ration. Six water molecules are situated on the edges of the complex, but none lie directly between the two benzene rings.

The behavior of 1-PSA is at least qualitatively consistent with the above calculations. Since aromatics do not "freeze" water molecules as effectively as do aliphatic chains, solvent release upon aggregation (with its attendant entropic benefits)[23] is not so important. Indeed, structured water collects primarily at the periphery of the aromatics rather than above or below the rings where the actual hydrocarbon-hydrocarbon contact takes place. Multimolecular stacking is not observed presumably because favorable van der Waals interactions are not sufficiently great to overcome an "edge" effect. Thus, a trimer could have difficulty accommodating at the circumference of its inner ring all the water molecules necessary to stabilize "double" association. Whatever its origins, however, the presence of only monomeric and dimeric Ar_n-X is fortunate because it permits the exploitation of hydrophobic and electronically active surfaces in water without the complication of aggregation.

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Acknowledgment. This work was supported by the National Institutes of Health.

Registry No. 1-PSA, 26651-23-0; *p*-NPDNB, 1523-21-3; *N*,*N*,*N*′,*N*′-tetramethyl-*N*-(1-methylpyrenyl)-3-aminopropanaminium bromide, 109244-71-5; 1-(bromomethyl)pyrene, 2595-90-6; *N*,*N*,*N*′,*N*′-tetramethyl-1,3-propanediamine, 110-95-2; phenol blue, 2150-58-5.

Substituent Control of Sigmatropic Periselectivity: Application to the Synthesis of (±)-Muscone

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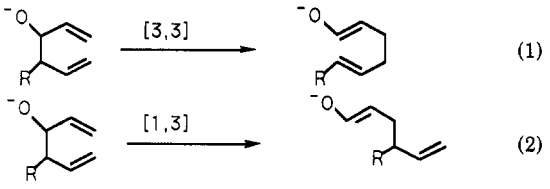
The thermal and anionic rearrangements of *trans*-1-vinylcyclotridec-3-en-1-ol compounds substituted in the α and β vinyl positions have been examined to determine whether the substituents can be used to control the periselectivity. For the anionic rearrangements, trimethylsilyl groups were found to be unsuitable, and terminal vinyl methyl or isopropyl groups did not provide a useful selectivity. Under thermal conditions, either a terminal trimethylsilyl or methyl gave high periselective control favoring the 1,3-shift siloxy Cope ring expansion relative to the 3,3-shift. This was used in a new synthsis of muscone.

A substantial number of recent papers describe applications of anionic oxy Cope reactions[1-3] (eq 1 and 2) to the synthesis of natural products with various ring sizes. For



(1)

(2)

example, the 3,3-shift has been elegantly used to prepare natural products containing 10-membered rings (eucannabinolide,[4] eupasimlicin A,[5] periplanone B[6]), 8-membered rings (poitediol,[7] ophiobolins[8]), and 6-membered rings (juvabione,[9] dihydronepetalactone[10]). The 3,3-shift has also been used to make key intermediates for syntheses aimed toward pseudoguianolides,[11] germacranes,[12] steroids[13], retigeranic acid,[14] and taxol.[15] A 5,5-shift variation[16] suggests a possible route to 14-membered ring compounds like albocycline and erythromycin A. Our studies have developed the 1,3-shift oxy Cope rearrangement as a ring-expansion method applicable to medium and large ring systems[17] including large-ring analogues of steroids.[18] The same principle has recently been used[19] to prepare 5-membered rings, which are common to many natural products such as damsinic acid, pentalene, and the hirsutenes. The 1,3-shift has also been used to produce 6-membered rings.[20,21] The thermal 3,3 oxy Cope has also been applied to natural produce synthesis, e.g., *Lycopodium* alkaloids[22] and *cis*-hydroisoquinolines.[23]

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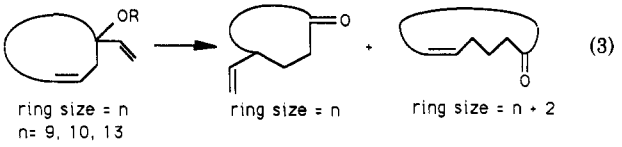
Our earlier studies of the thermal siloxy Cope[24-26] and the anionic oxy Cope[17] rearrangement process shown in eq 3 showed that ring size is an important factor, since it affects the rate of the reaction and also plays a significant role in determining the product distribution ratio. Under

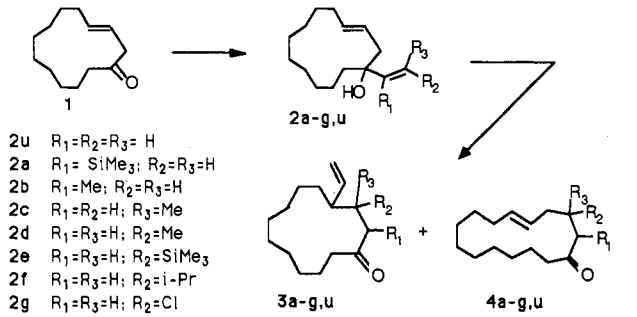


(3)

both thermal and anionic conditions, 9- and 10-membered rings favor the 1,3-shift ring-expansion process over the 3,3-shift process. On the other hand, the 13-membered ring gave an unselective 54:46 ratio of the 3,3/1,3 shift products upon pyrolysis. The ratio increased considerably in favor of the 3,3-shift product when the rearrangement was carried out under anionic conditions at lower temperatures.

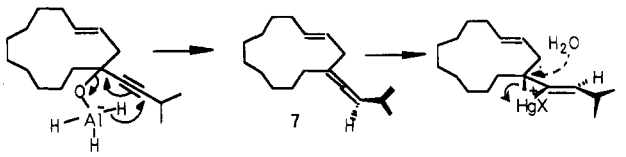
The present study[27] utilized ketone **1** to generate the 13-membered ring compounds **2a–g** to study what effects substituents on the 1-vinyl group have on the periselectivity of the 3,3 and 1,3 sigmatropic shifts leading to **3a–g** and **4a–g**, respectively. Could the synthetic potential of the 1,3-shift ring expansion be enhanced? Would the substituents cause any undesired side reactions? Would the substituents provide clues about the mechanism of the reaction?

Syntheses. Cyclododecene was converted to ketone **1** in five steps as outlined earlier.[25] Compounds **2a–g** were prepared from **1** either by Grignard addition of the appropriate vinylmagnesium bromide (**2a–d**) or by addition



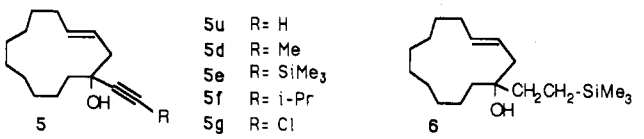
of the appropriate acetylide followed by lithium aluminum hydride reduction of the triple bond to the trans double bond (**2d–g**). In all cases, the additions did not go to completion because of competing enolate formation. Normal Grignard conditions gave yields of 26% for **2a**, 47% for **2c,d**, and 50% for **2b**. A $CeCl_3$ modification[28] designed to alleviate the enolization problem was tried with **2b**, which gave a slightly improved 55% yield. In the **2c,d** reaction, the Grignard reagent was prepared from a mixture of *cis*-, and *trans*-1-bromopropenes, which gave a 72:28 mixture of the *cis*/*trans*-propenyl alcohols. The trans stereochemistry of **2d** was confirmed by another reaction sequence; the ultrasonically mixed reaction of lithium and *trans*-1-chloropropene generated propynyllithium,[29] which added to **1** to produce **5d** as the sole product in 36% yield.

Scheme I

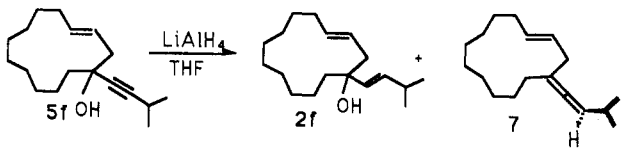


This product was converted to **2d** in 33% yield by a lithium aluminum hydride reduction of the triple bond, a process that is known to give predominant if not exclusive trans stereochemistry.[30] In the present case, only trans was observed.

In a similar way, reaction of ketone **1** with the acetylide obtained from (trimethylsilyl)acetylene and *n*-butyllithium in ether gave **5e** in 61% yield. The triple bond was reduced with $LiAlH_4$ to give a 54% yield of **2e** along with 12% of an overreduction product **6**.



The isopropyl-substituted compound **5f** was prepared in 75% yield with the lithium acetylide from 3-methyl-1-butyne. Reduction of the triple bond failed under the usual conditions. However, treatment with $LiAlH_4$ in refluxing THF produced the expected alcohol **2f** and an unexpected allene **7** in a 32:68 ratio in 65% yield. The byproduct allene **7** was cleanly converted in 36% yield to **2f** by oxymercuration followed by reduction with sodium borohydride under basic conditions.[31]



The lithium aluminum hydride reduction of propargylic alcohols normally proceeds through a mechanism involving complexation of the aluminum to the hydroxyl group followed by formation of a cyclic intermediate leading to *trans*-allylic alcohol product. For **5f**, the isopropyl group apparently greatly hinders formation of a crucial reduction intermediate even though a trimethylsilyl group does not do so. The more vigorous reduction conditions then gave mainly allene **7**. Formation of allenes from tertiary acetylenic alcohols has been observed previously[32] if they were treated with HCl and $LiAlH_4$. Scheme I shows a plausible mechanism for the formation of allene **7**, which is analogous to the related transformation of allenyl alcohols to dienes.[33] Apparently, delivery of the hydride at the β-acetylenic position is considerably more favorable than formation of the usual reduction intermediate.

The oxymercuration of allene **7** leading to **2f** with only trans stereochemistry can be rationalized in terms of a bridged mercurinium ion (Scheme I). Thus, attack of the nucleophile from the backside, followed by reductive

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Table I. Thermal Rearrangement/Hydrolysis of the Silyl Derivatives of the Substituted 1-Vinyl-*trans*-cyclotridec-3-en-1-ols (2u, 2a-g)

compd	pyrolytic conditions:[a] temp, °C; time, h	product ratio 3:4	yield, %
2u-Me_3Si[25]	299; 2.0	54:46	79
2a-Me_3Si (α-Me_3Si)	316; 4.0	77:23 (**3u**:**4u**)	74
2b-Me_3Si (α-Me)	306; 2.5	55:15[b] **3b** is 47:53 mixture of two diastereomers	47
2c-Me_3Si (cis β-Me)	318; 4.5	<2:>98	55
2d-Me_3Si (trans β-Me)	322; 4.5	<2:>98	53
2e-Me_3Si (trans β-Me_3Si)	310; 4.5	<2:>98	52
2f-Me_3Si (trans β-*i*-Pr)	326; 5.0	mixture of three isomeric trienes	94[c]
2g-Me_3Si (trans β-Cl)	320; 3.5	mixture of two unidentifiable compds	62[c]

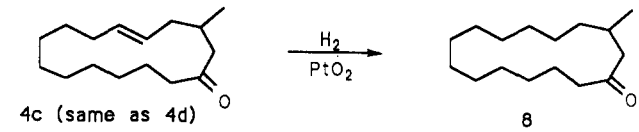
[a] The compound was heated in the gas phase, and the resultant enol ether products were hydrolyzed as described earlier.[35] [b] Thirty percent of an unidentifiable byproduct is also formed. [c] Recovery after pyrolysis only.

elimination of the mercurinium ion with sodium borohydride results in the stereospecific formation of the trans alcohol **2f**. Previous studies indicate that the product-forming, 3-membered ring intermediate will have the mercury atom cis to the bulky isopropyl group.[34] This is attributed to the fact that the mercurinium ion is formed reversibly prior to the rate-limiting step and is not subject to steric control. The opening of the mercurinium ion by the solvent then is both rate and product determining and is sensitive to steric influence of substituents at the opposite end of the allenic system.

Treatment of ketone **1** with the acetylide obtained from the reaction of *trans*-1,2-dichloroethylene and methyllithium generated **5g**. The $LiAlH_4$ reduction gave **2g** in only 12% yield along with 5% of **2u** and 8% of **5u**.

Thermal Rearrangements. Thermolyses were carried out on the silylated alcohols (**2a**-Me_3Si represents the *O*-trimethylsilyl derivative of **2a** etc.) These silyl derivatives were heated in sealed ampules at 300–325 °C. The pyrolysis products were then hydrolyzed[35] to give the product ketone ratios as shown in Table I.

The most dramatic feature of Table I is the striking change in periselectivity produced by substituents on the β-position of the vinyl group. Compounds **2c**-Me_3Si, **2d**-Me_3Si, and **2e**-Me_3Si undergo the thermal 1,3-shift ring expansion to **4c**, **4d** (same as **4c**), and **4e**, with <2% of the competing 3,3-shift, whereas **2u**-Me_3Si produces nearly a 50:50 ratio of 3,3 and 1,3 products. The dramatic change in periselectivity presumably arises because the methyl or trimethylsilyl group sterically destabilizes the transition state much more for the 3,3-shift than for the 1,3-shift. There is some precedent for this in earlier work,[24,26] which demonstrated that the more congested medium-sized rings disfavored the 3,3-shift much more than the 1,3-shift. This ring expansion is extremely sensitive to the steric interaction so that even the very small methyl group in either stereochemistry directs the rearrangement almost completely to the 1,3-shift pathway. This is synthetically very handy, because it is much easier to generate a mixture of **2c** and **2d** than to obtain either in pure form. Separation of **2c** and **2d** is not necessary, since both lead to the desired product. This opens up the rather straightforward route to muscone (**8**) as shown.[36,37] The hydrogenation of **4c** to muscone also confirms the carbon skeleton of **4c**. The position of the double bond in the ring-expanded, 15-membered ring ketone was assigned by analogy to **4u**, which was assigned earlier.[25]



4c (same as 4d) 8

Our earlier studies[25] of the activation parameters for the siloxy Cope rearrangement of **2u**-Me_3Si suggest that the 3,3-shift rearrangement proceeds through a concerted mechanism, although a diradical mechanism could not be totally ruled out.[24-26] The activation parameters provide a less clear distinction for the 1,3-shift case as pointed out by Berson's work.[38] A concerted mechanism for the 3,3-shift would involve either a chair or a boat conformation in the transition state, with the chair being normally preferred.[39,40] The strong disfavoring effect of β substituents is consistent with that mechanistic picture.

The α-substituted compounds gave product mixtures more like **2u**, in fact pyrolysis–hydrolysis of **2a**-Me_3Si (α-Me_3Si) resulted in **3u** and **4u**, rather than the expected **3a** and **4a**. Rearrangement of **2a**-Me_3Si initially gives the 13- and 15-membered ring silyl enol ethers with the trimethylsilyl group intact at the α-position. This is best evidenced by the proton NMR and infrared spectra of the compounds that were taken prior to hydrolysis. Also, the 3,3/1,3 shift ratio for **2a**-Me_3Si is different from that for **2u**-Me_3Si, which clearly indicates that the carbon-bound trimethylsilyl group must still be present in the rearrangement step. The α-trimethylsilyl group is then lost during the hydrolysis, which probably first converts the enol ether to the ketone. Such ketones are known to lose their α-trimethylsilyl group under similar conditions by a mechanism closely related to the Brook rearrangement.[41]

The rearrangement of **2b**-Me_3Si gives a rather unselective formation of **3b** and **4b**. Compound **3b** is a mixture of two diastereomers that result from hydrolysis of the enol ether formed in the thermal step. The structures were assigned from spectral data and analogy to the earlier **2u** case.[25] Further proof for the position of the double bond in the 1,3-shift ring-expanded product was obtained by a COSY study, carried out on ketone **4b**. From the spectrum it was concluded that the methyl group was α to the carbonyl group. The allylic protons were coupled to a pair of methylene protons, which in turn were coupled to a methine proton. This confirmed that the double bond was in the 5,6-position.

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Table II. Anionic Rearrangements of the Substituted 1-Vinyl-*trans*-cyclotridec-3-en-1-ols (2u, 2a–f)

compd	anionic conditions: temp, °C; time, h	product ratio, 3:4	yield, %
2u[17]	60; 4.5	87:13	70
2a (α-Me_3Si)	60; 4.0	88:12 (**3u**:**4u**; Me_3Si lost)	76
2b (α-Me)	54; 2.5	82:18; **3b** is 45:55 mixture of two diastereomers	62
2c (cis β-Me)	100; 2.0	54:45 (±3)[a][; **3c** diastereomers[b]	62
2d (trans β-Me)	102; 1.5	45:55 (±10)[a]; **3c** diastereomers[b,c]	39
2e (trans β-Me_3Si)	25; 11.0	**2u** (**2e** without the Me_3Si gp)	42
2f (trans β-*i*-Pr)	100; 2.5	27:35[d]; **3f** is 47:53 mixture of two diastereomers	69

[a] The **3:4** ratio is an average of four runs under similar conditions. [b] See Tables III and IV for typical diasteromer ratios. [c] **3c** = **3d** (a mixture of cis and trans isomers). [d] A ring fragmentation product **9** (38%) was also formed.

Surprisingly, pyrolysis of **2f** resulted in a mixture of three compounds, which were obtained by elimination of the trimethylsiloxy group rather than from the 3,3 and 1,3 sigmatropic shifts. The bulky isopropyl group apparently creates enough unfavorable steric interaction to prevent both 3,3 and 1,3 sigmatropic shifts. Still, it is hard to explain the dramatic change in products. In a repeat experiment, the ampules were oven dried overnight after being washed with water, acetone, and ammonium hydroxide, respectively, to minimize the possibility of any glass- or acid-catalyzed reactions, but the results were the same. The thermal rearrangement of **2g** gave a mixture of two products, which though not fully characterized do not appear to arise from 1,3 or 3,3 oxy Cope rearrangements (no vinylic protons in the NMR spectrum and no strong carbonyl bands in the infrared spectrum).

Anionic Rearrangements. The anions of **2a–f** were generated by use of potassium hydride in hexamethylphosphoramide (HMPA) with the results shown in Table II. In all cases, the starting compound reacted completely during the time given; in some cases the reaction was complete in a shorter time than listed. As discussed earlier,[17] the anionic rearrangements take place at much lower temperatures than the thermal rearrangements.

The results are much different under the KH in hexamethylphosphoramide (HMPA) conditions. The trimethylsilyl substituent, which was quite effective for the thermal conditions, is useless for the KH/HMPA conditions. The trimethylsilyl group is much too readily removed by the alkoxide species generated under those conditions. For **2a**, the ratio of products obtained is very comparable to the ratio obtained from alcohol **2u**, but the α-trimethylsilyl group is lost in the course of the rearrangement. This presumably takes place after the formation of the rearranged enolate by a mechanism similar to the Brook rearrangement.[41] Attempted rearrangement of the β-trimethylsilyl compound **2e** under anionic conditions rather surprisingly produced **2u**. Once again the trimethylsilyl group was lost, but this time no rearrangement took place at all. One possible rationale is that the alkoxide generated by KH removes the trimethylsilyl groups faster than the reaction can take place, and the resultant anion then prevents the rearrangement. The trimethylsilyl group appears to be lost much too easily under these anionic conditions to be useful.

The periselectivity for the rearrangement of alcohols **2a–f** is rather different under anionic conditions than under thermal ones.[42] Our earlier studies of **2u** found a dramatic change in the rate and product distribution ratio when compared with a thermal rearrangement of the same compound.[25] The activation parameters measured for the thermolysis were used to provide an estimate for what the 3,3 to 1,3 ratio should be for the anionic reaction at 60 °C. The 3,3-shift process would be facilitated by a factor of ca. 200 over the 1,3-shift process because of the change in the $T\Delta S^*$ term. When the rearrangement was actually carried out at 60 °C, the selectivity was not that high, but the product distribution ratio was heavily in favor of the 3,3-shift product.

Table III. Rearrangement of Alcohol 2c with KH in HMPA

% **2c** left	time of removal, min	temp at removal, °C	3,3 to 1,3 product ratio[a]	3,3-shift diastereomer ratio[a]
100	20	22	0:0	0:0
0	53	73	54:46	50:50
0	83	73	57:43	43:57
0	113	77	51:49	57:43
0	143	72	48:52	59:41
0	173	85	48:52	46:54
0	263	108	48:52	51:49

[a] GC ratios were determined with an electronic integrator.

Table IV. Rearrangement of Alcohol 2d with KH in HMPA

% **2d** left	time of removal, min	temp at removal, °C	3,3 to 1,3 product ratio	3,3-shift diastereomer ratio[a]
100	30	22	0:0	0:0
79	55	64	29:71	59:41
73	70	63	33:67	64:36
69	85	78	35:65	63:37
43	125	79	33:67	62:38
16	140	90	39:61	
0	205	90	22:78	57:43
0	220	90	24:76	62:38
0	250	90	21:79	71:29
0	280	108	33:67	69:31
0	315	102	24:76	70:30
0	370	120	35:65	67:33

[a] GC ratios were determined with an electronic integrator.

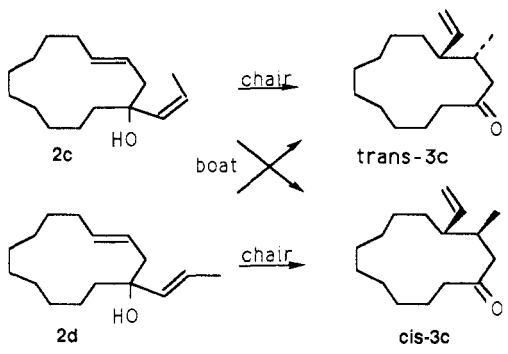
Not unexpectedly, the effect of an α-methyl substituent on the periselectivity for the anionic rearrangements was minimal (see Table II). The product ratio obtained from **2b** was very comparable to that for **2u**. Two diastereomeric 3,3-shift products, **3b**, are obtained from the rearrangement of **2b**. As with the thermal case, these result from protonation of the resultant enolate from both sides.

When the rearrangements of **2c** or **2d** are carried out by treating with KH/HPMA, the 1,3- to 3,3-shift ratio increases relative to **2u** but not to a useful selectivity for synthesis (see Table II). To see whether the product distribution ratio changes with time, **2c** and **2d** were stirred with KH in HMPA, and the reactions were monitored by analyzing aliquots by GC. The product and diastereomer ratios (Tables III and IV) showed considerable scatter but stayed essentially constant.

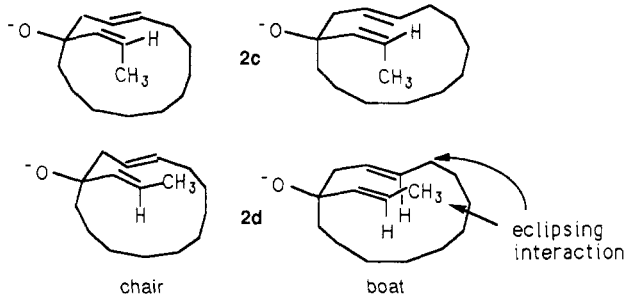
It is quite interesting that **2c** and **2d** both generate mixtures of diastereomers of **3c**. If each was rearranging only through a concerted chair–Cope transition state, then

(42) For other recent cases of competing or sequential 1,3 and 3,3 rearrangements of this type, see: Jung, M. E.; Hatfield, G. L. *Tetrahedron Lett.* **1984**, 2931. Uyehara, T.; Olimari, K.; Kabasawa, Y.; Kato, T. *Chem. Lett.* **1984**, 1879. Paquette, L. A.; Crouse, G. D.; Sharma, A. K. *J. Am. Chem. Soc.* **1982**, *104*, 4411.

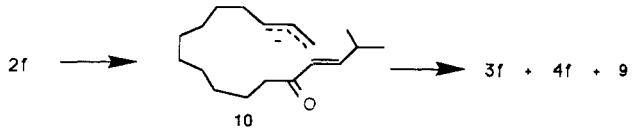
Scheme II



Scheme III



Scheme IV

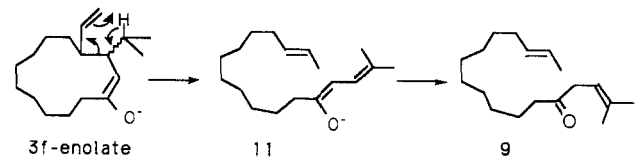


2d should give only *cis*-**3c**; whereas, **2c** should give only *trans*-**3c**. On the contrary, concerted 3,3-shifts utilizing only boat transition states would be stereospecific in the opposite sense (Scheme II).

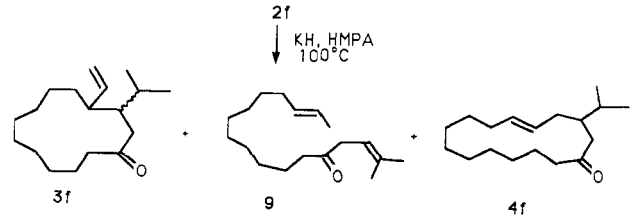
Clearly, if the mechanism is a concerted one, then both the chair and the boat transition states would have to be adopted. This seems especially unlikely for the trans case, **2d**, where the β-methyl generates a very unfavorable eclipsing interaction in the boat transition state (see Scheme III). The above arguments assume that the products do not interconvert. If they do interconvert, then the rearrangement could be stereospecific, and the mixtures could simply result from the interconversion. Tables III and IV support the assumption that the products are reasonably stable, since the 3,3 to 1,3 shift product ratio stayed essentially constant as did the diastereomer ratio, although there was considerable scatter in the data (Tables III and IV).

Earlier work on anionic sigmatropic rearrangements indicated that cleavage to an allylic or benzylic anion intermediate is a viable alternative mechanism for these rearrangements. Fragmentation products ascribable to such intermediates were observed in open-chain cases[43,44] and two cyclopropyl cases.[17] Substituted benzo compounds also indicated a buildup of negative charge at the carbon that migrates in the 1,3-shift.[18,43] Either the anionic intermediates are on the pathway leading to 3,3- and 1,3-shift products or they lie on an energetically similar competing path.

Scheme V



Fragmentation products were not seen with **2u** and **2a–e**, but the anionic rearrangements of **2f** produced a rather intriguing result. A new ring cleavage product, **9**, was obtained along with the two usual products of rearrangement. The three products could all result from fragmentation of the ring to give allylic anion intermediate **10** (Scheme IV). Recombination by an intramolecular Michael addition from either end of the allylic anion would then give the 3,3- and 1,3-shift products. Unlike **2u** and **2a–e**, where the intermediate anion can readily undergo the Michael addition, such addition would take place less readily for **2f** because of the bulky isopropyl group. An alternative pathway is the removal of the tertiary isopropyl proton by the less hindered terminal allylic position of the anion, to give an extended enolate, which after protonation at the α-position leads to the β,γ-unsaturated ketone **9**.



It is not totally clear that the allylic anion should only abstract the isopropyl proton using the terminal position. Another mechanism can be postulated that must make the transfer to that position (Scheme V). The rearranged enolate of the 3,3-shift product could rearrange again by a retro-ene fragmentation, which would give the extended enolate **11**, which then produces **9**. One interesting facet of this mechanism is that if **3f** rearranged to give **9**, then it would be the first case of a vinylogous, oxygen anion enhanced retro-ene reaction. Wender has reported a similar vinylogous oxygen anion accelerated 3,3-shift.[45] Ketone **3f** was subjected to the anionic oxy Cope rearrangement conditions, but no rearrangement was observed. No definite conclusion can be made on the Scheme V mechanism since any enolate made could have been on the wrong side, which would not have allowed rearrangement.

Although some mechanistic questions remain open, the present work provides a useful contribution to an understanding of periselectivity in the oxy Cope rearrangements. Such a control in periselectivity of the oxy Cope rearrangement could be well applied in organic synthesis, especially to that of natural products. The use of substituents that could later be removed after the rearrangement, while simultaneously introducing a functionality, could further enhance the scope of this rearrangement. The conversion of the product of thermal pyrolysis of alcohols **2c** and **2d** to (±)-muscone clearly illustrates the synthetic utility.

Experimental Section

General Procedures. Spectral measurements utilized Perkin-Elmer 727B and 621 infrared, Varian FT80 NMR, Bruker 400-MHz NMR, and CDC mass spectrometer instruments.

(43) Thies, R. W.; Meshgini, M.; Chiarello, R. H.; Seitz, E. P. *J. Org. Chem.* **1980**, *45*, 185.
(44) Carpenter, B. K.; Zoeckler, M. *J. Am. Chem. Soc.* **1981**, *103*, 2443.
(45) Wender, P. A. Ternansky, R. J.; Sieberth, S. M. *Tetrahedron Lett.* **1985**, 4319.

Double-intensity peaks in the ^{13}C NMR are designated 2×, etc. High-resolution mass spectra were measured at the NSF regional facility at the University of Nebraska. GC analyses were carried out on a Varian 1200 (fid) chromatograph using column A (4 ft × 0.125 in., 12% OV101 on 110/120 Ch.W) unless specified as column B (4 ft × 0.125 in., 3% DEGS on 120/140 Ch.W). Preparative GC used a Varian 920 chromatograph with a 3 ft × 0.25 in., 3% OV101 on 80/100 Ch.W. column. Flash chromatography[46] and radial chromatography[47] used EtOAc/hexane eluent with the percent indicated in parentheses.

Tetrahydrofuran (THF) and ether were distilled from sodium benzophenone ketyl under nitrogen. Hexamethylphosphoric triamide (HMPA) was dried by storing over 13× molecular sieves (predried under nitrogen at 350 °C for 4 h).

All reactions were conducted under nitogen with magnetic stirring. "Standard workup" means extracting with ether, washing the organic extract with saturated $NaHCO_3$ and saturated NaCl, drying over $MgSO_4$, filtering, and concentrating in vacuo on a rotary evaporator.

1-[1-(Trimethylsilyl)ethenyl]-*trans*-cyclotridec-3-en-1-ol (2a). A mixture of 0.121 g (4.98 mmol, 3.5 equiv) of magnesium pieces, 3 mL of THF, 50 μL of (α-bromovinyl)trimethylsilane, and 30 μL of 1,2-dibromoethane were reacted as described below for **2c** and **2d**, which gave 0.30 g of an orange liquid. The crude product was then purified[47] (5% EtOAc-hex/hexane, which gave 0.034 g (12%) of ketone **1**, 0.04 g (14%) of impurities, and 0.108 g (26%) of **2a**: ^1H NMR ($CDCl_3$) δ 5.60 (d, 1 H, J = 1.7 Hz), 5.46 (d, 1 H, J = 1.8 Hz), 5.42 (m, 2 H), 2.30 (d, 2 H), 2.00 (m, 2 H), 1.15–1.75 (m, 17 H), 0.20 (s, 9 H); ^{13}C NMR ($CDCl_3$) δ 159.13, 134.99, 126.22, 123.44, 79.50, 43.30, 37.35, 32.29, 27.65, 27.56, 27.32, 25.05, 24.92, 24.73, 19.34, 0.84; IR (neat) 3500, 3050, 2950, 2875, 1460, 1260, 990, 930, 860, 840 cm^{-1}; mass spectrum, m/e 294.2394 (calcd for $C_{18}H_{34}OSi$, 294.2428).

1-(1-Methylethenyl)-*trans*-cyclotridec-3-en-1-ol (2b). Cerium(III) chloride (1.30 g, 3.51 mmol, 1.2 equiv) was heated at 140 °C under vacuum for 1 h as described.[28] The $CeCl_3$ was cooled to 25 °C; 10 mL of THF was then added, and the solution was stirred for 2 h. Grignard reagent, prepared from 6 mL of THF, 1.416 g of 2-bromopropene (11.7 mmol), and 0.291 g of Mg (11.9 mmol), was then added to the $CeCl_3$ at 0 °C. After the mixture was stirred for 90 min at 0 °C, 0.568 g (2.9 mmol) of ketone **1** in 3 mL of THF was added. After 1.5 h at 0 °C, the reaction was quenched with 2% aqueous acetic acid and given the standard workup, which gave 0.747 g of an orange product. Purification[47] gave 0.108 g (19%) of **1** along with 0.380 g (55%) of alcohol **2b**: ^1H NMR ($CDCl_3$) δ 5.45 (m, 2 H), 4.95 (m, 2 H), 2.35 (d, 2 H), 2.00 (m, 2 H), 1.80 (s, 3 H), 1.20–1.70 (m, 17 H); ^{13}C NMR ($CDCl_3$) δ 149.96, 134.67, 126.42, 110.62, 76.47, 41.26, 35.29, 32.23, 27.53 (3×), 24.92 (2×), 24.71, 19.58, 18.84; IR (neat) 3400, 3075, 2925, 2850, 1640, 1450, 1370, 980, 910 cm^{-1}; mass spectrum, m/e 236.2137 (calcd for $C_{16}H_{28}O$, 236.2181).

1-(*cis*-1-Propenyl)- and 1-(*trans*-1-Propenyl)-*trans*-cyclotridec-3-enol (2c, 2d). A mixture of 0.249 g (10.2 mmol, 2.1 equiv) of Mg, 5 mL of dry THF, 30 μL of 1-bromo-1-propene, and four drops of 1,2-dibromoethane was allowed to react. Further 1-bromo-1-propene (total 1.225 g, 2.1 equiv) was added until all the Mg went into solution. The reaction flask was then cooled in an ice bath as 0.943 g (4.8 mmol) of *trans*-cyclotridec-3-en-1-one[25] (**1**) dissolved in 2 mL of dry THF was added. After 30 min, the ice bath was removed, and the reaction was stirred for 1 h. The reaction was then cooled in ice, quenched with saturated NH_4Cl, and given the standard workup. The resultant 0.940 g of an orange viscous material was then purified[46] (4% EtOAc/hexane), which gave 0.082 g (8.6%) of **1**, 0.385 g (34%) of **2c**, and 0.147 g (13%) of **2d** with the spectra shown. **2c**: mp 59.5–61.0 °C; ^1H NMR ($CDCl_3$) δ 5.25–5.50 (m, 4 H), 2.30 (br d, 2 H, J = 4 Hz), 1.75–2.00 (m, 5 H, contains 1.75 d, J = 6 Hz), 1.00–1.50 (m, 17 H); ^{13}C NMR ($CDCl_3$) δ 135.09, 133.39, 125.16, 124.86, 74.27, 43.06, 37.67, 30.99, 26.32 (2×), 26.14, 23.59, 23.42, 23.28, 18.07, 13.07; IR (CCl_4) 3410, 3020, 2940, 2870, 1460, 1440, 1000, 985, 970, 910, 740 cm^{-1}; mass spectrum, m/e 236.2143 (calcd for $C_{16}H_{28}O$, 236.2140). **2d**: ^1H NMR ($CDCl_3$) δ 5.60 (m, 2 H), 5.30 (m, 2 H), 2.20 (d, 2 H, J = 5 Hz), 2.00 (m, 2 H), 1.65 (d, 3 H, J = 5 Hz), 1.20–1.50 (m, 17 H); ^{13}C NMR ($CDCl_3$) δ 138.28, 134.71, 126.07, 123.09, 74.42, 43.08, 38.19, 32.31, 27.61 (2×), 27.41, 24.97, 24.88, 24.59, 19.28, 17.81; IR (neat) 3370, 3040, 2920, 2850, 1660, 1455, 1440, 970, 905, 730 cm^{-1}; mass spectrum, m/e 236.2143 (calcd for $C_{16}H_{28}O$, 236.2140).

1-(1-Propynyl)-*trans*-cyclotridec-3-en-1-ol (5d). A mixture of 0.154 g (22.3 mmol, 5 equiv) of finely cut lithium pieces, 2 mL of dry THF, and 40 μL (18 mmol, 4 equiv) of *trans*-1-chloro-1-propene was sonicated (Bransonic B220 ultrasonic cleaner) for 15 min. Further aliquots of *trans*-1-chloroprop-1-ene were added with sonication until the lithium was consumed (6 h). The reaction flask was cooled in ice as 0.867 g (4.46 mmol, 1 equiv) of the ketone dissolved in 2 mL of dry THF was added. The reaction was sonicated for 2 h, cooled in ice, diluted with ether, and quenched with saturated NH_4Cl. Standard workup gave 0.913 g of yellow viscous product, which was purified[46] (10% EtOAc/hexane) to yield 0.296 g (34.0%) of **1** and 0.381 g (36.4%) of **5d**: ^1H NMR ($CDCl_3$) δ 5.25 (m, 2 H), 2.30 (d, 2 H), 2.05 (s, 1 H), 1.80 (m, 2 H), 1.75 (sharp s, 3 H), 1.00–1.50 (m, 16 H); ^{13}C NMR ($CDCl_3$) δ 135.14, 125.44, 83.63, 79.37, 70.51, 44.83, 39.17, 32.21, 27.57, 27.45, 27.29, 24.90 (2×), 24.68, 19.78, 3.43; IR (neat) 3370, 2920, 2860, 1450, 1435, 975 cm^{-1}; mass spectrum, m/e 234.1978 (calcd for $C_{16}H_{26}O$, 234.1984).

Preparation of 2d by Reduction of 5d. A 0.263-g portion of $LiAlH_4$ was added to an ice-cooled solution of 0.132 g of **5d** in 1.5 mL of ether. After 10 min, the reaction was brought to reflux with an oil bath. After 6.5 h, the reaction was cooled in ice and quenched with 0.26 mL of H_2O, 0.26 mL of 15% NaOH, and 0.78 mL of H_2O. The white solid was refluxed several times with fresh ether, and the combined extracts were washed once with saturated NaCl and dried over $MgSO_4$. Filtration and concentration gave 86.5 mg of a colorless oil, which was purified[46] (5% EtOAc/hexane) to yield 9.1 mg (6.9%) of **5d** and 43.3 mg (32.6%) of **2d** (same spectra as above).

1-[2-(Trimethylsilyl)ethynyl]-*trans*-cyclotridec-3-en-1-ol (5e). A 1.28-mL (1.66 mmol, 1 equiv) portion of 1.30 M nBuLi was added to 196 mg of (trimethylsilyl)acetylene (1.99 mmol, 1.2 equiv) in 1 mL of ether at −78 °C. After 15 min, the temperature was raised to 0 °C and kept there for 15 min. A solution of 323 mg (1.66 mmol, 1 equiv) of **1** in 3 mL of ether was added. After 15 min at 0 °C and 2 h at room temperature, the reaction was quenched with saturated NH_4Cl. Standard workup gave 381 mg of an orange viscous liquid, which was purified[46] (8% EtOAc/hexane) resulting in 26.5 mg (8.2%) of recovered **1** and 300 mg (61%) of **5e**: ^1H NMR ($CDCl_3$) δ 5.40 (m, 2 H), 2.40 (br d, 2 H, J = 4 Hz), 2.00 (m, 3 H, contains OH), 1.1–1.8 (m, 16 H), 0.2 (s, 9 H); ^{13}C NMR ($CDCl_3$) δ 135.41, 125.23, 109.97, 87.78, 70.74, 44.68, 38.77, 32.24, 27.51 (2×), 27.20, 24.94 (2×), 24.69, 19.95, −0.03; IR (neat) 3360, 2930, 2865, 2175, 1460, 1440, 1250, 975, 845, 760 cm^{-1}; mass spectrum, m/e 292.2215 (calcd for $C_{18}H_{32}OSi$, 292.2222).

1-[*trans*-2-(Trimethylsilyl)ethenyl]-*trans*-cyclotridec-3-en-1-ol (2e). To a mixture of 43.8 mg (1.16 mmol, 2.2 equiv) of $LiAlH_4$ in 3 mL of diethyl ether at 0 °C was added 153 mg (0.525 mmol, 1 equiv) of **5e** in 2 mL of ether. The reaction mixture was stirred at 0 °C for 15 min and at room temperature for another 15 min and then refluxed for a period of 4 h. The reaction was treated in the same way as **5b**, which gave 118 mg of a colorless oil. This was purified[46] (4% EtOAc/hexane) and gave 19 mg (12%) of overreduction product **6** along with 82.4 mg (54%) of pure **2e**: ^1H NMR ($CDCl_3$) δ 6.15 (d, 1 H, J = 18 Hz), 5.80 (d, 1 H, J = 18 Hz), 5.35 (m, 2 H), 2.20 (br d, 2 H, J = 4 Hz), 1.95 (m, 2 H), 1.50 (s, 1 H), 1.10–1.45 (m, 16 H), 0.05 (s, 9 H); ^{13}C NMR ($CDCl_3$) δ 152.23, 134.92, 126.01, 125.86, 75.56, 42.78, 37.71, 32.28, 27.54 (2×), 27.42, 24.98, 24.86, 24.61, 19.28, −1.21; IR (neat) 3380, 2925, 2850, 1610, 1455, 1440, 1245, 990, 865, 840 cm^{-1}; mass spectrum, m/e 294.2383 (calcd for $C_{18}H_{34}OSi$, 294.2379); **6**: ^1H NMR ($CDCl_3$) δ 5.30 (m, 2 H), 2.20 (d, 2 H), 2.00 (m, 2 H), 1.25–1.70 (m, 19 H), 0.40–0.70 (m, 2 H), 0.05 (s, 9 H); ^{13}C NMR ($CDCl_3$) δ 134.28, 126.33, 74.87, 42.68, 36.82, 34.59, 32.26, 27.73, 27.57, 27.35, 25.05, 24.92, 24.54, 19.48, 8.75, −1.86; IR (neat) 3380, 2920, 2850, 1610, 1470, 1455, 1260, 990, 870, 840 cm^{-1}; mass spectrum, m/e 296.2542 (calcd for $C_{18}H_{36}OSi$, 296.2535).

1-(3-Methylbut-1-ynyl)-*trans*-cyclotridec-3-en-1-ol (5f). To a stirred solution of 2.0 g (2 mmol) of 3-methyl-1-butyne in 7 mL of diethyl ether at −78 °C was added 7.8 mL (11.78 mmol,

(46) Still, W. C.; Kahn, M.; Mitra, A. *J. Org. Chem.* **1978**, *43*, 2923.
(47) The Chromatotron apparatus is available from Harrison Research, Palo Alto, CA.

1 equiv) of 1.50 M *n*-BuLi. After 15 min, 2.29 g (11.78 mmol, 1 equiv) of ketone **1** in 15 mL of ether was added. After 10 min at −78 °C, 15 at 0 °C, and 30 min at 25 °C, the reaction was quenched with saturated aqueous NH_4Cl. Standard workup gave 2.29 g (75%) of a yellow product, which was used in the next step except for a small amount that was purified to give **5f**: ^1H NMR ($CDCl_3$) δ 5.40 (m, 2 H), 2.50 (septet, 1 H), 2.40 (d, 2 H), 2.00 (m, 3 H), 1.25–1.75 (m, 16 H), 1.20 (d, 6 H, J = 7 Hz); ^{13}C NMR ($CDCl_3$) δ 135.01, 125.69, 89.67, 83.51, 70.42, 45.09, 39.15, 32.20, 27.51 (2×), 27.25, 24.92 (2×), 24.67, 23.05 (2×), 20.34, 20.01; IR (neat) 3350, 2930, 2870, 2240, 1450, 1340, 975, 770 cm^{-1}; mass spectrum, m/e 262.2301 (calcd for $C_{18}H_{30}O$, 262.2296).

1-(3-Methyl-*trans*-butenyl)-*trans*-cyclotridec-3-en-1-ol (2f). To a stirred solution of 0.391 g (10.3 mmol) of $LiAlH_4$ in 6 mL of THF at 0 °C was added 1.35 g (3.1 mmol) of **5f** in 4 mL of THF (the reaction would not proceed in Et_2O). After reflux for 4 h, the reaction was cooled and quenched with 0.4 mL of H_2O, 0.4 mL of 15% NaOH, and 1.2 mL of H_2O to give a solid that was extracted with refluxing ether (2×) and refluxing THF (3×), which gave after solvent removal 1.10 g of crude product (a 32:68 mixture of **2f** and allene **7** by GC analysis). Chromatography[46] (5% EtOAc/hexane) gave 0.417 g (30%) of **2f** and 0.437 g (35%) of allene **7**. **7**: ^1H NMR ($CDCl_3$) δ 5.40 (m, 2 H), 5.20 (m, 1 H), 2.70 (d, 2 H), 1.75–2.50 (m, 5 H), 1.20–1.70 (m, 14 H), 1.10 (d, 6 H, J = 6.6 Hz); ^{13}C NMR ($CDCl_3$) δ 200.03, 131.71, 130.12, 103.84, 98.86, 38.58, 30.85, 29.52, 28.43, 26.91, 26.26, 26.15, 25.68, 25.37, 24.98, 24.80, 22.82, 22.71; IR (neat) 2920, 2850, 1940, 1445, 970 cm^{-1}; mass spectrum, m/e 246.2345 (calcd for $C_{18}H_{30}$, 246.2347). **2f**: ^1H NMR ($CDCl_3$) δ 5.60 (m, 2 H), 5.40 (m, 2 H), 2.25 (d overlapping m, 3 H), 2.00 (m, 3 H), 1.15–1.75 (m, 16 H), 1.05 (d, 6 H, J = 7 Hz); ^{13}C NMR ($CDCl_3$) δ 135.36, 134.57, 133.93, 126.12, 74.25, 43.11, 38.18, 32.27, 30.79, 27.56 (2×), 27.39, 24.87, 24.56, 22.48 (2×), 19.28; IR (neat) 3400, 3010, 2920, 2860, 1450, 975, 785, 760 cm^{-1}; mass spectrum, m/e 264.2460 (calcd for $C_{18}H_{32}O$ 264.2453).

1-(3-Methyl-*trans*-butenyl)-*trans*-cyclotridec-3-en-1-ol (2f) from Allene 7. A 5-mL portion of THF was added to 0.556 g (1.74 mmol) of $Hg(OAc)_2$ in 9 mL of H_2O, which resulted in a yellow color. Then 0.430 g of the allene **7** in 4 mL of THF was added. The color completely faded after 35 min. After a further 25 min, 9 mL of 3 M NaOH was added (orange color), which was followed by 9 mL of $NaBH_4$ in 3 M NaOH (gray color). Standard workup gave 0.696 g of the crude product, which was purified[47] to give 0.167 g (36%) of alcohol **2f**: ^1H NMR ($CDCl_3$) δ 5.65 (m, 2 H), 5.45 (m, 2 H), 2.30 (d overlapping m, 3 H), 2.05 (m, 3 H), 1.20–1.75 (m, 16 H), 1.10 (d, 6 H, J = 7 Hz); ^{13}C NMR ($CDCl_3$) δ 135.45, 134.67, 133.93, 126.12, 74.33, 43.17, 38.23, 32.31, 30.84, 27.60 (2×), 27.43, 24.97, 24.90, 24.60, 22.52, 19.33; IR (neat) 3350, 3020, 2930, 2860, 1460, 975, 790, 765 cm^{-1}; mass spectrum, m/e 264.2445 (calcd for $C_{18}H_{32}O$ 264.2453).

1-(2-Chloroethynyl)-*trans*-cyclotridec-3-en-1-ol (5g). To a solution of 0.805 g (8.30 mmol) of trans-1,2-dichloroethene in 2 mL of dry ether at 0 °C was added 4.07 mL (0.41 mmol) of 1.02 M MeLi. After the mixture was stirred at 0 °C for 40 min, 0.806 g (4.15 mmol) of **1** in 5 mL of dry ether was added. After 1.5 h at 25 °C, the reaction was cooled and quenched with saturated NH_4Cl. Standard workup gave 1.09 g of an orange liquid. A small amount was purified for the spectra of **5g**: ^1H NMR ($CDCl_3$) δ 5.45 (m, 2 H), 2.45 (d, 2 H), 2.00 (m, 3 H), 1.15–1.60 (m, 16 H); ^{13}C NMR ($CDCl_3$) δ 135.86, 124.62, 73.25, 71.07, 62.33, 44.45, 38.89, 32.23, 27.54, 27.41, 27.18, 24.94, 24.86, 24.60, 19.67; IR (neat) 3300, 2920, 2850, 2220, 1450, 1020, 980 cm^{-1}; mass spectrum, m/e 254.1457 (calcd for $C_{15}H_{23}OCl$ 254.1437).

1-(*trans*-2-Chloroethenyl)-*trans*-cyclotridec-3-en-1-ol (2g). To a solution of 0.231 g (0.9 mmol) of crude **5g** in 5 mL of dry ether at 0 °C was added 0.25 g (6.5 mmol) of $LiAlH_4$. After 3 h of reflux, the reaction was treated as described for **5b**, which gave 0.139 g of product. Chromatography[46] gave 0.030 g (12%) of the pure **2g**, 0.012 g (5%) of alcohol **2u**, and 0.018 g (8%) of a product identified as **5u**. **2g**: ^1H NMR ($CDCl_3$) δ 6.15 (dd, 2 H, J = 13 Hz), 5.40 (m, 2 H), 2.30 (d, 2 H), 2.00 (m, 2 H), 1.10–1.70 (m, 17 H); ^{13}C NMR ($CDCl_3$) δ 139.89, 135.74, 124.75, 118.16, 75.10, 43.05, 38.12, 32.26, 27.77, 27.51, 27.32, 24.96, 24.76, 24.53, 19.16; IR (neat) 3360, 3090, 3020, 2940, 2860, 1640, 1450, 975, 945 cm^{-1}; mass spectrum, m/e 256.1593 (calcd for $C_{15}H_{25}OCl$ 256.1594). **2u**: ^1H NMR ($CDCl_3$) δ 4.90–6.40 (m, 2 H overlapping ABC pattern of 3 H), 2.25 (d, 2 H), 1.90 (m, 2 H), 1.05–1.70 (m, 17 H); ^{13}C NMR ($CDCl_3$) δ 145.09, 135.06, 125.70, 112.01, 74.98, 42.79, 37.82, 32.30, 27.57, 27.54, 27.41, 24.97, 24.85, 24.59, 19.24; IR (neat) 3360, 3080, 2920, 2860, 1660, 1445, 970, 930, 915, 780 cm^{-1}; high-resolution mass spectrum, m/e 222.1962 (calcd for $C_{15}H_{26}O$ 222.1983). **5u**: ^1H NMR ($CDCl_3$) δ 5.45 (m, 2 H), 2.50 (sharp s, 1 H, overlapping d, 2 H), 2.00 (m, 2 H), 1.15–1.65 (m, 17 H); ^{13}C NMR ($CDCl_3$) δ 135.78, 124.79, 88.11, 71.59, 70.39, 44.48, 38.84, 32.25, 27.57, 27.46, 27.23, 24.92, 24.88, 24.61, 19.68; IR (neat) 3360, 3320, 3030, 2930, 2860, 1450, 985, 970, 790, 760 cm^{-1}; mass spectrum, m/e 220.1836 (calcd for $C_{15}H_{24}O$ 220.1827).

General Procedure for KH/HMPA Rearrangement of 2a–f. The procedure described in our previous work[17] was used except that 2 equiv of KH was used rather than 3 equiv (see tables for conditions) and the reaction was monitored by GC on column B.

Anionic Rearrangement of 1-[1-(Trimethylsilyl)-ethenyl]-*trans*-cyclotridec-3-en-1-ol (2a). A 116-mg (0.4 mmol) sample of **2a** gave 89 mg of product (88:12 mixture of the 3,3/1,3 shift products without the Me_3Si group; i.e., ketones **3u** and **4u** were formed). 4-Ethenylcyclotridecanone (**3u**): ^1H NMR ($CDCl_3$) δ 4.90–5.84 (m, ABC pattern, 3 H), 2.30–2.50 (m, 4 H), 1.50–1.80 (m, 5 H), 1.20–1.50 (m, 14 H); ^{13}C NMR ($CDCl_3$) δ 212.49, 142.83, 114.28, 42.12, 40.68, 40.02, 30.97, 28.88, 26.40, 25.67, 25.66, 24.63, 24.30, 23.71, 23.08; IR (neat) 3075, 2915, 2860, 1705, 1630, 1450, 910 cm^{-1}; mass spectrum, m/e 222.2004 (calcd for $C_{15}H_{16}O$ 222.1983). *trans*-Cyclopentadec-5-enone (**4u**): ^1H NMR ($CDCl_3$) δ 5.25 (m, 2 H), 2.25–2.45 (m, 4 H), 1.90–2.00 (m, 4 H), 1.50–1.65 (m, 4 H), 1.10–1.40 (m, 12 H); ^{13}C NMR ($CDCl_3$) δ 212.49, 132.35, 130.20, 41.71, 41.37, 31.46, 30.71, 28.31, 27.27, 27.01, 26.85, 26.26 (2×), 24.81, 21.74; IR (neat) 2915, 2860, 1705, 1450, 970 cm^{-1}; mass spectrum, m/e 222.2009 (calcd for $C_{15}H_{26}O$ 222.1983).

Anionic Rearrangement of 1-(1-Methylethenyl)-*trans*-cyclotridec-3-en-1-ol (2b). A 98-mg (0.4-mmol) sample of **2b** gave 61 mg (62%) of product, which GC indicated to be a 82:18 mixture of the 3,3/1,3 shift products **3b** and **4b**. The 3,3-shift product **3b** was a 45:55 mixture of two diastereomers. 4-Ethenyl-2-methylcyclotridecanone (**3b**): ^1H NMR ($CDCl_2$) δ 4.85–5.85 (two overlapping complex ABC patterns, 3 H), 2.25–2.90 (m, 4 H), 1.85–2.05 (m, 2 H), 1.10–1.50 (m, 16 H), 1.10 and 1.00 (overlapping d, 3 H, J = 7 Hz); ^{13}C NMR ($CDCl_3$) δ 215.84, 215.47, 143.23, 142.61, 114.77, 113.73, 44.28, 44.13, 40.68, 40.31, 40.08, 39.74, 39.23, 38.53, 32.25, 30.07, 26.62, 26.16, 25.94, 25.90, 25.85, 24.85, 24.75, 24.49, 24.26, 24.13, 24.01, 23.22, 23.20, 21.84, 18.47, 18.08; IR (neat) 3080, 2930, 2860, 1710, 1630, 1455, 910 cm^{-1}; mass spectrum GC/MS using a 30-m SE-54 column gave M^+ of 236 for each separated isomer. The high-resolution data were obtained on the mixture of two isomers, m/e 236.2143 (calcd for $C_{16}H_{28}O$ 236.2181). 2-Methyl-*trans*-cyclopentadec-5-enone (**4b**): ^1H NMR ($CDCl_3$) δ 5.30–5.50 (m, 2 H), 2.30–2.70 (m, 3 H), 1.90–2.10 (m, 4 H), 1.60–1.85 (m, 2 H), 1.20–1.50 (m, 14 H), 1.10 (d, 3 H, J = 7 Hz); ^{13}C NMR ($CDCl_3$) δ 215.99, 131.97, 130.09, 44.11, 39.94, 31.48, 31.44, 29.12, 27.91, 27.12, 27.10, 26.70, 26.23, 25.98, 24.31, 15.66; IR (neat) 2940, 2860, 1710, 1455, 970 cm^{-1}; mass spectrum, m/e 236.2139 (calcd for $C_{16}H_{28}O$ 236.2181).

Anionic Rearrangement of *trans*- and *cis*-1-(1-Propenyl)-*trans*-cyclotridec-3-en-1-ol (2c, 2d). About 40-mg portions of **2c** and **2d** were reacted separately, and the products were purified by GC (see Table II for yields and composition). 4-Ethenyl-3-methylcyclotridecanone (**3c**; same as **3d**, a mixture of cis and trans diastereomers): ^1H NMR ($CDCl_3$) δ 4.85–6.40 (two overlapping complex ABC patterns, 3 H), 2.30–2.90 (m, 4 H), 2.95 (m, 1 H, 1.20–1.50 (m, 17 H), 0.92 and 0.88 (overlapping d, 3 H, J = 6 Hz); ^{13}C NMR ($CDCl_3$) δ 195.96, 140.71, 139.15, 116.27, 114.96, 114.92, 48.91, 47.07, 45.40, 44.12, 41.94, 41.67, 33.40, 31.67, 30.33, 26.12, 25.97 (2×), 25.75, 25.44 (2×), 25.14, 24.86, 24.34, 24.23, 23.86 (2×), 23.63, 22.10, 16.91, 16.11 (only one carbonyl peak observed); IR (neat) 3080, 2940, 2860, 1705, 1635, 1455, 1440, 990, 910 cm^{-1}; mass spectrum GC/MS using a 6 ft × 0.125 in. HNU Permabond DEGS column gave M^+ of 236 for each separate isomer. The high-resolution data were obtained on a mixture of the two isomers, m/e 236.2144 (calcd for $C_{16}H_{28}O$ 236.2140). 3-Methyl-*trans*-cyclopentadec-5-enone (**4c**, same as **4d**): ^1H NMR ($CDCl_3$) δ 5.35 (m, 2 H), 2.30 (m, 4 H), 2.00 (m, 4 H), 1.10–1.50 (m, 15 H), 0.90 (d, 3 H, J = 6 Hz); ^{13}C NMR ($CDCl_3$) δ 132.61, 129.54, 49.17, 41.12, 39.73, 31.43, 28.31, 27.20, 26.94, 26.74, 26.23,

26.20, 26.13, 24.49, 21.26 (the carbonyl peak not observed); IR (neat) 2940, 2860, 1710, 1460, 1440, 975 cm^{-1}; mass spectrum, *m/e* 236.2140 (calcd for $C_{16}H_{28}O$ 236.2140).

Attempted Anionic Rearrangement of 1-[*trans*-2-(Trimethylsilyl)ethenyl]-*trans*-cyclotridec-3-en-1-ol (2e). A 113-mg (0.38-mmol) sample of **2e** gave 53 mg (42%) of product, which was purified by GC. Spectral analysis of the purified material revealed it to be the starting alcohol[25] without the trimethylsilyl group, i.e., **2u**.

Anionic Rearrangement of 1-(3-Methyl-*trans*-butenyl)-*trans*-cyclotridec-3-en-1-ol (2f). An 82-mg (0.3-mmol) sample of **2f** gave 57 mg (69%) of product, which GC indicated to be a 27:38:35 ratio of the products **3f**, **9**, and **4f**. Furthermore, **3f** was found to be a 47:53 mixture of two diastereomers. 4-Ethenyl-3-isopropylcyclotridecanone (**3f**): ^1H NMR ($CDCl_3$) δ 4.85–5.75 (two overlapping complex ABC patterns, 3 H), 1.80–2.80 (m, 5 H), 1.45–1.75 (m, 4 H), 1.16–1.50 (m, 14 H), 0.8 and 0.9 (two overlapping m, 6 H); ^{13}C NMR ($CDCl_3$) δ 211.99, 211.18, 141.89, 140.21, 115.19, 114.91, 49.44, 44.06, 42.47, 42.27, 42.11, 41.50, 41.44, 41.16, 30.97, 30.91, 30.14, 27.79, 26.60, 26.07, 26.02, 25.82, 25.78, 25.69, 24.82, 24.68, 24.64, 24.48, 23.72, 23.38, 23.18, 23.23, 21.77, 21.52, 20.99, 15.59; IR (neat) 3060, 2930, 2860, 1710, 1640, 1460, 1385, 1000, 910 cm^{-1}; mass spectrum, *m/e* 264.2494 (calcd for $C_{18}H_{32}O$ 264.2453. 2-Methylheptadeca-2,15-dien-5-one (**9**): ^1H NMR ($CDCl_3$) δ 5.40 (m, 2 H), 5.25 (m, 1 H), 3.05 (d, 2 H), 2.40 (t, 2 H), 1.90 (m, 2 H), 1.70 (s, 3 H), 1.60 (s, overlapping a d, 6 H), 1.15–1.40 (m, 14 H); ^{13}C NMR ($CDCl_3$) δ 209.85, 135.53, 131.63, 124.51, 116.08, 42.59, 42.25, 32.56, 29.57, 29.43, 29.40, 29.36, 29.20, 29.13, 25.69, 23.83, 18.00, 17.88; IR (neat) 2925, 2860, 1710, 1450, 1380, 970 cm^{-1}; mass spectrum, *m/e* 264.2494 (calcd for $C_{18}H_{32}O$ 264.2453). 3-Isopropyl-*trans*-cyclopentadec-5-enone (**4f**): ^1H NMR ($CDCl_3$) δ 5.30 (m, 2 H), 2.10–2.50 (m, 4 H), 1.70–2.00 (m, 4 H), 1.40–1.70 (m, 4 H), 1.10–1.40 (m, 12 H), 0.83 (d, 3 H, J = 6.7 Hz), 0.76 (d, 3 H, J = 6.9 Hz); ^{13}C NMR ($CDCl_3$) δ 211.82, 132.38, 130.26, 45.03, 41.39, 38.11, 33.80, 31.33, 31.26, 28.26, 27.10, 26.84, 26.60, 26.03, 26.00, 23.76, 20.10, 18.48; IR (neat) 3025, 2925, 2860, 1710, 1450, 1375, 990 cm^{-1}; mass spectrum, *m/e* 264.2494 (calcd for $C_{18}H_{32}O$ 264.2453).

Attempted Anionic Rearrangement of 4-Ethenyl-3-isopropylcyclotridecanone (3f). A mixture of 8 mg (7.9 mmol) of 24% KH (washed with hexane to remove the oil), 0.006 g (0.2 mmol) of ketone **3f**, and 1 mL of HMPA was stirred at 25 °C for 55 min, 90 min at 100 °C, and then 90 min at 137 °C. Aliquots analyzed by GC showed only starting ketone **3f**. Standard workup gave 3 mg (44%) of **3f**.

General Procedure for the Preparation of the Trimethylsilyl Derivatives of Alcohols. A 0.2–1.0-mmol portion of the alcohol dissolved in about 2 mL of pyridine was added to 5–10 mL of silylating mixture (pyridine, hexamethyldisilazane (HMDS), and chlorotrimethylsilane in a 10:2:1 ratio). After 15 h at 25 °C, the reaction mixture was taken up in 20 mL of hexane, washed three times with H_2O and twice with 5% H_2SO_4 solution, and then given the standard workup. The impure compound was then purified[46] (5% EtOAc/hexane) by column chromatography or by vacuum transfer in some cases.

1-(Trimethylsiloxy)-1-[1-(trimethylsilyl)ethenyl]-*trans*-cyclotridec-3-ene (2a-Me_3Si) was obtained in 62% yield: ^1H NMR ($CDCl_3$) δ 5.63 (d, 1 H, J = 1.6 Hz), 5.49 (d, 1 H, J = 1.6 Hz), 5.41 (m, 2 H), 2.45 (d, 2 H), 2.00 (m, 2 H), 1.15–1.55 (m, 16 H), 0.40 (s, 9 H), 0.30 (s, 9 H); ^{13}C NMR ($CDCl_3$) δ 158.35, 134.52, 127.18, 123.81, 82.16, 43.44, 38.36, 32.41, 27.69, 27.52, 27.39, 25.07 (2×), 24.94, 19.83, 2.96, 1.12; IR (neat) 3060, 2940, 2860, 1450, 1260, 1050, 980, 940, 830, 760, 690 cm^{-1}; mass spectrum, *m/e* 366.2812 (calcd for $C_{21}H_{42}OSi_2$ 366.2835).

1-(Trimethylsiloxy)-(1-methylethenyl)-*trans*-cyclotridec-3-ene (2b-Me_3Si) was obtained in 70% yield: ^1H NMR ($CDCl_3$) δ 5.40 (m, 2 H), 4.90 (br s, 2 H), 2.45 (d, 2 H), 2.00 (m, 2 H), 1.80 (s, 3 H), 1.15–1.50 (m, 16 H), 0.15 (s, 9 H); ^{13}C NMR ($CDCl_3$) δ 149.49, 134.18, 126.88, 111.32, 79.39, 40.68, 36.44, 32.51, 27.85, 27.77, 27.42, 24.99 (2×), 24.77, 24.48, 19.20, 2.22; IR (neat) 3045, 2930, 2860, 1635, 1445, 1250, 1050, 975, 835, 755 cm^{-1}; mass spectrum, *m/e* 308.2538 (calcd for $C_{19}H_{36}OSi$ 308.2582).

1-(Trimethylsiloxy)-1-(*cis*-1-propenyl)-*trans*-cyclotridec-3-ene (2c-Me_3Si) was obtained in 75% yield: ^1H NMR ($CDCl_3$) δ 5.25–5.40 (m, 4 H), 2.35 (br d, 2 H, J = 4 Hz), 1.95 (m, 2 H), 1.80 (d, 3 H, J = 6 Hz), 1.1–1.6 (m, 16 H), 0.10 (s, 9 H); ^{13}C NMR ($CDCl_3$) δ 136.78, 134.23, 126.85, 126.46, 77.98, 44.55, 39.94, 32.48, 27.87, 27.71, 27.39, 24.98 (2×), 24.56, 19.31, 14.93, 2.45; IR (neat) 3020, 2925, 2850, 1440, 1250, 1045, 970, 840, 750 cm^{-1}; mass spectrum, *m/e* 308.2539 (calcd for $C_{19}H_{36}OSi$ 308.2535).

1-(Trimethylsiloxy)-1-(*trans*-1-propenyl)-*trans*-cyclotridec-3-ene (2d-Me_3Si) was obtained in 58% yield: ^1H NMR ($CDCl_3$) δ 5.55 (m, 2 H), 5.35, (m, 2 H), 2.30 (br d, 2 H, J = 4 Hz), 2.00 (m, 2 H), 1.75 (d, 3 H, J = 3 Hz), 1.10–1.70 (m, 16 H), 0.10 (s, 9 H); ^{13}C NMR ($CDCl_3$) δ 138.52, 133.98, 126.89, 123.39, 77.22, 42.76, 38.46, 32.45, 27.80, 27.74, 27.45, 25.01 (2×), 24.57, 19.16, 17.89, 2.64; IR (neat) 3020, 2920, 2840, 1430, 1240, 1045, 975, 830, 745 cm^{-1}; mass spectrum, *m/e* 308.2531 (calcd for $C_{19}H_{36}OSi$ 308.2535).

1-(Trimethylsiloxy)-1-(*trans*-2-(trimethylsilyl)-ethenyl)-*trans*-cyclotridec-3-ene (2e-Me_3Si) was obtained in 76% yield: ^1H NMR ($CDCl_3$) δ 6.05 (d, 1 H, J = 19.2 Hz), 5.75 (d, 1 H, J = 19.2 Hz), 5.30 (m, 2 H), 2.25 (br d, 2 H, J = 4 Hz), 1.80 (m, 2 H), 1.10–1.50 (m, 16 H), 0.05 (s, 18 H); ^{13}C NMR ($CDCl_3$) δ 152.51, 134.16, 126.95, 126.62, 78.51, 42.15, 37.93, 32.45, 27.75 (2×), 27.42, 25.02 (2×), 24.58, 19.12, 2.74, −1.31; IR (neat) 2940, 2860, 1600, 1450, 1440, 1240, 1050, 990, 970, 860, 830 cm^{-1}; mass spectrum, *m/e* 366.2776 (calcd for $C_{21}H_{42}OSi_2$ 366.2774).

1-(Trimethylsiloxy)-1-(3-methyl-*trans*-butenyl)-*trans*-cyclotridec-3-ene (2f-Me_3Si) was obtained in 91% yield: ^1H NMR ($CDCl_3$) δ 5.45 (m, 2 H), 5.35 (m, 2 H), 2.50 (d, 2 H), 1.90 (m, 2 H), 1.10–1.60 (m, 17 H), 1.00 (d, 6 H, J = 7 Hz), 0.10 (s, 9 H); ^{13}C NMR ($CDCl_3$) δ 135.68, 134.16, 133.93, 126.89, 77.17, 42.67, 38.53, 32.45, 31.07, 27.75 (2×), 27.43, 25.02 (2×), 24.57, 22.35 (2×), 19.18, 2.73; IR (neat) 2920, 2860, 2860, 1450, 1250, 1050, 970, 840, 750 cm^{-1}; mass spectrum, *m/e* 336.2680 (calcd for $C_{21}H_{40}OSi$ 336.2848).

1-(Trimethylsiloxy)-1-(*trans*-2-chloroethenyl)-*trans*-cyclotridec-3-ene (2g-Me_3Si) was obtained in 72% yield: ^1H NMR ($CDCl_3$) δ 6.05 (dd, 2 H, J = 13.5), 5.70 (m, 2 H), 2.50 (d, 2 H), 2.00 (m, 2 H), 1.10–1.60 (m, 16 H), 0.15 (s, 9 H); ^{13}C NMR ($CDCl_3$) δ 140.44, 135.06, 125.60, 118.20, 77.50, 42.83, 38.24, 32.39, 27.62, 27.58, 27.34, 24.97, 24.90, 24.50, 19.09, 2.53; IR (neat) 3090, 2940, 2880, 1620, 1450, 1260, 1060, 985, 950, 850, 770 cm^{-1}; mass spectrum, *m/e* 328.1990 (calcd for $C_{18}H_{33}OSiCl$ 328.1989).

General Procedure for the Pyrolysis of the Trimethylsilyl Derivatives of the Alcohols. The silyl derivatives of the alcohols were dissolved in a few drops of ether and then introduced into an ampule. The ether was removed under vacuum, and the ampule was sealed under vacuum. About 30–60 mg of the material was pyrolyzed at a time. The pyrolysis was carried out at 310–325 °C by placing the sealed ampule in an aluminum block oven maintained by a ProportioNul temperature controller. At the appropriate time (see tables), the ampule was cooled and cut open and its contents rinsed out with CCl_4. The IR spectra of the crude pyrolysis mixtures obtained from **2c**-Me_3Si, **2d**-Me_3Si, and **2e**-Me_3Si showed the trimethylsilyl enol ether bands near 1600 cm^{-1}, and their ^1H NMR showed two doublets that presumably correspond to the *E* and *Z* isomers about the enol ether: products from **2c**-Me_3Si or **2d**-Me_3Si δ 4.45 (J = 8 Hz) and 4.25 (J = 8 Hz); products from **2e**-Me_3Si δ 4.45 (J = 11 Hz) and 4.10 (J = 8 Hz). Pyrolysis of **2f**-Me_3Si gave a crude mixture: ^1H NMR ($CDCl_3$) δ 5.00–6.00 (complex m, 5 H), 2.5–3.0 (m, 1 H), 1.75–2.50 (m, 6 H), 1.10–1.65 (m, 16 H), 1.00 (d, 6 H); IR (neat) 2940, 2870, 1450, 970 cm^{-1}. Pyrolysis of **2g**-Me_3Si gave a crude mixture: ^1H NMR ($CDCl_3$) δ 7.10 (s, 1 H), 2.00–2.80 (m, 6 H), 1.20–2.00 (m, 15 H), 0.80–1.15 (m, 2 H), 0.10–0.45 (m, 1 H); IR (neat) 2930, 2850, 1705, 1450, 810 cm^{-1}.

Hydrolysis of pyrolysis products was carried out as described earlier.[35] The spectra of the compounds were identical with the ones obtained from the anionic rearrangements with one additional compound, 3-(trimethylsilyl)-*trans*-cyclopentadec-5-enone (**4e**), which was obtained in 52% yield: ^1H NMR ($CDCl_3$) δ 5.25 (m, 2 H), 2.25–2.55 (m, 4 H), 1.90–2.25 (m, 4 H),1.10–1.75 (m, 14 H), 0.05 (m, 1 H), 0.00 (s, 9 H); ^{13}C NMR ($CDCl_3$) δ 211.52, 131.96, 131.00, 43.01, 41.31, 32.58, 31.19, 28.25, 27.05, 26.85, 26.55, 25.99, 25.87, 23.62, 18.82, −3.00; IR (neat) 3020, 2940, 2870, 1720, 1450, 1250, 970, 860, 840, 750, 690 cm^{-1}; mass spectrum, *m/e* 294.2384 (calcd for $C_{18}H_{34}OSi$ 294.2379).

3-Methylcyclopentadecan-1-one (Muscone; 8). A mixture of 48.4 mg (0.20 mmol) of **4c**, 1 mL of ether, and 2 mg of PtO_2 was stirred under H_2 for 3 h while being monitored by GC.

Filtration and removal of solvent gave 34.8 mg (71%) of 8, which was purified by preparative GC. The pure compound so obtained was found to be identical in GC retention time, ^{1}H NMR, IR and mass spectra with that of an authentic sample.[36]

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Conformational Analysis of 1,3-Dioxanes with Sulfide, Sulfoxide, and Sulfone Substitution at C(5). Finding an Eclipsed Conformation in *cis*-2-*tert*-Butyl-5-(*tert*-butylsulfonyl)-1,3-dioxane

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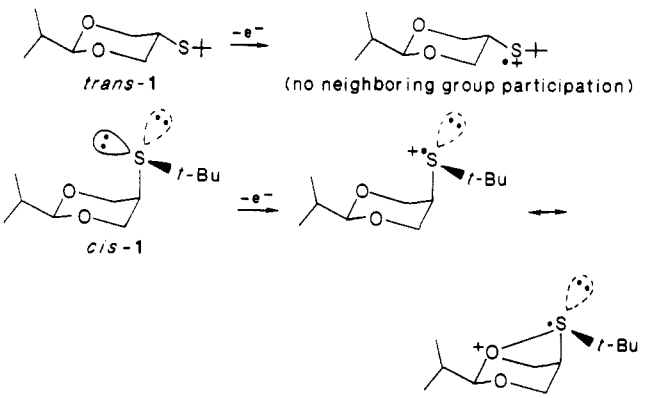
The positions of equilibrium, established by acid catalysis, between diastereomeric *cis*- and *trans*-5-(*tert*-butylthio)- (1), 5-(*tert*-butylsulfinyl)- (2), and 5-(*tert*-butylsulfonyl)-2-isopropyl-1,3-dioxanes (3) are reported and compared with previously published data for the 5-methylthio (4), 5-methylsulfinyl (5), and 5-methylsulfonyl (6) analogues. Although $\Delta G°$ values for the sulfides 1 and 4 are very similar, the difference in conformational behavior for sulfoxides 2 and 5 is significant, and the effect of changing from methyl to *tert*-butyl in the sulfones (6 → 3) is quite dramatic: the large preference of the methyl analogue for the axial position (1.19 kcal/mol) is reversed in 3 where the equatorial isomer is more stable by 1.14 kcal/mol. The conformational behavior in 1–6 is discussed in terms of the rotamer population of the axial isomer, in which steric and electrostatic effects are dominant. X-ray crystallographic data on *cis*-2-*tert*-butyl-5-(*tert*-butylsulfonyl)-1,3-dioxane (*cis*-9, axial sulfonyl) show that the *S*-*tert*-butyl group is outside the ring, with both sulfonyl oxygens above the dioxane ring and eclipsing the endocyclic C–C bonds. The electrochemical behavior of *cis*-1 and *trans*-1 supports the idea that lone-pair/lone-pair electron repulsion is responsible for the large predominance of the equatorial isomer.

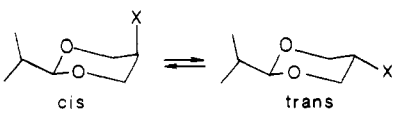
Several years ago, Eliel and Evans reported the conformational equilibrium of 5-(methylthio)-1,3-dioxane,[2] which shows a marked preference for the equatorial conformation ($\Delta G°$ = −1.82 kcal/mol in cyclohexane). Because this value is more negative than the corresponding value for (methylthio)cyclohexane (−1.00 to −1.07 kcal/mol[3]), a repulsive interaction of the m-shell electrons of sulfur with the p electrons of the ring oxygens was proposed.[4] On the other hand, Wilson et al.[5] observed that the electrochemical oxidation of aliphatic thioethers is significantly facilitated by suitably disposed electron-rich neighboring groups that experience lone-pair/lone-pair repulsion.

With this information, it was deemed of interest to measure the oxidation potentials of *cis*- and *trans*-2-isopropyl-5-(*tert*-butylthio)-1,3-dioxanes (*cis*-1 and *trans*-1), the 2-isopropyl group acting as an effective holding group for the 1,3-dioxane ring[6] and the *tert*-butyl group ensuring that at least one electron pair on sulfur in *cis*-1 is pointing into the ring and suitably disposed for lone-pair/lone-pair interaction (Scheme I) such that the electron/electron destabilizing interaction may be replaced by electrostatic attraction, or even bond formation on electron removal.[7]

Scheme I



Scheme II



1, X = S-*t*-Bu
2, X = S(O)-*t*-Bu
3, X = SO_2-*t*-Bu
4, X = SMe
5, X = S(O)Me
6, X = SO_2Me
7, *t*-Bu instead of *i*-Pr, X = S-*t*-Bu
8, *t*-Bu instead of *i*-Pr, X = S(O)-*t*-Bu
9, *t*-Bu instead of *i*-Pr, X = SO_2-*t*-Bu

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