 2:1) to afford 44.8 mg (95%) of the quinone as a red oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.20−7.35 (m, 5H), 5.59 (s, 1H), 4.00 (s, 3H), 3.85 (s, 3H), 2.04−2.12 (m, 4H), 1.54−1.64 (m, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 181.5, 180.2, 147.1, 145.0, 144.8, 141.0, 134.1, 132.0, 131.5, 131.2, 129.0, 127.5, 61.2, 27.9, 25.1, 22.2, 21.4; IR (neat) 2933, 2856, 1654, 1629, 1560 cm^{-1}; HRMS (EI) calcd for $C_{20}H_{20}O_4S$ 356.1082, found 356.1074; m/z 358 (23), 357 (23), 356 (100), 341 (18), 328 (29), 279 (17), 247 (22), 215 (16), 165 (15).

3-Methyl-1-(phenylthio)-1,2-butadiene. *n*-Butyllithium (13.4 mL, 21.5 mmol) was added to a solution of 2-chloro-2-methyl-3-butyne (2.0 g, 19.5 mmol) in freshly distilled THF (30 mL) at −78 °C. The mixture was stirred for 20 min. Thiophenol (2.14 g, 19.5 mmol) in THF (30 mL) was added to a solution of *n*-BuLi (13.4 mL, 21.5 mmol) at −78 °C, and the mixture was stirred for 20 min. The resulting lithium thiophenoxide solution was transferred *via* cannula to the lithiated propagyl chloride solution, and the mixture was allowed to stir for 1 h. The solution temperature was raised to −23 °C (CCl_4/dry ice). After another hour, the reaction was quenched with distilled water (50 mL). The aqueous portion was extracted with ether (3 × 30 mL). The combined organic layers were washed with brine and dried over anhyd $MgSO_4$. Purification was achieved by flash column chromatography (SiO_2, hexanes) to afford 2.0 g (58%) of the allene as a light yellow oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.40 (d, J = 7.0 Hz, 2H), 7.30 (t, J = 7.0 Hz, 2H), 7.02 (t, J = 7.0 Hz, 1H), 5.80 (m, 1H), 1.80 (s, 6H); IR (neat) 3058, 2982, 2910, 1952, 1872, 1795, 1729 cm^{-1}.

2,3-Dimethoxy-4-hydroxy-4-(3-methyl-1-(phenylthio)-1,2-butadienyl)-2-cyclobuten-1-one (9b). In a manner analogous to the preparation of **1a**, butyllithium (0.45 mL, 1.6 M, 0.737 mmol), 3-methyl-1-(phenylthio)-1,2-butadiene (0.130 g, 0.737 mmol) in THF (10 mL), and dimethyl squarate (0.100 g, 0.704 mmol) in THF (20 mL) gave 0.159 g (71%) of **9b** as a white solid: mp 105−106 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ

7.41 (d, J = 6.97 Hz, 2H), 7.24−7.30 (m, 3H), 3.94 (s, 3H), 3.91 (s, 3H), 3.12 (s, 1H), 1.70 (s, 3H), 1.69 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 201.6, 182.8, 164.1, 138.2, 135.9, 134.4, 131.8, 128.7, 127.4, 105.8, 99.3, 87.4, 59.6, 58.5, 20.3, 20.2; IR ($CDCl_3$) 3376, 2982, 2948, 2857, 1954, 1774, 1629 cm^{-1}; HRMS (EI) calcd for $C_{17}H_{18}O_4S$ 318.0926, found 318.0933; m/z 318 (56), 286 (19), 271 (54), 241 (39), 209 (100), 175 (15), 121 (35), 106 (64), 91 (40).

2,3-Dimethoxy-6-(1-methylethenyl)-5-(phenylthio)-1,4-benzenediol (11). A solution of **9b** (52.6 mmol, 0.165 mmol) in freshly distilled toluene (25 mL) was heated to reflux for 1 h. Purification was achieved by flash chromatography (SiO_2, hex:EtOAc, 2:1) to afford a quantitative yield of **11** as a yellow oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.20 (t, J = 7.70 Hz, 2H), 7.10 (t, J = 7.33 Hz, 1H), 7.02 (d, J = 7.33 Hz, 2H), 6.31 (s, 1H), 5.47 (s, 1H), 5.25 (s, 1H), 4.74 (s, 1H), 4.04 (s, 3H), 3.95 (s, 3H), 1.69 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 145.1, 142.3, 140.4, 139.1, 138.9, 136.8, 129.8, 128.9, 125.9, 125.5, 117.0, 108.8, 61.2, 60.9, 23.7; IR (neat) 3409, 3076, 2941, 1582 cm^{-1}; HRMS (EI) calcd for $C_{17}H_{18}O_4S$ 318.0925, found 318.0921; m/z 318 (100), 303 (15), 241 (15), 209 (71).

2,3-Dimethoxy-4-hydroxy-4-(3-methyl-1-((trimethylsilyl)ethynyl)-1,2-butadienyl)-2-cyclobuten-1-one (12). A solution of 1-methyl-6-(trimethylsilyl)-4-(triphenylstannyl)-2,3-hexadien-5-yne[19] in THF (40 mL) was cooled to −78 °C, and methyllithium (0.55 mL, 1.4 M) was added. The resulting yellow solution was stirred for 30 min. Then dimethyl squarate (0.10 g, 0.7 mmol) in THF (10 mL) was transferred at −78 °C *via* cannula to the lithiated allene solution. The mixture turned a light yellow color, and after 10 min, the reaction was quenched with a mixture of H_2O and ether (15 + 10 mL). The aqueous layer was extracted with ether (3 × 30 mL). The combined organic layers were washed with brine and dried over anhyd $MgSO_4$. Concentration in vacuo afforded the crude product which was partially purified by flash column chromatography (SiO_2, hex:EtOAc, 4:1) to afford 74.3 mg of **12** as an orange-colored oil (34%). This was used without further purification: ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.16 (s, 9H), 1.78 (s, 3H), 1.81 (s, 3H), 3.95 (s, 3H), 4.10 (s, 3H); IR (neat) 3384, 2956, 2144, 1952, 1776, 1630 cm^{-1}.

2,3-Dimethoxy-6-isopropenyl-5-((trimethylsilyl)ethynyl)-2,5-cyclohexadiene-1,4-dione (13). A solution of **12** (38.1 mg, 0.124 mmol) in freshly distilled toluene (30 mL) was refluxed under nitrogen for 60 min. The colorless solution turned light yellow during the reflux period. The solvent was removed in vacuo, and the crude hydroquinone was oxidized with Ag_2O (0.30 g) and K_2CO_3 (0.70 g) in benzene (15 mL). The mixture was stirred for 4.5 h and filtered through a pad of Celite. The solvent was removed under reduced pressure. Purification was achieved by flash chromatography (SiO_2, hex:EtOAc, 4:1) to obtain 28.2 mg (75%) of **13** as a red oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.38 (s, 1H), 5.07 (s, 1H), 4.02 (s, 3H), 3.98 (s, 3H), 1.98 (s, 3H), 0.22 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 182.0, 180.4, 148.9, 145.6, 143.7, 137.4, 125.2, 119.5, 113.7, 96.8, 61.3, 61.2, 21.9, −0.6; IR (neat) 2957, 2849, 2151, 1665, 1628 cm^{-1}; HRMS (EI) calcd for $C_{16}H_{20}O_4Si$ 304.1131, found 304.1146; m/z 304 (3), 275 (2.8), 261 (2), 246 (2.2), 231 (2.3), 218 (5.2), 203 (2.8), 190 (2.2), 175 (3.4), 162 (2.4), 147 (13), 73 (100).

1-*tert*-Butoxy-3,3-bis(trimethylsilyl)-1,2-propadiene. *n*-Butyllithium (7.50 mL, 11.9 mmol) was added (syringe) to a solution of 1-*tert*-butoxy-3-(trimethylsilyl)-2-propyne (1.00 g, 5.94 mmol) in freshly distilled ether (3 mL) at −78 °C. After 30 min (stirring), the reaction was quenched with chlorotrimethylsilane (0.75 mL, 5.94 mmol). The mixture was stirred for 1 h, and the reaction was quenched with aqueous ammonium chloride (5%). The aqueous portion was extracted with ether. The combined organic layers were washed with brine and dried over anhyd $MgSO_4$. The crude product was purified by flash chromatography (SiO_2, Hexanes) to afford 0.860 g (56%) of 1-*tert*-butoxy-3,3-bis(trimethylsilyl)-1,2-propadiene as a yellow oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.22 (s, 1H), 1.26 (s, 9H), 0.13 (s, 18H); IR (neat) 2973, 1921 cm^{-1}.

(19) (a) Ruitenberg, K.; Westmijze, H.; Kleijn, H.; Vermeer, P. *J. Organomet. Chem.* **1984**, *277*, 227. (b) Lequan, M.; Guillerm, G. *J. Organomet. Chem.* **1973**, *54*, 153.

2,3-Dimethoxy-4-hydroxy-4-(1-*tert*-butoxy-3,3-bis(trimethylsilyl)-1,2-propadienyl)-2-cyclobuten-1-one (14). *n*-Butyllithium (0.94 mL, 1.6 M, 1.50 mmol) was slowly added (syringe) to a solution of 1-*tert*-butoxy-3,3-bis(trimethylsilyl)-1,2-propadiene (0.385 g, 1.50 mmol) in 20 mL of anhyd THF at −78 °C (N_2). The resulting light yellow solution was stirred for 30 min and then transferred *via* cannula to a flask containing a solution of dimethyl squarate (0.200 g, 1.41 mmol) in 40 mL of THF at −78 °C. The solution was allowed to stir for an additional 15 min, and then equal portions of H_2O and ether (20 + 20 mL) were added. After warming to ambient temperature, the aqueous portion was extracted twice with ether (2 × 10 mL), and the combined organic layers were washed with brine and dried over anhyd $MgSO_4$. The solvent was removed to give a white solid which decomposes at room temperature upon prolonged exposure to air. Purification was achieved by flash column chromatography (silica gel, hexane:EtOAc, 4:1) to afford 0.23 g (40%) of **14** as a white sticky solid: ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.05 (s, 3H), 3.94 (s, 3H), 3.28 (s, 1H), 1.31 (s, 9H), 0.18 (s, 9H), 0.16 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 207.8, 183.8, 164.6, 135.5, 115.7, 113.9, 85.3, 78.8, 59.6, 58.4, 2.40, −0.15, −0.05; IR ($CDCl_3$) 3535, 2956, 2901, 1917, 1776, 1640 cm^{-1}; MS (EI) m/z calcd for $C_{19}H_{34}O_5Si_2$ 398.1945; M^+ − OH, 381 (9), 367 (6), 325 (3), 306 (63), 253 (100), 239 (11), 125 (2), 91 (28).

3-Phenyl-1-methoxy-3-(trimethylsilyl)-1,2-propadiene. To a solution of 1-methoxy-3-phenyl-2-propyne (0.52 g, 3.56 mmol) in freshly distilled ether (15 mL) was added *n*-BuLi (4.44 mL, 7.11 mmol) at −78 °C. The resulting green solution was stirred for 30 min, and the reaction was quenched with chlorotrimethylsilane (0.39 g, 3.58 mmol). After an additional 20 min, a solution of ammonium chloride (5%) was added. The aqueous portion was extracted with ether. The combined organic layers were washed with brine and dried over anhyd $MgSO_4$. The crude product was purified by flash chromatography (SiO_2, Hexanes) to afford 0.46 g (60%) of 3-phenyl-1-methoxy-3-(trimethylsilyl)-1,2-propadiene as a yellow oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.40 (d, J = 6.5 Hz, 2H), 7.35 (t, J = 7.5 Hz, 2H), 7.25 (t, J = 7.5 Hz, 1H), 6.90 (s, 1H), 3.40 (s, 3H), 0.30 (s, 9H); IR (neat) 2955, 1915, 1679 cm^{-1}.

2,3-Diisopropoxy-4-hydroxy-4-(1-methoxy-3-phenyl-3-(trimethylsilyl)-1,2-propadienyl)-2-cyclobuten-1-one (18) (Mixture of Diastereomers). In a manner similar to the preparation of **14**, 1-methoxy-3-phenyl-3-(trimethylsilyl)-1,2-propadiene (0.54 mmol, 0.118 g) and diisopropyl squarate (0.097 g, 0.49 mmol) gave 0.148 g (72%) of **18** as a yellow oil (mixture of diastereomers 1:1): R_f 0.39 (hex:EtOAc, 2:1); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.20−7.50 (m, 5H), 4.75−4.95 (m, 2H), [3.45/3.50] (s, 3H), [3.18/2.92] (s, 1H), 1.15−1.40 (m, 12H), [0.30/0.25] (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 198.1, 198.0, 182.6, 163.7, 162.9, 137.7, 137.3, 133.6, 133.6, 130.8, 130.4, 128.4, 127.7, 127.5, 127.3, 127.21, 123.9, 123.3, 85.0, 84.9, 76.8, 56.5, 22.6, 22.6, 22.5, 22.3, 22.1, −0.44, −0.47; IR (Neat) 3406, 2979, 2899, 2834, 1921, 1772, 1631 cm^{-1}; MS (EI) m/z calcd for $C_{23}H_{32}O_5Si$ 416.2019, found 416.2010; 416 (18), 401 (17), 359 (20), 331 (26), 317 (100), 300 (15), 240 (14), 227 (23), 158 (59), 115 (9), 73 (84).

4-(1,1-Dimethylethoxy)-2,3-dihydro-6,7-dimethoxy-2,2,3-trimethyl-3-(trimethylsilyl)-1,2-benzoxasilol-5-ol (17). A solution of **14** (52.1 mg, 0.131 mmol) in freshly distilled *p*-xylene (50 mL) was refluxed under nitrogen for 40 min. The clear solution turned light yellow during the reflux period. Removal of the solvent gave a yellow oil which was purified by flash column chromatography (SiO_2, Hexane:EtOAc, 9:1) to give a quantitative yield of **17** as a colorless oil: R_f 0.45 (Hexane:EtOAc, 4:1); ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.39 (s, 1H), 3.92 (s, 3H), 3.83 (s, 3H), 1.59 (s, 3H), 1.45 (s, 9H), 0.51 (S, 3H), 0.18 (s, 3H), −0.04 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 143.0, 138.9, 137.7, 136.1, 135.1, 123.4, 80.6, 61.3, 60.7, 29.7, 21.6, 15.9, −0.98, −1.84, −3.29; IR ($CDCl_3$) 3515, 2974, 1603 cm^{-1}; MS (CI) m/z calcd for $C_{19}H_{34}O_5Si_2$ 398.1945, found 398.1942; MS (EI) 398 (4), 342 (13), 327 (100), 311 (12), 296 (32), 279 (6), 259 (9), 237 (12), 192 (8), 133 (9), 97 (7), 73 (92), 57 (78); DEPT C (quaternary) 142.99, 138.86, 137.69, 136.12, 135.13, 123.40, 80.62, 21.60; (CH_3) 61.33, 60.70, 29.67, 15.93, −0.98, −1.84, −3.29.

4-Methoxy-2,3-dihydro-6,7-diisopropoxy-2,2,3-trimethyl-3-phenyl-1,2-benzoxasilol-5-ol (20). In a manner similar to the above, **18** (50.6 mg, 0.121 mmol) gave 47.6 mg (94%) of **20** as a light yellow oil: R_f 0.53 (hex:EtOAc, 2:1); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.20−7.23 (m, 2H), 7.07−7.00 (m, 3H), 5.26 (s, 1H), 4.74−4.79 (m, 1H), 4.44−4.48 (m, 1H), 3.32 (s, 3H), 1.85 (s, 3H), 1.29−1.32 (m, 12H), 0.35 (s, 3H), −0.13 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 147.1, 144.8, 141.3, 138.3, 137.4, 133.8, 128.0, 125.7, 125.1, 124.3, 75.2, 75.0, 59.5, 36.9, 22.6, 22.5, 22.4, 20.5, −2.30, −2.84; IR (Neat) 3521, 2973, 2934, 1597 cm^{-1}; MS (EI) *m*/*z* calcd for $C_{23}H_{32}O_5Si$ 416.2019, found 416.2019; 416 (100), 373 (19), 331 (73), 316 (34), 240 (43), 75 (10).

(*R*)-5,9-Dimethyl-1-(trimethylsilyl)-dec-8-en-1-yne (26). *n*-Butyllithium (4.4 mL, 1.6 M, 11 mmol) was added dropwise to a solution of trimethylsilyacetylene (1.10 g, 11 mmol) in THF (8 mL) at −78 °C. After 25 min, the dry ice/acetone bath was replaced with an ice bath (0 °C). To this solution was slowly added (*R*)-citronellyl bromide (2.0 g, 9.13 mmol) followed by anhyd DMSO (33 mL). After 10 min, the resulting slurry was allowed to warm to ambient temperature and was stirred for 4 h. The reaction mixture was then poured into ice cold water (30 mL). The aqueous portion was extracted with ether (4 × 10 mL). The combined extracts were washed with brine and dried over $MgSO_4$. The crude oil was filtered through a short path of silica gel, eluting with a solvent mixture of petroleum ether and diethylether (20:1) to afford 1.51 g (70%, >90% pure) of **26** as a colorless oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.09 (t, J = 7.0 Hz, 1H), 2.14−2.28 (m, 2H), 1.90−2.04 (m, 2H), 1.67 (s, 3H), 1.60 (s, 3H), 1.50−1.58 (m, 2H), 1.28−1.38 (m, 2H), 1.10−1.18 (m, 1H), 0.87 (d, J = 6.6 Hz, 3 Hz), 0.13 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 131.2, 124.8, 107.9, 84.2, 36.7, 35.8, 31.7, 25.8, 25.5, 19.2, 17.7, 17.6, 0.21; IR (neat) 2961, 2927, 2871, 2175 cm^{-1}; HRMS (CI) calcd for $C_{15}H_{28}Si$ 236.1960, found 236.1967; *m*/*z* 236 (16), 221 (21), 163 (40), 162 (100), 147 (28), 107 (31).

5,9-Dimethyl-3-(trimethylsilyl)-dec-8-en-1-yne (28) (Mixture of Diastereomers). *tert*-Butyllithium (4.2 mL, 1.7 M, 7.10 mmol) was added to a solution of **26** (1.40 g, 5.92 mmol) in THF (10 mL) at −23 °C. After 2 h of stirring, this solution was cooled to −78 °C, and the reaction was quenched with chlorotrimethylsilane (0.80 g, 7.40 mmol). After 10 min, the cold bath was removed to allow the solution to warm to ambient temperature. An aqueous workup was accomplished according to a reported procedure to afford the crude product **27** which was used without further purification.[20] Desilylation of the terminal acetylene was accomplished as described in the literature[20] to afford **28** (0.63 g, 45%) as a colorless oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.10 (m, 1H), 1.90−2.05 (m, 3H), 1.70−1.80 (m, 2H), 1.68 (s, 3H), 1.61 (s, 3H), 1.45−1.55 (m, 1H), 1.20−1.40 (m, 2H), 0.95−1.05 (m, 1H), 0.94, 0.87 (d, J = 7.0 Hz, 3H), 0.08 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 131.0, 125.0, 124.9, 86.9, 68.1, 37.9, 36.2, 35.8, 34.8, 31.7, 31.4, 25.7, 25.2, 20.3, 18.2, 17.7, 17.0, −3.4; IR (neat) 3315, 2959, 2918, 2852, 2099 cm^{-1}; HRMS (CI) calcd for $C_{15}H_{28}Si$ 236.1960, found 236.1970; *m*/*z* 236 (6), 221 (40), 163 (43), 162 (100), 147 (42).

2,3-Dimethoxy-4-hydroxy-4-(3-(trimethylsilyl)-5,9-dimethyldec-8-en-1-ynyl)-2-cyclobuten-1-one (30a) (Mixture of Diastereomers). *n*-Butyllithium (0.83 mmol, 0.52 mL, 1.6 M) was added dropwise to a solution of (5*R*)-3-(trimethylsilyl)-5,9-dimethyldec-8-en-1-ynyl (**28**) (0.83 mmol, 0.20 g) in THF (10 mL) at −78 °C, and the resulting reaction mixture was allowed to stir for 30 min. Then a solution of dimethyl squarate (0.703 mmol, 0.100 g) in THF (10 mL) at −78 °C was transferred *via* cannula to the lithiated alkyne solution. After an additional 10 min of stirring, the reaction was quenched with 2 mL of ammonium chloride (10%). The solution was allowed to warmed up to ambient temperature and was poured into a separatory funnel containing NH_4Cl (10%) and ether (5 + 5 mL). The aqueous portion was extracted with ether (3 × 5 mL). The combined organic layers were washed with brine (3 × 5 mL) and dried over anhyd $MgSO_4$. The crude product was purified by flash column chromatography (SiO_2, hex:EtOAc, 4:1) to afford **30a** (0.19 g, 71%) as a yellow oil (mixture of diastereomers): R_f 0.47 (hex:EtOAc, 2:1); ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.10 (m, 1H), 4.16 (s, 3H), 3.93 (s, 3H), 3.10 (m, 1H), 1.85−2.05 (m, 2H), 1.75−1.80 (m, 1H), 1.67 (s, 3H), 1.59 (s, 3H), 1.15−1.50 (m, 4H), 0.95−1.10 (m, 1H), [0.83 /0.85] (d and d, J = 6.6 Hz, 3H), 0.06 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 181.4, 165.2, 135.2, 131.0, 124.8, 93.4, 93.1, 79.0, 74.9, 59.6, 58.4, 37.7, 36.0, 35.8, 35.1, 32.1, 31.8, 25.5, 25.1, 20.1, 18.3, 17.7, 17.5, −3.3; IR (Neat) 3333, 2955, 2917, 2857, 2216, 1778, 1634 cm^{-1}; MS (CI) *m*/*z* calcd for $C_{21}H_{34}O_4Si$ 378.2226, found 378.2211; 379 (26), 361 (31) 347 (100), 331 (27), 319 (16), 303 (18), 291 (28), 275 (21), 267 (16), 251 (16), 225 (22).

4-Hydroxy-3-isopropoxy-2-phenyl-4-(3-(trimethylsilyl)-5,9-dimethyldec-8-en-1-ynyl)-2-cyclobuten-1-one (30b) (Mixture of Diastereomers). In a manner similar to the above, 3-isopropoxy-4-phenyl-3-cyclobutene-1,2-dione (0.462 mmol, 0.100 g) and (5*R*)-3-(trimethylsilyl)-5,9-dimethyldec-8-en-1-ynyl (0.508 mmol, 0.12 g) gave 0.169 g (80%) of **30b** (mixture of diastereomers): R_f 0.28 (hex:EtOAc, 6:1); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.75 (d, J = 8.43 Hz, 2H), 7.35 (t, J = 7.70 Hz, 2H), 7.25 (t, J = 7.30 Hz, 1H), 5.30−5.40 (m, 1H), 5.05 (s, 1H), 4.00−4.20 (m, 1H), 0.95−2.00 (m, 20H), [0.85 /0.90] (dd, dd, J = 7.4, 3.7 Hz, 3H), 0.02 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 185.4, 185.3, 185.2, 178.1, 178.0, 131.0, 129.1, 128.3, 127.9, 126.9, 125.0, 124.9, 124.8, 94.5, 94.3, 94.2, 84.1, 79.3, 75.0, 37.8, 36.1, 35.8, 35.0, 32.0, 31.7, 25.6, 25.1, 25.0, 23.3, 23.2, 23.0, 20.2, 18.2, 17.8, 17.7, 17.5, −3.2, −3.3; IR (Neat) 3277, 2959, 2919, 2214, 1748, 1628 cm^{-1}; MS (CI) *m*/*z* calcd for $C_{28}H_{40}O_3Si$ 452.2747, found 452.2747; 453 (100), 435 (12), 411 (40), 395 (13), 381 (10), 329 (10), 287 (16).

2,3-Dimethoxy-4-hydroxy-4-(5,9-dimethyldec-8-ene-1,2-dienyl)-2-cyclobuten-1-one (31a) (Mixture of Diastereomers). A solution of **30a** (0.114 mmol, 43.3 mg) in THF (4 mL) was treated with TBAF (0.172 mmol, 0.17 mL, 1 M in THF) with stirring at ambient temperature. After 15 min, the reaction was quenched with distilled H_2O (5 mL). The aqueous portion was separated and extracted with ether (3 × 5 mL). The combined organic layers were washed with brine, dried over anhyd $MgSO_4$, and then concentrated under vacuum to afford a crude product which was purified by flash column chromatography (SiO_2, hex:EtOAc, 2:1) to afford 30.8 mg (88%) of **31a** as a light yellow oil (mixture of diastereomers): R_f 0.28 (hex:EtOAc, 2:1); ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.40−5.5 (m, 1H), 5.30 (m, 1H), 5.05−5.10 (m, 1H), 3.90 (s, 3H), 4.30 (s, 3H), 3.15 (s, 1H), 1.90−2.15 (m, 4H), 1.65 (s, 3H), 1.60 (s, 3H), 1.50−1.60 (m, 1H), 1.30−1.40 (m, 1H), 1.10−1.20 (m, 1H), 0.88−0.94 (m, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 203.2, 184.6, 184.5, 166.3, 134.1, 131.4, 124.5, 95.9, 95.7, 91.0, 90.8, 84.3, 59.9, 59.8, 58.5, 36.5, 36.5, 36.2, 36.2, 32.7, 32.6, 25.7, 25.5, 19.3, 17.7; IR (Neat) 3373, 2956, 2921, 2855, 1962, 1774, 1627 cm^{-1}; MS (EI) *m*/*z* calcd for $C_{18}H_{26}O_4$ 306.1831, found 306.1827; 306 (37), 263 (19), 221 (13), 196 (17), 183 (100), 167 (11), 159 (21), 109 (19), 81 (21), 69 (65).

(6a*R*,9*R*,10a*R*)-6,6,9-Trimethyl-2-hydroxy-3,4-dimethoxy-6a,7,8,9,10,10a-hexahydro-6*H*-dibenzo[*b*,*d*]pyran (33a). A solution of **31a** (0.0863 mmol, 26.6 mg) in benzene (5 mL) was heated (oil bath) at 50 °C for 36 h. Purification was achieved by flash chromatography (SiO_2, hex:EtOAc, 6:1) to afford 22.9 mg (86%) of **33a** as a yellow oil: $[\alpha]_D$ = −37.9° (c = 1, $CHCl_3$), T = 23 °C; ^{1}H NMR (500 MHz, $CDCl_3$) and 2-D COSY (500 MHz, $CDCl_3$) δ 6.58 (s, H-1), 5.31 (s, −OH), 3.92 (s, $-OCH_3$), 3.86 (s, $-OCH_3$), 2.34 (dt, $J_{10a,6a} = J_{10a,10\beta}$ = 11.4, $J_{10a,10\alpha}$ = 3.7 Hz, H-10a), 2.27−2.32 (m, H-10α), 1.79−1.85 (m, H-7β, H-8α), 1.50−1.60 (m, H-9), 1.42 (s, $CH_{3\beta}$-6), 1.36 (td, $J_{6a,10a} = J_{6a,7\alpha}$ = 11.7, $J_{6a,7\beta}$ = 2.57 Hz, H-6a), 1.13 (s, CH_3-6α), 1.00−1.05 (m, H-7α, H-8β), 0.97 (d, J = 6.6 Hz, CH_3-9), 0.80−0.90 (q, $J_{10\beta,10\alpha} = J_{10\beta,10a} = J_{10\beta,H9}$ = 11.9 Hz, H-10β); ^{13}C NMR (125 MHz, $CDCl_3$) δ 141.5, 141.1, 140.3, 138.5, 121.5, 105.9, 77.2, 61.3, 60.7, 46.9, 39.7, 35.6, 34.8, 32.4, 28.0, 27.5, 22.5, 19.8; IR (Neat) 3427, 2928, 2864, 1590 cm^{-1}; MS (EI) *m*/*z* calcd for $C_{18}H_{26}O_4$ 306.1831, found 306.1828; 306 (100), 263 (23), 221 (9), 183 (46).

(6a*R*,9*R*,10a*R*)-6,6,9-Trimethyl-2-hydroxy-3-methoxy-4-phenyl-6a,7,8,9,10,10a-hexahydro-6*H*-dibenzo[*b*,*d*]pyran (33b). To a solution of **30b** (0.0667 mmol, 30.2 mg) in

(20) (a) Colvin, E. W. *Silicon Reagents in Organic Synthesis (Best Synthetic Methods)*; Academic Press: San Diego, 1988. (b) Rajagopalan, S.; Zweifel, G. *Synthesis* **1984**, 1120.

undistilled THF (3 mL) was added tetra-*n*-butylammonium fluoride (TBAF) (0.09 mmol, 0.09 mL, 1 M) with stirring at ambient temperature. The reaction was completed in 5 min, and the workup was done in the same manner as above. The crude product was placed under vacuum to remove all traces of solvents. It was then heated in anhyd benzene (10 mL) at 40 °C (oil bath) for 7 h. The crude product was purified by chromatotron chromatography (hex:EtOAc, 10:1) to afford 20 mg (79%) of **33b** as a light yellow oil: $[\alpha]_D = -18.8°$ (c = 1, $CHCl_3$), T = 23 °C; R_f 0.33 (hex:EtOAc, 10:1); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.40 (d, J = 8.43 Hz, 2H), 7.30 (t, J = 7.70 Hz, 2H), 7.20 (t, J = 7.33 Hz, 1H), 6.84 (s, 1H), 5.43 (s, 1H), 3.50−3.54 (m, 1H), 2.35−2.45 (m, 2H), 1.75−1.85 (m, 2H), 0.9−1.6 (m, 20H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 143.7, 142.6, 140.8, 134.7, 130.9, 127.4, 126.5, 122.9, 121.4, 110.3, 75.3, 46.9, 39.8, 36.0, 34.8, 32.5, 27.8, 27.5, 22.6, 22.1, 20.0; IR (Neat) 3534, 2973, 2927, 2866, 1468, 991, 911, 733, 697 cm^{-1}; MS (EI) *m*/*z* calcd for $C_{25}H_{32}O_3$ 380.2351, found 380.2357; 380 (57), 338 (100), 337 (10), 295 (10), 215 (14).

4-Hydroxy-3,4-diisopropoxy-4-[3-(trimethylsilyl)-5,9-dimethyldec-8-en-ynyl)]-2-cyclobuten-1-one (Mixture of Diastereomers). In a manner similar to that used for the preparation of **30a**, 3,4-diisoproxy-3-cyclobutene-1,2-dione (0.504 mmol, 0.143 g), (*S*)-5,9-dimethyl-3-(trimethylsilyl)dec-8-en-1-yne (0.605 mmol, 0.12 g), and *n*-butyllithium (0.36 mL, 0.58 mmol, 1.6 M) gave 0.178 g (81%) of the title compound as a yellow oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.05−5.10 (m, 1H), 4.95−5.00 (m, 1H), 4.80−4.85 (m, 1H), 3.00−3.10 (m, 1H), 1.80−2.00 (m, 2H), 1.73−1.78 (m, 1H), 1.65 (s, 3H), 1.58 (s, 3H), 1.40 (dd, J = 9.38, 6.25 Hz, 6H), 1.25 (dd, J = 7.81, 6.25 Hz, 6H), 1.1−1.4 (m, 4H), 0.95−1.05 (m, 1H), [0.90 /0.82] (d and d, J = 6.25 Hz, 3H), 0.05 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 181.7, 165.2, 133.3, 133.2, 131.1, 131.0, 124.9, 124.8, 92.4, 92.3, 92.1, 78.9, 77.4, 75.2, 75.1, 73.7, 37.8, 36.0, 35.7, 35.0, 32.0, 31.7, 25.7, 25.6, 25.1, 22.6, 22.5, 20.2, 18.3, 18.2, 17.6, 17.5, 17.4, 3.3; IR (neat) 3324, 2978, 2923, 2218, 1778, 1621 cm^{-1}; HRMS (EI) calcd for $C_{25}H_{42}O_4Si$ 434.2852, found 434.2839; *m*/*z* 434 (3), 275 (4), 223 (16), 197 (6), 109 (3), 73 (100).

4-Hydroxy-2,3-diisopropoxy-4-(5,9-dimethyldec-8-ene-1,2-dienyl)-2-cyclobuten-1-one (Mixture of Diastereomers). In a manner similar to that used to prepare **31a**, the above alkynylcyclobutenone (79.3 mg, 0.182 mmol) and TBAF (0.27 mL, 0.27 mmol, 1 M) gave 60.3 mg (91%) of the title compound as a yellow oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.40−5.50 (m, 1H), 5.25−5.32 (m, 1H), 5.05−5.10 (m, 1H), 4.85−4.90 (m, 2H), [2.80/2.85] (s, 1H), 1.85−2.15 (m, 4H), 1.67 (s, 3H), 1.59 (s, 3H), 1.50−1.55 (m, 1H), 1.37−1.39 (m, 6H), 1.28 (d, J = 6.23 Hz, 3H), 1.26 (d, J = 6.23 Hz, 3H), 1.10−1.20 (m, 2H), 0.90 (d, J = 6.60 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 203.1, 184.4, 184.2, 166.0, 165.8, 140.3, 132.3, 131.3, 124.6, 124.5, 95.8, 95.7, 95.6, 95.5, 91.2, 91.0, 83.9, 83.8, 73.6, 36.6, 36.5, 36.4, 36.3, 36.1, 36.0, 32.7, 32.6, 25.7, 25.5, 25.4, 22.7, 22.6, 22.5, 22.4, 19.3, 19.2, 17.6; IR (neat) 3373, 2978, 2927, 1962, 1769, 1613 cm^{-1}; HRMS (EI) calcd for $C_{22}H_{34}O_4$ 362.2457, found 362.2449; *m*/*z* 362 (8), 320 (5), 278 (50), 235 (40), 209 (11), 193 (28), 168 (29), 156 (39), 155 (97), 154 (45), 139 (9), 123 (23), 109 (26), 93 (12), 81 (27), 69 (100), 55 (28).

6a,7,8,9,10,10a-Hexahydro-6,6,9-trimethyl-3,4-bis(1-methylethoxy)-[6a*S*-(6ab,9b,10aa)]-6*H*-dibenzo[*b*,*d*]pyran-2-ol (38). Using the standard thermolysis conditions employed for the synthesis of **33**, the above allenylcyclobutenone (60.3 mg, 0.166 mmol) gave 60 mg (95%) of **38** as a yellow oil: $[\alpha]_D$ = 38.8° (*c* = 1, $CHCl_3$), T = 23 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.55 (s, 1H), 5.30 (s, 1H), 4.73 (septet, J = 6.0 Hz, 1H), 4.35 (septet, J = 6.0 Hz, 1H), 2.25−2.40 (m, 2H), 1.75−1.85 (m, 2H), 1.50−1.55 (m, 1H), 1.40 (s, 3H), 1.20−1.35 (m, 13H), 1.10 (s, 3H), 1.00−1.10 (m, 2H), 0.95 (d, J = 6.6 Hz, 3H), 0.85 (q, J = 11.9 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 142.6, 140.7, 139.2, 136.7, 121.2, 105.3, 75.3, 75.0, 47.0, 39.7, 35.7, 34.8, 32.4, 28.0, 27.5, 22.7, 22.6, 22.5, 22.3, 19.8; IR ($CDCl_3$) 3538, 2973, 2927, 2866, 1590 cm^{-1}; HRMS (EI) calcd for $C_{22}H_{34}O_4$ 362.2457, found 362.2442; *m*/*z* 364 (3), 363 (23), 362 (88), 320 (13), 280 (2), 279 (18), 278 (100), 277 (11), 235 (28), 193 (10), 155 (36), 123 (10), 55 (12).

Table 1. Percent Composition of Compounds 45, 42, 47, and 49

compd	*m*/*z* (relative intensity)	correction for the ^{13}C satellite peak (20%)	% composition
45	288 (36)	18	10
42	287 (100)	90	53
47	286 (53)	50.5	30
49	285 (12.3)	12.3	7

4-Hydroxy-3-isopropoxy-2-phenyl-4-[3-methyl-*d*$_3$-3-(trimethylsilyl)-1-butynyl]-2-cyclobuten-1-one (Mixture of Diastereomers). Using standard conditions, 3-isopropoxy-2-phenyl-2-cyclobutene-1,2-diones (0.22 g), propargyl silane (0.763 g), and *n*-butyllithium (0.90 mL, 1.6 M, 1.4 mmol) gave 0.283 g (79%) of product as a white solid: mp 146−148 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.75 (d, J = 7.0 Hz, 2H), 7.35 (t, J = 7.7 Hz, 2H), 7.24−7.27 (m, 1H), 5.38 (septet, J = 6.2 Hz, 1H), 4.17 (s, 1H), 1.56 (d, J = 6.2 Hz, 3H), 1.54 (d, J = 5.9 Hz, 3H), [1.14/1.13] (s, 3H), 0.04 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 185.4, 178.2, 129.1, 128.4, 128.0, 126.9, 124.9, 99.3, 84.1, 79.4, 74.5, 23.5, 23.3, 22.9, 17.2, −4.5; IR (CH_2Cl_2) 3564, 2960, 2214, 1758, 1629, 1598 cm^{-1}; HRMS (EI) calcd for $C_{21}H_{25}D_3O_3Si$ 359.1996, found 359.1995; *m*/*z* 360 (9), 359 (33), 318 (24), 317 (100), 316 (44), 303 (11), 302 (38), 301 (43), 300 (27), 272 (14), 271 (44).

4-Hydroxy-3-isopropoxy-2-phenyl-4-(3-methyl-*d*$_3$-1,2-butadienyl)-2-cyclobuten-1-one (39) (Mixture of Diastereomers). Using standard conditions, 4-hydroxy-3-isopropoxy-2-phenyl-4-[3-methyl-*d*$_3$-3-(trimethylsilyl)-1-butynyl]-2-cyclobuten-1-one (50 mg, 0.17 mmol) and TBAF (0.20 mL, 0.20 mmol) gave 34 mg (85%) of **39** as a white solid (mixture of diastereomers 1:1): mp 106−107 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.73−7.76 (m, 2H), 7.33−7.36 (m, 2H), 7.24−7.27 (m, 1H), 5.38 (q, J = 3 Hz, 1H), 5.15 (septet, J = 6.2 Hz, 1H), 4.10 (s, 1H), [1.78/1.73] (d, J = 2.9 Hz, 3H), 1.52 (d, J = 6.2 Hz, 3H), 1.48 (d, J = 6.2 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 200.4, 189.2, 180.0, 128.9, 128.3, 127.8, 126.9, 123.4, 102.5, 90.1, 90.0, 78.6, 23.2, 23.0, 20.4, 20.1; IR (neat) 3319, 2982, 1965, 1741, 1623, 1595 cm^{-1}; HRMS (CI) calcd for $C_{18}H_{17}D_3O_3$ 287.1598, found 287.1595; *m*/*z* 289 (26), 288 (100), 287 (76), 286 (21), 246 (16), 245 (58), 244 (44), 243 (22).

3-Isopropoxy-6-(1-methyl-*d*$_4$-ethenyl-*d*$_1$)-2-phenyl-1,4-benzenediol (45), 3-Isopropoxy-6-(1-methyl-*d*$_3$-ethenyl)-2-phenyl-1,4-benzenediol (42), 3-Isopropoxy-6-(1-methylethenyl-*d*$_2$)-2-phenyl-1,4-benzenediol (47), and 3-Isopropoxy-6-(1-methylethenyl-*d*$_1$)-2-phenyl-1,4-benzenediol (49). A solution of **39** (13 mg, 0.045 mmol) in benzene (4 mL) was heated to 30 °C for 12 h. Purification of the crude product was achieved by flash column chromatography (SiO_2, Hexanes:EtOAc 3:1) to give >95% of a mixture of **45**, **42**, **47**, and **49** as a yellow oil. See Table 1 for percent compositions: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.45−7.50 (m, 4H), 7.36−7.41 (m, 1H), 6.80 (s, 1H), 5.43 (s, C=CH_2), 5.30 (s, C=CH_2), 5.23 (s, 1H), 5.18 (s, 1H), 3.60 (septet, J = 6.2 Hz, 1H), 2.12 (s, −CH_3), 0.98 (d, J = 6.2 Hz, 6H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 143.5, 143.4, 143.2, 142.1, 134.3, 131.2, 129.3, 128.4, 125.7, 122.8, 116.2, 114.1, 76.5, 24.4, 22.7; IR (CH_2Cl_2) 3513, 3060, 2974, 2931, 1466 cm^{-1}; HRMS (EI) calcd for $C_{18}H_{16}O_3D_4$ 288.1663, found 288.1642; calcd for $C_{18}H_{17}O_3D_3$ 287.1601, found 287.1596; calcd for $C_{18}H_{18}O_3D_2$ 286.1538, found 286.1536; calcd for $C_{18}H_{19}O_3D_1$ 285.1476, found 285.1472.

3-Isopropoxy-6-(1-methylethenyl)-2-phenyl-1,4-benzenediol (50). *n*-Butyllithium (0.75 mL, 1.2 mmol, 1.6 M) was added to a solution of 3-methyl-1,2-butadiene (0.123 mg, 1.85 mmol) in THF (5 mL) at −78 °C. After 1 h, it was transferred *via* cannula to a solution of 2-phenyl-3-isopropoxy-2-cyclobutene-1,2-dione in THF (10 mL) at −78 °C. The reaction was quenched with a 5% solution of ammonium chloride followed by a standard aqueous workup. The crude product was flashed through a short column of silica gel and washed with ether. The solvent was removed in vacuo to afford the crude product. This was dissolved in anhyd benzene (30 mL), and the resulting solution was refluxed for 2 h. The solvent was removed in vacuo, and the crude product was purified by

chromatography (SiO_2, Hexanes:EtOAc, 5:1) to afford **50** (67.8 mg, 26%) as a colorless oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.45−7.50 (m, 4H), 7.36−7.41 (m, 1H), 6.82 (s, 1H), 5.49 (s, 1H), 5.31 (s, 1H), 5.27 (s, 1H), 5.19 (s, 1H), 3.62 (septet, J = 6.2 Hz, 1H), 2.14 (s, 3H), 0.99 (d, J = 6.2 Hz, 6H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 142.8, 142.7, 142.6, 141.4, 133.5, 130.5, 128.6, 127.8, 124.9, 121.9, 115.5, 113.2, 75.8, 23.9, 22.1; IR (neat) 3516, 2974, 2930, 1465, 1431, 952, 896 cm^{-1}; HRMS (EI) calcd for $C_{18}H_{20}O_3$ 284.1412, found 284.1410.

4-Isopropoxy-2-(1-methyl-1-ethoxyethyl)-6-phenyl-1,4-benzenediol (52). A solution of **50** in anhyd ethanol was refluxed for 24 h. Removal of solvent gave a mixture of starting material **50** and product **52** as a colorless oil. ^{1}H NMR analysis of the product mixture showed a 3:1 ratio of **52** to **50**. Compound **52**: ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.61 (s, 1H), 7.45−7.51 (m, 2H), 7.43 (t, J = 7.3 Hz, 2H), 7.32 (t, J = 7.3 Hz, 1H), 6.72 (s, 1H), 5.43 (s, 1H), 3.59 (septet, J = 6.2 Hz, 1H), 3.42 (q, J = 7 Hz, 2H), 1.62 (s, 6H), 1.19 (t, J = 7.0 Hz, 3H), 0.98 (d, J = 5.9 Hz, 6H); HRMS (CI) calcd for $C_{20}H_{26}O_4$ 330.1831, found 330.1820; m/z 331 (8), 330 (55), 286 (16), 285 (72), 284 (86), 243 (40), 242 (100).

3-Isopropoxy-6-(1-methylethenyl-d_1)-2-phenyl-1,4-benzenediol (53). A solution of **50** (16 mg, 0.056 mmoL) in freshly distilled benzene and ethanol-d_1 (0.07 mL) was maintained at 30 °C for 12 h. Purification of the crude product was achieved by chromatography (SiO_2, Hexanes:EtOAc, 5:1) to afford a mixture of the starting material **50** and the monodeuterio analog **53**. Mass spectral analysis of the mixture revealed a 10% enhancement of the m/z 285 peak corresponding to the monodeuteriophenol **53**.

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Supporting Information Available: NMR spectra (37 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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