Synthesis of the Spatane Nucleus (*cis-anti-cis*-tricyclo[5.3.0.0^{2,6}]decane) using the Pauson−Khand Reaction with a Remarkable Reversal in Regioselectivity

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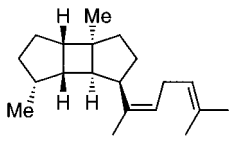
The Pauson−Khand reaction of cyclobutenes **3**−**5** with a variety of acetylenes yielded *cis-anti cis*-tricyclo[5.3.0.0^{2,6}]decanes **9**−**17**. The unwanted regioisomers **9a** and **10a** were the sole products using acetylene, but there was a remarkable reversal in orientation of the cyclobutene component yielding the desired regioisomer **13b** upon using (trimethylsilyl)acetylene. The importance of the allylic methyl group in the cyclobutenes in directing the regiochemical outcome was substantiated by the lack of selectivity in Pauson−Khand reactions of desmethylcyclobutene **5** with acetylene and (trimethylsilyl)acetylene. The relative unimportance of electronic control of regiochemistry was concluded from the consistent ratio of Pauson−Khand reaction products from norbornenone **22** with various acetylenes. A hypothesis rationalizing the regiochemical outcome was based on steric interactions of the allylic methyl group from the cyclobutene component with either the smaller acetylene substituent or the CO ligands on the cobalt. This steric interaction was further hypothesized to be influenced by the larger acetylene substituent sterically crowding the CO ligands on the cobalt.

Introduction

The Pauson−Khand reaction, that was first reported in 1973, has received much attention because of the utility of this cyclopentenone formation.[1] A great variety of acetylenes and alkenes have been coupled to make synthetically useful cyclopentenones. In many cases there is good regiochemical and stereochemical control.

The spatane diterpenes, that are of biological interest, have been synthetically approached by several different methods.[2] One of the main challenges in synthesizing spatanes has been efficiently making an appropriately functionalized *cis-anti-cis*-tricyclo[5.3.0.0^{2,6}]decane nucleus. In our total synthesis of spatadiene (**1**) and formal synthesis of spatol (**2**), we employed the retrosynthetic



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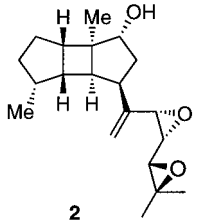

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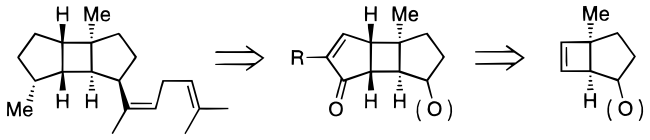
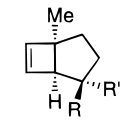
analysis outlined in Scheme 1.[3] The most critical step in the process was the use of a Pauson−Khand reaction to annulate a cyclopentenone, regioselectively

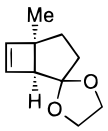
Scheme 1



and stereoselectively, on an appropriately functionalized cyclobutene. In this paper, we report our complete synthetic efforts at making the *cis-anti-cis*-tricyclo-[5.3.0.0^{2,6}]decane nucleus using Pauson−Khand methodology.



3 R=OH, R'=H
3a R=H, R'=OH



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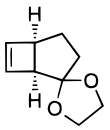

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Results and Discussion

Cyclobutene Syntheses. Three different cyclobutenes (**3**−**5**) were synthesized as substrates for study of the Pauson−Khand reaction. Cyclobutene **4** was synthesized by the route outlined in Scheme 2. The first step was a photo [2 + 2] reaction between 3-methyl-2-cyclopentenone (**6**) and 1,2-dichloroethylene to produce cyclobutane **7**. This photoreaction was done in cyclohexane with a large excess of 1,2-dichloroethylene to minimize dimerization of 3-methyl-2-cyclopentenone which was added in two

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(1) Reviews: (a) Schore, N. E. *Org. React.* **1991**, *40*, 1. (b) Shore, N. E. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon: Oxford, 1991; Vol. 5, pp 1037−1064. (c) Pauson, P. L. *Tetrahedron* **1985**, *41*, 5855. (d) Pauson, P. L. *Organometallics in Organic Synthesis*; de Meijere, A., tom Dieck, H., Eds.; Springer-Verlag: Berlin, 1987; p 233. (e) Schore, N. E. *Chem. Rev.* **1988**, *88*, 1081.

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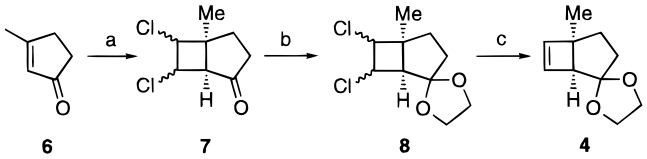
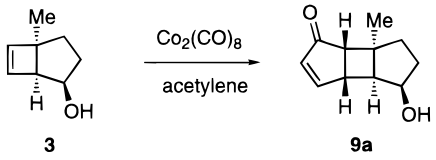
Scheme 2[a]



[a] (a) *hν*, 1,2-dichloroethylene, 89%; (b) ethylene glycol, PPTs, 96%; (c) sodium naphthalenide, 77%.

Table 1. Optimization of Pauson–Khand Reaction



run	solvent	temp (°C)	time (h)	concn (M)	yield (%)
1	heptane	65–70	8	0.15	50
2	heptane	65–70	17	0.14	50
3	DME	65–70	15	0.16	50
4[a]	heptane	65–70	8	0.14	53
5	heptane	55–60	8	0.15	59
6	heptane	65–70	8	0.031	73

[a] *n*-Bu_3PO (1.2 equiv).

portions to keep its relative concentration low, helping to further reduce dimerization. A Pyrex filter was used to cut off light of low wavelengths that would be destructive. The ketone of cyclobutane **7** was protected as a ketal to give **8**. The desired cyclobutene **4** was made by reduction of vicinal dichloride **8** using sodium naphthalenide.[4] Cyclobutene **5** was made from 2-cyclopentenone following a similar route to that for cyclobutene **4**. Cyclobutene **3** was made by a L-Selectride reduction of ketone **7** followed by reductive elimination of the vicinal dichloride using sodium naphthalenide. The cyclobutenol product was mainly **3** (85%) along with a minor amount of **3a** (15%).

Pauson–Khand Reaction Optimization. The Pauson–Khand reaction between cyclobutene **3** and acetylene was used to optimize the reaction conditions (see Table 1). The reactions were run by adding cyclobutene **3** (containing 15% **3a**) to the complex formed between $Co_2(CO)_8$ (1.2 equiv) and acetylene and then heating the mixture to the appropriate temperature under an atmosphere of CO and acetylene to give tricyclic cyclopentenone **9a**. The first entry was run in heptane giving a yield of 50%. In entry 2, the reaction time was doubled, in entry 3, the solvent was switched to dimethoxymethane, and in entry 4, n-Bu_3PO[5] was added but all conditions produced essentially the same yield of 50%. In run 5, the reaction temperature was lowered 10 °C increasing the yield to 59%. The most useful improvement in yield came in run 6 when the concentration of cyclobutene **3** was lowered by a factor of 5 to 0.031 M, giving **9a** in 73% yield. The only product isolated in these Pauson–Khand reactions was **9a** derived from **3** and not **3a**.

Pauson–Khand Reactions. Pauson–Khand reactions of cyclobutenes **3**–**5** with various acetylenes were carried out, and the results are presented in Table 2.

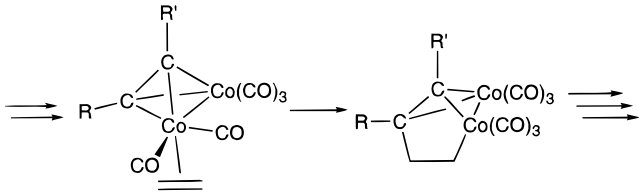
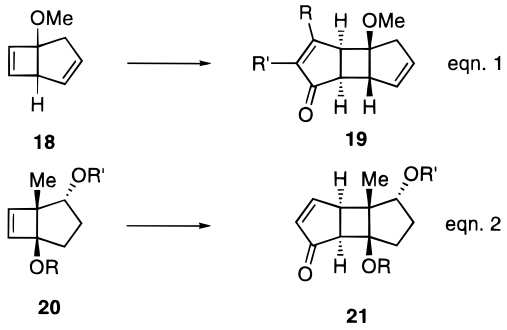


Figure 1. Reaction mechanism key step.

Alkenes **3**–**5** were all good substrates for the cyclopentenone annulations as anticipated since cyclobutenes are generally good substrates for the Pauson–Khand reaction.[6] The orientation of the acetylene component in the adducts of table entries 3–5, 7, and 9 followed the trend typically observed, i.e., with the larger substituent on the initial acetylene α to the carbonyl group in the newly formed cyclopentenone.[1]

To understand the orientation of the alkene (cyclobutene) component in the adducts, the postulated mechanism must be considered.[1a,b,e,6b,7] Thus, the initial steps in the Pauson–Khand reaction are complexation of the acetylene component with dicobalt octacarbonyl, followed by complexation of the alkene to one cobalt atom by a reversible dissociative process involving the loss of a CO ligand. A key step in the mechanism is the subsequent irreversible insertion of the cobalt-complexed face of the alkene π bond into one of the formal cobalt–carbon bonds of the alkyne complex (see Figure 1). This step is believed to be both rate and product determining. The product is formed by subsequent CO insertion, reductive elimination of one cobalt, and decomplexation of the second cobalt.

Two closely related previous examples of Pauson–Khand reactions of unsymmetrically substituted cyclobutenes are the **18** to **19** (eq 1)[6a] and **20** to **21** (eq 2)[6b,c] conversions. A rationale for the preferred orientation in



these remarkably selective reactions is based on a steric argument. Thus, the bigger allylic substituent (methoxy for **18** and methyl for **20**) and a CO ligand on cobalt are in a 1,3-pseudodiaxial relationship in the disfavored regioisomeric intermediate creating an unfavorable steric

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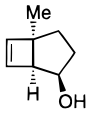
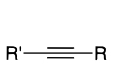
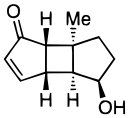
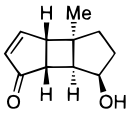
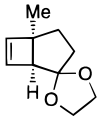
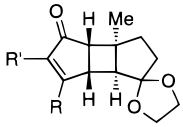
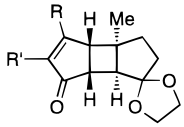
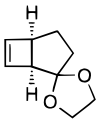
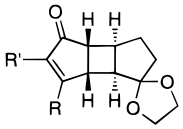
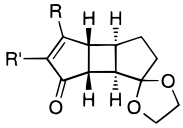
Table 2. Pauson–Khand Reactions

Entry	Alkene	Acetylene R'	Acetylene R	Products		Product Ratio a / b	Yield (%)
							
1	**3**	H	H	**9a**	**9b**	100 / 0	73
							
2	**4**	H	H	**10a**	**10b**	100 / 0	83
3	**4**	n-Pr	H	**11a**	**11b**	1.32 / 1.0	72
4	**4**	t-Bu	H	**12a**	**12b**	1.0 / 5.3	78
5	**4**	TMS	H	**13a**	**13b**	0 / 100	86
6	**4**	Me	Me	**14a**	**14b**	5.3 / 1.0	77
7	**4**	TMS	Me	**15a**	**15b**	0 / 100	37
							
8	**5**	H	H	**16a**	**16b**	1.0 / 1.0	63
9	**5**	TMS	H	**17a**	**17b**	1.0 / 1.5	80

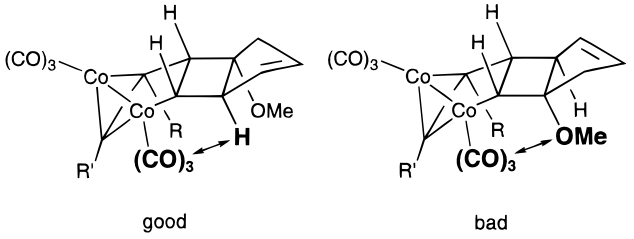


Figure 2. 1,3-Pseudodiaxial steric interaction.

interaction (see Figure 2). In the favored regioisomeric intermediate, the smaller allylic substituent and a CO ligand on cobalt are in a 1,3-pseudodiaxial relationship. The orientation of the alkene component in Pauson–Khand reactions of several other bicyclic alkenes were rationalized previously by similar steric considerations.[1a,b,e,6b,8]

The preferential formation of cyclopentenone **9a** in the Pauson–Khand reaction of cyclobutene **3** was unexpected in view of the steric rationale mentioned above. Thus, the four possible reaction-determining intermediates in the reaction of **9a** with acetylene and dicobaltoctacarbonyl (Table 2, entry 1) are depicted in Figure 3. In intermediates A and B, the 1,3-pseudodiaxial interaction between the allylic methyl group, which is clearly bigger than the allylic hydrogen, and a CO ligand on cobalt would be unfavorable. In intermediates C and D, the disfavored 1,3-pseudodiaxial interaction between the methyl group and a CO ligand on cobalt is absent. Therefore, intermediates C/D are predicted to be favored over intermediates A/B. Intermediates C/D lead to **9b** which is, therefore, expected to be the favored product. However, **9a** is the actual product formed, presumably, through intermediate A and/or B. As for **3**, the steric argument outlined above clearly is inadequate to properly predict the orientation of cyclobutene addition in the Pauson–Khand reaction of **4** with acetylene.

We propose a modified steric argument to explain the orientation of cyclobutene addition for the Pauson–Khand reactions summarized in Table 2. Thus, our model also is based on steric interactions in the intermediates of Figure 3. In intermediates A/B the allylic methyl group has a 1,3-pseudodiaxial steric interaction with a CO ligand on cobalt. In intermediates C/D the allylic methyl group has a 1,3-pseudodiaxial steric interaction with the acetylenic substituent R (R = H). The 1,3-pseudodiaxial interaction of the R group (R = H) with the allylic methyl is apparently greater than that between a CO ligand and the allylic methyl group in A/B. Therefore, intermediates A/B are favored. Perhaps the CO ligands for these intermediates can be accommodated and not cause much steric interaction with the allylic methyl group. This new steric hypothesis also rationalizes the orientation of cyclobutene addition in the Pauson–Khand reaction of **4** with acetylene (Table 2, entry 2).

The unexpected regiochemistry of entries 1 and 2 (Table 2) prompted the investigation of 1-(trimethylsilyl)-propyne in an effort to take advantage of the unexpected

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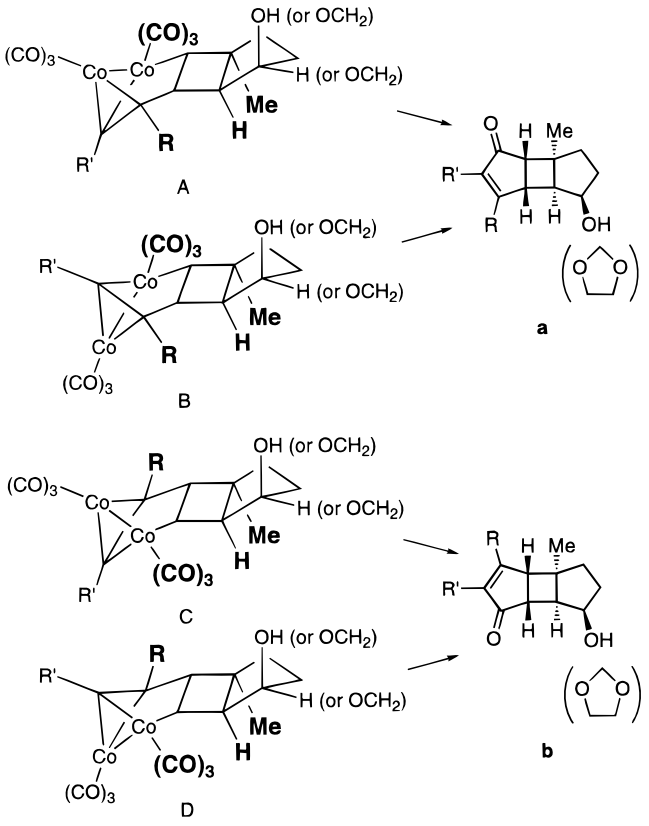

Figure 3. The four possible Pauson−Khand alkene insertion intermediates.

regiochemistry and make **15a** with the methyl group in the correct place for spatanes. However, the opposite regioisomer **15b** was produced (Table 2, entry 7). The difficulty in predicting the regiochemistry in the Pauson−Khand reactions of many unsymmetrical olefins points out the delicate balance of factors involved in many systems including this series of examples. The systematic investigation of the acetylenes substitution pattern appeared critical in this series to understand the regiochemical outcome and to develop an efficient synthesis of the spatane nucleus. In the literature, the effect of disubstituted acetylenes on the regiochemical outcome of the olefin has been investigated and will be discussed in due course, but the systematic investigation of the effect of monosubstituted acetylenes has not been undertaken and was crucial in this study.[9] The reactions of Table 2, entries 3−5, were carried out to study the effect of differing monosubstituted acetylenes on the orientation of the alkene addition.

For entry 3 in Table 2, the same orientation, i.e., favoring regioisomer **11a**, in the Pauson−Khand reaction of olefin **4** predominated as in entries 1 and 2, but only by a small margin over the other regioisomer **11b**. In entry 4, the opposite regioisomer **12b** became the major product instead of **12a**. In entry 5, the remarkable reversal in regiochemistry was complete with only **13b** produced. Examining the possible intermediates A/B versus C/D, it is surprising that for entries 2 through 5 intermediates C/D became not only competitive with intermediates A/B but became the sole intermediate for entry 5. The only difference between these entries was in R′ which is remote to anything on the alkene derived portion of intermediates A/B or C/D. However, we believe the R′ group plays a critical role by sterically congesting the CO ligands on cobalt. The larger the R′ group results in more congested CO ligands which cannot, in turn, as easily accommodate steric interactions with other groups. The size of the CO ligands, therefore, becomes effectively larger. Reevaluation of the steric interactions for intermediates A/B reveals that increasing the size of the CO ligands makes the interaction with the allylic methyl more significant and less favorable. In intermediates C/D the increasing effective size of the CO ligands can be more easily accommodated with H rather than methyl at the ring juncture. Therefore, as the acetylenic R′ group increases in size from entry 2 through 5, intermediates C/D become more favorable compared to intermediates A/B corresponding with the switch from product a to b.

The TMS group in entry 5 (Table 2) had an even greater effect than the *t*-Bu group in entry 4. This may be due to the different bond distances of the TMS group, which may more optimally interact with the CO ligands, or the Si may have a subtle electronic reinforcing effect. The electronic effect of the Si will be discussed later.

For entries 6 and 7 (Table 2), the acetylenes are disubstituted which gives them both a R′ substituent and a R substituent which can both affect the orientation of the alkene component.[9] The R′ = Me group for entry 6 would be expected to have a similar directing effect as the n-Pr group in entry 3, slightly favoring intermediates A/B. However, the R = Me group for entry 6 also plays a role. In intermediates A/B the R = Me group has a 1,3-pseudodiaxial steric interaction with the ring juncture H, but in intermediates C/D it has a 1,3-pseudodiaxial steric interaction with the angular Me which must disfavor intermediates C/D. The greater selectivity for **14a** over **14b** compared to entry 3 is therefore understandable.

The large magnitude of the directing influence of the R′ = TMS group is demonstrated in entry 7. The R′ = TMS group greatly favors intermediates C/D versus intermediates A/B by analogy to entry 5, but the R = Me group's influence is opposite, favoring intermediates A/B versus intermediates C/D by analogy to entry 6. The production of only **15b** clearly illustrates the dominance of the R′ = TMS group's influence on the orientation of the alkene in the Pauson−Khand reaction of cyclobutene **4** with 1-(trimethylsilyl)propyne.

Cyclobutene **5** was prepared without an angular Me group to more clearly define the role of this Me group. In both entries 8 and 9 the low regioselectivity suggests the ring juncture Me group is indeed extremely important for high regioselectivity. The ketal functionality maintained in alkene **5** apparently has little directing influence itself.

While steric control arguments are usually postulated to rationalize regioselectivities, electronic control has also been used to rationalize product distribution.[10] The complete change in regioselectivity of entries 1−7 could potentially be rationalized based on the electronic argument that the polarization of the cobalt−acetylene complex has somehow changed based on the substitution of the acetylene. The ability of silicon to stabilize a positive charge on a β carbon, thus affecting the polarization, is

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(10) (a) MacWhorter, S. E.; Sampath, V.; Olmstead, M. M.; Schore, N. E. *J. Org. Chem.* **1988**, *53*, 203. (b) MacWhorter, S. E.; Schore, N. E. *J. Org. Chem.* **1991**, *56*, 338.

Table 3. Pauson–Khand Reactions of Norbornenone

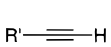
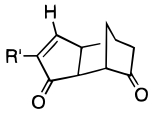
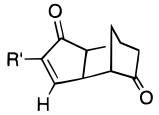
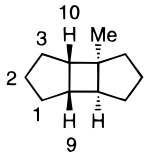
Alkene	Acetylene R'	Products		Product Ratio a / b	Yield (%)
					
22	H	**23a**	**23b**	2.2 / 1.0	57
22	t-Bu	**24a**	**24b**	3.1 / 1.0	64
22	TMS	**25a**	**25b**	2.5 / 1.0	42

Table 4. Selected ^{1}H NMR Spectral Data of Pauson–Khand Adducts



	^{1}H NMR (chemical shift (ppm), multiplicity, coupling constant (Hz))				
compound	H-1	H-2	H-3	H-9	H-10
9a	7.77 dd J = 3.1, 5.4	6.28 d J = 5.3	–	3.34 m	2.51 d J = 4.9
10a	7.73 dd J = 3.1, 5.4	6.23 d J = 5.4	–	3.14 m	2.55 d J = 4.9
11a	7.34 s(br)	–	–	3.02 s(br)	2.62 d J = 4.8
11b	–	–	7.33 s(br)	2.66 dd J = 3.2, 5.0	2.88 m
12a	7.26 d	–	–	2.91 ddd J = 2.7, 3.0, 5.2	2.53 d J = 5.2
12b	–	–	7.26 d J = 3.4	2.60 dd J = 3.1, 5.0	2.77 dd J = 3.4, 5.0
13b	–	–	7.75 d J = 3.0	2.55 dd J = 3.2, 4.9	2.93 dd J = 3.3,4.9
14a	–	–	–	2.76 s(br)	2.50 d J = 5.0
14b	–	–	–	2.61 dd J = 3.0, 5.0	2.75 d J = 4.8
15b	–	–	–	2.53 dd J = 2.9,5.2	2.76 d J = 5.3

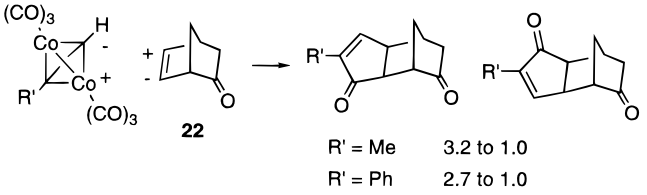


Figure 4. Norbornenone Pauson–Khand reactions.

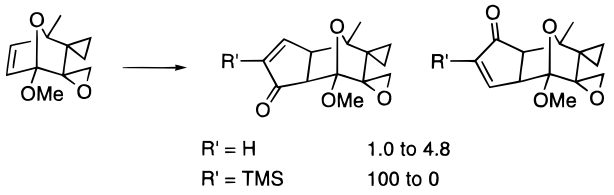


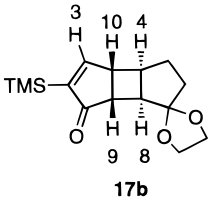
Figure 5. Similar reversal in regioselectivity.

suggestive that it may contribute to the great seletivity for entries 5 and 7 in Table 2.[11] One of the most clearly defined examples of electronic control is with norbornenone **22** shown in Figure 4.[10] To investigate further the possible influence of the R′ substituent on the polarization of the cobalt–acetylene complex, Pauson–Khand reactions of norbornenone **22** with several other monosubstituted acetylenes (R′ = H, *t*-Bu, and TMS) were examined (see Table 3). The regioselectivity was 2.2/1 to 3.1/1 which was remarkably similar to the literature examples in Figure 4. This seems to rule out any switch of the polarization of the cobalt–acetylene complex as a rational for the change in regioselectivity demonstrated in Table 2. The only example we know of in the literature that demonstrates a similar reversal, although not complete, in orientation of the alkene component as a consequence of varying the substitution in the acetylene component of a Pauson–Khand reaction is shown in Figure 5.[12]

Analysis of ^{1}H NMR Spectral Data. The ^{1}H NMR spectral data were a valuable tool for structural assignment of Pauson–Khand adducts **9a**–**17b** (see Table 4).

(11) (a) Gabelica, V.; Kresge, A. J. *J. Am. Chem. Soc.* **1996**, *118*, 3838. (b) Colvin, E. W. *Silicon in Organic Synthesis*; Butterworths: London, 1981.

(12) (a) de Meijere, A.; Wessjohann, L. *Synlett* **1990**, 20. (b) Reference 1a, pp 68–69.



17b

Figure 6.

The analysis for **9a** was done as follows. There were two possible cyclopentenones annulated onto cyclobutene **3** resulting in either structure **9a** or **9b**. The vinyl proton at 6.28 ppm (doublet) was assigned as α to the carbonyl (H-2) and the vinyl proton at 7.77 ppm (doublet of doublets) as β to the carbonyl (H-1) because of their coupling patterns. The proton at 3.34 ppm (H-9) was coupled to the β vinyl proton, therefore, it was assigned as next to the β vinyl carbon. The proton at 2.51 ppm (H-10) was coupled only to the proton at 3.34 ppm; therefore, it was assigned as next to the proton at 3.34 ppm, and structure **9b** could be ruled out, because the proton at 2.51 ppm was only a doublet. The proton−proton coupling of protons H1, 2, 9, and 10 were determined by homonuclear decoupling experiments. Structural assignment of enone **10a** was based on the same arguments and similarity to enone **9a**. The regiochemistry of enones **11a**, **11b**, **12a**, **12b**, **13b**, all having β vinyl protons, were assigned based on similar reasoning.

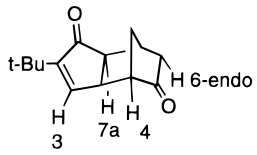
The assignment of the regiochemistry of the carbonyl at C-1 or C-3 for enones **14a**, **14b**, and **15b** could not be made based on coupling of a vinyl proton to H-9 or H-10 as above. The assignment, however, could be based on the knowledge that the proton on the cyclobutane carbon adjacent to the β carbon of the enone was further downfield than the cyclobutane proton on the carbon adjacent to the carbonyl in all the compounds already assigned (**9a**, **10a**, **11a**, **11b**, **12a**, **12b**, **13b**). Therefore, with the assignment of which proton of the two protons in question is adjacent to each end of the enone functionality, the multiplicity of the H-9 and H-10 protons was sufficient to assign the regiochemistry.

The monosubstituted acetylenes used to make **11a**, **11b**, **12a**, **12b**, and **13b** all gave the α-substituted enones as expected. This assignment was based on their vinyl protons having a chemical shift of over 7.2 ppm, indicating the protons as β not α to the carbonyl based on comparison to the chemical shifts of the vinyl protons of **9a** and **10a**.

The orientation of the allylic methyl group at 2.12 ppm in enone **15b** was assigned on the β carbon of the enone. This assignment was based on comparison to enones **14a** and **14b** which have the protons of the α methyl group at 1.62 ppm and 1.75 ppm, but their β methyl protons at 1.93 and 2.02 ppm.

The structure of **17b** was determined by analysis of the proton NMR spectral data. Protons H-3, H-4, H-8, H-9, and H-10 were assigned based on their coupling using a COSY spectrum (see Figure 6). The H-8 proton was a doublet of doublets, and H-4 was a multiplet which is consistent with **17b** and not **17a**.

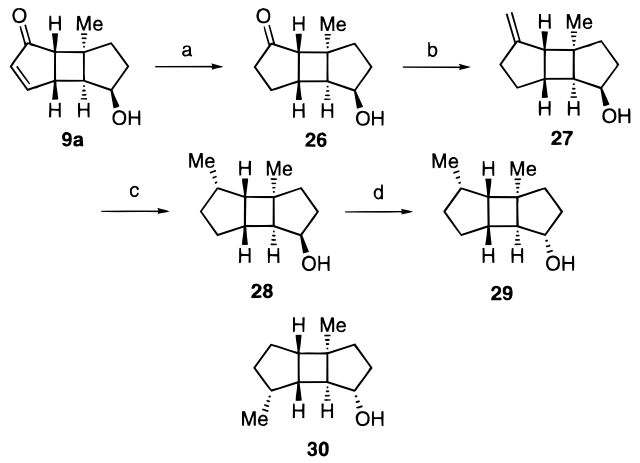
The structures of the adducts with norbornenone **22** were assigned based on the β vinyl proton NMR spectral data. The chemical shift of the β vinyl proton for the anti-diketones appeared approximately 0.1 ppm upfield of that in the corresponding syn-diketone isomers.[10]



24b

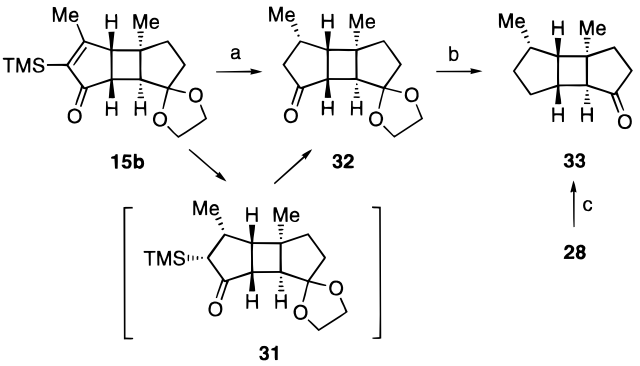
Figure 7.

Scheme 3[a]



[a] (a) H_2, Pd/C, 100%; (b) sodium *tert*-amylate, $Ph_3CH_3{}^+I^-$, 80%; (c) diimide, 92%; (d) Mitsunobu, 92%.

Scheme 4[a]



[a] (a) H_2, Pd/C, 74%; (b) (1) $TsNHNH_2$; (2) $NaBH_4$; (3) H^+, 54%; (c) Swern oxidation, 99%.

Supporting NOESY (nuclear Overhauser effect spectroscopy) was carried out on Pauson−Khand adduct **24b**. Interactions were evident between H-3 and H-4 and between H-6-endo and H-7a (see Figure 7). These interactions are consistent with an anti-diketone **24b** and a syn-diketone **24a**.

Chemical Structure Proof. Pauson−Khand adduct **13b** in a separate publication was a key intermediate in a formal total synthesis of spatol (**2**) and a total synthesis of spatadiene (**1**).[3] This chemical proof of structure confirmed both the regiochemical and stereochemical assignment of this Pauson−Khand adduct.

In a similar chemical sequence to what was used for **13b**, Pauson−Khand adduct **9a** was converted to alcohol **29** for comparison to known alcohol **30** (see Scheme 3). Adduct **9a** was first hydrogenated using 5% palladium on carbon as catalyst to give ketone **26**. The attachment of C-11 was achieved using a Wittig reaction under Conia equilibrating conditions, which involved the use of so-

dium *tert*-amylate as the base in THF, giving exocyclic methylene **27**.[13] Reduction of the exocyclic double bond of **27** was done with diimide generated from anhydrous hydrazine and 30% hydrogen peroxide in THF/EtOH.[14] The reduction gave **28** with the reduction occurring from the top face giving the α methyl group. The stereochemistry of the alcohol was inverted using Mitsonubu conditions to give alcohol **29**.[15] Alcohol **29** was compared known alcohol **30**. Thus, comparison of the spectral data confirmed the structure assigned to alcohol **29** and, therefore, also confirmed the assignment of Pauson−Khand adduct **9a**.

Definitive chemical proof of the structural assignment of Pauson−Khand adduct **15b** was done by converting **15b** into ketone **33** (see Scheme 4). Adduct **15b** was hydrogenated with concurrent loss of the trimethylsilyl group to give **32**. On larger scale runs, ketone **31** could be isolated in minor amounts, indicating that hydrogenation occurred first followed by loss of the trimethylsilyl group due to the acidic nature of the reaction conditions. Ketone **33** was made by reduction of the tosylhydrazone of **32** with $NaBH_4$ followed by deketalization. Ketone **33** proved identical to the ketone produced by Swern oxidation of alcohol **28**, confirming the structural assignments made.[16]

Experimental Section

All reagents were obtained from commercial suppliers. For NMR spectra, coupling constants are reported in Hz. Silica gel chromatography was performed using Silica Gel 60 (230−400 mesh ASTM) from VWR Scientific. The HPLC used was a Waters model M-6000A pump equipped with a recycle valve and a Whatman M-9 column with 10/50 Partisil packing operating at 4.0 mL/min. All solutions were concentrated using a rotary evaporator followed when necessary with high vacuum. Elemental analyses were performed by the Microanalytical Laboratory operated by the College of Chemistry, University of California, Berkeley, CA.

6,7-Dichloro-5-methylbicyclo[3.2.0]heptan-2-one (7). A 2.1 L Hanovia reactor was thoroughly washed, treated with a 5% Me_2Cl_2Si in toluene, MeOH-rinsed, and oven-dried. Into the reactor were placed a mixture of 1,2-dichloroethylene (550 mL) and cyclohexane (1550 mL) filtered (4.5 × 11 cm column) through alumina (no. 1 neutral) and 3-methylcyclopent-2-enone (5.05 g). The solution was degassed using N_2, and a constant N_2 flow was maintained throughout the irradiation. The solution was irradiated (250 W) through a Pyrex filter, while stirring with a magnetic stirring bar, for 20 h. More 3-methylcyclopent-2-enone (5.11 g) was added, and the irradiation was continued for another 24 h. The excess 1,2-dichloroethylene was distilled from the mixture for reuse, and the remaining solution was concentrated. The residue was purified by chromatography (4.5 × 12 cm column) using 20% ethyl acetate in hexanes as the eluent. The resulting residue was further purified by chromatography (4.5 × 15 cm column) using a gradiant of 10 to 20% ethyl acetate in hexanes as the eluent to give **7** (18.06 g, 89%) as a clear liquid: IR (KBr) 2975, 1745 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 1.39−1.51 (3 singlets, 3), 1.63−2.87 (m, 5) 4.05−4.92 (m, 2). Anal. Calcd for $C_8H_{10}OCl_2$: C, 49.77; H, 5.22; Cl, 36.72. Found: C, 49.71; H, 5.12; Cl, 36.68.

6,7-Dichloro-5-methylspiro[bicyclo[3.2.0]heptane-2,2′-[1,3]dioxolane] (8). In a flask equipped with a Dean−Stark trap were placed dichloro ketone **7** (25.90 g), ethylene glycol (40 mL), pyridinium *p*-toluenesulfonate (2.75 g), and benzene (500 mL). The mixture was refluxed overnight. The solution was cooled, and the ethylene glycol was separated. The benzene layer was washed with aqueous $NaHCO_3$ (125 mL) and aqueous NaCl (125 mL). The solution was dried over $MgSO_4$, filtered, and concentrated to give **8** (30.50 g, 96%) as clear liquid: ^1H NMR (250 MHz, $CDCl_3$) δ 1.17−1.28 (singlets (biggest at 1.23), 3), 1.38−2.73 (m, 5), 3.74−3.91 (m, 4), 3.94−4.79 (m, 2). Anal. Calcd for $C_{10}H_{14}O_2Cl_2$: C, 50.65; H, 5.95; Cl, 29.90. Found: C, 50.81; H, 5.87; Cl, 29.68.

5-Methylspiro[bicyclo[3.2.0]hept-6-ene-2,2′-[1,3]dioxolane] (4). In a N_2-swept flask equipped with a glass-coated stirring bar were placed naphthalene (70.0 g), THF (300 mL), and sodium ribbon (10.4 g). The solution was stirred overnight at room temperature and stored in a refrigerator. In a separate N_2-swept flask were placed dichloro ketal **8** (29.3 g) and THF (150 mL). The solution was placed in an ice/water bath, and the sodium naphthalide solution was added via a small cannula using N_2 pressure until the dichloro ketal solution remained deeply colored. After 20 min, the reaction was quenched with methanol (3 mL), aqueous NH_4Cl (30 mL), and water (100 mL). The mixture was extracted with ethyl ether (200 mL) three times. The combined organic layers were dried over $MgSO_4$, filtered, and concentrated. The residue was purified by chromatography (6 × 20 cm column) using a solvent gradient starting with hexanes up to 10% ethyl ether in hexanes as the eluent. The resulting residue was further purified by chromatography (6 × 20 cm column) using a solvent gradient starting with *n*-pentane up to 20% ethyl ether in *n*-pentane to give **4** (15.75 g, 77%) as a clear liquid: IR (KBr) 3040, 2960, 1455, 1440, 1340 cm^{-1}; ^1H NMR (250 MHz, $CDCl_3$) δ 1.30 (s, 3), 1.35−1.58 (m, 2), 1.72 (dd, 1, J = 6.8, 12.9), 2.23 (ddd, 1, J = 7.4, 12.9, 12.9), 2.47 (s, 1), 3.84−3.98 (m, 4), 6.07 (s, 1), 6.09 (s, 1). Anal. Calcd for $C_{10}H_{14}O_2$: C, 72.26; H, 8.49. Found: C, 72.09; H, 8.49.

Spiro[bicyclo[3.2.0]hept-6-ene-2,2′-[1,3]dioxolane] (5) via 6,7-Dichlorobicyclo[3.2.0]heptan-2-one. A Hanovia reactor was treated with a solution of 5% Me_2SiCl_2 in toluene, rinsed with methanol, and dried. The reactor was charged with a solution of 500 mL of cyclohexane and 100 mL of 1,2-dichloroethylene (a mixture of *cis* and *trans* isomers). The solution was first filtered through alumina (neutral, 4.5 × 11 cm). The solution was degassed using nitrogen, and a constant nitrogen flow was maintained throughout the irradiation. The 2-cyclopentenone (7.0 g, 85 mmol) was added via a syringe pump over 18 h. During this time, the solution was irradiated (250 W) through a Pyrex filter, while stirring. When all the 2-cyclopentenone was added, the irradiation was continued for another 18 h while the reaction was monitored by infrared spectroscopy. The solution was concentrated under reduced pressure. The residue was purified by column chromatography (10% EtOAc/hexane, 7 × 13 cm) to give dichloro ketone as an oil (11.12 g, 73%). For spectroscopic purposes, one pure fraction was collected in the middle of the elution of the product. Three diastereomers are present in this sample. No effort was made to separate these isomers. The reported ^1H NMR spectrum represents a mixture of the three isomers. In the ^{13}C NMR spectrum, it was possible (by signal heights) to report one diastereomer separately from the other two. IR 1750, 1725, 1165 cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.01−2.62 (m, 4), 2.87−3.43 (m, 2), 4.15−4.20 (m, 0.5), 4.37−4.52 (m, 1), 4.66 (dd, 0.5, J = 6.75, 8.63); ^{13}C NMR ($CDCl_3$) first diastereomer δ 213.26, 62.62, 56.31, 47.70, 45.05, 37.29, 25.52; second and third diastereomers δ 215.16, 214.01, 61.69, 60.07, 58.17, 57.97, 52.61, 52.46, 46.73, 38.07, 37.86, 37.06, 23.75, 20.56. Anal. Calcd for $C_7H_8Cl_2O$: C, 46.96; H, 4.50. Found: C, 47.34; H, 4.58.

A 250 mL flask was charged with 8.6 g (48 mmol) of dichloro ketone from above, 10.7 mL (192 mmol) of ethylene glycol, and 200 mL of benzene. A few milligrams of *p*-toluenesulfonic acid were added, and a Dean−Stark trap was attached. The solution was heated under reflux for 12 h, giving about 1 mL of water in the trap. The solution was transferred into a separatory funnel, and the lower, dark ethylene glycol layer was drained. The benzene layer was washed with 50 mL of

(13) Conia, J. M.; Limasset, J. C. *Bull. Soc. Chim. Fr.* **1967**, 1936.
(14) Paquette, L. A.; Ternansky, R. J.; Balogh, D. W.; Kentgen, G. *J. Am. Chem. Soc.* **1983**, *105*, 5446.
(15) Varasi, M.; Walker, K. A. M.; Maddox, M. L. *J. Org. Chem.* **1987**, *52*, 4235.
(16) Mancuso, A. J.; Swern, D. *Synthesis* **1981**, 165.

saturated sodium bicarbonate and 50 mL of saturated brine. The benzene solution was dried over magnesium sulfate, filtered, and concentrated under reduced vacuum to 9.23 g of a brown oil.

A 500 mL, three-necked flask containing a glass stirbar, 35 g of naphthalene, and 150 mL of tetrahydrofuran was blanketed with argon. Sodium (5.2 g) was added in portions over 1 min. The solution was allowed to stir overnight under argon during which time the solution attained a dark blue color.

The ketal (7.20 g, 32.3 mmol) was added to a 500 mL flask, and 50 mL of tetrahydrofuran was added. A nitrogen atmosphere was established, and the flask was immersed in an ice bath. The sodium dihydronaphthalide solution (~100 mL) was added via cannula over 15 min. The endpoint was determined when the ketal solution remained blue. The solution was allowed to stir 45 min, and 5 mL of methanol was added. The solution was transferred into a separatory funnel containing 40 mL of saturated ammonium chloride. The mixture was extracted with diethyl ether (2 × 100 mL). Then 50 mL of water was added to the aqueous layer to dissolve all the precipitates, and this was further extracted with 100 mL of diethyl ether. The combined organic extracts were washed with 40 mL of saturated brine. The organic layers were dried over magnesium sulfate, filtered, and concentrated under reduced pressure to afford an oil which was subjected to column chromatography. The naphthalene was eluted with hexane, and the product was eluted with 10% EtOAc/hexane to give **5** as an oil (2.77 g, 57%): IR 2960, 1340, 1165, 1120, 1030, 750 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.48−1.70 (m, 3); 2.18−2.26 (m, 1), 2.90 (d, 1, J = 3.14), 3.23 (dd, 1, J = 3.14, 6.62), 3.85−3.93 (m, 4), 6.03 (d, 1, J = 2.72), 6.06 (d, 1, J = 2.72); ^{13}C NMR ($CDCl_3$) δ 140.05, 136.72, 115.09, 64.84, 63.72, 52.01, 45.88, 31.28, 22.63. Anal. Calcd for $C_9H_{12}O_2$: C, 71.02; H, 7.95. Found: C, 71.13; H, 8.05.

(1α,2α,5α)- and (1α,2*β*,5α)-5-Methylbicyclo[3.2.0]hept-6-en-2-ol (3 and 3a) via (1α,2α,5α)- and (1α,2*β*,5α)-6,7-Dichloro-5-methylbicyclo[3.2.0]heptan-2-ol. In a N_2-swept flask equipped with an addition funnel and a magnetic stirrer were placed ketone **7** (16.85 g) and 300 mL of THF. The solution was cooled to −78 C, and L-selectride (105 mL, 1.0 M in THF) was added dropwise via the addition funnel over 15 min. The solution was left at −78 C for 1 h and allowed to warm to room temperature (3 h). To quench the reaction, MeOH (15 mL), water (15 mL), 20% aqueous NaOH (15 mL), and dropwise 30% H_2O_2 (20 mL) were added with ice/water bath surrounding the entire mixture. Most of the THF was removed using a rotary evaporator. The residue was diluted with ethyl ether (300 mL), and this was washed with aqueous NaCl twice (150 mL). The solution was dried over Na_2SO_4 and concentrated. The residue was kugelruhr distilled at 6 mmHg and 140−175 °C to give a mixture of dichloro alcohols (16.41 g, 96.4%) as a clear liquid, or the residue was purified by chromatography (4.5 × 16 cm column) using 30% ethyl acetate in hexanes as the eluent to give dichloro alcohols (15.85, 93%) as a clear liquid: IR (KBr) 3420(br), 2970 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 1.23−1.33 (4 singlets, 3), 1.37−2.78 (m, 5), 4.24−5.01 (m, 3).

In a oven-dried, N_2-swept flask equipped with a glass-coated magnetic stirrer bar were placed naphthalene (76.9 g), THF (300 mL), and sodium ribbon (9.6 g). The solution was stirred overnight at room temperature to dissolve all the sodium and stored in a refrigerator. In a separate N_2-swept flask was placed dichloro alcohols from above (18.33 g) and THF (100 mL) which was cooled to 0 °C in an ice/water bath. Using a small cannula and N_2 pressure, a portion of the sodium naphthalide solution was transferred into the dichloro alcohol solution until the solution remained deeply colored. The reaction was quenched by adding MeOH (30 mL) and aqueous ammonium chloride (20 mL). The resulting mixture was diluted with water (100 mL) and extracted with ethyl ether (100 mL) five times. The combined ether layers were dried over Na_2SO_4, filtered, and concentrated. The residue was purified by chromatography (6.5 × 15 cm column) using a solvent gradient starting with pentane up to 1/1 pentane/ethyl ether as the eluent. The resulting residue was further purified by chromatography (6.5 × 15 cm column) using a solvent gradient starting with 30% ethyl ether in pentane up to 1/1 ethyl ether/pentane to give **3** and **3a** (10.01 g, 86%, 81.5 to 18.5 ratio of **3** to **3a**) as a clear liquid: IR (KBr) 3345, 3040, 2950 cm^{-1}; ^1H NMR (250 MHz, $CDCl_3$) δ 1.07−1.21 (m, 1), 1.21 (s, 3), 1.40−1.47 (m, 1), 1.79−1.89 (m, 2), 2.57 (s(br), 1), 2.69 (d, 1, J = 7.0), 3.99 (ddd, 1(major isomer), J = 7.2, 7.2, 9.3), 4.32 (ddd, 1(minor isomer)), 6.00 (s(br), 2(minor isomer)), 6.06 (m, 2(major isomer)); ^{13}C NMR (50 MHz, $CDCl_3$) major isomer only δ 143.89, 131.60, 71.92, 55.60, 53.39, 31.93, 29.63, 22.87; HRMS calcd for $C_8H_{12}O$: 124.0889, found 124.0883.

General Pauson−Khand Reaction Procedure Using Acetylene. (3a*β*,3bα,4*β*,6aα,6b*β*)-3a,3b,4,5,6,6a-Hexahydro-4-hydroxy-6a-methylcyclobuta[1,2:3,4]dicyclopenten-1(6b*H*)-one (9a). In a N_2-swept flask equipped with a magnetic stirrer were placed $Co_2(CO)_8$ (5.98 g) and *n*-heptane (460 mL). Acetylene was swept slowly for 1 h over the solution which gave off gas and turned reddish. Alcohol **3** (1.81 g, 81.5 to 18.5 mixture of alcohols **3** and **3a**) dissolved in *n*-heptane (5 mL) was added to the solution, and an atmosphere of acetylene and CO was generated over the solution. The solution was heated to 65−70 °C for 8 h. The solution was cooled to room temperature, and the reaction mixture was filtered through a pad of Celite with the aid of ethyl ether (450 mL). The solution was concentrated, and the residue purified by chromatography (4.5 × 12 cm column) using 2% MeOH in ethyl ether as the eluent. The resulting residue was further purified by chromatography (2.7 × 12 cm column) using 2% MeOH in ethyl ether as the eluent to give **9a** (1.54 g, 73% based on major cyclobutene alcohol) as a clear oil: IR (KBr) 3420(br), 2970, 1690, 1580 cm^{-1}; ^1H NMR (250 MHz, $CDCl_3$) δ 1.03 (s, 3), 1.36−1.50 (m, 1), 1.75−2.11 (m, 4), 2.22 (s(br), 1), 2.51 (d, 1, J = 4.9), 3.33−3.35 (m, 1), 4.32−4.41 (m, 1), 6.28 (d, 1, J = 5.3), 7.77 (dd, 1, J = 3.1, 5.4); ^{13}C NMR (50 MHz, $CDCl_3$) δ 212.20 (C), 167.61 (CH), 136.03 (CH), 73.51 (CH), 51.51 (CH), 49.09 (CH), 44.04 (C), 38.50 (CH_2), 34.88 (CH), 32.56 (CH_2), 23.62 (CH_3); HRMS calcd for $C_{11}H_{14}O_2$: 178.0994, found 178.0990.

(3aα,3b*β*,6a*β*,6bα)-1,2,3,3a,6a,6b-Hexahydro-3a-methylspiro[cyclobuta[1,2:3,4]dicyclopentene-1(3b*H*),2′-[1,3]dioxolan]-4-one (10a). Following the general procedure for **9a**, a Pauson−Khand reaction using $Co_2(CO)_8$ (1.23 g, 1.2 equiv), *n*-heptane (94.9 mL), and cyclobutene **4** (0.50 g, 1.0 equiv) dissolved in *n*-heptane (2 mL) was carried out at 65−70 °C for 8 h; workup and silica gel chromatography (solvent gradient starting from 10% ethyl ether in hexanes up to ethyl ether, and the second column using a solvent gradient starting with 1/1 ethyl ether/pentane up to ethyl ether) provided **10a** (0.55 g, 83%) as a clear oil: IR (KBr) 2960, 1700, 1580 cm^{-1}; ^1H NMR (250 MHz, $CDCl_3$) δ 1.03 (s, 3), 1.51−2.19 (m, 5), 2.55 (d, 1, J = 4.9), 3.12−3.16 (m, 1), 3.80−3.95 (m, 4), 6.23 (d, 1, J = 5.4), 7.73 (dd, 1, J = 3.1, 5.4); ^{13}C NMR (50 MHz, $CDCl_3$) δ 211.30 (C), 166.02 (CH), 135.89 (CH), 117.07 (C), 64.82 (CH_2), 64.12 (CH_2), 50.89 (CH), 50.69 (CH), 43.48 (C), 38.55 (CH_2), 38.26 (CH), 33.69 (CH_2), 23.55 (CH_3). Anal. Calcd for $C_{13}H_{16}O_3$: C, 70.89; H, 7.32. Found: C, 70.68; H, 7.23.

General Pauson−Khand Procedure Using a Liquid Acetylene. (3aα,3b*β*,6a*β*,6bα)-1,2,3,3a,6a,6b-Hexahydro-3a-methyl-5-propylspiro[cyclobuta[1,2:3,4]dicyclopentene-1(3b*H*),2′-[1,3]dioxolan]-4-one (11a) and (3aα,3b*β*,6a*β*,-6bα)-1,2,3,3a,6a,6b-Hexahydro-3a-methyl-5-propylspiro[cyclobuta[1,2:3,4]dicyclopentene-1(3b*H*),2′-[1,3]dioxolan]-6-one (11b). In a N_2-swept flask was placed $Co_2(CO)_8$ (0.62 g, 1.2 equiv), *n*-octane (48 mL), and 1-pentyne (0.124 g, 1.2 equiv). After 50 min, a CO atmosphere was generated, and cyclobutene **4** (0.2514 g, 1.0 equiv) was added. The solution was heated at 122 °C for 5.5 h. The cooled solution was purified by chromatography (1.8 × 13 cm column with 1.8 × 2 cm of Celite on top of the column) using a solvent gradient starting with hexanes up to ethyl acetate. The resulting residue was further purified by chromatography (1.8 × 14 cm column) using a solvent gradient starting with 10% ethyl acetate in hexanes up to 30% ethyl acetate in hexanes to give a mixture of **11a** and **11b** (0.2847 g, 72%, ratio of 1.32/1.0 of **11a** to **11b**). The mixture was separated by HPLC (15

mg/run, 5 recycles through the column) using 30% ethyl acetate in hexanes as the eluent.

The first fraction was concentrated to **11b** as a clear oil: ^{1}H NMR (250 MHz, $CDCl_3$) δ 0.94 (t, 3, J = 7.4), 0.99 (s, 3), 1.50−1.96 (m, 6), 2.18−2.26 (m, 3), 2.66 (dd, 1, J = 5.0, 3.2), 2.88 (m, 1), 3.89−3.96 (m, 4), 7.33 (s(br), 1); ^{13}C NMR (50 MHz, $CDCl_3$) δ 210.21, 158.12, 149.56, 117.44, 64.73, 64.11, 49.28, 48.08, 45.46, 41.90, 37.57, 33.90, 27.07, 22.94, 21.19, 13.93; HRMS calcd for $C_{16}H_{22}O_3$: 262.1570, found: 262.1571.

The second fraction was concentrated to give **11a** as a clear oil: ^{1}H NMR (250 MHz, $CDCl_3$) δ 0.92 (t, 3, J = 7.2), 1.00 (s, 3), 1.47−2.25 (m, 9), 2.62 (d, 1, J = 4.8), 3.02 (s(br), 1), 3.85−3.93 (m, 4), 7.34 (s(br), 1); ^{13}C NMR (50 MHz, $CDCl_3$) δ 210.83, 158.95, 147.92, 117.24, 64.85, 64.11, 51.25, 43.45, 38.54, 35.54, 33.83, 26.79, 23.57, 20.99, 13.90; HRMS calcd for $C_{16}H_{22}O_3$: 262.1570, found: 262.1570.

(3aα,3b*β*,6a*β*,6bα)-1,2,3,3a,6a,6b-Hexahydro-3a-methyl-5-(1,1-dimethylethyl)spiro[cyclobuta[1,2:3,4]dicyclopentene-1(3b*H*),2′-[1,3]dioxolan]-4-one (12a) and (3aα,3b*β*,6a*β*,6bα)-1,2,3,3a,6a,6b-Hexahydro-3a-methyl-5-(1,1-dimethylethyl)spiro[cyclobuta[1,2:3,4]dicyclopentene-1(3b*H*),2′-[1,3]dioxolan]-6-one (12b). Following the general procedure for **11a** and **11b**, a Pauson−Khand reaction using $Co_2(CO)_8$, *n*-octane, *tert*-butylacetylene, and cyclobutene **4** was carried out at 120−125 °C for 22 h; workup and silica gel chromatography (started with hexane followed with 20% EtOAc/hexane) provided **12a** and **12b** (78% yield, ratio of 5.3 to 1.0 of **12b** to **12a**). The mixture was separated by HPLC.

The first fraction was concentrated to give **12a** as a solid: mp 85−87 °C; IR 2980, 1700, 1330, 1140, 1115 cm^{-1}: ^{1}H NMR ($CDCl_3$) δ 0.98 (s, 3), 1.16 (s, 9), 1.50−1.85 (m, 4), 2.06−2.14 (m, 1), 2.53 (d, 1, J = 5.16), 2.91 (ddd, 1, J = 2.73, 2.98, 5.16), 3.82−3.92 (m, 4), 7.26 (d, 1, J = 2.98); ^{13}C NMR ($CDCl_3$) δ 210.00, 156.92, 155.42, 117.26, 64.82, 64.06, 52.16, 51.18, 43.60, 38.57, 34.46, 33.80, 31.96, 28.23, 23.26.

The second fraction was concentrated to give **12b** as an oil: IR 2980, 1700, 1320, 1110 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.95 (s, 3), 1.19 (s, 9), 1.61−1.89 (m, 4), 2.17−2.26 (m, 1), 2.60 (dd, 1, J = 3.14, 5.02), 2.77 (dd, 1, J = 3.42, 5.02), 3.87−3.93 (m, 4), 7.26 (d, 1, J = 3.42); ^{13}C NMR ($CDCl_3$) δ 209.41, 157.14, 156.37, 117.43, 64.63, 64.04, 49.32, 48.16, 44.18, 42.92, 37.51, 33.92, 32.07, 28.35, 22.81. Anal. Calcd for $C_{17}H_{24}O_3$: C, 73.88; H, 8.75. Found: C, 73.82; H, 8.93.

(3aα,3b*β*,6a*β*,6bα)-1,2,3,3a,6a,6b-Hexahydro-3a-methyl-5-(trimethylsilyl)spiro[cyclobuta[1,2:3,4]dicyclopentene-1(3b*H*),2′-[1,3]dioxolan]-6-one (13b). Following the general procedure for **11a** and **11b**, a Pauson−Khand reaction using $Co_2(CO)_8$ (18.52 g, 1.2 equiv), *n*-octane (1424 mL), (trimethylsilyl)acetylene (5.31 g, 1.2 equiv), and cyclobutene **4** (7.50 g, 1.0 equiv) in *n*-octane (5 mL) was carried out at 112−118 °C for 23 h; workup and silica gel chromatography (solvent gradient starting with 20% ethyl ether in hexanes up to 1/1 ethyl ether/hexanes, and a second column using a solvent gradient starting from 20% ethyl ether in hexanes up to 1/1 ethyl ether/hexanes) provided **13b** (11.33 g, 86%) as a white solid: mp 74−76 °C; IR (solution cell, $CDCl_3$) 2970, 2900, 1685, 1570 cm^{-1}; ^{1}H NMR (250 MHz, $CDCl_3$) δ 0.15 (s, 9), 0.93 (s, 3), 1.57−2.28 (m, 5), 2.55 (dd, 1, J = 3.2, 4.9), 2.93 (dd, 1, J = 3.3, 4.9), 3.85−3.88 (m, 4), 7.75 (d, 1, J = 3.0); ^{13}C NMR (50 MHz, $CDCl_3$) δ 214.00 (C), 172.82 (CH), 150.49 (C), 117.27 (C), 64.53 (CH_2), 63.93 (CH_2), 49.24 (CH), 49.00 (CH), 48.36 (C), 42.08 (CH), 37.43 (CH_2), 33.77 (CH_2), 22.83 (CH_3), −1.87 (CH_3). Anal. Calcd for $C_{16}H_{24}O_3Si$: C, 65.71; H, 8.27. Found: C, 65.64; H, 8.28.

(3aα,3b*β*,6a*β*,6bα)-1,2,3,3a,6a,6b-Hexahydro-3a,5,6-trimethylspiro[cyclobuta[1,2:3,4]dicyclopentene-1(3b*H*),2′-[1,3]dioxolan]-4-one (14a) and (3aα,3b*β*,6a*β*,6bα)-1,2,3,-3a,6a,6b-Hexahydro-3a,4,5-trimethylspiro[cyclobuta[1,2:3,4]dicyclopentene-1(3b*H*),2′-[1,3]dioxolan]-6-one (14b). Following the general procedure for **11a** and **11b**, a Pauson−Khand reaction using $Co_2(CO)_8$ (0.62 g, 1.2 equiv), *n*-decane (48 mL), 2-butyne (0.098 g, 1.2 equiv), and cyclobutene **4** (0.2515 g, 1.0 equiv) was carried out at 172−174 °C for 5.5 h; workup and chromatography (solvent gradient starting with hexanes up to ethyl acetate, second column using a solvent gradient starting with 10% ethyl acetate in hexanes up to 30% ethyl acetate in hexanes) provided **14a** and **14b** (0.2897 g, 77%, ratio of **14a**/**14b** of 5.3/1.0). The mixture (38 mg/run) was separated by HPLC using 30% ethyl acetate in hexanes as the eluent.

The first fraction was concentrated to give **14a** as a clear oil: ^{1}H NMR (250 MHz, $CDCl_3$) δ 0.90 (s, 3), 1.51−2.21 (m, 5), 1.62 (s, 3), 1.93 (s, 3), 2.50 (d, 1, J = 5.0), 2.76 (s(br), 1), 3.77−3.90 (m, 4); ^{13}C NMR (50 MHz, $CDCl_3$) δ 210.10, 170.91, 138.19, 117.08, 64.59, 63.91, 50.99, 50.86, 44.46, 39.77, 38.30, 33.64, 23.38, 14.56, 7.99; HRMS calcd for $C_{15}H_{20}O_3$: 248.1413, found: 248.1417.

The second fraction was concentrated to give **14b** as a clear oil: ^{1}H NMR (250 MHz, $CDCl_3$) δ 0.96 (s, 3), 1.67−2.28 (m, 5), 1.75 (s, 3), 2.02 (s, 3), 2.61 (dd, 1, J = 3.0, 5.0), 2.75 (d, 1, J = 4.8), 3.86−3.98 (m, 4); ^{13}C NMR (50 MHz, $CDCl_3$) δ 209.98, 170.94, 139.48, 117.36, 64.70, 64.06, 50.12, 48.29, 48.06, 41.23, 37.80, 33.91, 22.45, 17.76, 8.24; HRMS calcd for $C_{15}H_{20}O_3$: 248.1413, found: 248.1417.

(3aα,3b*β*,6a*β*,6bα)-1,2,3,3a,6a,6b-Hexahydro-3a,4-dimethyl-5-(trimethylsilyl)spiro[cyclobuta[1,2:3,4]dicyclopentene-1(3b*H*),2′-[1,3]dioxolan]-6-one (15b). Following the general procedure for **11a** and **11b**, a Pauson−Khand reaction using $Co_2(CO)_8$ (0.62 g, 1.2 equiv), *n*-decane (47.5 mL), 1-(trimethylsilyl)propyne (0.20 g, 1.2 equiv), and cyclobutene **4** (0.25 g, 1.0 equiv) in *n*-decane (2 mL) was carried out at 155−164 °C for 75 h; workup and chromatography (solvent gradient starting with 20% ethyl ether in hexanes up to 1/1 ethyl ether/hexanes) provided **15b** (0.17 g, 37%) as a solid: mp 55−57 °C; IR (solution cell, CCl_4) 2980, 1695, 1585 cm^{-1}; ^{1}H NMR (250 MHz, $CDCl_3$) δ 0.22 (s, 9), 0.97 (s, 3), 1.66−2.30 (m, 5), 2.12 (s, 3), 2.53 (dd, 1, J = 2.9, 5.2), 2.76 (d, 1, J = 5.3), 3.87−3.93 (m, 4); ^{13}C NMR (50 MHz, $CDCl_3$) δ 214.51 (C), 186.45 (C), 142.58 (C), 117.27 (C), 64.54 (CH_2), 63.92 (CH_2), 53.82 (CH), 48.41 (CH), 48.36 (C), 42.67 (CH), 37.75 (CH_2), 33.88 (CH_2), 22.27 (CH_3), 20.91 (CH_3), −0.62 (CH_3). Anal. Calcd for $C_{17}H_{26}O_3Si$: C, 66.62; H, 8.55. Found C, 66.57; H, 8.62.

(3aα,3b*β*,6a*β*,6bα)-1,2,3,3a,6a,6b-Hexahydrospiro-[cyclobuta[1,2:3,4]dicyclopentene-1(3b*H*),2′-[1,3]dioxolan]-4-one (16a) and (3aα,3b*β*,6a*β*,6bα)-1,2,3,3a,6a,6b-Hexahydrospiro[cyclobuta[1,2:3,4]dicyclopentene-1(3b*H*),2′-[1,3]-dioxolan]-6-one (16b). Following the general procedure for **9a**, a Pauson−Khand reaction using $Co_2(CO)_8$, *n*-heptane, acetylene, and cyclobutene **5** was carried out at 90−95 °C for 22 h; workup and silica gel chromatography (started with hexane followed with 20% EtOAc/hexane) provided **16a** and **16b** in 63% yield. The regioisomers were subjected to HPLC, but they did not separate well enough to be characterized separately. The components were characterized as a mixture: IR 2980, 1700, 1355, 1110 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.67−2.23 (m, 5), 2.43−2.51 (m, 1.5), 2.69 (dd, 0.5, J = 3.23, 4.74), 2.92−2.95 (m, 0.5), 3.22−3.25 (m, 0.5), 3.81−3.93 (m, 4), 6.26 (dd, 0.5, J = 1.04, 5.43), 6.27 (dd, 0.5, J = 0.90, 5.45), 7.70 (dd, 0.5, J = 3.18, 5.45), 7.75 (dd, 0.5, J = 3.15, 5.46); ^{13}C NMR ($CDCl_3$) δ 211.98, 211.14, 166.17, 165.75, 135.39, 135.34, 117.32, 117.16, 64.94, 64.77, 64.04, 48.18, 47.47, 45.16, 43.30, 42.88, 42.18, 40.70, 37.48, 32.96, 32.94, 29.42, 28.75. Anal. Calcd for $C_{12}H_{14}O_3$: C, 69.89; H, 6.84. Found: C, 69.53; H, 6.99.

(3aα,3b*β*,6a*β*,6bα)-1,2,3,3a,6a,6b-Hexahydro-5-(trimethylsilyl)spiro[cyclobuta[1,2:3,4]dicyclopentene-1(3b*H*),2′-[1,3]dioxolan]-4-one (17a) and (3aα,3b*β*,6a*β*,6bα)-1,2,3,-3a,6a,6b-Hexahydro-5-(trimethylsilyl)spiro[cyclobuta[1,2:3,4]dicyclopentene-1(3b*H*),2′-[1,3]dioxolan]-6-one (17b). Following the general procedure for **11a** and **11b**, a Pauson−Khand reaction using $Co_2(CO)_8$, *n*-heptane, (trimethylsilyl)-acetylene, and cyclobutene **5** was carried out at 90−95 °C for 22 h; workup and silica gel chromatography (started with hexane followed with 20% EtOAc/hexane) provided **17a** and **17b** in 80% yield. The mixture was separated by HPLC.

The first fraction was concentrated to give **17b** as a solid: mp 62−63 °C; IR 2990, 1700, 1295, 1265, 1110 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.15 (s, 9), 1.66−1.71 (m, 1), 1.83−1.93 (m, 2), 2.08 (dd, 1, J = 3.06, 5.77), 2.17−2.24 (m, 1), 2.44−2.47 (m, 1), 2.66

(dd, 1, J = 3.06, 4.98), 2.88 (ddd, 1, J = 2.67, 2.86, 4.98), 3.83−3.94 (m, 4), 7.81 (d, 1, J = 2.86); ^{13}C NMR δ 214.41, 173.46, 147.97, 117.44, 64.69, 63.96, 46.25, 44.30, 42.94, 42.34, 33.00, 28.78, −1.90. Anal. Calcd for $C_{15}H_{22}SiO_3$: C, 64.71; H, 7.96. Found: C, 64.50; H, 8.15.

The second fraction was concentrated to give **17a** as an oil: ~2:1 **17a**:**17b**; ^{1}H NMR ($CDCl_3$) δ (* = assigned to **17a**, other values are mixtures of **17a** and **17b**) 0.15 (s, 9), 1.66−2.22 (m, 5), 2.41−2.45 (m, 2), 3.16−3.18* (m, 1), 3.83−3.94 (m, 4), 7.75* (d, 1, J = 3.00); ^{13}C NMR ($CDCl_3$) δ (**17a** only) 215.21, 172.99, 148.03, 117.32, 64.94, 64.04, 48.50, 48.21, 41.75, 37.64, 32.97, 29.44, −1.91. Anal. Calcd for $C_{15}H_{22}SiO_3$: C, 64.71; H, 7.96. Found: C, 64.45; H, 8.03.

(3aα,4α,7α,7aα)-4,5,7,7a-Tetrahydro-4,7-methano-1*H*-indene-1,6(3a*H*)-dione (23a) and (3aα,4α,7α,7aα)-3a,4,6,7,-7a-Tetrahydro-4,7-methano-1*H*-indene-1,5(4*H*)-dione (23b). Following the general procedure for **9a**, a Pauson−Khand reaction using $Co_2(CO)_8$ (7.60 g, 22.2 mmol), heptane (500 mL), acetylene, and norbornenone (2.00 g, 18.5 mmol) was carried out at 90−95 °C for 22 h; workup and silica gel chromatography (started with hexane followed with 20% EtOAc/hexane) provided **23a** and **23b** as a solid (1.71 g, 57%). The mixture was separated by HPLC.

The first fraction was concentrated to give **23b**: mp 108−109 °C; IR 2980, 1750, 1710, 1580, 1340, 1310 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.32−1.36 (m, 1), 1.47−1.51 (m, 1), 1.86 (dd, 1, J = 4.35, 17.84), 2.08 (dd, 1, J = 4.50, 17.84), 2.33 (d, 1, J = 5.19), 2.50 (s, 1), 2.75−2.76 (m, 1), 3.02−3.04 (m, 1), 6.32 (dd, 1, J = 1.58, 5.62), 7.44 (dd, 1, J = 2.74, 5.62); ^{13}C NMR ($CDCl_3$) δ 214.61, 208.68, 162.30, 138.02, 51.47, 50.79, 44.63, 42.93, 37.01, 30.22. Anal. Calcd for $C_{10}H_{10}O_2$: C, 74.06; H, 6.21. Found: C, 73.81; H, 6.27.

The second fraction was concentrated to give **23a**, contaminated with about 15−20% of **23b**: mp 58−59 °C, IR 1765, 1715, 1360, 1195, 1170 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.48−1.52 (m, 2), 1.95 (dd, 1, J = 4.06, 17.84), 2.18 (dd, 1, J = 4.52, 17.84), 2.41 (d, 1, J = 5.24), 2.62−2.63 (m, 1), 2.76 (s, 1), 3.02−3.04 (m, 1), 6.37 (dd, 1, J = 1.57, 5.66), 7.61 (dd, 1, J = 2.65, 5.66); ^{13}C NMR ($CDCl_3$) δ 213.39, 207.65, 164.68, 138.48, 51.18, 49.41, 46.18, 43.46, 36.70, 30.18. Anal. Calcd for $C_{10}H_{10}O_2$: C, 74.06; H, 6.21. Found: C, 73.73; H, 6.39.

(3aα,4α,7α,7aα)-4,5,7,7a-Tetrahydro-2-(1,1-dimethylethyl)-4,7-methano-1*H*-indene-1,6(3a*H*)-dione (24a) and (3aα,4α,7α,7aα)-3a,4,6,7,7a-Tetrahydro-2-(1,1-dimethylethyl)-4,7-methano-1*H*-indene-1,5(4*H*)-dione (24b). Following the general procedure for **11a** and **11b**, a Pauson−Khand reaction using $Co_2(CO)_8$, *n*-heptane, *tert*-butylacetylene, and norbornenone was carried out at 90−95 °C for 22 h; workup and silica gel chromatography (started with hexane followed with 20% EtOAc/hexane) provided **24a** and **24b** in 64% yield. The mixture was separated by HPLC.

The first fraction was concentrated to give **24b**: mp 133−134 °C; IR 1755, 1710, 1370, 1330, 1220, 1165 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.18 (s, 9), 1.31 (d, 1, J = 10.99), 1.48 (d, 1, J = 10.99), 1.89 (dd, 1, J = 4.37, 17.82), 2.12 (dd, 1, J = 4.51, 17.82), 2.37 (d, 1, J = 5.54), 2.51 (s, 1), 2.79 (d, 1, J = 4.51), 2.86 (dd, 1, J = 2.82, 5.54), 7.00 (d, 1, J = 2.82); ^{13}C NMR ($CDCl_3$) δ 215.33, 207.42, 158.57, 153.20, 52.99, 51.46, 43.04, 41.13, 37.30, 32.15, 30.14, 28.26. Anal. Calcd for $C_{14}H_{18}O_2$: C, 77.03; H, 8.31. Found: C, 77.23; H, 8.73.

The second fraction was concentrated to give **24a**: mp 100−102 °C; IR 2980, 1755, 1710, 1270 cm^{-1}; ^{1}H NMR δ ($CDCl_3$) 1.17 (s, 9), 1.38−1.49 (m, 2), 1.94 (dd, 1, J = 4.28, 17.79), 2.17 (dd, 1, J = 4.50, 17.79), 2.41 (d, 1, J = 5.20), 2.65 (s, 1), 2.75 (s, 1), 2.81 (dd, 1, J = 2.76, 5.20), 7.15 (d, 1, J = 2.76); ^{13}C NMR ($CDCl_3$) δ 214.05, 206.30, 159.00, 155.80, 51.56, 47.56, 45.74, 43.66, 37.04, 32.14, 30.04, 28.30. Anal. Calcd for $C_{14}H_{18}O_2$: C, 77.03; H, 8.31. Found: C, 77.41; H, 8.59.

(3aα,4α,7α,7aα)-4,5,7,7a-Tetrahydro-2-(trimethylsilyl)-4,7-methano-1*H*-indene-1,6(3a*H*)-dione (25a) and (3aα,4α,-7α,7aα)-3a,4,6,7,7a-Tetrahydro-2-(trimethylsilyl)-4,7-methano-1*H*-indene-1,5(4*H*)-dione (25b). Following the general procedure for **11a** and **11b**, a Pauson−Khand reaction using $Co_2(CO)_8$, *n*-heptane, (trimethylsilyl)acetylene, and norbornenone was carried out at 90−95 °C for 22 h; workup and silica gel chromatography (started with hexane followed with 20% EtOAc/hexane) provided **25a** and **25b** in 42% yield. The mixture was separated by HPLC.

The first fraction was concentrated to give **25b**: mp 141 °C; IR 1760, 1705, 1315, 1280, 1260 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.17 (s, 9), 1.25−1.28 (m, 1), 1.48−1.51 (m, 1), 1.91 (dd, 1, J = 4.33, 17.81), 2.12 (dd, 1, J = 4.47, 17.81), 2.37 (d, 1, J = 5.35), 2.54 (s, 1), 2.80 (s, 1), 3.03 (dd, 1, J = 2.58, 5.35), 7.49 (d, 1, J = 2.58); ^{13}C NMR ($CDCl_3$) δ 215.34, 212.07, 169.07, 152.29, 52.76, 51.28, 45.79, 43.19, 37.41, 30.45, −1.90. Anal. Calcd for $C_{13}H_{18}SiO_2$: C, 66.62; H, 7.74. Found: C, 66.61; H, 7.91.

The second fraction was concentrated to give **25a**: mp 105−106 °C; IR 1760, 1705, 1290, 1260, 1170 cm^{-1}: ^{1}H NMR ($CDCl_3$) δ 0.15 (s, 9), 1.32−1.35 (m, 1), 1.46−1.50 (m, 1), 1.95 (dd, 1, J = 4.29, 17.77), 2.17 (dd, 1, J = 4.50, 17.77), 2.39 (d, 1, J = 5.34), 2.59−2.60 (m, 1), 2.75 (s, 1), 2.96 (dd, 1, J = 2.52, 5.34), 7.63 (d, 1, J = 2.52); ^{13}C NMR ($CDCl_3$) δ 231.99, 210.87, 171.72, 152.40, 51.48, 50.66, 47.11, 43.57, 36.94, 30.27, −1.93. Anal. Calcd for $C_{13}H_{18}SiO_2$: C, 66.62; H, 7.74. Found: C, 66.67; H, 7.78.

(3a*β*,3bα,4*β*,6aα,6b*β*)-Octahydro-4-hydroxy-6a-methylcyclobuta[1,2:3,4]dicyclopenten-1(2*H*)-one (26). In a flask mounted on a shaker were placed enone **9a** (1.08 g), ethyl acetate (24 mL), and 5% palladium on carbon (0.72 g). The flask was purged of air, and an atmosphere of hydrogen was generated. The flask was shook for 1.5 h. The reaction mixture was filtered through a pad of Celite and then through a plug (1.8 × 3 cm column) of silica gel using ethyl acetate as the eluent. The filtrate was concentrated to give **26** (1.09 g, 100%) as a clear liquid: IR (KBr) 3425(br), 2970, 1740 cm^{-1}; ^{1}H NMR (250 MHz, $CDCl_3$) δ 1.03 (s, 3), 1.47 (ddd, 1, J = 6.9, 12.9, 12.9), 1.74 (dd, 1, J = 6.5, 13.1), 1.84−2.58 (m, 9), 2.81−2.84 (m, 1), 4.34 (ddd, 1, J = 6.6, 6.6, 10.3); ^{13}C NMR (50 MHz, $CDCl_3$) δ 221.93 (C), 74.30 (CH), 52.92 (CH), 43.38 (C), 38.58 (CH_2), 38.30 (CH_2), 32.56 (CH_2), 28.21 (CH, CH_2), 22.37 (CH, CH_3). Anal. Calcd for $C_{11}H_{16}O_2$: C, 73.30; H, 8.95. Found: C, 73.06; H, 8.88.

(1*β*,3aα,3b*β*,6a*β*,6bα)-Decahydro-3a-methyl-4-methylenecyclobuta[1,2:3,4]dicyclopenten-1-ol (27). Into a N_2-swept flask equipped with an addition funnel were placed methyltriphenylphosphonium iodide (5.75 g, 2.3 equiv), THF (30 mL), and sodium *tert*-amylate (12.93 mL, 1 M solution in toluene, 2.1 equiv). The solution was stirred for 15 min. Into the ylide solution via the addition funnel was added keto alcohol **26** (1.11 g, 1.0 equiv) dissolved in THF (50 mL) over 3 h. The reaction was stirred for 19 h. The reaction was quenched with water (50 mL) and extracted with ethyl ether (50 mL) five times. The combined ethyl ether layers were dried over Na_2SO_4, filtered, and concentrated. The residue was purified by chromatography (2.7 × 11.5 cm column) using 10% ethyl acetate/90% methylene chloride as the eluent. The resulting residue was further purified by chromatography (2.7 × 16 cm column) using 10% ethyl acetate/90% methylene chloride as the eluent to give **27** (0.88 g, 80%) as an oil which crystallized upon standing to white crystals: mp 61−64 °C, IR (solution cell, CCl_4) 3650, 3350(br), 3090, 2960, 1665 cm^{-1}; ^{1}H NMR (250 MHz, $CDCl_3$) δ 0.88 (s, 3), 1.43−2.00 (m, 8), 2.30−2.53 (m, 3), 2.60−2.67 (m, 1), 4.27 (ddd, 1, J = 6.9, 6.9, 9.6), 4.70 (s(br), 4.96 (s(br),1); ^{13}C NMR (50 MHz, $CDCl_3$) δ 154.21 (C), 107.32 (CH_2), 75.05 (CH), 52.03 (CH), 51.74 (CH), 42.39 (C), 38.70 (CH_2), 34.01 (CH_2), 32.72 (CH_2), 32.33 (CH), 32.11 (CH_2), 21.70 (CH_3). Anal. Calcd for $C_{12}H_{18}O$: C, 80.85; H, 10.18. Found: C, 81.01; H, 10.16.

(1*β*,3aα,3b*β*,4α,6a*β*,6bα)-Decahydro-3a,4-dimethylcyclobuta[1,2:3,4]dicyclopenten-1-ol (28). In a 1-L round-bottomed flask were placed olefin **27** (2.75 g), ethanol (500 mL), THF (100 mL), and anhydrous hydrazine (20 mL). The solution was cooled to 0 °C in an ice/water bath. Over 10 min, 30% hydrogen peroxide (66 mL) was added. After 15 min, the cooling bath was removed, and the solution was stirred overnight. The solution was concentrated to 40 mL. The concentrate was diluted with aqueous NaCl (100 mL) and extracted with CH_2Cl_2 (100 mL) five times. The combined organic layers were dried over Na_2SO_4, filtered, and concentrated. The residue was purified by chromatography (4.5 ×

15 cm column) with 10% ethyl acetate/90% methylene chloride as the eluent to give **28** (2.55 g, 92%) as an oil which slowly crystallized to white crystals: mp 59−61 °C, IR (solution cell, CCl_4) 3640, 2960 cm^{-1}; ^1H NMR (250 MHz, $CDCl_3$) δ 1.11 (s, 3), 1.15 (d, 3, J = 6.9), 1.25−1.96 (m, 10), 2.04 (dd, 1, J = 7.0, 7.0), 2.33 (s(br), 1), 2.38−2.45 (m, 1), 4.18 (ddd, 1, J = 7.1, 7.1, 9.4); ^{13}C NMR (50 MHz, $CDCl_3$) δ 74.77 (CH), 52.53 (CH), 49.94 (CH), 43.84 (C), 40.36 (CH, CH_2), 33.63 (CH_2), 32.95 (CH_2), 32.76 (CH_2), 31.52 (CH), 23.85 (CH_3), 14.57 (CH_3). Anal. Calcd for $C_{14}H_{20}O$: C, 79.94; H, 11.18. Found: C, 80.05; H, 11.35.

(1α,3aα,3b*β*,4α,6a*β*,6bα)-Decahydro-3a,4-dimethylcyclobuta[1,2:3,4]dicyclopenten-1-ol (29). In a N_2-swept flask were placed alcohol **28** (0.19 g, 1.0 equiv), THF (0.5 mL), diethyl azodicarboxylate (0.249 mL, 1.5 equiv), and trifluoroacetic acid (0.122 mL, 1.5 equiv). To this solution was added triphenylphosphine (0.416 g, 1.5 equiv) dissolved in THF (1.6 mL). The solution was stirred for 5 min, and sodium benzoate (0.2364 g, 1.6 equiv) was added. After 20 h, the solution was concentrated removing most of the THF. The flask was equipped with a reflux condenser, and the residue was dissolved in methanol (2.2 mL). The solution was refluxed for 4 h. The solution was concentrated removing most of the methanol. The residue was diluted with water (10 mL) and extracted with methylene chloride (10 mL) five times. The combined organic layers were dried over Na_2SO_4, filtered, and concentrated. The residue was purified by chromatography (2.8 × 16 cm column) using 10% ethyl acetate/90% methylene chloride as the eluent to give **29** (0.1743 g, 92%) as a clear oil which crystallized upon standing: mp 64−66 °C; IR (solution cell, CCl_4) 3350(br), 2950 cm^{-1}; ^1H NMR (250 MHz, $CDCl_3$) δ 1.17 (d, 3, J = 6.7), 1.25 (s, 3), 1.51−2.18 (m, 10), 4.04 (d, 1, J = 3.5); ^{13}C NMR (50 MHz, $CDCl_3$) δ 79.38 (CH), 57.64 (CH), 48.34 (CH), 44.93 (C), 41.31 (CH_2), 40.26 (CH), 36.94 (CH), 34.08 (CH_2), 33.58 (CH_2), 32.75 (CH_2), 24.37 (CH_3), 14.63 (CH_3); HRMS calcd for $C_{12}H_{20}O$: 180.1515, found 180.1511.

(1α,3aα,3b*β*,6α,6a*β*,6bα)-Decahydro-3a,6-dimethylcyclobuta[1,2:3,4]dicyclopenten-1-ol (30). ^1H NMR (200 MHz, $CDCl_3$) δ 0.94 (d, 3, J = 6.0), 1.01 (s, 3), 1.23−2.18 (m, 13), 3.92 (d, 1, J = 3.6); ^{13}C NMR (50 MHz, $CDCl_3$) δ 79.66, 57.92, 50.18, 44.39, 42.04, 39.63, 36.82, 34.17, 33.99, 28.06, 20.64, 13.70. Anal. Calcd for $C_{12}H_{20}O$: C, 79.94; H, 11.18. Found: C, 79.68; H, 10.87.

(3aα,3b*β*,4α,6a*β*,6bα)-Octahydro-3a,4-dimethylspiro[cyclobuta[1,2:3,4]dicyclopentene-1(6*H*),2′-[1,3]dioxolan]-6-one (32). In a flask mounted on a shaker were placed enone **15b** (0.0296 g), ethyl acetate (5 mL), and 5% palladium on carbon (0.0342 g). The flask was purged of air, and a hydrogen atmosphere was generated. The solution was shook for 3 d. The solution was filtered through a plug (1 × 6 cm) of silica gel using ethyl acetate as the eluent. The solution was concentrated, and the residue was purified by chromatography (1 × 11 cm column) using a solvent gradient starting with 25% ethyl ether in hexanes up to 50% ethyl ether in hexanes to give **32** (0.0169 g, 74%) as white crystals: mp 66−67 °C; IR (solution cell, CCl_4) 2980, 1753 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 1.24 (d, 3, J = 5.9), 1.30 (s, 3), 1.55 (ddd, 1, J = 6.9, 13.5, 13.5), 1.67 (dd, 1, J = 7.4, 12.6), 1.76 (s(br), 1), 1.83 (dd, 1, J = 6.9, 13.2), 2.18 (ddd, 1, J = 7.4, 13.6, 13.6), 2.35−2.54 (m, 5), 3.82−3.92 (m, 4); ^{13}C NMR (50 MHz, $CDCl_3$) δ 221.23 (C), 117.69 (C), 64.70 (CH_2), 64.06 (CH_2), 50.55 (CH), 46.70 (CH), 45.50 (C), 44.99 (CH_2), 44.70 (CH), 40.11 (CH_2), 35.58 (CH), 33.74 (CH_2), 24.92 (CH_3), 15.75 (CH_3); HRMS calcd for $C_{14}H_{20}O_3$: 236.1413, found 236.1405. In a larger scale runs, **31** could be isolated in small amounts: ^1H NMR (250 MHz, $CDCl_3$) δ 0.09 (s, 9), 1.21 (d, 3, J = 6.9), 1.25 (s, 3), 1.32−2.57 (m, 9), 3.86−3.92 (m, 4).

(3aα,3b*β*,4α,6a*β*,6bα)-Octahydro-3a,4-dimethylcyclobuta[1,2:3,4]dicyclopenten-1(2*H*)-one (33) from 32. In a flask equipped with a reflux condenser and drying tube were placed ketone **32** (0.0841 g, 1.0 equiv), methanol (5 mL), and *p*-toluenesulfonhydrazide (0.13 g, 2.0 equiv). The solution was refluxed for 2 h. The solution was cooled, and sodium borohydride (0.13 g) was added slowly. The solution was refluxed for 5 h. The cooled solution was concentrated, removing most of the methanol. To the residue was added water (30 mL), and the mixture was extracted with ethyl ether (30 mL) three times. The combined organic layers were dried over $MgSO_4$, filtered, and concentrated. The residue was purified by chromatography (1.7 × 12 cm column) using 20% ethyl ether in hexanes as the eluent to give a clear oil (0.0418 g). In a flask were placed a portion of the above isolated oil (0.0180 g), THF (4 mL), water (0.5 mL), and concentrated HCl (10 drops). After 4 h, the solution was concentrated removing most of the THF. To the residue was added water (20 mL), and the mixture was extracted with ethyl ether (20 mL) three times. The combined organic layers were dried over $MgSO_4$, filtered, and concentrated. The residue was purified by chromatography (1.2 × 10 cm column) using 20% ethyl ether in hexanes as the eluent to give **33** (0.0148 g, 54%) as a clear liquid: IR (KBr) 2960, 1745 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 1.17 (s, 3), 1.17 (d, 3, J = 7.1), 1.62−2.45 (m, 11), 2.67 (ddd, 1, J = 9.7, 9.7, 17.4); ^{13}C NMR (50 MHz, $CDCl_3$) δ 221.23 (C), 56.26 (CH), 50.79 (CH), 42.07 (C), 40.08 (CH), 39.22 (CH_2), 38.82 (CH), 37.32 (CH_2), 33.08 (CH_2), 32.92 (CH_2), 23.63 (CH_3), 14.42 (CH_3). Anal. Calcd for $C_{12}H_{18}O$: C, 80.85; H, 10.18. Found: C, 80.53; H, 10.17.

(3aα,3b*β*,4α,6a*β*,6bα)-Octahydro-3a,4-dimethylcyclobuta[1,2:3,4]dicyclopenten-1(2*H*)-one (33) from 28. In a N_2-swept flask cooled to −78 °C were placed methylene chloride (10 mL) and oxalyl chloride (0.416 mL, 1.9 equiv). Dimethyl sulfoxide (0.677 mL, 3.8 equiv) was added dropwise, and after 5 min, alcohol **28** (0.45 g, 1.0 equiv) was added dissolved in methylene chloride (8 mL). After 20 min, triethylamine (1.66 mL, 4.8 equiv) was added. After 10 min, the solution was taken out of the −78 °C bath for 30 min which allowed the solution to come to room temperature. The reaction was poured into water (50 mL) and extracted with methylene chloride (30 mL) twice. The combined organic layers were washed with aqueous NaCl (50 mL), dried over Na_2SO_4, filtered, and concentrated. The residue was purified by chromatography (1.7 × 13.5 cm column) using 10% ethyl acetate in hexanes as the eluent to give **33** (0.44 g, 99%) as a clear liquid, identical to **33** isolated above.

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Supporting Information Available: Copies of ^1H and ^{13}C NMR spectra (13 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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