Ring Expansion of 4-Alkynylcyclobutenones. Synthesis of Enantiomerically Pure Pyranoquinones from 4-(4-Oxo-1,6-enynyl)-4-hydroxycyclobutenones and 4-(4-Oxo-1,6-dialkynyl)-4-hydroxycyclobutenones

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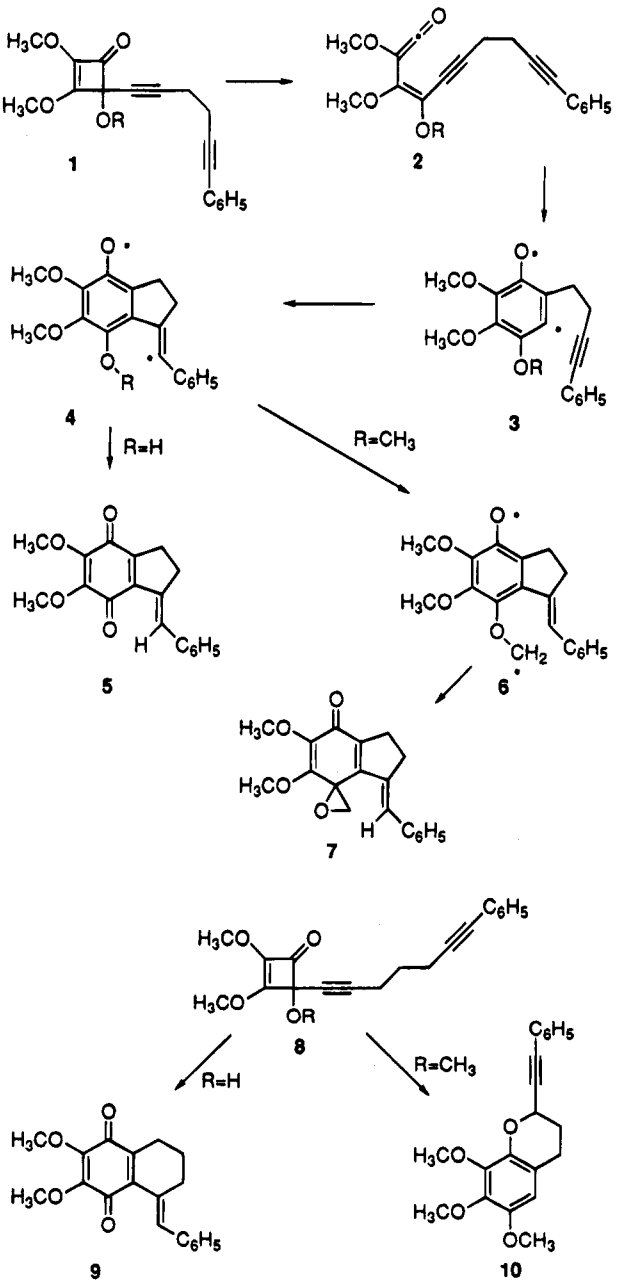
Thermolysis of 4-(4-oxo-1,6-enynyl)-4-hydroxycyclobutenones **23** in refluxing toluene provides an enantiospecific synthesis of pyranoquinones **27**. The 4-methoxy analog **32** was shown to give a quinone methide **35** and ultimately the trimer **36**.

Reported here are unusual thermal rearrangements of 4-(4-oxo-1,6-dialkynyl)-4-hydroxycyclobutenones **15** and 4-(4-oxo-1,6-enynyl)-4-hydroxycyclobutenones **23** to highly substituted pyranoquinones, **16** and **27**, respectively. The mechanisms for these transformations are unusual, and the synthetic scope is of interest since pyranoquinones constitute a large class of biologically active natural products.[1] The ring expansions of cyclobutenones **23** are of particular note since this provides a concise enantiospecific route to the pyranoquinone nucleus. As a result, selected enantiomerically pure quinones are now available.

The ring enlargements outlined here are analogous to those presented in a preliminary account which outlined the ring expansion of 4-(1,5-dialkynyl)-4-methoxy- and 4-(1,5-dialkynyl)-4-hydroxycyclobutenones to carbocyclic annulated spirocyclohexadienones and quinones, e.g., **1** → **5** and **7**.[2,3] For reference, the mechanisms of these transformations (Scheme 1) require the cyclobutenones, e.g., **1**, to undergo electrocyclic ring opening to the enynylketene **2** which then leads to diradical **3** upon ring closure. The more reactive ring-based radical center in **3** adds to the proximal alkyne group to give the new diradical **4** which undergoes intramolecular H-atom abstraction by the vinyl radical center, thus providing the observed quinone **5**. In comparison, the 4-methoxy analog of **1** leads to **6** and ultimately to the spiroepoxide **7**. In a related study, the 4-hydroxy- and 4-methoxycyclobutenones **8** were observed to give **9** and **10**, respectively. The former arises *via* the same sequence as involved in the formation of **5**. The latter stems from the diradical analogous to **3** which suffers intramolecular transfer of the propargylic H-atom followed by radical–radical coupling.

Extensions of these annulation studies into the heterocyclic quinone arena are outlined in Scheme 2. Specifically, thermolyses of 4-(4-oxo-1,6-dialkynyl)-4-hydroxycyclobutenones **15a–d** were observed to give the pyranoquinones **16a–d** in good yields (52–75%). The required

Scheme 1



4-oxo-1,6-diynes **13a–c** were readily prepared from propargyl bromide **11** and the corresponding alcohol **12**. Addition of the lithium salt of the diynes to the cyclo-

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

(1) For members of this family and the syntheses of the biologically active compounds in this family see: Thomson, R. H. *Naturally Occurring Quinones*, 2nd ed.; Academic Press: New York, 1981. Thomson, R. H. *Naturally Occurring Quinones*, 3rd ed.; Academic Press: New York, 1987. Patai, S.; Rappoport, Z. *The Chemistry of Quinonoid Compounds* John Wiley & Sons Ltd: New York, 1988; Vol. II, Chapter 8.

(2) Xia, H.; Moore, H. W. *J. Org. Chem.* **1992**, *57*, 3765.

(3) For a recent review on the synthetic utility of cyclobutenones see: Moore, H. W.; Yerxa, B. R. *ChemTracts* **1992**, *5*, 273. Moore, H. W.; Yerxa, B. R. *Adv. Strain Org. Chem.*, in press.

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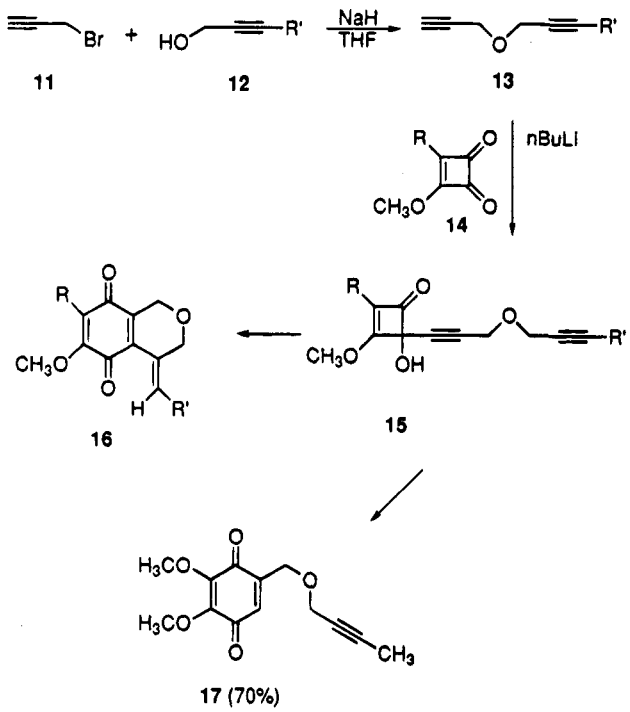
Scheme 2



	R	R'	Yield 13	Yield 15	Yield 16
a	OCH_3	CH_3	62	90	61
b	OCH_3	Bu	80	60	67
c	OCH_3	Ph	82	66	75
d	Bu	Ph	82	-	52*

* overall yield from **14d**

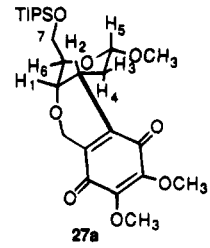
butenediones **14** provided the key cyclobutenones **15a–d** in good to excellent yields (60–90%). Thermolysis of these in refluxing toluene at a concentration of approximately 10^{-3} M gave the pyranoquinones **16a–d**. As an illustration of the experimental simplicity of these rearrangements, crude cyclobutenone **15d** was used directly to give the pyranoquinone **16d** in 52% overall yield from **14d**.

The dilute concentration (10^{-3} M) employed in these thermolyses is necessary in order to avoid or minimize a competitive bimolecular reaction occurring at higher concentrations. For example, thermolysis of **15a** under the same conditions as described above except at a concentration of 10^{-1} M gave the quinone **17** in 70% yield and only a minor amount (9%) of **16a**. Quinone **17** is envisaged as arising from intermolecular H-atom abstraction between two molecules of the diradical intermediate analogous to **3** and is thus favored at higher concentration.

The scope of the pyranoquinone synthesis was expanded to include the more complicated and stereochemically challenging cyclobutenones **23a–e** (Scheme 3). Synthesis of the required alkynyl glycopyranoside **21** was accomplished in four steps. Specifically, treatment of commercially available tri-*O*-acetyl-D-glucal **18** with methanol and boron trifluoride etherate followed by ester saponification (K_2CO_3) gave **19** in 66% yield.[4,5] Selective protection of the primary alcohol using triisopropylsilyl chloride gave **20** in 73% yield.[6] Treatment of this with propargyl bromide provided **21** in 90% yield.

(4) Ferrier, R. J.; Prasad, N. *J. Chem. Soc. C* **1969**, 570.
(5) Plattner, J. J.; Gless, R. D.; Rapoport, H. *J. Am. Chem. Soc.* **1972**, *94*, 8613.

Table 1. ^{1}H NMR Data for Compound 27a



proton	chemical shift (ppm)	coupling constant (Hz)
H_1	3.63	$J_{1,6} = 3.7$ $J_{1,2} = 6.0$ $J_{1,3} = 1.6$
H_2	2.63	$J_{2,3} = 3.2$ $J_{2,4} = 12.8$
H_3	2.13	$J_{3,4} = 13$ $J_{3,5} = 6.1$
H_4	1.55	$J_{4,5} = 7.9$
H_5	4.91	$J_{5,3} = 6.1$ $J_{5,4} = 7.9$
H_6	3.76	$J_{6,7a} = 3.8$ $J_{6,7b} = 5.5$

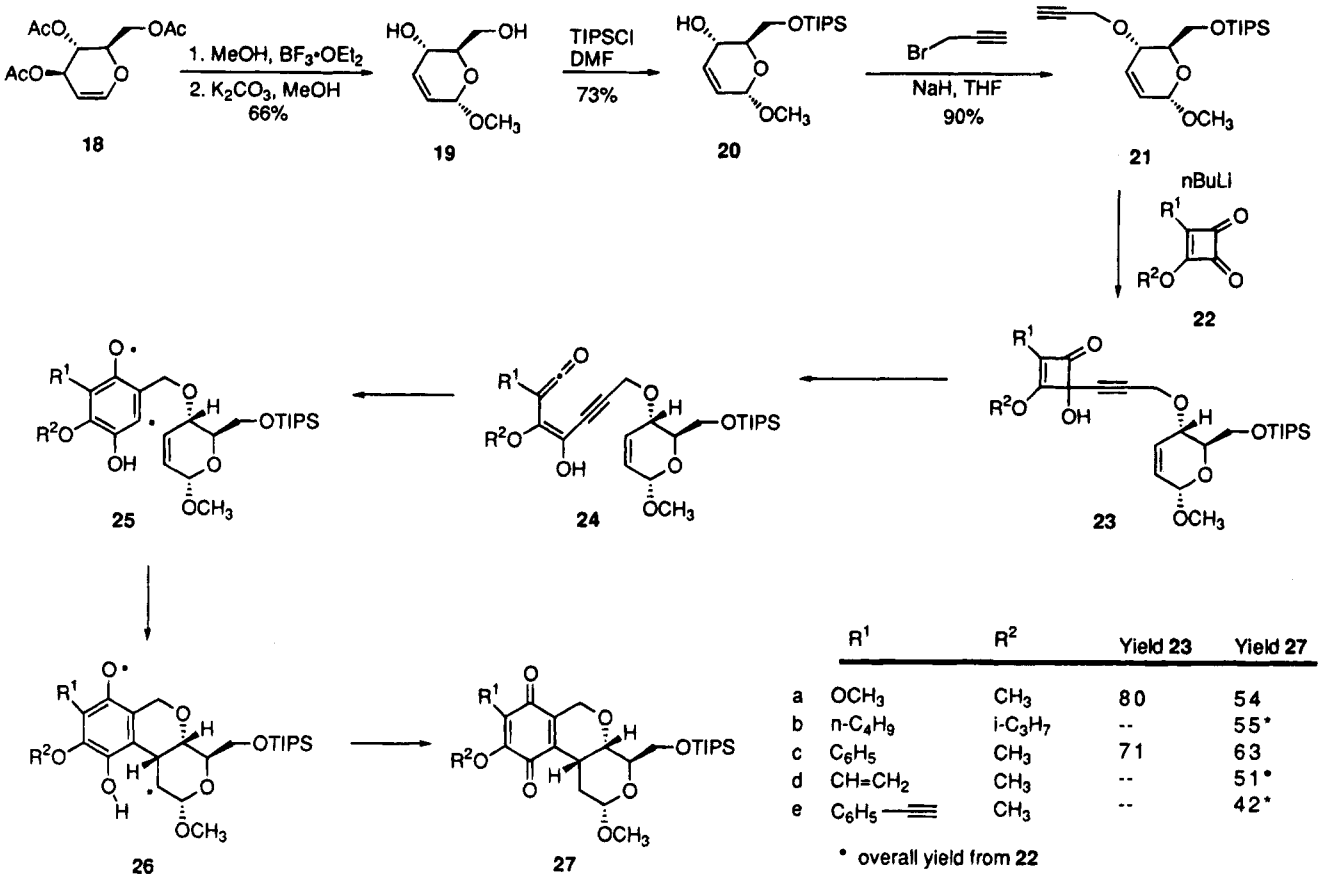
Addition of the lithium salt of **21** to dimethyl squarate (**22a**) in THF at −78 °C gave **23a** (80% yield). This was then thermolyzed in refluxing toluene (10^{-3} M) for 1.5 h to give pyranoquinone **27a** as a single diastereomer (^{1}H and ^{13}C NMR analysis) in 54% yield. In a similar manner, **27b,c,d,e** were obtained in 55%, 63%, 51%, and 42% yield, respectively, from the corresponding cyclobutenones **23b,c,d,e**. In three cases, the crude cyclobutenones **23b,d,e** were directly employed in the thermolyses.

The structures and stereochemistry of the pyranoquinones are based on spectral and analytical data. Their ^{1}H NMR spectra were particularly revealing. In one case (**27a**) assignments of the individual chemical shifts were made on the basis of 2-D H–H COSY experiments (Table 1); the following characteristic coupling constants were obtained: $J_{2,1} = 6.0$ Hz, $J_{2,3} = 3.2$ Hz, $J_{2,4} = 12.8$ Hz. The coupling between H_1 (δ, 3.63) and H_2 (δ, 2.63) is consistent with the assigned equatorial–axial cis-stereochemistry.[7] Further supporting evidence was revealed by NOE experiments which showed an enhancement of 4% (43% saturation) for the H_2 absorption upon irradiation of H_1. Finally, the observed long-range coupling between H_1 and H_3 (J = 1.6 Hz) provides confirming evidence for their proposed W(or M) relationship as found in the assigned conformation **27a**. On the basis of these data analogous structure assignments are assumed for **27b–e**.

The rearrangements are envisaged to proceed *via* the mechanism involving the ketene **24** and diradical intermediates **25** and **26**. This mechanism illustrates the more reactive ring-based radical center in **25** adding to the proximal alkene moiety of the tethered sugar to give **26**. The resulting alkyl radical then abstracts a H-atom

(6) Ogilvie, K. K.; Thompson, E. A.; Quilliam, M. A.; Westmore, J. B. *Tetrahedron Lett.* **1974**, 2865.
(7) For coupling constants in carbohydrates and cyclohexane systems, see: (a) Stoddart, J. F. *Stereochemistry of Carbohydrates*; John Wiley & Sons, Inc.: New York 1971; Chapter 4. (b) Silverstein, R. M.; Bassler, G. C.; Morrill, T. C. *Spectrometric Identification of Organic Compounds*, 5th ed.; John Wiley & Sons, Inc.: New York, 1991; Chapter 4.

Scheme 3



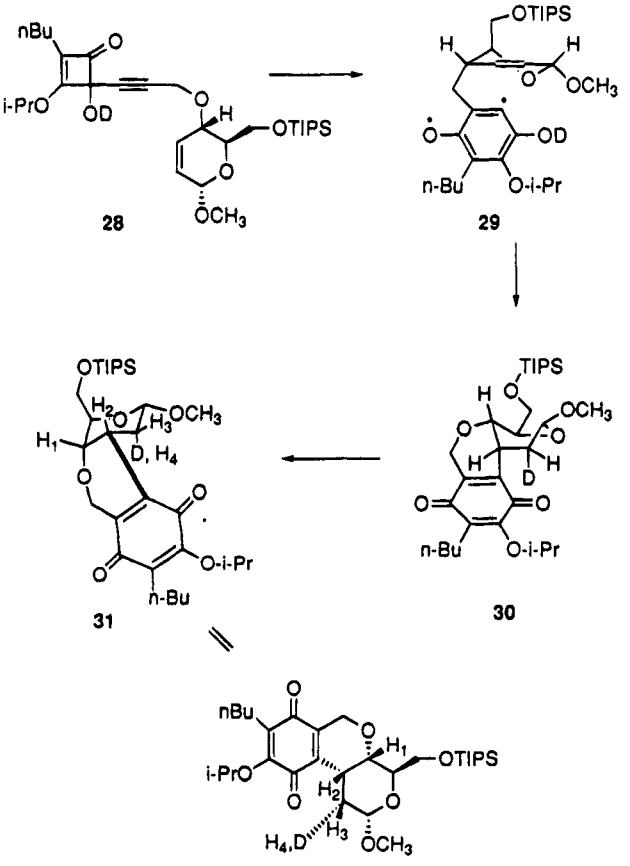
	R^1	R^2	Yield 23	Yield 27
a	OCH_3	CH_3	80	54
b	$n\text{-}C_4H_9$	$i\text{-}C_3H_7$	--	55*
c	C_6H_5	CH_3	71	63
d	$CH{=}CH_2$	CH_3	--	51*
e	$C_6H_5{-}{\equiv}$	CH_3	--	42*

* overall yield from 22

from the adjacent hydroxy group to give pyranoquinones **27**.[8] Cis stereochemisty for this overall addition was established by deuterium labeling studies and NMR analyses. Specifically, thermolysis of the deuteroxy analog **28** (85% enriched in deuterium) leads to the diradical **29**. Cis diaxial addition to the alkene group would give the boat conformer **30**. Equilibration then leads to the chair **31** (Scheme 4) whose ^1H NMR spectrum is in agreement with the assigned structure. That is, the cis ring junction is confirmed by the absorption for H_2 which appears as a doublet of doublets (J = 3.1 and 5.9 Hz). Significantly, the trans diaxial coupling of 12.8 Hz ($J_{2,4}$), observed in the protio analog **27b**, is absent in **31**. Thus, a trans diaxial relationship between H_2 and D is apparent as expected for a formal intramolecular cis addition of the diradical **29** to the double bond of the glucal moiety to ultimately give the chair conformer.

Thermolysis of a 4-(4-oxo-1,6-enynyl)-4-methoxycyclobutenone differs from the 4-hydroxy analog in that fragmentation rather than annulation occurs. Specifically, thermolysis of **32** gave the trimer **36** (72%) as the only isolable product (Scheme 5). The starting 4-methoxycyclobutenone **32** was obtained in 80% yield upon treatment of cyclobutenone **23a** with methyl iodide, potassium carbonate, and silver oxide. The trimer **36** was then obtained after 2 h in refluxing toluene. This transformation is envisaged as arising from the *o*-quinone methide **35**.[9] This, in turn, stems from the diradical **34**

Scheme 4



which is formed from **33** *via* an intramolecular hydrogen atom abstraction.

The structure of **36** was assigned on the basis of its

(8) For reviews on radical cyclizations see: (a) Jasperse, C. P.; Curran, D. P.; Fevig, T. L. *Chem. Rev.* **1991**, *91*, 1237. (b) Curran, D. P. *Synthesis* **1988**, *6*, 417. (c) Curran, D. P. *Synthesis* **1988**, *7*, 489.

(9) For selected references concerning the generation of quinone methides and their trimerizations see: (a) Bolon, D. A. *J. Org. Chem.* **1970**, *35*, 715. (b) Dean, M. S. C.; McDonald, S.; Robinson, M. S. *J. Chem. Soc., Perkin Trans. 1* **1973**, 359. (c) Bohmer, V.; Goldman, H.; Bavoux, C.; Perrin, M. *J. Chem. Soc., Perkin Trans. 2* **1989**, 2059.

Scheme 5

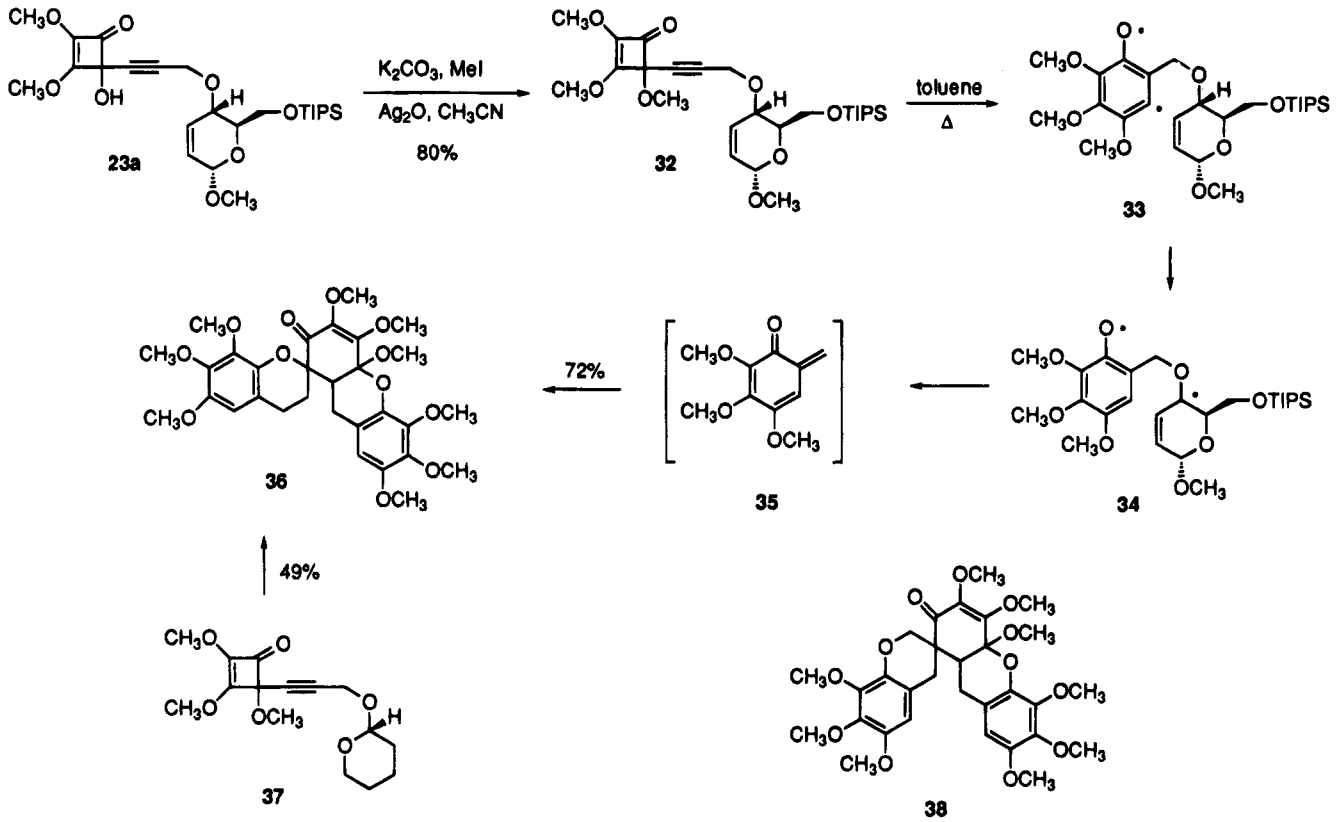
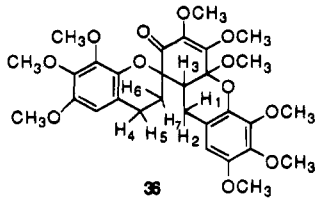


Table 2. ^{1}H NMR Data for Compound 36



proton	chemical shift (ppm)	coupling constant (Hz)
H_1	3.22	$J_{1,2} = 16.8$ $J_{1,3} = 6.0$
H_2	2.86	$J_{2,3} = 11.3$
H_3	2.76	$J_{3,2} = 11.3$ $J_{3,1} = 6.0$
H_4	2.56	$J_{4,5} = 12.8$ $J_{4,6} = 6.6$ $J_{4,7} = 3.7$
H_5	2.50	$J_{5,6} = 5.5$ $J_{5,7} = 7.5$
H_6	2.46	$J_{6,7} = 12.5$
H_7	2.14	$J_{7,4} = 3.7$ $J_{7,5} = 7.5$ $J_{7,6} = 12.5$

spectral data (^{1}H NMR and ^{13}C NMR) and 2-D H–H COSY experiments (Table 2). Although these data do not allow an unambiguous assignment to be made, they are in agreement with structure **36** and clearly rule out **38**, the other reasonable structure that could have formed based upon precedence.[9] The key to differentiating between **36** and **38** is the lack of any absorptions in the methyleneoxy region of the ^{1}H NMR spectrum; the presence of such would be required for **38**. In addition, the presence of complex multiplet absorptions between 2.14 and 2.56 were observed to be due to adjacent diastereotropic methylene groups as are found in structure **36**. Finally, **36** is identical to the product obtained from the trimerization of the *o*-quinone methide generated in the thermolysis of **37**.[10]

In conclusion, the following significant points are noted: (1) an annulative ring expansion of cyclobutenones involving unusual diradical intermediates is presented; (2) the ring expansions provide a concise method for the synthesis of enantiomerically pure pyranoquinone.

Experimental Section

General procedure. All air- or water-sensitive reactions were run in flame-dried glassware under an atmosphere of dry (Drierite) nitrogen. Tetrahydrofuran was freshly distilled from calcium hydride and then sodium/benzophenone. Other anhydrous solvents (benzene, toluene, and acetonitrile) were freshly distilled from calcium hydride. Commercial reagents were used without any further purification unless otherwise noted. All reactions were followed by thin layer chromatography using E. Merck precoated plates of silica gel 60 F254. Silica gel used in flash column chromatography was E. Merck silica gel 60 (mesh 230–400). ^{1}H NMR spectra were acquired on a General Electric QE 300 FT NMR or G.E. OMEGA 500 FT NMR. IR data were obtained on a Perkin-Elmer FTIR spectrophotometer Model 1600. High-resolution mass spectra were obtained from a 7070 EVG analytical organic mass spectrophotometer interfaced to a VG Analytical LTD 11/250 data system.

4-Oxo-1,6-octadiyne (13a). To a solution of 2-butyn-1-ol (3.5 g, 50 mmol) in THF (100 mL) was added sodium hydride (3.12 g, 50% oil suspension, 65 mmol); gas evolution was observed. The mixture was stirred at room temperature for 2 h. To the cooled (0 °C) solution was slowly added propargyl bromide (9.67 g, 80% in toluene, 65 mmol). The resulting

(10) The same trimer was obtained from the thermolysis of **37**, but the wrong regioisomer was inadvertently drawn in the original paper. It should have appeared as **36** and not as **38**. See: Foland, L. D.; Karlsson J. O.; Perri, S. T.; Schwabe, R.; Xu, S. L.; Patil, S.; Moore, H. W *J. Am. Chem. Soc.* **1989**, *111*, 975.

mixture was stirred at room temperature for 3 h and quenched with saturated ammonium chloride (50 mL), and the aqueous layer was separated and extracted with ether (2 × 30 mL). The combined organic layers were washed with saturated sodium chloride (40 mL), dried over magnesium sulfate, and concentrated *in vacuo*. Distillation (90 °C/70 Torr) gave **13a** (3.35 g, 62%) as a light yellow liquid: IR (neat) 3290, 2857, 2294, 2227, 1443, 1347, 1137, 1079 cm^{-1}; ^1H NMR ($CDCl_3$, 500 MHz) δ 4.22 (d, J = 2.6 Hz, 2H), 4.20 (q, J = 2.2 Hz, 2H), 2.42 (t, J = 2.6 Hz, 1H), 1.85 (t, J = 2.4 Hz, 3H); ^{13}C NMR($CDCl_3$, 125 MHz) δ 83.0, 78.9, 74.5, 74.0, 56.8, 56.0, 3.3; exact mass calcd for C_7H_8O 108.0575, found 108.0578.

4-Oxo-1,6-undecadiyne (13b). In analogy to the above procedure, **13b** (1.20 g, 80%) was obtained as a light yellow liquid (chromatography, hexanes/EtOAc = 95/5): IR (neat) 3290, 2958, 2359, 1457, 1345, 1134, 1078 cm^{-1}; ^1H NMR ($CDCl_3$, 500 MHz) δ 4.21−4.20 (m, 4H), 2.41 (t, J = 2.2 Hz, 1H), 2.21−2.17 (m, 2H), 1.48−1.44 (m, 2H), 1.39−1.35 (m, 2H), 0.88 (t, J = 7.3 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 87.6, 79.1, 74.7, 74.5, 57.0, 56.0, 30.5, 21.8, 18.3, 13.4; exact mass calcd for $C_{10}H_{14}O$ 150.1045, found 150.1049.

4-Oxo-7-phenyl-1,6-heptdiyne (13c). In analogy to the above procedure, **13c** (1.40 g, 82%) was obtained as a light yellow liquid (chromatography, hexanes/EtOAc = 8/1): IR (neat) 3294, 2853, 2240, 2117, 1490, 1442, 1345, 1082 cm^{-1}; ^1H NMR ($CDCl_3$, 500 MHz) δ 7.47−7.45 (m, 2H), 7.33−7.31 (m, 3H), 4.49 (s, 2H), 4.33 (d, J = 2.2 Hz, 2H), 2.49 (t, J = 2.2 Hz, 1H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 131.6, 128.5, 128.2, 122.3, 86.7, 84.0, 78.9, 74.9, 57.2, 56.4; exact mass calcd for $C_{12}H_{10}O$ 170.0732, found 170.0728.

General Procedure for the Synthesis of Compounds 15a-d. 2,3-Dimethoxy-4-(4-oxo-1,6-octadiynyl)-4-hydroxy-2-cyclobuten-1-one (15a). A solution of alkynyllithium produced by adding *n*-butyllithium (1.6 M, 2.86 mL, 4.58 mmol) to 4-oxo-1,6-octadiyne (495 mg, 4.58 mmol) in THF (40 mL) at −78 °C was cannulated to a solution of dimethyl squarate (DMS) (500 mg, 3.52 mmol) in THF (50 mL) at −78 °C. The mixture was stirred at −78 °C for 40 min and then poured into aqueous ammonium chloride solution (10%, 50 mL), and the organic layer was collected. The aqueous layer was extracted with ethyl acetate (2 × 25 mL), and the combined organic portion was dried over magnesium sulfate and concentrated *in vacuo*. Chromatography (hexanes:ethyl acetate = 2.5:1) gave **15a** (795 mg, 90%) as a light yellow solid: mp 52−54 °C; IR ($CDCl_3$) 3577, 3370, 2952, 2859, 2249, 1781, 1641, 1468, 1344, 1138, 1040 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 4.29−4.28 (m, 2H), 4.18−4.15 (m, 6H), 3.94−3.92 (m, 3H), 1.84−1.82 (m, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 180.5, 164.6, 135.3, 84.5, 83.3, 80.7, 78.1, 74.0, 60.1, 58.5, 57.2, 56.4, 3.50; exact mass calcd for $C_{13}H_{15}O_5$ 251.0919 (MH^+), found 251.0923.

2,3-Dimethoxy-4-(4-oxo-1,6-undecadiynyl)-4-hydroxy-2-cyclobuten-1-one (15b). The product (121 mg, 60%) was isolated as a viscous yellow oil after chromatography (hexanes: ethyl acetate = 3:1): IR ($CDCl_3$) 3577, 3367, 2934, 2862, 2250, 1781, 1641, 1468, 1344, 1135, 1040 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 4.28 (s, 2H), 4.18 (s, 2H), 4.17 (s, 3H), 4.08 (s, 1H), 3.93 (s, 3H), 2.20−2.15 (m, 2H), 1.46−1.38 (m, 4H), 0.90−0.86 (m, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 180.4, 164.5, 135.4, 87.9, 84.6, 80.7, 78.2, 74.6, 60.1, 58.6, 57.3, 56.3, 30.5, 21.8, 18.3, 13.5; exact mass calcd for $C_{16}H_{20}O_5$ 292.1311, found 292.1302.

2,3-Dimethoxy-4-(4-oxo-7-phenyl-1,6-heptadiynyl)-4-hydroxy-2-cyclobuten-1-one (15c). The product (434 mg, 66%) was isolated as a light yellow solid after chromatography (hexanes:ethyl acetate = 2.5:1): mp 91−92 °C; IR ($CDCl_3$) 3576, 3370, 2930, 2854, 2246, 1781, 1630, 1468, 1344, 1151, 1075, 1040, 840 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 7.40−7.36 (m, 2H), 7.25−7.23 (m, 3H), 4.40 (s, 2H), 4.33 (s, 2H), 4.24 (s, 1H), 4.12 (s, 3H), 3.88 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 180.5, 164.6, 135.3, 131.7, 128.5, 128.2, 122.2, 86.8, 84.3, 83.9, 81.0, 78.2, 60.1, 58.6, 57.5, 56.7; exact mass calcd for $C_{18}H_{16}O_5$ 312.0998, found 312.1013.

2-Butyl-3-methoxy-4-(4-oxo-7-phenyl-1,6-heptdiynyl)-4-hydroxy-2-cyclobuten-1-one (15d). To a solution of **13c** (28 mg, 0.16 mmol) in THF (5 mL) at −78 °C was added *n*-BuLi (0.10 mL, 1.6 M in hexanes, 0.16 mmol), and the solution was stirred for 30 min at the same temperature and transferred to a solution of 2-butyl-3-methoxycyclobutenedione (25 mg, 0.15 mmol) in THF (5 mL) *via* a cannula. The resulting solution was stirred for 1 h at −78 °C, quenched with saturated ammonium chloride (10 mL), and extracted with diethyl ether (2 × 10 mL). The combined organic portion was washed with brine (15 mL), dried over magnesium sulfate, and concentrated *in vacuo*. The crude product was subjected to thermolysis directly.

7-Ethylidene-3,4-dimethoxy-2,5-dioxo-9-oxabicyclo-[4.4.0]deca-1,3-diene (16a). The solution of **15a** (115 mg, 0.46 mmol) in freshly distilled toluene (120 mL, 3.83 × 10^{-3} M) was refluxed under nitrogen for 2 h. The solution was cooled to room temperature and concentrated *in vacuo*. Chromatography (hexanes:ethyl acetate = 4:1) gave **16a** (70 mg, 61%) as a red solid: mp 85−86 °C; IR ($CDCl_3$) 2950, 2839, 1659, 1636, 1586, 1454, 1272, 1226, 1134, 1021 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 7.02 (q, J = 7.4 Hz, 1H), 4.52 (s, 2H), 4.34 (s, 2H), 3.99 (s, 3H), 3.97 (s, 3H), 1.81 (d, J =7.4 Hz, 3H); ^{13}-CNMR ($CDCl_3$, 125 MHz) δ 183.1, 182.9, 144.8, 143.9, 134.7, 133.7, 132.4, 125.8, 64.5, 63.4, 61.3, 61.1, 14.5; exact mass calcd for $C_{13}H_{14}O_5$ 250.0841, found 250.0847.

7-Pentylidene-3,4-dimethoxy-2,5-dioxo-9-oxabicyclo-[4.4.0]deca-1,3-diene (16b). The solution of **15b** (24 mg , 0.082 mmol) in freshly distilled toluene (60 mL, 1.37 × 10^{-3} M) was refluxed under nitrogen for 2 h. The solution was cooled to room temperature and concentrated *in vacuo*. Chromatography (hexanes:ethyl acetate = 4:1) gave **16b** (16 mg, 67%) as a red solid: mp 60−62 °C; IR ($CDCl_3$) 2957, 2859, 1638, 1586, 1455, 1272, 1145 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 6.95 (t, J = 7.0 Hz, 1H), 4.53 (s, 2H), 4.33 (s, 2H), 4.00 (s, 3H), 3.98 (s, 3H), 2.17 (q, J = 7.0 Hz, 2H), 1.47−1.33 (m, 4H), 0.90 (t, J = 7.1 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 183.1, 182.9, 144.8, 143.9, 139.8, 134.8, 132.5, 124.8, 64.6, 63.4, 61.3, 61.1, 31.1, 28.5, 22.4, 13.8; exact mass calcd for $C_{16}H_{20}O_5$ 292.1311, found 292.1313.

7-Benzylidene-3,4-dimethoxy-2,5-dioxo-9-oxabicyclo-[4.4.0]deca-1,3-diene (16c). The solution of **15c** (120 mg , 0.38 mmol) in freshly distilled toluene (120 mL, 3.2 × 10^{-3} M) was refluxed under nitrogen for 2 h. The solution was cooled to room temperature and concentrated *in vacuo*. Chromatography (hexanes:ethyl acetate = 4:1) gave **16c** (90 mg, 75%) as a red solid: mp 110−111 °C; IR ($CDCl_3$) 2951, 2839, 1638, 1584, 1453, 1268, 1229, 1139, 1026 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 8.02 (s, 1H), 7.38−7.33 (m, 3H), 7.20−7.18 (m, 2H), 4.60 (s, 2H), 4.54 (s, 2H), 4.03 (s, 3H), 4.02 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 183.1, 182.6, 145.0, 143.8, 137.0, 136.3, 136.1, 132.5, 129.5, 128.5, 128.2, 126.3, 65.3, 63.8, 61.3, 61.2; exact mass calcd for $C_{18}H_{16}O_5$ 312.0998, found 312.1000.

7-Benzylidene-3-butyl-4-methoxy-2,5-dioxo-9-oxabicyclo[4.4.0]deca-1,3-diene (16d). The crude cyclobutenone **15d** in freshly distilled toluene (30 mL) was added dropwise to a refluxing toluene solution (120 mL) in 25 min under nitrogen, and the mixture was further refluxed for 20 min. The solution was cooled to room temperature and concentrated *in vacuo*. Chromatography (toluene:ethyl acetate = 100:1) gave **16d** (26 mg, 52% overall yield from **14d**) as an orange solid: mp 98−100 °C; IR ($CDCl_3$) 2933, 1666, 1635, 1446, 1401, 1271, 1134, 969, 859 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 7.97 (s, 1H), 7.40−7.30 (m, 3H), 7.21−7.19 (m, 2H), 4.61 (s, 2H), 4.55 (s, 2H), 4.00 (s, 3H), 2.44 (t, J = 7.1 Hz, 2H), 1.41−1.34 (m, 4H), 0.93 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 186.5, 182.4, 156.4, 137.8, 136.2, 136.0, 132.7, 132.3, 129.4, 128.3, 128.0, 126.5, 65.3, 63.9, 61.0, 30.9, 22.8, 22.6, 13.8; exact mass calcd for $C_{21}H_{22}O_4$ 338.1517, found 338.1505.

2,3-Dimethoxy-5-(2-oxo-4-hexynyl)-1,4-benzoquinone (17). The solution of **15a** (150 mg, 0.60 mmol) in freshly distilled toluene (1 mL, 0.6 M) was refluxed under nitrogen for 2 h. The solution was cooled to room temperature and concentrated *in vacuo*. Chromatography (hexanes:ethyl acetate = 4:1) gave **17** (105 mg, 70%) as a red solid: mp 78−80 °C; IR ($CDCl_3$) 2951, 2855, 1657, 1605, 1454, 1275, 1141, 1057 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 6.63 (t, J = 2.10 Hz, 1H), 4.40 (d, J = 2.10 Hz, 2H), 4.19 (q, J = 2.8 Hz, 2H), 4.01 (s, 3H), 3.97(s, 3H), 1.83 (t, J = 2.8 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 183.8, 183.5, 145.0, 144.9, 143.6, 129.7, 83.5, 74.3,

64.6, 61.2, 61.1, 59.1, 3.5; exact mass calcd for $C_{13}H_{14}O_5$ 250.0841, found 250.0848.

Methyl 2,3-Didedoxy-4,6-dihydroxy-α-D-*erythro*-hex-2-enopyranoside (19). To a solution of tri-*O*-acetyl-D-glucal (**18**) (13.6 g, 50 mmol) in freshly distilled benzene (50 mL) was added dry methanol (5 mL, 124 mmol) and boron trifluoride etherate (3 mL). The mixture was stirred at room temperature for 3 h. A dark green solution was obtained. The mixture was quenched with saturated sodium bicarbonate (40 mL), washed with water (2 × 40 mL), dried over magnesium sulfate, and concentrated *in vacuo*. The crude mixture was then dissolved in methanol (30 mL), and potassium carbonate (6.9 g, 50 mmol) was added. The mixture was stirred at room temperature for 2 h. The solid was filtered, and the filtrate was concentrated *in vacuo*. The residue was subjected to chromatography (hexanes:ethyl acetate = 1:10) to give **19** (5.35 g, 66%) as a light-brown oil: IR (neat) 3411, 2895, 1462, 1392, 1187, 1048, 961, 728 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 5.93 (d, J =10 Hz, 1H), 5.71 (dt, J = 2.2, 10.2 Hz, 1H), 4.84 (s, 1H), 4.15 (s, 1H), 3.81−3.84 (m, 2H), 3.65−3.61 (m, 2H), 3.41 (s, 3H), 3.11 (s, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 133.7, 125.7, 95.3, 71.5, 63.8, 62.3, 55.8; exact mass calcd for $C_7H_{11}O_4$ 159.0658 $(M - H)^+$, found 159.0673.

Methyl 2,3-Didedoxy-4-hydroxy-6-*O*-[tris(1-methylethyl)silyl]-α-D-*erythro*-hex-2-enopyranoside (20). To a solution of **19** (1.89 g, 11.81 mmol) in anhydrous DMF (30 mL) was added imidazole (1.77 g, 26 mmol) and triisopropylsilyl chloride (2.50 g, 13 mmol). The mixture was stirred at room temperature overnight. The resulting solution was washed with saturated ammonium chloride (20 mL) and extracted with methylene chloride (2 × 30 mL). The combined organic layers were back-washed with water (3 × 30 mL), dried over magnesium sulfate, and concentrated *in vacuo*. Chromatography (hexanes:ethyl acetate = 5:1) provided **20** (2.73 g, 73%) as a light-yellow oil: IR (neat) 3425, 2942, 2866, 1463, 1390, 1054 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.94 (d, J = 10.2 Hz, 1H), 5.74 (dt, J = 2.3, 10.2 Hz, 1H), 4.83 (s, 1H), 4.23−4.19 (m, 1H), 4.04−3.98 (m, 1H), 3.90−3.84 (m, 1H), 3.79−3.74 (m, 1H), 3.43 (s, 3H), 3.13 (d, J = 3.0 Hz, 1H), 1.09−1.07 (m, 21H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 132.9, 125.6, 95.2, 70.0, 67.5, 66.2, 55.6, 17.9, 11.8; exact mass calcd for $C_{16}H_{31}O_4Si$ 315.1992 $(M-H)^+$, found 315.1974.

Methyl 2,3-Didedoxy-4-*O*-(2-propynyl)-6-*O*-[tris(1-methylethyl)silyl]-α-D-*erythro*-hex-2-enopyranoside (21). To a solution of **20** (2.65 g, 8.40 mmol) in freshly distilled THF (70 mL) was added sodium hydride (605 mg, 12.6 mmol, 50% oil suspension) in portions; gas evolution was observed. The mixture was stirred at room temperature for 2.5 h, and then propargyl bromide (2.5 g, 80% in toluene, 16.8 mmol) was added at 0° C. The mixture was stirred at room temperature overnight. The resulting suspension was quenched with saturated ammonium chloride (30 mL) and extracted with diethyl ether (2 × 30 mL). The combined organic layers were washed with brine (50 mL), dried over magnesium sulfate, and concentrated *in vacuo*. Chromatography (hexanes:ethyl acetate = 6:1) provided **21** (2.66 g, 90%) as a light-yellow oil: IR (neat) 2942, 2866, 1464, 1397, 1125, 1094, 1056, 1014, 967, 882, 785 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 6.07 (d, J =10.2 Hz, 1H), 5.76 (dt, J = 2.2, 10.2 Hz, 1H), 4.86 (s, 1H), 4.23 (d, J = 2.3 Hz, 2H), 4.14−4.11 (m, 1H), 4.01−3.96 (m, 1H), 3.89−3.85 (m, 1H), 3.78−3.75 (m, 1H), 3.43 (s, 3H), 2.40 (t, J = 2.3 Hz, 1H), 1.09−1.07 (m, 21H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 130.4, 126.7, 95.1, 79.8, 74.4, 70.6, 70.1, 63.0, 56.4, 55.5, 17.9, 11.9; exact mass calcd for $C_{19}H_{33}O_4Si$ 353.2148 $(M - H)^+$, found 353.2135.

Methyl 2,3-Dideoxy-4-*O*-[3-(1-hydroxy-2,3-dimethoxy-4-oxo-2-cyclobuten-1-yl)-2-propynyl]-6-*O*-[tris(1-methylethyl)silyl]-α-D-*erythro*-hex-2-enopyranoside (23a). A solution of alkynyllithium produced by adding *n*-butyllithium (1.6 M, 1.25 mL, 2 mmol) to **21** (708 mg, 2 mmol) in THF (16 mL) at −78 °C was cannulated to a solution of dimethyl squarate (**22a**) (284 mg, 2 mmol) in THF (20 mL) at −78 °C. The mixture was stirred at −78 °C for 60 min and then poured into saturated ammonium chloride solution (30 mL), and the organic layer was collected. The aqueous layer was extracted with ethyl acetate (2 × 20 mL), and the combined organic portion was washed with brine (30 mL), dried over magnesium sulfate, and concentrated *in vacuo*. Chromatography (hexanes: ethyl acetate = 1.5:1) gave **23a** (796 mg, 80%) as a mixture of diastereomers as a yellow oil: IR (neat) 3374, 2944, 2866, 1781, 1642, 1468, 1343, 1051 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 6.05 (d, J = 10.1 Hz, 1H), 5.76−5.73 (m, 1H), 4.83 (s, 1H), 4.28 (s, 2H), 4.16 (s, 3H), 4.08−4.04 (m, 1H), 3.94 (s, 3H), 3.86−3.75 (m, 3H), 3.40 (s, 3H), 1.07−1.05 (m, 21H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 180.2, 164.4, 135.5, 130.5, 130.4, 126.8, 95.1, 85.3, 80.5, 78.3, 70.8, 70.7, 70.6, 63.1, 63.2, 60.1, 58.6, 56.7, 55.5, 17.9, 11.9; exact mass calcd for $C_{25}H_{44}NO_8Si$ 514.2836 $(M^+ NH_4)^+$, found 514.2830.

Methyl 2,3-Dideoxy-4-*O*-[3-(1-hydroxy-3-butyl-2-isopropoxy-4-oxo-2-cyclobuten-1-yl)-2-propynyl]-6-*O*-[tris(1-methylethyl)silyl]-α-D-*erythro*-hex-2-enopyranoside (23b). A solution of alkynyllithium produced by adding *n*-butyllithium (1.6 M, 0.25 mL, 0.4 mmol) to **21** (142 mg, 0.4 mmol) in THF (5 mL) at −78 °C was cannulated to a solution of 2-butyl-3-isopropoxy cyclobutenedione (**22b**) (78.4 mg, 0.4 mmol) in THF (5 mL) at −78 °C. The mixture was stirred at −78 °C for 60 min and then poured into saturated ammonium chloride solution (15 mL), and the organic layer was collected. The aqueous layer was extracted with ethyl acetate (2 × 10 mL), and the combined organic portion was washed with brine (20 mL), dried over magnesium sulfate, and concentrated *in vacuo*. The crude cyclobutenone was subjected to thermolysis directly.

Methyl 2,3-Dideoxy-4-*O*-[3-(1-hydroxy-2-methoxy-3-phenyl-4-oxo-2-cyclobuten-1-yl)-2-propynyl]-6-*O*-[tris(1-methylethyl)silyl]-α-D-*erythro*-hex-2-enopyranoside (23c). A solution of alkynyllithium produced by adding *n*-butyllithium (1.6 M, 0.94 mL, 1.5 mmol) to **21** (531 mg, 1.5 mmol) in THF (10 mL) at −78 °C was cannulated to a solution of 3-methoxy-2-phenyl cyclobutenedione (**22c**) (282 mg, 1.5 mmol) in THF (20 mL) at −78 °C. The mixture was stirred at −78 °C for 60 min and then poured into saturated ammonium chloride solution (30 mL). The aqueous layer was extracted with ethyl acetate (2 × 25 mL), and the combined organic portion was washed with brine (30 mL), dried over magnesium sulfate and concentrated *in vacuo*. Chromatography (hexanes: ethyl acetate = 2:1) provided **23c** (574 mg, 71%) as a mixture of diastereomers as a yellow oil: IR (neat) 3332, 2943, 2866, 1759, 1638, 1596, 1497, 1461, 1365, 1094, 1002, 966, 909 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.72−7.70 (m, 2H), 7.37−7.32 (m, 2H), 7.30−7.27 (m, 1H), 6.04 (dd, J = 4.7, 4.7 Hz, 1H), 5.74−5.71 (m, 1H), 4.81 (s, 1H), 4.58−4.52 (m, 1H), 4.39 (s, 3H), 4.32−4.31 (m, 2H), 4.08−4.05 (m, 1H), 3.95−3.91 (m, 1H), 3.86−3.83 (m, 1H), 3.81−3.76 (m, 1H), 3.41 (s, 3H), 1.06−1.03 (m, 21H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 183.4, 177.1, 130.5, 130.3, 128.6, 128.5, 128.2, 127.1, 126.4, 95.2, 87.3, 83.4, 80.3, 70.8, 70.7, 70.6, 63.2, 63.1, 60.3, 56.7, 55.5, 17.9, 12.0; exact mass calcd for $C_{30}H_{42}O_7Si$ 542.2700, found 542.2710.

Methyl 2,3-Dideoxy-4-*O*-[3-(1-hydroxy-3-ethenyl-2-methoxy-4-oxo-2-cyclobuten-1-yl)-2-propynyl]-6-*O*-[tris(1-methylethyl)silyl]-α-D-*erythro*-hex-2-enopyranoside (23d). A solution of alkynyllithium produced by adding n-butyllithium (1.6 M, 0.25 mL, 0.4 mmol) to **21** (142 mg, 0.4 mmol) in THF (5 mL) at −78 °C was cannulated to a solution of 2-ethenyl-3-methoxy cyclobutenedione (**22d**) (55.2 mg, 0.4 mmol) in THF (5 mL) at −78 °C. The mixture was stirred at −78 °C for 60 min and then poured into saturated ammonium chloride solution (15 mL), and the organic layer was collected. The aqueous layer was extracted with ethyl acetate (2 × 10 mL), and the combined organic portion was washed with brine (20 mL), dried over magnesium sulfate and concentrated *in vacuo*. The crude cyclobutenone was subjected to thermolysis directly.

Methyl 2,3-Dideoxy-4-*O*-[3-(1-hydroxy-2-methoxy-3-(phenylacetynyl)-4-oxo-2-cyclobuten-1-yl)-2-propynyl]-6-*O*-[tris(1-methyl-ethyl)silyl]-α-D-*erythro*-hex-2-enopyranoside (23e). A solution of alkynyl lithium produced by adding *n*-butyllithium (1.6 M, 0.25 mL, 0.4 mmol) to **21** (142 mg, 0.4 mmol) in THF (5 mL) at −78 °C was cannulated to a solution of 3-methoxy-2-(phenylacetynyl)cyclobutenedione (**22e**) (85 mg, 0.4 mmol) in THF (5 mL) at −78 °C. The mixture was stirred at −78 °C for 60 min and then poured into saturated ammonium chloride solution (15 mL), and the organic layer was collected. The aqueous layer was extracted with ethyl acetate (2 × 10 mL), and the combined organic

portion was washed with brine (20 mL), dried over magnesium sulfate, and concentrated *in vacuo*. The crude cyclobutenone was subjected to thermolysis directly.

[2*S*-(2α,4β,4aβ,10bβ)]-1,2,4,4a,6,10b-Hexahydro-2,8,9-trimethoxy-4-[[tris(1-methylethyl)silyl]oxy]pyrano[3,4-*c*][2]benzopyran-7,10-dione (27a). The solution of **23a** (70 mg, 0.14 mmol) in freshly distilled toluene (10 mL) was added dropwise to a refluxing toluene solution (130 mL) in 1 h under nitrogen and was further refluxed for 30 min after the addition. The solution was cooled to room temperature and concentrated *in vacuo*. Chromatography (hexanes:ethyl acetate = 3:1) gave **27a** (38 mg, 54%) as a red-orange oil: IR ($CDCl_3$) 2945, 2866, 1660, 1609, 1454, 1268, 1204, 1127, 1051 cm^{-1}; ^1H NMR ($CDCl_3$, 500 MHz) δ 4.91 (dd, J = 6.1, 7.9 Hz, 1H), 4.61 (d, J = 18.7 Hz, 1H), 4.20 (dd, J = 2.8, 18.7 Hz, 1H), 3.98 (s, 3H), 3.97 (s, 3H), 3.88 (dd, J = 3.8, 10.9 Hz, 1H), 3.85 (dd, J = 5.5, 10.9 Hz, 1H), 3.76 (ddd, J = 3.8, 3.8, 5.5 Hz, 1H), 3.63 (ddd, J = 1.6, 3.7, 6.0 Hz, 1H), 3.37 (s, 3H), 2.63 (ddd, J = 3.2, 6.1, 12.8 Hz, 1H), 2.13 (dddd, J = 1.7, 3.2, 6.1, 13 Hz, 1H), 1.55 (ddd, J = 8, 13, 13 Hz, 1H), 1.15–1.05 (m, 21H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 182.6, 182.4, 144.9, 144.2, 139.3, 138.7, 99.2, 72.5, 72.1, 64.2, 62.1, 61.2, 54.9, 30.2, 27.8, 17.9, 11.8; $[\alpha]^{20}_D$ 115.8° (c = 0.25, $CHCl_3$); exact mass calcd for $C_{25}H_{44}NO_8Si$ 514.2836 $(M + NH_4)^+$, found 514.2834.

[2*S*-(2α,4β,4aβ,10bβ)]-1,2,4,4a,6,10b-Hexahydro-8-butyl-9-isopropoxy-2-methoxy-4-[[tris(1-methylethyl)silyl]oxy]-pyrano[3,4-*c*][2]benzopyran-7,10-dione (27b). The crude cyclobutenone **23b** in toluene (15 mL) was added dropwise to a refluxing toluene solution (150 mL) in 25 min under nitrogen, and the mixture was further refluxed for 30 min. The solution was cooled to room temperature and concentrated *in vacuo*. Chromatography (hexanes:ethyl acetate = 6:1) gave **27b** (121 mg, 55% overall yield from **22b**) as an orange-yellow oil: IR ($CDCl_3$) 2960, 2942, 2866, 1656, 1637, 1603, 1465, 1384, 1099, 1052 cm^{-1}; ^1H NMR ($CDCl_3$, 500 MHz) δ 4.90 (dd, J = 6.4, 7.5 Hz, 1H), 4.85 (quintet, J = 6.2 Hz, 1H), 4.63 (d, J = 18.7 Hz, 1H), 4.23 (dd, J = 2.9, 18.7 Hz, 1H), 3.89 (dd, J = 3.6, 10.6 Hz, 1H), 3.86 (dd, J = 5.8, 11 Hz, 1H), 3.79–3.75 (m, 1H), 3.64 (ddd, J = 1.5, 3.7, 6.0 Hz, 1H), 3.39 (s, 3H), 2.63 (dd, J = 3.1, 6.1, 12.8 Hz, 1H), 2.40 (t, J = 7.3 Hz, 2H), 2.14–2.11 (m, 1H), 1.64–1.55 (m, 1H), 1.38–1.32 (m, 6H), 1.27–1.24 (m, 4H), 1.14–1.06 (m, 21H), 0.90 (t, J = 7.3 Hz, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 186.5, 182.4, 154.5, 140.8, 138.5, 133.8, 99.2, 75.8, 72.5, 72.0, 64.2, 62.4, 55.0, 30.8, 30.2, 27.7, 23.0, 22.9, 22.9, 22.8, 17.9, 13.8, 11.9; $[\alpha]D^{20}_D$ 56° (c = 0.5, $CHCl_3$); exact mass calcd for $C_{30}H_{50}O_7Si$ 550.3326, found 550.3322.

[2*S*-(2α,4β,4aβ,10bβ)]-1,2,4,4a,6,10b-Hexahydro-2,9-dimethoxy-8-phenyl-4-[[tris(1-methylethyl)silyl]oxy]pyrano[3,4-*c*][2]benzopyran-7,10-dione (27c). The solution of **23c** (70 mg, 0.129 mmol) in toluene (10 mL) was added dropwise to a refluxing toluene solution (150 mL) in 20 min under nitrogen in dark, and the mixture was further refluxed for 40 min. The solution was cooled to room temperature and concentrated *in vacuo*. Chromatography (hexanes:ethyl acetate = 6:1) gave **27c** (44 mg, 63%) as an orange-red oil: IR ($CDCl_3$) 2944, 2867, 1654, 1595, 1457 cm^{-1}; ^1H NMR ($CDCl_3$, 500 MHz) δ 7.43–7.36 (m, 3H), 7.28–7.27 (m, 2H), 4.95 (dd, J = 6.2, 7.7 Hz, 1H), 4.69 (d, J = 19 Hz, 1H), 4.29 (dd, J = 2.9, 19 Hz, 1H), 3.92 (dd, J = 3.7, 11 Hz, 1H), 3.88 (dd, J = 5.5, 11 Hz, 1H), 3.82–3.79 (m, 1H), 3.75 (s, 3H), 3.71 (ddd, J = 1.6, 3.7, 6.1 Hz, 1H), 3.42 (s, 3H), 2.72 (ddd, J = 3.1, 6.2, 13 Hz, 1H), 2.24–2.19 (m, 1H), 1.68–1.61 (m, 1H), 1.08–1.06 (m, 21H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 185.7, 182.1, 154.9, 141.1, 138.9, 130.5, 129.9, 128.6, 127.9, 127.8, 99.2, 72.6, 72.1, 64.3, 62.6, 61.4, 55.1, 30.1, 27.8, 17.9, 11.9; $[\alpha]D^{20}_D$ 62° (c = 1.0, $CHCl_3$); exact mass calcd for $C_{30}H_{42}O_7Si$ 542.2700, found 542.2697.

[2*S*-(2α,4β,4aβ,10bβ)]-1,2,4,4a,6,10b-Hexahydro-8-ethenyl-2,9-dimethoxy-4-[[tris(1-methylethyl)silyl]oxy]pyrano-[3,4-*c*][2]benzopyran-7,10-dione (27d). The crude cyclobutenone **23d** in freshly distilled benzene (25 mL) was added dropwise to a refluxing toluene solution (120 mL) in 35 min under nitrogen, and the mixture was further refluxed for 10 min. The solution was cooled to room temperature and concentrated *in vacuo*. Chromatography (hexanes:ethyl acetate = 5:1) gave **27d** (100 mg, 51% overall yield from **22d**) as an orange-red oil: IR ($CDCl_3$) 2944, 2866, 1657, 1464, 1384, 1124, 1052 cm^{-1}; ^1H NMR ($CDCl_3$, 500 MHz) δ 6.66 (dd, J = 12, 18 Hz, 1H), 6.29 (dd, J = 1.8, 18 Hz, 1H), 5.66 (dd, J = 2.2, 12 Hz, 1H), 4.92 (dd, J = 6.2, 7.6 Hz, 1H), 4.66 (d, J = 19 Hz, 1H), 4.25 (dd, J = 2.9, 19, 1H), 4.07 (s, 3H), 3.91 (dd, J = 3.7, 11 Hz, 1H), 3.86 (dd, J = 5.5, 11 Hz, 1H), 3.79–3.76 (m, 1H), 3.66 (ddd, J = 1.5, 3.7, 6.0 Hz, 1H), 3.41(s, 3H), 2.66 (dd, J = 3.0, 6.1, 12.6 Hz, 1H), 2.17–2.13 (m, 1H), 1.63–1.56 (m, 1H), 1.08–1.06 (m, 21H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 186.0, 182.1, 154.7, 140.9, 138.9, 125.5, 124.8, 99.2, 72.6, 72.1, 64.3, 62.4, 61.1, 55.1, 30.1, 27.7, 18.0, 11.9; $[\alpha]^{20}_D$ 61.1° (c = 0.5, $CHCl_3$); exact mass calcd for $C_{26}H_{41}O_7Si$ (MH^+) 493.2621, found 493.2627.

[2*S*-(2α,4β,4aβ,10bβ)]-1,2,4,4a,6,10b-Hexahydro-2,9-dimethoxy-8-(phenylacetynyl)-4-[[tris(1-methylethyl)silyl]oxy]pyrano[3,4-*c*][2]benzopyran-7,10-dione (27e). The crude cyclobutenone **23e** in freshly distilled toluene (10 mL) was added dropwise to a refluxing toluene solution (150 mL) in 25 min under nitrogen, and the mixture was further refluxed for 20 min. The solution was cooled to room temperature and concentrated *in vacuo*. Chromatography (hexanes: ethyl acetate = 5:1) gave **27e** (94 mg, 42% overall yield from **22e**) as an orange-red oil: IR ($CDCl_3$) 2945, 1867, 1658, 1586, 1321, 1300, 1240, 1120, 1048 cm^{-1}; ^1H NMR ($CDCl_3$, 500 MHz) δ 7.53–7.50 (m, 2H), 7.38–7.33 (m, 3H), 4.93 (dd, J = 6.2, 7.7 Hz, 1H), 4.70 (d, J = 18.7 Hz, 1H), 4.43 (s, 3H), 4.29 (dd, J = 2.9, 19, 1H), 3.91 (dd, J = 3.7, 10.6 Hz, 1H), 3.86 (dd, J = 5.5, 10.6 Hz, 1H), 3.81–3.77 (m, 1H), 3.67 (ddd, J = 1.6, 3.7, 6.1 Hz, 1H), 3.41 (s, 3H), 2.69 (ddd, J = 3.3, 6.2, 12.8 Hz, 1H), 2.19–2.14 (m, 1H), 1.62–1.56 (m, 1H), 1.08–1.06 (m, 21H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 182.8, 180.2, 158.0, 141.7, 139.4, 131.5, 129.3, 128.5, 128.3, 122.4, 109.0, 103.9, 99.1, 79.9, 72.6, 72.1, 64.3, 62.5, 60.7, 55.1, 55.0, 30.0, 27.9, 17.9, 11.9; $[\alpha]^{20}_D$ 141.8° (c = 0.2, $CHCl_3$); exact mass calcd for $C_{32}H_{43}O_7Si$ 567.2778, found 567.2804.

Methyl 2,3-Dideoxy-4-*O*-[3-(1-deuteroxy-3-butyl-2-isopropoxy-4-oxo-2-cyclobuten-1-yl)-2-propynyl]-6-*O*-[tris-(1-methylethyl)silyl]-α-D-*erythro*-hex-2-enopyranoside (28). A solution of alkynyllithium produced by addition of *n*-butyllithium (1.6 M, 0.19 mL, 0.3 mmol) to **21** (106 mg, 0.3 mmol) in THF (5 mL) at −78 °C was cannulated into a solution of 2-butyl-3-isopropoxy cyclobutenedione (59 mg, 0.3 mmol) in THF (5 mL) at −78 °C. The mixture was stirred at −78 °C for 60 min and then quenched with deuterium oxide. The mixture was dried over magnesium sulfate and concentrated *in vacuo*. The crude cyclobutenone was subjected to thermolysis directly.

[2*S*-(2α,4β,4aβ,10bβ)]-1-Deuterio-2,4,4a,6,10b-pentahydro-8-butyl-9-isopropoxy-2-methoxy-4-[[tris(1-methylethyl)silyl]oxy]pyrano[3,4-*c*][2] benzopyran-7,10-dione (31). The crude cyclobutenone **28** was subjected to thermolysis in analogy to **23b**. The product **31** (66 mg, 40% overall yield from **22b**) was isolated (hexanes:ethyl acetate = 6:1) as an orange-yellow oil. This was observed to be approximately 85% deuterium enriched as evidenced by the one proton absorption at δ 1.86–1.82, which integrated to approximately 1/6th of a proton. The ^1H NMR spectrum of **31** follows: ^1H NMR (C_6D_6, 500 MHz) δ 4.86 (quintet, J = 6.2 Hz, 1H), 4.80 (d, J = 6.2 Hz, 1H), 4.63 (d, J = 18.3 Hz, 1H), 4.06 (dd, J = 3.0, 18.4 Hz, 1H), 4.02–3.98 (m, 1H), 3.90 (d, J = 4.4 Hz, 2H), 3.51 (ddd, J =1.5, 4.0, 5.8 Hz, 1H), 3.30 (s, 3H), 2.60 (dd, J = 3.1, 5.9 Hz, 1H), 2.52 (t, J = 7.0 Hz, 2H), 2.22–2.18 (m, 1H), 1.86–1.82 (m, 1/6H), 1.53–1.50 (m, 2H), 1.35 (sextet, J = 7.3 Hz, 2H), 1.18 (d, J = 6.2 Hz, 3H), 1.14–1.12 (m, 21H), 1.04 (d, J = 6.2 Hz, 3H), 0.90 (t, J = 7.3 Hz, 3H); ^{13}C NMR (C_6D_6, 125 MHz) δ 186.2, 182.5, 154.6, 141.1, 138.5, 133.4, 99.8, 75.7, 72.6, 72.5, 64.8, 62.5, 54.8, 31.3, 30.2 (triplet, CHD), 28.1, 23.3, 23.2, 23.1, 22.9, 18.2, 14.1, 12.3; exact mass calcd for $C_{30}H_{49}DO_7Si$ 551.3388, found 551.3370, m/z (rel intensity) 549 (3.60), 550 (16.80), 551 (100), 552 (36.90), 553 (8.60). The deuterium enrichment was confirmed from the mass spectrum which showed the relative intensity of the peak at m/z 550 and 551 to be 15.20% and 84.80%, respectively, after correction for the M + 1 peak of the protio compound. Thus, the ratio of $C_{30}H_{49D}O_7Si$ to $C_{30}H_{50}O_7Si$ is 84.80%:15.20%.

Methyl 2,3-Dideoxy-4-*O*-[3-(1,2,3-trimethoxy-4-oxo-2-cyclobuten-1-yl)-2-propynyl]-6-*O*-[tris(1-methylethyl)silyl]-α-D-*erythro*-hex-2-enopyranoside (32). To a solution

of **23a** (451 mg, 0.91 mmol) in acetonitrile (10 mL) were added methyl iodide (1.29 g, 9.1 mmol), potassium carbonate (1.25 g, 9.1 mmol), and silver oxide (422 mg, 1.82 mmol). The mixture was stirred at room temperature overnight and then filtered through a short silica gel plug. The filtrate was concentrated *in vacuo*, and the residue was subjected to chromatography (hexanes:ethyl acetate = 3:1) to give **32** (371 mg, 80%) as a mixture of diastereomers as a light yellow oil: IR (neat) 2944, 2866, 2360, 1782, 1650, 1469, 1345, 1064 cm^{-1}; ^1H NMR ($CDCl_3$, 500 MHz) δ 6.06 (d, J = 10.3 Hz, 1H), 5.75 (dt, J = 2.2, 10.3 Hz, 1H), 4.84 (s, 1H), 4.33 (s, 2H), 4.13 (s, 3H), 4.09–4.07 (m, 1H), 3.95 (s, 3H), 3.86–3.76 (m, 3H), 3.51 (s, 3H), 3.41 (s, 3H), 1.07–1.05 (m, 21H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 179.2, 163.6, 135.8, 13.04, 126.8, 95.1, 86.6, 83.5, 78.5, 70.7, 70.6, 70.5, 63.1, 60.2, 58.6, 56.8, 55.5, 54.7, 17.9, 11.9, 11.8; exact mass calcd for $C_{26}H_{42}O_{18}Si$ 510.2649, found 510.2648.

3,4,9′,9′a-Tetrahydro-3′,4′,4′a,5′,6,6′,7,7′,8-nonamethoxyspiro[2*H*-1-benzopyran-2,1′-[1*H*]xanthen]-2′-(4′a*H*)-one (36). The solution of **32** (163 mg, 0.32 mmol) in freshly distilled toluene (140 mL, 2.28×10^{-3} M) was refluxed under nitrogen for 2 h. The solution was cooled to room temperature and concentrated *in vacuo*. Chromatography (hexanes:ethyl acetate = 2:1) gave **36** (45 mg, 72%) as a white solid: mp 53–54 °C (lit.[10] mp, 53–54 °C); IR ($CDCl_3$) 2940, 1683, 1611, 1491, 1467, 1298, 1221, 1131 cm^{-1}; ^1H NMR (C_6D_6, 500 MHz) δ 6.16 (s, 1H), 6.08 (s, 1H), 3.96 (s, 3H), 3.88 (s, 3H), 3.81 (s, 3H), 3.76 (s, 3H), 3.54 (s, 3H), 3.40 (s, 3H), 3.39 (s, 3H), 3.35 (s, 3H), 3.22 (dd, J = 6.0, 16.8 Hz, 1H), 3.19 (s, 3H), 2.86 (dd, J = 11.3, 16.8 Hz, 1H), 2.76 (dd, J = 6.0, 11.3 Hz, 1H), 2.56 (ddd, J = 3.7, 6.6, 12.8 Hz, 1H), 2.50 (ddd, J = 5.5, 7.5, 12.8, 1H), 2.46 (ddd, J = 5.5, 6.6, 12.5 Hz, 1H), 2.14 (ddd, J = 3.7, 7.5, 12.5 Hz, 1H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 192.9, 157.6, 147.9, 146.7, 142.2, 141.9, 141.5, 141.5, 141.2, 139.4, 137.0, 117.2, 116.0, 106.7, 105.8, 99.2, 80.3, 61.3, 61.3, 61.2, 61.1, 60.7, 60.5, 56.2, 56.2, 51.1, 44.1, 29.5, 26.1, 21.7; exact mass calcd for $C_{30}H_{36}O_{12}$ 588.2206, found 588.2186.

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Supporting Information Available: Copies of NMR spectra (24 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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