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Formation and ring-opening of 8-oxabicyclo[3.2.1]oct-6-en-3-ones from (4+3)-cycloaddition of furan and chlorocyclopentanone derivatives

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ABSTRACT

During the course of studying an ene reaction of an oxyallylic cation derived from a 2-chlorocyclopentanone system, the reactive species was found to undergo quite facile (4+3)-cycloadditions with furans. Moreover, the (4+3)-cycloadducts derived from furans were prone to ring-opening, which resulted in the formation of 2-furanyl cyclopentanones in excellent yields. An acid-catalyzed mechanism was proposed for the ring-opening process. Several examples of both reactions were identified.

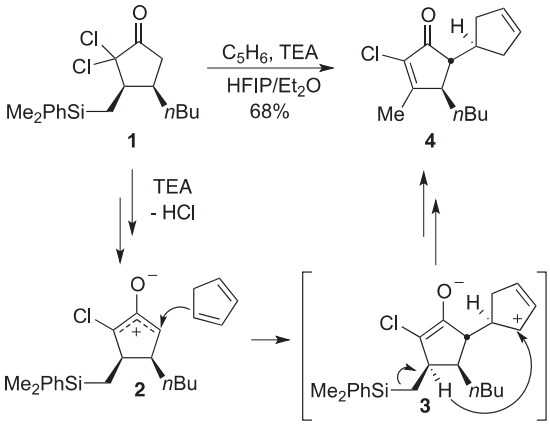
1. Introduction

The (4+3)-cycloaddition of allylic cations with dienes is a useful tool for the synthesis of seven-membered rings.[1] It has been used for the total synthesis of a number of biologically active natural products.[2] In the past few decades, the study of (4+3)-cycloadditions has been focused on the areas of allylic cation generation and enantioselective and diastereoselective reactions.[3] Although many aspects of the process have been investigated, there are still many opportunities associated with the dienophiles in the (4+3)-cycloaddition that warrant continued development.

For example, we recently reported an interrupted (4+3)-cycloaddition between a chloro-substituted oxyallylic cation and cyclopentadiene.[4] Thus, the reaction of **1** with cyclopentadiene in the presence of base produced the product **4** in very good yield (Scheme 1). This formal ene reaction presumably occurred via the intermediacy of oxyallylic cation **2** and clearly indicates that allylic cations can react with dienes in ways that do not lead to (4+3)-cycloaddition.[5] Furthermore, intermediates, such as **3** might be trapped or quenched intramolecularly to afford products that result in a divergence from a cyclization pathway. The reaction shown in Scheme 1 was exciting, as it was the first time that such reactions had been reported to proceed in synthetically useful yields. We initially set out to see if we could develop the process further, particularly in the context of an ene reaction that would be enantioselective by virtue of a desymmetrization of the reactive intermediate involved in the process.

2. Results and discussion

What we aimed to do was generate an oxyallylic cation that was symmetrical and appropriately substituted to afford ene reaction



Scheme 1.

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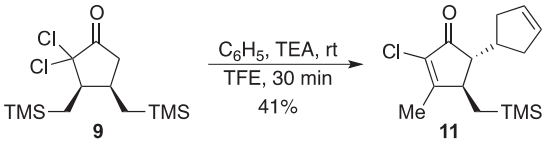
products. The generation of such a species would be accomplished by a chiral base, such that the interaction between the conjugate acid of the base and the oxyallylic species would generate an intermediate that was chiral and capable of reacting with other molecules in a facially selective fashion.

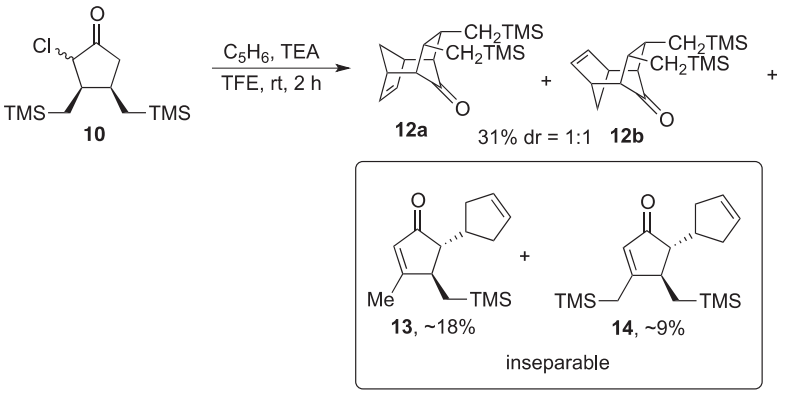
To that end, we prepared compound **10** as a progenitor to a symmetrical oxyallylic cation that contained structural features we considered important in promoting the ene reaction. Thus, metal-halogen exchange of 1,4-dichlorobutyne with lithium metal followed by trapping of the resulting organolithium afforded the disilylated alkyne **6** in 75% yield (Scheme 2).[6] Semi-hydrogenation of **6** afforded **7**, which underwent cycloaddition upon exposure to dichloroketene, giving cyclobutanone **8** in 89% yield. Ring expansion with diazomethane led to the facile formation of cyclopentanone **9**. This could be monodechlorinated with zinc and acetic acid to give the target compound **10**.[7]

Since it most closely resembled substrate **1**, we initially examined the reaction of **9** with cyclopentadiene. This worked exactly as expected with respect to regioselectivity and diastereoselectivity, though not quite with respect to yield. Exposure of **9** in a solution of TFE (trifluoroethanol) in the presence of 5 equiv of cyclopentadiene afforded the adduct **11** in 41% yield (Eq. 1). When the reaction was run with TFE/Et_2O (1:1) instead of TFE, the yield was 53%, but the product was not pure by NMR, even after attempted chromatographic purification.

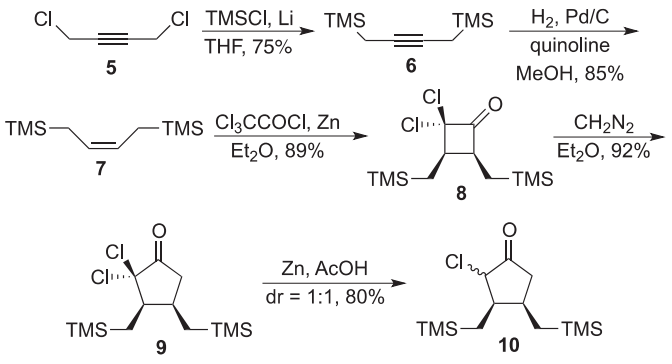


(1)

Encouraged by this result, we treated **10** under the same reaction conditions. As summarized in Eq. 2, the outcome was complicated. We obtained a mixture of (4+3)-cycloadducts **12a** and **12b** as well as what appeared to be an inseparable mixture of two ene reaction products, **13** and **14**.[8,9] This rather complex array of products gave us some pause and before proceeding further, we decided to examine the reactivity of **10** under conditions that might favor its successful reaction with simple dienes in order to assess how well behaved it could be under such 'ideal' conditions.



(2)

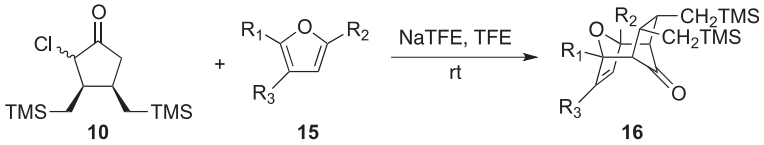


Scheme 2.

We thus undertook a study of the chemistry of **10** upon treatment with sodium trifluoroethoxide (NaTFE) in the presence of various furans. The results are summarized in Table 1. In general, only 2 equiv of the furan reaction partner were used in this process. The reaction was run at room temperature for 30 min. Furan itself gave essentially a quantitative yield of product requiring no further purification beyond filtration through a short pad of alumina (Table 1, entry 1). In general, 2-substituted furans gave excellent yields of cycloaddition product (Table 1, entries 2–4). However, the yields for 2-benzyl and 2-butylfuran were lower than those for simpler furans (Table 1, entries 10, 12). On the other hand, furan **15l** gave cycloadduct in 79% yield (Table 1, entry 13), while **15j** afforded **16j** in only 32% yield (Table 1, entry 11). We speculate that problems associated with loss of the TBS group in the latter case contributed to the lower yield. We were disappointed to find that both **15g** and **15h** gave only low yields of product, but no attempt was made to optimize the reaction for these substrates (Table 1, entries 8–9).

Typically, 2,5-dialkylfurans give good yields of cycloaddition product in (4+3)-cycloadducts and this held true with **10** as the precursor to the oxyallylic cation dienophile. 2,5-Dimethylfuran and the more sterically crowded **15e** afforded cycloadducts **16d** and **16e** in 90% and 84% yield, respectively (Table 1, entries 5–6).

Table 1
(4+3)-Cycloaddition reactions of **10**

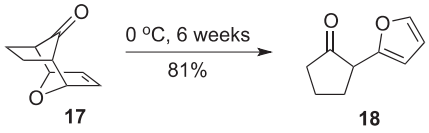


Entry	15	R_1	R_2	R_3	16	Yield (%)[a]
1	**a**	H	H	H	**a**	100
2	**b**	Me	H	H	**b**	98
3	**b**	Me	H	H	**b**	98
4	**c**	Et	H	H	**c**	93
5	**d**	Me	Me	H	**d**	90[c]
6	**e**	Me	^{i}Pr	H	**e**	84
7	**f**	H	H	Br	**f**	81
8	**g**	CH_2OMe	H	H	**g**	19
9	**h**	CH_2OTBS	H	H	**h**	24
10	**i**	Bn	H	H	**i**	48
11	**j**	$(CH_2)_4OTBS$	H	H	**j**	32
12	**k**	^{n}Bu	H	H	**k**	[b]
13	**l**	$(CH_2)_3Cl$	H	H	**l**	79

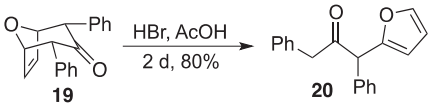
[a] Product was purified on an alumina column.
[b] Pure compound not obtained due to facility of fragmentation to **23k** (see Table 2, entry 7).
[c] Structure was confirmed by X-ray crystallography.

Interestingly, 3-bromofuran functioned quite well in this process giving the corresponding cycloadduct **16f** in 81% yield (Table 1, entry 7). Furans containing olefin, ketone, aldehyde, ester, and free alcohol functionalities generally did not react cleanly in this process.

The cycloadducts obtained in these reactions are at the border of structural stability. Indeed, it has been known for some time that (4+3)-cycloadducts, derived from furans in particular, are subject to degradation. In addition, such cycloadducts derived from cyclopentenyl dienophiles are even more disposed to decomposition due to strain.[10] However, this decomposition can be productive.

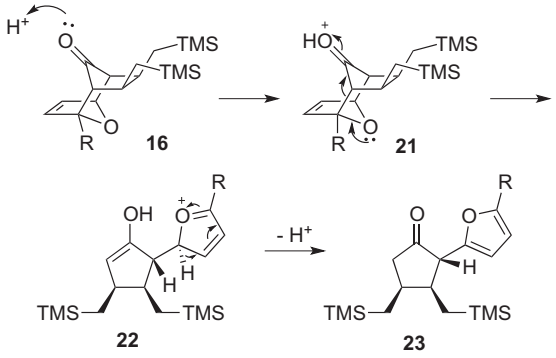


(3)



(4)

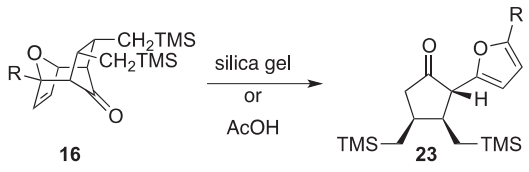
For example, cycloadduct **17** was reported to convert to **18** over 6 weeks at 0 °C in 81% yield (Eq. 3).[11] The cycloadduct **19** gave **20** upon treatment with HBr in acetic acid at room temperature for 2 days (Eq. 4).[12] The yield for the process was 80%. From a synthetic perspective, this points to the utility of oxyallylic cations as enolonium ion equivalents,[13] a synthetically useful situation in its own right.[14] Mechanistically, the pathway that leads from cycloadducts to substituted furans is a Grob fragmentation,[15] as represented in Scheme 3. The leaving group is the π^* orbital of the carbonyl moiety. We found that certain cycloadducts would traverse this route either upon attempted silica gel chromatography or, more conveniently, upon treatment with acetic acid. The results are summarized in Table 2. We knew that this fragmentation could be mitigated by reduction and indeed, treatment of several cycloadducts with lithium aluminum hydride gave the corresponding alcohols **24** with complete stereoselectivity and these alcohols were stable (Table 3). The stereochemical assignment of the reduction products was based upon **24i**, whose structure and stereochemistry were established by X-ray analysis.



Scheme 3.

While these results were encouraging, we really wanted to use compounds like **10** to study asymmetric ene reactions. We did attempt an ene process with styrene under the conditions used for successful (4+3)-cycloadditions with furans. In the event, the

Table 2
Ring-opening of cycloadducts



Entry	16	R	23	Yield (%)
1	**a**	H	**a**	57[a]
2	**b**	Me	**b**	47[a]
3	**b**	Me	**b**	100[b]
4	**c**	Et	**c**	100[b]
5	**i**	Bn	**i**	70[b]
6	**j**	$(CH_2)_4OTBS$	**j**	45[b]
7	**k**	^{n}Bu	**k**	61[b]
8	**l**	$(CH_2)_3Cl$	**l**	56[b]

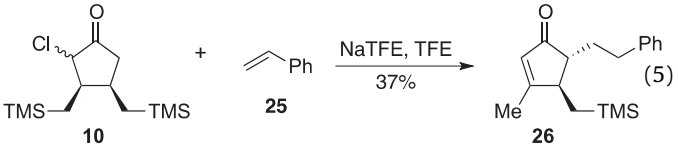
[a] Product was obtained by isomerization on a silica gel column.
[b] Product was obtained by isomerization using acetic acid.

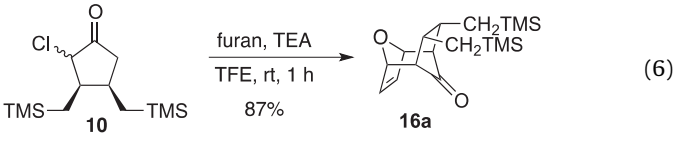
Table 3
Reduction of selected cycloadducts

Entry	16	R	24	Yield (%)
1	**i**	Bn	**i**[a]	66
2	**j**	$(CH_2)_4OTBS$	**j**	30
3	**k**	^nBu	**k**	68
4	**l**	$(CH_2)_3Cl$	**l**	82

[a] Structure was confirmed by X-ray crystallography.

reaction of **10** with styrene in the presence of sodium trifluoroethoxide in trifluoroethanol did indeed produce the expected product, but only in 37% yield (Eq. 5). A similar attempt with ethyl vinyl ether failed. More recently, we have found that the reaction of **10** with furan in trifluoroethanol using triethylamine as base gave the cycloadduct **16a** in 87% yield (Eq. 6). Thus, it is possible, in principle, for us to pursue asymmetric (4+3)-cycloadditions with **10** and related oxyallylic cation progenitors using chiral amine bases.





3. Conclusion

In the course of investigating problems associated with the ene reaction of the oxyallylic cation generated from **10**, we discovered that under the appropriate conditions the intermediate is quite effective in undergoing intermolecular (4+3)-cycloaddition reactions with assorted furans. Further, the cycloadducts obtained in this process are at the very edge of stability and fragment readily upon exposure to mild acid to α-furanyl cyclopentanones. The cycloadducts can be made more stable by eliminating the pathway for fragmentation by reduction of the carbonyl group to the corresponding alcohol. The fact that cyclopentenyl oxyallylic cations can be generated with relative ease makes them good candidates for exploring the use of chiral bases for establishing asymmetric (4+3)-cycloaddition, ene, and possibly other reactions. We have a continuing interest in effecting such chemistry. Further studies will be reported in due course.[16]

4. Experimental

4.1. General methods

All reactions were carried out in an oven-dried or flame-dried flask under an atmosphere of nitrogen. 2,2,2-Trifluoroethanol, 1,1,1,3,3,3-hexafluoro-2-propanol, and triethylamine were distilled over calcium hydride. THF was distilled over benzophenone and sodium. Cyclopentadiene was freshly distilled from dicyclopentadiene. Sodium trifluoroethoxide (1 M) solution was prepared by reacting sodium metal with trifluoroethanol. Analytical thin layer chromatography was performed on silica gel plates with UV indicator. Flash chromatography was carried out using 230–400 mesh silica gel with HPLC grade solvents. ^{1}H NMR spectra were recorded on a Bruker ARX-250 (250 MHz), DRX-300 (300 MHz) or DRX-500 (500 MHz) spectrometer. ^{13}C NMR spectra were obtained on the same instruments at 62.5, 75, or 125 MHz in $CDCl_3$ solution with tetramethylsilane (^{1}H spectra) or $CDCl_3$ (^{13}C spectra) as an internal reference. Melting points were determined with a Fisher-Johns melting point apparatus. Infrared spectra were recorded on a Perkin Elmer 1600 series FT-IR spectrometer. High-resolution mass spectra were performed by College of Science Major Instrumentation Center, Old Dominion University, with a Bruker 12 T APEX-Qe FTICR-MS. X-ray diffraction data were collected by Dr. Charles Barnes at the Department of Chemistry, University of Missouri-Columbia.

4.2. Experimental procedures

*4.2.1. General procedure for (4+3)-cycloaddition. Synthesis of **16**.* To a solution of 2-chloro-3,4-bis((trimethylsilyl)methyl)-cyclopentanone (100 mg, 0.344 mmol) and furan derivative (0.687 mmol, 2 equiv) in 2,2,2-trifluoroethanol (1.5 mL) was added a 1 M sodium 2,2,2-trifluoroethoxide solution (0.52 mmol, 1.5 equiv) at room temperature and stirred for 0.5 h. The solution was then filtered through a very short pad of alumina (Al_2O_3) and concentrated under reduced pressure. The crude product was weighed and purified by column chromatography (alumina, 10% EtOAc/hexanes).

*4.2.2. General procedure for 2-furanyl cyclopentanones. Synthesis of **23**.* The crude product obtained from the procedure above was dissolved in 5 mL CH_2Cl_2 (0.07 M) and two drops of acetic acid were added. The solution was stirred at room temperature for 0.5 h and was then concentrated under reduced pressure. The crude product was purified by column chromatography (silica gel, 5% EtOAc/hexanes).

*4.2.3. General procedure for the reduction of ketone. Synthesis of **29**.* The crude product from the (4+3)-cycloaddition reaction was dissolved in 5 mL THF (0.07 M). To the solution was added $LiAlH_4$ (13 mg, 0.344 mmol). The suspension was stirred at room temperature for 1 h and was then quenched with dilute NaOH solution (10%, 5 mL). The aqueous layer was extracted with EtOAc (10 mL×2). The combined organic layers were washed with brine, dried over $MgSO_4$, and concentrated under reduced pressure. The crude product was purified by column chromatography (silica gel, 10% EtOAc/hexanes).

4.3. Characterization data

*4.3.1. (Z)-1,4-Bis(trimethylsilyl)but-2-ene (**7**).*[6] To a solution of 1,4-bis(trimethylsilyl)but-2-yne (5 g, 25 mmol) in 500 mL MeOH was added 0.5 mL (4 mmol) quinoline and 0.5 g 10% Pd/C. The suspension was bubbled with hydrogen and stirred vigorously with a magnetic stir bar for 2 h, monitored by ^{13}C NMR. Upon completion of the reaction, the suspension was filtered through a sintered funnel to recover the palladium catalyst. To the filtrate was added 100 mL hexanes, after fully mixing, 200 mL water was added. The top layer was collected, and the bottom layer was extracted with another 100 mL hexanes. The combined 200 mL hexanes was washed with 50 mL dilute HCl solution (5%), water (100 mL×2), brine, dried over $MgSO_4$, and concentrated in vacuo, which afforded 4.26 g (85% yield) of (*Z*)-1,4-bis(trimethylsilyl)but-2-ene as an oil.

4.3.2. (3S,4S*)-2,2-Dichloro-3,4-bis((trimethylsilyl)methyl)cyclobutanone (**8**).* Zinc powder was washed with acetone, acetic acid,

water, and then acetone, and dried by high vacuum before use. A 1-L two-necked flask was charged with (*Z*)-1,4-bis(trimethylsilyl)but-2-ene (12.4 g, 62 mmol), Et_2O (120 mL), Zn (24.3 g, 371 mmol), and equipped with a magnetic stir bar and a condenser. The solution was chilled in an ice water bath. While stirring, freshly distilled 6.95 mL trichloroacetyl chloride (62 mmol) was injected into the flask slowly. After stirring at 0 °C for 30 min, the solution was stirred at rt for 3 h. The reaction was monitored by TLC and ^{13}C NMR. Upon completion, the reaction mixture was filtered through cotton, washed with saturated NH_4Cl solution, water, and brine, and dried over $MgSO_4$. The solution was concentrated in vacuo to give 17.2 g (55 mmol, 89% yield) of an oil, which was further purified by Kugelrohr distillation (160 °C, 2 Torr) to give 13.6 g (43.7 mmol, 71% yield) pure product. R_f=0.41 (10% CH_2Cl_2/hexanes). ^1H NMR (300 MHz, $CDCl_3$) δ 3.63 (dt, *J*=5.5, 11.0 Hz, 1H), 3.06 (dt, *J*=5.1, 10.0 Hz, 1H), 0.94 (dd, *J*=3.9, 14.7 Hz, 1H), 0.91 (dd, *J*=5.4, 15.0 Hz, 1H), 0.71 (ddd, *J*=5.4, 10.5, 14.7 Hz, 2H), 0.12 (s, 9H), 0.06 (s, 9H), ^{13}C NMR (75 MHz, $CDCl_3$) δ 198.2, 89.2, 55.7, 47.5, 13.3, 13.2, −0.9 (3C), −1.3 (3C); IR (cm^{-1}): 2954, 2897, 1867, 1804, 1415, 1251, 1192, 938, 859, 757, 700; HRMS *m*/*z* calcd for $(C_{12}H_{24}Cl_2OSi_2)Na^+$: 333.0635, found: 333.0633.

4.3.3. (3S,4R*)-2,2-Dichloro-3,4-bis((trimethylsilyl)methyl)cyclopentanone (**9**).* 2,2-Dichloro-3,4-bis((trimethylsilyl)methyl)cyclobutanone (1.51 g, 4.85 mmol) was dissolved in 100 mL ether in an Erlenmeyer flask, and 1.5 equiv diazomethane in ether solution was added. The reaction was allowed to stir at rt for 8 h. Upon completion of the reaction (monitored by NMR), the reaction was quenched with acetic acid and the solution was concentrated under reduced pressure. The product was purified by recrystallization using MeOH, which resulted in 1.46 g (4.49 mmol, 92% yield) product as a white solid; mp=75–76 °C, R_f=0.37 (10% EtOAc/hexanes). ^1H NMR (500 MHz, $CDCl_3$) δ 2.72–2.63 (m, 2H), 2.50–2.42 (m, 1H), 2.38 (dd, *J*=3.0, 19.0 Hz, 1H), 1.03–0.94 (m, 2H), 0.78 (d, *J*=14.5 Hz, 1H), 0.66 (t, *J*=14.0 Hz, 1H), 0.10 (s, 9H), 0.04 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 203.4, 89.4, 53.5, 41.3, 32.7, 16.8, 12.3, −0.8 (6C); IR (cm^{-1}) 2953, 2898, 1767, 1416, 1250, 1190, 1171, 1116, 963, 861, 777, 760, 692; HRMS *m*/*z* calcd for $(C_{13}H_{26}Cl_2OSi_2)Na^+$: 347.0791, found: 347.0800.

4.3.4. (3S,4R*)-2-Chloro-3,4-bis((trimethylsilyl)methyl)cyclopentanone (**10**).* To 2,2-dichloro-3,4-bis((trimethylsilyl)methyl) cyclopentanone (236 mg, 0.73 mmol) dissolved in 3.6 mL acetic acid was added 284 mg (4.35 mmol) Zn powder. The solution was stirred at rt for 1 h and monitored by TLC (10% EtOAc/hexanes). Upon completion of the reaction, 15 mL hexanes were added to the solution. After filtration through cotton, 10 mL water was added to the solution. The organic layer was dried over $MgSO_4$, concentrated under reduced pressure, and purified by column chromatography (silica gel, 10% EtOAc/hexanes). A mixture of two diastereomers (170 mg, 0.58 mmol, 80% yield) was obtained (dr=1:1). The mixture was used for 4+3 cycloaddition directly. Further purification by column chromatography (silica gel, 50% CH_2Cl_2/hexanes) resulted in two isolated diastereomers A and B (the stereochemistry of A and B were not established).

Diastereomer A. R_f=0.59 (50% CH_2Cl_2/hexanes). ^1H NMR (500 MHz, $CDCl_3$) δ 3.81 (d, *J*=7.0 Hz, 1H), 2.65–2.56 (m, 1H), 2.50 (dd, *J*=8.0, 19.0 Hz, 1H), 2.28–2.21 (m, *J*=7.0 Hz, 1H), 2.08 (dd, *J*=6.0, 19.0 Hz, 1H), 0.82 (dd, *J*=7.0, 15.0 Hz, 1H), 0.74 (dd, *J*=3.0, 14.5 Hz, 1H), 0.58 (dd, *J*=8.0, 15.0 Hz, 1H), 0.39 (dd, *J*=12.0, 14.0 Hz, 1H), 0.07 (s, 9H), 0.04 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 211.1, 64.2, 47.1, 42.7, 33.2, 16.7, 14.2, −0.8 (3C), −0.9 (3C); IR (cm^{-1}): 2953, 2901, 1757, 1419, 1250, 839, 691; HRMS *m*/*z* calcd for $(C_{13}H_{27}ClOSi_2)Na^+$: 313.1181, found: 313.1189.

Diastereomer B. R_f=0.50 (50% CH_2Cl_2/hexanes). ^1H NMR (500 MHz, $CDCl_3$) δ 4.21 (d, *J*=7.0 Hz, 1H), 2.54–2.48 (m, 1H), 2.44 (dd, *J*=8.0, 19.0 Hz, 1H), 2.37–2.29 (m, 1H), 2.12 (dd, *J*=6.0, 19.0 Hz, 1H), 0.81 (dd, *J*=2.5, 14.5 Hz, 1H), 0.75 (dd, *J*=8.0, 15.0 Hz, 1H), 0.63 (dd, *J*=8.5, 15.0 Hz, 1H), 0.61 (d, *J*=14.5 Hz, 1H), 0.06 (s, 9H), 0.03 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 211.2, 64.7, 42.8, 42.7, 35.3, 18.4, 12.0, −0.8 (3C), −0.9 (3C); IR (cm^{-1}): 2953, 2900, 1757, 1405, 1249, 840, 757, 692; HRMS *m*/*z* calcd for $(C_{13}H_{27}ClOSi_2)Na^+$: 313.1181, found: 313.1187.

4.3.5. (1R,5R*)-3-Chloro-4-methyl-5-((trimethylsilyl)methyl)-[1,1′-bi(cyclopentane)]-3,3′-dien-2-one (**11**).* To a solution of 50 mg (0.15 mmol) 2,2-dichloro-3,4-bis((trimethylsilyl)methyl)cyclopenta none in 1.5 mL 2,2,2-trifluoroethanol at room temperature was added 63 μL (0.75 mmol) cyclopentadiene followed by 63 μL (0.45 mmol) triethylamine. The solution was stirred at room temperature for 30 min. Upon completion of the reaction, the solvent was removed under reduced pressure. The product was purified by column chromatography, affording 18 mg (0.064 mmol) of product as a colorless oil (41% yield). R_f=0.32 (1:1 CH_2Cl_2/hexanes). ^1H NMR (500 MHz, $CDCl_3$) δ 5.67 (s, 2H), 2.65–2.55 (m, 2H), 2.46–2.30 (m, 3H), 2.28–2.16 (m, 2H), 2.11 (s, 3H), 1.06 (dd, *J*=15.0, 4.0 Hz, 1H), 0.73 (dd, *J*=15.0, 9.0 Hz, 1H), 0.04 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 202.1, 173.8, 130.7, 130.0, 129.8, 55.1, 44.4, 40.0, 35.7, 35.6, 21.7, 15.5, −0.4; IR (cm^{-1}): 3055, 2952, 2923, 2850, 1716, 1627, 1421, 1377, 1250, 1175, 977, 838, 763, 691; HRMS *m*/*z* calcd for $C_{15}H_{23}ClOSiNa^+$: 305.1099, found: 305.1098.

*4.3.6. Cycloaddition reaction to form **12a** and **12b**.* To 2-chloro-3,4-bis((trimethylsilyl)methyl)cyclopentanone (43.6 mg, 0.15 mmol) in 2,2,2-trifluoroethanol (1.5 mL) at room temperature was added cyclopentadiene (63 μL, 0.75 mmol, 5 equiv). While stirring, 63 μL (0.45 mmol, 3 equiv) triethylamine was added to the reaction. The solution was stirred for 2 h and then concentrated under reduced pressure. The crude product was purified by column chromatography (alumina, 1:1 CH_2Cl_2/hexanes), which yielded 15 mg (31% yield) product as colorless oil (1:1 mixture of two diastereomers **12a** and **12b**, which were separable), the structures of which were identified by comparing ^1H NMR with known compounds.[8] Meanwhile, 10 mg of an inseparable mixture (**13** and **14**, ratio 2:1, total yield 27%) was also obtained. Pure **13** was obtained and characterized by carrying out the reaction with NaTFE instead of TEA. Compound **14** was not characterized due to purification difficulty.

4.3.7. (7R,8S*)-7,8-Bis(trimethylsilyl)tricyclo[4.2.1.1^{2,5}]dec-3-en-9-one (**12a**).* Colorless oil. ^1H NMR (500 MHz, $CDCl_3$) δ 6.13 (s, 2H), 2.76 (s, 2H), 2.16–2.10 (m, 2H), 2.10 (d, *J*=11.0 Hz, 1H) 1.95 (d, *J*=5.5 Hz, 2H), 1.56 (dt, *J*=11.0, 3.5 Hz, 1H), 0.70 (dd, *J*=1.5, 14.5 Hz, 2H), 0.40–0.31 (m, 2H), 0.03 (s, 18H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 212.5, 136.1, 56.5, 44.7, 38.2, 36.4, 18.5, −0.7; IR (cm^{-1}): 3066, 2951, 2932, 2905, 1739, 1250, 1192, 967, 861, 836, 715, 690; HRMS *m*/*z* calcd for $(C_{18}H_{32}OSi_2)H^+$: 321.2064, found: 321.2063.

4.3.8. (1R,6S*,7R*,8S*)-7,8-Bis(trimethylsilyl)tricyclo[4.2.1.1^{2,5}]dec-3-en-9-one (**12b**).* Colorless oil. ^1H NMR (500 MHz, $CDCl_3$) δ 6.50 (s, 2H), 2.93 (d, *J*=9.0 Hz, 2H), 2.15 (d, *J*=9.0 Hz, 2H), 1.88–1.81 (m, 2H), 1.56 (s, 1H), 1.44 (dt, *J*=11.0, 3.5 Hz, 1H), 0.51 (dd, *J*=2.0, 14.5 Hz, 2H), 0.32–0.23 (m, 2H), 0.00 (s, 18H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 216.9, 139.1, 58.4, 42.8, 40.5, 34.4, 18.1, −0.7; IR (cm^{-1}): 3068, 2951, 2904, 2884, 1737, 1249, 1001, 899, 860, 848, 826, 773, 689; HRMS *m*/*z* calcd for $(C_{18}H_{32}OSi_2)H^+$: 321.2064, found: 321.2064.

4.3.9. (1R,5R*)-4-Methyl-5-((trimethylsilyl)methyl)-[1,1′-bi(cyclopentane)]-3,3′-dien-2-one (**13**).* Colorless oil ^1H NMR (500 MHz, $CDCl_3$) δ 5.83 (s, 1H), 5.66 (s, 2H), 2.62–2.53 (m, 2H), 2.42 (dd, *J*=8.5, 15.5 Hz, 1H), 2.34 (dd, *J*=9.0, 16.0 Hz, 1H), 2.27–2.17 (m, 3H), 2.07 (s, 3H), 1.03 (dd, *J*=15.0, 3.5 Hz, 1H), 0.68 (dd, *J*=15.0, 9.0 Hz, 1H), 0.04 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 211.0, 182.9, 130.1, 129.9, 129.9, 57.3, 46.2, 39.8, 35.8, 35.5, 21.6, 17.5, −0.4; IR (cm^{-1}): 3053, 2951, 2898,

2849, 1696, 1623, 1438, 1377, 1290, 1250, 1185, 856, 759; HRMS *m*/*z* calcd for $C_{15}H_{24}OSiNa^+$: 271.1489, found: 271.1487.

4.3.10. (1R,2R*,3S*,4R*,5S*,6S*)-3,4-Bis((trimethylsilyl)methyl)-9-oxatricyclo[4.2.1.1^{2,5}]dec-7-en-10-one (**16a**).* White solid; mp=133–134 °C. R_f=0.33 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.32 (s, 2H), 4.71 (d, *J*=3.5 Hz, 2H), 2.49–2.43 (m, 2H), 2.07 (d, *J*=3.5 Hz, 2H), 0.73 (d, *J*=14.5 Hz, 2H), 0.39–0.30 (m, 2H), 0.03 (s, 18H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 209.6, 133.2 (2C), 81.9 (2C), 59.2 (2C), 35.2 (2C), 17.7 (2C), −0.7 (6C); IR (cm^{-1}): 2951, 2925, 1742, 1312, 1250, 1242, 1182, 1162, 1135, 1015, 1003, 954, 925, 839, 711, 694; HRMS *m*/*z* calcd for $(C_{17}H_{30}O_2Si_2)Na^+$: 345.1677, found: 345.1674.

4.3.11. (1R,2R*,3S*,4R*,5S*,6S*)-1-Methyl-3,4-bis((trimethylsilyl)methyl)-9-oxatricyclo [4.2.1.1^{2,5}]dec-7-en-10-one (**16b**).* White solid; mp=102–103 °C. R_f=0.28 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.22 (dd, *J*=1.5, 6.0 Hz, 1H), 6.11 (d, *J*=5.5 Hz, 1H), 4.67 (dd, *J*=1.5, 4.0 Hz, 1H), 2.43–2.35 (m, 2H), 2.00 (dd, *J*=2.0, 4.0 Hz, 1H), 1.98 (d, *J*=2.0 Hz, 1H), 1.45 (s, 3H), 0.73 (ddd, *J*=2.0, 14.5, 19.0 Hz, 2H), 0.39–0.28 (m, 2H), 0.04 (s, 9H), 0.02 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 209.9, 136.7, 133.1, 87.4, 81.8, 63.5, 57.1, 34.2, 33.8, 20.2, 18.2, 17.6, −0.7 (6C); IR (cm^{-1}): 2949, 2924, 1737, 1376, 1314, 1241, 1182, 1166, 1136, 1105, 996, 924, 854, 831, 749, 717, 689; HRMS *m*/*z* calcd for $(C_{18}H_{32}O_2Si_2)Na^+$: 359.1833, found: 359.1832.

4.3.12. (1R,2R*,3S*,4R*,5S*,6S*)-1-Ethyl-3,4-bis((trimethylsilyl)methyl)-9-oxatricyclo [4.2.1.1^{2,5}]dec-7-en-10-one (**16c**).* White solid; mp=93–94 °C. R_f=0.39 (10% EtOAc/hexanes).^{1}H NMR (500 MHz, $CDCl_3$) δ 6.24 (d, *J*=5.5 Hz, 1H), 6.12 (d, *J*=5.5 Hz, 1H), 4.71 (dd, *J*=1.0, 4.0 Hz, 1H), 2.43–2.35 (m, 2H), 2.02 (dd, *J*=2.0, 4.0 Hz, 1H), 2.00 (d, *J*=2.0 Hz, 1H), 1.93–1.84 (m, *J*=7.0 Hz, 1H), 1.72–1.63 (m, *J*=7.0 Hz, 1H), 0.96 (t, *J*=7.5 Hz, 3H), 0.73 (ddd, *J*=2.0, 15.0, 22.5 Hz, 2H), 0.40–0.28 (m, 2H), 0.04 (s, 9H), 0.03 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 210.1, 135.0, 133.5, 91.2, 81.9, 62.9, 57.7, 34.4, 33.9, 26.1, 18.2, 17.7, 8.7, −0.7 (6C); IR (cm^{-1}) 2952, 2893, 1748, 1417, 1304, 1248, 1092, 1002, 919, 857, 836, 718, 691; HRMS *m*/*z* calcd for $(C_{19}H_{34}O_2Si_2)Na^+$: 373.1990, found: 373.1989.

4.3.13. (1R,2R*,3S*,4R*,5S*,6S*)-1,6-Dimethyl-3,4-bis((trimethylsilyl)methyl)-9-oxatricyclo [4.2.1.1^{2,5}]dec-7-en-10-one (**16d**).* White solid; mp=125–126 °C. R_f=0.30 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.04 (s, 2H), 2.37–2.30 (m, 2H), 1.92 (s, 2H), 1.44 (s, 6H), 0.74 (dd, *J*=1.5, 15.0 Hz, 2H), 0.33 (dd, *J*=12.5, 14.5 Hz, 2H), 0.04 (s, 18H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 210.3, 136.7 (2C), 87.1 (2C), 61.4 (2C), 32.7 (2C), 20.3 (2C), 18.2 (2C), −0.7 (6C); IR (cm^{-1}) 2969, 2935, 2889, 1738, 1374, 1248, 1138, 997, 903, 860, 836, 757, 725, 693; HRMS *m*/*z* calcd for $(C_{19}H_{34}O_2Si_2)Na^+$: 373.1990, found: 373.1988.

4.3.14. (1R,2R*,3S*,4R*,5S*,6S*)-1-Isopropyl-6-methyl-3,4-bis((trimethylsilyl)methyl)-9-oxatricyclo[4.2.1.1^{2,5}]dec-7-en-10-one (**16e**).* White solid; mp=104–105 °C, R_f=0.42 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.04 (s, 2H), 2.38–2.27 (m, 2H), 2.15 (d, *J*=1.5 Hz, 1H), 2.07–2.00 (m, *J*=6.5 Hz, 1H), 1.92 (d, *J*=1.5 Hz, 1H), 1.44 (s, 3H), 1.02 (d, *J*=7.0 Hz, 3H), 0.94 (d, *J*=6.5 Hz, 3H), 0.78 (dd, *J*=4.0, 15.0 Hz, 1H), 0.71 (dd, *J*=3.0, 15.0 Hz, 1H), 0.38–0.31 (m, 2H), 0.04 (s, 18H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 210.7, 137.1, 132.4, 93.9, 86.9, 61.9, 59.0, 33.0, 32.9, 29.4, 20.2, 18.7, 18.6, 18.3, 18.1, −0.7 (6C); IR (cm^{-1}) 2952, 2900, 1736, 1449, 1412, 1372, 1294, 1249, 1173, 1130, 958, 859, 838, 769, 691; HRMS *m*/*z* calcd for $(C_{21}H_{38}O_2Si_2)_2Na^+$: 779.4709, found: 779.4709.

4.3.15. (1S,2R*,3S*,4R*,5S*,6R*)-7-Bromo-3,4-bis((trimethylsilyl)methyl)-9-oxatricyclo [4.2.1.1^{2,5}]dec-7-en-10-one (**16f**).* White solid; mp=92–93 °C. R_f=0.44 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.35 (d, *J*=1.5 Hz, 1H), 4.69 (d, *J*=4.0 Hz, 1H), 4.57 (d, *J*=4.0 Hz, 1H), 2.53–2.39 (m, 2H), 2.25 (dd, *J*=2.5, 4.0 Hz, 1H), 2.11 (dd, *J*=2.5, 4.0 Hz, 1H), 0.74 (ddd, *J*=3.0, 9.5, 14.5 Hz, 2H), 0.38 (ddd, *J*=9.0, 13.0, 14.5 Hz, 2H), 0.05 (s, 9H), 0.03 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 207.7, 131.6, 123.3, 85.9, 83.3, 58.2, 57.9, 36.0, 35.0, 17.6, −0.7 (6C); IR (cm^{-1}) 2952, 2893, 1750, 1580, 1418, 1313, 1249, 1181, 1134, 1002, 947, 857, 833, 750, 694; HRMS *m*/*z* calcd for $(C_{17}H_{29}BrO_2Si_2)Na^+$: 423.0782, found: 423.0779.

4.3.16. (1R,2R*,3S*,4R*,5S*,6S*)-1-(Methoxymethyl)-3,4-bis((trimethylsilyl)methyl)-9-oxatricyclo[4.2.1.1^{2,5}]dec-7-en-10-one (**16g**).* Colorless oil. R_f=0.25 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.29 (dd, *J*=1.5, 6.0 Hz, 1H), 6.22 (d, *J*=5.5 Hz, 1H), 4.74 (dd, *J*=1.5, 4.0 Hz, 1H), 3.60 (s, 2H), 3.41 (s, 3H), 2.53–2.40 (m, 2H), 2.15 (d, *J*=2.0 Hz, 1H), 2.04 (dd, *J*=2.0, 3.5 Hz, 1H), 0.72 (ddd, *J*=2.5, 10.0, 14.5 Hz, 2H), 0.36 (dd, *J*=12.5, 14.5 Hz, 1H), 0.31 (dd, *J*=12.5, 15.0 Hz, 1H), 0.04 (s, 9H), 0.03 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 209.1, 134.3, 133.6, 89.1, 82.2, 72.7, 60.1, 59.5, 57.8, 34.5, 33.9, 18.1, 17.7, −0.7 (3C), −0.9 (3C); IR (cm^{-1}) 2952, 2897, 1750, 1418, 1318, 1249, 1200, 1139, 1119, 1006, 942, 923, 858, 839, 753, 720, 693; HRMS *m*/*z* calcd for $(C_{19}H_{34}O_3Si_2)Na^+$: 389.1939, found: 389.1940.

4.3.17. (1R,2R*,3S*,4R*,5S*,6S*)-1-(((tert-Butyldimethylsilyl)oxy)methyl)-3,4-bis((trimethylsilyl)methyl)-9-oxatricyclo[4.2.1.1^{2,5}]dec-7-en-10-one (**16h**).* White solid; mp=114–115 °C. R_f=0.50 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.29 (d, *J*=5.5 Hz, 1H), 6.25 (dd, *J*=1.0, 6.0 Hz, 1H), 4.71 (dd, *J*=1.5, 4.0 Hz, 1H), 3.84 (d, *J*=10.5 Hz, 1H), 3.70 (d, *J*=10.0 Hz, 1H), 2.42–2.33 (m, 2H), 2.31 (d, *J*=2.0 Hz, 1H), 2.03 (dd, *J*=2.0, 4.0 Hz, 1H), 0.90 (s, 9H), 0.72 (ddd, *J*=2.5, 11.0, 14.5 Hz, 2H), 0.40–0.29 (m, 2H), 0.08 (s, 3H), 0.07 (s, 3H), 0.04 (s, 9H), 0.03 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 209.7, 134.6, 132.8, 90.1, 82.2, 62.4, 59.1, 57.7, 34.4, 33.7, 25.9 (3C), 18.4, 18.0, 17.7, −0.7 (6C), −5.3, −5.4; IR (cm^{-1}) 2954, 2930, 2900, 2859, 1750, 1472, 1416, 1362, 1303, 1249, 1163, 1124, 1094, 1005, 925, 841, 778, 717, 692; HRMS *m*/*z* calcd for $(C_{24}H_{46}O_3Si_3)Na^+$: 489.2647, found: 489.2643.

4.3.18. (1R,2R*,3S*,4R*,5S*,6S*)-1-Benzyl-3,4-bis((trimethylsilyl)methyl)-9-oxatricyclo[4.2.1.1^{2,5}]dec-7-en-10-one (**16i**).* White solid; mp=103–104 °C, R_f=0.35 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.30–7.25 (m, 2H), 7.24–7.20 (m, 3H), 6.13–6.09 (m, 2H), 4.66 (dd, *J*=1.5, 4.0 Hz, 1H), 3.21 (d, *J*=14.5 Hz, 1H), 2.91 (d, *J*=14.5 Hz, 1H), 2.57 (ddd, *J*=4.5, 10.0, 11.5 Hz, 1H), 2.45 (ddd, *J*=3.0, 9.5, 13.0 Hz, 1H), 2.11 (d, *J*=2.0 Hz, 1H), 2.02 (dd, *J*=2.0, 4.0 Hz, 1H), 0.83 (dd, *J*=4.5, 15.0 Hz, 1H), 0.73 (dd, *J*=3.0, 15.0 Hz, 1H), 0.39 (dd, *J*=8.0, 15.0 Hz, 1H), 0.37 (dd, *J*=10.0, 14.5 Hz, 1H), 0.10 (s, 9H), 0.04 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 209.6, 136.1, 134.8, 133.2, 130.2 (2C), 128.2 (2C), 126.7, 90.4, 81.7, 63.8, 57.8, 39.9, 34.2, 34.1, 18.3, 17.8, −0.6 (3C), −0.7 (3C); IR (cm^{-1}) 3030, 2952, 1747, 1497, 1455, 1315, 1249, 1182, 1128, 1003, 924, 858, 836, 743, 718, 700; HRMS *m*/*z* calcd for $(C_{24}H_{36}O_2Si_2)Na^+$: 435.2146, found: 435.2145.

4.3.19. (1R,2R*,3S*,4R*,5S*,6S*)-1-(4-((tert-Butyldimethylsilyl)oxy)butyl)-3,4-bis((trimethylsilyl)methyl)-9-oxatricyclo[4.2.1.1^{2,5}]dec-7-en-10-one (**16j**).* White solid; mp=85–86 °C. R_f=0.33 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.22 (dd, *J*=1.0, 6.0 Hz, 1H), 6.11 (d, *J*=6.0 Hz, 1H), 4.68 (dd, *J*=1.5, 4.0 Hz, 1H), 3.64–3.56 (m, 2H), 2.42–2.34 (m, 2H), 2.01 (dd, *J*=2.0, 4.0 Hz, 1H), 1.98 (d, *J*=2.0 Hz, 1H), 1.85 (ddd, *J*=5.0, 12.0, 14.0 Hz, 1H), 1.64 (ddd, *J*=5.0, 11.5, 14.0 Hz, 1H), 1.60–1.52 (m, 2H), 1.51–1.32 (m, 2H), 0.88 (s, 9H), 0.73 (ddd, *J*=2.5, 14.5, 23.0 Hz, 2H), 0.39–0.28 (m, 2H), 0.04 (s, 9H), 0.03 (s, 6H), 0.02 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 210.0, 135.2, 133.3, 90.7, 81.8, 63.2, 62.9, 57.6, 34.4, 34.0, 33.2, 33.1, 26.0 (3C), 20.7, 18.4, 18.2, 17.7, −0.7 (6C), −5.3 (2C); IR (cm^{-1}) 2952, 2858, 1748, 1249, 1099, 1005, 923, 857, 836, 775, 720, 693; HRMS *m*/*z* calcd for $(C_{27}H_{52}O_3Si_3)Na^+$: 531.3116, found: 531.3106.

4.3.20. (1R,2R*,3S*,4R*,5S*,6S*)-1-(3-Chloropropyl)-3,4-bis((trimethylsilyl)methyl)-9-oxatricyclo[4.2.1.1^{2,5}]dec-7-en-10-one (**16l**).* Colorless o

il. R_f=0.29 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.26 (d, J=6.0 Hz, 1H), 6.11 (d, J=6.0 Hz, 1H), 4.70 (dd, J=1.5, 4.0 Hz, 1H), 3.64–3.54 (m, 2H), 2.42–2.35 (m, 2H), 2.06–1.90 (m, 4H), 1.85–1.75 (m, 2H), 0.77 (dd, J=2.5, 14.5 Hz, 1H), 0.72 (dd, J=2.0, 14.5 Hz, 1H), 0.40–0.29 (m, 2H), 0.05 (s, 9H), 0.04 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 209.5, 135.0, 133.9, 90.1, 81.9, 63.4, 57.5, 45.1, 34.4, 34.0, 30.5, 27.5, 18.2, 17.7, −0.7 (6C); IR (cm^{-1}) 2953, 1748, 1445, 1419, 1314, 1249, 1199, 1181, 1137, 1127, 1009, 922, 858, 837, 720, 694; HRMS m/z calcd for $(C_{20}H_{35}ClO_2Si_2)Na^+$: 421.1756, found: 421.1754.

4.3.21. (2S,3R*,4S*)-2-(Furan-2-yl)-3,4-bis((trimethylsilyl)methyl) cyclopentanone (**23a**).* Colorless oil. R_f=0.55 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.35 (d, J=1.0 Hz, 1H), 6.32 (dd, J=2.0, 3.0 Hz, 1H), 6.12 (d, J=3.5 Hz, 1H), 3.17 (d, J=9.5 Hz, 1H), 2.59–2.43 (m, 3H), 2.25–2.17 (m, 1H), 0.84–0.76 (m, 2H), 0.58 (dd, J=6.0, 14.5 Hz, 1H), 0.35 (dd, J=12.5, 14.5 Hz, 1H), 0.05 (s, 9H), 0.00 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 215.5, 151.3, 142.1, 110.3, 107.7, 54.7, 45.7, 43.4, 34.2, 16.1, 15.5, −0.7 (3C), −0.9 (3C); IR (cm^{-1}) 2953, 2899, 1749, 1504, 1411, 1249, 1148, 1010, 860, 838, 730, 691; HRMS m/z calcd for $(C_{17}H_{30}O_2Si_2)Na^+$: 345.1677, found: 345.1675.

4.3.22. (2S,3R*,4S*)-2-(5-Methylfuran-2-yl)-3,4-bis((trimethylsilyl) methyl)cyclopentanone (**23b**).* Colorless oil. R_f=0.48 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.98 (d, J=3.0 Hz, 1H), 5.88 (d, J=2.0 Hz, 1H), 3.09 (d, J=9.5 Hz, 1H), 2.58–2.43 (m, 3H), 2.24 (s, 3H), 2.23–2.16 (m, 1H), 0.82–0.76 (m, 2H), 0.58 (dd, J=6.0, 15.0 Hz, 1H), 0.34 (dd, J=12.5, 14.5 Hz, 1H), 0.04 (s, 9H), 0.00 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 215.9, 151.7, 149.4, 108.5, 106.2, 54.8, 45.8, 43.3, 34.1, 16.1, 15.5, 13.6, −0.7 (3C), −0.9 (3C); IR (cm^{-1}) 2953, 2900, 1747, 1567, 1410, 1249, 1022, 860, 838, 780, 734, 691; HRMS m/z calcd for $(C_{18}H_{32}O_2Si_2)Na^+$: 359.1833, found: 359.1832.

4.3.23. (2S,3R*,4S*)-2-(5-Ethylfuran-2-yl)-3,4-bis((trimethylsilyl) methyl)cyclopentanone (**23c**).* Colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.00 (d, J=3.0 Hz, 1H), 5.89 (d, J=3.0 Hz, 1H), 3.10 (d, J=9.5 Hz, 1H), 2.59 (q, J=7.0 Hz, 2H), 2.56–2.44 (m, 3H), 2.23–2.15 (m, 1H), 1.19 (t, J=7.5 Hz, 3H), 0.82–0.75 (m, 2H), 0.57 (dd, J=14.5, 6.0 Hz, 1H), 0.34 (dd, J=14.5, 12.0 Hz, 1H), 0.04 (s, 9H), 0.00 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 215.9, 157.4, 149.2, 108.2, 104.5, 54.9, 45.7, 43.3, 34.1, 21.4, 16.1, 15.5, 12.0, −0.7, −0.9; IR (cm^{-1}) 2953, 2900, 1749, 1559, 1411, 1249, 1012, 860, 837, 776, 690; HRMS m/z calcd for $C_{19}H_{34}O_2Si_2Na^+$: 373.1990, found: 373.1985.

4.3.24. (2S,3R*,4S*)-2-(5-Benzylfuran-2-yl)-3,4-bis((trimethylsilyl) methyl)cyclopentanone (**23i**).* Colorless oil. R_f=0.52 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.31–7.26 (m, 2H), 7.24–7.19 (m, 3H), 6.03 (d, J=3.5 Hz, 1H), 5.91 (d, J=3.0 Hz, 1H), 3.93 (s, 2H), 3.12 (d, J=9.5 Hz, 1H), 2.56–2.42 (m, 3H), 2.24–2.17 (m, 1H), 0.82–0.75 (m, 2H), 0.58 (dd, J=6.0, 15.0 Hz, 1H), 0.35 (dd, J=12.0, 14.0 Hz, 1H), 0.05 (s, 9H), −0.02 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 215.6, 154.0, 150.1, 138.1, 128.6 (2C), 128.4 (2C), 126.3, 108.5, 107.0, 54.8, 45.8, 43.3, 34.5, 34.0, 16.0, 15.4, −0.7 (3C), −0.9 (3C); IR (cm^{-1}) 3064, 3030, 2952, 2900, 1748, 1604, 1560, 1496, 1454, 1411, 1249, 1157, 1111, 1074, 1014, 967, 860, 837, 782, 703, 693; HRMS m/z calcd for $(C_{24}H_{36}O_2Si_2)Na^+$: 435.2146, found: 435.2142.

4.3.25. (2S,3R*,4S*)-2-(5-(4-((tert-Butyldimethylsilyl)oxy)butyl)furan-2-yl)-3,4-bis((trimethylsilyl)methyl)cyclopentanone (**23j**).* Colorless oil. R_f=0.33 (5% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.99 (d, J=3.0 Hz, 1H), 5.90 (d, J=3.0 Hz, 1H), 3.61 (t, J=6.0 Hz, 2H), 3.09 (d, J=9.5 Hz, 1H), 2.58 (t, J=7.5 Hz, 2H), 2.55–2.42 (m, 3H), 2.22–2.15 (m, 1H), 1.69–1.61 (m, 2H), 1.58–1.51 (m, 2H), 0.89 (s, 9H), 0.82–0.75 (m, 2H), 0.57 (dd, J=6.5, 15.0 Hz, 1H), 0.34 (dd, J=12.0, 14.0 Hz, 1H), 0.04 (s, 15H), 0.00 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 215.9, 155.9, 149.3, 108.2, 105.4, 62.9, 54.9, 45.7, 43.3, 34.1, 32.3, 27.8, 26.0 (3C), 24.3, 18.4, 16.0, 15.6, −0.7 (3C), −0.9 (3C), −5.3 (2C); IR (cm^{-1}) 2953, 2898, 2858, 1749, 1560, 1472, 1463, 1410, 1250, 1161, 1105, 1011, 972, 837, 776, 691; HRMS m/z calcd for $(C_{27}H_{52}O_3Si_3)Na^+$: 531.3116, found: 531.3116.

4.3.26. (2S,3R*,4S*)-2-(5-Butylfuran-2-yl)-3,4-bis((trimethylsilyl) methyl)cyclopentanone (**23k**).* Colorless oil. R_f=0.50 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.99 (d, J=3.0 Hz, 1H), 5.88 (d, J=3.0 Hz, 1H), 3.10 (d, J=9.0 Hz, 1H), 2.59–2.44 (m, 5H), 2.22–2.15 (m, 1H), 1.61–1.54 (m, 2H), 1.38–1.30 (m, 2H), 0.90 (t, J=7.5 Hz, 3H), 0.82–0.75 (m, 2H), 0.57 (dd, J=6.0, 15.0 Hz, 1H), 0.35 (dd, J=12.5, 14.0 Hz, 1H), 0.04 (s, 9H), 0.00 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 215.9, 156.1, 149.2, 108.2, 105.3, 54.9, 45.7, 43.3, 34.1, 30.1, 27.7, 22.2, 16.0, 15.5, 13.8, −0.7 (3C), −0.9 (3C); IR (cm^{-1}) 2955, 2874, 1749, 1560, 1411, 1249, 1180, 1162, 1111, 1077, 1013, 966, 860, 838, 779, 691; HRMS m/z calcd for $(C_{21}H_{38}O_2Si_2)Na^+$: 401.2306, found: 401.2306.

4.3.27. (2S,3R*,4S*)-2-(5-(3-Chloropropyl)furan-2-yl)-3,4-bis((trimethylsilyl)methyl) cyclopentanone (**23l**).* Colorless oil. R_f=0.43 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.01 (d, J=3.0 Hz, 1H), 5.96 (d, J=2.5 Hz, 1H), 3.53 (t, J=6.0 Hz, 2H), 3.10 (d, J=9.0 Hz, 1H), 2.75 (t, J=7.5 Hz, 2H), 2.56–2.42 (m, 3H), 2.23–2.16 (m, 1H), 2.10–2.03 (m, J=7.0 Hz, 2H), 0.83–0.75 (m, 2H), 0.56 (dd, J=6.5, 15.0 Hz, 1H), 0.34 (dd, J=12.5, 14.0 Hz, 1H), 0.04 (s, 9H), 0.00 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 215.7, 153.9, 149.9, 108.4, 106.4, 54.8, 45.8, 44.1, 43.3, 34.1, 30.9, 25.2, 16.1, 15.5, −0.7 (3C), −0.9 (3C); IR (cm^{-1}) 2953, 2901, 1748, 1560, 1411, 1249, 1184, 1152, 1111, 1076, 1014, 968, 860, 838, 783, 691; HRMS m/z calcd for $(C_{20}H_{35}ClO_2Si_2)Na^+$: 421.1756, found: 421.1755.

4.3.28. (1R,2S*,3S*,4R*,5R*,6S*,10R*)-1-Benzyl-3,4-bis((trimethylsilyl) methyl)-9-oxatricyclo [4.2.1.1^{2,5}]dec-7-en-10-ol (**24i**).* White solid; mp=122–123 °C, R_f=0.19 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.30–7.25 (m, 2H), 7.23–7.18 (m, 3H), 6.47 (dd, J=1.5, 6.0 Hz, 1H), 6.42 (d, J=6.0 Hz, 1H), 4.49–4.46 (m, 1H), 3.97–3.91 (m, J=12.5 Hz, 1H), 3.08 (d, J=14.0 Hz, 1H), 2.92 (d, J=12.0 Hz, 1H), 2.90 (d, J=14.0 Hz, 1H), 2.48 (dt, J=4.5, 9.5 Hz, 1H), 2.33 (ddd, J=2.5, 9.0, 13.0 Hz, 1H), 1.90 (dd, J=2.0, 3.5 Hz, 1H), 1.80–1.76 (m, 1H), 0.91 (dd, J=4.5, 15.0 Hz, 1H), 0.73 (dd, J=3.0, 15.0 Hz, 1H), 0.46 (dd, J=10.0, 15.0 Hz, 1H), 0.40 (dd, J=13.5, 14.5 Hz, 1H), 0.10 (s, 9H), 0.04 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 138.4, 136.5, 136.4, 130.3 (2C), 128.1 (2C), 126.4, 87.4, 81.0, 73.5, 55.8, 49.4, 41.1, 37.5, 19.4, 18.7, −0.6 (3C), −0.7 (3C); IR (cm^{-1}) 3609, 3457, 3064, 3029, 2950, 1496, 1454, 1314, 1248, 1182, 1092, 1020, 1001, 837, 740, 697; HRMS m/z calcd for $(C_{24}H_{38}O_2Si_2)Na^+$: 437.2303, found: 437.2308.

4.3.29. (1R,2S*,3S*,4R*,5R*,6S*,10R*)-1-(4-((tert-Butyldimethylsilyl) oxy)butyl)-3,4-bis((trimethylsilyl)methyl)-9-oxatricyclo[4.2.1.1^{2,5}] dec-7-en-10-ol (**24j**).* Colorless oil. R_f=0.21 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.59 (d, J=5.5 Hz, 1H), 6.43 (d, J=6.0 Hz, 1H), 4.50–4.48 (m, 1H), 3.88 (d, J=12.0 Hz, 1H), 3.64–3.54 (m, 2H), 2.93 (d, J=12.0 Hz, 1H), 2.30–2.21 (m, 2H), 1.80–1.77 (m, 1H), 1.77–1.74 (m, 1H), 1.74–1.66 (m, 1H), 1.66–1.58 (m, 1H), 1.58–1.51 (m, 2H), 1.45–1.27 (m, 2H), 0.88 (s, 9H), 0.82 (d, J=15.0 Hz, 1H), 0.74 (d, J=15.0 Hz, 1H), 0.37 (dd, J=11.0, 14.5 Hz, 2H), 0.03 (s, 15H), 0.02 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 138.8, 136.7, 87.6, 81.2, 73.5, 63.1, 54.9, 49.4, 37.8, 37.4, 34.3, 33.3, 26.0 (3C), 20.1, 19.5, 18.6, 18.4, −0.6 (3C), −0.7 (3C), −5.3 (2C); IR (cm^{-1}) 3619, 3474, 2951, 2897, 2858, 1472, 1463, 1248, 1194, 1088, 1007, 836, 775, 751, 697; HRMS m/z calcd for $(C_{27}H_{54}O_3Si_3)Na^+$: 533.3273, found: 533.3272.

4.3.30. (1R,2S*,3S*,4R*,5R*,6S*,10R*)-1-Butyl-3,4-bis((trimethylsilyl) methyl)-9-oxatricyclo [4.2.1.1^{2,5}]dec-7-en-10-ol (**24k**).* Colorless oil. R_f=0.21 (10% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.60 (d, J=5.0 Hz, 1H), 6.44 (d, J=5.5 Hz, 1H), 4.51–4.49 (m, 1H), 3.89 (d, J=12.0 Hz, 1H), 2.94 (d, J=12.0 Hz, 1H), 2.32–2.22 (m, 2H), 1.81–1.78 (m, 1H), 1.78–1.75 (m, 1H), 1.75–1.67 (m, 1H), 1.63–1.58 (m, 1H),

1.40–1.31 (m, 3H), 1.30–1.21 (m, 1H), 0.91 (t, J=7.0 Hz, 3H), 0.82 (dd, J=3.0, 15.0 Hz, 1H), 0.75 (dd, J=2.5, 14.5 Hz, 1H), 0.41–0.34 (m, 2H), 0.04 (s, 9H), 0.02 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 139.0, 136.6, 87.6, 81.2, 73.5, 54.9, 49.4, 37.8, 37.4, 34.3, 26.0, 23.2, 19.5, 18.6, 14.0, −0.7 (6C); IR (cm^{-1}) 3619, 3466, 2953, 2873, 1457, 1419, 1301, 1248, 1191, 1087, 1009, 836, 787, 751, 690; HRMS m/z calcd for $(C_{21}H_{40}O_2Si_2)Na^+$: 403.2459, found: 403.2466.

4.3.31. (1R,2S*,3S*,4R*,5R*,6S*,10R*)-1-(3-Chloropropyl)-3,4-bis((trimethylsilyl)methyl)-9-oxatricyclo[4.2.1.1^{2,5}]dec-7-en-10-ol (**24l**).* White solid; mp=76–78 °C. R_f=0.41 (20% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.62 (d, J=5.5 Hz, 1H), 6.41 (d, J=6.0 Hz, 1H), 4.51–4.48 (m, 1H), 3.89 (d, J=12.0 Hz, 1H), 3.63–3.51 (m, 2H), 2.87 (d, J=12.0 Hz, 1H), 2.31–2.21 (m, 2H), 1.94–1.83 (m, 2H), 1.82–1.70 (m, 4H), 0.82 (dd, J=3.0, 15.0 Hz, 1H), 0.75 (dd, J=2.5, 15.0 Hz, 1H), 0.38 (ddd, J=3.0, 11.0, 15.0 Hz, 2H), 0.05 (s, 9H), 0.03 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 138.5, 137.2, 87.1, 81.3, 73.4, 55.2, 49.4, 45.4, 37.8, 37.5, 31.6, 26.9, 19.5, 18.6, −0.6 (3C), −0.7 (3C); IR (cm^{-1}) 3614, 3463, 2951, 1445, 1307, 1248, 1191, 1084, 1004, 836, 788, 750, 698; HRMS m/z calcd for $(C_{20}H_{37}ClO_2Si_2)Na^+$: 423.1913, found: 423.1922.

4.3.32. (4R,5R*)-3-Methyl-5-phenethyl-4-((trimethylsilyl)methyl)cyclopent-2-enone (**26**).* To 2-chloro-3,4-bis((trimethylsilyl)methyl)cyclopentanone (100 mg, 0.344 mmol) in 2,2,2-trifluoroethanol (1.5 mL) at −78 °C was added styrene (79 μL, 0.687 mmol, 2 equiv). While stirring, 0.52 mL 1 M sodium 2,2,2-trifluoroethanolate (0.52 mmol, 1.5 equiv) was added to the reaction. The solution was allowed to warm to rt and stir for 1 h and was then filtered through a very short pad of alumina (Al_2O_3). The solution was concentrated under reduced pressure. The crude product was weighed and purified by column chromatography (alumina, 10% EtOAc/hexanes), which yielded 37 mg (38% yield) colorless oil. R_f=0.29 (10% EtOAc/hexanes) ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.29–7.24 (m, 2H), 7.21–7.15 (m, 3H), 5.85 (s, 1H), 2.71 (ddd, J=5.5, 10.5, 13.5 Hz, 1H), 2.63 (ddd, J=5.5, 10.5, 13.5 Hz, 1H), 2.49 (d, J=10.5 Hz, 1H), 2.13 (t, J=6.0 Hz, 1H), 2.08 (s, 3H), 1.99–1.83 (m, 2H), 1.06 (dd, J=3.5, 14.5 Hz, 1H), 0.55 (dd, J=11.0, 15.0 Hz, 1H), 0.02 (s, 9H), ^{13}C NMR (125 MHz, $CDCl_3$) δ 211.1, 182.9, 141.9, 129.0, 128.5 (2C), 128.3 (2C), 125.9, 53.4, 47.6, 33.9, 32.3, 21.3, 17.3, −0.7 (3C); IR (cm^{-1}) 3063, 3027, 2951, 2893, 2864, 1696, 1622, 1496, 1454, 1376, 1291, 1250, 1185, 854, 837, 755, 699; HRMS m/z calcd for $(C_{18}H_{26}OSi)Na^+$: 309.1645, found: 309.1641.

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Supplementary data

^{1}H and ^{13}C NMR spectra for all new compounds. Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.tet.2013.05.051.

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16. Crystallographic data (excluding structure factors) for the structure in this paper has been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 928784 (**16d**) and 928783 (**24i**). Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax: +44(0)-1223-336033 or e-mail; deposit@ccdc.cam.ac.uk].