A One-Step Synthesis of 2-Norbornanone Ethylene Acetals from 2-Cyclopenten-1-one Ethylene Acetals and Dienophiles via [2 + 4] Cycloaddition of *in Situ* Generated 2-(2-Hydroxyethoxy)cyclopenta-1,3-dienes and Intramolecular Reacetalization

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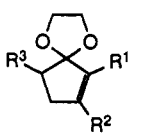
2-(2-Hydroxyethoxy)cyclopenta-1,3-diene (**5**) which is generated reversibly from 2-cyclopenten-1-one ethylene acetal (**1**) under mild, neutral conditions can be intercepted with a variety of dienophiles ultimately to give 2-norbornanone ethylene acetals in 62–100% yields. The addition reactions are highly stereo- and regioselective. Of the several solvents examined, acetonitrile is the most satisfactory. In $CHCl_3$ or CCl_4, decomposition of **1** is induced, leading to diminished yields of the adducts. The intermediate **5** is detected by UV spectroscopy, and its content relative to **1** at a stationary state at 70 °C in acetonitrile is estimated to be ca. 0.2%. The reactions of the 2-, 3-, and 5-methyl-substituted derivatives **2–4** with dienophiles similarly led to the production of the corresponding 2-norbornanone acetals through the additions of the dienophiles to the 1,3-cyclopentadien-2-yl ether intermediates **6–8** selectively derived from **2–4** via 1,2-elimination. The formation of isomeric adducts resulting either from 1,4-elimination in **1–4** or from [1,5] hydrogen migration in the enol ether intermediates is not detected. The addition of 2-chloroacrylonitrile, a ketene equivalent, to **1–4** followed by alkaline hydrolysis provides singly acetalized 2,5-norbornadiones in two steps in good yields. 2-Cyclohexen-1-one ethylene acetal (**44**) also undergoes the addition of dienophiles in the [2 + 4] manner directly to give bicyclo[2.2.2]octan-2-one ethylene acetals, but is substantially less reactive than **1** toward this type of reaction.

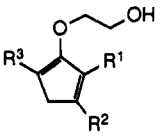
Introduction

The Diels–Alder addition is one of the most widely used reactions in organic synthesis due to its versatility and its control of stereochemistry.[1] Of a wide range of dienes taking part in the Diels–Alder reaction, oxygenated butadiene derivatives are particularly useful owing to the high regioselectivity shown in reactions with unsymmetrical dienophiles and to the diversity of products which can be obtained from the initial adducts.[1,2] Thus, the addition of dienophiles to 2-alkoxy-1,3-cyclopentadiene, followed by hydrolysis, appears to provide a convenient synthetic route to stereoselectively functionalized 2-norbornanone derivatives, useful synthons in organic synthesis. 2-Alkoxy-1,3-cyclopentadiene, however, is prone to polymerize as a neat liquid and, moreover, is readily contaminated by the 1- and 5-substituted isomers through [1,5] hydrogen migration.[3,4]

We recently have found that mild heating of a mixture of commercially available 2-cyclopenten-1-one ethylene acetal (**1**) and a dienophile directly provides 2-norbornanone ethylene acetal.[5] It is well documented that cyclic



1: $R^1 = R^2 = R^3 = H$
2: $R^1 = CH_3$, $R^2 = R^3 = H$
3: $R^1 = R^3 = H$, $R^2 = CH_3$
4: $R^1 = R^2 = H$, $R^3 = CH_3$



5: $R^1 = R^2 = R^3 = H$
6: $R^1 = CH_3$, $R^2 = R^3 = H$
7: $R^1 = R^3 = H$, $R^2 = CH_3$
8: $R^1 = R^2 = H$, $R^3 = CH_3$

acetals interconvert with ring-opened enol ether forms in a reversible manner usually under catalysis of acid.[6] To our knowledge, the equilibration has been little exploited to date, however, probably because it is generally heavily displaced in favor of the acetal. The equilibrating enol ethers should be able to be utilized as reactive intermediates, if intercepted efficiently enough to overcome the unfavorable equilibrium. Our findings suggest that a highly reactive enol ether **5** is generated from **1** in adequate concentration to be trapped by a variety of dienophiles and that the resultant Diels–Alder adducts **9** in situ undergo intramolecular acetalization and ultimately give the 2-norbornanone acetals **10** (Scheme I). The reactions of three methyl-substituted derivatives **2**, **3**, and **4** with dienophiles also provide the corresponding 2-norbornanone acetals derived from the addition of the latter to

(1) (a) Sauer, J. *Angew. Chem., Int. Ed. Engl.* **1967**, *6*, 16. (b) Sauer, J.; Sustmann, R. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 779. (c) Carruthers, W. *Cycloaddition Reactions in Organic Synthesis*; Pergamon Press: Oxford, England, 1990. (d) Fringuelli, F.; Taticchi, A. *Dienes in The Diels–Alder Reaction*; John Wiley & Sons: New York, 1990.

(2) Petrzilka, M.; Grayson, J. I. *Synthesis* **1981**, 753.

(3) (a) Kirmse, W.; Loosen, K. *Chem. Ber.* **1981**, *114*, 400. (b) Kirmse, W.; Loosen, K.; Sluma, H.-D. *J. Am. Chem. Soc.* **1981**, *103*, 5935. (c) Mironov, V. A.; Lukyanov, V. T.; Bernadskii, A. A. *Zh. Org. Khim.* **1984**, *20*, 69.

(4) (a) Cimarusti, C. M.; Wolinsky, J. *J. Am. Chem. Soc.* **1968**, *90*, 113. (b) Rubottom, G. M.; Krueger, D. S. *Tetrahedron Lett.* **1977**, 611. (c) Snowden, R. L. *Tetrahedron Lett.* **1981**, *22*, 97. (d) De Lucchi, O.; Lucchi, V.; Zamai, M.; Modena, G.; Valle, G. *Can. J. Chem.* **1984**, *62*, 2487. (e) Hansson, L.; Carlson, R. *Acta Chem. Scand.* **1989**, *43*, 188.

(5) For a preliminary account of this work, see: Ohkita, M.; Tsuji, T.; Nishida, S. *J. Chem. Soc., Chem. Commun.* **1991**, 37.

(6) Marquet, A.; Dvolaitzky, M.; Kagan, H. B.; Mamlok, L.; Ouannes, C.; Jacques, J. *Bull. Soc. Chim. Fr.* **1961**, 1822. (b) House, H. O. *Modern Synthetic Reactions*, 2nd ed.; Benjamin: Menlo Park, CA, 1972; Chapter 8.

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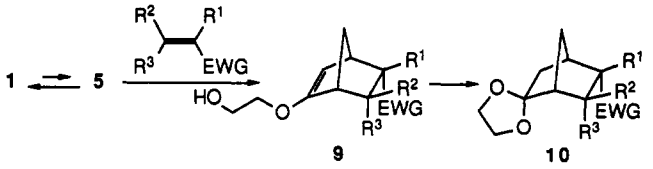
Scheme I



9 10

Table I. Reactions of 1 with Dienophiles in Acetonitrile

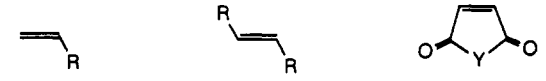
$[1]_0$[a]	dienophile	$[dienophile]_0$[a]	temp, °C	time	product	yield[b] %	a:b[c]
0.33	11	1.00	70	3 w	22	81[d,e]	67:37
0.33	11	1.00	100	3 d	22	80[d]	64:36
0.33	12	1.00	100	2 d	23	83[d]	75:25
0.50	13	1.50	70	6 w	24	100[d]	91:9
0.33	13	1.00	100	2 d	24	82[d]	89.11
0.33	14	1.00	70	3 w	25	73[d,f]	95:5
0.33	14	1.00	100	2 d	25	81[d]	78:22
0.67	15	0.67	70	9 d	26	93	58:42
0.67	16	0.67	70	17 d	27	93	60:40
0.14	17	0.11	80	3 h	28	77[g]	88:12
0.33	18	0.37	50	2 h	29	62[h]	93:7
0.40	19	0.37	70	9 d	30	84[g]	96:4
0.33	20	2.20	70	2 d	34	94	
0.40	21	1.20	70	20 h	38	80[i]	*j*

[a] Initial reactant concentration in M. [b] Isolated yield based on amount of 1 used. Conversion of 1 was almost complete unless otherwise indicated. [c] Determined by ^{1}H NMR and/or GC. [d] Hydroquinone was added as an inhibitor. [e] Conversion of 1 was 65%. [f] Conversion of 1 was 60%. [g] Based on amount of dienophile used. [h] GC yield. [i] 2,6-Dimethylpyridine (0.06 M) was added.[8] [j] A mixture of two stereoisomers in a ratio of 83:17.

the enol ether intermediates **6**, **7**, and **8**, respectively. Thus, the enol ethers seem to be generated selectively via 1,2-elimination from the cyclopentenone acetals. Apart from the simplicity of the reaction procedure, the formation of variously functionalized 2-norbornanones in their form is particularly valuable in terms of versatility for further synthetic manipulations. In this paper, we report the details of those reactions together with the results of mechanistic investigations.

Results and Discussion

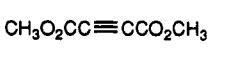
Reaction of 2-Cyclopenten-1-one Ethylene Acetal (1) with Dienophiles. The [2 + 4] cycloaddition reaction of 1[7] with a variety of dienophiles proceeded under mild, neutral conditions to give the corresponding 2-norbornanone acetals. The reaction time required to finish the cycloaddition appeared to reflect the reactivity of the latter.[1] Thus, the addition of maleic anhydride (**18**) to 1 was complete within 2 h at 50 °C in acetonitrile, while that of acrylonitrile (**11**) required 20 d at 70 °C (3 d at 100 °C). The reactions were usually very clean, and the only products detected by GC were the [2 + 4] adducts. The results are summarized in Table I.



11: R = CN
12: R = CHO
13: R = $COCH_3$
14: R = CO_2CH_3

15: R = CO_2CH_3
16: R = $CO_2C_2H_5$
17: R = SO_2Ph

18: Y = O
19: Y = NPh



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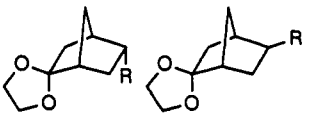
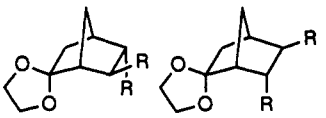
21

The structures of two isomeric adducts obtained from the reaction of 1 with acrylonitrile (**11**) were analyzed on the basis of their 500-MHz ^{1}H NMR and 2D-homonuclear shift correlation spectra, and principal interproton coupling constants were determined. It is well documented that, in the bicyclo[2.2.1]heptane system, vicinal coupling to a bridgehead proton is significantly smaller for the endo methylene protons (0–2 Hz) than for the exo protons (3–4 Hz) and that the long-range coupling of the endo proton to the anti methylene-bridge proton is generally in the range of 3–4 Hz whereas that of the exo proton to the methylene-bridge protons is negligible.[9] Thus, on the basis of coupling constants, the major product could unambiguously be assigned to the endo adduct **22a** and the minor product to the exo adduct **22b**. Stereochemical assign-



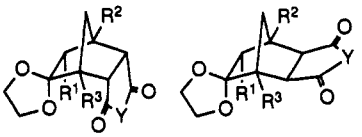
a b

22: R = CN
23: R = CHO
24: R = $COCH_3$
25: R = CO_2CH_3



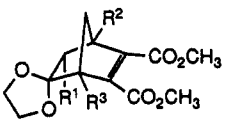
a b

26: R = CO_2CH_3
27: R = $CO_2C_2H_5$
28: R = SO_2Ph

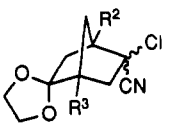


a b

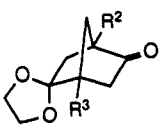
29: Y = O, $R^1 = R^2 = R^3 = H$
30: Y = NPh, $R^1 = R^2 = R^3 = H$
31: Y = NPh, $R^1 = CH_3$, $R^2 = R^3 = H$
32: Y = NPh, $R^1 = R^3 = H$, $R^2 = CH_3$
33: Y = NPh, $R^1 = R^2 = H$, $R^3 = CH_3$



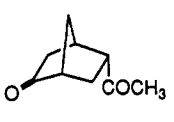
34: $R^1 = R^2 = R^3 = H$
35: $R^1 = CH_3$, $R^2 = R^3 = H$
36: $R^1 = R^3 = H$, $R^2 = CH_3$
37: $R^1 = R^2 = H$, $R^3 = CH_3$



38: $R^2 = R^3 = H$
39: $R^2 = CH_3$, $R^3 = H$
40: $R^2 = H$, $R^3 = CH_3$



41: $R^2 = R^3 = H$
42: $R^2 = CH_3$, $R^3 = H$
43: $R^2 = H$, $R^3 = CH_3$



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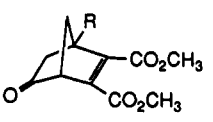


45: R = H
46: R = CH_3

ments to the other products were made by comparing the coupling patterns of absorption signals in their 500-MHz ^{1}H NMR spectra with those in the spectra of **22a** and **22b**. The reactions of **18** and **19** with 1 were thus found to lead mainly to the endo adducts, **29a** and **30a**, and those of **11**–**14** with 1 to **22a,b**–**25a,b**, respectively, without contamination by regioisomers. Accordingly, the additions of the dienophiles to 1 in the [2 + 4] manner are highly

(7) Garbisch, E.W., Jr. *J. Org. Chem.* **1965**, *30*, 2109.
(8) In the absence of the base, the yield of adduct was <20%.
(9) Jackman, L. M.; Sternhell, S. *Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry*, 2nd ed.; Pergamon Press: Oxford, England, 1969.

Table II. Reactions of the Substituted 2-Cyclopentenone Ethylene Acetals 2–4 with Dienophiles in Acetonitrile

acetal	[acetal]$_0$[a]	dienophile	[dienophile]$_0$[a]	temp, °C	time	product	yield,[b] %	a:b[c]
2	0.16	19	0.20	reflux	2 d	31	87	97:3
2	0.15	20	0.18	reflux	4 d	35	86	
3	0.18	19	0.19	70	2 d	32	89	94:6
3	0.12	20	0.23	70	2 d	36	86	
3	0.28	21	0.40	70	2 d	39	81[d]	e
4	0.20	19	0.34	reflux	3 d	33	82	97:3
4	0.20	20	0.34	reflux	4 d	37	85	
4	0.20	21	0.60	reflux	5 d	40	80[d]	f

[a] Initial reactant concentration in M. [b] Isolated yield based on amount of 1 used. Conversion of 1 was almost complete. [c] Determined by ^{1}H NMR and/or GC. [d] 2,6-Dimethylpyridine (0.06 M) was added.[8] [e] The product was stereochemically homogeneous. [f] A mixture of two stereoisomers in a ratio of 82:18.

stereo- and regioselective as has been observed in the usual Diels–Alder reactions.[10]

The reaction of 1 with 21, which afforded 38 in only less than 20% yield in acetonitrile or dioxane, was found to be remarkably improved by adding 2,6-dimethylpyridine to the reaction mixture, and 38 was obtained in 80% yield. As we will discuss later, 1 is apt to decompose in the presence of acid. Acidic impurities liberated from 21 and/or its reaction products probably induced decomposition of 1 in the absence of the base.

The deprotection of the 2-norbornanone acetals will be readily accomplished as exemplified by the quantitative formation of 44 from 24a in an acidic aqueous THF solution.

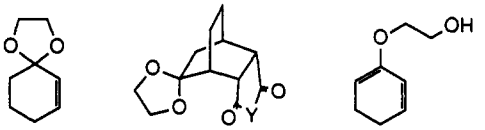
Reactions of Substituted Cyclopentenone Acetals with Dienophiles. To explore the scope of this cycloaddition, the reactions of the three methyl-substituted derivatives of 1 were studied. Thus, heating a mixture of the 2-methyl derivative 2[11] and 20 in refluxing acetonitrile led to the formation of a single adduct in 86% yield to which the structure 35 was assigned. The magnitude of coupling (3.4 Hz) between the proton geminal to the methyl substituent and the vicinal bridgehead proton and the absence of appreciable coupling between the former and the methylene bridge protons unequivocally indicated the arrangement of the methyl exclusively in the endo position. Analogously, of the two products produced in a ratio of 97:3 (87%) in the reaction of 2 with 19, the major one was assigned the structure 31a primarily on the basis of its 500-MHz ^{1}H NMR spectrum. The minor one was not isolated, but the similarity of its GC–MS spectrum to that of 31a suggested that it might well be 31b.

The reactions of the 3-methyl derivative 3[12] with 19–21 proceeded slightly faster than the corresponding reactions of 1 or 2 and afforded 32a, 36, and 39, respectively, as the major or exclusive product. The formation of isomers bearing the methyl substituent on the methylene bridge was not detected. The 5-methyl derivative 4 also reacted smoothly, though somewhat sluggishly relative to 1, with 19–21 to give 33, 37, and 40, respectively, in 80–85% yields.

The deprotection of 36 was readily accomplished in aqueous acetic acid, and 46 was obtained as a sole product.

It is particularly noteworthy that the adducts were not contaminated by the isomers which could be derived by way of the 1,4-elimination in 2–4 or [1,5] hydrogen migration in the cyclopentadiene intermediates 6–8. Thus, the methyl-substituted acetals 2–4 react with the dienophiles not only in the same manner as the parent acetal 1, but also regioselectively to give *endo*-3-methyl-, 4-methyl-, and 1-methyl-2-norbornanone acetals, respectively.

Reaction of 2-Cyclohexen-1-one Ethylene Acetal with Dienophiles. To examine the generality of the [2 + 4] addition of dienophiles to conjugated enone acetals, the reaction of 2-cyclohexen-1-one ethylene acetal (47) was



47 48: Y = O 50
49: Y = NPh

briefly studied. Compound 47 did undergo the addition of dienophiles in the [2 + 4] manner, but was substantially less reactive than 1. Thus, the reaction of 47 with 18 in acetonitrile required heating of the mixture at 120 °C for a period of 3 d for its completion, and with 19 it took 4 d at the same temperature. In addition, adduct yields were not very satisfactory: from the former reaction, 48 as a single major product was isolated in 25% yield and, from the latter, a 98:2 mixture of adducts in 55% yield from which the major one was isolated and assigned as 49 on the basis of its spectroscopic properties including NOE experiments.

Reaction Mechanism and Detection of Intermediates. The formation of [2 + 4] adducts from 1 and the dienophiles strongly suggests that the enol ether 5 was in situ generated from the former. The stereo- and regioselectivity observed in those reactions are best accommodated by the mechanism involving the Diels–Alder additions of the dienophiles to 5, followed by the cyclization of resultant 9 to the acetals 10. To our knowledge, the extent of the isomerization of 1 to 5 in organic solvents is not known. The ^{1}H NMR spectrum of 1 in CD_3CN indicates that 5 is not contained in a detectable amount. The UV spectrum of freshly distilled 1, however, exhibits a weak absorption extending to 280 nm in acetonitrile. When the solution was heated at 70 °C, slow enhancement of the absorption was observed showing a maximum at 252 nm. The growth of the absorption ceased within 8 h, and extended heating only led to an increase in the absorption intensity at the shorter wavelength. Intensity

(10) The reactions of *trans*-disubstituted dienophiles 15–17 with 1 afforded pairs of stereoisomeric adducts 26a,b–28a,b, respectively, which were analyzed as mixtures and not separated from each other. The additions of 21 to 1, 3, and 4 proceeded regioselectively to afford stereoisomeric pairs of adducts 38, 39, and 40, respectively. Each pair of adducts was analyzed as a mixture, and the isomers were not differentiated from each other.

(11) Smith, A. B., III; Branca, S. J.; Pilla, N. N.; Guaciaro, M. A. *J. Org. Chem.* **1982**, *47*, 1855.

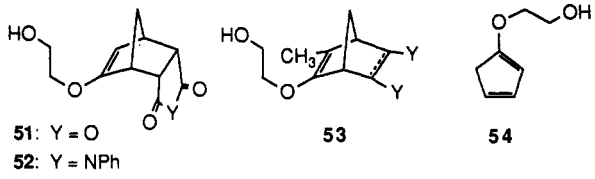
(12) Janssen, C. G. M.; Simons, L. H. J. G.; Godefroi, E. F. *Synthesis* **1982**, 389.

(13) Absorption signals observed (400 MHz, CD_3CN, 80 °C): δ 1.63 (dt, J = 8.5, 1.5 Hz, 1 H), 1.89 (dt, J = 8.5, 1.5 Hz, 1 H), 2.57 (br t, J = 5 Hz, 1 H), 3.22–3.25 (m, 1 H), 3.32–3.35 (m, 1 H), 3.49 (dd, J = 8, 4 Hz, 1 H), 3.52 (dd, J = 8, 4 Hz, 1 H), 3.65–3.73 (m, 4 H), 4.82 (br d, J = 3 Hz, 1 H).

of the developed absorption decayed to about one half when the solution was allowed to stand overnight at room temperature. [(Trimethylsilyl)oxy]-1,3-cyclopentadiene[4] as a ca. 1:7 mixture of 1- and 2-substituted derivatives exhibits λ_{max} at 252 nm, thus proving that the absorption observed above is compatible with **5**. The proportion of **5** at a stationary state at 70 °C is estimated to be ca. 0.2%, on the assumption that the molar absorptivity of **5** at 252 nm is similar in magnitude to that of the silyl ether mixture.

In contrast with the above observation, heating an acetonitrile solution of **47** at 70 °C did not lead to the development of UV absorption ascribable to **50**, suggesting that the generation of **50** from **47** is thermodynamically less favorable than that of **5** from **1**. Thus, the low reactivity of **47** toward this type of cycloaddition seems to arise from the less favorable equilibrium for the ring-opened form in the system **47**/**50** than in **1**/**5**, in addition to the lower reactivity of **50** compared to **5**[1] to dienophiles.

Although attempts to directly observe **5** by ^{1}H NMR were unsuccessful owing to its low equilibrium concentration, the intermediate **9** was readily detectable. Thus, when the reaction of **1** with **19** in CD_3CN was carried out inside the probe of an NMR spectrometer preheated at 80 °C and monitored intermittently, absorption signals consistent with the structure of **52** initially grew[13] but were



subsequently overwhelmed by those due to **30a** as shown in Figure 1. The signals ascribed to **52** remained observable after the sample stood overnight at room temperature, suggesting that the ring closure in **52** giving **30a** was a relatively slow process in neutral acetonitrile. The exclusive formation of *endo*-3-methyl derivatives in the reactions of **2** with the dienophiles is readily explained in terms of the preferential protonation of the enol double bond in the intermediates **53** from the exo face upon cyclization. The production of the maleic anhydride adducts **29a,b** in unexpectedly low yields may be due to the interception of relatively long-lived **51** and possibly also **5** at the free hydroxyl residue by maleic anhydride **18**.

The formation of the 2-norbornanone acetals in good yields from **1** implies that **5** is generated (via 1,2-elimination) essentially unaccompanied by the 1,4-elimination giving **54**. A possibility that **54** was generated but underwent [1,5] hydrogen migration to give **5** faster than it reacted with the dienophiles may be ruled out, since it is known that 2-methoxy-1,3-cyclopentadiene is not particularly favored thermodynamically over the 1-methoxy derivative[3] and that the adducts derived from the latter have been obtained as the major products from the reaction of a mixture of the two isomers with methyl acrylate.[3] In fact, the reactions of **2** and **4** with the dienophiles **19** and **20** led to the exclusive formation of **31**/**35** and **33**/**37**, respectively, unaccompanied by the formation of common products in detectable amounts (Scheme II). Thus, it is concluded that the enol ether intermediates were selectively generated from the cyclopentenone acetals via 1,2-elimination and reacted with the dienophiles or reverted

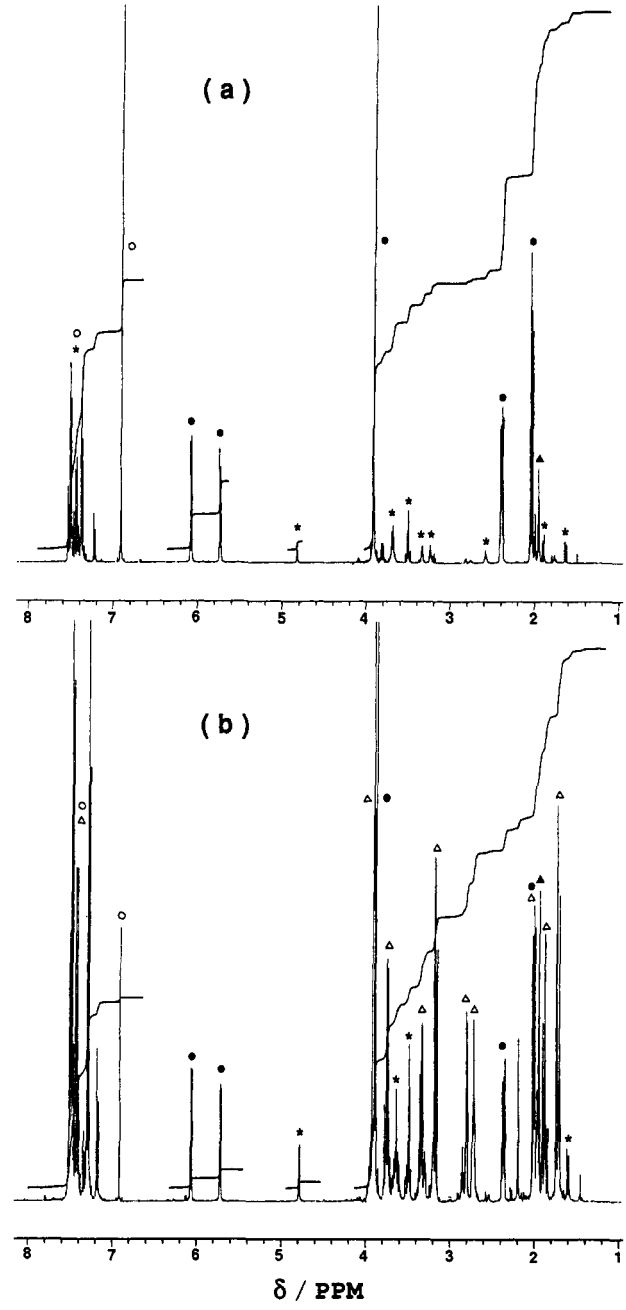


Figure 1. ^{1}H NMR spectra (400 MHz) of the **1**–**19** system in CD_3CN taken (a) after 0.5 h reaction time at 80 °C (recorded at the same temperature) and (b) after 7.5 h at 80 °C (recorded immediately at 25 °C). The signals marked with an asterisk are due to an intermediate to which the structure **52** was assigned: (●) **1**; (○) **19**; (△) **30a**; (▲) CHD_2CN.

to the starting acetals faster than they underwent [1,5] hydrogen migration.[14]

Effect of Solvent Polarity. The rate of the reaction of **1** with dienophile is thought to be dependent not only on the reactivity of the latter but also on the rate of the formation of **5** from **1** and/or the equilibrium concentration of **5**. To learn the effect of solvent polarity on the reaction rate, the reaction of **1** with **20** was examined in four solvents of different polarities: CH_3CN, dioxane, toluene, and CCl_4 (Table III).[15] While the yield of **34** based on the consumption of **1** was good in the former three solvents, it

(14) To our knowledge, the rate of [1,5] hydrogen migration in alkoxy-1,3-cyclopentadiene is not known. For the rate in methyl-1,3-cyclopentadiene, see: McLean, S.; Haynes, P. *Tetrahedron* **1965**, *21*, 2329.

Scheme II

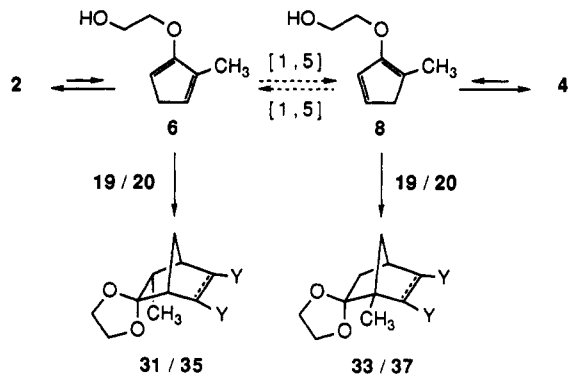


Table III. Solvent Effects in the Reaction of 1 with 20[a]

solvent	conversn of 1, %	yield of 34,[b] %
CH_3CN	85	90
dioxane	26	83
toluene	24	91
CCl_4	88	20

[a] A solution of 1 and **20** (0.33 M each) was heated at 80 °C for 20 h in a glass ampule. [b] GC yield based on the consumption of 1.

turned out that the reaction proceeded much more slowly in weakly polar dioxane or toluene than in CH_3CN. The effect of solvent polarity on the rate of Diels–Alder reaction is known to be generally only modest, and CH_3CN is not particularly superior to other solvents in facilitating the reaction.[1] It seems that the intermediate **5** is substantially more polar than **1**, and hence the isomerization of **1** into **5** is more favored in CH_3CN than in dioxane or toluene. The majority of the reactions of **1**–**4** with the dienophiles, therefore, were conducted in dry CH_3CN.

Of the solvents examined, CCl_4 was least satisfactory. Thus, the reaction of **1** with **20** in CCl_4 resulted in the relatively rapid consumption of **1** but the formation of **34** in a greatly inferior yield. We observed similar fast consumption of **1** along with the formation of adduct in a low yield in the reaction of **1** with **17** in $CHCl_3$. We suspect that in those halogenated solvents the decomposition of **1** was induced by acidic impurities derived from the solvents.[16]

Preparation of Selectively Protected Norbornanone Derivatives. A salient feature of the present reaction is the direct production of 2-norbornanone derivatives in the acetalized form. This provides a simple method for the preparation of selectively protected norbornanone derivatives. Thus, from the reactions of **12** and **13** with **1** were obtained the adducts in which the ring carbonyl group was selectively acetalized. By employing a ketene equivalent as dienophile,[17] selectively protected 2,5-norbornanediones were readily prepared. Hydrolysis of a mixture of the chloroacrylonitrile adducts **38** in an aqueous alkaline solution thus afforded **41** in 59% yield, in 47% yield in two steps from **1** and **21**. It should be noted that **41** has previously been prepared in seven steps in an overall yield of 15%.[18] The additions of **21** to **3** and **4** followed by the alkaline hydrolysis, moreover, provided **42** and **43** in overall yields of 44% and 49%, respectively. It is noteworthy that **43**, in which the more sterically hindered of the two carbonyl groups was selectively acetalized, was obtained in a satisfactory yield in two steps without contamination by the seemingly more readily accessible isomer **42**.

Reactivity of 1 relative to 2-Cyclopenten-1-one toward the Diels–Alder Reaction as Diene Component. Certain α,β-unsaturated ketones have been known to undergo [2 + 4] cycloaddition with dienophiles via the enol forms to give cyclohexanone derivatives.[2] It is of considerable interest to evaluate the reactivity of **1** relative to 2-cyclopenten-1-one with regard to the [2 + 4] reaction with dienophiles via **5** and **55**, respectively. Accordingly,

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a mixture of **20** and 10 equiv each of **1** and 2-cyclopenten-1-one was heated at 70 °C in acetonitrile. The GC analysis of the resultant mixture showed the almost exclusive formation of **34** together with only a trace amount of **45** (**34**:**45** = >50:1). Thus, the acetal **1** may be regarded as activated, relative to 2-cyclopenten-1-one, with respect to the in situ generation of enol derivative, while the former provides the 2-norbornanone derivatives in the protected forms.

Conclusions

2-Cyclopenten-1-one ethylene acetal undergoes cycloaddition with a variety of dienophiles in the enol ether form, 2-(2-hydroxyethoxy)cyclopenta-1,3-diene, in situ generated under mild, neutral conditions. The initial adducts subsequently cyclize ultimately to give 2-norbornanone ethylene acetals. Consistent with this mechanism, the reaction is highly regio- and stereoselective. Methyl-substituted cyclopentenone ethylene acetals analogously react with dienophiles to afford the corresponding 2-norbornanone acetals regioselectively. The direct formation of variously functionalized 2-norbornanones in the protected form coupled with the simplicity of the procedure promises to provide a useful synthetic route to norbornane derivatives.

Experimental Section

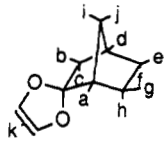
^1H and ^{13}C NMR spectra were measured at 500 MHz and at 25 MHz, respectively, on a JEOL FX-500 spectrometer in $CDCl_3$ unless otherwise indicated in the High-Resolution NMR Laboratory, Hokkaido University. Mass spectra were recorded at an ionizing voltage of 70 eV. Elementary analysis was performed by the Center for Instrumental Analysis of Hokkaido University. In the ^1H NMR spectral data of products, protons are designated with alphabetical suffix in the order shown in the formulas **56** and **57**. The acetals **1**,[7] **2**,[11] **3**,[12] and **47**[7] were prepared following known procedures. The dienophiles used in this study were purchased from commercial sources and purified by recrystallization or distillation prior to use.

(15) $E_T(30)$ values of CH_3CN, dioxane, toluene, and CCl_4 are 46.0, 36.0, 33.9, and 32.5, respectively. Dimroth, K.; Reichardt, C.; Siepmann, T.; Bohlmann, F. *Ann.* **1963**, *661*, 1. Kosower, E. M. *An Introduction to Physical Organic Chemistry*; John Wiley & Sons: New York, 1968.

(16) Since the ring-opening reaction of the cyclic acetals is supposed to be subject to acid catalysis, acidic additives are expected to exert a facilitating effect on the reactions of **1** and **48** with the dienophiles. The addition of various Brønsted acids such as *p*-TsOH, PPTS, adipic acid, oxalic acid, and trichloroacetic acid to the reaction mixtures in acetonitrile, however, only induced decomposition of the acetals and did not lead to the promotion of the addition reactions.

(17) Ranganathan, S.; Ranganathan, D.; Mehrotra, A. K. *Synthesis* **1977**, 289.

(18) (a) Werstiuk, N. H.; Taillefer, R. *Can. J. Chem.* **1978**, *56*, 1134. (b) Hawkins, R. T.; Hsu, R. S.; Wood, S. G. *J. Org. Chem.* **1978**, *43*, 4648. (c) Menger, F. M.; Chow, J. F.; Kaiserman, H.; Vasques, P. C. *J. Am. Chem. Soc.* **1983**, *105*, 4996.



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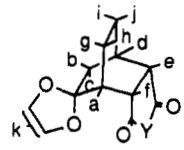

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Preparation of 5-Methylcyclopenten-2-one Ethylene Acetal (4). A mixture of 5-methylcyclopenten-2-one[19] (0.96 g, 10 mmol), ethylene glycol (12.4 g, 0.20 mol), and 1-hydroxy-3-isothiocyanatotetrabutyldistannoxane[20] (0.10 g, 0.2 mmol) in 200 mL of benzene was heated to boiling, and the condensate was returned to the mixture through a column packed with 4-Å molecular sieves (pellets) to remove the water formed. The relative peak area of 4 to the starting enone by GC (FID detector) reached ca. 0.7 within 2 d but did not increase further, and extended heating only induced decomposition of the enone and 4. The mixture was washed successively with aqueous KF and brine and dried with Na_2CO_3/Na_2SO_4. After removal of the solvent, the residue was distilled (bp 70–95 °C/17 mmHg) to give an oily mixture which was subjected to preparative GC to afford 0.38 g of 4 (27%): ^{1}H NMR δ 1.05 (d, J = 7.3 Hz, 3H), 1.8–2.7 (m, 3H), 3.8–4.1 (m, 4H), 5.65 (dt, J = 6.2, 3.5 Hz, 1 H), 6.04 (dt, J = 6.2, 4.7 Hz, 1 H); IR (neat) 3050, 1610, 1350, 1100 cm^{-1}; MS m/z 140 (M, 6), 112 (98), 96 (20), 86 (25), 68 (100), 55 (20), 39 (33). Anal. Calcd for $C_8H_{12}O_2$: C, 68.53; H, 8.64. Found: C, 68.41; H, 8.74.

Reaction of 1 with Acrylonitrile (11). A solution of 1 (1.26 g, 10 mmol), 11 (2.0 mL, 30 mmol), and hydroquinone (10 mg) in 30 mL of CH_3CN was heated at 70 °C for 3 weeks under Ar. After removal of the solvent in vacuo, the residue was chromatographed on silica gel to afford 0.44 g of unreacted 1 (1:9–2:8 Et_2O–hexane) and 0.93 g (52%; 81% based on the reacted 1) of **22a** and **22b** as a mixture (2:8–3:7 Et_2O–hexane, 63:37 by GC), and these were isolated by preparative GC. When a solution of 1 (42 mg, 0.33 mmol), 11 (53 mg, 1.0 mmol), and hydroquinone (1 mg) in 1 mL of CH_3CN was heated at 100 °C in a glass ampule, the reaction was complete within 3 d, and the preparative GC of the resultant mixture afforded 47 mg (80%) of **22a** and **22b** as a 64:36 mixture. **22a**: ^{1}H NMR δ 1.35 (ddt, J = 10.7, 3.4, 1.5 Hz, H_j), 1.82 (ddd, J = 10.7, 2.4, 1.5 Hz, H_i), 1.87 (ddd, J = 13.5, 4.9, 2.5 Hz, H_b), 1.90 (ddd, J = 13.5, 11.7, 4.4 Hz, H_g), 2.03 (ddd, J = 13.5, 5.4, 2.4 Hz, H_h), 2.04 (dd, J = 13.5, 3.4 Hz, H_c), 2.22 (br d, J = 4.4 Hz, H_a), 2.56 (ddd, J = 4.9, 3.9, 1.5 Hz, H_d), 2.73 (dddd, J = 11.7, 5.4, 3.9, 2.5 Hz, H_e), 3.81–3.89 (m, 2 H_k), 3.90–4.00 (m, 2 H_k); J_{bc} = 13.5, J_{gh} = 13.5, J_{eg} = 11.7, J_{ij} = 10.7, J_{eh} = 5.4, J_{bd} = 4.9, J_{ag} = 4.4, J_{de} = 3.9, J_{cj} = 3.4, J_{be} = 2.5, J_{hi} = 2.4, J_{ai} = 1.5, J_{aj} = 1.5, J_{dj} = 1.5 Hz; IR (neat) 2231, 1340, 1100 cm^{-1}; MS m/z 179 (M, 15), 139 (22), 138 (26), 126 (83), 125 (25), 99 (48), 86 (100), 66 (22). Anal. Calcd for $C_{10}H_{13}NO_2$: C, 67.02; H, 7.31; N, 7.82. Found: C, 67.15; H, 7.36; N, 7.85. **22b**: ^{1}H NMR δ 1.46 (dd, J = 14.1, 3.4 Hz, H_c), 1.67 (dddd, J = 10.7, 3.4, 1.9, 1.5 Hz, H_j), 1.74 (ddd, J = 13.2, 4.9, 4.4 Hz, H_g), 1.80 (br ddd, J = 10.7, 3.9, 2.5 Hz, H_i), 1.90 (dd, J = 14.1, 4.9 Hz, H_b), 2.22 (ddd, J = 13.2, 9.3, 2.5 Hz, H_h), 2.26 (br d, J = 4.4 Hz, H_a), 2.47 (ddd, J = 9.3, 4.9, 3.9 Hz, H_f), 2.62 (br d, J = 4.9 Hz, H_d), 3.80–3.97 (m, 4 H_k); J_{bc} = 14.1, J_{gh} = 13.2, J_{ij} = 10.7, J_{fh} = 9.3, J_{bd} = 4.9, J_{fg} = 4.9, J_{ag} = 4.4, J_{fi} = 3.9, J_{cj} = 3.4, J_{hi} = 2.5, J_{aj} = 1.9, J_{dj} = 1.5 Hz; IR (neat) 2233, 1346, 1100 cm^{-1}; MS m/z 179 (M, 19), 138 (23), 126 (71), 125 (22), 99 (33), 86 (100). Anal. Calcd for $C_{10}H_{13}NO_2$: C, 67.02; H, 7.31; N, 7.82. Found: C, 67.11; H, 7.37; N, 7.83.

Reaction of 1 with Acrolein (12). A solution of 1 (126 mg, 1.0 mmol), 12 (168 mg, 3.0 mmol), and hydroquinone (3 mg) in 3 mL of CH_3CN was heated at 100 °C for 2 d in a glass ampule. After removal of the solvent, the residue was chromatographed on silica gel (1:4 Et_2O–hexane) to afford 151 mg (81%) of **23a** and **23b** as a mixture (75:25 by GC and ^{1}H NMR), and the former was isolated by preparative GC. Although the minor product was obtained only as a mixture with **23a**, it was assigned to the exo adduct **23b** on the basis of the partially resolved ^{1}H NMR spectrum of the mixture and the close similarity of its GC–MS spectrum to that of **23a**. **23a**: ^{1}H NMR (C_6D_6) δ 1.02 (br d, J = 9.8 Hz, H_j), 1.23 (ddd, J = 12.2, 11.7, 4.4 Hz, H_g), 1.66 (br s, H_b and H_c), 1.69 (br d, J = 9.8 Hz, H_i), 1.99 (br d, J = 4.4 Hz, H_a), 2.11 (dt, J = 11.7, 4.9 Hz, H_e), 2.22–2.24 (m, H_d), 2.24 (ddd, J = 12.2, 4.9, 2.2 Hz, H_h), 3.25–3.49 (m, 4 H_k), 9.58 (d, J = 1.5 Hz, CHO); IR (neat) 2716, 1720, 1340, 1100 cm^{-1}; MS m/z 182 (M, 3), 126 (50), 125 (14), 99 (40), 86 (100), 82 (16), 73 (14); HRMS calcd for $C_{10}H_{14}O_3$ 182.0943, found 182.0944. **23b**: ^{1}H NMR δ 1.23 (ddt, J = 10, 3.5, 1.5 Hz, H_j), 1.83 (ddd, J = 13, 6, 4 Hz, H_g), 1.87 (ddd, J = 13, 8, 1.5 Hz, H_h), 1.94 (dd, J = 13.5, 4.5 Hz, H_b), 2.23 (br d, J = 4 Hz, H_a), 2.46 (br dd, J = 8, 6 Hz, H_f), 2.62 (br d, J = 4.5 Hz, H_d), 9.69 (d, J = 1.5 Hz, CHO); the signals of H_c, H_i, and H_k were not resolved from those due to **23a**; MS m/z 182 (M, 6), 141 (25), 126 (51), 125 (14), 99 (33), 86 (100), 73 (14); HRMS calcd for $C_{10}H_{14}O_3$ 182.0943, found 182.0936. Anal. Calcd for $C_{10}H_{14}O_3$: C, 65.90; H, 7.76. Found for a mixture of **23a** and **23b** C, 65.92; H, 7.77.

Reaction of 1 with 3-Buten-2-one (13). Heating a solution of 1 (1.26 g, 10 mmol), 13 (2.5 mL, 30 mmol), and hydroquinone (10 mg) in 20 mL of CH_3CN at 70 °C for 40 d under Ar led to the formation of two products (91:9 by AC). After removal of the solvent in vacuo, the residue was distilled to give 1.96 g (100%) of a colorless oil (bath temperature 105–125 °C/1 mmHg) which soon solidified. Crystallization from i-Pr_2O afforded analytically pure **24a**. Although the minor product was not isolated, it was tentatively assigned to the exo adduct **24b** on the basis of the close similarity of its GC–MS spectrum to that of **24a**. When a solution of 1 (42 mg, 0.33 mmol), 13 (70 mg, 1.0 mmol), and hydroquinone (1 mg) in 1 mL of CH_3CN was heated at 100 °C in a glass ampule, the reaction was complete within 2 d and the preparative GC of the resultant mixture afforded 53 mg (82%) of **24a** and **24b** as a 89:11 mixture. **24a**: mp 54.5–55 °C; ^{1}H NMR δ 1.47 (dd, J = 13.5, 3.5 Hz, H_c), 1.49 (br d, J = 10 Hz, H_j), 1.54 (ddd, J = 13, 12, 5 Hz, H_g), 1.72 (br dd, J = 13.5, 5 Hz, H_b), 1.79 (br dd, J = 10, 2.5 Hz, H_i), 2.16 (s, CH_3), 2.18 (br d, J = 5 Hz, H_a), 2.22 (ddd, J = 13, 5.5, 2.5 Hz, H_h), 2.65 (br t, J = 5 Hz, H_d), 2.80 (dddd, J = 12, 5.5, 5, 2 Hz, H_e), 3.80–3.93 (m, 4 H_k); IR (KBr) 1704, 1338, 1100 cm^{-1}; MS m/z 196 (M, 27), 155 (61), 126 (100), 125 (28), 99 (47), 86 (89). Anal. Calcd for $C_{11}H_{16}O_3$: C, 67.32; H, 8.22. Found: C, 67.17; H, 8.29.

Reaction of 1 with Methyl Acrylate (14). A solution of 1 (1.26 g, 10 mmol), 14 (2.7 mL, 30 mmol), and hydroquinone (10 mg) in 30 mL of CH_3CN was heated at 70 °C for 3 weeks under Ar. After removal of the solvent in vacuo, the residue was chromatographed on silica gel to afford 0.50 g of unreacted 1 (15:85 Et_2O–hexane) and 0.93 g (44%; 73% based on the reacted 1) of **25a** and **25b** as a mixture (2:8 Et_2O–hexane, 95:5 by GC), and these were isolated by preparative GC. When a solution of 1 (42 mg, 0.33 mmol), 14 (86 mg, 1.0 mmol), and hydroquinone (1 mg) in 1 mL of CH_3CN was heated at 100 °C in a glass ampule, the reaction was complete within 2 d, and the preparative GC of the resultant mixture afforded 57 mg (81%) of **25a** and **25b** as a 78:22 mixture. **25a**: ^{1}H NMR δ 1.45 (ddt, J = 10, 3.4, 2 Hz, H_j), 1.62 (dd, J = 14, 3.4 Hz, H_c), 1.69 (ddd, J = 13, 12, 5 Hz, H_g), 1.74–1.78 (m, H_i and H_b), 2.16 (ddd, J – 13, 5.4, 2.5 Hz, H_h), 2.18 (br d, J = 5 Hz, H_a), 2.59 (br t, J = 4 Hz, H_d), 2.78 (dddd, J = 12, 5.4, 4, 2 Hz, H_e), 3.70 (s, OCH_3), 3.82–3.86 (m, 2 H_k), 3.88–3.94 (m, 2 H_k); IR (neat) 1738, 1198, 1174 cm^{-1}; MS m/z 212 (M, 20), 153 (20), 126 (100), 99 (43), 86 (67). Anal. Calcd for $C_{11}H_{16}O_4$: C, 62.25; H, 7.60. Found: C, 62.23; H, 7.67. **25b**: ^{1}H NMR δ 1.54 (dd, J = 13.5, 3.5 Hz, H_c), 1.55 (ddt, J = 10, 3.5, 2 Hz, H_j), 1.62 (br d, J = 10 Hz, H_i), 1.80 (dt, J = 13, 5 Hz, H_g), 1.90 (dd, J = 13.5, 5 Hz, H_b), 2.00 (ddd, J = 13, 9, 2 Hz, H_h), 2.21 (br d, J = 5 Hz, H_a), 2.46 (br dd, J = 9, 5 Hz, H_f), 2.55 (br d, J = 5 Hz, H_d), 3.69 (s, OCH_3), 3.85–3.98 (m, 4 H_k); IR (neat) 1738, 1206, 1178 cm^{-1}; MS m/z 212 (M, 36), 153 (52), 126 (100), 125 (29), 99 (54), 86 (76).

Reaction of 1 with Dimethyl Fumarate (15). A solution of 1 (2.52 g, 20 mmol) and 15 (2.88 g, 20 mmol) in 30 mL of CH_3CN was heated at 70 °C for 9 d under Ar. After removal of the solvent in vacuo, the residue was chromatographed on silica gel (Et_2O) to afford 5.03 g (93%) of **26a** and **26b** as a mixture (7:5 by ^{1}H NMR), which was further purified by preparative GC and analyzed: ^{1}H NMR **26a** δ 1.71 (d, J = 9.3 Hz, H_i), 1.78 (br dd, J = 14, 4 Hz, H_b), 2.46 (s, H_a), 2.66 (br s, H_d), 3.23 (ddd, J = 5.9,

(19) Rizzo, C. J.; Dunlap, N. K.; Smith, A. B., III. *J. Org. Chem.* **1987**, *52*, 5280.

(20) Otera, J.; Dan-oh, N.; Nozaki, H. *J. Org. Chem.* **1991**, *56*, 5307; *Tetrahedron* **1992**, *48*, 1449.

3.9, 2 Hz, H_e), 3.41 (d, J = 5.9 Hz, H_b), 3.70 (s, 2 OCH_3); **26b** δ 1.67 (dd, J = 9.8, 1.5 Hz, H_i), 1.69 (dd, J = 13.7, 3.4 Hz, H_c), 1.98 (dd, J = 13.7, 5.1 Hz, H_b), 2.57 (br d, J = 5 Hz, H_d), 2.70 (br d, J = 4 Hz, H_a), 3.04 (br d, J = 5.4 Hz, H_f), 3.19 (dd, J = 5.4, 4 Hz, H_g), 3.70 (s, OCH_3), 3.71 (s, OCH_3), 1.54–1.62 (m, H_c and H_j of **26a** and H_j of **26b**), 3.64–3.78 (m, 1 H_k of **26b**), 3.83–3.99 (m, 4 H_k of **26a** and 3 H_k of **26b**); IR (neat) 1738, 1198 cm^{-1}; MS m/z 270 (M, 15), 239 (21), 211 (100), 151 (48), 126 (81), 86 (49). Anal. Calcd for $C_{13}H_{18}O_6$: C, 57.77; H, 6.71. Found: C, 57.70; H, 6.68.

Reaction of 1 with Diethyl Fumarate (16). A solution of 1 (2.52 g, 20 mmol) and **16** (3.44 g, 20 mmol) in 30 mL of CH_3CN was heated at 70 °C for 17 d under Ar. Workup as described above for **26** gave 5.56 g (93%) of a mixture of **27a** and **27b** (60:40 by ^1H NMR) as a colorless oil: ^1H NMR **27a** δ 1.77 (ddd, J = 14.2, 4.9, 2 Hz, H_b), 2.45 (br s, H_a), 2.65 (br dd, J = 5, 4.5 Hz, H_d), 3.22 (ddd, J = 6.4, 4.4, 2 Hz, H_e), 3.39 (dd, J = 5.9, 1.5 Hz, H_b); **27b** δ 1.65 (dt, J = 10.3, 1.5 Hz, H_i), 1.97 (dd, J = 13.7, 4.9 Hz, H_b), 2.56 (br d, J = 5 Hz, H_d), 2.70 (br d, J = 4 Hz, H_a), 3.01 (br d, J = 5.4 Hz, H_f), 3.20 (dd, J = 5.4, 4.4 Hz, H_g), 1.23–1.30 (m, CH_3 of **27a** and **27b**), 1.55–1.62 (m, H_i and H_j of **27a** and H_j of **27b**), 1.68–1.73 (m, H_c of **27a** and of **27b**), 3.72–3.78 and 3.84–3.98 (m, H_k of **27a** and of **27b**), 4.05–4.26 (m, OCH_2 of **27a** and **27b**); IR (neat) 1736, 1184 cm^{-1}; MS m/z 298 (M, 5), 253 (17), 225 (55), 151 (71), 126 (100), 86 (78). Anal. Calcd for $C_{15}H_{22}O_6$: C, 60.39; H, 7.43. Found: C, 60.21; H, 7.38.

Reaction of 1 with (*E*)-1,2-Bis(phenylsulfonyl)ethene (17). A solution of 1 (1.76 g, 14 mmol) and 17 (3.39 g, 11 mmol) in 100 mL of CH_3CN was heated at 80 °C for 3 h under Ar. After removal of the solvent in vacuo, the residue was dissolved in 100 mL of CH_2Cl_2 and then diluted with 300 mL of Et_2O and 50 mL of hexane to give 3.66 g (77%) of **28a** and **28b** as a crystalline mixture (13:2 by ^1H NMR): ^1H NMR **28a** δ 1.78 (d, J = 10.8 Hz, H_i), 1.83 (ddd, J = 14.7, 4, 2 Hz, H_b), 1.95 (br d, J = 10.8 Hz, H_j), 2.56 (s, H_a), 2.68 (dd, J = 14.7, 3.4 Hz, H_c), 2.76 (br s, H_d), 3.44–3.50 (m, 1 H_k), 3.65–3.71 (m, 1 H_k), 3.87–3.94 (m, 2 H_k), 4.03 (ddd, J = 6.4, 4, 1.5 Hz, H_e), 4.23 (dd, J = 6.4, 1.5 Hz, H_b), 7.56 (br t, J = 8 Hz, 4 H), 7.66 (br t, J = 8 Hz, 2 H), 7.85 (dd, J = 8, 1.5 Hz, 2 H), 7.92 (dd, J = 8, 1.5 Hz, 2 H); **28b** δ 1.77 (dd, J = 14, 4 Hz, H_c), 1.84 (br d, J = 11 Hz, H_i), 1.97 (br dd, J = 11, 4 Hz, H_j), 2.02 (dd, J = 14, 5.5 Hz, H_b), 2.45 (br d, J = 5.5 Hz, H_d), 3.03 (br d, J = 3 Hz, H_a), 3.73 (dd, J = 6, 3 Hz, H_g), 4.03–4.08 (m, 1 H_k), 4.17–4.22 (m, 2 H_k), 7.53–7.58 (m, 2 H), 7.61–7.68 (m, 2 H), 7.76 (d, J = 8 Hz, 2 H), 7.96 (d, J = 8 Hz, 2 H); H_f and one of the H_ks could not be assigned because their signals overlapped with much stronger absorptions due to **28a**; IR (KBr) 1310, 1150, 588 cm^{-1}; MS m/z 434 (M, 0.15), 293 (89), 152 (21), 151 (100), 86 (39). Anal. Calcd for $C_{21}H_2O_6S_2$: C, 58.05; H, 5.10; S, 14.76. Found: C, 57.90; H, 5.08; S, 14.55.

Reaction of 1 with Maleic Anhydride (18). A solution of 1 (1.14 g, 9 mmol) and 18 (0.29 g, 3 mmol) in 10 mL of dioxane was stirred at 24 °C for 10 d. After removal of the solvent in vacuo, the residue was subjected to flash chromatography (4:6–6:4 Et_2O–hexane) to afford 0.15 g (22%) of **29a** and **29b** as a mixture (95:5 by GC), and these are isolated by preparative GC. The reaction of 1 (1.26 g, 10 mmol) with 18 (1.08 g, 11 mmol) in 30 mL of CH_3CN at 50 °C for 2 h under Ar produced a 93:7 mixture of **29a** and **29b** in 62% yield (by GC). **29a**: mp 169–171.5 °C; ^1H NMR δ 1.68 (ddt, J = 10.7, 4, 2 Hz, H_j), 1.90 (dd, J = 15, 4 Hz, H_c), 1.99 (dt, J = 10.7, 1.5 Hz, H_i), 2.08 (ddd, J = 15, 5, 2 Hz, H_b), 2.80–2.84 (m, Ha and H_d), 3.29 (dd, J = 10.7, 5.3 Hz, H_g), 3.47 (ddd, J = 10.7, 5.8, 2 Hz, H_e), 3.80–4.02 (m, 4 H_k); IR (KBr) 1848, 1776, 1086 cm^{-1}; MS m/z 24 (M, 14), 152 (15), 126 (20), 86 (100). Anal. Calcd for $C_{11}H_{12}O_5$: C, 58.92; H, 5.40. Found: C, 58.94; H, 5.57. **29b**: mp 123.5–125.5 °C: ^1H NMR δ 1.37 (ddt, J = 12, 3.5, 2 Hz, H_j), 1.61 (dd, J = 14, 3.5 Hz, H_c), 1.80 (dt, J = 12, 1.5 Hz, H_i), 2.00 (dd, J = 14, 5 Hz, H_b), 2.66 (br s, H_a), 2.85 (br d, J = 5 Hz, H_d), 3.01 (d, J = 7.5 Hz, H_b), 3.44 (d, J = 7.5 Hz, H_f), 3.86–3.90 (m, 1 H_k), 3.93–3.95 (m, 2 H_k), 4.01–4.04 (m, 1 H_k); IR (KBr) 1776, 1098, 922 cm^{-1}; MS m/z 224 (M, 14), 152 (11), 126 (22), 86 (100).

Reaction of 1 with *N*-Phenylmaleimide (19). A solution of 1 (1.51 g, 12 mmol) and 19 (1.90 g, 11 mmol) in 30 mL of CH_3CN was heated at 70 °C for 9 d under Ar. After removal of the solvent in vacuo, the residue was dissolved in 150 mL of hot 2:8 benzene–hexane to remove brown viscous impurities. From the supernatant solution, 2.1 g (64%) of **30a** was crystallized. The mother liquid was concentrated and subjected to chromatography on silica gel to afford unreacted 1 (2:8 Et_2O–hexane) and an additional 0.67 g (84% in total) of **30a** (Et_2O). Together with **30a**, the reaction afforded a minor product which exhibited a fragmentation pattern in its GC–MS spectrum very similar to that in the spectrum of **30a** and hence was tentatively assigned to **30b** (96:4 by GC). **30a**: mp 146–147 °C; ^1H NMR δ 1.70 (ddt, J = 10.7, 4, 2 Hz, H_j), 1.86 (dd, J = 15, 4 Hz, H_c), 1.98 (br d, J = 10.7 Hz, H_i), 2.05 (ddd, J = 15, 5.5, 4 Hz, H_b), 2.84–2.87 (m, H_a and H_d), 3.16 (dd, J = 10, 5.4 Hz, H_g), 3.32 (ddd, J = 10, 5.5, 2 Hz, H_e), 3.83–3.99 (m, 4 H_k), 7.30 (d, J = 7.3 Hz, 2 H), 7.39 (t, J = 7.3 Hz, 1 H), 7.46 (t, J = 7.3 Hz, 2 H); IR (KBr) 1710, 1382, 1194 cm^{-1}; GC–MS m/z 299 (m, 87), 126 (87), 99 (55), 86 (100), 79 (25). Anal. Calcd for $C_{17}H_{17}NO_4$: C, 68.21; H, 5.73; N, 4.68. Found: C, 68.19; H, 5.85; N, 4.66. **30b**: GC–MS m/z 299 (M, 52), 126 (79), 99 (39), 86 (100), 79 (2).

Reaction of 1 with Dimethyl Acetylenedicarboxylate (20). A solution of 1 (1.26 g, 10 mmol) and **20** (8.0 mL, 65 mmol) in 30 mL of CH_3CN was heated at 70 °C for 2 d under Ar. After removal of the solvent in vacuo, the residue was chromatographed on silica gel to afford unreacted **20** (2:8 Et_2O–hexane) and 2.51 g (94%) of **34** (1:1 Et_2O–hexane) as colorless crystals: mp 63–64 °C; ^1H NMR δ 1.81 (br d, J = 9 Hz, H_i), 1.83 (dd, J = 13, 3 Hz, H_c), 1.94 (br d, J = 9 Hz, H_j), 2.08 (dd, J = 13, 3.5 Hz, H_b), 3.17 (m, H_d), 3.19 (m, H_a), 3.77 (s, OCH_3), 3.78 (s, OCH_3), 3.93–4.04 (m, 4 H_k); IR (KBr) 1722, 1630, 1270 cm^{-1}; MS m/z 268 (M, 4), 237 (2.5), 151 (5.5), 86 (100). Anal. Calcd for $C_{13}H_{16}O_6$: C, 58.20; H, 6.01. Found: C, 58.16; H, 6.05.

Reaction of 1 with 2-Chloroacrylonitrile (21). A solution of 1 (7.66 g, 0.06 mol), **21** (15, 8 g, 0.18 mol), and 2,6-dimethylpyridine (1 mL) in 150 mL of CH_3CN was heated at 70 °C for 20 h under Ar. After removal of the solvent in vacuo, the residue was chromatographed on silica gel to afford 10.3 g (80%) of **38** (2:8 Et_2O–hexane) as a 83:17 mixture of the stereoisomers: ^1H NMR (the major component) δ 1.92 (ddt, J = 10.5, 3.5, 1.5 Hz, H_j), 1.94 (dd, J = 14, 4.5 Hz, H_b), 2.02 (ddt, J = 10.5, 3.5, 1.5 Hz, H_i), 2.26 (br d, J = 5 Hz, H_a), 2.30 (dd, J = 14, 3.5 Hz, H_c), 2.32 (dd, J = 14, 3.5 Hz, H_b), 2.54 (dd, J = 14, 5 Hz, H_g), 2.78 (br d, J = 4.5 Hz, H_d), 3.82–3.87 (m, 2 H_k), 3.92–4.00 (m, 2 H_k); IR (neat) 2235, 1340, 1112 cm^{-1}; MS m/z 213 (M, 4.5), 126 (57), 99 (22), 86 (100). Anal. Calcd for $C_{10}H_{12}NO_2Cl$: C, 56.21; H, 5.66; N, 6.56. Found: C, 56.29; H, 5.77; N, 6.57.

When conducted in the absence of 2,6-dimethylpyridine, the reaction was much less clean and provided **38** in only 10% yield, together with several unidentified byproducts. By using 3 equiv of 1 in dioxane, the yield was doubled to 19% (based on the amount of **21** used), but was still very unsatisfactory.

Reaction of 2 with *N*-Phenylmaleimide (19). A solution of **2** (87 mg, 0.62 mmol) and 19 (139 mg, 0.80 mmol) in 4 mL of CH_3CN was heated at reflux for 2 d. After removal of the solvent in vacuo, the residue was subjected to flash chromatography (Et_2O) to afford 163 mg (87%) of **31a**, which was recrystallized from 1:1 Et_2O–hexane to give an analytically pure sample. The GC analysis of the reaction mixture showed the formation of a minor product which was not isolated, but which might be **31b** (97:3 by GC). **31a**: mp 185–185.5 °C; ^1H NMR δ 0.96 (d, J = 7.8 Hz, CH_3), 1.64 (dt, J = 10.3, 1.5 Hz, H_i or H_j), 1.87 (dt, J = 10.3, 1.5 Hz, H_j or H_i), 2.35 (qd, J = 7.8, 3.9 Hz, H_b), 2.84–2.87 (m, H_d), 2.94 (br d, J = 5.4 Hz, H_a), 3.16 (dd, J = 10.3, 5.4 Hz, H_g), 3.23 (ddd, J = 10.3, 5.4, 1 Hz, H_e), 3.90–4.01 (m, 4 H_k), 7.32–7.36 (m, 2 H), 7.37–7.42 (m, 1 H), 7.46–7.51 (m, 2 H); IR (KBr) 1712, 1370, 1180 cm^{-1}; MS m/z 313 (M, 100), 140 (75), 125 (43), 113 (47), 100 (70), 99 (50), 86 (86). Anal. Calcd for $C_{18}H_{19}NO_4$: C, 68.98; H, 6.12; N, 4.47. Found: C, 68.91; H, 6.14; N, 4.49.

Reaction of 2 with Dimethyl Acetylenedicarboxylate (20). A solution of **2** (82 mg, 0.58 mmol) and **20** (99 mg, 0.70 mmol) in 4 mL of CH_3CN was heated at reflux for 4 d. After removal of the solvent in vacuo, the residue was chromatographed on silica gel (Et_2O–benzene) to afford 141 mg (86%) of **35** as a colorless oil: ^1H NMR δ 0.94 (d, J = 7.3 Hz, CH_3), 1.79 (dt, J = 9.8, 1.5 Hz, H_i or H_j), 1.97 (dt, J = 9.8, 1.5 Hz, H_j or H_i), 2.32 (qd, J = 7.3, 3.4 Hz, H_b), 3.05–3.08 (m, H_d), 3.14–3.16 (m, H_a), 3.77 (s, OCH_3), 3.78 (s, OCH_3), 3.87–3.95 (m, 2 H_k), 3.95–4.04 (m, 2 H_k); IR (neat) 1720, 1626, 1266 cm^{-1}; MS m/z 282 (M, 0.2), 151 (6), 101 (9), 100 (100), 99 (20). Anal. Calcd for $C_{14}H_{18}O_6$: C, 59.56; H, 6.44. Found: C, 59.48; H, 6.46.

Reaction of 3 with *N*-Phenylmaleimide (19). A solution of **3** (75 mg, 0.54 mol) and **19** (100 mg, 0.58 mmol) in 3 mL of CH_3CN was heated at 70 °C for 2 d. After removal of the solvent in vacuo, the residue was chromatographed on silica gel (Et_2O) to afford 150 mg (89%) of crystalline product, which was recrystallized from 2:8 Et_2O–hexane to give an analytically pure **32a**. Together with **32a**, the reaction afforded a minor product which exhibited a fragmentation pattern in its GC–MS spectrum similar to that in the spectrum of **32a** and hence was tentatively assigned to **32b** (94:6 by GC). **32a**: mp 144–145 °C; ^1H NMR δ 1.44 (s, CH_3), 1.66 (ddd, J = 10.7, 3.5, 1.5 Hz, H_j), 1.86 (dd, J = 10.7, 1.5 Hz, H_i), 1.89 (dd, J = 14.7, 2 Hz, H_b), 1.96 (dd, J = 14.7, 3.5 Hz, H_c), 2.76 (br, d, J = 5.4 Hz, H_a), 2.98 (dd, J = 10.3, 2 Hz, H_e), 3.23 (dd, J = 10.3, 5.4 Hz, H_g), 3.82–4.00 (m, 4 H_k), 7.31 (d, J = 7.3 Hz, 2 H), 7.37 (t, J = 7.3 Hz, 1 H), 7.46 (t, J = 7.3 Hz, 2 H); IR (KBr) 1710, 1382, 1182 cm^{-1}; MS m/z 313 (M, 100), 298 (17), 153 (57), 140 (72), 139 (39), 126 (30), 113 (70), 86 (78). Anal. Calcd for $C_{18}H_{19}NO_4$: C, 68.98; H, 6.12; N, 4.47. Found: C, 69.02; H, 6.19; N, 4.39. **32b**: GC–MS m/z 313 (M, 55), 298 (45), 153 (60), 140 (88), 139 (80), 126 (100), 113 (43), 86 (89).

Reaction of 3 with Dimethyl Acetylenedicarboxylate (20). A solution of **3** (50 mg, 0.36 mmol) and **20** (100 mg, 0.70 mmol) in 3 mL of CH_3CN was heated at 70 °C for 2 d. After removal of the solvent in vacuo, the residue was subjected to preparative GC to afford 88 mg (86%) of **36** as colorless crystals: mp 59–60 °C; ^1H NMR δ 1.31 (s, CH_3), 1.75 (dd, J = 9.3, 1.5 Hz, H_i), 1.81 (ddd, J = 9.3, 3.4, 1.5 Hz, H_j), 1.87 (d, J = 12.7 Hz, H_b), 1.94 (dd, J = 12.7, 3.4 Hz, H_c), 3.16 (t, J = 1.5 Hz, H_a), 3.73 (s, OCH_3), 3.83 (s, OCH_3), 3.91–4.03 (m, 4 H_k); IR (neat) 1728, 1630, 1274 cm^{-1}; MS m/z 282 (M, 4), 251 (2), 165 (7), 105 (6), 87 (23), 86 (100). Anal. Calcd for $C_{14}H_{18}O_6$: C, 59.56; H, 6.44. Found: C, 59.36; H, 6.43.

Reaction of 3 with 2-Chloroacrylonitrile (21). A solution of **3** (194 mg, 1.38 mmol), **21** (175 mg, 2.0 mmol), and 2.6-dimethylpyridine (37 mg, 0.34 mmol) in 5 mL of CH_3CN was heated at 70 °C for 2 d. After removal of the solvent in vacuo, the residue was subjected to preparative GC to afford 254 mg (81%) of **39** as a colorless oil which was shown to be stereochemically homogeneous by ^1H NMR: ^1H NMR δ 1.35 (s, CH_3), 1.76 (dd, J = 14.7, 1 Hz, H_b), 1.82 (ddd, J = 11.6, 3.7, 1.8 Hz, H_j), 1.88 (ddd, J = 11.6, 3.4, 1.8 Hz, H_i), 2.08 (br d, J = 5.2 Hz, H_a), 2.35 (dd, J = 14.7, 3.7 Hz, H_c), 2.44 (dd, J = 14.7, 3.4 Hz, H_h), 2.65 (dd, J = 14.7, 5.2 Hz, H_g), 3.80–3.87 (m, 2 H_k), 3.90–3.96 (m, 1 H_k), 3.96–4.01 (m, 1 H_k); IR (KBr) 2236, 1342, 1100 cm^{-1}; MS m/z 227 (M, 9), 192 (34), 140 (100), 125 (45), 99 (51), 86 (88). Anal. Calcd for $C_{11}H_{14}NO_2Cl$: C, 58.02; H, 6.21; N, 6.15; Cl, 15.57. Found: C, 58.00; H, 6.22; N, 6.07; Cl, 15.49.

Reaction of 4 with *N*-Phenylmaleimide (19). A solution of **4** (140 mg, 1.0 mmol) and **19** (295 mg, 1.7 mmol) in 5 mL of CH_3CN was refluxed for 3 d. The acetal was largely consumed to produce two products in a 97:3 ratio (by GC). After removal of the solvent, the residue was chromatographed on silica gel (Et_2O) to afford 255 mg (82%) of **33a**. Although the minor product was not isolated, it was tentatively assigned to the exo adduct **33b** on the basis of the close similarity of its GC–MS spectrum to that of **33a**. **33a**: mp 158.5–159 °C; ^1H NMR δ 1.42 (s, CH_3), 1.59 (ddd, J = 10.3, 3.4, 2.0 Hz, H_j), 1.84 (dd, J = 14.7, 3.4 Hz, H_c), 1.95 (br d, J = 10.3 Hz, H_i), 2.02 (ddd, J = 14.7, 5.4, 1.5 Hz, H_b), 2.75 (br t, J = 5.4 Hz, H_d), 2.95 (d, J = 10.3 Hz, H_g), 3.38 (ddd, J = 10.3, 5.4, 1.5 Hz, H_e), 3.86–4.02 (m, 4 H_k), 7.28–7.48 (m, 5 H); IR (KBr) 1710, 1375, 1110 cm^{-1}; MS m/z 314 (M + 1, 22), 313 (M, 100), 269 (39), 140 (520, 125 (23), 99 (24), 93 (56), 86 (68), 80 (78). Anal. Calcd for $C_{18}H_9NO_4$: C, 68.98; H, 6.12; N, 4.47. Found: C, 68.90; H, 5.98; N, 4.52.

Reaction of 4 with Dimethyl Acetylenedicarboxylate (20). A solution of **4** (140 mg, 1.0 mmol) and **20** (240 mg, 1.7 mmol) in 5 mL of CH_3CN was refluxed for 4 d. The acetal was largely consumed to produce a single major product. After removal of the solvent, the residue was chromatographed on silica gel (1:9–2:8 Et_2O–hexane) to afford 240 mg (85%) of **37** as a colorless oil: ^1H NMR δ 1.27 (s, CH_3), 1.82 (br d, J = 9.4 Hz, H_i or H_j), 1.84 (br d, J = 12.7 Hz, H_c), 1.85 (br d, J = 9.4 Hz, H_j or H_i), 2.03 (dd, J = 12.7, 3.9 Hz, H_b), 3.11 (br s, H_d), 3.74 (s, CO_2CH_3), 3.81 (s, CO_2CH_3), 3.88–4.06 (m, 4 H_k); IR (neat) 1725, 1630, 1270 cm^{-1}; MS m/z 282 (M, 8), 251 (6), 165 (7), 151 (6), 100 (84), 86 (100). Anal. Calcd for $C_{14}H_{18}O_6$: C, 59.56; H, 6.44. Found: C, 59.51; H, 6.38.

Reaction of 4 with 2-Chloroacrylonitrile (21). A solution of **4** (140 mg, 1.0 mmol), **21** (263 mg, 3.0 mmol), and 2.6-dimethylpyridine (27 mg, 0.25 mmol) in 5 mL of CH_3CN was refluxed for 5 d. After removal of the solvent, the residue was chromatographed on silica gel (1:1 Et_2O–hexane) to afford 182 mg (80%) of **40** as a 82:18 mixture of the stereoisomers: ^1H NMR (the major component) δ 1.05 (s, CH_3), 1.79 (br d, J = 12 Hz, H_i or H_j), 1.93 (dd, J = 14.7, 4.9 Hz, H_b), 1.95 (br d, J = 12 Hz, H_j or H_i), 2.30 (d, J = 14.7 Hz, H_g), 2.33 (dd, J = 14.7, 3.4 Hz, H_c or H_h), 2.44 (dd, J = 14.7, 3.4 Hz, H_h or H_c), 2.70 (br d, J = 4.9 Hz, H_d), 3.80–4.03 (m, 4 H_k); IR (neat) 2235, 1345, 1105 cm^{-1}; MS m/z 227 (M, 5), 152 (100), 140 (19), 99 (35), 86 (66). Anal. Calcd for $C_{11}H_{14}NO_2Cl$: C, 58.02; H, 6.21; N, 6.15; Cl, 15.57. Found: C, 57.96; H, 6.22; N, 6.17; Cl, 15.48.

Reaction of 47 with Maleic Anhydride (18). A solution of **47** (63 mg, 0.45 mmol), **18** (73 mg, 0.75 mmol), and 2,6-dimethylpyridine (13 mg, 0.11 mmol) in 1 mL of CH_3CN was heated at 120 °C for 4 d in a glass ampoule. After removal of the solvent in vacuo, the residue was chromatographed on silica gel (AcOEt) to afford 30 mg (25%) of **48**: ^1H NMR δ 1.46 (dddt, J = 12.7, 10.8, 3.4, 2.4 Hz, H_j), 1.53 (tt, J = 12.7, 2.9 Hz, H_h), 1.73 (ddt, J = 12.7, 10.8, 3.4 Hz, H_i), 1.88 (dt, J = 15.5, 2.0 Hz, H_b), 1.94 (tt, J = 12.7, 2.4 Hz, H_g), 1.99 (dt, J = 15.5, 3.4 Hz, H_c), 2.42 (q, J = 2.9 Hz, H_a), 2.46–2.51 (m, H_d), 3.02 (dd, J = 10.7, 2.9 Hm, H_f), 3.08 (ddd, J = 10.7, 3.9, 2.0 Hz, H_e), 3.80–3.87 (m, 1 H_k), 3.87–3.99 (m, 3 H_k); IR (KBr) 1774, 952, 910 cm^{-1}; MS m/z 238 (M, 31), 125 (77), 112 (38), 99 (36), 87 (39), 86 (100), 80 (32); HRMS calcd for $C_{12}H_{14}O_2$ m/z 238.0841, found 238.0850.

Reaction of 47 with *N*-Phenylmaleimide (19). A solution of **47** (70 mg, 0.50 mmol) and **19** (100 mg, 0.60 mmol) in 1 mL of CH_3CN was heatead at 120 °C for 4 d in a glass ampule. After removal of the solvent in vacuo, the residue was chromatographed on silica gel (Et_2O) to afford 83 mg (55%) of **49** which was further purified by crystallization from 3:7 benzene–hexane: mp 168–168.5 °C; ^1H NMR δ 1.52–1.62 (m, H_h and H_j), 1.70–1.79 (m, H_g or H_i), 1.88 (dd, J = 15.6, 2.0 Hz, H_b or H_c), 1.95–2.04 (m, H_c or H_b and H_i or H_g), 2.49 (br d, J = 2.5 Hz, H_a), 2.51–2.55 (m, H_d), 2.95 (br s, H_e and H_f), 3.82–3.99 (m, 4 H_k), 7.30 (d, J = 7.3 Hz, 2 H), 7.39 (t, J = 7.3 Hz, 1 H), 7.47 (t, J = 7.3 Hz, 2 H); irradiation of H_e and H_f at δ 2.93 induced positive NOEs in the signals at δ 1.57 (H_h and H_j), 2.49 (H_a), and 2.53 (H_d); IR (KBr) 1710, 1328, 1178 cm^{-1}; MS m/z 313 (M, 100), 139 (38), 138 (70), 125 (70), 112 (28), 99 (34), 86 (59). Anal. Calcd for $C_{18}H_{19}NO_4$: C, 68.98; H, 6.12; N, 4.47. Found: C, 69.14; H, 6.12; N, 4.60.

Deacetalization of 24a. A solution of **24a** (98 mg, 0.50 mmol) and PPTS (6 mg, 0.03 mmol) in 10 mL of 50% aqueous THF was heated for 13 h at 50 °C. The mixture was cooled, treated with 20 mL of 5% aqueous $NaHCO_3$, evaporated to remove THF, saturated with NaCl, and extracted with ether (3 × 100 mL). The extracts were combined, dried with Na_2SO_4, filtered, concentrated, and chromatographed on silica gel (Et_2O) to afford 66 mg (87%) of **44**: ^1H NMR (400 MHz) δ 1.77–1.93 (m, 4H), 1.98 (br dd, J = 17.6, 4.9 Hz, H_b), 2.05 (ddd, J = 13.7, 5.4, 2.5 Hz, H_h), 2.20 (s, CH_3), 2.63 (br d, J = 4.9 Hz, H_a), 3.01 (br s, H_d), 3.14 (dtd, J = 11.5, 5.4, 1.5 Hz, H_e) (0.7 equivalent of Eu(dpm)$_3$ was added) δ 2.15 (dd, J = 10.5, 3.5 Hz, H_j), 2.25 (br d, J = 10.5 Hz, H_i), 2.33 (ddd, J = 13.7, 11.5, 4.9 Hz, H_g), 2.68 (dd, J = 17.6, 3.5 Hz, H_c), 2.75 (s, CH_3), 2.84 (dd, J = 17.6, 4.9 Hz, H_b), 2.92 (dd, J = 13.7, 5.5 Hz, H_h), 3.34 (d, J = 4.9 Hz, H_a), 3.50 (br s, H_d), 3.74 (dt, J = 11.5, 5.4 Hz, H_e); IR (neat) 1750, 1700, 1370 cm^{-1}; MS m/z 152 (M, 14), 111 (90), 83 (46), 67 (18), 43 (100); HRMS calcd for $C_9H_{12}O_2$ 152.0873, found 152.0837.

Deacetalization of 36. A solution of **36** (141 mg, 0.50 mmol) in 10 mL of 30% aqueous AcOH was heated at 90 °C. After **36** was consumed, (141 mg, 0.50 mmol) in 10 mL of 30% aqueous AcOH was heated at 90 °C. After **36** was consumed, the mixture was cooled, diluted with 30 mL of water, and extracted with ether (3 × 100 mL). The ethereal extracts were combined, washed with aqueous $NaHCO_3$, dried with Na_2SO_4, filtered, concentrated, and chromatographed on silica gel (1:4 Et_2O–hexane) to afford 85 mg (72%) of **46**: ^1H NMR δ 1.43 (3, CH_3), 1.94 (dd, J = 9.8, 1.5 Hz, H_i), 1.97 (d, J = 16.6 Hz, H_b), 2.23 (dd, J = 16.6, 4.4 Hz, H_c), 2.31 (ddd, J = 9.8, 4.4, 1.5 Hz, H_j), 3.53 (t, J = 1.5 Hz, H_a),

3.76 (s, OCH_3), 3.87 (s, OCH_3); IR (neat) 1750, 1736, 1728 cm^{-1}; MS *m/z* 238 (M, 8), 196 (18), 178 (17), 165 (51), 154 (100), 136 (53), 145 (54); HRMS calcd for $C_{12}H_{14}O_5$ *m/z* 238.0842, found 238.0816. Anal. Calcd for $C_{12}H_{14}O_5$: C, 60.49; H, 5.93. Found: C, 60.01; H, 5.99.

2,5-Norbornanedione Monoethylene Acetal (41). To a stirred solution of KOH (10 g, 0.15 mmol) in 5 mL of water was added a solution of **38** (10 g, 47 mmol) in 40 mL of DMSO at 55 °C. After 2 h at the same temperature, the mixture was poured into water was added a solution of **38** (10 g, 47 mmol) in 40 mL of DMSO at 55 °C. After 2 h at the same temperature, the mixture was poured into water (500 mL), and the product was extracted with Et_2O (4 × 200 mL). The extracts were combined, washed with water, dried ($MgSO_4$), and concentrated in vacuo. Chromatography of the residue on silica gel (1:1 Et_2O–hexane) afforded to 4.7 g (59%) of **41** which was further purified by distillation at 85–95 °C (bath temperature)/1 mmHg: ^1H NMR δ 1.79 (m, H_j), 1.81 (dd, J = 14, 3 Hz, H_c), 1.99 (dd, J = 18, 5 Hz, Hg), 2.01 (m, H_i), 2.13 (dd, J = 14, 5 Hz, H_b), 2.32 (dd, J = 18, 4 Hz, H_h), 2.51 (br d, J = 5 Hz, H_a), 2.59 (br d, J = 5 Hz, H_d), 3.88–4.04 (m, 4 H_k); ^{13}C NMR δ 36.30, 38.29, 38.87, 43.09, 49.49, 64.32, 64.73, 114.43, 215.87; IR (neat) 1752, 1336, 1090 cm^{-1}; MS *m/z* 168 (M, 52), 99 (100), 86 (50), 55 (49). Anal. Calcd for $C_9H_{12}O_3$: C, 64.27; H, 7.19. Found: C, 64.15; H, 7.22.

1-Methylnorbornane-2,5-dione Monoethylene Acetal (42). To a solution of **39** (100 mg, 0.44 mmol) in 3 mL of DMSO was added a solution of KOH (1 g, 15 mmol) in 0.5 mL of water. The resultant mixture was stirred at 55 °C for 4 h, worked up as described above for **41**, and then subjected to preparative GC to afford 47 mg (59%) of **42** as colorless crystals: mp 63.5–64 °C; ^1H NMR δ 1.13 (s, CH_3), 1.62 (ddd, J = 10.7, 3.4, 1.5 Hz, H_j), 1.75 (dd, J = 13.7, 3.4 Hz, H_c), 1.91 (dd, J = 13.7, 1 Hz, H_b), 2.00 (ddd, J = 10.7, 4.5, 1.5 Hz, H_i), 2.05 (dd, J = 18.3, 4.5 Hz, H_g), 2.41 (dd, J = 18.3, 4.5 Hz, H_h), 2.44–2.47 (m, H_a), 3.87–3.95 (m, 3 H_k), 3.95–4.03 (m, 1 H_k); ^{13}C NMR δ 14.1 (q), 38.9 (t), 42.2 (d), 42.4 (d), 45.5 (t), 53.6 (s), 64.4 (t), 64.8 (t), 115.1 (s), 216.8 (s); IR (KBr) 1736, 1342, 1100 cm^{-1}; MS *m/z* 182 (M, 35), 126 (23), 113 (24), 99 (100), 86 (25), 55 (23). Anal. Calcd for $C_{10}H_{14}O_3$: C, 65.90; H, 7.76. Found: C, 66.08; H, 7.71.

1-Methylnorbornane-2,5-dione Monoethylene Acetal (43). To a solution of **40** (159 mg, 0.70 mmol) in 10 mL of DMSO was added a solution of KOH (1 g, 15 mmol) in 0.5 mL of water. The resultant mixture was stirred at 55 °C for 6 h, worked up as described above for **41**, and then subjected to preparative GC to afford 78 mg (61%) of **43** as a colorless oil: ^1H NMR δ 1.14 (s, CH_3), 1.60 (ddd, J = 10.8, 3.4, 2.0 Hz, H_j), 1.80 (dd, J = 13.7, 3.4 Hz, H_c), 1.83 (br d, J = 18.1 Hz, H_g), 1.94 (br dd, J = 10.8, 4.4 Hz, H_i), 2.11 (dd, J = 13.7, 5.4 Hz, H_b), 2.46 (dd, J = 18.1, 4.4 Hz, H_h), 2.55 (br, d, J = 5.4 Hz, H_d), 3.84–4.02 (m, 4 H_k); IR (neat) 1735, 1345, 1105 cm^{-1}; MS *m/z* 182 (M, 3), 167 (32), 149 (68), 113 (22), 81 (54), 69 (100), 57 (94), 43 (67). Anal. Calcd for $C_{10}H_{14}O_3$: C, 65.90; H, 7.76. Found: C, 66.03; H, 7.90.