JOC The Journal of Organic Chemistry

Note

pubs.acs.org/joc

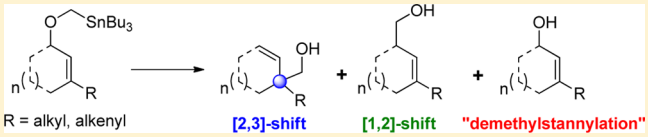
Studies toward the Generation of Functionalized Quaternary Carbon Centers Relying on Wittig and Wittig–Still Allylic Ether Anionic Transpositions

Stephen Hanessian,* Stéphane Dorich, Amit Kumar Chattopadhyay, and Martin Büschleb

Department of Chemistry, Université de Montréal, Station Centre-Ville, C.P. 6128, Montreal, Qc, H3C 3J7, Canada

Supporting Information

ABSTRACT: Although the [2,3]-Wittig and Wittig–Still rearrangements have long been known, their application in the generation of quaternary carbon centers in carbocyclic ring systems is sparse. Model studies utilizing this strategy and possible mechanisms are discussed herein. Unprecedented examples of an α-elimination pathway from stannylmethyl allyl ethers as a major undesired product in some Wittig–Still rearrangements are reported.



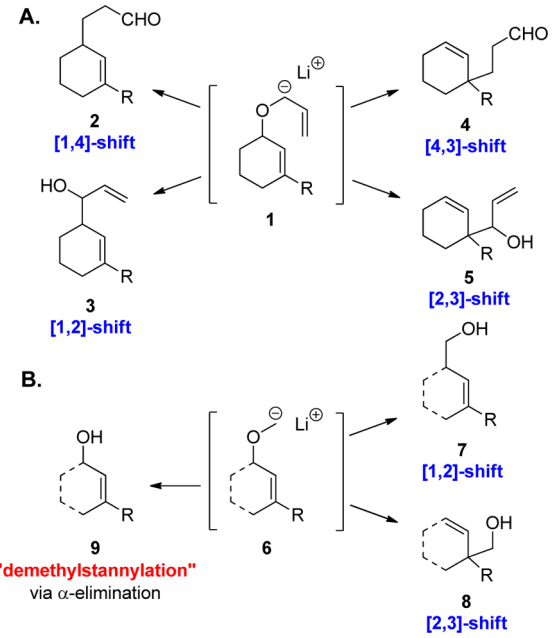
The formation of C–C bonds to generate quaternary carbon centers remains a major challenge in organic functional group transformations.[1] Apart from synthetic and mechanistic considerations, securing relative or absolute stereochemistry at the newly created quaternary carbon center can be a daunting task.[2] Elegant solutions to such problems have been found in the context of natural product synthesis, where specific methods were adapted to the target molecule in question.[3] Clearly, steric congestion, proximity effects, and propensities for skeletal rearrangements present major obstacles in arriving at a predictable outcome of reactions leading to quaternary carbon centers. Cognizant of these challenges, methods are constantly sought which introduce quaternary carbon atoms relying on energetically favorable transition states, and under mild conditions.

Among such methods are allylic ether transpositions involving carbanionic intermediates that take place at temperatures as low as −100 °C. In this context, the [2,3]-Wittig rearrangement[4] of allylic ethers is a well-known process to transpose an allylic alcohol group to the distal carbon atom. In the case of doubly allylic ethers, the less substituted allylic moiety is rearranged to give 1,5-dien-3-ols, although different pathways leading to other products are also possible.[5]

An extension of the [2,3]-Wittig rearrangement, introduced by Still and Mitra,[6] involves the formal transfer of a hydroxymethyl group from a tributylstannylmethyl allylic ether onto the distal olefinic carbon atom. Early examples include applications in the synthesis of dendrolasin,[7] plumericin,[8] 12,25-dihydroxyvitamin D,[9] and laurenene intermediates.[10] Although extensively studied over the years, examples of creating *quaternary carbon centers* using [2,3]-Wittig or [2,3]-Wittig–Still rearrangements are limited. Examples of introducing a hydroxymethyl group at a quaternary center using a [2,3]-Wittig–Still rearrangement in the context of natural products synthesis are found in the structures of punctatin A,[11] cobyric acid,[12] retigeranic acid A,[13] anisatin,[14] and maoecrystal V.[15] These reactions were achieved to various degrees of efficiency, depending on the structure at hand.[16]

We report herein a study involving the [2,3]-Wittig and the [2,3]-Wittig–Still rearrangements of model 3-substituted 2-cyclohexenol and 2-cyclopentenol 1-ethers. In Scheme 1, we show the theoretically possible transposition products from allyl ether carbanion (**1**) and the anionic organolithium ether species (**6**) derived from the corresponding tributylstannylmethyl ether. In principle, [2,3]- and [4,3]-shifts from the

Scheme 1. Possible Products from Rearrangement of 1 and 6



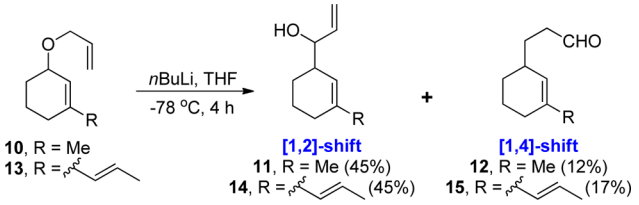
Received: July 25, 2013
Published: August 5, 2013

   dx.doi.org/10.1021/jo401488y | J. Org. Chem. 2013, 78, 8915–8921

allylic ether carbanion (**1**) would lead to the desired quaternary carbon centered substituents as in **4** and **5** (Scheme 1A). Undesired [1,2]- and [1,4]-shifts would simply introduce a three-carbon appendage at the original cyclohexyl ether carbon atom as in **2** and **3**. In the case of the lithium anion (**6**) derived from the corresponding tributylstannylmethyl ether via transmetalation (Scheme 1B), the desired compound **8** would result via a [2,3]-shift, while a [1,2]-shift would lead to compound **7**. A hitherto undocumented alternative "demethylstannylation" pathway could lead to the starting alcohol (**9**) via an α-elimination mechanism.[17]

Treatment of the allyl ether **10**[18] under standard conditions cleanly led to the products **11** and **12** resulting from [1,2]- and [1,4]-shifts in 45% and 12% yields, respectively (Scheme 2).

Scheme 2. [1,2]- and [1,4]-Rearrangement Products Observed from Allyl Ethers 10 and 13



The same reaction with the extended diene allyl ether **13** led to the products **14** and **15** in 45% and 17% yields, respectively. None of the expected [2,3]-rearrangement products corresponding to **5** were observed in either case.

We then turned our attention to the [2,3]-Wittig–Still rearrangement. Formation of the lithium anion from **16** in THF at −78 °C led, surprisingly, only to the ether cleavage product **19** (35%) (Table 1). Interestingly, the nature of the base had no significant influence on the outcome of the reaction (Table 1, entries 1–3). However, a profound temperature effect was observed in going from −78 to 0 °C, affording variable yields of the desired **17**,[19] in addition to **18**[20] and **19** as significant byproducts (Table 1, entries 4–8). An optimal yield of **17** (48%) was achieved at −20 °C, showing a stronger propensity for the [2,3]-rearranged product **17** to form at higher temperatures, whereas the ether cleavage product **19** is formed at lower temperatures.

Notably, maintaining the reaction temperature at −78 °C for 4 h, then at 0 °C for 1 h, afforded **17** (22%), **18** (13%), and the ether cleavage product **19** (40%), suggesting that the latter is obtained kinetically (Table 1, entry 8). Lastly, a change in solvent[21] led to a drastic change in the ratio of the products and their yields (Table 1, entries 9–11). Quenching the reaction mixture from entry 6 with deuterium oxide led to **17** and **18** with no incorporation of deuterium on the carbon skeleton.

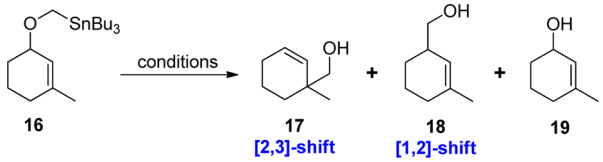
When the reaction was done with the extended diene **20**, only the desired [2,3]-rearranged product **21** (40%) and the undesired [1,2]-shift product **22** (33%) were formed (Scheme 3A). Surprisingly, the allylic stannylmethyl ether **23** led only to ether cleavage affording the starting cyclopentene **24** in 55% yield. To assess the influence of conformational restriction and stereochemistry, the *syn*- and *anti*- diastereomeric stannylmethyl allyl ethers **25** and **28**, respectively, were subjected to the optimized Wittig–Still rearrangement conditions. Only the *syn*-diastereomer **25** led to the [2,3]-rearrangement product **26**, albeit in only 17% yield. The major product formed from **25** and **28**, as a result of a [1,2]-rearrangement, was **27** in 73% and 83% yields respectively (Scheme 3A).

To further probe the influence of geometric constraints, we subjected the stannyl ethers **29** and **30** to rearrangement (Scheme 3B). We were pleased to find that the expected [2,3]-rearrangement product **33** was formed in 70% yield from **30**, with the other product being starting allylic alcohol **34** (5%). The corresponding cyclopentene derivative **29** also led to the expected [2,3]-rearrangement product **31** accompanied by a regioisomeric byproduct (3:2, 60%; see Supporting Information), as well as the ether cleavage product **32** (10%).

Lastly, the exocyclic stannylmethyl allylic ethers **35**, **36**, and **37** afforded the desired [2,3]-rearrangement products **38**,[22] **39**, and **40** as major products in 60%, 69%, and 64% yields respectively (Scheme 3C).

It is well-known that bond reorganization in the [2,3]-Wittig rearrangement involves a six-electron five-membered cyclic transition state in which the allylic oxycarbanion is the migrating entity.[23] This thermally allowed concerted process

Table 1. [2,3]- and [1,2]-Rearrangement and Cleavage Products Obtained from the Li Anion of 16

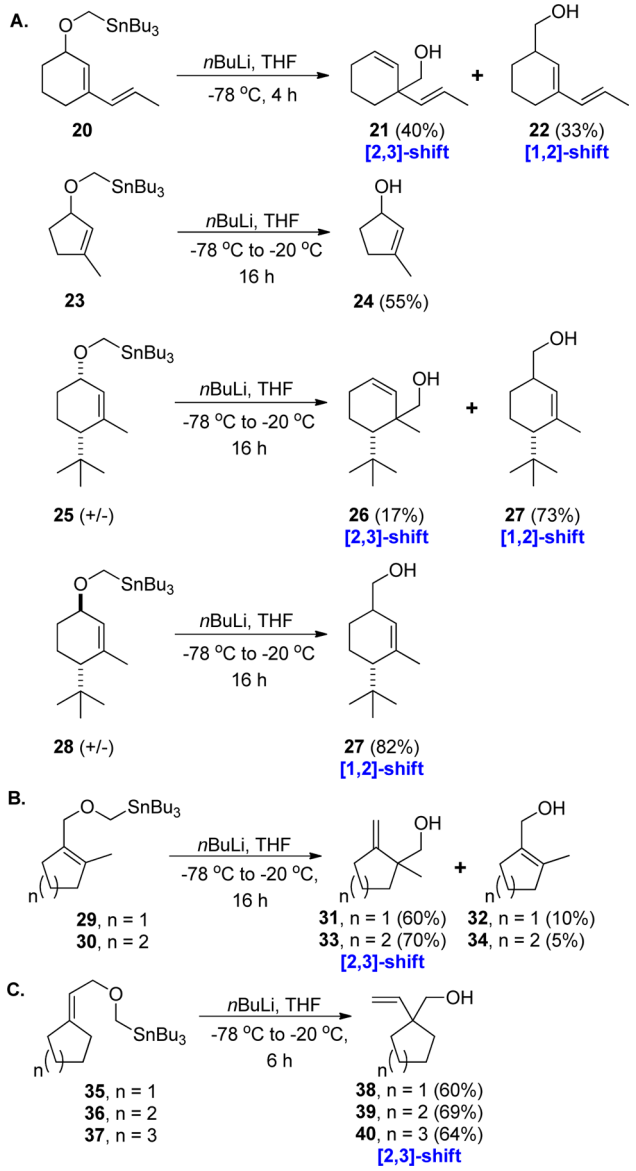


entry	conditions	17 (%)[a]	18 (%)[a]	19 (%)[a]
1	*n*BuLi, THF, −78 °C, 4 h	–	–	35
2	*s*BuLi, THF, −78 °C, 4 h	–	–	38
3	*t*BuLi, THF, −78 °C, 4 h	–	–	35
4	*t*BuLi, THF, −78 °C, then 0 °C, 1 h	30	37	–
5	*n*BuLi, THF, −78 °C, then 0 °C, 1 h	33	33	–
6	*n*BuLi, THF, −78 °C, then −20 °C, 8 h	48	22	–
7	*n*BuLi, THF, −78 °C, then −40 °C, 8 h	44	29	traces
8	*n*BuLi, THF, −78 °C (4 h), then 0 °C (1 h)	22	13	40
9	*n*BuLi, Et_2O, −78 °C, then −20 °C, 8 h	18	32	6
10	*n*BuLi, THF/HMPA (10:1), −78 °C, then −20 °C, 8 h	20	12	35
11	*n*BuLi, hexanes, −78 °C, then −20 °C, 8 h	48	28	10

[a]Isolated yields.

dx.doi.org/10.1021/jo401488y | J. Org. Chem. 2013, 78, 8915–8921

Scheme 3. [2,3]-Wittig–Still Rearrangements and Related Products

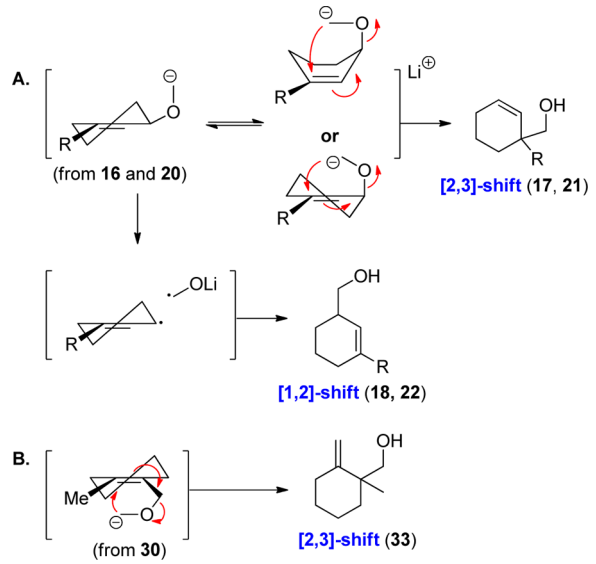


is favored when the energy gap between the HOMO of the attacking allylic anion and the LUMO of the "receiving" allylic partner is small. The competing [1,2]-process is nonconcerted and believed to proceed by a radical pair dissociation–recombination mechanism that is favored at higher temperatures. In spite of many applications of the [2,3]-Wittig rearrangement in the transposition of an allyl group in unsaturated cyclic systems, the results can be dramatically different depending on the nature of the substrate.[24]

Our results shown in Scheme 2 are of interest since they extend the original study by Nakai and co-workers to the prospects of allylic transposition to form a *quaternary carbon center* in substituted cyclic systems. Since no [2,3]-rearrangement product was observed, the activation barrier of the stepwise radical dissociation–recombination pathway dominates over the concerted process, leading to the [1,2]-rearrangement products **11** and **14** in preponderance.

In contrast to the results of [2,3]-Wittig allylic transpositions of Nakai and co-workers, Still and Mitra had reported that the [2,3]-rearrangement of the tributylstannylmethyl ether of 1-cyclohexen-2-ol via transmetalation with BuLi (compound **6**, R = H, Scheme 1) led to the expected 1-hydroxymethyl-2-cyclohexene (compound **8**, R = H, Scheme 1) in 95% yield. However, extension to the tributylstannylmethyl ether of cyclodecen-2-ol to generate an angular quaternary center led to mixtures of [1,2]- and [2,3]-rearrangement products in unspecified low yields. It is therefore of interest that the tributylstannyl ethers **16** and **20** afforded the [2,3]-rearranged products **17** and **21** containing a quaternary carbon in 48% and 40% yields respectively, although significant amounts of the [1,2]-rearranged products **18** and **22** are also formed. Thus, the activation energy barrier difference between the concerted and radical dissociation–recombination pathways may not be significant in these cases. Furthermore, the trajectory of anionic attack may be geometrically more favorable compared to the expected [2,3]-Wittig rearrangement pathway. Possible reactive intermediates are shown in Scheme 4.

Scheme 4. Possible Mechanisms Accounting for [2,3]- and [1,2]-Rearrangement Products from Lithium Carbanions of 16, 20, and 30



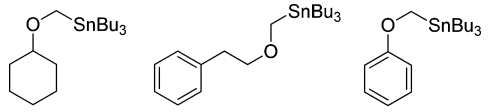
For the [1,2]-Wittig rearrangement to occur, the radicals formed from the carbanion terminus and/or the migrating moiety must be stabilized.[25] In the case of **16** and **20**, only the 3-substituted cyclohexenyl radical is stabilized, while the CH_2OLi radical is not (Scheme 4A). This results in the [2,3]-Wittig–Still products **17** and **21** to predominate over the [1,2]-Wittig products **18** and **22** (Table 1, Schemes 3 and 4A). When the conformation is locked into the appropriate half-chair, as for *syn*-ether **25**, the rearrangement seems to be slightly more favorable compared to **28** where only the [1,2]-rearrangement product **27** is formed (Scheme 3B). Furthermore, both substrates **25** and **28** lead to one and the same product **27**, further validating the radical dissociation–recombination mechanism. When the geometric constraints are minimized as in the case of the extended stannylmethyl allyl ethers **29**, **30**, **35**, **36**, and **37**, the desired [2,3]-rearrangement products predominate (Scheme 3). Evidently, the energy barrier for the [2,3]-rearrangement is more favorable in these extended ethers, since the anion is geometrically better oriented

dx.doi.org/10.1021/jo401488y | J. Org. Chem. 2013, 78, 8915–8921

in the same plane as the olefin to interact with the π^* orbital at the methyl-bearing olefinic terminus.

The formation of variable amounts of allylic alcohols, either as the kinetic product **19** (Table 1, entries 1−3) or as the only isolable product in the attempted [2,3]-Wittig−Still rearrangements of **16** and **23**, is of interest. We are unaware of related apparent "demethylstannylations" of allylic ethers in such anionic rearrangements of stannylmethyl allyl ethers. In order to test the generality of this reaction, we treated simple tributylstannyl ethers **41**,[26] **42**, and **43**[27] with *n*BuLi in THF at −78 °C under the same conditions of the original [2,3]-Wittig−Still rearrangement. The starting alcohols (not shown) were isolated in 71%, 78%, and 54% yields respectively, along with Bu_4Sn (Scheme 5). It is well-known that the Bu_3Sn group

Scheme 5. Facile "Demethylstannylation" of Unactivated Stannylmethyl Ethers



41 **42** **43**

does not acidify the α-protons in such stannylmethyl ethers and that an organotin/organolithium exchange (transmetalation) is a fast process at −78 °C. Thus, demethylstannylation takes place in favor of other pathways at such temperatures (Table 1, entries 1−3). The reaction may proceed via an α-elimination to form a carbene and the Li alkoxide.

We have studied the prospects of generating a quaternary carbon center in 3-substituted-1-cyclohex-2-ene-1-ol allyl and tributylstannylmethyl ethers via rearrangements of their respective lithium carbanions. In the case of Wittig allylic transpositions, the major product arises from [1,2]-rearrangement. The desired [2,3]-transposition competes effectively with the [1,2]-shift in the Wittig−Still rearrangement depending on the substrate. When the nucleophilic carbon atom in the Li-anion is in the same plane as the olefin, facile [2,3]-rearrangement takes place. A radical dissociation−recombination process can prevail when the two moieties are stabilized, leading to [1,2]-rearrangement. Otherwise, the product distribution will depend on the nature of the substrate, the geometric constraints, and the temperature. Demethylstannylation of stannylmethyl allyl ethers during [2,3]-Wittig−Still rearrangements can predominate especially at low temperature. The products containing a hydroxymethyl group on a quaternary carbon atom in the model cycloalkene systems described herein could find applications in the synthesis of densely functionalized natural products of interest, while being cognizant of potential byproducts.

EXPERIMENTAL SECTION

(±)-1-(3-Methylcyclohex-2-enyl)prop-2-en-1-ol (11) and (±)-3-(3-Methylcyclohex-2-enyl)propanal (12). A solution of the bis-allylether **10** (40 mg, 0.263 mmol) in dry THF (1.5 mL) was cooled to −78 °C, maintained under argon, and slowly treated with *n*BuLi (2.5 M in hexanes, 125 μL, 0.316 mmol). The reaction mixture was stirred as such for 4 h, after which an aqueous saturated solution of NH_4Cl (5 mL) was added, and the mixture was allowed to warm up to rt. The biphasic mixture was separated and the aqueous phase was extracted with Et_2O (3 × 5 mL). The solvent was removed under reduced pressure without heating. Purification of the residue by flash chromatography (hexanes/Et_2O = 100/0 to 90/10) gave a mixture of the [1,2]-rearrangement product **11** (15 mg, 45%) and the [1,4]-rearrangement product **12** (4 mg, 12%), both as colorless oils. A minor impurity could not be separated from **12**. [1,2]-Rearrangement product (**11**): IR (neat): ν_{max} = 3329, 2925, 2857, 1448, 916 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ = 5.96−5.86 (1H, m), 5.42 (1H, brs), 5.28 (1H, d, J = 17.2 Hz), 5.19 (1H, d, J = 10.5 Hz), 3.99 (1H, brs), 2.27 (1H, brs), 2.00−1.84 (2H, m), 1.84−1.70 (2H, m), 1.71 (3H, s), 1.66−1.48 (2H, m), 1.43−1.30 (1H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 139.7, 137.4, 119.8, 114.6, 76.0, 41.0, 29.8, 25.1, 23.8, 21.6; HRMS (ESIMS): calcd for $C_{10}H_{17}O$ $[M+H]^+$ 153.1274, found 153.1269. [1,4]-Rearrangement product (**12**): ^1H NMR (400 MHz, $CDCl_3$): δ = 9.80 (1H, s), 5.26 (1H, s), 2.50 (2H, t, J = 1.8 Hz), 2.08 (1H, brs), 2.01−1.82 (2H, m), 1.79−1.71 (2H, m), 1.69−1.52 (3H, m), 1.67 (3H, s), 1.16−1.09 (1H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 202.6, 134.7, 124.5, 41.1, 34.4, 29.8, 28.2, 28.1, 23.5, 21.0; HRMS (ESIMS): calcd for $C_{10}H_{16}ONa$ $[M+Na]^+$ 175.1093, found 175.1100.

(±)-(*E*)-3-(Prop-1-enyl)cyclohex-2-enol. A solution of the commercially available cyclohexadione (200 mg, 1.470 mmol) in CH_2Cl_2/MeOH (1:1, 10 mL) was cooled to 0 °C, and $CeCl_3{\cdot}7H_2O$ (725 mg, 0.294 mmol) and $NaBH_4$ (67 mg, 1.763 mmol) were added in portions. After stirring for 2 h, an aqueous saturated solution of NH_4Cl (15 mL) was added to the mixture, the biphasic mixture was separated, and the aqueous phase was extracted with CH_2Cl_2 (3 × 10 mL). The solvent was removed under reduced pressure without heating. Purification of the residue by flash chromatography (hexanes/Et_2O = 80/20) gave the title allylic alcohol (160 mg, 79%) as a colorless light oil. IR (neat): ν_{max} = 3294, 2930, 2860, 1448, 1034, 962 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ = 6.03 (1H, d, J = 15.6 Hz), 5.76−5.63 (1H, m), 5.61 (1H, s), 4.26 (1H, s), 2.20−2.01 (3H, m), 1.84−1.76 (2H, m), 1.76 (3H, d, J = 6.5 Hz), 1.65−1.48 (2H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 138.0, 133.4, 127.8, 124.1, 65.8, 31.7, 24.1, 18.6, 17.9; HRMS (ESIMS): calcd for $C_9H_{14}ONa$ $[M+Na]^+$ 161.0937, found 161.0939.

(±)-(*E*)-3-(Allyloxy)-1-(prop-1-enyl)cyclohex-1-ene (13). A solution of (*E*)-3-(prop-1-enyl)cyclohex-2-enol (75 mg, 0.543 mmol) in THF (3 mL) was cooled to 0 °C and treated with KHMDS (0.5 M in toluene, 130 μL, 0.652 mmol) under argon. After 5 min, allyl iodide (75 μL, 0.815 mmol) was added at the same temperature and the mixture was allowed to stir as such for 2 h. The reaction mixture was quenched at 0 °C with a saturated solution of NH_4Cl (5 mL). The biphasic mixture was separated, and the aqueous phase was extracted with Et_2O (3 × 20 mL). The solvent was removed under reduced pressure without heating. Purification of the residue by flash chromatography (hexanes/Et_2O = 100/0 to 95/5) gave the title compound (65 mg, 71%) as a colorless light oil. R_f = 0.6 (hexanes/EtOAc = 95/5) [$KMnO_4$]. IR (neat): ν_{max} = 2930, 1645, 1374, 1339, 1076 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ = 6.05 (1H, d, J = 17.4 Hz), 6.00−5.85 (1H, m), 5.73−5.65 (2H, m), 5.28 (1H, d, J = 17.2 Hz), 5.14 (1H, d, J = 10.3 Hz), 4.05−3.96 (3H, m), 2.19−2.04 (2H, m), 1.86−1.75 (2H, m), 1.76 (3H, d, J = 6.4 Hz), 1.66−1.51 (2H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 138.8, 135.5, 133.9, 126.0, 124.2, 116.5, 73.0, 69.1, 28.6, 24.7, 19.3, 18.3; HRMS (ESIMS) could not be done due to the volatility of the product.

(±)-(*E*)-1-(3-(Prop-1-enyl)cyclohex-2-enyl)prop-2-en-1-ol (14) and (±)-(*E*)-3-(3-(Prop-1-enyl)cyclohex-2-enyl)propanal (15). Obtained from the bis-allylether **13** (30 mg, 0.169 mmol) using the same procedure as that for compounds **11** and **12**. Purification of the residue by flash chromatography (hexanes/Et_2O = 100/0 to 90/10) gave a mixture of the [1,2]-rearrangement product **14** (14 mg, 45%) and the [1,4]-rearrangement product **15** (5 mg, 17%) as colorless oils. A minor impurity could not be separated from **15**. [1,2]-Rearrangement product (**14**): IR (neat): ν_{max} = 3359, 2928, 2858, 1447, 963 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ = 6.10 (1H, d, J = 15.4 Hz), 5.95−5.86 (1H, m), 5.69−5.60 (2H, m), 5.28 (1H, d, J = 17.2 Hz), 5.19 (1H, d, J = 10.5 Hz), 4.01 (1H, brs), 2.42−2.34 (1H, m), 2.24−2.00 (2H, m), 1.95−1.80 (1H, m), 1.77 (3H, d, J = 6.3 Hz), 1.66−1.48 (2H, m), 1.43−1.25 (2H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 139.8, 138.4, 134.5, 125.6, 122.5, 115.3, 76.4, 41.9, 25.6, 24.7, 21.6, 18.2; HRMS (ESIMS): calcd for $C_{12}H_{18}ONa$ $[M+Na]^+$ 201.1250, found 201.1244. [1,4]-Rearrangement product (**15**): IR (neat): ν_{max} = 2927, 2856, 1724, 1447, 963 cm^{-1}; ^1H NMR (400 MHz,

dx.doi.org/10.1021/jo401488y | J. Org. Chem. 2013, 78, 8915−8921

$CDCl_3$): δ = 9.81 (1H, s), 6.05 (1H, d, J = 15.2 Hz), 5.53−5.54 (1H, m), 5.47 (1H, s), 2.50 (2H, t, J = 1.8 Hz), 2.24−2.01 (3H, m), 1.82−1.47 (6H, m), 1.76 (3H, d, J = 6.5 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 202.4, 136.0, 134.0, 129.6, 122.0, 41.0, 34.8, 28.4, 27.8, 24.3, 21.0, 17.9; HRMS (ESIMS): calcd for $C_{12}H_{19}O$ $[M+H]^+$ 179.1430, found 179.1422.

(±)-*syn*-4-(*tert*-Butyl)-3-methylcyclohex-2-enol and (±)-*anti*-4-(*tert*-Butyl)-3-methylcyclohex-2-enol. A solution of the known 4-(*tert*-butyl)-cyclohex-2-enone[28] (500 mg, 3.29 mmol) in dry Et_2O (13 mL) was cooled to −78 °C and treated with MeLi (1.6 M in Et_2O, 8.12 mL). Then, the mixture was warmed up to 0 °C, and MeLi (1.6 M in Et_2O, 8.12 mL) was added again. The solution was stirred as such for 10 min, after which a solution of the known 4-(*tert*-butyl)-cyclohex-2-enone (500 mg, 3.29 mmol) in dry Et_2O (1 mL) was slowly added and the mixture was stirred for 2 h. Then, TEA (0.915 mL, 6.57 mmol) and TMSCl (0.830 mL, 6.57 mmol) were added, and the mixture was stirred for 2 h while warming up to rt. The reaction was then quenched with H_2O (20 mL), and the aqueous phase was extracted with hexanes (3 × 10 mL). The combined organic phases were dried over Na_2SO_4 and then concentrated under reduced pressure. Without further purification, the crude silylenolether was dissolved in MeCN (15 mL) and $Pd(OAc)_2$ (1.05 equiv) was added at rt. The reaction mixture was stirred for 16 h and then filtered on Celite, and the solvent was removed under reduced pressure. The residue was purified by flash chromatography (hexanes/EtOAc = 80/20) to give the known 4-(*tert*-butyl)-3-methyl-cyclohex-2-enone[29] (410 mg, 83%). The latter enone (370 mg, 2.43 mmol) was subjected to the reduction conditions used for preparing (±)-(*E*)-3-(prop-1-enyl)cyclohex-2-enol. The residue was purified by flash chromatography (hexanes/EtOAc = 100/0 to 90/10) to give the two title alcohols (360 mg, d.r. = 3:2, 96%) as separable colorless oils. *syn*-4-(*tert*-Butyl)-3-methylcyclohex-2-enol: IR (neat): ν_{max} = 3319, 2946, 2868, 1441, 1367, 1275, 1198, 1138, 1084, 987 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.64 (1H, brs), 4.18 (1H, m), 1.88−1.77 (2H, m), 1.86 (3H, s), 1.72−1.63 (4H, m), 1.04 (9H, s); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 141.5, 128.3, 86.0, 48.1, 33.5, 30.2, 29.9, 26.8, 23.1; HRMS (ESIMS): calcd for $C_{11}H_{20}ONa$ $[M+Na]^+$ 191.1406, found 191.1398. *anti*-4-(*tert*-Butyl)-3-methylcyclohex-2-enol: IR (neat): ν_{max} = 3323, 2950, 2864, 1445, 1367, 1276, 1220, 1171, 1132, 1004 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.56 (1H, brs), 4.08 (1H, brs), 2.03−1.97 (2H, m), 1.88−1.83 (1H, m), 1.86 (3H, s), 1.78−1.70 (1H, m), 1.55−1.45 (1H, m), 1.42−1.33 (1H, m), 0.96 (9H, s); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 139.3, 130.2, 86.4, 48.2, 34.1, 31.4, 29.7, 26.8, 23.1; HRMS (ESIMS): calcd for $C_{11}H_{20}ONa$ $[M+Na]^+$ 191.1406, found 191.1398.

Typical Procedure for the Synthesis of 16, 20, 23, 25, 28, 29, 30, 35, 36, 37, and 42. A solution of the starting alcohol (1 equiv) in dry THF (0.2 M) was slowly added to a suspension of KH in mineral oil (30%, 1 mL) at rt under argon. After stirring for 2 h at rt, the suspension was cooled to 0 °C and quenched very carefully with water (10 mL). The organic and aqueous phases were then separated, and the aqueous phase was extracted with Et_2O (3 × 10 mL). The combined organic layers were then dried over Na_2SO_4, and the solvent was removed under reduced pressure.

(±)-Tributyl ((3-Methylcyclohex-2-enyloxy)methyl)stannane (16). Obtained from 3-methylcyclohex-2-enol (100 mg, 0.892 mmol) using the general procedure. The residue was purified by flash chromatography (hexanes/EtOAc = 100/0 to 97.5/2.5) to give the stannane **16** (250 mg, 68%) as a light colorless liquid. IR (neat): ν_{max} = 2923, 2853, 1454, 1059 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.54 (1H, brs), 3.83 (1H, d, J = 10.0 Hz), 3.75 (1H, d, J = 10.0 Hz), 3.59 (1H, brs), 1.99−1.82 (2H, m), 1.77−1.67 (1H, m), 1.69 (3H, s), 1.65−1.42 (8H, m), 1.39−1.27 (6H, m), 1.01−0.83 (16H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 137.7, 122.2, 58.2, 30.0, 28.8, 27.1, 26.9, 26.5, 23.4, 19.1, 13.3, 8.6; HRMS (ESIMS): calcd for $C_{20}H_{40}OSnNa$ $[M+Na]^+$ 439.1993, found 439.1997.

(±)-(*E*)-Tributyl ((3-(Prop-1-enyl)cyclohex-2-enyloxy)-methyl)stannane (20). Obtained from (±)-(*E*)-3-(prop-1-enyl)-cyclohex-2-enol (±) (85 mg, 0.616 mmol) using the general procedure. The residue was purified by flash chromatography (hexanes 100%) to give the stannane **20** (120 mg, 44%) as a light colorless liquid. IR (neat): ν_{max} = 2922, 2852, 1455, 1068, 962 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 6.08 (1H, d, J = 15.7 Hz), 5.73−5.66 (2H, m), 3.85 (1H, d, J = 10.0 Hz), 3.76 (1H, d, J = 10.0 Hz), 3.72 (1H, brs), 2.16−2.02 (2H, m), 1.88−1.79 (2H, m), 1.80 (3H, d, J = 6.4 Hz), 1.62−1.46 (8H, m), 1.41−1.27 (6H, m), 1.01−0.80 (15H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 137.8, 133.8, 126.3, 123.5, 77.6, 58.3, 28.8, 27.6, 26.9, 24.4, 19.0, 17.9, 13.4, 8.6; HRMS (ESIMS): calcd for $C_{22}H_{43}OSn$ $[M+H]^+$ 443.2336, found 443.2330.

(±)-Tributyl ((3-Methylcyclopent-2-enyloxy)methyl)-stannane (23). Obtained from 3-methylcyclopent-2-enol (100 mg, 0.0892 mmol) using the general procedure. The residue was purified by flash chromatography (hexanes/EtOAc = 100/0 to 92/8) to give the stannane **23** (300 mg, 84%) as a light colorless liquid. IR (neat): ν_{max} = 2962, 2925, 1458, 1379, 1350, 1157, 1055 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.49 (1H, s), 4.29 (1H, brs), 3.72 (1H, d, J = 10.5 Hz), 3.66 (1H, d, J = 10.5 Hz), 2.43−2.29 (1H, m), 2.20−2.05 (2H, m), 1.83−1.71 (1H, m), 1.77 (3H, s), 1.61−1.39 (6H, m), 1.30 (6H, m), 0.98−0.80 (15H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 145.7, 125.3, 88.8, 58.5, 35.3, 30.3, 29.1, 27.3, 16.9, 13.7, 9.0; HRMS (ESIMS): calcd for $C_{19}H_{38}ONaSn$ $[M+Na]^+$ 425.1837, found 425.1838.

(±)-Tributyl (((*syn*-4-(*tert*-Butyl)-3-methylcyclohex-2-en-1-yl)oxy)methyl)stannane (25). Obtained from *syn*-4-(*tert*-butyl)-3-methylcyclohex-2-enol (150 mg, 0.893 mmol) described above, using the general procedure. The residue was purified by flash chromatography (hexanes/EtOAc = 100/0 to 95/5) to give the stannane **25** (361 mg, 86%) as a light colorless liquid. IR (neat): ν_{max} = 2956, 2867, 1460, 1372, 1196, 1084, 1044, 924 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.63 (1H, brs), 3.84 (1H, d, J = 12.0 Hz), 3.76 (1H, d, J = 12.0 Hz), 3.51 (1H, m), 2.04−1.96 (1H, m), 1.94−1.88 (1H, m), 1.85 (3H, s), 1.80−1.73 (1H, m), 1.59−1.50 (6H, m), 1.38−1.30 (8H, m), 0.98 (9H, s), 0.96−0.90 (15H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 138.6, 128.7, 55.6, 48.6, 34.1, 31.6, 29.5, 29.2, 27.5, 27.3, 26.7, 23.4, 22.7, 14.1, 13.7, 9.0; HRMS (ESIMS): calcd for $C_{24}H_{48}ONaSn$ $[M+Na]^+$ 495.2624, found 495.2616.

(±)-Tributyl (((*anti*-4-(*tert*-Butyl)-3-methylcyclohex-2-en-1-yl)oxy)methyl)stannane (28). Obtained from *anti*-4-(*tert*-butyl)-3-methylcyclohex-2-enol (100 mg, 0.595 mmol) described above, using the general procedure. The residue was purified by flash chromatography (hexanes/EtOAc = 100/0 to 95/5) to give the stannane **28** (208 mg, 74%) as a light colorless liquid. IR (neat): ν_{max} = 2954, 2921, 2850, 1717, 1457, 1346, 1173, 1048, 957 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.68 (1H, brs), 3.80 (1H, d, J = 12.0 Hz), 3.75 (1H, d, J = 12.0 Hz), 3.60 (1H, m), 1.88−1.83 (1H, m), 1.86 (3H, s), 1.80−1.69 (2H, m), 1.59−1.51 (6H, m), 1.38−1.28 (8H, m), 1.03 (9H, s), 0.96−0.92 (15H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 140.8, 126.6, 58.2, 48.4, 33.7, 31.6, 30.2, 29.2, 27.3, 27.0, 26.1, 23.4, 22.7; HRMS (ESIMS): calcd for $C_{24}H_{48}ONaSn$ $[M+Na]^+$ 495.2624, found 495.2622.

(±)-Tributyl (((2-Methylcyclopent-1-enyl)methoxy)methyl)-stannane (29). Obtained from the known (2-methylcyclopent-1-enyl)methanol[30] (100 mg, 0.892 mmol) using the general procedure. The residue was purified by flash chromatography (hexanes/EtOAc = 100/0 to 94/6) to give the stannane **29** (180 mg, 70%) as a light colorless liquid. IR (neat): ν_{max} = 2961, 2925, 2850, 1466, 1379, 1050, 876 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 3.90 (2H, s), 3.71−3.62 (2H, m), 2.42−2.26 (4H, m), 1.84−1.73 (2H, m), 1.68 (3H, s), 1.60−1.41 (6H, m), 1.30 (6H, sept, J = 7.3 Hz), 0.97−0.79 (15H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 136.2, 132.4, 71.3, 60.7, 38.8, 34.6, 29.1, 27.3, 21.6, 13.9, 13.7, 8.9; HRMS (ESIMS): calcd for $C_{20}H_{40}ONaSn$ $[M+Na]^+$ 439.1993, found 439.1991.

(±)-Tributyl (((2-Methylcyclohex-1-enyl)methoxy)methyl)-stannane (30). Obtained from the known (2-methylcyclohex-1-enyl)methanol[30] (100 mg, 0.892 mmol) using the general procedure. The residue was purified by flash chromatography (hexanes/EtOAc = 100/0 to 94/6) to give the stannane **30** (320 mg, 94%) as a light colorless liquid. IR (neat): ν_{max} = 2961, 2928, 2861, 2346, 1460, 1379, 1251, 1140, 1052, 875 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 3.83 (2H, s), 3.68 (2H, m), 2.03−1.94 (4H, m), 1.67 (3H, s), 1.62−1.56

dx.doi.org/10.1021/jo401488y | J. Org. Chem. 2013, 78, 8915−8921

(4H, m), 1.54−1.46 (6H, m), 1.30 (6H, sept, J = 7.3 Hz), 1.00−0.80 (15H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 132.1, 127.6, 74.9, 60.8, 32.0, 29.2, 27.6, 27.3, 23.1, 19.1, 13.7, 8.9; HRMS (ESIMS): calcd for $C_{21}H_{42}ONaSn$ $[M+Na]^+$ 453.2150, found 453.2156.

Tributyl ((2-Cyclopentylideneethoxy)methyl)stannane (35). Obtained from the known 2-cyclopentylideneethanol[31] (150 mg, 1.34 mmol) using the general procedure. The residue was purified by flash chromatography (hexanes/EtOAc = 100/0 to 96/4) to give the stannane **35** (400 mg, 72%) as a light colorless liquid. IR (neat): ν_{max} = 2954, 2921, 2850, 1717, 1457, 1346, 1173, 1048, 957 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.47−5.41 (1H, m), 3.86 (2H, d, J = 6.2 Hz), 3.76−3.72 (2H, m), 2.34−2.22 (4H, m), 1.74−1.57 (4H, m), 1.58−1.49 (7H, m), 1.39−1.26 (7H, m), 0.97−0.79 (15H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 147.6, 117.1, 73.0, 61.2, 33.7, 29.1, 28.8, 27.3, 26.3, 26.1, 13.7, 9.0; HRMS (ESIMS): calcd for $C_{20}H_{40}ONaSn$ $[M+Na]^+$ 439.1993, found 439.1981.

Tributyl ((2-Cyclohexylideneethoxy)methyl)stannane (36). Obtained from the known 2-cyclohexylideneethanol[31] (160 mg, 1.27 mmol) using the general procedure. The residue was purified by flash chromatography (hexanes/EtOAc = 100/0 to 96/4) to give the stannane **36** (350 mg, 64%) as a light colorless liquid. IR (neat): ν_{max} = 2922, 2849, 1453, 1047, 866 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.31−5.24 (1H, m), 3.88 (2H, d, J = 6.2 Hz), 3.76−3.72 (2H, m), 2.22−2.18 (2H, m), 2.16−2.12 (2H, m), 1.59−1.46 (11H, m), 1.32−1.26 (7H, m), 0.97−0.79 (15H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 144.3, 118.2, 70.6, 61.0, 37.1, 29.1, 29.1, 28.5, 27.8, 27.3, 26.7, 13.7, 9.0; HRMS (ESIMS): calcd for $C_{21}H_{42}ONaSn$ $[M+Na]^+$ 453.2150, found 453.2142.

Tributyl ((2-Cycloheptylideneethoxy)methyl)stannane (37). Obtained from the known 2-cycloheptylideneethanol[32] (170 mg, 1.21 mmol) using the general procedure. The residue was purified by flash chromatography (hexanes/EtOAc = 100/0 to 98/2) to give the stannane **37** (380 mg, 71%) as a light colorless liquid. IR (neat): ν_{max} = 2919, 2850, 1454, 1377, 1059, 869 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.35−5.27 (1H, m), 3.86 (2H, d, J = 5.6 Hz), 3.76−3.72 (2H, m), 2.28−2.22 (4H, m), 1.63−1.44 (14H, m), 1.35−1.25 (6H, m), 0.95−0.84 (15H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 145.4, 122.0, 71.4, 61.2, 37.7, 30.2, 29.8, 29.1, 29.0, 28.9, 27.3, 27.2, 13.7, 9.0; HRMS (ESIMS) could not be done.

Tributyl (Phenethoxymethyl)stannane (42). Obtained from phenethyl alcohol (136 mg, 1.12 mmol) using the general procedure. The residue was purified by flash chromatography (hexanes/EtOAc = 100/0 to 97.5/2.5) to give the stannane **42** (365 mg, 77%) as a light colorless liquid. IR (neat): ν_{max} = 2954, 2921, 2851, 1454, 1080 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.35−7.25 (5H, m), 3.81 (2H, s), 3.60 (2H, t, J = 7.0 Hz), 2.92 (2H, t, J = 7.0 Hz), 1.67−1.44 (6H, m), 1.40−1.34 (9H, m), 0.98−0.93 (12H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 139.5, 129.0, 128.2, 126.0, 76.3, 62.0, 36.4, 29.2, 27.4, 13.7, 9.0; HRMS (ESIMS): calcd for $C_{21}H_{38}OSnNa$ $[M+Na]^+$ 449.1837, found 449.1833.

Typical Procedure for the Wittig−Still Rearrangement from the Stannyl Ethers 20, 25, 28, 29, 30, 35, 36, and 37. A solution of the starting stannyl ether (1 equiv) in dry THF (0.2 M) was cooled to −78 °C and slowly treated with *n*BuLi (2.5 M in hexanes, 1.05 equiv). The reaction mixture was stirred as such for 20 min, after which it was transferred to a −20 °C cooling bath (unless otherwise stated) and stirred for the indicated time. Then, the reaction was quenched upon addition of an aqueous saturated solution of NH_4Cl, and the mixture was allowed to warm up to rt. The biphasic mixture was separated, and the aqueous phase was extracted with Et_2O (3 × 5 mL).

(±)-(*E*)-(1-(Prop-1-enyl)cyclohex-2-enyl)methanol (21) and (±)-(*E*)-(3-(Prop-1-enyl)cyclohex-2-enyl)methanol (22). Obtained from the tin ether **20** (90 mg, 0.204 mmol) using the general procedure. Purification of the residue by flash chromatography (hexanes/Et_2O = 100/0 to 90/10) gave a mixture of the [2,3]-rearrangement product **21** (12 mg, 40%) and the [1,2]-rearrangement product **22** (10 mg, 33%), both as colorless oils. [2,3]-Rearrangement product (**21**): IR (neat): ν_{max} = 3294, 2930, 1447, 1032, 970 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.89−5.80 (1H, m), 5.54−5.32 (3H, m), 3.50−3.37 (3H, m), 2.02−1.97 (1H, m), 1.63 (3H, d, J = 6.8 Hz), 1.59−1.49 (5H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 135.4, 129.4, 129.3, 126.7, 69.6, 43.3, 30.6, 29.8, 25.1, 18.0; HRMS (ESIMS): calcd for $C_{10}H_{16}ONa$ $[M+Na]^+$ 175.1098, found 175.1104. [1,2]-Rearrangement product (**22**): IR (neat): ν_{max} = 3302, 2923, 2856, 1445, 1052, 963, 909 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 6.08 (1H, d, J = 15.7 Hz), 5.72−5.61 (1H, m), 5.55 (1H, s), 3.57 (2H, d, J = 6.3 Hz), 2.42 (1H, brs), 2.24−2.17 (1H, m), 2.17−2.04 (1H, m), 1.86−1.73 (2H, m), 1.76 (3H, d, J = 6.5 Hz), 1.64−1.55 (1H, m), 1.46 (1H, brs), 1.42−1.32 (1H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 137.9, 134.3, 126.7, 122.6, 61.7, 38.9, 25.6, 24.8, 21.1, 18.2; HRMS (ESIMS): calcd for $C_{10}H_{16}ONa$ $[M+Na]^+$ 175.1099, found 175.1089.

(±)-(6-(*tert*-Butyl)-1-methylcyclohex-2-en-1-yl)methanol (26) and (±)-(4-(*tert*-Butyl)-3-methylcyclohex-2-en-1-yl)-methanol (27). Obtained from the tin ether **25** (100 mg, 0.212 mmol) using the general procedure. Purification of the residue by flash chromatography (hexanes/EtOAc = 100/0 to 80/20) gave a mixture of the [2,3]-rearrangement product **26** (6 mg, 17%) and the [1,2]-rearrangement product **27** (25 mg, 71%). [1,2]-Rearrangement product (**27**): IR (neat): ν_{max} = 3327, 2946, 2864, 1461, 1367, 1196, 1030 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.44 (1H, brs), 3.54 (2H, d, J = 6.2 Hz), 2.34 (1H, brs), 1.95−1.84 (2H, m), 1.84 (3H, m), 1.63−1.57 (1H, m), 1.52−1.43 (2H, m), 1.00 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$) of the mixture: δ = 138.8, 126.1, 66.8, 47.3, 38.6, 33.0, 30.4, 27.0, 25.0, 22.0; HRMS (ESIMS): calcd for $C_{12}H_{22}OLi$ $[M+Li]^+$ 189.1825, found 189.1823. [2,3]-Rearrangement product (**26**): R_f = 0.25 (15% EtOAc/hexanes), [$KMnO_4$], not seen by UV. IR (neat): ν_{max} = 3415, 2958, 2903, 2836, 1482, 1396, 1367, 1227, 1043, 1004, 892 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.93−5.88 (1H, m), 4.22 (1H, d, J = 5.2 Hz), 3.92−3.86 (1H, m), 3.53−3.47 (1H, m), 2.15−2.07 (1H, m), 2.03−1.92 (1H, m), 1.77−1.62 (2H, m), 1.36−1.33 (1H, m), 1.29−1.25 (1H, m), 1.15 (3H, s), 1.07 (9H, s); ^{13}C NMR (100 MHz, $CDCl_3$) of the mixture: δ = 136.5, 128.7, 87.6, 52.8, 42.6, 34.6, 30.1, 28.0, 26.5, 23.3; HRMS (ESIMS): calcd for $C_{12}H_{22}ONa$ $[M+Na]^+$ 205.1563, found 205.1567.

(±)-(1-Methyl-2-methylenecyclopentyl)methanol (31) and (±)-(1,2-Dimethylcyclopent-2-en-1-yl)methanol. Obtained from the tin ether **29** (150 mg, 0.361 mmol) using the general procedure. Purification of the residue by flash chromatography (hexanes/EtOAc = 100/0 to 87/13) gave an inseparable mixture of the [2,3]-rearrangement product **31** and its regioisomer (3:2, 27 mg, 60%) as well as 2-methylcyclopent-1-enyl)methanol **32**[33] as determined by ^{1}H NMR (4 mg, 10%). IR (neat): ν_{max} = 3352, 2958, 2872, 1653, 1453, 1382, 1043, 1022 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 4.98 (1H, brs), 4.77 (1H, brs), 3.48 (1H, d, J = 7.4 Hz), 3.33 (1H, d, J = 7.4 Hz), 2.46−2.29 (2H, m), 1.84−1.76 (1H, m), 1.69−1.55 (3H, m), 1.52−1.42 (1H, m), 1.06 (3H, s); ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.46 (1H, brs), 3.36 (2H, dd, J = 31.5, 10.8 Hz), 2.27−2.21 (2H, m), 2.08−2.00 (1H, m), 1.69−1.55 (2H, m), 1.61 (3H, s), 0.98 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$) of the mixture: δ = 158.1, 142.7, 127.1, 105.2, 69.3, 68.7, 51.6, 47.4, 36.9, 34.8, 33.9, 29.6, 23.9, 22.6, 21.5, 12.3; HRMS (ESIMS): calcd for $C_8H_{15}O$ $[M+H]^+$ 127.1117, found 127.1119.

(±)-1-Methyl-2-methylenecyclohexanol (33). Obtained from the tin ether **30** (150 mg, 0.349 mmol) using the general procedure. Purification of the residue by flash chromatography (hexanes/EtOAc = 100/0 to 88.0/12.0) gave the [2,3]-rearrangement product **33** (34 mg, 70%) as a colorless oil, as well as **34** (2 mg, 5%). IR (neat): ν_{max} = 3345, 2933, 2863, 1639, 1449, 1050, 1027 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 4.89 (1H, s), 4.76 (1H, s), 3.69 (1H, d, J = 10.6 Hz), 3.42 (1H, d, J = 10.6 Hz), 2.30−2.05 (2H, m), 1.73−1.48 (4H, m), 1.47−1.19 (3H, m), 1.09 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 152.3, 109.0, 67.9, 41.8, 36.4, 33.1, 28.0, 23.4, 22.1; HRMS (ESIMS): calcd for $C_9H_{17}O$ $[M+H]^+$ 141.1274, found 141.1272.

(1-Vinylcyclopentyl)methanol (38). Obtained from the tin ether **35** (200 mg, 0.480 mmol) using the general procedure. Purification of the residue by flash chromatography (hexanes/EtOAc = 100/0 to 90/10) gave a mixture of the [2,3]-rearrangement product **38** (36 mg, 60%). IR (neat): ν_{max} = 3357, 2949, 2866, 1635, 1454, 1040, 1001, 909 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.83 (1H, dd, J = 17.5, 10.8

dx.doi.org/10.1021/jo401488y | J. Org. Chem. 2013, 78, 8915−8921

Hz), 5.18 (1H, d, J = 10.8 Hz), 5.16 (1H, d, J = 17.5 Hz), 3.41 (2H, s), 1.66−1.50 (13H, m); ^{13}C NMR (100 MHz, $CDCl_3$) δ = 144.3, 113.6, 68.6, 51.5, 33.6, 24.2; HRMS (ESIMS): calcd for $C_8H_{14}OLi$ $[M+Li]^+$ 133.1199, found 133.1204.

(1-Vinylcycloheptyl)methanol (40). Obtained from the tin ether **37** (250 mg, 0.450 mmol) using the general procedure. Purification of the residue by flash chromatography (hexanes/EtOAc = 100/0 to 90/10) gave a mixture of the [2,3]-rearrangement product **40** (44 mg, 64%). IR (neat): ν_{max} = 3358, 2916, 2855, 1635, 1459, 1058, 1022, 910 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.68 (1H, dd, J = 17.7, 10.9 Hz), 5.18 (1H, d, J = 10.9 Hz), 5.06 (1H, d, J = 17.7 Hz), 3.27 (2H, s), 1.63−1.41 (13H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 145.3, 114.4, 69.6, 45.6, 34.1, 30.4, 22.6; HRMS (ESIMS): calcd for $C_{10}H_{18}OLi$ $[M+Li]^+$ 161.1512, found 161.1518.

■ ASSOCIATED CONTENT

Supporting Information

Copies of the ^{1}H and ^{13}C NMR spectra of new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: stephen.hanessian@umontreal.ca.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We acknowledge financial support from NSERC, and FQRNT for a fellowship to S.D. We thank the CFI for a departmental grant.

■ REFERENCES

(1) For an authoritative monograph, see: (a) *Quaternary Stereocenters: Challenges and Solutions for Organic Chemistry*; Christoffers, J., Baro, A., Eds.; Wiley-VCH: Weinheim, 2005. (b) Fuji, K. *Chem. Rev.* **1993**, *93*, 2037−2066.

(2) For selected examples, see: (a) Corey, E. J.; Guzman-Perez, A. *Angew. Chem., Int. Ed.* **1998**, *37*, 388−401. (b) Denissova, I.; Barriault, L. *Tetrahedron* **2003**, *59*, 10105−10146. (c) Douglas, C. J.; Overman, L. E. *Proc. Natl. Acad. Sci. U.S.A.* **2004**, *101*, 5363−5367. (d) Trost, B. M.; Jiang, C. *Synthesis* **2006**, 369−396.

(3) See for example: (a) Martin, C. L.; Overman, L. E. *J. Am. Chem. Soc.* **2010**, *132*, 4894−4906. (b) Jones, S. B.; Simmons, B.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2009**, *131*, 13606−13607. (c) Arineuto, H.; Uemura, D. In *Quaternary Stereocenters: Challenges and Solutions for Organic Chemistry*; Christoffers, J., Baro, A., Eds.; Wiley-VCH: Weinheim, 2005; Chapter 1, pp 1−24.

(4) (a) Wittig, G.; Döser, H.; Lorenz, I. *Liebigs Ann. Chem.* **1949**, *562*, 192−205. (b) Nakai, T.; Mikami, K. *Chem. Rev.* **1986**, *86*, 885−902. (c) Marshall, M. A. In *Comprehensive Organic Synthesis*, Vol. 3; Trost, B. M., Fleming, I., Eds.; Pergamon: Oxford, 1991; pp 975−1014. (d) Marshall, M. A. In *Comprehensive Organic Synthesis*, Vol. 6; Trost, B. M., Fleming, I., Eds.; Pergamon: Oxford, 1991; pp 873−903. (e) Nakai, T.; Mikami, K. *Org. React.* **1994**, *46*, 105−209. (f) *Organolithiums: Selectivity for Synthesis*; Clayden, J., Ed.; Pergamon: Oxford, 2002; Chapter 8.

(5) (a) Nakai, T.; Mikami, K.; Taya, S.; Fujita, Y. *J. Am. Chem. Soc.* **1981**, *103*, 6492−6494. (b) Mikami, K.; Kimura, Y.; Kishi, N.; Nakai, T. *J. Org. Chem.* **1983**, *48*, 279−281. (c) Mikami, K.; Uchida, T.; Hirano, T.; Wu, Y.-D.; Houk, K. N. *Tetrahedron* **1994**, *50*, 5917−5926. (d) Tomooka, K.; Igarashi, T.; Watanabe, M.; Nakai, T. *Tetrahedron* **1992**, *33*, 5795−5798.

(6) Still, W. C.; Mitra, A. *J. Am. Chem. Soc.* **1978**, *100*, 1927−1928.

(7) Still, W. C. *J. Am. Chem. Soc.* **1978**, *100*, 1481−1487.

(8) Trost, B. M.; Mao, M. K.-T.; Balkovec, J. M.; Buhlmayer, P. *J. Am. Chem. Soc.* **1986**, *108*, 4965−4973.

(9) Castedo, L.; Mascareñas, J. L.; Mourinõ, A. *Tetrahedron Lett.* **1987**, *28*, 2099−2102.

(10) Crimmins, M. T.; Gould, L. D. *J. Am. Chem. Soc.* **1987**, *109*, 6199−6200.

(11) Sugimura, T.; Paquette, L. A. *J. Am. Chem. Soc.* **1987**, *109*, 3017−3024.

(12) Mulzer, J.; Riether, D. *Org. Lett.* **2000**, *2*, 3139−3141.

(13) Paquette, L. A.; Wright, J.; Drtina, G. J.; Roberts, R. A. *J. Org. Chem.* **1987**, *52*, 2960−2962.

(14) Ogura, A.; Yamada, K.; Yokoshima, S.; Fukuyama, T. *Org. Lett.* **2012**, *14*, 1632−1635.

(15) Peng, F.; Danishefsky, S. J. *J. Am. Chem. Soc.* **2012**, *134*, 18860−18867.

(16) Millar, J. G.; Moreira, J. A.; McElfresh, J. S.; Daane, K. M.; Freund, A. S. *Org. Lett.* **2009**, *11*, 2683−2685.

(17) For example, see: Cockerill, A. F. In *Comprehensive Chemical Kinetics, Addition and Elimination Reactions of Aliphatic Compounds*, Vol. 9; Bamford, C. H., Tipper, C. F. H., Eds.; Elsevier Science: New York, 1973; Chapter 3.

(18) Mantrand, N.; Renaud, P. *Tetrahedron* **2008**, *64*, 11860−11864.

(19) Zhu, M.-K.; Chen, Y.-C.; Loh, T.-P. *Chem.—Eur. J.* **2013**, *19*, 5250−5254.

(20) Umehara, T.; Inouye, Y.; Kakisawa, H. *Bull. Chem. Soc. Jpn.* **1981**, *54*, 3492−3494.

(21) Hirokawa, Y.; Kitamura, M.; Mizubayashi, M.; Nakatsuka, R.; Kobori, Y.; Kato, C.; Kurata, Y.; Maezaki, N. *Eur. J. Org. Chem.* **2013**, 721−727.

(22) Ryu, I.; Hirai, A.; Suzuki, H.; Sonoda, N.; Murai, S. *J. Org. Chem.* **1990**, *55*, 1409−1410.

(23) (a) Schöllkopf, U. *Angew. Chem., Int. Ed.* **1970**, *9*, 763−765. (b) Schöllkopf, U.; Fellenberger, K.; Rizk, M. *Justus Liebigs Ann. Chem.* **1970**, *734*, 106−115. (c) Baldwin, J. E.; Patrick, J. E. *J. Am. Chem. Soc.* **1971**, *93*, 3556−3558. (d) Rautenstrauch, V. *Helv. Chim. Acta* **1972**, *55*, 594−609.

(24) (a) Sayo, N.; Kimura, Y.; Nakai, T. *Tetrahedron Lett.* **1982**, *23*, 3931−3934. (b) Nakai, T.; Mikami, K. *Org. React.* **1994**, *46*, 114.

(25) Tomooka, K.; Igarashi, T.; Nakai, T. *Tetrahedron* **1994**, *50*, 5927−5932.

(26) Didier, P.; Pommier, J.-C. *J. Organomet. Chem.* **1978**, *150*, 203−214.

(27) Boche, G.; Bosold, F.; Lohrenz, J. C. W.; Opel, A.; Zulauf, P. *Chem. Ber.* **1993**, *126*, 1873−1885.

(28) Diao, T.; Stahl, S. S. *J. Am. Chem. Soc.* **2011**, *133*, 14566−14569.

(29) Matoba, K.; Maeda, T.; Nagase, K.; Yamazaki, T. *Chem. Pharm. Bull.* **1976**, *24*, 165−168.

(30) Lemieux, R. M.; Meyers, A. I. *J. Am. Chem. Soc.* **1998**, *120*, 5453−5457.

(31) Srikishna, A.; Kumar, P. P. *Tetrahedron* **2000**, *56*, 8189−8195.

(32) Clark, J. R.; French, J. M.; Jecs, E.; Diver, S. T. *Org. Lett.* **2012**, *14*, 4178−4181.

(33) Akers, J. A.; Bryson, T. A. *Tetrahedron Lett.* **1989**, *30*, 2187−2190.