with $x_1$ and $x_2$ being the values of $x$ for which

$$x^2 - K_{ij}x(r + 1)/(K_{ij} - 1) + K_{ij}r/(K_{ij} - 1) = 0$$

Then $x_1$, $x_2$, $k_{ij}$, and $K_{ij}$ were obtained by iterative computation.

All the $K_{ij}$ constants were determined according to the experimental conditions summarized in Table VI. In some cases, the duration of the experiment was limited by the occurrence of side reactions. Those were detected both by testing the spectral stabilities of separated solutions of each component $A_i^+$, $A_j^+$, $A_i$H, and $A_j$H within the same time scale and by monitoring the coherence of the evolution of the spectrum of the reaction mixture over the whole wavelength range. For example, the experiments allowing the determinations of $K_{37}$ and $K_{56}$ were ended before the formation of appreciable amounts of unidentified byproducts, which provoke abnormal changes in the absorbance at 350 and below 290 nm in the former case and in the 220 to 320 nm region (with a maximum effect at 295 nm) in the second case.

**Spectrophotometric Determinations of the $K_{OH}$'s and $K_{B_x}$'s.** The $K_{OH}$ and $K_{B_x}$ equilibrium constants were determined from spectra in a series of buffer solutions given in Table V. The spectra at pH or $B_x$H concentration high enough to ensure the total consumption of $A^+$ were taken as the spectra of the pseudobases unless otherwise specified. Regeneration of at least 95% of $A^+$ upon neutralization with $HClO_4$ ascertained the reversibility of the $HO^-$ or B addition. Such a reversibility was always obtained when the time elapsed between the introduction of $A^+$ in the buffer and the neutralization with $HClO_4$ did not exceed 30 s. Within this time scale, the system was always at equilibrium except for the OH adducts of $A^+_3$ and $A^+_4$. However, in the cases of $A^+_3$ and/or $A^+_4$, reaching the equilibrium between the kinetically favored adduct at the 2 position and the thermodynamically favored adduct at the 4 position took less than 30 min and addition of $HClO_4$ after such a while still brought on regeneration of the original $A_i^+$. The word "stable" in Table III indicates that the total regeneration of $A^+$ could still be performed after an hour (at least). The spectrophotometric characteristics of the adducts, $\lambda_{max}$ and $\epsilon_{max}$ (when the latter could be evaluated with confidence), are also gathered in Table III together with the wavelengths $\lambda_w$ and molar absorbances $\epsilon_w$, which were used in order to determine the concentrations at equilibrium and therefore calculate the equilibrium constants. The identification of the isosbestic points appearing during the transformation of the adduct at the 2 position to the adduct at the 4 position enabled us to determine the true apparent constants ($pK_{OH}^{app}$) of the cations $A_3^+$ and $A_4^+$. In the cases of the pyridinium cations $A_5^+$, $A_6^+$, and $A_7^+$, it is well known that the preferred products of kinetic and thermodynamic control are quite dependent on both the substituent on the ring and the nature of the attacking nucleophile.[13b,16,27] The $pK_{OH}^{app}$ and $pK_{B_x}^{app}$ values given in Table V were obtained after making the following approximations: for $A_5$OH, $A_6$OH, $A_7$OH, $AB_3$, and $AB_2$, the molar absorbance of the adduct at the 4 position and its isomers, which were only minor products, were assumed identical at $\lambda_w$.

**Acknowledgment.** Y. Besace (Laboratoire RMN de l'Ecole Nationale Supérieure de Chimie de Paris) is thanked for running the NMR spectra.

(27) Ohno, A.; Ushida, S.; Oka, S. *Bull. Chem. Soc. Jpn.* **1984**, *57*, 506.

# Acid-Catalyzed Ring Expansion of 1-(1-Methoxy-1,2-propadienyl)-2-cyclobuten-1-ols. Synthesis of 5-Hydroxy-5-vinyl-2-cyclopenten-1-ones and Their Stereoselective Transformation to 5-(2-Acetoxyethylidene)-2-cyclopenten-1-ones

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The addition of 1-lithio-1-methoxy-1,2-propadiene to various cyclobutenones, cyclobutanones, and benzocyclobutenones produces sensitive 1,2-adducts that, in the presence of acid, rearrange to 5-hydroxy-5-vinyl-2-cyclopenten-1-ones in good to excellent yields. Acid-catalyzed ring expansion of the addition products of 1-lithio-1-methoxy-1,2-propadiene to cyclobutenones bearing a substituent at the 4-position occurs in a stereospecific fashion providing cyclopentenones with the 4-substituent and the 5-hydroxyl group in a cis relationship. After conversion of the 5-hydroxy-5-vinyl-2-cyclopenten-1-ones to the corresponding allylic acetates, palladium(II)-catalyzed [3,3]-sigmatropic rearrangement can be effected, furnishing 5-(2-acetoxyethylidene)-2-cyclopenten-1-ones with high kinetic selectivity favoring the isomer with the alkylidene substituent and the carbonyl group syn (*Z* stereochemistry in most cases). On exposure to a trace of acid, equilibration occurs to the more stable isomer with the alkylidene substituent and carbonyl group anti.

## Introduction

Ring-enlargement reactions are commonly used to access cycloalkanoid derivatives; many of these methodologies utilizing ring strain in consort with the generation of positive charge on an atom adjacent to the ring as a driving force for the reaction.[2] During the course of studies on electrophilic transition-metal-catalyzed ring expansion–functionalization reactions of alkynyl-substituted cyclobutenol derivatives,[3] 1-(1-methoxy-1,2-propadienyl)-2-cyclobuten-1-ols (**2**), were prepared from the corresponding cyclobutenones **1** in anticipation of exploring similar metal-catalyzed transformations on allenyl-substituted cyclobutenols. However, the 1-(1-methoxy-1,2-propadienyl)-2-cyclobuten-1-ols were sensitive to exposure

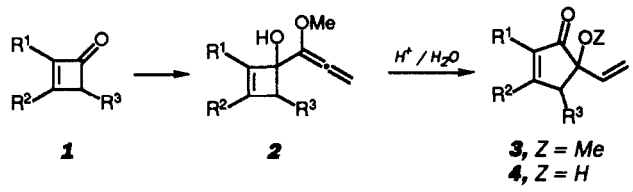
(1) Camille and Henry Dreyfus Foundation Teacher-Scholar, 1985–1990.

(2) Leading references: Cohen, T.; Brockunier, L. *Tetrahedron* **1989**, *45*, 2917. Salaün, J.; Karkour, B.; Ollivier, J. *Tetrahedron* **1989**, *45*, 3151. Salaün, J. R. Y. *Topics Curr. Chem.* **1988**, *144*, 1. Krief, A. *Topics Curr. Chem.* **1987**, *135*, 1. Trost, B. M. *Topics Curr. Chem.* **1986**, *133*, 1. Wong, H. N. C.; Lau, K.-L.; Tam, K.-F. *Topics Curr. Chem.* **1986**, *133*, 83. Trost, B. M. *Topics Curr. Chem.* **1986**, *133*, 3. Gutsche, C. D.; Redmore, D. *Carbocyclic Ring Expansion Reactions*; Academic: New York, 1968.

(3) Liebeskind, L. S.; Chidambaram, R.; Mitchell, D.; Foster, B. S. *Pure Appl. Chem.* **1988**, *60*, 2734. Liebeskind, L. S.; Mitchell, D.; Foster, B. S. *J. Am. Chem. Soc.* **1987**, *109*, 7908. Liebeskind, L. S. *Tetrahedron Symposium in Print* **1989**, *45*, 3053–3060. Liebeskind, L. S.; Lescosky, L. J.; McSwain, C. M., Jr. *J. Org. Chem.* **1989**, *54*, 1435. Mitchell, D.; Liebeskind, L. S. *J. Am. Chem. Soc.* **1990**, *112*, 291.

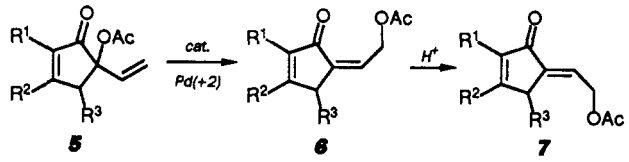
0022-3263/90/1955-4614$02.50/0 

to mild acid, and without recourse to electrophilic metal catalysis, ring-expansion reactions leading to mixtures of the 5-methoxy- and 5-hydroxy-substituted 5-vinyl-2-cyclopenten-1-ones (**3** and **4**, respectively) were observed, either on attempted purification on silica gel or during workup in the separatory funnel (eq 1). A study of this




(1)

reaction was undertaken and conditions providing exclusive formation of the 5-hydroxy-5-vinyl-2-cyclopenten-1-ones (**4**) were developed. The acetates (**5**) of compounds **4** were converted to 5-alkylidene-2-cyclopenten-1-ones by treatment with catalytic amounts of $Pd(CH_3CN)_2Cl_2$, kinetically forming the isomers (**6**) with very good selectivity in most cases. These compounds were transformed to the more stable isomers (**7**) on treatment with acid (eq 2).




(2)

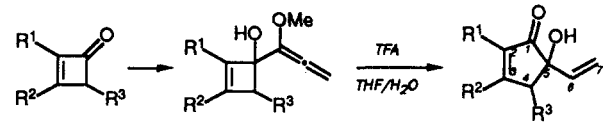
Many examples exist of biologically active cyclopentenone natural products bearing either 5-oxygenation[4] or 5-alkylidene substituents,[5] suggesting various future synthetic applications for this newly uncovered reaction sequence. The results of the ring expansion and allylic acetate isomerization studies are described herein.

## Results and Discussion

1-Lithio-1-methoxyallene was added to the cyclobutenones **1a–f** and to benzocyclobutenones **1g** and **1h** giving the adducts **2** listed in Table I. In addition to their sensitivity to acid, the allenyl adducts showed varying degrees of thermal instability. As a result of this lability, only one of the adducts could be purified without decomposition (**2g**, by recrystallization) and only two gave acceptable combustion analysis (**2g** and **2h**). However, analysis of the $^1H$ NMR spectra of the crude addition products indicated that the addition had proceeded cleanly and efficiently, and the crude material was considered suitable for subsequent reactions. In the case of the 4-substituted cyclobutenones, **2b** and **2c**, only one of the two possible stereoisomers was observed; literature precedent suggested that addition had occurred trans to the 4-substituent.[6]

Allenyl adducts **2a–e,g,h**, dissolved in 1:1 $THF/H_2O$, on treatment with trifluoroacetic acid underwent a hydrolysis–ring-expansion reaction providing the 5-hydroxy-5-vinyl-2-cyclopenten-1-ones **4** in good isolated yields (62–92%). The endocyclic enol ether moiety of **2f** did not survive these acidic reaction conditions; however, the desired ring expansion could be achieved by using $SiO_2/H_2O$. The ring-expansion reactions took from 0.5 to 4 h to reach completion, the 4-chloro-substituted cyclobutenone **2b** taking the longest.

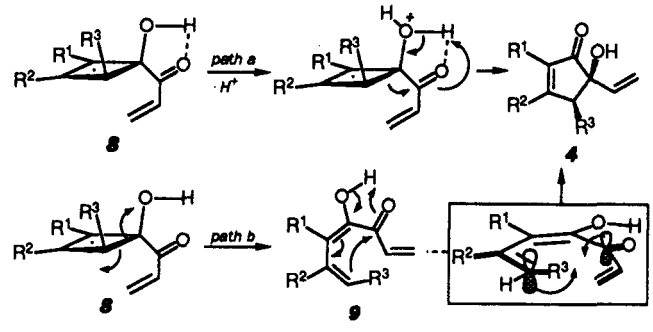
**Table I. Synthesis of 5-Hydroxy-5-vinyl-2-cyclobuten-1-ones**




| compd | $R^1$ | $R^2$ | $R^3$ | 2, yield[a] (%) | 4, yield[b] (%) |
|---|---|---|---|---|---|
| a | Me | Me | H | 87 | 76 |
| b | Me | Me | Cl | 82 | 70 |
| c | Me | Me | Me | 91 | 72 |
| d | H | *n*-Bu | H | 82 | 76 |
| e | H | $SiMe_3$ | H | 98 | 62[c] |
| f | H | OEt | H | 72 | 40 |
| g |  | | H | 72[d] | 83 |
| h |  | | H | 94 | 92[d] |

[a] Except where noted otherwise, yields of crude product are indicated. [b] Isolated yield of material purified by chromatography. [c] Yield based on GC. [d] Yield after recrystallization.

**Scheme I**




Ring expansion of the allene adducts of trisubstituted cyclobutenones **2b** and **2c** occurred with high stereoselectivity, providing only the stereoisomer with a cis relationship between OH and $R^3$ in each case. The assignment of stereochemistry was based on NOE difference experiments. Irradiation of the C-4 methine hydrogen (see numbering of structure **4** in Table I) caused significant enhancement of the C-6 olefinic hydrogen (14% for **4b** and 10% for **4c**). Irradiation of the C-4 methyl substituent of **4c** resulted in enhancement of the C-4 methine absorption (9%) without influencing the vinyl group hydrogens.

Formation of the cyclopentenones **4** proceeds via an enone intermediate **8** formed by rapid hydrolysis of the alkoxyallene under the conditions of the reaction. Stereospecific transformation of **8** into the cyclopentenone **4** can occur by one of two pathways, either direct acid-catalyzed, conformation-specific ring expansion, or selective-conrotatory cyclobutenol ring opening to the hydroxy trienone **9** (OH outward, Houk[7]) followed by conrotatory electrocyclization (Scheme I).

(4) Umino, K.; Furumai, T.; Matsuzawa, N.; Awataguchi, Y.; Ito, Y.; Okuda, T. *J. Antibiot.* **1973**, *26*, 506. Hatano, K.; Hasegawa, T.; Izawa, M.; Asai, M.; Iwasaki, H. (Takeda Chemical Industries, Ltd.) *Jpn. Kokai Tokkyo Koho* **75**, *70*, (June 1975), 597; *Chem. Abstr.* **1976**, *84*, 3287u. Noble, M.; Noble, D.; Fletton, R. A. *J. Antibiot.* **1978**, *31*, 15. Verlaak, J. M. J.; Klunder, A. J. H.; Zwanenburg, B. *Tetrahedron Lett.* **1982**, *23*, 5463. Klunder, A. J. H.; Houwen-Classen, A. A. M.; Kooy, M. G.; Zwanenburg, B. *Tetrahedron Lett.* **1987**, *28*, 1329.

(5) Some recent references are as follows: Nagaoka, H.; Iguchi, K.; Miyakoshi, T.; Yamada, N.; Yamada, Y. *Tetrahedron Lett.* **1986**, 223–226. Iguchi, K.; Kaneta, S.; Mori, K.; Yamada, Y.; Honda, A.; Mori, Y. *J. Chem. Soc., Chem. Commun.* **1986**, 981–982. Baker, B. J.; Okuda, R. K.; Yu, P. T. K.; Scheuer, P. J. *J. Am. Chem. Soc.* **1985**, *107*, 2976–2877. Nagaoka, H.; Miyaoka, H.; Miyakoshi, Y.; Yamada, Y. *Ibid.* **1986**, 5019–5021. Fukushima, M.; T. T.; Yamada, Y.; Kitagawa, I.; Kurozumi, S.; Scheuer, P. *J. Proc. Am. Assoc. Cancer Res.* **1985**, *26*, 249.

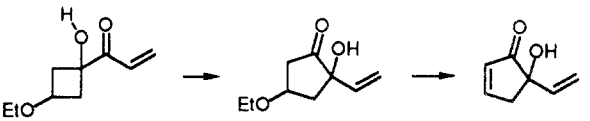
(6) Brook, P. R.; Duke, A. J. *J. Chem. Soc., Chem. Commun.* **1970**, 652.

(7) (a) Houk, K. N.; Spellmeyer, D. G.; Jefford, C. W.; Rimbault, C. G.; Wang, Y.; Miller, R. D. *J. Org. Chem.* **1988**, *53*, 2125. (b) Randan, N. G.; Houk, K. N. *J. Am. Chem. Soc.* **1985**, *107*, 2099. (c) Rudolf, K.; Spellmeyer, D. C.; Houk, K. N. *J. Org. Chem.* **1987**, *52*, 3708.

Evidence for the existence of both pathways was obtained. An indication of the electrocyclic ring opening–ring closure path comes from a detailed spectroscopic analysis ($^1$H NMR, IR, and UV) of the reaction mixture acquired during the early stages of the ring expansion of **2b** (throughout the following discussion, $R^1 = R^2 = Me$; $R^3 = Cl$, for structures in Scheme I). A reaction mixture cross section was obtained by addition of 1-lithio-1-methoxyallene to cyclobutenone **1b** followed by treatment with TFA in $THF/H_2O$ for 30 min at room temperature. After neutralization with $NaHCO_3$, a sample of the reaction mixture in $CD_3CN$ in an NMR tube was monitored over a 3-day period. Concurrent with the NMR analysis, UV spectra were acquired on a dilute sample of the neutralized reaction mixture in $CH_3CN$. During the course of the analysis, three species were observed and assigned structures **8**, **9**, and **4b**. Assignment of peaks in the $^1$H NMR spectrum of the mixture to **4b** was straightforward, since it is the product isolated at the end of the reaction, with olefinic absorptions appearing at 5.75 (dd, $J$ = 17.2 Hz, $J$ = 10.5 Hz), 5.50 (dd, $J$ = 17.2 Hz, $J$ = 0.9 Hz), and 5.30 (dd, $J$ = 10.6 Hz, $J$ = 0.9 Hz). Additional vinyl resonance groupings appeared at 6.70 (dd, $J$ = 17.3 Hz, $J$ = 10.4 Hz), 6.52 (dd, $J$ = 17.2 Hz, $J$ = 1.8 Hz), and 5.80 (dd, $J$ = 10.3 Hz, $J$ = 1.8 Hz) and at 6.95 (dd, $J$ = 17.0 Hz, $J$ = 10.4 Hz) 6.37 (dd, $J$ = 16.9 Hz, $J$ = 1.8 Hz), and 5.70 (dd, $J$ = 10.5 Hz, $J$ = 1.9 Hz) and were assigned to the cyclobutenol **8** and the hydroxy trienone **9**, respectively. Integration of the $^1$H NMR spectrum at $t$ = 0 showed a mixture consisting of product **4b**, enone **8**, and ring-opened product **9** in a ratio of 3.3:1.3:1. Over an 8-h period, the peaks assigned to enone **8** completely disappeared with a corresponding increase in the absorptions assigned to the cyclobutenone ring opening product **9**. Then **9** gradually disappeared leaving pure **4b** after a 3-day period. At the initial time of the analysis, the UV spectrum showed major absorbances at 221, 238, and 305 nm, consistent with UV absorptions expected for the chromophores contained in **8** (calcd 215), **4b** (calcd 236), and **9** (calcd 310), respectively. Within 8 h the absorption at 221 had disappeared with concomitant growth in the 305 peak. Then, over a 3-day period the 305 peak slowly disappeared while the 234 absorption grew, also confirming complete conversion of the reaction mixture intermediates into **4b**.

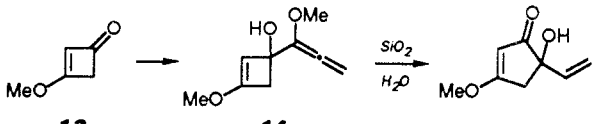
The spectra taken at $t$ = 0 along with the indicated changes with time are suggestive of separate acid catalyzed and thermal reaction paths leading to product **4b**. Under the aqueous acidic conditions used prior to the $NaHCO_3$ quench (TFA in $THF/H_2O$, 30 min, room temperature) cyclobutenol enone **8** is rapidly formed and probably undergoes acid-catalyzed ring expansion according to path a in Scheme I, accounting for the product mixture rich in **4b** observed *at the beginning of the $^1$H NMR and UV experiments*. The spectroscopic experiments suggest that, after neutralization of the acid, the direct ring expansion is inhibited and enone **8** undergoes electrocyclic ring opening to the hydroxy trienone intermediate **9** over a period of 8 h (path b).[8] Subsequent conrotatory cyclization establishes the cyclopentenone ring with the hydroxyl and chloro substituents cis. The observation of the cyclobutenol ring opened product **9** is limited to substrate **2b**, which undergoes much slower acid-catalyzed ring expansion than the other substrates because of the presence of an electron-withdrawing chlorine substituent at C-4.

Additional support for the direct, acid-catalyzed ring expansion path was obtained by preparation of the relatively stable cyclobutanol **10** (treatment of 3-ethoxycyclobutanone[9] with 1-lithio-1-methoxyallene followed by acid hydrolysis (only one diastereomer formed). The usual aqueous acid conditions did not rapidly induce ring expansion; however, exposure of **10** to $SiO_2$ provided the ring-expanded cyclopentanone product **11** (one diastereomer only), while treatment of **10** with $ZnCl_2$ in refluxing $CH_2Cl_2$ led to the cyclopentenone **12**, presumably via **11** (eq 3).



**10** **11** **12** (3)

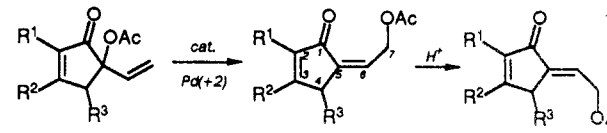
A short, efficient synthesis of racemic 5-hydroxy-3-methoxy-5-vinyl-2-cyclopenten-1-one (**15**) one of the few naturally occurring 5-hydroxy-5-vinyl cyclopentenones,[10] was undertaken (eq 4). 3-Methoxy-2-cyclobuten-1-one (**13**) on treatment with 1-lithio-1-methoxyallene produced the sensitive 1,2-adduct **14**. Attempted ring expansion under standard conditions (TFA in $THF/H_2O$) led to hydrolysis of both enol ether moieties; however, warming a solution of **14** in $THF/H_2O$ to 30 °C for 1 h in the presence of $SiO_2$ induced ring expansion without destruction of the endocyclic enol ether providing **15** in 35% yield after purification.



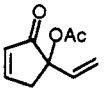
**13** **14** **15** (4)

The allylic alcohol functionality of the cyclopentenones **4** suggested the use of the palladium(II)-catalyzed 3,3-sigmatropic rearrangement of allylic acetates[11] as a means of accessing 5-alkylidene-2-cyclopenten-1-ones, the core

**Table II. Formation of Alkylidenecyclopentenones via Palladium-Catalyzed [3,3]-Shift**



**5** **6** **7**

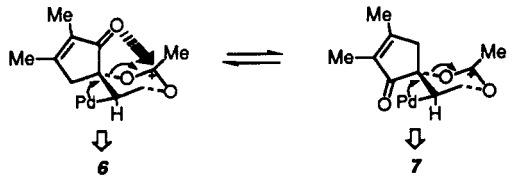
| compound[a] (% yield from **4**) | $CH_2Cl_2$ %/6:7 ratio/reactn time (h) | $C_6H_6$ %/6:7 ratio/reactn time (h) | 6:7 ratio after $H^+$ treatment |
|---|---|---|---|
| **5a** (91) | 94/9:1/2.5 | 96/20:1/20 | 1:16 |
| **5b** (90) | 96/1.5:1/26 | | 1:6 |
| **5c** (94) | | 96/15:1/29 | 1:3.6 |
| **5d** (88) | 91/1:1.14/14 | 94/3:1/72 | 1:14 |
| **5e** (93) | 97/1:15/5.5 | 94/4:1/14 | 1:15 |
| **5g** (87) | 98/11:1/11 | 96/16:1/48 | 1:16 |
| **5h** (85) | 96/7.6:1/14 | 90/17:1/36 | 1:16 |
|  **5i** (93% from **12**) | | 90/8:1/45 | 1:14 |

[a] Refer to Table I for assignment of substituents **a**–**h**.

(8) Thermal opening of 3-formylcyclobutene at 25 °C occurs with a half-life of approximately 50 h[7c] supporting the proposed electrocyclic process.

(9) Sieja, J. B. *J. Am. Chem. Soc.* **1971**, *93*, 130.
(10) Strunz, G. M.; Ren, W.-Y.; Stillwell, M. A.; Valenta, Z. *Can. J. Chem.* **1977**, *55*, 2610.
(11) (a) Overman, L. E. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 579. (b) Overman, L. E.; Knoll, F. M. *Tetrahedron Lett.* **1979**, 321.

**Scheme II. Transition Structure Rationalization of *Z* Selective Alkylidene Formation**




6 7

unit found in a number of biologically active, naturally occurring compounds (eq 2).[5] Conversion of allylic alcohols **4** to the allylic acetates **5** was achieved with $Ac_2O$/$Et_3N$/4-(*N*,*N*-dimethylamino)pyridine. A survey of the palladium-catalyzed [3,3]-shift was performed with substrates **5** in both $CH_2Cl_2$ and benzene at room temperature (Table II). Exposure to 5% $Pd(CH_3CN)_2Cl_2$ (Table II) led to complete isomerization of **5** into mixtures of the exocyclic double bond isomers **6** and **7**. The stereoselectivity of the isomerization was dependent on the solvent and the reaction conditions. High kinetic selectivity providing isomer **6** (*Z* stereochemistry for all cases except **6b**) was achieved for most compounds, benzene being superior to $CH_2Cl_2$. Since the isomers **6** were easily isomerized to the thermodynamically more stable isomers **7** (*E* stereochemistry for all cases except **7b**) by traces of acid (see below), the low selectivity in some cases was attributed to **6** to **7** leakage induced by traces of acid generated under the reaction conditions. In fact, capillary GLC analysis of the $CH_2Cl_2$ run of **4a** at low conversion showed a **6**/**7** ratio of 50:1; the ratio degrading to 9:1 by the time the reaction was complete. Isolation of analytically pure samples of the mixtures of **6** and **7** was achieved by filtration of the reaction through a small plug of Florisil. On exposure of the **6**-enriched mixtures to a trace of trifluoroacetic acid in $CDCl_3$ in an NMR tube, equilibration occurred quantitatively to a mixture highly enriched in **7** within a period of 12–72 h.

Assignment of double-bond stereochemistry was based on the downfield shifts seen in the $^1H$ NMR spectra for the vinyl hydrogen of **7** relative to **6** (anisotropic deshielding by the carbonyl group) and on NOE difference experiments performed on **6a** and **7a**. Irradiation of the C-4 methylene group absorption of **6a** caused 22% enhancement of the vinyl hydrogen absorption of the exocyclic double bond, while irradiation of the same resonance on **7a** led to no enhancement at the vinyl hydrogen and 3% enhancement of the methylene group adjacent to the OAc (see numbering of structure **6** in Table II).

The kinetic stereoselectivity of the palladium-catalyzed [3,3]-shift favoring isomer **6** can be rationalized by invoking selective reaction from one of two chairlike transition state structures. It is possible that the transition structure that leads to isomer **6** is stabilized by interaction of a carbonyl oxygen nonbonding electron pair with the positive charge developed at what was the acetate carbonyl carbon (Scheme II).[12]

## Conclusions

A general method for the stereoselective synthesis of 5-alkylidene-2-cyclopenten-1-ones has been developed. Cyclobutenones react with 1-lithio-1-methoxyallene to give 1,2-addition products that rearrange with facility to 5-hydroxy-5-vinyl-2-cyclopenten-1-ones on treatment with trifluoroacetic acid in THF/$H_2O$. Subsequent conversion of the allylic alcohol to the acetate and treatment with catalytic Pd(+2) induces a [3,3]-sigmatropic rearrangement resulting in a high yield synthesis of 5-(2-acetoxyethylidene)-2-cyclopenten-1-ones, predominantly bearing the acetoxymethyl substituent and the carbonyl group syn. On treatment with catalytic acid the exocyclic double bond isomerizes to the more stable double bond isomer with the acetoxymethyl and carbonyl groups anti.

## Experimental Section

**General Information.** NOE difference spectroscopy, performed at 360 MHz and used to assign structures to **4b**, **4c**, **6a**, **7a**, with the observed enhancements described in the text, was performed with 10-mg samples (0.5 mL of 99.8% atom D $CDCl_3$) which were freeze–pump–thaw degassed and sealed. Data was acquired with use of 16 K of memory with resolutions of 0.16 Hz (**6a**/**7a**) and 0.23 Hz (**4b** and **4c**) per data point. The spectra were obtained by the method of Hall and Sanders.[13] Preirradiation times of 15–20 s, resulting in 70–90% reduction of intensity, were used to transfer polarization; data acquisition commenced after a delay of 10 μs. Data acquisition was followed by a delay of 7 s for return to equilibrium before repetition of the experiment. The resulting free-induction decays were subjected to exponential multiplication, resulting in line broadening of 0.8–1.5 Hz, transformed, and subtracted. Routine gravity chromatography was performed with flash grade silica gel 60 (EM Science). Radial chromatography was performed on a Model 7924 Chromatotron from Harrison Research with glass rotors (2.0 mm) coated with silica gel PF-254, type 60 (EM Science) with $CaSO_4 \cdot {}^1/_2 H_2O$ as a binder. Gas–liquid chromatography (GLC) was performed on a 5% phenylmethylsilane crossed-linked capillary column with a film thickness of 0.33 μm and total length of 25 m.

**Preparation of Cyclobutenones and Benzocyclobutenones. 2,3-Dimethyl-2-cyclobuten-1-one (1a)** was prepared according to the procedure of Dreiding and co-workers.[14]

**4-Chloro-2,3-dimethyl-2-cyclobuten-1-one (1b).**[15] To a dry 1-L flask equipped with a pressure-equalizing funnel, a dry ice condensor, and a nitrogen inlet tube were added freshly prepared zinc/copper couple (15 g, 0.23 mol, 3.5 equiv) and 300 mL of dry $Et_2O$. The flask was cooled to 0 °C with an ice bath, and 2-butyne (3.6 g, 0.07 mol) was added to the magnetically stirred mixture via syringe. The dry ice condensor was filled with dry ice/acetone, and the ice bath was removed. Dichloroacetyl chloride (19.7 g, 0.14 mol, 2 equiv) in 40 mL of dry $Et_2O$ was added dropwise over a 1-h period at such a rate that the exothermic reaction maintained a gentle reflux (careful warming with a heat gun was used to initiate some of the reactions). After the addition was complete, the mixtured was allowed to stir for an additional hour. The mixture was then decanted into 250 mL of ice–water, and the organic layer was separated and washed with an equal volume of water (2×), followed by saturated aqueous $NaHCO_3$, and then dried ($MgSO_4$). Filtration and removal of solvent on a rotary evaporator followed by a vacuum pump left a dark orange oil. Distillation (0.8 mmHg, 50–55 °C) gave 5.5 g (60%) of **1b** as a colorless oil with spectroscopic data consistent with the assigned structure: IR ($CH_2Cl_2$) 2950, 2780, 1770, 1625, 1465 $cm^{-1}$; $^1H$ NMR ($CDCl_3$, 300 MHz) δ 5.15 (m, 1 H), 2.19 (m, 3 H), 1.70 (m, 3 H).

**2,3,4-Trimethyl-2-cyclobuten-1-one (1c)**[16] **and 3-*n*-butyl-2-cyclobuten-1-one (1d)**[17] were prepared according to literature procedures.

**3-(Trimethylsilyl)-2-cyclobuten-1-one (1e).** 4,4-Dichloro-3-(trimethylsilyl)-2-cyclobuten-1-one[18] (1.0 g, 4.78 mmol) was dissolved in 35 mL of dry THF under an argon atmosphere. A solution of $CrCl_2$ in water[19] (38.2 mmol, 8 equiv) was added slowly

(12) We thank Professor Clark Still of Columbia University for suggesting this rationalization to us.

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(15) Brink, V. D.; Marinus, J.; Austermuehle-Bertola, H.; Kramer, P. A. Ger. Patent DE 2539048, 1976; *Chem. Abstr.* **1976**, *85*, 20680a.
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via a cannula over 30 min, and the resulting green solution was stirred for an additional 5 h. To the reaction mixture was added 100 mL each of $Et_2O$ and $H_2O$. The aqueous layer was extracted with an equal volume of ether. The combined ether layers were washed with saturated $NaHCO_3$ and NaCl and then were dried ($MgSO_4$). Removal of solvent gave a light yellow oil that was chromatographed on $SiO_2$ (10% EtOAc in hexanes, $R_f$ = 0.42) to give 0.22 g (1.59 mmol, 35%) of **1e** as a colorless oil: IR ($CH_2Cl_2$) 2980, 2920, 1760, 1400, 1240, 845 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 6.4 (s, 1 H), 3.28 (s, 2 H), 0.33 (s, 9 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) $\delta$ 188.30, 184.02, 147.74, 52.34, 3.39. Anal. Calcd for $C_7H_{12}OSi$: C, 59.95; H, 8.62. Found: C, 60.29; H, 8.12.

**3-Ethoxy-2-cyclobuten-1-one (1f),**[20] **1,2-dihydrobenzocyclobutenone (1g),**[21] **and 1,2-dihydro-5,6-(methylenedioxy)benzocyclobutenone (1h)**[22] were prepared according to literature procedures.

**Addition of 1-Lithio-1-methoxyallene to Cyclobutenones and Benzocyclobutenones. General Experimental Procedure.** A 4.0 M solution of methoxyallene[23] in dry THF was added dropwise to a 1.3 M solution (1 molar equiv) of *n*-BuLi in dry THF with stirring under $N_2$ at −42 °C.[24] The slightly yellow mixture was allowed to stir for 20 min, and then a 4.0 M solution (0.83 equiv) of the cyclobutenone or benzocyclobutenone in dry THF was added dropwise. The dark orange solution was stirred at −42 °C until the enone was consumed (0.5–1.5 h) as indicated by GLC analysis of an aliquot quenched at −42 °C with saturated aqueous $NaHCO_3$ and extracted into $Et_2O$. When the reaction was complete, the mixture was quenched at −42 °C with a saturated aqueous solution of $NaHCO_3$ equal to one-tenth the volume of the reaction mixture. The ice bath was removed, and the reaction was allowed to warm to room temperature. It was diluted with $Et_2O$ (4 mL/mmol of cyclobutenone), and the organic layer was separated. The aqueous layer was washed with $Et_2O$, and the combined organic layers were washed with an equal volume of saturated aqueous $NaHCO_3$ and then dried ($MgSO_4$). Removal of solvent on a rotary evaporator followed by a vacuum pump left the crude product. *Because of sensitivity of the products to acid and heat*, characterization was limited to IR and $^1H$ NMR analysis of the crude products in most cases. In parentheses following each of the compounds shown below is an indication of the scale of the reaction, the reaction time, and the yield of the crude product.

**2,3-Dimethyl-1-(1-methoxypropadienyl)-2-cyclobuten-1-ol (2a)** (10.5 mmol, 45 min, 87%): IR ($CH_2Cl_2$) 3570, 2900–2960, 2850, 1950, 1460, 1200 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 5.54 (d, $J$ = 7.6 Hz, 1 H), 5.50 (d, $J$ = 7.6 Hz, 1 H), 3.40 (s, 3 H), 2.64 (br d, $J$ = 12.2 Hz, 1 H), 2.59 (s, 1 H), 2.35 (br d, $J$ = 12.2 Hz, 1 H), 1.64 (m, 3 H), 1.55 (m, 3 H).

**4-Chloro-2,3-dimethyl-1-(1-methoxypropadienyl)-2-cyclobuten-1-ol (2b)** (1.11 mmol, 50 min, 82%): IR ($CH_2Cl_2$) 3550, 2950, 2900, 1960, 1695, 1450, 1210 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 5.64 (d, $J$ = 8.3 Hz, 1 H), 5.61 (d, $J$ = 8.2 Hz, 1 H), 4.93 (br s, 1 H), 3.45 (s, 3 H), 2.78 (s, 1 H), 1.70 (m, 3 H), 1.65 (m, 3 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) $\delta$ 143.84, 134.78, 120.03, 93.19, 68.12, 65.79, 56.30, 50.56, 10.12, 9.34.

**1-(1-Methoxypropadienyl)-2,3,4-trimethyl-2-cyclobuten-1-ol (2c)** (5.20 mmol, 30 min, 91%): IR ($CH_2Cl_2$) 3570, 2900–2940, 2840, 1950, 1460, 1200 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 5.56 (d, $J$ = 7.6 Hz, 1 H), 5.52 (d, $J$ = 7.6 Hz, 1 H), 3.50 (s, 3 H), 2.78 (br q, $J$ = 6.9 Hz, 1 H), 2.30 (s, 1 H), 1.60 (m, 3 H), 1.56 (m, 3 H), 1.05 (d, $J$ = 6.9 Hz, 3 H).

**3-*n*-Butyl-1-(1-methoxypropadienyl)-2-cyclobuten-1-ol (2d)** (6.10 mmol, 60 min, 82%): IR ($CH_2Cl_2$) 3600, 3000–2900, 1965, 1640, 1270, 910 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 5.80 (s, 1 H), 5.50 (m, 2 H), 3.80 (s, 1 H), 3.45 (s, 3 H), 2.75 (d, $J$ = 12.7 Hz, 1 H), 2.45 (d, $J$ = 12.7 Hz, 1 H), 2.05 (m, 2 H), 1.18 (m, 4 H), 0.90 (m, 3 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) $\delta$ 195.88, 135.93, 129.24, 91.13, 91.11, 73.00, 55.80, 44.67, 29.70, 27.67, 21.66, 13.17.

**1-(1-Methoxypropadienyl)-3-(trimethylsilyl)-2-cyclobuten-1-ol (2e)** (8.57 mmol, 25 min, 98%): IR ($CH_2Cl_2$) 3600, 3000–2910, 1960, 1640, 1270, 920 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 6.58 (s, 1 H), 5.58 (s, 2 H), 3.50 (s, 3 H), 2.92 (br s, 1 H), 2.86 (d, $J$ = 12.6 Hz, 1 H), 2.62 (d, $J$ = 12.6 Hz, 1 H), 0.10 (s, 9 H).

**3-Ethoxy-1-(1-methoxypropadienyl)-2-cyclobuten-1-ol (2f)** (3.06 mmol, 20 min, 67%): IR ($CH_2Cl_2$) 3580, 2930, 1955, 1630, 1305, 1075, 1055 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 5.52 (s, 2 H), 4.68 (s, 1 H), 3.95 (q, $J$ = 7.1 Hz, 2 H), 3.55 (s, 3 H), 2.92 (d, $J$ = 12.5 Hz, 1 H), 2.64 (d, $J$ = 12.5 Hz, 1 H), 2.54 (s, 1 H), 1.42 (t, $J$ = 7.0 Hz, 3 H).

**1,2-Dihydro-1-(1-methoxypropadienyl)benzocyclobuten-1-ol (2g)** (8.47 mmol, 30 min, 72%). Light yellow needles (recrystallization from hexanes): mp 96–98 °C; IR ($CH_2Cl_2$) 3580, 3010, 2940, 1960, 1600, 1460, 1210 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 7.26 (m, 1 H), 7.20 (d, $J$ = 4.3 Hz, 2 H), 7.13 (d, $J$ = 7.0 Hz, 1 H), 5.53 (d, $J$ = 13.9 Hz, 1 H), 5.50 (d, $J$ = 14.0, 1 H), 3.62 (d, $J$ = 14.0 Hz, 1 H), 3.48 (s, 3 H), 3.30 (d, $J$ = 14.0 Hz, 1 H), 3.15 (s, 1 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) $\delta$ 195.98, 146.87, 141.63, 135.11, 128.97, 126.55, 123.00, 121.10, 92.14, 77.69, 56.15, 44.92; MS (low-resolution EI) $m/e$ (relative intensity) 188 ($M^+$, 13), 172 (100), 158 (22), 145 (82), 128 (52), 115 (70), 102 (24), 91 (60), 77 (25), 62 (19). Anal. Calcd for $C_{12}H_{12}O_2$: C, 76.57; H, 6.43. Found: C, 76.47; H, 6.48.

**1,2-Dihydro-1-(1-methoxypropadienyl)-5,6-(methylenedioxy)benzocyclobuten-1-ol (2h)** (4.51 mmol, 45 min, 94%). Analytically pure yellow oil: IR ($CH_2Cl_2$) 3560, 2960, 2940, 2900, 1960, 1460, 1255, 1215, 1050 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 6.75 (d, $J$ = 7.6 Hz, 1 H), 6.57 (d, $J$ = 7.6 Hz, 1 H), 5.94 (d, $J$ = 1.2 Hz, 1 H), 5.86 (d, $J$ = 1.2 Hz, 1 H), 5.59 (d, $J$ = 7.6 Hz, 1 H), 5.51 (d, $J$ = 7.6 Hz, 1 H), 3.52 (d, $J$ = 14.0 Hz, 1 H), 3.50 (s, 3 H), 3.46 (s, 1 H), 3.25 (d, $J$ = 13.9 Hz, 1 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) $\delta$ 195.36, 146.97, 138.52, 134.70, 125.51, 115.26, 109.48, 100.50, 92.26, 76.27, 56.25, 44.51; MS (low-resolution EI) $m/e$ (relative intensity) 232 ($M^+$, 25), 217 (100), 189 (71), 162 (39), 121 (25), 102 (47), 89 (14), 77 (25), 62 (22). Anal. Calcd for $C_{13}H_{12}O_4$: C, 67.23; H, 5.21. Found: C, 67.17; H, 5.26.

**Acid-Catalyzed Ring Expansion of Allenylcyclobutenols. General Experimental Procedure.** Trifluoroacetic acid (1.2 molar equiv) was added dropwise at the rate of about 1 drop/5 s to a rapidly stirring solution of the allenylcyclobutenols **2a–e,g,h** (0.14 M in 1:1/THF/$H_2O$). This mixture was stirred until the allenylcyclobutenol was consumed (0.3–4.0 h) as detected by GLC. When complete, the mixture was diluted with an equal volume of $Et_2O$, and the organic layer was separated. The aqueous layer was extracted (1×) with an equal volume of $Et_2O$, and the organic layers were then combined and washed (2×) with an equal volume of a saturated aqueous $NaHCO_3$ solution. The organic layer was dried ($MgSO_4$) and filtered, and the solvents were removed by rotary evaporation followed by a vacuum pump leaving the crude product. The products (**4a–e,g,h**) were purified by chromatography or recrystallization. In parentheses following each of the compounds shown below is an indication of the scale of the reaction, the reaction time, the means of purification, and the yield of the product.

**2,3-Dimethyl-5-ethenyl-5-hydroxy-2-cyclopenten-1-one (4a)** (9.87 mmol, 2 h, gravity $SiO_2$ with 50% EtOAc in hexanes, 76%). A light yellow oil: IR ($CH_2Cl_2$) 3550, 3450, 2920, 1705, 1645, 1635, 1430, 1390, 1330 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 5.70 (dd, $J$ = 17.2 Hz, $J$ = 10.6 Hz, 1 H), 5.25 (dd, $J$ = 17.3 Hz, $J$ = 0.9 Hz, 1 H), 5.05 (dd, $J$ = 10.6 Hz, $J$ = 0.9 Hz, 1 H), 3.60 (s, 1 H), 2.60 (m, 2 H), 2.04 (m, 3 H), 1.65 (m, 3 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) $\delta$ 207.75, 168.13, 138.34, 132.97, 113.95, 77.79, 46.36, 16.99, 7.88; MS (low-resolution FAB) $m/e$ (relative intensity) 159 ((M + Li)$^+$,50). Anal. Calcd for $C_9H_{12}O_2$: C, 71.03; H, 7.95. Found: C, 70.77; H, 8.00.

**4-Chloro-2,3-dimethyl-5-ethenyl-5-hydroxy-2-cyclopenten-1-one (4b)** (1.07 mmol, 2 h, radial $SiO_2$ chromatography with 25% EtOAc in hexanes, 70%). A yellow oil: IR ($CH_2Cl_2$) 3540, 2980, 2920, 2880, 1720, 1645 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 5.75 (dd, $J$ = 17.1 Hz, $J$ = 10.6 Hz, 1 H), 5.50 (d, $J$ = 17.1 Hz, 1 H), 5.30 (d, $J$ = 10.5 Hz, 1 H), 4.47 (m, 1 H), 3.00 (br s, 1 H), 2.17 (m, 3 H), 1.82 (m, 3 H); an NOE difference experiment

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described in the Results and Discussion section indicated a cis disposition of the Cl and OH groups; $^{13}C$ NMR (75.48 MHz, $CDCl_3$) δ 202.86, 163.24, 136.72, 135.80, 117.06, 77.61, 67.23, 15.04, 8.39; MS (low-resolution FAB) *m/e* (relative intensity) 187 ((M + H)$^+$,10), 149 (20), 122 (20), 108 (60), 55 (100), 27 (40); also 192 ((M + Li)$^+$,32), 151 (25), 55 (100), 27 (60); UV ($CH_3CN$) 194, 238 nm. Anal. Calcd for $C_9H_{11}O_2Cl$: C, 57.92; H, 5.94; Cl, 19.00. Found: C, 57.76; H, 6.01; Cl, 18.90.

**5-Ethenyl-5-hydroxy-2,3,4-trimethyl-2-cyclopenten-1-one (4c)** (3.61 mmol, 1.5 h, radial chromatography with 25% EtOAc in hexanes, 72%). A colorless oil: IR ($CH_2Cl_2$) 3540, 3450, 3000–2900, 1700, 1640, 1390, 1340, 980 cm$^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) δ 5.63 (ddd, *J* = 17.1 Hz, *J* = 10.5 Hz, and *J* = 0.6 Hz, 1 H), 5.26 (br d, *J* = 17.0 Hz, 1 H), 5.04 (br d, *J* = 10.6 Hz, 1 H), 3.20 (s, 1 H), 2.60 (br q, *J* = 7.3 Hz, 1 H), 1.93 (m, 3 H), 1.65 (m, 3 H), 1.04 (dd, *J* = 7.2 Hz, *J* = 0.5 Hz, 3 H); only one isomer was formed, OH and Me cis, as indicated by an NOE difference experiment described in the Results and Discussion section; $^{13}C$ NMR (75.48 MHz, $CDCl_3$) δ 207.67, 173.46, 139.40, 132.00, 113.56, 79.83, 49.07, 15.33, 14.11, 7.88. Anal. Calcd for $C_{10}H_{14}O_2$: C, 72.26; H, 8.49. Found: C, 72.15; H, 8.45.

**3-*n*-Butyl-5-ethenyl-5-hydroxy-2-cyclopenten-1-one (4d)** (2.78 mmol, 2.5 h, radial chromatography with 17% EtOAc in hexanes, 76%). A light yellow oil: IR ($CH_2Cl_2$) 3540, 3435, 3000–2880, 1710, 1610, 1655 cm$^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) δ 5.96 (s, 1 H), 5.83 (dd, *J* = 17.2 Hz, *J* = 10.6 Hz, 1 H), 5.36 (d, *J* = 17.2 Hz, 1 H), 5.16 (dd, *J* = 10.6 Hz, *J* = 0.5 Hz, 1 H), 3.65 (br s, 1 H), 2.79 (br s, 2 H), 2.45 (t, *J* = 7.4 Hz, 2 H), 1.60 (m, 2 H), 1.38 (m, 2 H), 0.94 (t, *J* = 7.3 Hz, 3 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) δ 207.50, 180.46, 137.61, 124.99, 113.66, 78.35, 45.30, 32.76, 28.07, 21.66, 13.07; MS (low-resolution EI) *m/e* (relative intensity) 180 (M$^+$,12), 162 (19), 152 (10), 128 (24), 122 (99), 110 (21), 95 (48), 81 (20), 67 (18), 32 (100). Anal. Calcd for $C_{11}H_{16}O_2$: C, 73.30; H, 8.95. Found: C, 73.29; H, 9.02.

**5-Ethenyl-5-hydroxy-3-(trimethylsilyl)-2-cyclopenten-1-one (4e)** (2.38 mmol, 0.5 h, gravity $SiO_2$ with 17% EtOAc in hexanes, 62%). A yellow oil: IR ($CH_2Cl_2$) 3565, 3480, 2980, 1715, 1750, 1630 cm$^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) δ 6.33 (t, *J* = 2.0 Hz, 1 H), 5.75 (dd, *J* = 17.2 Hz, *J* = 10.6 Hz, 1 H), 5.30 (d, *J* = 17.2 Hz, 1 H), 5.14 (d, *J* = 10.6 Hz, 1 H), 3.43 (br s, 1 H), 2.87 (dd, *J* = 3.8 Hz, *J* = 2.0 Hz, 2 H), 0.08 (s, 9 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) δ 208.23, 182.23, 137.53, 136.62, 113.68, 77.85, 45.39, -3.32. Anal. Calcd for $C_{10}H_{16}O_2Si$: C, 61.18; H, 8.21. Found: C, 60.95; H, 8.28.

**2-Ethenyl-2-hydroxyindan-1-one (4g)** (2.87 mmol, 1 h, radial chromatography with 20% EtOAc in hexanes, 83%). A light yellow oil: IR ($CH_2Cl_2$) 3550, 2980, 2940, 3180, 3450, 1725, 1610, 1470, 1300, 1215 cm$^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) δ 7.78 (d, *J* = 7.7 Hz, 1 H), 7.64 (t, *J* = 7.5 Hz, 1 H), 7.46 (d, *J* = 7.7 Hz, 1 H), 7.41 (t, *J* = 7.5 Hz, 1 H), 5.90 (dd, *J* = 17.2 Hz, *J* = 10.6 Hz, 1 H), 5.42 (d, *J* = 17.3 Hz, 1 H), 5.21 (d, *J* = 10.7 Hz, 1 H), 3.39 (d, *J* = 16.9 Hz, 1 H), 3.37 (s, 1 H), 3.30 (d, *J* = 16.9 Hz, 1 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) δ 205.04, 150.39, 137.42, 135.29, 133.23, 127.32, 126.03, 124.28, 114.49, 80.26, 40.66; MS (low-resolution EI) *m/e* (relative intensity) 174 (M$^+$,89), 157 (20), 145 (28), 129 (42), 115 (30), 105 (28), 91 (60), 77 (20), 62 (25), 55 (100). Anal. Calcd for $C_{11}H_{10}O_2$: C, 75.84; H, 5.79. Found: C, 75.85; H, 5.81.

**2-Ethenyl-2-hydroxy-6,7-(methylenedioxy)indan-1-one (4h)** (2.39 mmol, 1.5 h, recrystallization from 10% $CH_2Cl_2$ in hexanes, 92%). A light yellow solid: mp 105–106.5 °C; IR ($CH_2Cl_2$) 3540, 2905, 1720, 1635, 1505, 1470, 1245 cm$^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) δ 7.04 (d, *J* = 7.8 Hz, 1 H), 6.83 (d, *J* = 7.9 Hz, 1 H), 6.12 (s, 2 H), 5.83 (dd, *J* = 17.0 Hz, *J* = 10.7 Hz, 1 H), 5.38 (d, *J* = 17.0 Hz, 1 H), 5.19 (d, *J* = 10.7 Hz, 1 H), 3.30 (d, *J* = 16.4 Hz, 1 H), 3.19 (d, *J* = 16.4 Hz, 1 H), 3.18 (s, 1 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) δ 201.71, 147.30, 143.80, 141.39, 137.26, 117.86, 116.08, 114.67, 102.49, 80.91, 40.24; MS (low-resolution EI) *m/e* (relative intensity) 218 (M$^+$, 100), 190 (22), 162 (91), 149 (30), 125 (57), 105 (25), 89 (11), 77 (43). Anal. Calcd for $C_{12}H_{10}O_4$: C, 66.05; H, 4.62. Found: C, 66.12; H, 4.67.

**Modified Procedure for Ring Expansion of 3-Ethoxy-2-cyclobuten-1-ol (2f).** Hydrolysis of the allenyl ether and ring expansion to the 3-alkoxycyclopentenone without loss of the ring enol ether moiety was accomplished as follows. A 1.4 M solution of the cyclobutenol (250 mg, 1.37 mmol) in 1:1 THF/$H_2O$ was mixed with silica gel 60 (230–400 mesh ASTM, 5 g/mmol) and warmed to 30 °C with constant mixing with use of a rotary evaporator. After 1 h, the slurry was extracted with ether, and the organic portion was washed once with a saturated aqueous $NaHCO_3$ solution. After the solution was dried ($MgSO_4$) and filtered and the solvent was removed, an orange oil was obtained that solidified upon complete removal of solvent with use of a vacuum pump. The material was purified by $SiO_2$ chromatography (30% hexanes in EtOAc) providing **5-ethenyl-3-ethoxy-5-hydroxy-2-cyclopenten-1-one (4f)** in 40% yield (92 mg) as a light yellow solid: mp 96–98 °C (10% $CH_2Cl_2$ in hexanes); IR ($CH_2Cl_2$) 3540, 2950, 1700, 1585, 1380, 1340 cm$^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) δ 5.87 (dd, *J* = 17.2 Hz, *J* = 10.6 Hz, 1 H), 5.43 (d, *J* = 17.1 Hz, 1 H), 5.27 (s, 1 H), 5.23 (d, *J* = 10.6 Hz, 1 H), 4.12 (q, *J* = 7.1 Hz, 2 H), 2.91 (s, 1 H), 2.85 (d, *J* = 17.7 Hz, 1 H), 2.77 (d, *J* = 17.6 Hz, 1 H), 1.45 (t, *J* = 7.1 Hz, 3 H); $^{13}C$ NMR ($CDCl_3$, 75.48 MHz) δ 203.94, 186.94, 137.67, 114.64, 100.39, 77.83, 67.38, 42.32, 13.47. Anal. Calcd for $C_9H_{12}O_3$: C, 64.27; H, 7.19. Found: C, 64.17; H, 7.26.

**Synthesis of the Natural Product 5-Ethenyl-5-hydroxy-3-methoxy-2-cyclopenten-1-one.[10] 3-Methoxy-2-cyclobuten-1-one (13).** Although **13** can be prepared by the addition of ketene to methoxyacetylene by following the Wasserman procedure for the ethoxy analogue,[19] methoxyacetylene is no longer commercially available and the literature preparation[25] of the acetylene proved to be dangerous.[26] As an alternative, a safer method for the preparation of **13** was developed following a related literature procedure.[27] Cyclobutane-1,3-dione (0.30 g, 3.75 mmol), prepared by hydrolysis of 3-ethoxy-2-cyclobuten-1-one (**1f**) with aqueous acid,[20b] was dissolved in 25 mL of 20% $CH_2Cl_2$ in $Et_2O$ and treated with a 3-fold excess of diazomethane in $Et_2O$ at 0 °C under a nitrogen atmosphere. The resulting yellow mixture was stirred for an additional 2 h at 0 °C over which time the color gradually faded. The solvent and excess diazomethane were removed carefully with a water aspirator leaving 0.35 g of an orange oil. Purification by radial chromatography ($SiO_2$, 33% EtOAc in hexanes, $R_f$ = 0.17) gave 0.30 g (82%) of **13** as a colorless oil: IR ($CH_2Cl_2$) 2980, 2940, 2880, 1735, 1690, 1380, 1245 cm$^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) δ 4.98 (s, 1 H), 4.00 (s, 3 H), 3.20 (s, 2 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) δ 183.56, 181.69, 106.41, 59.46, 47.44. Anal. Calcd for $C_5H_6O_2$: C, 61.22; H, 6.16. Found: 61.08; H, 6.19.

Addition of 1-lithio-1-methoxyallene was effected by following the same general procedure described above for the addition of 1-lithio-1-methoxyallene to cyclobutenones and benzocyclobutenones providing **3-methoxy-1-(1-methoxypropadienyl)-2-cyclobuten-1-ol (14)** as an unstable oil (2.05 mmol scale, 20 min reaction time, 80% yield): IR ($CH_2Cl_2$) 3600, 2950, 1640, 1600, 1320 cm$^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) δ 5.55 (s, 2 H), 4.77 (m, 1 H), 3.68 (s, 3 H), 3.50 (s, 3 H), 2.95 (d, *J* = 12.5 Hz, 1 H), 2.67 (d, *J* = 12.5 Hz, 1 H), 2.58 (s, 1 H).

Hydrolysis and ring expansion of **14** to **15** was carried out by using the $SiO_2$-based modified procedure described above for the conversion of **2f** into **4f** providing **5-ethenyl-5-hydroxy-3-methoxy-2-cyclopenten-1-one (15)** (1.18 mmole scale, $SiO_2$ chromatography with 50% EtOAc in hexanes, $R_f$ = 0.18, 38% yield) as a light yellow solid: mp 66–68 °C (30% $Et_2O$ in hexanes); IR ($CH_2Cl_2$) 3540, 2940, 1700, 1590, 1360, 910 cm$^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) δ 5.87 (dd, *J* = 17.3 Hz, *J* = 10.6 Hz, 1 H), 5.43 (d, *J* = 17.3 Hz, 1 H), 5.32 (s, 1 H), 5.23 (d, *J* = 10.7 Hz, 1 H), 3.90 (s, 3 H), 3.12 (s, 1 H), 2.86 (d, *J* = 17.6 Hz, 1 H), 2.78 (d, *J* = 17.5 Hz, 1 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) δ 203.79, 187.89, 137.57, 114.12, 100.28, 78.09, 58.21, 42.09. Anal. Calcd for $C_8H_{10}O_3$: C, 62.33; H, 6.54. Found: C, 62.24; H, 6.57.

**3-Ethoxycyclobutanone Reactions. 3-Ethoxycyclobutan-1-one** was prepared by the addition of ketene to ethyl vinyl ether according to the procedure of Sieja.[28] Addition of 1-lithio-1-methoxyallene to 3-ethoxycyclobutan-1-one following the same

(25) (a) Wasserman, H. H.; Wharton, P. S. *J. Chem. Soc., Chem. Commun.* **1960**, *82*, 661. (b) Jones, E. R. H.; Eglinton, G.; Whiting, M. C.; Shaw, B. L. *Org. Synth.* **1954**, *34*, 46.

(26) **WARNING**: The sodium salt of methoxyacetylene is very pyrophoric and the literature procedures call for a quench of this solid directly with aqueous NaCl solution. In *all* of our attempts to perform this procedure, a fire resulted.

(27) Ganguli, M.; Burka, L. T.; Harris, T. M. *J. Org. Chem.* **1984**, *49*, 3767.

(28) Sieja, J. B. *J. Am. Chem. Soc.* **1971**, *93*, 130.

general procedure described above for the addition of 1-lithio-1-methoxyallene to cyclobutenones and benzocyclobutenones provided one stereoisomer (undefined) of **3-ethoxy-1-(1-methoxypropadienyl)cyclobutan-1-ol** (15.9 mmol scale, 20 min reaction time, 80% yield): IR (neat film) 3420, 2980, 2940, 2870, 1955, 1460, 1235 $cm^{-1}$; $^1H$ NMR (360 MHz, $CD_3NO_2$) $\delta$ 5.52 (s, 2 H), 4.70 (m, 2 H), 3.55 (t, $J$ = 6.9 Hz, 1 H), 3.46 (s, 3 H), 3.36 (q, $J$ = 7.0 Hz, 2 H), 3.11 (s, 1 H), 2.64 (m, 2 H), 2.0 (m, 2 H), 1.10 (t, $J$ = 7.0 Hz, 3 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) $\delta$ 195.63, 137.19, 92.57, 66.48, 64.91, 63.29, 56.50, 42.92, 15.09. Full characterization of this compound was not feasible because of its sensitivity to chromatography. The compound did not undergo rapid ring expansion on treatment with aqueous acid, and simply suffered hydrolysis of the allenyl ether moiety to enone **10** by twice washing an ether solution of the adduct (50 mL/g of adduct) with an equal volume of 15% HCl. Washing the ether layer with saturated aqueous $NaHCO_3$, drying ($MgSO_4$), filtering, and removing the solvent left **3-ethoxy-1-(1-oxo-2-propenyl)cyclobutan-1-ol (10)** as a viscous orange oil (77%, 1.13 g, from 1.47 g of 3-ethoxycyclobutan-1-one) that on standing in the refrigerator partially converted into **11**, and that could not be purified further because of sensitivity to chromatography: IR (neat film) 3440, 2900–3000, 1695, 1615, 1410, 1240, 1190 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 6.80 (dd, $J$ = 17.1 Hz, $J$ = 10.4 Hz, 1 H), 6.55 (d, $J$ = 17.1 Hz, 1 H), 5.88 (d, $J$ = 10.3 Hz, 1 H), 4.02 (s, 1 H), 3.85 (m, 1 H), 3.52 (q, $J$ = 7.0 Hz, 2 H), 2.85 (m, 2 H), 2.35 (m, 2 H), 1.20 (t, $J$ = 7.0 Hz, 3 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) $\delta$ 199.86, 130.84, 128.22, 72.13, 64.07, 62.87, 41.98, 14.61; MS (low-resolution EI) $m/e$ (relative intensity) $M^+$ = 170.

Conversion of **10** into either **11** or **12** could be achieved by proper choice of the ring expansion conditions.

**Conversion of 10 into 11.** The enone **10** ring expands upon exposure to mild acid for prolonged times producing **11**, which also reacts under acidic conditions to lose ethanol forming **12**. Attempted ring expansions were always accompanied by some amount of ethanol elimination. The best conditions found for preparation of **11**(1–5 mmol scale) were stirring overnight in 5% TFA/wet $CH_3CN$ followed by chromatography (radial chromatography, Merck Kieselgel 60PF, EtOAc/hexane 10–20% gradient elution). Flash silica gel chromatography alone was sufficient to convert a substantial amount of the cyclopentanone into the cyclopentenone. The chromatographically purified cyclopentanone **11** showed: IR (neat) 3460 br, 2980, 2940, 2890, 1753, 1640, 1380, 1355, 1105 $cm^{-1}$; $^1H$ NMR (360 MHz, $CDCl_3$) $\delta$ 5.78 (dd, $J$ = 17.3 Hz, $J$ = 10.7 Hz, 1 H), 5.35 (dd, $J$ = 17.3 Hz, $J$ = 0.9 Hz, 1 H), 5.28 (dd, $J$ = 10.7 Hz, $J$ = 0.9 Hz, 1 H), 4.15 (m, 2 H), 3.51 (m, 1 H), 3.31 (br s, 1 H), 2.65 (dd, $J$ = 19.2 Hz, $J$ = 1.3 Hz, 1 H), 2.48 (ddd, $J$ = 19.2 Hz, $J$ = 4.3 Hz, $J$ = 1.8 Hz, 1 H), 2.43 (ddd, $J$ = 13.7 Hz, $J$ = 5.3 Hz, $J$ = 1.2 Hz, 1 H), 2.14 (ddd, $J$ = 13.7 Hz, $J$ = 5.6 Hz, $J$ = 1.8 Hz, 1 H), 1.20 (t, $J$ = 7.0 Hz, 3 H).

**For Direct Formation of 12 from 10.** Under a nitrogen atmosphere a 0.2 M solution of **10** (2.96 mmol, 504 mg) in dry $CH_2Cl_2$ was added via syringe to 1.9 molar equiv of anhydrous $ZnBr_2$[29] in a dry round-bottomed flask equipped with a magnetic stirrer. The mixture was stirred at room temp for 2 h and then was heated at gentle reflux for 10 h. During this time the mixture became very dark. The reaction was monitored by GLC, and upon consumption of starting material $Et_2O$ (10 mL/mmol) was added, and the organic portion was washed once with an equal volume of 1 N HCl and then with a saturated aqueous $NaHCO_3$ solution. The organic portion was dried ($MgSO_4$) and filtered, and solvent was removed to give **5-ethenyl-5-hydroxy-2-cyclopenten-1-one (12)** (45%) as a yellow oil ($SiO_2$ chromatography, 25% EtOAc in hexanes, $R_f$ = 0.32): IR ($CH_2Cl_2$) 3560, 3450, 3000–2900, 1720, 1595, 1360, 1120 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 7.78 (m, 1 H), 6.22 (m, 1 H), 5.80 (dd, $J$ = 17.2 Hz, $J$ = 10.6 Hz, 1 H), 5.40 (d, $J$ = 17.2 Hz, 1 H), 5.23 (d, $J$ = 10.6 Hz, 1 H), 2.95 (s, 1 H), 2.90 (s, 2 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) $\delta$ 207.84, 161.89, 137.08, 130.36, 114.15, 77.27, 42.62. Anal. Calcd for $C_7H_8O_2$: C, 67.73; H, 6.50. Found: C, 67.62; H, 6.52.

**Palladium-Catalyzed [3,3]-Shift Reactions of Allylic Acetates. General Experimental Procedure for Acetylation of the 5-Hydroxy-5-ethenyl-2-cyclopenten-1-ones (4).** The 5-ethenyl-5-hydroxy-2-cyclopenten-1-one was mixed with dry $Et_3N$ and acetic anhydride (2 molar equiv of each) with stirring under $N_2$. To this mixture was added dimethylaminopyridine (DMAP, 0.1 molar equiv), and the resulting dark orange mixture was stirred (1–2 h) until GLC indicated that all of the alcohol had been consumed. The reaction mixture was diluted with $Et_2O$ (10 mL/mmol of alcohol) and was washed twice with equal portions of $H_2O$, 1.5 N HCl, and saturated aqueous $NaHCO_3$. The organic layer was dried ($MgSO_4$) and filtered, and the solvent was removed by rotary evaporator and vacuum pump leaving the crude allylic acetate **5**. The products were purified by chromatography or recrystallization as indicated. In parentheses following each of the compounds shown below is an indication of the scale of the reaction, the reaction time, the means of purification, and the yield of the product.

**5-Acetoxy-2,3-dimethyl-5-ethenyl-2-cyclopenten-1-one (5a)** (9.87 mmol, 2 h, radial chromatography with 20% EtOAc in hexanes, 91%). A light yellow oil: IR ($CH_2Cl_2$) 2950, 2940, 1745, 1715, 1650, 1380, 1220 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 5.68 (dd, $J$ = 17.3 Hz, $J$ = 10.7 Hz, 1 H), 5.30 (d, $J$ = 17.2 Hz, 1 H), 5.15 (dd, $J$ = 10.7 Hz, $J$ = 0.4 Hz, 1 H), 2.95 (br d, $J$ = 17.1 Hz, 1 H), 2.69 (br d, $J$ = 17.1 Hz, 1 H), 2.15 (s, 3 H), 2.05 (s, 3 H), 1.57 (s, 3 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) $\delta$ 201.85, 169.47, 164.52, 134.89, 133.69, 115.46, 82.58, 43.70, 20.93, 16.80, 8.07; MS (low-resolution FAB) $m/e$ (relative intensity) 201 ((M + Li)$^+$, 100), 160 (48), 125 (25). Anal. Calcd for $C_{11}H_{14}O_3$: C, 68.02; H, 7.27. Found: C, 67.78; H, 7.30.

**5-Acetoxy-4-chloro-2,3-dimethyl-5-ethenyl-2-cyclopenten-1-one (5b)** (1.07 mmol, 2 h, radial chromatography with 20% EtOAc in hexanes, 90%). A light orange oil: IR ($CH_2Cl_2$) 2920, 1750, 1728, 1650 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 5.58 (dd, $J$ = 17.3 Hz, $J$ = 10.8 Hz, 1 H), 5.35 (d, $J$ = 17.3 Hz, 1 H), 5.29 (d, $J$ = 10.7 Hz, 1 H), 5.00 (br s, 1 H), 2.17 (s, 3 H), 2.15 (br s, 3 H), 1.82 (m, 3 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) $\delta$ 197.46, 168.98, 161.18, 136.18, 133.63, 117.10, 81.15, 64.73, 20.31, 14.37, 8.00. Anal. Calcd for $C_{11}H_{13}O_3Cl$: C, 57.78; H, 5.73. Found: C, 57.84; H, 5.74.

**5-Acetoxy-5-ethenyl-2,3,4-trimethyl-2-cyclopenten-1-one (5c)** (3.61 mmol, 1.5 h, no purification necessary, 94%). An analytically pure yellow oil: IR ($CH_2Cl_2$) 2950, 2940, 1745, 1715, 1650, 1380, 1220 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 5.82 (dd, $J$ = 17.3 Hz, $J$ = 10.7 Hz, 1 H), 5.30 (d, $J$ = 17.3 Hz, 1 H), 5.18 (d, $J$ = 10.7 Hz, 1 H), 3.04 (q, $J$ = 7.0 Hz, 1 H), 2.15 (s, 3 H), 2.05 (s, 3 H), 1.74 (s, 3 H), 1.10 (d, $J$ = 7.1 Hz, 3 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) $\delta$ 200.60, 169.31, 169.22, 135.91, 131.93, 114.66, 84.46, 47.86, 20.41, 14.63, 13.14, 7.53. Anal. Calcd for $C_{12}H_{16}O_3$: C, 69.21; H, 7.74. Found: C, 69.28; H, 7.76.

**5-Acetoxy-3-*n*-butyl-5-ethenyl-2-cyclopenten-1-one (5d)** (2.78 mmol, 2.5 h, radial chromatography with 14% EtOAc in hexanes, 88%). A light orange oil: IR ($CH_2Cl_2$) 3000–2900, 1740, 1715, 1615 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 5.98 (s, 1 H), 5.76 (dd, $J$ = 17.2 Hz, $J$ = 10.7 Hz, 1 H), 5.38 (d, $J$ = 17.2 Hz, 1 H), 5.20 (d, $J$ = 10.8 Hz, 1 H), 3.10 (d, $J$ = 18.0 Hz, 1 H), 2.81 (d, $J$ = 18.0 Hz, 1 H), 2.41 (t, $J$ = 7.5 Hz, 2 H), 2.10 (s, 3 H), 1.60 (m, 2 H), 1.38 (m, 2 H), 0.93 (t, $J$ = 7.3 Hz, 3 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) $\delta$ 201.18, 176.91, 168.81, 134.18, 125.67, 115.00, 82.73, 42.46, 32.49, 28.05, 21.60, 20.28, 13.06; MS (low-resolution EI), $m/e$ (relative intensity) 222 ($M^+$,5), 180 (65), 162 (18), 151 (18), 128 (20), 122 (22), 110 (20), 95 (20), 91 (22), 67 (13), 32 (100). Anal. Calcd for $C_{13}H_{18}O_3$: C, 70.24; H, 8.16. Found: C, 70.05; H, 8.12.

**5-Acetoxy-5-ethenyl-3-(trimethylsilyl)-2-cyclopenten-1-one (5e)** (2.38 mmol, 0.5 h, radial chromatography with 14% EtOAc in hexanes, 93%). A colorless oil: IR ($CH_2Cl_2$) 2980, 1750, 1715, 1655, 1390 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 6.24 (s, 1 H), 5.63 (dd, $J$ = 17.2 Hz, $J$ = 10.7 Hz, 1 H), 5.20 (d, $J$ = 17.2 Hz, 1 H), 5.07 (d, $J$ = 10.7 Hz, 1 H), 3.04 (d, $J$ = 18.2 Hz, 1 H), 2.86 (d, $J$ = 18.2 Hz, 1 H), 2.00 (s, 3 H), 0.11 (s, 9 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) $\delta$ 201.64, 178.13, 168.77, 137.16, 134.03, 114.90, 82.45, 42.50, 20.23, -3.36. Anal. Calcd for $C_{12}H_{18}O_3Si$: C, 60.47; H, 7.61. Found: C, 60.36; H, 7.61.

**2-Acetoxy-2-ethenylindan-1-one (5g)** (2.87 mmol, 1 h, radial chromatography with 20% EtOAc in hexanes, 87%). A light yellow oil: IR ($CH_2Cl_2$) 3080, 2940, 2880, 1730, 1745, 1620, 1380, 1240, 1220 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) $\delta$ 7.76 (d, $J$ = 7.6 Hz, 1 H), 7.60 (dd, $J$ = 7.6 Hz, $J$ = 7.3 Hz, 1 H), 7.42 (d, $J$ = 7.7 Hz, 1 H), 7.37 (t, $J$ = 7.6 Hz, 1 H), 5.84 (dd, $J$ = 17.3 Hz, $J$ =

(29) Steglich, W.; Holfe, G. *Angew. Chem., Int. Ed. Engl.* **1969**, *8*, 981.

10.7 Hz, 1 H), 5.41 (d, $J$ = 17.3 Hz, 1 H), 5.23 (d, $J$ = 10.8 Hz, 1 H), 3.57 (d, $J$ = 16.9 Hz, 1 H), 3.40 (d, $J$ = 16.9 Hz, 1 H), 2.12 (s, 3 H); $^{13}$C NMR (75.48 MHz, $CDCl_3$) $\delta$ 198.72, 168.98, 148.42, 134.88, 133.73, 133.46, 127.33, 125.73, 124.12, 115.90, 84.06, 37.87, 20.17; MS (low-resolution EI) $m/e$ (relative intensity) 216 ($M^+$,9), 174 (100), 145 (43), 128 (40), 117 (72), 102 (15), 90 (23), 77 (17), 62 (24). Anal. Calcd for $C_{13}H_{12}O_3$: C, 72.21; H, 5.59. Found: C, 72.28; H, 5.61.

**2-Acetoxy-5-ethenyl-6,7-(methylenedioxy)indan-1-one (5h)** (2.39 mmol, 1.5 h, recrystallization from 10% $CH_2Cl_2$ in hexanes, 85%). A light yellow, fluffy solid: mp 142–144 °C; IR ($CH_2Cl_2$) 1730, 1740, 1635, 1470, 1245 cm$^{-1}$; $^1$H NMR (300 MHz, $CDCl_3$), $\delta$ 6.98 (d, $J$ = 7.9 Hz, 1 H), 6.78 (d, $J$ = 7.8 Hz, 1 H), 6.05 (d, $J$ = 2.8 Hz, 2 H), 5.80 (dd, $J$ = 17.3 Hz, $J$ = 10.8 Hz, 1 H), 5.39 (d, $J$ = 17.3 Hz, 1 H), 5.21 (d, $J$ = 10.8 Hz, 1 H), 3.42 (d, $J$ = 16.5 Hz, 1 H), 3.30 (d, $J$ = 16.6 Hz, 1 H), 2.10 (s, 3 H); $^{13}$C NMR (75.48 MHz, $CDCl_3$), $\delta$ 195.68, 169.00, 147.35, 143.87, 139.74, 133.65, 117.53, 116.44, 116.14, 114.19, 102.45, 84.45, 37.55, 20.23; MS (low-resolution EI) $m/e$ (relative intensity) 260 ($M^+$,4), 218 (22), 200 (100), 159 (23), 121 (37), 115 (25), 89 (10), 77 (17). Anal. Calcd for $C_{14}H_{12}O_5$: C, 64.61; H, 4.65. Found: C, 64.49; H, 4.65.

**5-Acetoxy-5-ethenylcyclopenten-1-one (5i)** (0.16 mmol, 2 h, $SiO_2$ chromatography with 25% EtOAc in hexanes, 90%). A light yellow oil: IR ($CH_2Cl_2$) 3000–2900, 1745, 1705, 1655, 1645, 1380, 1240 cm$^{-1}$; $^1$H NMR (300 MHz, $CDCl_3$) $\delta$ 7.65 (m, 1 H), 6.28 (m, 1 H), 5.76 (dd, $J$ = 17.2 Hz, $J$ = 10.5 Hz, 1 H), 5.43 (d, $J$ = 17.2 Hz, 1 H), 5.25 (d, $J$ = 10.5 Hz, 1 H), 3.16 (dt, $J$ = 18.8 Hz, $J$ = 2.3 Hz, 1 H), 2.94 (doublet of multiplets, $J$ = 18.8 Hz, 1 H), 2.22 (s, 3 H); $^{13}$C NMR (75.48 MHz, $CDCl_3$) $\delta$ 201.34, 171.47, 164.43, 133.78, 132.69, 115.56, 82.58, 43.70, 20.93. Anal. Calcd for $C_9H_{10}O_3$: C, 65.05; H, 6.07. Found: C, 65.14; H, 6.09.

**General Experimental Procedure for the Palladium-Catalyzed [3,3] Sigmatropic Rearrangement of Allylic Acetates 5.**[10] Dichlorobis(acetonitrile)palladium(II) (0.05 molar equiv) was added to a 0.1 M solution of the allylic acetate **5** in a dry solvent ($CH_2Cl_2$ or $C_6H_6$) with stirring under $N_2$. The reaction was terminated when GLC monitoring indicated complete consumption of the starting material (1.5–72 h). Analytically pure product was isolated by filtration of the reaction mixture through a small plug of Florisil (1 inch of adsorbant packed in a disposable pipet) followed by solvent removal with a rotary evaporator and a vacuum pump. The isomer with the carbonyl and the acetate in a cis relationship (usually $Z$) is the kinetic isomer and was formed in excess of the other isomer (3–20×). The reaction run in $C_6H_6$ typically gave the largest excess of the kinetic isomer (up to 20:1), but the rearrangement in $CH_2Cl_2$ was up to 8 times faster. The mixture could be equilibrated with a trace of acid (1 drop of trifluoroacetic-$d$ acid/30 mg of sample in 0.5 mL of $CDCl_3$ for 12–72 h), so that the thermodynamic isomer dominated (3.6–16×) as determined by $^1$H NMR. Isomer ratios were determined by GLC and $^1$H NMR integration and are shown in Table II along with reaction times and isolated yields for the $C_6H_6$ and $CH_2Cl_2$ runs. In parentheses following each of the compounds shown below is an indication of the scale of the reaction. Spectroscopic data and analyses were determined on the mixture of the two isomers.

**5-(2-Acetoxyethylidene)-2,3-dimethyl-2-cyclopenten-1-one (6a/7a) (0.26 mmol).** Assignments of $Z$ and $E$ stereochemistry were based on NOE difference experiments performed on a mixture of the isomers as described in the Results and Discussion section. This assignment is assumed to be the same for **6/7b–d,g–i** as well: IR($CH_2Cl_2$) 2920, 1740, 1690, 1670, 1630, 1390, 1350, 1235 cm$^{-1}$; $^1$H NMR (300 MHz, $CDCl_3$) ($Z$ isomer) $\delta$ 5.90 (tt, $J$ = 5.7 Hz, $J$ = 1.4 Hz, 1 H), 5.30 (dt, $J$ = 5.7 Hz, $J$ = 1.1 Hz, 2 H), 3.0 (m, 2 H), 2.07 (s, 3 H), 2.04 (br s, 3 H), 1.72 (s, 3 H); ($E$ isomer) $\delta$ 6.45 (tt, $J$ = 6.2 Hz, $J$ = 1.9 Hz, 1 H), 4.74 (d, $J$ = 6.3 Hz, 2 H), 3.09 (m, 2 H), 2.08 (s, 3 H), 2.04 (m, 3 H), 1.72 (m, 3 H); $^{13}$C NMR (75.48 MHz, $CDCl_3$) ($Z$ isomer) $\delta$ 196.64, 170.62, 163.26, 139.06, 134.19, 130.82, 61.23, 37.16, 20.78, 16.42, 7.91; ($E$ isomer) $\delta$ 195.75, 170.48, 163.16, 138.03, 136.54, 124.77, 61.50, 34.80, 20.67, 16.58, 8.08; MS (low-resolution FAB) $m/e$ (relative intensity) 201 ((M + Li)$^+$, 100), 160 (24), 125 (13). Anal. Calcd for $C_{11}H_{14}O_3$: C, 68.02; H, 7.27. Found: C, 67.78; H, 7.30.

**5-(2-Acetoxyethylidene)-4-chloro-2,3-dimethyl-2-cyclopenten-1-one (6b/7b)** (0.15 mmol): IR ($CH_2Cl_2$) 2920, 1745, 1705, 1645 cm$^{-1}$; $^1$H NMR (300 MHz, $CDCl_3$) ($Z$ isomer) $\delta$ 6.33 (dt, $J$ = 5.6 Hz, $J$ = 1.0 Hz, 1 H), 5.35 (ddd, $J$ = 10.8 Hz, $J$ = 6.0 Hz, $J$ = 0.6 Hz, 2 H), 5.15 (m, 1 H), 2.12 (m, 3 H), 2.10 (s, 3 H), 1.80 (m, 3 H); (E isomer) $\delta$ 6.62 (ddd, $J$ = 6.9 Hz, $J$ = 5.3 Hz, $J$ = 1.5 Hz, 2 H), 5.34 (m, 1 H), 5.04 (dd, $J$ = 15.3 Hz, $J$ = 7.1 Hz, 1 H), 4.91 (dd, $J$ = 15.2 Hz, $J$ = 5.6 Hz, 1 H), 2.16 (m, 3 H), 2.13 (s, 3 H), 1.85 (s, 3 H); $^{13}$C NMR (75.48 MHz, $CDCl_3$) $Z$ isomer) $\delta$ 192.17, 169.95, 160.23, 141.74, 135.75, 129.31, 60.42, 58.52, 20.26, 13.48, 7.74; ($E$ isomer) $\delta$ 191.23, 169.84, 160.23, 140.69, 134.97, 129.31, 60.25, 56.37, 20.09, 13.37, 7.93. Anal. Calcd for $C_{11}H_{13}O_3Cl$: C, 57.78; H, 5.73. Found: C, 57.84; H, 5.74.

**5-(2-Acetoxyethylidene)-2,3,4-trimethyl-2-cyclopenten-1-one (6c/7c)** (0.14 mmol): IR ($CH_2Cl_2$) 2920, 1745, 1690, 1670, 1630, 1390, 1350, 1235 cm$^{-1}$; $^1$H NMR (300 MHz, $CDCl_3$) ($Z$ isomer) $\delta$ 5.90 (dt, $J$ = 5.7 Hz, $J$ = 1.2 Hz, 1 H), 5.34 (br t, $J$ = 5.2 Hz, 2 H), 3.06 (q, $J$ = 7.0 Hz, 1 H), 2.10 (s, 3 H), 2.02 (s, 3 H), 1.75 (s, 3 H), 1.24 (d, $J$ = 7.2 Hz, 3 H); ($E$ isomer) $\delta$ 6.45 (dt, $J$ = 6.5 Hz, $J$ = 1.6 Hz, 1 H), 4.82 (d, $J$ = 6.5 Hz, 2 H), 3.30 (q, $J$ = 7.1 Hz, 1 H), 2.10 (s, 3 H), 2.05 (s, 3 H), 1.75 (s, 3 H), 1.20 (d, $J$ = 7.1 Hz, 3 H); $^{13}$C NMR (75.48 MHz, $CDCl_3$) ($Z$ isomer) $\delta$ 195.77, 170.08, 166.96, 139.45, 137.43, 129.88, 60.85, 40.71, 20.28, 16.79, 13.73, 7.38; $^{13}$C assignments for the $E$ isomer were not determined due to a limited amount of material. Anal. Calcd for $C_{12}H_{16}O_3$: C, 69.21; H, 7.74. Found: C, 69.28; H, 7.76.

**5-(2-Acetoxyethylidene)-3-*n*-butyl-2-cyclopenten-1-one (6d/7d)** (0.15 mmol): IR ($CH_2Cl_2$) 3000–2900, 1740, 1705, 1665, 1610, 1230 cm$^{-1}$; $^1$H NMR (300 MHz, $CDCl_3$) ($Z$ isomer) $\delta$ 6.09 (s, 1 H), 5.95 (t, $J$ = 5.6 Hz, 1 H), 5.32 (d, $J$ = 5.6 Hz, 2 H), 3.13 (s, 2 H), 2.45 (m, 2 H), 2.08 (s, 3 H), 1.60 (m, 2 H) 1.38 (m, 2 H), 0.93 (m, 3 H); ($E$ isomer) $\delta$ 6.48 (t, $J$ = 6.2 Hz, 1 H), 6.15 (s, 1 H), 4.79 (d, $J$ = 6.2 Hz, 2 H), 3.20 (s, 2 H), 2.47 (t, $J$ = 7.5 Hz, 2 H), 2.10 (s, 3 H), 1.60 (m, 2 H), 1.39 (m, 2 H), 0.95 (t, $J$ = 7.3 Hz, 3 H); $^{13}$C NMR (75.48 MHz, $CDCl_3$) ($E$ isomer) $\delta$ 195.29, 175.77, 169.92, 136.66, 130.03, 124.89, 60.94, 33.93, 32.29, 28.40, 21.77, 20.14, 13.13; $^{13}$C assignments for the $Z$ isomer were not determined because of rapid isomerization to the $E$ isomer. Anal. Calcd for $C_{13}H_{18}O_3$: C, 70.24; H, 8.16. Found: C, 70.00; H, 8.11.

**5-(2-Acetoxyethylidene)-3-(trimethylsilyl)-2-cyclopenten-1-one (6e/7e)** (0.13 mmol). A light yellow solid: recrystallization from hexanes provided the pure $Z$ isomer, mp 82–84 °C; IR ($CH_2Cl_2$) 2980, 1745, 1700, 1665 cm$^{-1}$; $^1$H NMR (300 MHz, $CDCl_3$) ($Z$ isomer) $\delta$ 6.49 (br s, 1 H), 6.04 (t, $J$ = 5.6 Hz, 1 H), 5.32 (d, $J$ = 5.6 Hz, 2 H), 3.26 (br s, 2 H), 2.10 (s, 3 H), 0.24 (s, 9 H); ($E$ isomer) $\delta$ 6.56 (t, $J$ = 2.1 Hz, 1 H), 6.51 (tt, $J$ = 6.2 Hz, $J$ = 1.8 Hz, 1 H), 4.80 (d, $J$ = 6.2 Hz, 2 H), 3.30 (br s, 2 H), 2.12 (s, 3 H), 0.26 (s, 9 H); $^{13}$C NMR (75.48 MHz, $CDCl_3$) ($E$ isomer) $\delta$ 195.82, 175.67, 169.95, 142.04, 136.40, 126.21, 61.09, 33.94, 20.14, -3.06; $^{13}$C assignments for the $Z$ isomer were not determined because of rapid isomerization to the $E$ isomer. Anal. Calcd for $C_{12}H_{18}O_3Si$: C, 60.47; H, 7.61. Found: C, 60.25; H, 7.65.

**2-(2-Acetoxyethylidene)indan-1-one (6g/7g)** (0.21 mmol). A white solid: recrystallization from hexanes provided the pure $Z$ isomer, mp 108.5–109.5 °C; IR ($CH_2Cl_2$) 3050, 2980, 1740, 1700, 1650, 1610, 1365, 1230 cm$^{-1}$; $^1$H NMR (300 MHz, $CDCl_3$) ($Z$ isomer) $\delta$ 7.81 (d, $J$ = 7.5 Hz, 1 H), 7.59 (t, $J$ = 7.5 Hz, 1 H), 7.46 (d, $J$ = 7.6 Hz, 1 H), 7.38 (t, $J$ = 7.5 Hz, 1 H), 6.25 (tt, $J$ = 5.6 Hz, $J$ = 1.6 Hz, 1 H), 5.45 (dt, $J$ = 5.6 Hz, $J$ = 1.5 Hz, 2 H), 3.73 (s, 2 H), 2.13 (s, 3 H); ($E$ isomer) $\delta$ 7.91 (d, $J$ = 7.5 Hz, 1 H), 7.75 (t, $J$ = 7.5 Hz, 1 H), 7.55 (d, $J$ = 7.6 Hz, 1 H), 7.45 (t, $J$ = 7.5 Hz, 1 H), 6.90 (tt, $J$ = 6.2 Hz, $J$ = 2.2 Hz, 1 H), 4.94 (d, $J$ = 6.2 Hz, 2 H), 3.81 (s, 2 H), 2.22 (s, 3 H); $^{13}$C NMR (75.48 MHz, $CDCl_3$ ($Z$ isomer) $\delta$ 193.51, 170.15, 148.94, 138.43, 135.21, 135.08, 134.04, 126.95, 125.59, 123.59, 61.25, 31.65, 20.30; ($E$ isomer) $\delta$ 195.00, 172.18, 149.68, 137.37, 136.49, 135.71, 131.00, 127.52, 125.86, 124.44, 61.69, 26.27, 20.02; MS (low-resolution EI) $m/e$ (relative intensity) 216 ($M^+$,4), 174 (100), 156 (35), 145 (55), 128 (52), 115 (38), 102 (14), 91 (14), 77 (16), 62 (15). Anal. Calcd for $C_{13}H_{12}O_3$: C, 72.21; H, 5.59. Found: C, 72.06; H, 5.64.

**2-(2-Acetoxyethylidene)-6,7-(methylenedioxy)indan-1-one (6h/7h)** (0.19 mmol). A yellow solid: recrystallization from hexanes provided the pure $E$ isomer, mp 129.5–131.5 °C; IR ($CH_2Cl_2$) 2920, 1745, 1705, 1645, 1655, 1480, 1230, 1050 cm$^{-1}$; $^1$H NMR (300 MHz, $CDCl_3$) ($Z$ isomer) $\delta$ 7.05 (d, $J$ = 7.9 Hz, 1 H), 6.85 (d, $J$ = 7.9 Hz, 1 H), 6.20 (t, $J$ = 5.5 Hz, 1 H), 6.15 (s, 2 H), 5.40 (dt, $J$ = 5.5 Hz, $J$ = 1.7 Hz, 2 H), 3.65 (s, 2 H), 2.10 (s, 3 H); ($E$ isomer) $\delta$ 7.12 (d, $J$ = 7.8 Hz, 1 H), 6.95 (d, $J$ = 7.9 Hz, 1 H), 6.90 (t, $J$ = 5.7 Hz, 1 H), 6.15 (s, 2 H), 4.85 (d, $J$ = 5.9 Hz, 2 H),

2.20 (s, 3 H), 3.75 (s, 2 H); $^{13}C$ NMR (75.48 MHz, $CDCl_3$) (*Z* isomer) δ 190.86, 170.16, 146.97, 143.59, 140.86, 135.51, 135.23, 121.67, 117.36, 113.70, 102.33, 102.28, 61.20, 31.57, 20.31; (*E* isomer) δ 192.73, 173.82, 147.38, 144.70, 141.01, 138.20, 130.87, 117.78, 115.60, 111.82, 102.67, 62.15, 29.09, 20.08; MS (low-resolution EI) *m/e* (relative intensity) 260 ($M^+$,9), 218 (48), 200 (100), 172 (30), 121 (26), 115 (38), 101 (22), 89 (11), 77 (20), 62 (18). Anal. Calcd for $C_{14}H_{12}O_5$: C, 64.61; H, 4.65. Found: C, 64.54; H, 4.65.

**5-(2-Acetoxyethylidene)-2-cyclopenten-1-one (6i/7i)** (0.18 mmol): IR ($CH_2Cl_2$) 2880–2980, 1745, 1705, 1670, 1660, 1380, 1240 $cm^{-1}$; $^1H$ NMR (300 MHz, $CDCl_3$) (*Z* isomer) δ 7.58 (m, 1 H), 6.38 (M, 1 H), 6.08 (t, *J* = 5.5 Hz, 1 H), 5.33 (d, *J* = 5.6 Hz, 2 H), 3.25 (s, 2 H), 2.10 (s, 3 H); (*E* isomer) δ 7.62 (m, 1 H), 6.54 (t, *J* = 5.6 Hz, 1 H), 6.38 (m, 1 H), 4.80 (d, *J* = 5.6 Hz, 2 H), 3.32 (s, 2 H), 1.22 (s, 3 H); $^{13}C$ NMR ($CDCl_3$, 75.48 MHz) (*Z* isomer) δ 196.64, 171.62, 163.26, 139.06, 134.34, 132.82, 61.67, 38.75, 21.56; $^{13}C$ assignments for the *E* isomer were not determined due to a limited amount of material. Anal. Calcd for $C_9H_{10}O_3$: C, 65.05; H, 6.07. Found: C, 64.95; H, 6.10.

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**Registry No.** **1a**, 83897-48-7; **1b**, 127230-91-5; **1c**, 127230-92-6; **1d**, 38425-48-8; **1e**, 127230-93-7; **1e** (4,4-dichloro derivative), 85973-82-6; **1f**, 4683-54-9; **1g**, 3469-06-5; **1h**, 118112-19-9; **2a**, 127230-99-3; **2b**, 127231-00-9; **2c**, 127231-01-0; **2d**, 127231-02-1; **2e**, 127231-03-2; **2f**, 127231-04-3; **2g**, 127231-05-4; **2h**, 127231-06-5; **4a**, 127231-07-6; **4b**, 127231-08-7; **4c**, 127231-09-8; **4d**, 127231-10-1; **4e**, 127231-11-2; **4f**, 127231-12-3; **4g**, 127231-13-4; **4h**, 127231-14-5; **5a**, 127231-16-7; **5b**, 127231-17-8; **5c**, 127231-18-9; **5d**, 127231-19-0; **5e**, 127231-20-3; **5g**, 127231-21-4; **5h**, 127231-22-5; **5i**, 127231-23-6; **6a**, 127231-24-7; **6b**, 127231-25-8; **6c**, 127231-26-9; **6d**, 127231-27-0; **6e**, 127231-28-1; **6g**, 127231-29-2; **6h**, 127231-30-5; **6i**, 127231-31-6; **7a**, 127231-32-7; **7b**, 127231-33-8; **7c**, 127231-34-9; **7d**, 127231-35-0; **7e**, 127231-36-1; **7g**, 127231-37-2; **7h**, 127231-38-3; **7i**, 127231-39-4; **10**, 127230-94-8; **11**, 127230-95-9; **12**, 127230-96-0; **13**, 127230-97-1; **14**, 127230-98-2; **15**, 71721-73-8; $MeOCH{=}C{=}CH_2$, 13169-00-1; $H_3CC{\equiv}CCH_3$, 503-17-3; $ClC(O)CHCl_2$, 79-36-7; $HC{\equiv}CCH_3$, 6443-91-0; cyclobutane-1,3-dione, 15506-53-3; 3-ethoxycyclobutan-1-one, 30830-26-3; 3-ethoxy-1-(1-methoxypropadienyl)-cyclobutan-1-ol, 127231-15-6.

**Supplementary Material Available:** $^1H$ and/or $^{13}C$ NMR spectra for compounds **2a–2f**, **10**, **11**, and **14** (12 pages). See any current masthead page for ordering information.

# Host–Guest Complexation. 53. Functional Groups Preorganized in Hemispherands for Binding Alkali Metal and Ammonium Cations[1]

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The synthesis and free energies are reported for 10 new hemispherands (**1**, **2**, **4**, **6**, **7–9**, **11–13**) binding alkali metal and ammonium picrate salts at 25 °C in $CDCl_3$ saturated with $D_2O$. These hemispherands possess the general structure I, in which two 4-substituted anisole units flank and preorganize for binding the heteroatoms of substituted aromatic or heterocyclic systems. These macrocycles, like three previously reported (**3**, **5**, **10**), contain 18-membered rings with common $(CH_2OCH_2)_3$ and two $ArOCH_3$ units but differing central A units (I). Most of the 13 hemispherands compared show the highest binding for $Na^+$ and the exceptions, for $K^+$. Arrangement of the 13 systems in decreasing order of their contributions to their systems binding $Na^+$ is as follows, with the $-\Delta G°$ values (kcal $mol^{-1}$) appearing in parentheses: **1**, 4-$CH_3C_6H_2CON(CH_3)_2$ (15.1); **2**, 4-$CH_3C_6H_2CO_2CH_3$ (12.4); **3**, 4-$CH_3C_6H_2OCH_3$ (12.2); **4**, pyridine oxide (12.2); **5**, $(CH_2)_3N_2C{=}O$ (12.0); **12**, 4-$CH_3C_6H_2SOCH_3$ (11.4); **6**, 4-$CH_3C_6H_2NO_2$ (11.0); **7**, pyridine (10.8); **11**, 4-$CH_3C_6H_2SCH_3$ (10.8); **13**, 4-$CH_3C_6H_2SO_2CH_3$ (9.5); **8**, 4-$CH_3C_6H_2NH_2$ (9.3); **9**, furan (8.9); **10**, 4-$CH_3C_6H_2OH$ (7.9). The largest specificities for hosts binding $Na^+$ over hosts binding $K^+$ involved **12**, with A = $CH_3C_6H_2SOCH_3$ [$-\Delta(\Delta G°) = 3.8$] and **13** with A = $CH_3C_6H_2SO_2CH_3$ [$-\Delta(\Delta G°) = 3.2$ kcal $mol^{-1}$]. The corresponding specificites for these two systems binding $Na^+$ over $Li^+$ were $-\Delta(\Delta G°) = 3.7$ and 2.8 kcal $mol^{-1}$, respectively. The crystal structures of **1**, **2**, **2**·$NaSbF_6$, **4**, **6**, and **6**·$NaSbF_6$ are reported.

A central objective in this series of papers is to correlate the structures of hosts and guests with their binding free energies in the applications of the principles of complementarity and preorganization to host design.[2] There is vast literature on the binding of the alkali metal ions by corands containing aliphatic ether oxygen, amine nitrogen, or sulfide sulfur, reflecting the fact that these functional groups are readily introduced as ring members into macrocycles and macrobicycles to provide systems partially preorganized for binding by their respective macroring systems.[3] Crystal structures of hemispherands established that three or four anisole units attached to one another at their 2- and 6-positions and incorporated into respective 18- and 20-membered macrorings[4] provide a means of preorganizing methoxyaryl oxygens for binding alkali metal

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