Intramolecular Alkoxide Induced Heterolysis of Perhydronaphthalene-1,4-diol Monosulfonate Esters through Orbital Interactions over Three C–C Single Bonds

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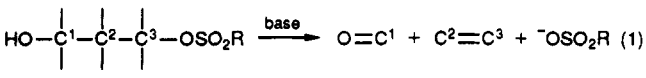
The course of the reactions that occur when stereochemically rigid *trans*-perhydronaphthalene-1,4-diol monosulfonate esters (1–4) are treated with alkali metal *tert*-amylate in refluxing benzene depends on the relative orientation of the leaving group and the tertiary hydroxyl group. An equatorial sulfonate ester group favors homofragmentation leading to the cyclopropane derivative **15**. In case of an axial sulfonate ester group β-elimination, which strongly depends on the stereochemistry of the tertiary deprotonated hydroxyl group, is the main reaction path. The O-silylated mesylates **5** and **6** show no reaction at all upon treatment with strong base; fast reactions are observed when **5** and **6** are treated with TBAF. Generation of an alcoholate is crucial for the observed reactions. Homofragmentation and an internal return reaction with inversion of configuration of the mesylate group in the axial mesylates **1** and **3** is explained by assuming a stabilized 1,3-bridged intermediate carbocation. This also explains why the equatorial mesylates react slightly faster than the axial mesylates. The reactivity of the α-mesylates is controlled by through-bond induction alone, whereas the reactivity of the corresponding β-mesylates is determined by the sum of a through-bond and a through-space (1,3-bridging) interaction.

Introduction

Although an extensive literature on theoretical and experimental studies of through-bond and through-space orbital interactions exists,[1] there are relatively few examples of the chemical consequences of orbital interactions through C–C single bonds.[2] The best-known example is probably the heterolytic Grob fragmentation,[3] which is almost certainly the result of orbital interactions through three σ-bonds.[4]

The base-induced fragmentation of cyclic 1,3-diol monosulfonate esters, known as the Wharton reaction,[5] is an typical example of the Grob fragmentation. In the Wharton reaction the compounds can undergo olefin-forming fragmentation with release of an electrofugal carbonyl fragment (eq 1). In this instance the base does not play its usual role in elimination reactions but instead serves to remove a proton from the hydroxyl group, which enables the sulfonate ester group to come off more easily since O^- is a powerful electron donor.



It has been shown that stereochemical[6] and stereoelectronic[7] factors are important in this reaction. A fast concerted fragmentation process requires the antiperiplanarity of the bonds undergoing cleavage (C(1)–C(2) and C(3)–OSO_2R in eq 1). A stepwise pathway involving an intermediate carbocation may occur if a gauche relationship exists between these bonds. In this case the compounds react slower and may undergo typical cationic reactions such as β-elimination and/or interception by nucleophiles in addition to, or instead of, fragmentation.

These considerations raised the question whether the same or different effects would be observed when (cyclic *1,4-diol* monosulfonate esters are treated with base.[8] In these compounds the carbinol group is separated from the nucleofugal sulfonate ester group by an additional carbon atom.

From our previous work on the total synthesis of sesquiterpenes,[9,10] it is known that cyclic 1,4-diol monosulfonate esters react smoothly upon treatment with sodium *tert*-amylate in refluxing apolar solvents like benzene or toluene to give rearrangement and/or elimination products. The examples most relevant to the present work are the base-induced elimination reactions of the mesylates **1** and **2**, which both afford the olefin **13** as the main product.[10] A concerted intramolecular alkoxide-induced anti elimination mechanism[11,12] might explain the fast and almost selective formation of **13** from **1**. On the other hand, the preferential formation of **13** from **2** must proceed via a syn elimination. Normally, anti elimination is much faster than syn elimination in fixed six-membered ring systems. The elimination rate of **1** and **2**, however, was practically the same. These results

(1) For example, see: (a) Hoffman, R. *Acc. Chem. Res.* **1971**, *4*, 1. (b) Gleiter, R. *Angew. Chem., Int. Ed. Engl.* **1974**, *13*, 696. (c) Martin, H.-D.; Mayer, B. *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 283. (d) Paddon-Row, M. N.; Jordan, K. D. In *Modern Models of Bonding and Delocalization*; Liebman, J. F., Greenberg, A., Eds.; VCH Publishers: New York, 1988, Chapter 3.

(2) (a) Paddon-Row, M. N.; Hartcher, R. *J. Am. Chem. Soc.* **1980**, *102*, 662 and 671. (b) Adcock, W.; Coope, J.; Shiner, V. J., Jr.; Trout, N. A. *J. Org. Chem.* **1990**, *55*, 1411.

(3) Grob, C. A. *Angew. Chem.* **1969**, *81*, 543.

(4) Gleiter, R.; Stohrer, W.-D.; Hoffman, R. *Helv. Chim. Acta* **1972**, *55*, 893.

(5) For an extensive review of the Wharton reaction, see: Caine, D. *Org. Prep. Proced. Int.* **1988**, *20*, 1.

(6) Wharton, P. S.; Hiegel, G. A. *J. Org. Chem.* **1965**, *30*, 3254.

(7) Deslongchamps, P. *Stereoelectronic Effects in Organic Chemistry*; Pergamon Press: Oxford, 1983; pp 259–261.

(8) To our knowledge, no previous reports on this subject are known.

(9) Wijnberg, J. B. P. A.; Jenniskens, L. H. D.; Brunekreef, G. A.; de Groot, Ae. *J. Org. Chem.* **1990**, *55*, 941.

(10) Jenniskens, L. H. D.; Wijnberg, J. B. P. A.; de Groot, Ae. *J. Org. Chem.* **1991**, *56*, 6585.

(11) Menger, F. M.; Chow, J. F.; Kaiserman, H.; Vasquez, P. C. *J. Am. Chem. Soc.* **1983**, *105*, 4996.

(12) Lansbury, P. T.; Mojica, C. A. *Tetrahedron Lett.* **1986**, *27*, 3967.

0022-3263/93/1958-1199$04.00/0

Scheme I

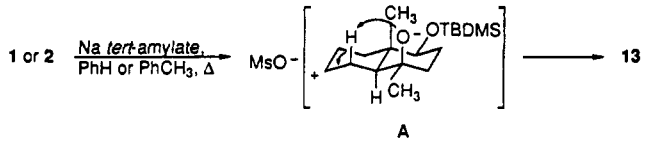


Chart I

1: R^1 = OH; R^2 = CH_3 2: R^1 = OH; R^2 = CH_3
3: R^1 = CH_3; R^2 = OH 4: R^1 = CH_3; R^2 = OH
5: R^1 = CH_3; R^2 = OTMS 6: R^1 = CH_3; R^2 = OTMS

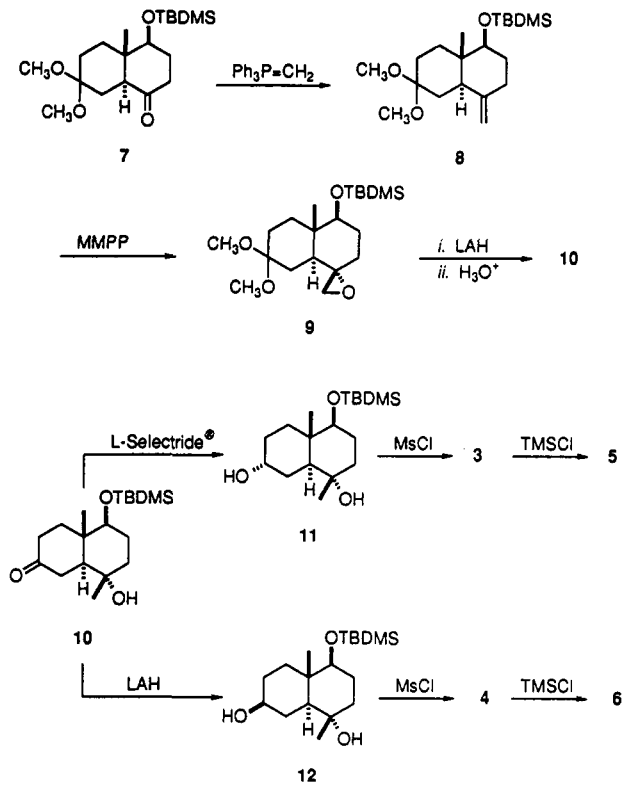
have led to the conclusion that both the anti and the syn elimination probably proceed via an identical mechanism in which the deprotonation of the hydroxyl group is the crucial and rate-limiting factor.[13] In refluxing benzene or toluene deprotonation of the hydroxyl group is thought to be attended with ionization of the sulfonate ester bond leading to the dipolar intermediate A (Scheme I). In this intermediate the carbocationic center will facilitate elimination[14] with the intramolecular process as the most favorable one.

The ionization of the sulfonate ester bond, induced by deprotonation of the hydroxyl group, can only be rationalized by assuming a long-range orbital interaction that couples the alkoxide group and the nucleofugal sulfonate ester group through the intervening C–C single bonds. Furthermore, in the context of this paper it is important to note that during the elimination reaction of **2** some side products were formed. In our primary experiments the interest was focused on an optimum yield of the olefin **13** and little attention was paid to the presence of these side products. However, a more careful examination revealed the presence of a fragmentation product, whose identity was established as **15** (vide infra). This result stimulated us to examine the reactivity of this type of cyclic 1,4-diol monosulfonate ester under strongly basic conditions in more detail. In addition to **1** and **2**, the mesylates **3** and **4** (Chart I) were investigated to obtain more information about the stereochemical factors in these reactions. The O-silylated mesylates **5** and **6** were subjected to strongly basic conditions as well in order to gather more evidence for our assumption that deprotonation of the hydroxyl group induces ionization of the sulfonate ester bond. Finally, experiments were performed to affect the electron-donating ability of the alkoxide group in order to determine the impact on reaction rate and product composition in these processes. In this paper we describe in detail the results of these studies.

Results and Discussion

The mesylates **1** and **2** were prepared from the readily available monoacetalized TBDMS-ether **7** as described.[10] For the synthesis of the mesylates **3** and **4**, compound **7** was converted into **8** via a Wittig condensation with $Ph_3P{=}CH_2$ in DMSO (Scheme II). Epoxidation of **8** with MMPP in a mixture of trimethyl orthoformate and

Scheme II



MeOH[15] gave the epoxy acetal **9**. After reduction of **9** with $LiAlH_4$ in refluxing THF and subsequent hydrolysis of the dimethyl acetal function, the ketone **10** was obtained. Reduction of **10** with L-Selectride (Aldrich) in THF at −78 °C[16] afforded exclusively the secondary 7α-alcohol **11**. For the preparation of the 7β-alcohol **12**, the ketone **10** was reduced with $LiAlH_4$ in THF at room temperature. Treatment of the alcohols **11** and **12** with MsCl in pyridine provided the mesylates **3** and **4**, respectively, in high yield. Reaction of **3** and **4** with TMSCl in combination with HMDS produced the O-silylated mesylates **5** and **6**, respectively. The axial hydroxyl group of **1** and **2** could not be silylated under these conditions, probably as a result of steric hindrance of the angular methyl group at C(4a).

In order to obtain comparable data about the effects of strong bases on the reactivity of the mesylates **1**–**6**, all compounds were subjected to the same reaction conditions. The reactions were run in benzene at reflux temperature with ca. 5 equiv of sodium *tert*-amylate. Apart from sodium *tert*-amylate, also lithium *tert*-amylate and sodium *tert*-amylate in combination with 15-crown-5 were used. A reaction time of 10 min was maintained in all cases, unless otherwise noted. Except for the reactions in which 15-crown-5 was used, the reaction time of 10 min was too short to complete the reactions. By comparing the quantities of recovered starting material, a rough estimate of the relative reaction rates could be obtained. The results of these studies are collected in Table I.

The initial reactions of the mesylates **1**-**4** with sodium *tert*-amylate in refluxing benzene (entries 1–4) were performed to investigate the influence of the stereochemistry of the hydroxyl and sulfonate ester group on the course of the reaction. The α-mesylate **1** gave a 12:1 mixture (78%) of the olefins **13** and **14** (Chart II), respectively, together with 18% of recovered **1**. The olefins

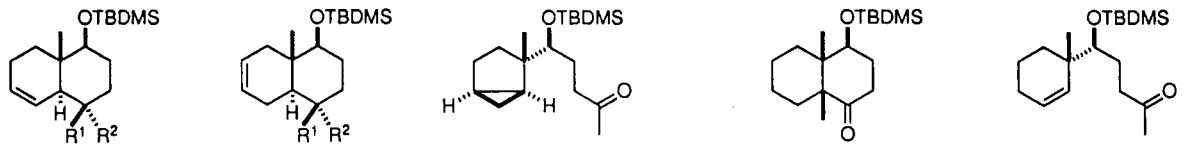
(13) In both cases the reaction rate was dependent on the base concentration; unpublished results.
(14) Bordwell, F. G. *Acc. Chem. Res.* **1972**, *5*, 374.
(15) Kesselmans, R. P. W.; Wijnberg, J. B. P. A.; de Groot, Ae.; de Vries, N. K. *J. Org. Chem.* **1991**, *56*, 7232.
(16) Brown, E.; Lebreton, J. *Tetrahedron* **1987**, *43*, 5827.

Table I. Reactions of the Mesylates 1–6 with Alkali-Metal *tert*-Amylate or TBAF

entry	mesylate	conditions[b]	products, % yield[a] 13 = 14[c]	15	16 = 17[c]	18	other	recov of mesylate, yield %[d]
1	1	A	78 (12:1)					18
2	2	A	53 (6.5:1)	22				8
3	3	A		2	58 (2.8:1)	4	*e*	24
4	4	A		69	7.5 (2.2:1)	2		8
5	5	A (3 h)						96
6	6	A (3 h)						98
7	2	B	7 (1.2:1)	1				84
8	2	B (3 h)	72 (1.2:1)	5				
9	4	B		5		3		91
10	4	B (7 h)		20	23 (1.2:1)	22		
11	1	C	98 (60:1)					
12	2	C	20 (8.5:1)	54				
13	3	C			100 (1:10)			
14	4	C		83	2 (1:2)	1.5		
15	5	C (24 h)					*f*	53
16	6	C (24 h)						84
17	5	D			78 (1:1)			
18	6	D		77				

[a] Based on GC analysis. [b] All reactions were performed in refluxing benzene with ca. 5 equiv of base (entries 1–16) or with 1 equiv of TBAF (entries 17 and 18). Reaction time was 10 min unless otherwise noted. A, sodium *tert*-amylate; B, lithium *tert*-amylate; C, sodium *tert*-amylate = 0.5 equiv of 15-crown-5; D, TBAF. [c] Ratio in parentheses were determined by GC. [d] Isolated yields. [e] In this reaction 4% of **19** was formed. [f] In this reaction 46% of **20** was formed.

Chart II



13: R^1 = OH; R^2 = CH_3 **14**: R^1 = OH; R^2 = CH_3 **15** **18** **19**

16: R^1 = CH_3; R^2 = OH **17**: R^1 = CH_3; R^2 = OH

20: R^1 = CH_3; R^2 = OTMS

13 and **14** were also obtained from the β-mesylate **2** but now in a ratio of 6.5:1, respectively, and in a lower yield (53%).[17] In this reaction a smaller amount (8%) of starting material was regained. Additionally, a 22% yield of a fragmentation product, the cyclopropane derivative **15**, was isolated. It should be noted that the yield of this product was somewhat diminished by aldol condensation reactions.[18] The presence of a cyclopropane ring in **15** was concluded from the proton-coupled ^{13}C NMR spectrum. The signals of the tertiary cyclopropane carbon atoms appear at δ 17.59 (d, J_{CH} = 166 Hz) and 24.58 (d, J_{CH} = 167 Hz), while the signal due to the secondary cyclopropane carbon atom appears at δ 6.07 (t, J_{CH} = 158 Hz).

The α-mesylate **3** produced predominantly a 2.8:1 mixture (58%) of the olefins **16** and **17**, respectively. As minor products, **15** (2%), the cis-fused ketone **18** (4%), and another fragmentation product (4%) whose identity was established as **19**, were formed. The quantity of regained **3** amounted to 24%. The most valuable information for the identification of the olefins **16** and **17** was obtained from the signals of the olefinic protons in their ^1H NMR spectra. In the ^1H NMR spectrum of **16**, the olefinic signals appear as a broad singlet at δ 5.66. After addition of 0.5 equiv of $Eu(fod)_3$ to the ^1H NMR sample of **16**, the original olefinic two-proton signal (br s) at δ 5.66 splits up into two signals appearing at δ 5.89 (ddd, *J* = 3, 7, 10 Hz, 1 H) and 6.83 (dd, *J* = 2, 10 Hz, 1 H). The ^1H NMR spectrum of **17** shows the olefinic signals at δ 5.54 (ddd, *J* = 3.2, 5.0, 10.1 Hz, 1 H) and 5.61 (ddd, *J* = 2.4, 4.7, 10.1 Hz, 1 H). These multiplicities unequivocally establish the identity of **16** and **17**. In the NMR spectra of **18** recorded at room temperature, coalescence was observed for some signals which frustrated the interpretation of these spectra. However, increase of the temperature to 67 °C led to sharpening of these signals through which the structure of **18** could be established.

Treatment of the β-mesylate **4** with sodium *tert*-amylate afforded the cyclopropane derivative **15** as the major product (69%),[18] together with small amounts of a 2.2:1 mixture (7.5%) of the olefins **16** and **17**, respectively, the cis-fused ketone **18** (2%), and recovered **4** (8%).

The importance of the presence of a free hydroxyl group in the substrates was demonstrated with the O-silylated mesylates **5** and **6**. After prolonged heating (3 h) with sodium *tert*-amylate, these compounds showed no reaction at all (entries 5 and 6). The mesylates **5** and **6** were regained almost quantitatively.

Using lithium *tert*-amylate instead of sodium *tert*-amylate retarded the reaction rates considerably (entries 7–10). Also the product composition changed dramatically. Heating of the β-mesylate **2** until completion of the reaction (3 h) led to a 1.2:1 mixture (72%) of **13** and **14**, respectively, together with a small amount of **15**. The cyclopropane derivative **15** (20%),[18] a 1.2:1 mixture (23%) of **16** and **17**, respectively, and a considerable amount (22%) of the cis-fused ketone **18** were formed after completion of the reaction of the β-mesylate **4** (7 h).

Both the reaction rate and the selectivity increased when sodium *tert*-amylate in combination with 15-crown-5 was

(17) These reactions performed in toluene gave similar product ratios of **13** and **14**.[10]

(18) During this reaction, a "dimeric" product with a molecular weight of 602 was formed. Although the structure of this product could not be elucidated, its formation is probably the result of an aldol condensation reaction of **15** under the influence of the strong base used in this reaction. See ref 5 and references cited therein.

used (entries 11–14). The α-mesylates 1 and 3 both showed a fast reaction in which olefin formation was the only process observed. The α-mesylate 1 afforded a 60:1 mixture (98%) of 13 and 14, respectively, while in case of 3 a 1:10 mixture of 16 and 17, respectively, was produced in quantitative yield. On the other hand, with the β-mesylates 2 and 4 a fast fragmentation leading to the cyclopropane derivative 15 was the main process (54 and 83% yield,[18] respectively).

The O-silylated α-mesylate 5 reacted only very slowly under these conditions (entry 15). After a reaction time of 24 h, the O-silylated olefin 20 (46%) and unreacted 5 (53%) were isolated. Selective desilylation of 20 to the known olefin 17 confirmed its structure. The corresponding β-mesylate 6 did not give any detectable reaction product after a 24-h reflux period (entry 16). On the contrary, fast reactions were observed when 5 and 6 were treated with 1 equiv of TBAF (entries 17 and 18). Within 10 min both reactions were completed and either elimination or fragmentation was observed dependent on the orientation of the mesylate group.

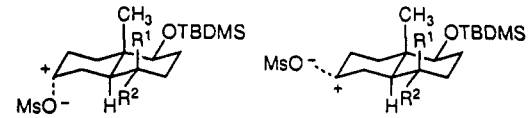
These results clearly show that the structural features of the mesylates studied have profound effects on the course of the reactions of these compounds. It is also demonstrated that the product composition and reaction rate are dependent on the nature of the base. Finally, deprotonation of the tertiary hydroxyl group appears to be of great importance to the reactivity of these mesylates. The experiments with 5 and 6, in which the hydroxyl proton is replaced by a TMS group, show this nicely (entries 5, 6, and 15–18). The enormous differences in reaction rate found in the reactions of 5 and 6 with sodium *tert*-amylate, in the absence or presence of 15-crown-5, and with TBAF must be attributed to alkoxide formation. The very slow but selective formation of the olefin 20 in the reaction of 5 with sodium *tert*-amylate and 15-crown-5 is probably the result of an intermolecular anti E2 mechanism[19] in which the less sterically hindered β H-6 is abstracted exclusively.[20]

Alkoxide formation must also be responsible for the reactivity of the mesylates 1–4, a feature they have in common with the Wharton reaction. The above results suggest the existence of a long-range orbital interaction through the intervening C–C single bonds between the alkoxide and the mesylate group as a result of which the mesylate group splits off more easily. Nucleophilic participation by the solvent (benzene) or by the poor nucleophilic base (alkali metal *tert*-amylate) in the ionization process can be excluded.

Because all reactions are performed in benzene, contact ion pairs are probably involved in the intramolecularly induced departure of the mesylate group.[21] This means that the α-mesylates (1 and 3) and the β-mesylates (2 and 4) will react via the stereoisomeric dipolar intermediates A1 and A2 (Chart III), respectively. If the mesylate group remains associated with the carbocationic center, long enough to affect seriously the behavior of that ion, this will lead to different products and/or differences in product ratios. The results collected in Table I show that this is the case.

The α-mesylates 1 and 3, which are supposed to react via the intermediate A1, can undergo facile intra- and/or

Chart III



(1): $R^1 = O^-$; $R^2 = CH_3$ (2): $R^1 = O^-$; $R^2 = CH_3$
(3): $R^1 = CH_3$; $R^2 = O^-$ (4): $R^1 = CH_3$; $R^2 = O^-$

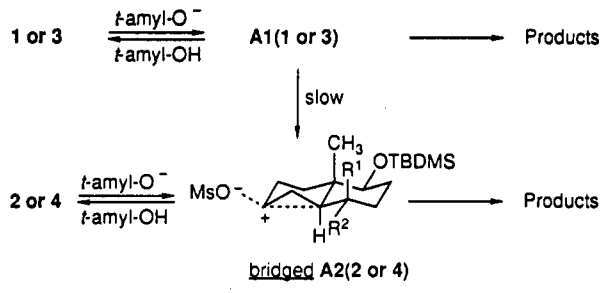
intermolecular anti elimination. In the intermediate A1(1) the tertiary alkoxide group and the β H-8 are 1,3-diaxially positioned. This makes the intramolecular proton abstraction to 13 the most favorable process (entry 1). A similar intramolecular elimination is not possible in the intermediate A1(3) because the tertiary alkoxide group and the β H-8 are not properly aligned. An intramolecular elimination of the α H-8 is rejected because of stereoelectronic factors.[22] Therefore, intermolecular elimination becomes more important. The observed small elimination product ratio of 2.8:1 for the olefins 16 and 17, respectively, suggests a more thermodynamically controlled elimination process (entry 3). The reaction of 5 with TBAF (entry 17) supports this supposition. Since no external base is present when TBAF is used and an intramolecular elimination is unlikely (vide supra), the elimination ratio of 1:1 found for 16 and 17 in this reaction must be the consequence of thermodynamic control. Further support is obtained from MM2 force field calculations[23] which also give the conclusion that 16 and 17 are equal in energy.

The presence of intermediate A1(3) can explain the formation of the other products 18 and 19 from 3 as well. A 1,2-H shift of the β H-8 to the carbocationic center at C(7) is not unlikely since this H atom and the associated mesylate group are oriented in an anti fashion.[24] The resulting secondary carbocationic intermediate can undergo a Grob fragmentation to give the olefinic fragmentation product 19, but can also react further by way of a 1,2-H shift (C(8a) → C(8)) and a 1,2-Me shift (C(1) → C(8a)) to afford the ketone 18. The formation of a small amount (2%) of 15 in this reaction will be discussed later.

The two chief pathways by which the intermediate A2 (derived from the β-mesylates 2 and 4) reacts are elimination and homofragmentation[25] (entries 2 and 4). The formation of the olefin 13 from 2 can be explained by an intramolecular syn elimination in which the intermediate A2(2) is involved. This mechanism is similar to that given in Scheme I. The homofragmentation process leading to 15 can be rationalized by assuming a through-space interaction (1,3-bridging)[26] in the intermediates A2. The back lobe of the C(8a)–C(1)–O⁻ orbital at C(8a) overlaps with the incipient empty p orbital of the carbocationic center at C(7) and this will ultimately lead to C(7)–C(8a) bond formation with simultaneous breaking of the C(1)–C(8a) bond. If intramolecular elimination is not possible, as is the case with 4, homofragmentation is the preferred pathway. The formation of a small amount of 18 in this reaction must proceed via a direct 1,3-H shift (C(8a) → C(7)) and a successive (or simulataneous) 1,2-Me shift

(19) Bartsch, R. A.; Allaway, J. R.; Lee, J. G. *Tetrahedron Lett.* **1977**, 779.
(20) Saunders, W. H.; Cockerill, A. F. *Mechanisms of Elimination Reactions*; Wiley-Interscience: New York, 1973; pp 217–235.
(21) Collins, C. J. *Chem. Soc. Rev.* **1975**, *4*, 251.
(22) See ref 7, pp 190–191.
(23) Allinger, N. L. *J. Am. Chem. Soc.* **1977**, *99*, 8127.
(24) Sorensen, T. S.; Whitworth, S. M. *J. Am. Chem. Soc.* **1990**, *112*, 6647.
(25) Flury, P.; Grob, C. A. *Helv. Chim. Acta* **1983**, *66*, 1971.
(26) Fischer, W.; Grob, C. A.; Hanreich, R.; von Sprecher, G.; Waldner, A. *Helv. Chim. Acta* **1981**, *64*, 2298.

Scheme III



(C(1) → C(8a)). This route to **18** differs from the one which starts from **3** owing to the stereospecificity of these shifts.

Another point of interest is the tendency of the equatorial β-mesylates **2** and **4** to react slightly faster then the axial α-mesylates **1** and **3** under the same conditions as can be concluded from the quantities of recovered starting material (entries 1–4). This means that the intermediates **A2** derived from **2** and **4** are formed more easily and thus are better stabilized, by 1,3-bridging, than the intermediates **A1** generated by the reactions of **1** and **3**. When the mesylate group is axially positioned (as in **A1**) 1,3-bridging is greatly reduced owing to repulsion of the electrons around C(8a) by the mesylate anion of the incipient ion pair at C(7).[27]

Circumstantial evidence for the occurrence of the *bridged* intermediate **A2** comes from the following observations: (1) The formation of the cyclopropane derivative **15**, which must be the result of a bonding 1,3-interaction, is only observed when the intermediates **A2** are involved. (2) Careful analysis of the regained starting materials has revealed that during the reactions of the axial α-mesylates **1** and **3** small but distinct amounts of the β-mesylates **2** and **4**, respectively, are formed. These findings are confirmed by independent experiments in which **1** and **3** were treated with sodium *tert*-amylate in refluxing benzene for 3 min. In both cases the regained starting material contained about 10% of its equatorial C(7) isomer. This inversion process also explains the formation of the small amount (2%) of **15** in the reaction of **3** (entry 3). A direct formation of **15** from the intermediate **A1** is not very likely. Internal return with inversion of the stereochemistry of the mesylate group was not observed during the reactions of the β-mesylates **2** and **4**. These results suggest a reaction pathway in which both the axial and the equatorial mesylates react via a stepwise mechanism with **A1** and the somewhat more stable *bridged* **A2**, respectively, as intermediates (Scheme III).

The ionization of the axial mesylate group in the α-series must be ascribed to through-bond induction alone and results in the unbridged intermediates **A1**. In the β-series, with an equatorial mesylate group, through-space induction (1,3-bridging) accompanies through-bond induction resulting in the *bridged* intermediates **A2**.

The reactions of **2** and **4** with lithium *tert*-amylate and sodium *tert*-amylate in combination with 15-crown-5 underline the existence of 1,3-bridging in this type of compound. As expected, due to the relatively low basicity of lithium *tert*-amylate,[28] deprotonation of the tertiary hydroxyl group will be more difficult. Hence, the reaction rates slow down considerably (entries 7 and 9). Completion of the reactions (entries 8 and 10) shows that the formation of **15** is reduced compared with the reactions of **2** and **4** in which sodium *tert*-amylate is used. An explanation for this behavior is found in the decrease of the electron-donating ability of the alkoxide group when Li^+ is the counterion.[29] This decrease of inductivity[31] gives rise to less overlap of the back lobe of the C(8a)–C(1)–O^- orbital at C(8a) with the incipient empty p orbital at C(7), which results in weakly bridged intermediates **A2**. The rate of formation of the cyclopropane derivative **15** is therefore diminished. Elimination, and in case of **4** also formation of **18**, becomes now more important. It is evident that the β-mesylate **2** cannot give any **18** because the methyl group at C(1) has the wrong stereochemistry.

It is also noteworthy that the elimination product ratios approach unity when lithium *tert*-amylate is used as the external base. In case of **4**, this leveling could be ascribed to an E1-like mechanism in which the weakly bridged intermediate **A2(4)** loses either its β H-6 or its β H-8 under thermodynamic control. This view is supported by MM2 force field calculations. For the olefins **13** and **14** the MM2 force field calculations predicted a thermodynamic 1:6 mixture, respectively.[32] The result of these calculations is in strong contrast with the 1.2:1 mixture found experimentally for these olefins (entries 7 and 8). This means that in the weakly bridged intermediate **A2(2)** intramolecular proton abstraction must still be the main elimination pathway.

The use of sodium *tert*-amylate in combination with 15-crown-5 in the reactions of **2** and **4** (entries 12 and 14) shows a considerable increase of both the reaction rate and the yield of the cyclopropane derivative **15** as compared with the reactions in which only sodium *tert*-amylate is used. It is known that addition of crown ethers to solutions of alkali-metal alkoxides results in stronger bases.[33] Consequently, deprotonation of the tertiary hydroxyl group and hence the reaction will be faster. Because the Na^+ counterion will be captured by the crown ether, the resulting "naked" alcoholate function at C(1) will exhibit a more intense *I* effect. This leads to a strengthening of the 1,3-bridging as a result of which homofragmentation occurs more readily.

Another remarkable outcome of the use of 15-crown-5 is the almost exclusive formation of **13** from **1** (entry 11). This indicates that in this case the elimination process is highly intramolecularly directed. On the other hand, the preferential formation of **17** in the reaction of **3** (entry 13) must be the result of an intermolecular elimination process. Apparently, the specific features of the alkali metal alkoxide-crown ether mixture[20,21] control the elimination process here.

Concluding Remarks

It is evident that deprotonation of the alcohol function of the mesylates studied here is needed to split off the sulfonate ester group in apolar solvents such as benzene. The 1,4-diol monosulfonate esters react stepwise and involve initial ionization of the sulfonate ester group to

(27) Grob, C. A. *Acc. Chem. Res.* **1983**, *16*, 426.
(28) Bank, S. *J. Org. Chem.* **1972**, *37*, 114.
(29) The Li^+–O^- bond has a more covalent character than the Na^+–O^- bond.[30] As a result, the electron-donating ability of the alkoxide function with Li^+ as the counterion will be diminished.
(30) Paquette, L. A.; Gilday, J. P. *J. Org. Chem.* **1988**, *53*, 4972.
(31) This term was introduced by Grob[27] to designate the intensity with which the *I* effect is transmitted to the reaction center.
(32) Since the mesylates **1** and **2** could not be silylated, it was not possible to verify these MM2 force field calculations experimentally.
(33) Bartsch, R. A. *Acc. Chem. Res.* **1975**, *8*, 239.

form dipolar intermediates. The observed internal return with inversion of the axial mesylate group gives extra support for this idea. The reactivity of the α-mesylates is controlled by through-bond induction alone, whereas the reactivity of the corresponding β-mesylates is determined by the sum of a through-bond and a through-space interaction. In the latter compounds the additional through-space interaction (1,3-bridging) leads to the more stable *bridged* intermediates. As a result, the β-mesylates react slightly faster than the corresponding α-mesylates. The extent of 1,3-bridging varies with the inductivity of the alkoxide function and is reflected in the degree of cyclopropane ring formation in the homofragmentation process. If 1,3-bridging is strongly inhibited, as is the case in the α-mesylates, elimination is the main pathway. Thus, not only are the relative reaction rates of the α- and β-mesylates determined by the degree of bridging but also the product distributions. Finally, dependent on the stereochemistry a highly selective product formation can occur, especially when sodium *tert*-amylate in combination with 15-crown-5 is used.

Experimental Section

General.[34] A stock solution of sodium *tert*-amylate (2.2 M in toluene) was prepared by the procedure of Conia[35] and stored under an Ar atmosphere in a refrigerator. A stock solution of lithium *tert*-amylate was prepared by dropwise addition of 1 equiv of dry *tert*-amyl alcohol to a stirred solution of *t*-BuLi (1.7 M in pentane) in toluene at −78 °C under an Ar atmosphere. When the addition was complete, the reaction mixture was allowed to come to rt. Stirring was continued at rt for 2 h, after which time the pentane was removed by distillation. The so-obtained stock solution of lithium *tert*-amylate (1.7 M in toluene) was stored under an Ar atmosphere in a refrigerator.

(1α,4α,4aα,7β,8aβ)- and (1α,4α,4aα,7α,8aβ)-[(*tert*-Butyldimethylsilyl)oxy]decahydro-1,4a-dimethyl-1,7-naphthalenediol 7-(Methanesulfonates) (1 and 2). The mesylates 1 and 2 were prepared as described previously.[10]

(4aα,5α,8aβ)-5-[(*tert*-Butyldimethylsilyl)oxy]decahydro-2,2-dimethoxy-4a-methyl-8-methylenenaphthalene (8). To a stirred solution of 200 mL of 0.275 M (dimethylsulfinyl)sodium in dry DMSO was added 22.0 g (60 mmol) of Ph_3PCH_3Br in small portions at rt. The reaction mixture was stirred at 40 °C for 1 h, after which time a solution of 9.00 g (25.3 mmol) of 7[10] in 150 mL of dry DMSO was added dropwise. Stirring was continued at 50 °C for 2 h. After cooling to rt, the reaction mixture was diluted with 500 mL of water and extracted with ten 100-mL portions of petroleum ether (bp 40–60 °C). The combined organic layers were washed with 250 mL of brine and dried. After evaporation, the remaining residue was flash chromatographed on silica gel (petroleum ether (bp 40–60 °C)) to give 8.21 g (92%) of 8 as a colorless oil: ^{1}H NMR (90 MHz) δ −0.21 (s, 6 H), 0.53 (s, 3 H), 0.79 (s, 9 H), 1.00–2.33 (m, 11 H), 3.00 (s, 3 H), 3.10 (s, 3 H), 3.26 (dd, J = 5, 11 Hz, 1 H), 4.33 (br s, 1 H), 4.64 (br s, 1 H); MS m/z (relative intensity) 354 (M^+, 2.5), 322 (23), 297 (14), 265 (100), 167 (33), 107 (10), 75 (45); calcd for $C_{20}H_{38}O_3Si$ (M^+) m/z 354.2590, found m/z 354.2580.

(1α,4β,4aβ,8aα)-4-[(*tert*-Butyldimethylsilyl)oxy]octahydro-7,7-dimethoxy-4a-methylspiro[naphthalene-1(2*H*),2′-oxirane] (9). A solution of 8.21 g (23.2 mmol) of 8, 30 mL of $CH(OCH_3)_3$, and 0.315 g of *p*-TsOH in 300 mL of CH_3OH was stirred at rt for 45 min, after which time 16.5 g (26.7 mmol) of magnesium monoperoxyphthalate (MMPP) was added. The reaction mixture was stirred at rt for 40 h and then concentrated under reduced pressure. The resulting residue was taken up in a mixture of 200 mL of 10% aqueous $Na_2S_2O_3$ and 400 mL of saturated aqueous $NaHCO_3$ and then extracted with six 100-mL portions of CH_2Cl_2. The combined organic layers were dried over a 1:1 mixture of anhyd K_2CO_3 and Na_2SO_4. After evaporation, the resulting product was flash chromatographed on silica gel (10:1 petroleum ether (bp 40–60 °C)/EtOAc) to give 7.49 g (87%) of 9 as a clear oil: ^{1}H NMR (90 MHz) δ −0.13 (s, 6 H), 0.70 (s, 12 H), 0.91–1.87 (m, 11 H), 2.31 (d, J = 4.5 Hz, 1 H), 2.49 (d, J = 4.5 Hz, 1 H), 2.96 (s, 3 H), 3.01 (s, 3 H), 3.19 (m, $W_{1/2}$ = 15 Hz, 1 H); MS m/z (relative intensity) 370 (M^+, 3.5), 338 (19), 313 (39), 281 (91), 265 (10), 175 (20), 101 (35), 75 (100), 55 (19); calcd for $C_{20}H_{38}O_4Si$ (M^+) m/z 370.2539, found m/z 370.2529.

(4aα,5α,8β,8aβ)-5-[(*tert*-Butyldimethylsilyl)oxy]octahydro-8-hydroxy-4a,8-dimethyl-2(1*H*)-naphthalenone (10). To a solution of 2.49 g (6.73 mmol) of 9 in 300 mL of dry THF was added 1.20 g (32 mmol) of $LiAlH_4$ at 0 °C. The reaction mixture was refluxed for 1 h and then, after cooling to 0 °C, carefully quenched with a small amount of saturated aqueous Na_2SO_4. After addition of 200 mL of EtOAc, the reaction mixture was dried and evaporated to yield 2.48 g (99%) of a crude hydroxy dimethyl acetal [^{1}H NMR (90 MHz) δ −0.12 (s, 3 H), −0.10 (s, 3 H), 0.73 (s, 9 H), 0.90 (s, 3 H), 1.00 (s, 3 H), 1.03–2.50 (m, 12 H), 3.17 (m, 1 H), 3.21 (s, 3 H), 3.27 (s, 3 H)]. This crude product was dissolved in 75 mL of acetone and 10 mL of 10% HCl was added. The reaction mixture was stirred at rt for 15 min and neutralized with 10 mL of saturated aqueous $NaHCO_3$. The reaction mixture was concentrated under reduced pressure, taken up in 50 mL of water, and extracted with three 25-mL portions of CH_2Cl_2. The combined organic layers were dried and evaporated. The resulting product was crystallized from petroleum ether (bp 40–60 °C) to give 1.68 g (77%) of 10 as white crystals: mp 135–137 °C; ^{1}H NMR (90 MHz) δ −0.15 (s, 6 H), 0.80 (s, 9 H), 0.90–2.40 (m, 12 H), 1.00 (s, 3 H), 1.11 (s, 3 H), 3.21 (dd, J = 4.8, 9.0 Hz, 1 H); MS m/z (relative intensity) 326 (M^+, 2), 311 (2), 269 (100), 251 (25), 193 (17), 159 (24), 133 (10), 119 (17), 75 (85), 43 (38); calcd for $C_{14}H_{25}O_3Si$ (M^+ − 57) m/z 269.1573, found m/z 269.1571. Anal. Calcd for $C_{18}H_{34}O_3Si$: C, 66.20; H, 10.49. Found: C, 65.93; H, 10.46.

(1α,4β,7α,8aα)-4-[(*tert*-Butyldimethylsilyl)oxy]decahydro-1,4a-dimethyl-1,7-naphthalenediol (11). To a solution of 1.15 g (3.50 mmol) of hydroxy ketone 10 in 100 mL of dry THF was added dropwise 5 mL of 1 M L-Selectride in THF at −78 °C. The solution was stirred at −78 °C for 30 min and allowed to warm to rt over a 30-min period, and then a mixture of 100 mL of C_2H_5OH and 25 mL of water was added. After stirring at rt for 2 h, 70 mL of 6 M aqueous NaOH and 85 mL of 30% H_2O_2 were added at −20 °C, and stirring was continued at 0 °C for an additional 16 h. The organic solvents were distilled off under reduced pressure, and the remaining aqueous layer was extracted with ten 50-mL portions of CH_2Cl_2. The combined organic layers were washed with three 50-mL portions of water, dried, and then evaporated. The resulting residue was flash chromatographed on silica gel (1:1 petroleum ether (bp 40–60 °C)/EtOAc) to yield 1.075 g (93%) of 11 as white crystals: mp 174–175 °C (from diisopropyl ether); ^{1}H NMR (200 MHz) δ 0.01 (s, 6 H), 0.83 (s, 3 H), 0.85 (s, 9 H), 1.06 (s, 3 H), 1.21–2.35 (m, 13 H), 3.62 (dd, J = 7.0, 8.0 Hz, 1 H), 4.14 (br s, $W_{1/2}$ = 7 Hz, 1 H); MS m/z (relative intensity) 328 (M^+, 0.5), 313 (3), 271 (100), 253 (12), 195 (4), 161 (70), 119 (40), 105 (40), 75 (70), 43 (44); calcd for $C_{14}H_{27}O_3Si$ (M^+ − 57) m/z 271.1729, found m/z 271.1725. Anal. Calcd for $C_{18}H_{36}O_3Si$: C, 65.80; H, 11.04. Found: C, 65.72; H, 11.05.

(1α,4β,4aβ,7β,8aα)-4-[(*tert*-Butyldimethylsilyl)oxy]decahydro-1,4a-dimethyl-1,7-naphthalenediol (12). To a solution of 1.120 g (3.44 mmol) of hydroxy ketone 10 in 150 mL of dry THF was added 1.4 g (36 mmol) of $LiAlH_4$. The reaction mixture was allowed to stir at rt for 15 min and then quenched by the careful addition of a small amount of saturated aqueous Na_2SO_4. The reaction mixture was dried and evaporated. The resulting product was crystallized from diisopropyl ether to afford 1.069 g (95%) of diol 12 as white crystals: mp 184–187 °C; ^{1}H NMR (200 MHz) δ 0.00 (s, 3 H), 0.01 (s, 3 H), 0.73–1.88 (m, 12 H), 0.85 (s, 12 H), 1.11 (s, 3 H), 2.03 (m, 1 H), 3.19 (dd, J = 6.0, 7.5 Hz, 1 H), 3.58 (m, $W_{1/2}$ = 24 Hz, 1 H); MS m/z (relative intensity) 271 (M^+ − 57, 65), 253 (19), 235 (77), 161 (76), 133 (22), 119 (44), 105 (51), 93 (37), 75 (100), 43 (59); calcd for $C_{14}H_{27}O_3Si$ (M^+ − 57) m/z 271.1729, found m/z 271.1729. Anal. Calcd for $C_{18}H_{36}O_3Si$: C, 65.80; H, 11.04. Found: C, 65.59; H, 11.00.

(1α,4β,4aβ,7α,8aα)-4-[(*tert*-Butyldimethylsilyl)oxy]decahydro-1,4a-dimethyl-1,7-naphthalenediol 7-(Methanesulfonate) (3). To a stirred solution of 1.080 g (3.29 mmol) of diol 11 in 75

(34) For a general description of the experimental procedures employed in this research, see ref 10. GC analyses were carried out with H_2 as carrier gas.

(35) Conia, M. J.-M. *Bull. Soc. Chim.* **1950**, *17*, 537.

mL of dry pyridine was added 0.25 mL (3.7 mmol) of MsCl. The reaction mixture was stirred at 40 °C for 45 min and then concentrated under reduced pressure. The resulting residue was taken up in 75 mL of EtOAc and washed sequentially with two 50-mL portions of 10% aqueous H_2SO_4, two 50-mL portions of saturated aqueous $NaHCO_3$, and one 50-mL portion of brine. The organic layer was dried and evaporated. The remaining residue was flash chromatographed on silica gel (2:1 petroleum ether (bp 40–60 °C)/EtOAc) to give 1.262 g (94%) of **3** as a white solid: mp 140–143 °C (from diisopropyl ether); ^{1}H NMR (200 MHz) δ 0.00 (s, 6 H), 0.83 (s, 12 H), 1.05 (s, 3 H), 1.21–2.04 (m, 11 H), 2.21 (br d, J = 9.5 Hz, 1 H) 3.01 (s, 3 H), 3.33 (dd, J = 6.1, 7.0 Hz, 1 H), 5.06 (m, $W_{1/2}$ = 9 Hz, 1 H); ^{13}C NMR (50 MHz) δ -5.05 (q), -4.18 (q), 12.32 (q), 17.79 (s), 21.99 (q), 25.59 (3 q), 26.07 (t), 26.71 (t), 28.83 (t), 34.60 (t), 38.63 (q), 39.27 (s), 40.82 (t), 45.66 (d), 70.63 (s), 78.96 (d), 79.76 (d); MS m/z (relative intensity) 310 (M^+ - 96, 1), 295 (1), 253 (83), 159 (36), 119 (32), 105 (61), 75 (100), 43 (44); calcd for $C_{18}H_{34}O_2Si$ (M^+ - 96) m/z 310.2328, found m/z 310.2328. Anal. Calcd for $C_{19}H_{38}O_5SSi$: C, 56.11; H, 9.42. Found: C, 55.97; H, 9.35.

(1α,4β,4aβ,7β,8aα)-4-[(*tert*-Butyldimethylsilyl)oxy]decahydro-1,4a-dimethyl-1,7-naphthalenediol 7-(Methanesulfonate) (4). The diol **12** (1.456 g, 4.44 mmol) was treated with MsCl for 2 h as described above for the mesylation of the diol **11**. Workup and flash chromatography on silica gel (2:1 petroleum ether (bp 40–60 °C)/EtOAc) gave 1.677 g (93%) of **4** as a white solid: mp 99–100 °C (from diisopropyl ether); ^{1}H NMR (200 MHz) δ -0.02 (s, 3 H), 0.00 (s, 3 H), 0.83 (s, 9 H), 0.86 (s, 3 H), 0.87–2.00 (m, 11 H), 1.08 (s, 3 H), 2.22 (m, 1 H), 2.98 (s, 3 H), 3.19 (dd, J = 5.5, 7.2 Hz, 1 H), 4.58 (m, $W_{1/2}$ = 25 Hz, 1 H); ^{13}C NMR (50 MHz) δ -5.12 (q), -4.20 (q), 13.01 (q), 17.76 (s), 22.44 (q), 25.56 (3 q), 27.47 (t), 28.21 (t), 28.78 (t), 38.57 (q), 38.72 (s), 38.74 (t), 40.60 (t), 50.70 (d), 70.81 (s), 79.07 (d), 82.39 (d); MS m/z (relative intensity) 310 (M^+ - 96, 1.5), 277 (5), 253 (100), 159 (33), 105 (54), 75 (89), 43 (39); calcd for $C_{18}H_{34}O_2Si$ (M^+ - 96) m/z 310.2328, found m/z 310.2328. Anal. Calcd for $C_{19}H_{38}O_5SSi$: C, 56.11; H, 9.42. Found: C, 56.07; H, 9.41.

(2α,4aβ,5β,8α,8aα)-5-[(*tert*-Butyldimethylsilyl)oxy]decahydro-4a,8-dimethyl-8-[(trimethylsilyl)oxy]-2-naphthalenol 2-(Methanesulfonate) (5). To a solution of 0.375 g (0.92 mmol) of mesylate **3** in 15 mL of dry pyridine were added 1 mL (4.7 mmol) of hexamethyldisilazane (HMDS) and 0.5 mL (3.5 mmol) of TMSCl. The reaction mixture was stirred at rt for 3 h and then concentrated under reduced pressure. The resulting residue was flash chromatographed on silica gel (2:1 petroleum ether (bp 40–60 °C)/EtOAc) to afford 0.422 g (96%) of **5** as a colorless oil: ^{1}H NMR (200 MHz) δ -0.04 (s, 9 H), -0.01 (s, 6 H), 0.83 (s, 12 H), 1.06 (s, 3 H), 1.07–1.96 (m, 10 H), 2.14 (m, 1 H), 2.97 (s, 3 H), 3.27 (dd, J = 7.0, 8.1 Hz, 1 H), 5.04 (m, $W_{1/2}$ = 8 Hz, 1 H); ^{13}C NMR (50 MHz) δ -5.07 (q), -4.24 (q), 2.53 (3 q), 12.62 (q), 17.75 (s), 22.70 (q), 25.57 (3 q), 25.84 (t), 26.90 (t), 28.82 (t), 34.98 (t), 38.96 (q), 39.22 (s), 40.54 (t), 46.15 (d), 74.35 (s), 78.93 (d), 80.14 (d); MS m/z (relative intensity) 421 (M^+ - 57, 33), 335 (40), 331 (20), 324 (16), 251 (12), 239 (67), 235 (33), 165 (100), 56 (60), 54 (60); calcd for $C_{18}H_{37}O_5SSi_2$ (M^+ - 57) m/z 421.1900, found m/z 421.1888.

(2α,4aα,5α,8β,8aβ)-5-[(*tert*-Butyldimethylsilyl)oxy]decahydro-4a,8-dimethyl-8-[(trimethylsilyl)oxy]-2-naphthalenol 2-(Methanesulfonate) (6). The mesylate **4** (0.290 g, 0.71 mmol) was treated with HMDS and TMSCl for 3.5 h as described above for the silylation of the mesylate **3**. Workup and flash chromatography on silica gel (2:1 petroleum ether (bp 40–60 °C)/EtOAc) gave 0.328 g (97%) of **6** as a colorless oil: ^{1}H NMR (200 MHz) δ -0.03 (s, 3 H), -0.01 (s, 3 H), 0.00 (s, 3 H), 0.05 (s, 6 H), 0.83 (s, 9 H), 0.85 (s, 3 H), 0.88–2.11 (m, 10 H), 1.09 (s, 3 H), 2.19 (m 1 H), 3.00 (s, 3 H), 3.19 (dd, J = 6.9, 7.8 Hz, 1 H), 4.57 (m, $W_{1/2}$ = 24 Hz, 1 H); ^{13}C NMR (50 MHz) δ -5.04 (q), -4.21 (q), 2.53 (3 q), 13.35 (q), 17.74 (s), 22.82 (q), 25.57 (3 q), 27.47 (t), 28.30 (t), 28.89 (t), 38.62 (q), 38.68 (s), 39.09 (t), 40.66 (t), 51.44 (d), 74.30 (s), 79.16 (d), 82.88 (d); MS m/z (relative intensity) 421 (M^+ - 57, 60), 335 (62), 331 (38), 324 (12), 251 (12), 239 (44), 235 (28), 165 (100), 56 (48), 54 (46); calcd for $C_{18}H_{37}O_5SSi_2$ (M^+ - 57) m/z 421.1900, found m/z 421.1894.

Base-Promoted Reactions of the Mesylates. General Procedure. All reactions were carried out on 0.25–0.50 mmol of substrate at a concentration of ca. 0.1 M in dry benzene. These solutions were degassed and refluxed under an Ar atmosphere. The stock solutions of sodium and lithium *tert*-amylate (2.2 and 1.7 M, respectively, in toluene) were used. Ca. 5 equiv of sodium or lithium *tert*-amylate was added at once, via syringe, to the refluxing solution of the mesylate in dry benzene. Unless otherwise indicated, the reaction mixture was heated at reflux temperature for 10 min, quenched with precooled saturated aqueous NH_4Cl, and then quickly cooled to 0 °C. The mixture was vigorously stirred for 20 min, followed by extraction with ten 15-mL portions of CH_2Cl_2. The combined organic layers were dried and evaporated to afford the crude reaction product. Product ratios, yields, and pure compounds were obtained by chromatographical techniques.

Reactions of the Mesylates 1–6 with Sodium *tert*-Amylate.

a. The general procedure was employed by using 0.190 g (0.47 mmol) of **1** in 5 mL of dry benzene and 1.25 mL of 2.2 M sodium *tert*-amylate in toluene. Workup and flash chromatography on silica gel (5:1 petroleum ether (bp 40–60 °C)/EtOAc) afforded 0.114 g (78%) of a 12:1 mixture of **13** and **14**, respectively, and 0.035 g (18%) of unreacted **1**. The spectroscopic data for **13** and **14** were identical with those reported previously.[10]

b. The general procedure was employed by using 0.194 g (0.48 mmol) of **2** in 5 mL of dry benzene and 1.25 mL of 2.2 M sodium *tert*-amylate in toluene. Workup and flash chromatography on silica gel (10:1 petroleum ether (bp 40–60 °C)/EtOAc) gave 0.134 g of a mixture of at least three compounds and 0.016 g (8%) of unreacted **2**. Column chromatography of the mixture (0.134 g) on silica gel (50:1 petroleum ether (bp 40–60 °C)/EtOAc) afforded 0.018 g of a "dimeric" oil[36] [MS m/z (relative intensity) 602 (M^+, <0.1), 587 (0.3), 545 (10), 507 (23), 413 (10), 375 (5), 305 (26), 253 (32), 239 (100), 219 (40), 215 (18), 75 (35); calcd for $C_{35}H_{63}O_3Si_2$ (M^+ - 15) m/z 587.4312, found m/z 587.4316], 0.078 g (53%) of a 6.5:1 mixture of **13** and **14**, respectively, and 0.033 g (22%) of **(5*R*)-5-[(*tert*-butyldimethylsilyl)oxy]-5-[(1′α,2′α,5′α)-2′-methylbicyclo[3.1.0]hexan-2′-yl]pentan-2-one (15)**: ^{1}H NMR (200 MHz) δ 0.02 (s, 3 H), 0.03 (s, 3 H), 0.05 (m, 1 H), 0.28 (m, 1 H), 0.62–1.25 (m, 3 H), 0.88 (s, 9 H), 0.93 (s, 3 H), 1.47–2.03 (m, 5 H), 2.12 (s, 3 H), 2.37–2.73 (m, 2 H), 3.37 (dd, J = 3.6, 6.7 Hz, 1 H); ^{13}C NMR (50 MHz) δ -4.13 (q), -3.31 (q), 6.07 (t, J = 158 Hz), 17.59 (d, J = 166 Hz), 18.43 (s), 20.99 (q), 24.58 (d, J = 167 Hz), 26.18 (3 q), 26.98 (t), 27.19 (t), 30.05 (q), 31.30 (t), 41.25 (t), 48.32 (s), 77.00 (d), 209.19 (s); MS m/z (relative intensity) 295 (M^+ - 15, 0.5), 253 (19), 239 (2), 215 (100), 199 (3), 173 (5), 145 (12), 115 (5), 95 (12), 73 (36); calcd for $C_{14}H_{25}O_2Si$ (M^+ - 57) m/z 253.1624, found m/z 253.1623.

c. The general procedure was employed by using 0.200 g (0.49 mmol) of **3** in 5 mL of dry benzene and 1.25 mL of 2.2 M sodium *tert*-amylate in toluene. Workup and flash chromatography on silica gel (10:1 petroleum ether (bp 40–60 °C)/EtOAc) gave 0.105 g of a mixture of at least five compounds and 0.048 g (24%) of unreacted **3**. The mixture (0.105 g) was column chromatographed on silica gel (50:1 petroleum ether (bp 40–60 °C)/EtOAc) to afford, in order of elution, 0.015 g (10%) of a 1:2:2 mixture of **15**, **18**, and **19**, respectively, 0.040 g (26%) of pure **16**, and 0.048 g (32%) of a 1.1:1 mixture of **16** and **17**, respectively. The spectroscopic data of **17** and **18** are given in the following experiments; those of **16** and **19**[37] are shown below.

(1α,4β,4aβ,8aα)-4-[(*tert*-Butyldimethylsilyl)oxy]-1,2,3,4,4a,5,6,8a-octahydro-1,4a-dimethyl-1-naphthalenol (16): ^{1}H NMR (200 MHz) δ 0.01 (s, 6 H), 0.81 (s, 3 H), 0.87 (s, 9 H), 1.11 (s, 3 H), 1.14–1.83 (m, 7 H), 1.99–2.05 (m, 3 H), 3.30 (dd, J = 5.9, 9.0 Hz, 1 H), 5.66 (br s, 2 H); ^{13}C NMR (50 MHz) δ -5.09 (q), -4.22 (q), 12.45 (q), 17.83 (s), 22.29 (q), 22.57 (t), 25.62 (3 q), 29.09 (t), 35.88 (t), 38.23 (s), 40.56 (t), 52.30 (d), 71.39 (s), 78.06 (d), 124.71 (d), 127.01 (d); MS m/z (relative intensity) 295 (M^+ - 15, 1), 253 (80), 177 (16), 159 (27), 145 (20), 119 (35), 105 (55), 91 (32), 75 (100), 43 (51); calcd for $C_{18}H_{34}O_2Si$ (M^+) m/z 310.2328, found m/z 310.2330. In the ^{1}H NMR (200 MHz) of a 2:1 mixture of **16** and Eu(fod)$_3$, respectively, the following main signals are observed: δ 3.27 (br s, 1 H), 3.65 (dd, J = 5, 9 Hz, 1 H), 5.89 (ddd, J = 3, 7, 10 Hz, 1 H), 6.83 (dd, J = 2, 10 Hz, 1 H).

(5*R*)-5-[(*tert*-Butyldimethylsilyl)oxy]-5-[(3′α)-3′-methylcyclohex-1′-en-3′-yl]pentan-2-one (19): ^{1}H NMR (200 MHz)

(36) Although the structure of this oil could not be established with certainty, the NMR data reveal the presence of cyclopropane rings.

(37) This compound could not be isolated in pure form with column chromatography.

(main peaks) δ 0.01 (s 6 H), 0.88 (s, 9 H), 1.22 (s, 3 H), 2.10 (s, 3 H), 2.31–2.76 (m, 2 H), 3.37 (dd, J = 3.4, 6.9 Hz, 1 H), 5.38 (br d, J = 10.2 Hz, 1 H), 5.60 (dt, J = 3.6, 3.6, 10.2 Hz, 1 H); ^{13}C NMR (50 MHz) (main peaks) δ 126.65 (d), 134.49 (d), 208.83 (s); MS m/z (relative intensity) 295 (M^+ – 15, 0.6), 253 (22), 215 (77), 159 (8), 145 (29), 115 (14), 95 (12), 73 (100), 43 (20).

d. The general procedure was employed by using 0.200 g (0.49 mmol) of **4** in 5 mL of dry benzene and 1.25 mL of 2.2 M sodium *tert*-amylate in toluene. Workup and column chromatography on silica gel (50:1 to 15:1 petroleum ether (bp 40–60 °C)/EtOAc) gave, in order of elution, 0.010 g of the "dimeric" oil, 0.127 g (78.5%) of a 33:2.5:1.1:1 mixture of **15**, **16**, **17**, and **18**, respectively, and 0.016 g (8%) of unreacted **4**.

e. When the mesylates **5** and **6** were treated with sodium *tert*-amylate for 3 h according to the general procedure, these compounds were recovered in 96 and 98%, respectively.

Reactions of the Mesylates 2 and 4 with Lithium *tert*-Amylate. a. The general procedure was employed by using 0.050 g (0.12 mmol) of **2** in 1.5 mL of dry benzene and 0.4 mL of 1.7 M lithium *tert*-amylate in toluene. Workup and flash chromatography on silica gel (10:1 petroleum ether (bp 40–60 °C)/EtOAc) gave 0.003 g (8%) of a 4:3:1 mixture of **13**, **14**, and **15**, respectively, and 0.042 g (84%) of unreacted **2**.

b. The same as above, except that the reaction mixture was heated at reflux temperature until completion (3 h). Workup and column chromatography on silica gel (50:1 petroleum ether (bp 40–60 °C/EtOAc) gave 0.005 g of the "dimeric" oil and 0.030 g (77%) of a 8:6.5:1 mixture of **13**, **14**, and **15**, respectively.

c. The general procedure was employed by using 0.100 g (0.25 mmol) of **4** in 2.5 mL of dry benzene and 0.75 mL of 1.7 M lithium *tert*-amylate in toluene. Workup and flash chromatography on silica gel (15:1 petroleum ether (bp 40–60 °C)/EtOAc) gave 0.006 g (8%) of a 1.7:1 mixture of **15** and **18**, respectively, and 0.091 g (91%) of unreacted **4**. Trace amounts of **16** and **17** were also detected.

d. The same as above, except that the reaction mixture was heated at reflux temperature until completion (7 h). Starting from 0.200 g (0.49 mmol) of **4**, workup and column chromatography on silica gel (50:1 petroleum ether (bp 40–60 °C)/EtOAc) gave, in order of elution, 0.040 g of the "dimeric" oil, 0.065 g (42%) of a 1:1.1 mixture of **15** and **18**, respectively, and 0.035 g (23%) of a 1.2:1 mixture of **16** and **17**, respectively. Preparative GC of the mixture of **15** and **18** afforded a pure sample of **(4α,4aα,8aα)-4-[(*tert*-butyldimethylsilyl)oxy)]octahydro-4a,8a-dimethyl-1(2*H*)-naphthalenone (18)**: ^{1}H NMR (C_6D_6, 200 MHz, 67 °C) δ 0.03 (s, 3 H), 0.06 (s, 3 H), 0.87 (s, 3 H), 0.96 (s, 9 H), 1.02–2.12 (m, 10 H), 1.20 (s, 3 H), 2.27 (m, 1 H), 2.49 (m, 1 H), 3.85 (m, $W_{1/2}$ = 15.0 Hz, 1 H); ^{13}C NMR (C_6D_6, 50 MHz, 67 °C) δ –5.33 (q), –4.68 (q), 17.40 (q), 17.65 (s), 20.40 (q), 20.89 (t), 21.43 (t), 25.44 (3 q), 29.44 (t), 32.14 (t), 32.66 (t), 33.74 (t), 43.12 (s), 51.68 (s), 71.75 (d), 211.81 (s); MS m/z (relative intensity) 295 (M^+ – 15, 6), 253 (95), 161 (91), 143 (60), 119 (60), 105 (38), 91 (17), 75 (100), 41 (47); calcd for $C_{14}H_{25}O_2Si$ (M^+ – 57) m/z 253.1624, found m/z 253.1627.

Reactions of the Mesylates 1–6 with Sodium *tert*-Amylate in the Presence of 15-Crown-5. a. The general procedure was employed by using a mixture of 0.086 g (0.21 mmol) of **1** and 0.027 g (0.12 mmol) of 15-crown-5 in 2.5 mL of dry benzene, and 0.6 mL of 2.2 M sodium *tert*-amylate in toluene. Workup and flash chromatography on silica gel (10:1 petroleum ether (bp 40–60 °C)/EtOAc) gave 0.065 g (98%) of a 60:1 mixture of **13** and **14**, respectively.

b. The general procedure was employed by using a mixture of 0.195 g (0.48 mmol) of **2** and 0.055 g (0.25 mmol) of 15-crown-5 in 5 mL of dry benzene and 1.25 mL of 2.2 M sodium *tert*-amylate in toluene. Workup and column chromatography on silica gel (50:1 petroleum ether (bp 40–60 °C)/EtOAc) gave, in order of elution, 0.027 g of the "dimeric" oil, 0.081 g (54%) of **15**, and 0.030 g (20%) of an 8.5:1 mixture of **13** and **14**, respectively.

c. The general procedure was employed by using a mixture of 0.200 g (0.49 mmol) of **3** and 0.055 g (0.25 mmol) of 15-crown-5 in 5 mL of dry benzene, and 1.25 mL of 2.2 M sodium *tert*-amylate in toluene. Workup gave 0.150 g (100%) of a 1:10 mixture of **16** and **17**, respectively. Careful column chromatography on silica gel (100:1 to 25:1 petroleum ether (bp 40–60 °C)/EtOAc) afforded a pure sample of **(1α,4β,4aβ,8aα)-4-[(*tert*-butyldimethylsilyl)oxy]-1,2,3,4,4a,5,8,8a-octahydro-1,4a-dimethyl-1-naphthalenol (17)**: ^{1}H NMR (200 MHz) δ 0.01 (s, 6 H), 0.80 (s, 3 H), 0.85 (s, 9 H), 1.16 (s, 3 H), 1.31–2.22 (m, 10 H), 3.30 (dd, J = 6.0, 9.7 Hz, 1 H), 5.54 (ddd, J = 3.2, 5.0, 10.1 Hz, 1 H), 5.61 (ddd, J = 2.4, 4.7, 10.1 Hz, 1H); ^{13}C NMR (50 MHz) δ-5.08 (q), –4.15 (q), 12.12 (q), 17.81 (s), 22.40 (t), 22.73 (q), 25.60 (3 q), 29.01 (t), 38.33 (s), 40.66 (t), 42.02 (t), 48.75 (d), 71.62 (s), 79.87 (d), 124.73 (d), 125.25 (d); MS m/z (relative intensity) 310 (M^+, 1), 295 (1), 253 (54), 159 (32), 119 (30), 105 (55), 91 (27), 75 (100), 43 (50); calcd for $C_{18}H_{34}O_2Si$ (M^+) m/z 310.2328, found m/z 310.2326.

d. The general procedure was employed by using a mixture of 0.100 g (0.25 mmol) of **4** and 0.027 g (0.12 mmol) of 15-crown-5 in 2.5 mL of dry benzene, and 0.6 mL of 2.2 M sodium *tert*-amylate in toluene. Workup and column chromatography on silica gel (50:1 petroleum ether (bp 40–60 °C)/EtOAc) gave, in order of elution, 0.010 g of the "dimeric" oil and 0.067 g (86.5%) of a 67:0.5:1:1 mixture of **15**, **16**, **17**, and **18**, respectively.

e. The general procedure was employed by using a mixture of 0.239 g (0.50 mmol) of **5** and 0.055 g (0.25 mmol) of 15-crown-5 in 5 mL of dry benzene, and 1.25 mL of 2.2 M sodium *tert*-amylate in toluene. After heating at reflux temperature for 24 h, the mixture was quenched. Workup and flash chromatography on silica gel (50:1 petroleum ether (bp 40–60 °C)/EtOAc) gave 0.124 g (53%) of unreacted **5** and 0.087 g (46%) of **(1α,4β,4aβ,8aα)-4-[(*tert*-butyldimethylsilyl)oxy]-1,2,3,4,4a,5,8,8a-octahydro-1-[(trimethylsilyl)oxy]-1,4a-dimethylnaphthalene (20)**: ^{1}H NMR (200 MHz) δ 0.03 (s, 6 H), 0.07 (s, 9 H), 0.81 (s, 3 H), 0.87 (s, 9 H), 1.19 (s, 3 H), 1.41–2.32 (m, 9 H), 3.30 (dd, J = 5.8, 8.7 Hz, 1 H), 5.49–5.62 (m, 2 H); ^{13}C NMR (50 MHz) δ –5.07 (q), –4.14 (q), 2.59 (3 q), 12.38 (q), 17.84 (s), 22.65 (t), 23.34 (q), 25.63 (3 q), 29.12 (t), 38.37 (s), 40.77 (t), 42.45 (t), 49.23 (d), 75.04 (s), 79.95 (d), 124.45 (d), 125.99 (d); MS m/z (relative intensity) 382 (M^+, 0.6), 367 (5), 325 (80), 248 (40), 239 (100), 235 (90), 160 (60), 56 (70), 54 (50); calcd for $C_{21}H_{42}O_2Si_2$ (M^+) m/z 382.2723, found m/z 382.2728.

f. When the mesylate **6** was treated with sodium *tert*-amylate in the presence of 15-crown-5 for 24 h according to the general procedure, no reaction products could be isolated. The starting material was recovered in 84%.

Treatment of the Mesylates 5 and 6 with TBAF. a. A solution of 0.050 g (0.11 mmol) of **5** in 1.5 mL of dry benzene was treated according to the general procedure, using 0.1 mL of 1.1 M tetrabutylammonium fluoride (TBAF) in THF in place of alkali-metal *tert*-amylate. Workup and flash chromatography on silica gel (10:1 petroleum ether (bp 40–60 °C)/EtOAc) gave 0.028 g (78%) of a 1:1 mixture of **16** and **17**.

b. A solution of 0.060 g (0.13 mmol) of **6** in 1.8 mL of dry benzene was treated with 0.13 mL of 1.1 M TBAF in THF as described above. Workup and flash chromatography on silica gel (10:1 petroleum ether (bp 40–60 °C)/EtOAc) yielded 0.030 g (77%) of **15** as the sole product.

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Supplementary Material Available: ^{1}H NMR spectra for compounds **5**, **6**, **8**, **9**, **15**, **16**, **17**, **18**, **19**, and **20** (11 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.