New Cobalt-Catalyzed Cycloisomerization of ϵ-Acetylenic β-Keto Esters. Application to a Powerful Cyclization Reactions Cascade

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Received January 9, 1996[⊗]

The full details of investigations into the cobalt(I)-catalyzed ene type reaction of ϵ-acetylenic β-keto esters to form highly functionalized methylenecyclopentanes are described. The observed regio-, chemo-, and stereoselectivities support a process of cycloisomerization which controls the relative stereochemistry of two contiguous stereogenic centers. An efficient route to the basic skeleton of the phyllocladane family has been achieved *via* a one-pot sequence of cyclizations: ene type, [2 + 2 + 2], [4 + 2]. This new cascade created six carbon−carbon bonds and four rings in a totally stereoselective manner from an easily accessible acyclic polyunsaturated precursor.

Introduction

Transition-metal-mediated cyclizations of substrates containing two or more unsaturations have provided new catalytic strategies for the construction of polycyclic molecules.[1,2] Toward this aim, the use of cobalt complexes has seen many applications during the past fifteen years.[3] For instance, the [2 + 2 + 2] cocyclization of alkynes affords a versatile entry to the total synthesis of natural compounds.[4] In addition, the intramolecular version including the use of enediynes or triynes led to new syntheses of natural or unnatural steroids[5] as well as various important sesquiterpenes[6] and tetracyclic diterpenes.[7]

Recently, we disclosed a new (η^5-cyclopentadienyl)-dicarbonyl cobalt [$CpCo(CO)_2$]-catalyzed cycloisomerization of ϵ-acetylenic β′-alkyl β-keto esters with the diastereoselective generation of highly functionalized methylenecyclopentanes[8,9] enhancing the synthetic utility of this thermal[10] or Lewis acid[11] -catalyzed reaction and the basic carbopalladation reaction.[12]

Here, we present full details of the scope, limitations, and the investigations into the mechanism of such a new cobalt(I)-mediated ene type reaction and its application in the field of cascade chemistry.[13] By using only one transition-metal, we disclosed a new one-pot combination of reactions: ene type reaction, [2 + 2 + 2] cyclization, and intramolecular [4 + 2] reaction to afford the basic skeleton of a tetracyclic diterpene of the phyllocladane family in a totally controlled manner.[14] This one-pot sequence created six carbon−carbon bonds and four rings from an acyclic polyunsaturated precursor.

Results and Discussion

Scope, Limitations, and Mechanistic Aspects. The ϵ-acetylenic β-keto ester **1** was prepared in 90% yield by alkylation of the methyl acetoacetate sodium enolate with 5-bromo-1-pentyne according to an usual procedure.[15] When a xylenes solution of **1** was heated to reflux (137−140 °C) in the presence of 5 mol % $CpCo(CO)_2$, a fast reaction afforded a 3:1 mixture of compounds **2** and **3** in 92% yield (Scheme 1).

The migration of the double bond, already described,[4d] seems to result from a partial decomposition of the catalyst at high temperature which generates more electrophilic cobalt species. As expected, when the reac-

[⊗] Abstract published in *Advance ACS Abstracts,* March 15, 1996.

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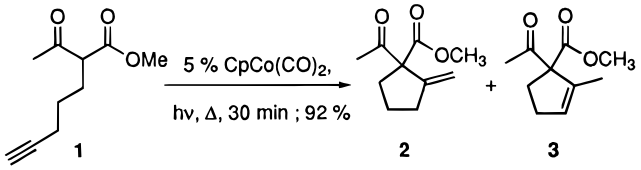
Scheme 1



Scheme 2

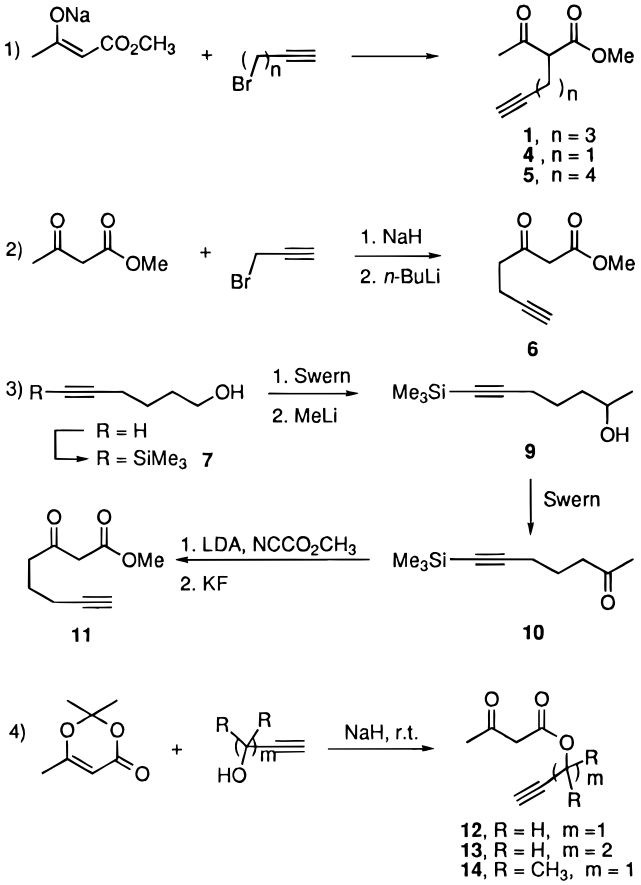


Table 1. Cycloisomerization of 1 in Different Solvents in Presence of 5 mol % of $CpCo(CO)_2$

solvent (Δ)	time (h)	yield (%)	**2/3**
xylenes	0.5	92	3/1
benzene	1	93	100/0
THF	3	76	100/0

tion was performed in lower boiling solvents (Table 1), **2** was the sole product of the reaction. Thus, in refluxing benzene **2** was isolated in 93% yield; in THF, longer reaction time was required but some decomposition was observed.

To define the scope of the reaction, the behavior of different substrates was examined (Scheme 2).

ω-Acetylenic β-keto esters **4** and **5**, prepared following the same procedure as **1**,[15] failed to cyclize under our conditions and after a longer reaction time, decomposition of the starting materials occurred. An important ring strain during the formation of a three-membered ring could be invoked to explain the lack of reactivity of **4**; in contrast, the behavior of the β-keto ester **5** was quite surprising. The difficulty in forming six-membered rings has been already reported[1a] in the palladium(0)-mediated cycloisomerization and was ascribed to the poorer ability of 1,7-enynes to function as bidentate ligands. This difficulty was partially circumvented by the use of the Ni−Cr catalyst system[16] or by the introduction of a substituent on the alkene moiety able to coordinate to the metal.[1j]

We, then, prepared γ-functionalized ω-acetylenic β-keto esters **6**, **11**, and β-keto esters **12-14**. The alkylation of the dianion of methyl acetoacetate[17] with 3-bromo-1-propyne afforded **6** in 79% yield; **11** was made as described in Scheme 2. Compounds **12-14** were synthesized by using a basic modification of the Carroll method[18] which consists of the opening of 2,2,6-trimethyl-1,3 dioxen-4-one by the propargylic alkoxides. Attempts to execute the cobalt-catalyzed cycloisomerization of the ω-acetylenic β-keto esters **6**, **11-14** under our standard conditions met with failure. No consumption of starting material was observed after 5 h in refluxing benzene or xylenes.

Thus, this new cobalt-catalyzed cyclization showed a preference for formation of methylenecyclopentanes over the six-membered analogs. Although some precursors did not afford the corresponding cycloadducts, they contribute to the understanding of the mechanism. First of all, a thermal ene-reaction has to be rejected because it usually requires usually high temperature (≈280 °C).[10] Nevertheless, control experiments showed that **1** was totally recovered after 5 h, in the absence of $CpCo(CO)_2$ in boiling xylenes with or without irradiation, indicating the crucial role of the catalyst. Moreover, it is unlikely that $CpCo(CO)_2$, could be considered as a Lewis acid[19] catalyzing an ene-reaction. Free-radical cyclizations could be also considered, but some elements allow us to exclude such mechanisms: (i) the compounds **5**−**14** are unreactive under our conditions whereas related compounds are known to cyclize under oxidative free-radical reactions[20] and the very well-documented 5-*exo* and 6-*endo dig* radical chain processes;[21] (ii) the cyclization of ω-ethylenic β-keto ester **15** failed even with a stoichiometric amount of $CpCo(CO)_2$ whereas in presence of Mn(III), Co(II), and Fe(II) complexes[20c,22] related compounds gave efficiently the corresponding cycloadducts; (iii) moreover, **2** was the sole product of the cyclization of **1** in benzene, even in presence of radical inhibitor.

Finally, we checked the reactivity of a ϵ-disubstituted acetylenic β-keto ester **16** which was prepared by a Pd−Cu coupling reaction between **1** and iodobenzene.[23] Exposure of **16** to the standard conditions of the cyclization gave the methylenecyclopentane **17** as only one diastereomer where the configuration of the double bond[24] is opposite to the one expected in a radical process.[20c,25]

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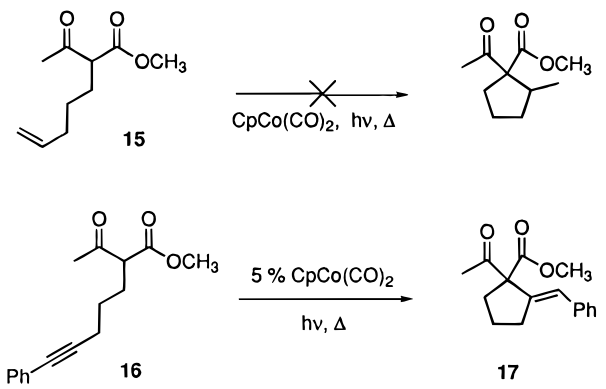
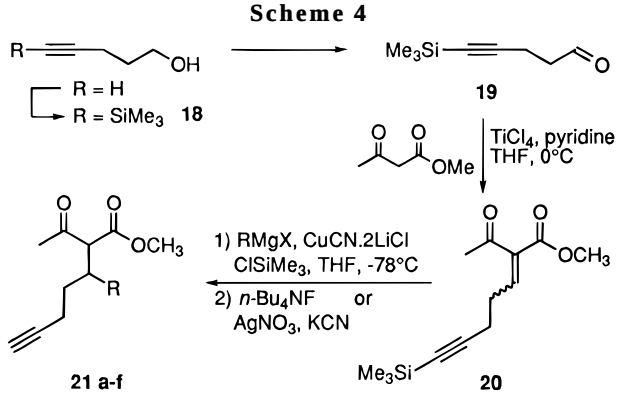
Scheme 3



Scheme 4



21a R = Ph ; **21b** R = Me ; **21c** R = *n*-Bu ; **21d** R = *i*-Pr ; **21e** R = CH_2SiMe_3 ; **21f** R = *t*-Bu

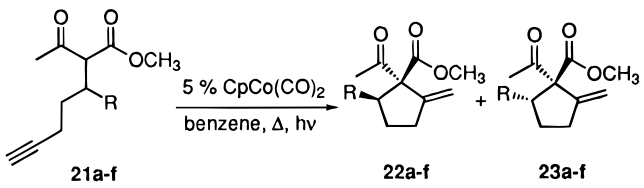
Thus, the most probable mechanism seems to be similar to the palladium(0)-mediated cycloisomerizations[1] or to the first step of the intramolecular Pauson−Khand reaction.[3a,26] Here, the β-keto ester through its enol tautomer should be the reactive intermediate[27] and could form a complex with the triple bond (see Scheme 6).

Studies on Diastereo- and Chemoselectivities. We next chose to investigate the cycloisomerization of ϵ-acetylenic β′-substituted β-keto esters for several purposes, one would be the stereocontrol over two contiguous stereogenic centers[28] as well as the diastereoselective entry into highly functionalized methylenecyclopentanes. Indeed, the enol form of the β-keto ester and the presence of substituents in the β′ position could control the diastereoselective formation of a new stereogenic center. The straightforward preparation[9] of the precursors **21a-f** is outlined in Scheme 4.

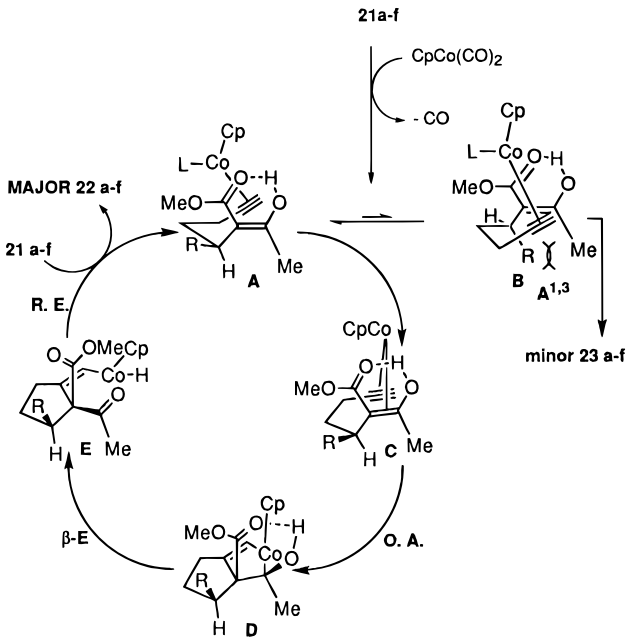
Under the standard conditions of the cyclization, **21** furnished the cycloadducts **22** and **23** with moderate to high level of diastereoselectivity (Scheme 5).[29]

The diastereoselectivities observed could be reasonably explained by the conformational rigidity of the enol-yne

Scheme 5



Scheme 6



O. A.: oxidative addition; **β-E.**: β-elimination; **R. E.**: reductive elimination for the major cycloadduct (analog mechanism for the minor one)

Table 2. Diastereoselectivity of the Cycloisomerization of 21

entry	R	yield (%)[a]	**22**/**23**[b]	de (%)
21a	Ph	69	56/44	12
21b	Me	69	77/23	54
21c	*n*-Bu	74	89/11	78
21d	*i*-Pr	52	87/13	74
21e	CH_2-$SiMe_3$	72	85/15	70
21f	*t*-Bu	64	96/04	92

[a] Isolated yield as a mixture of **22** and **23**. [b] Ratio calculated by ^{1}H-NMR based on the integration of the CH_3 of the ester group.

cobalt(I) complex which is the effective participant of the cyclization. In fact, the process of the complexation entails the coplanarity of the double bond of the enol and the triple bond creating an allylic 1,3-strain between the methyl group of the enol and the bulky substituent in β′ (rotamer **B**, Scheme 6).

According to the increasing size of the β′ substituent, the complex **A** will be favored, and thus the diastereomeric excess will increase. Nevertheless, a too bulky substituent like CH_2SiMe_3 in **21e** seems to generate an antagonist 1,2 steric interaction with the ester group, decreasing the diastereomeric excess.

The experiments with β-keto ester **16** (*vide infra*) seemed to confirm this proposed mechanism (Scheme 7). Indeed, **16** after oxidative addition would lead to the cobaltacyclopentene **16D** which establishes the configuration of the double bond. Successive β- and reductive eliminations allowed the formation of **17** with retention of the *E*-configuration of the double bond. These observations have been already noticed in the transition metal-

(24) The *E* configuration of the double bond of **17** was deduced from differential NOE experiments: irradiation of the aromatic hydrogens caused a neat Overhauser effect on the allylic hydrogens H_1 whereas irradiation of the ethylenic proton H_2 had no effect.

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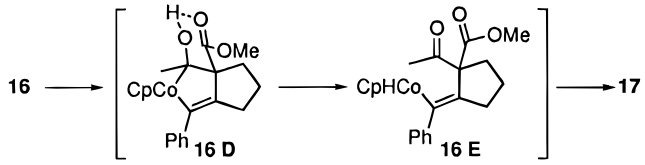
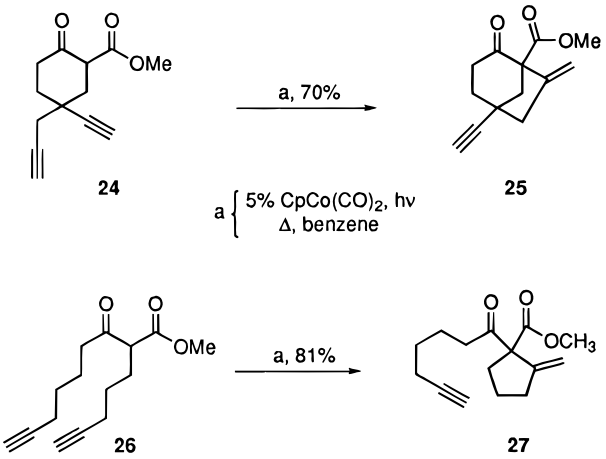
(29) The configuration of the cycloadducts was assigned by NOE experiments: see reference 9.

Scheme 7



Scheme 8



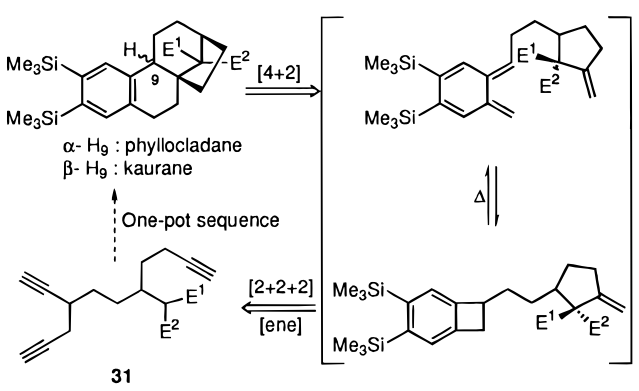
catalyzed cycloisomerizations involving disubstituted triple bonds.[1a,j,k]

In addition, for synthetic purposes we had to examine the reactivity of the β-keto ester **24**.[30] In presence of $CpCo(CO)_2$, **24** furnished the bicyclo[3.2.1]octane derivative **25** in 70% isolated yield, indicating the total chemoselectivity of this cycloisomerization (Scheme 8). When the reaction was performed under the [2 + 2 + 2] cyclization conditions (bis(trimethylsilyl)ethyne as solvent), no traces of benzocyclobutene adduct were observed showing the total selectivity of this new catalysis: cycloisomerization *versus* [2 + 2 + 2]. The reaction of β-keto ester **26** with a stoichiometric amount of $CpCo(CO)_2$ demonstrated the chemoselectivity as well, since the triple bond at γ-position remained untouched.

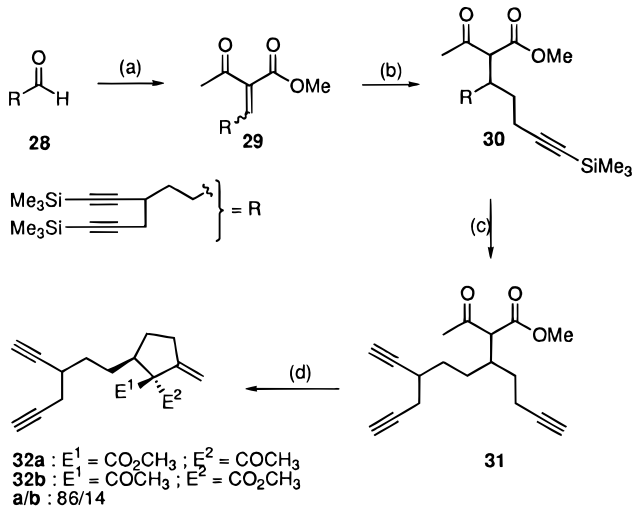
Application in Synthesis. Since cobalt(I) species catalyze both cycloisomerization and [2 + 2 + 2] cocyclization, we could envisage to combine them in a one-pot sequence. In this context, a new stereoselective approach to the basic skeleton of tetracyclic diterpenes of phyllocladane and kaurane families appears possible. Our retrosynthesis depicted in Scheme 9 deserves some comments: the cobalt(I)-ene type reaction of the ϵ-acetylenic β-keto ester moiety and the cobalt(I)-mediated cocyclization between the 1,5-diyne unit and bis(trimethylsilyl)ethyne will furnish the corresponding benzocyclobutene having a methylenecyclopentane unit. Then, after the thermal rearrangement of this latter in orthoquinodimethane, an intramolecular [4 + 2] cyclization will afford in the same pot the basic framework of the diterpenes phyllocladane (α-H_9) and/or kaurane (β-H_9).

Although we have already accomplished a rapid access to these diterpenes *via* three consecutive cyclization reactions,[4d] the challenge still remains to achieve a shorter and more efficient synthesis. The use of only one transition-metal catalysis in a one-pot sequence of reactions: cycloisomerization, [2 + 2 + 2], and [4 + 2], which will create six carbon−carbon bonds and four rings, would constitute an ultimate development.

Scheme 9



Scheme 10



(a) $TiCl_4$, $CH_3COCH_2CO_2Me$,THF, pyridine, 0°C,12h, 75% ; (b) $ClSiMe_3$, CuCN.2LiCl (2 equiv), $Me_3SiC{\equiv}CCH_2CH_2MgCl$, THF, 1h, -78°C, 94% ; (c) *n*-Bu_4NF,THF, 0°C, 1h, 94% ; (d) 5% $CpCo(CO)_2$, hν, benzene, Δ, 8 h, 76%

Before performing this sequence in a one-pot operation, we determined the optimal conditions for each synthetic transformation. The preparation of the triyne **31** was efficiently achieved in three steps from the known aldehyde **28**[4d] in 66% overall yield according to the Scheme 10. Exposure of the triyne **31** to 5 mol % $CpCo(CO)_2$ in boiling benzene under irradiation for 8 h afforded the ene cycloadducts **32a** and **32b** in 76% yield.

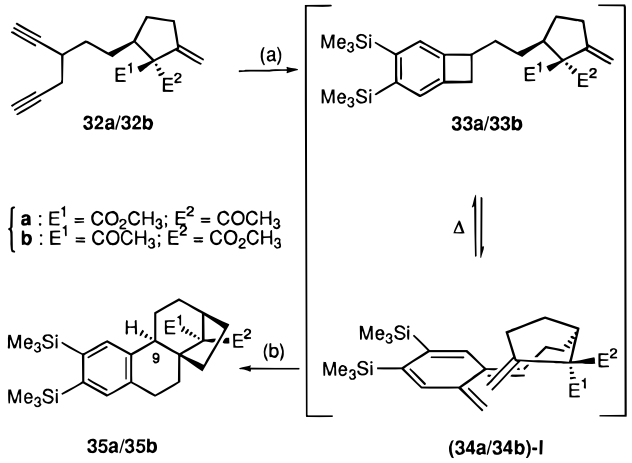
Compounds **32a** and **32b** were inseparable by flash chromatography on silica gel. The diastereoselectivity **32a**/**32b** = 86/14 was determined on the crude mixture by ^{1}H-NMR and was consistent with our previous finding.

Cooligomerization of the diyne moiety **32a** and **32b** with 20 equiv of bis(trimethylsilyl)ethyne catalyzed by 5 mol % $CpCo(CO)_2$ in refluxing xylenes (necessary to the solubilization of **32a**+**b**) provided after 30 min, under irradiation, the benzocyclobutenes **33a**/**33b** in 93% yield (Scheme 11). However we observed 9% of benzocyclobutenes in which the double bond had migrated in the thermodynamically more stable endocyclic position.

Thermolysis of **33a** and **33b** in refluxing decane for 12 h led to two tetracyclic compounds **35a** and **35b** in a ratio 86/14 in 92% yield, corrected from the 9% of endocyclic double bond **33a**+**b**. After separation by flash chromatography, elucidation of the structures **35a** and **35b** included a combination of spectroscopic and X-ray crys-

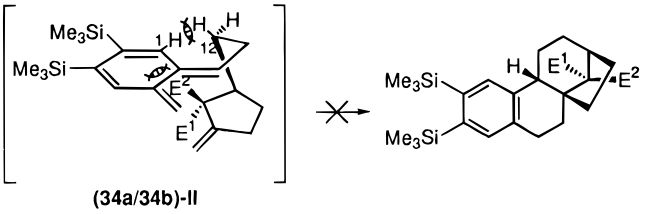
(30) **24** has been synthesized from an intermediate described in Stammler, R.; Halvorsen, K.; Gotteland, J.-P.; Malacria, M. *Tetrahedron Lett.* **1994**, *35*, 417−420; its full preparation will be given later.

Scheme 11



(a) 20 eq. btmse, Δ, hv, xylenes, 93% ; (b) decane, Δ, 12h, 92%

Scheme 12



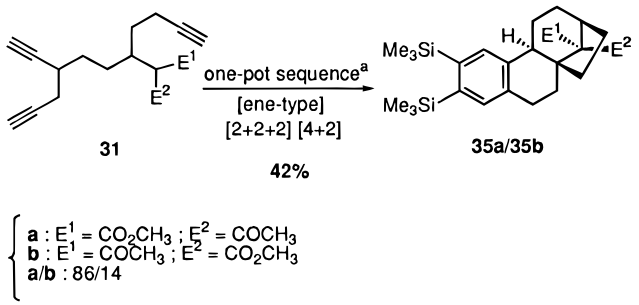
tallographic techniques. The assigned stereochemistry of **35a** was unambiguously established by a X-ray analysis,[31] indicating the configuration of the phyllocladane skeleton. The coupling pattern, doublet of doublet, for the proton at the B/C ring junction corresponding to *trans* diaxial (J = 10.4 Hz) and axial−equatorial (J = 5.5 Hz) couplings characterizes the phyllocladane framework. In addition, a NOE effect between H_9 and CH_3 of the ketone in the minor compound **35b** confirmed that **35a** and **35b** are epimers at the β-keto ester position.

The ratio 86/14 of the tetracyclic compounds **35a** and **35b** resulted from the diastereoselectivity of the initial ene type reaction and a total stereoselectivity during the intramolecular Diels−Alder reaction through the transition state **(34a/34b)-I** *versus* **(34a/34b)-II** (Scheme 12). Indeed, a severe H_1-H_{12} nonbonding interaction, as we reported earlier,[4d] with an additional destabilizing steric hindrance between the bulky *gem*-dicarbonyl substituent and the orthoquinodimethane were developed for the latter.

Having secured the optimal conditions for each individual synthetic transformation, we performed the reactions cascade in a one-pot operation. However, our initial attempts did not lead to the formation of the tetracyclic compounds but gave untractable materials and trace amount of benzocyclobutenes in which the double bond had migrated in the thermodynamically more stable endocyclic position. As mentioned above, this migration results from a partial decomposition of the catalyst due to a too long reaction time in refluxing decane. In order to avoid this migration and to achieve the one-pot sequence, we added a strong donor ligand such as diphenylphosphinoethane (dppe) which is able to strongly associate the cobalt species.[32]

(31) The authors have already deposited the atomic coordinates of **34** with the Cambridge Crystallographic Data Center: see reference 14.

Scheme 13



One-pot sequence : [a]Reaction conditions: (i) 5% $CpCo(CO)_2$, hv, 80°C, 8 h; (ii) btmse, 136°C, hv, 15 min; (iii) 5% dppe, decane, 175°C, 12 h.

Furthermore, treatment of triyne **31** with 5 mol % $CpCo(CO)_2$ under irradiation at 80 °C for 8 h produced the ene cycloadducts **32a** and **32b**. Those underwent cycloaddition to hot bis(trimethylsilyl)acetylene (btmse), after its immediate addition, to provide the benzocyclobutenes **33a** and **33b** (each synthetic individual transformation was evidenced by TLC). After 5 mol % diphenyldiphosphinoethane (dppe) was added, the reaction mixture was heated in refluxing decane for 12 h and gratifyingly, we observed the formation of a 86:14 mixture of tetracyclic compounds **35a** and **35b** in 42% overall isolated yield. The Scheme 13 summarizes this remarkable and powerful one-pot sequence of cyclizations cascade: ene type, [2 + 2 + 2], and [4 + 2], which allowed the formation of six carbon−carbon bonds and four rings in total regio- and chemoselectivity and with a high level of diastereoselectivity from an acyclic polyunsaturated precursor bearing three uncontrolled centers.

Conclusion

The catalytic cobalt-mediated ene type reaction of ϵ-acetylenic β-keto ester provides a useful new method for the stereoselective preparation of highly functionalized methylenecyclopentanes. We investigated the mechanism of this new cyclization: the observed regio-, chemo-, and stereoselectivities seem to support a process of cycloisomerization: enol−yne complexation, oxidative addition, β- and reductive eliminations. We demonstrated that this cycloisomerization controlled the relative stereochemistry of two contiguous stereogenic centers.

Finally, we have described, in a one-pot sequence, a rapid construction of tetracyclic systems belonging to the phyllocladane family by using a cascade of cyclization reactions: ene type, [2 + 2 + 2], [4 + 2]. This concise strategy can be viewed as an illustration of the very high performance of cobalt(I) tandem catalyses to the synthesis of complex polycyclic molecules.

Experimental Section

Preparation of ω-acetylenic and ω-ethylenic β-keto esters. I. General Procedure for the Preparation of 1, 4, 5, 15. To a cooled (−10 °C), stirred suspension of 80% sodium hydride (0.19 g; 6.3 mmol) in THF (6 mL) was added dropwise methyl acetoacetate (0.7 g; 6.0 mmol). After being stirred at −10 °C for 10 min and at room temperature for 1h, a solution of bromoalkyne (6.6 mmol) in THF (4 mL) and hexamethylphosphoramide (HMPA; 1.1 mL; 6 mmol) was

(32) Butenschön, H.; Kettenbach, R. T.; Krüger, C. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 1066−1068.

added. The resulting mixture was heated at 50 °C for 12 h, cooled at room temperature, and diluted with ether (50 mL). The organic layer was washed successively with a saturated solution of NH_4Cl (2 × 20 mL) and brine (20 mL), dried over Na_2SO_4, filtered, and concentrated. The crude residue was purified by flash chromatography[33] (petroleum ether/ether = 80/20) or distillation to afford the ω-acetylenic β-keto esters **1, 4, 5** and the ω-ethylenic β-keto ester **15**.

Methyl 2-(1-oxoethyl)-6-heptynoate (1): 1.0 g, 92%; ^{1}H-NMR (200 MHz, $CDCl_3$) δ 3.71 (s, 3H), 3.43 (t, J = 7.3 Hz, 1H), 2.20 (s, 3H), 2.19 (td, J = 7.3, 2.6 Hz, 2H), 1.95 (m, 3H), 1.50 (m, 2H); ^{13}C-NMR (50 MHz, $CDCl_3$) δ 202.4, 172.6, 83.7, 68.9, 68.3, 59.1, 52.3, 27.1, 26.1, 18.1; IR (neat) 3300, 2960, 2120, 1730, 1710, 1640, 1610 cm^{-1}. Anal. Calcd for $C_{10}H_{14}O_3$: C, 65.91; H, 7.74. Found: C, 65.95; H, 7.84.

Methyl 2-(1-oxoethyl)-4-pentynoate (4): 0.80 g, 87%; bp = 55 °C (15 mmHg); ^{1}H-NMR (200 MHz, $CDCl_3$) δ 3.71 (s, 3H), 3.67 (t, J = 7.4 Hz, 1H), 2.65 (dd, J = 7.4, 2.6 Hz, 2H), 2.25 (s, 3H), 1.96 (t, J = 2.6 Hz, 1H); ^{13}C-NMR (50 MHz, $CDCl_3$) δ 200.7, 168.4, 80.3, 70.2, 58.0, 52.5, 29.3, 17.4; IR (neat) 3300, 2960, 2120, 1740, 1710, 1640, 1610 cm^{-1}. MS (m/z) 155, 137, 133, 127, 123, 111, 95, 83, 69, 43. Anal. Calcd for $C_8H_{10}O_3$: C, 62.33; H, 6.54. Found: C, 62.27; H, 6.67.

Methyl 2-(1-oxoethyl)-7-octynoate (5): 1.07 g, 91%; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 3.77 (s, 3H), 3.47 (t, J = 7.1 Hz, 1H), 2.26 (s, 3H), 2.23 (td, J = 7.1, 2.7 Hz, 2H), 1.97 (t, J = 2.7 Hz, 1H), 1.90 (m, 2H), 1.58 (quint, 2H), 1.45 (m, 2H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 203.2, 170.5, 84.3, 68.8, 59.7, 52.7, 29.1, 28.3, 27.9, 26.7, 18.4; IR (neat) 3300, 2960, 2120, 1740, 1710, 1640, 1610 cm^{-1}. Anal. Calcd for $C_{11}H_{16}O_3$: C, 67.33; H, 8.22. Found: C, 67.22; H, 8.21.

Methyl 2-(1-oxoethyl)-6-heptenoate (15): 0.64 g, 58%; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 5.75 (m, 1H), 5.02−4.94 (m, 2H), 3.73 (s, 3H), 3.42 (t, J = 7.1 Hz, 1H), 2.21 (s, 3H), 2.06 (dt, J = 6.6, 7.1 Hz, 2H), 1.84 (m, 2H), 1.38 (m, 2H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 203.1, 170.3, 137.8, 115.1, 59.5, 52.4, 33.3, 28.8, 27.6, 26.6; IR (neat) 2940, 1740, 1710, 1640, 1430, 1240, 910 cm^{-1}. MS (m/z) 185, 167, 153, 142, 129, 109, 87, 81, 69, 55, 43. Anal. Calcd for $C_{10}H_{16}O_3$: C, 65.19; H, 8.95. Found: C, 65.30; H, 8.95.

II. Preparation[16] of 6 and 26. Methyl 3-Oxo-6-heptynoate (6). To a cooled (−10 °C), stirred suspension of 80% sodium hydride (0.165 g; 5.5 mmol) in THF (10 mL) was added dropwise methyl acetoacetate (0.57 g; 5.0 mmol). After being stirred at −10 °C for 10 min and at room temperature for 1 h, *n*-butyllithium (1.5 M in hexane; 3.5 mL; 5.25 mmol) was added dropwise and the yellow to orange solution of dianion was stirred for an additional 10 min before adding propargyl bromide (80% in toluene; 0.61 mL; 5.5 mmol). After 15 min of stirring, the reaction mixture was diluted with ether (20 mL) and washed successively with a saturated solution of NH_4Cl (2 × 10 mL) and brine (10 mL), dried over Na_2SO_4, and concentrated. The residue was purified by flash chromatography (petroleum ether/ether = 80/20) affording **6** (0.61 g, 79%): ^{1}H-NMR (400 MHz, $CDCl_3$) δ 3.70 (s, 3H), 3.46 (s, 3H), 2.78 (t, J = 7.1 Hz, 2H), 2.42 (td, J = 7.1, 2.7 Hz, 2H), 1.96 (t, J = 2.7 Hz, 1H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 200.3, 167.1, 82.3, 68.8, 52.1, 48.6, 41.3, 12.5; IR (neat) 3300, 2960, 2120, 1750, 1710 cm^{-1}; MS (m/z) 155, 147, 139, 133, 126, 123, 113, 101, 95, 89, 81, 65, 53, 43. Anal. Calcd for $C_8H_{10}O_3$: C, 62.33; H, 6.54. Found: C, 62.23; H, 6.65.

Methyl 3-Oxo-2-(4-pentynyl)-8-nonynoate (26). A solution of dianion (4.3 mmol) in THF was prepared as above, and a solution of 5-bromo-1-pentyne (1.4 g; 9.5 mmol) in THF (12 mL) and HMPA (1.5 mL; 8.6 mmol) was added dropwise. The resulting mixture was heated at reflux for 12 h. After being cooled and worked-up as above, the residue was flash chromatographed (petroleum ether/ether = 70/30) to give **26** (0.65 g, 61%): ^{1}H-NMR (400 MHz, $CDCl_3$) δ 3.68 (s, 3H), 3.44 (t, J = 7.4 Hz, 1H), 2.59−2.43 (m, 2H), 2.16 (td, J = 7.6, 2.8 Hz, 4H), 1.94 (t, J = 2.8 Hz, 1H), 1.92 (t, J = 2.7 Hz, 1H), 1.90 (t, J = 7.6 Hz, 2H), 1.66 (quint, J = 7.8 Hz, 2H), 1.47 (quint, J = 7.5 Hz, 4H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 204.6, 170.1, 83.9, 83.5, 69.1, 68.8, 58.4, 52.5, 41.3, 27.7, 27.2, 26.2, 22.5, 18.2, 18.1; IR (neat) 3300, 2960, 2120, 1750, 1710 cm^{-1}. MS (m/z) 249, 217, 201, 189, 171, 159, 145, 119, 109, 81, 61, 53. Anal. Calcd for $C_{15}H_{20}O_3$: C, 72.55; H, 8.12. Found: C, 72.36; H, 8.25.

III. Preparation of Methyl 3-Oxo-7-octynoate (11). 6-(Trimethylsilyl)-5-hexyn-1-ol (7).[34] To a cooled (−78 °C) solution of 5-hexyn-1-ol (1.96 g; 20 mmol) in THF (40 mL) was added *n*-butyllithium (1.5 M in hexane; 26.7 mL; 40 mmol). After being stirred at −78 °C for 30 min, the reaction was warmed to 0 °C over 2 h. The solution was then cooled to −78 °C, and trimethylsilyl chloride (4.5 g; 42 mmol) was added. The resulting mixture was heated to reflux for 12 h, cooled to room temperature, treated with 10% HCl (22.6 mL), and stirred for 30 min. The reaction mixture was extracted with ether (100 mL), washed with brine (2 × 40 mL), dried (Na_2SO_4), and concentrated. The residue was purified by flash chromatography (petroleum ether/ether = 50 /50) to yield **7** (2.40 g; 70%): ^{1}H-NMR (400 MHz, $CDCl_3$) δ 3.63 (t, J = 6.0 Hz, 2H), 2.26 (t, J = 6.6 Hz, 2H), 1.65, (m, 4H), 0.14 (s, 9H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 107.0, 84.7, 62.3, 31.7, 24.7, 19.5, 0.0; IR (neat) 3400, 2960, 2160, 1250, 840, 750 cm^{-1}.

6-(Trimethylsilyl)-5-hexynal (8). A solution of dimethyl sulfoxide (DMSO; 2.3 mL; 32.5 mmol) in CH_2Cl_2 (8 mL) was added dropwise at −78 °C to a solution of oxalyl chloride (1.5 mL; 16.8 mmol) in CH_2Cl_2 (32 mL). After 5 min, a solution of **7** (2.4 g; 14.1 mmol) in CH_2Cl_2 (15 mL) was added dropwise. After the solution was stirred at −78 °C for 15 min, triethylamine (9.8 mL; 70.5 mmol) was added. The reaction mixture was warmed to room temperature, diluted with ether (250 mL), and washed with saturated solutions of NH_4Cl (100 mL), $CuSO_4$ (2 × 100 mL), and brine (3 × 100 mL), dried over Na_2SO_4, filtered, and concentrated. Purification by flash chromatography (petroleum ether/ether = 50/50) furnished **8** (2.20 g, 93%): ^{1}H-NMR (400 MHz, $CDCl_3$) δ 9.80 (s, 1H), 2.57 (t, J = 6.7 Hz, 2H), 2.28 (t, J = 6.7 Hz, 2H), 1.85 (quint, J = 6.7 Hz, 2H), 0.12 (s, 9H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 201.8, 105.8, 85.7, 42.6, 20.9, 19.2, 0.0; IR (neat) 3400, 2960, 2160, 1250, 840, 750 cm^{-1}.

7-(Trimethylsilyl)-6-heptyn-2-ol (9). To a cooled (−78 °C) solution of the aldehyde **8** (2.0 g; 11.9 mmol) in THF (50 mL) was added dropwise methyllithium (1.5 M in ether; 7.9 mL; 11.9 mmol). After the addition, the reaction mixture was warmed to room temperature and diluted with ether (100 mL). The organic layer was washed with a saturated solution of NH_4Cl (2 × 30 mL) and brine (30 mL), dried over Na_2SO_4, and concentrated. The crude residue was purified by flash chromatography (petroleum ether/ether = 50 /50) to give **9** (1.97 g, 90%): ^{1}H-NMR (400 MHz, $CDCl_3$) δ 3.81 (sextet, J = 6.0 Hz, 1H), 2.22 (t, J = 6.6 Hz, 2H), 1.58 (m, 4H), 1.17 (d, J = 6.0 Hz, 3H), 0.12 (s, 9H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 107.1, 84.6, 67.4, 38.2, 24.7, 23.4, 19.7, 0.0; IR (neat) 3350, 2960, 2160, 1250, 840, 750 cm^{-1}.

7-(Trimethylsilyl)-6-heptyn-2-one (10). 10 was prepared using the procedure described for **8**. Ketone **10** (1.75 g, 90%) was purified by flash chromatography (petroleum ether/ether = 50/50): ^{1}H-NMR (200 MHz, $CDCl_3$) δ 2.50 (t, J = 7.2 Hz, 2H), 2.18 (t, J = 6.9 Hz, 2H), 2.09 (s, 3H), 1.69 (quint, J = 7.0 Hz, 2H), 0.07 (s, 9H); ^{13}C-NMR (50 MHz, $CDCl_3$) δ 207.8, 106.2, 85.3, 42.0, 29.8, 22.4, 19.1; IR (neat) 2960, 2160, 1720, 1250, 840, 750 cm^{-1}.

Methyl 3-Oxo-7-octynoate (11). (a) At −78 °C, a solution of ketone **10** (1.75 g; 9.63 mmol) in ether (60 mL) was added dropwise to a solution of lithium diisopropylamide (10.6 mmol) in ether (50 mL). After being stirred at −78 °C for 1 h, the reaction mixture was cooled to −100 °C and a solution of methyl cyanoformate (0.92 mL; 11.6 mmol) in ether (30 mL) was added dropwise. After the mixture was stirred for 1 h at −100 °C, it was allowed to warm to room temperature and was diluted with ether (50 mL), washed with saturated solution of NH_4Cl (3 × 50 mL) and brine (2 × 40 mL), dried over Na_2SO_4, and concentrated. The crude residue was

(33) Still, W. C.; Kahn, M.; Mitra, A. *J. Org.Chem.* **1978**, *43*, 2923−2925.

(34) Negishi, E.-I.; Boardman, L. D.; Sawada, H.; Baghen, V.; Stoll, A. T.; Tour, J. M.; Rand, C. L. *J. Am. Chem. Soc.* **1988**, *110*, 5383−5396.

purified by flash chromatography (petroleum ether/ether = 90/10) to give the alkylated compound (1.06 g, 46%): ^{1}H-NMR (200 MHz, $CDCl_3$) δ 3.61 (s, 3H), 3.36 (s, 2H), 2.57 (t, J = 7.1 Hz, 2H), 2.15 (t, J = 6.9 Hz, 2H), 1.67 (quint, J = 7.0 Hz, 2H), 0.02 (s, 9H); ^{13}C-NMR (50 MHz, $CDCl_3$) δ 201.7, 167.3, 105.9, 85.4, 52.0, 48.9, 41.3, 22.1, 18.9, 0.0; IR (neat) 2960, 2160, 1750, 1710, 1250, 840, 750 cm^{-1}. (b) To a DMSO (20 mL) solution of potassium fluoride (0.59 g; 10.1 mmol) was added a solution of the preceding compound (0.48 g; 2.0 mmol) in DMSO (10 mL). After being stirred at room temperature for 3 h, the reaction mixture was filtered and diluted with ether (100 mL). The organic layer was washed with brine (3 × 40 mL), dried (Na_2SO_4), filtered, and concentrated. Purification of the crude residue by flash chromatography (petroleum ether/ether = 80/20) furnished **11** (0.27 g, 80%): ^{1}H-NMR (200 MHz, $CDCl_3$) δ 3.69 (s, 3H), 3.43 (s, 2H), 2.66 (t, J = 7.1 Hz, 2H), 2.19 (td, J = 6.8, 2.5 Hz, 2H), 1.93 (t, J = 2.5 Hz, 1H), 1.76 (tt, J = 7.1, 6.9 Hz, 2H); ^{13}C-NMR (50 MHz, $CDCl_3$) δ 201.7, 167.4, 83.2, 69.1, 52.2, 49.0, 41.3, 22.0, 17.5; IR (neat) 3300, 2960, 2100, 1740, 1710 cm^{-1}. MS (m/z) 169, 160, 153, 137, 127, 109, 101, 95, 81, 65, 55, 43. Anal. Calcd for $C_9H_{12}O_3$: C, 64.27; H, 7.19. Found: C, 64.22; H, 7.28.

IV. General Procedure for the Preparation of 12−14. At room temperature, to a suspension of 80% sodium hydride (0.214 g; 7.1 mmol) in THF (5 mL) was added dropwise the alkynol (7.1 mmol) in THF (5 mL). After being stirred for 30 min, a solution of 2,2,6-trimethyl-1,3 dioxen-4-one (1.0 g; 7.1 mmol) in THF (10 mL) was added dropwise. After 2 h, the solution was then partitioned between ether (50 mL) and saturated solution of NH_4Cl (30 mL). The organic layer was separated, washed with brine (2 × 40 mL), dried ($MgSO_4$), and concentrated. The crude residue was purified by flash chromatography (petroleum ether/ether = 50/50) to afford the keto esters **12**−**14**.

2-Propynyl-3-oxobutanoate (12): 0.72 g, 73%; ^{1}H-NMR (200 MHz, $CDCl_3$) δ 4.76 (d, J = 2.6 Hz, 2H), 2.68 (s, 3H), 3.51 (s, 2H), 2.48 (t, J = 2.4 Hz, 1H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 207.2, 166.7, 76.7, 74.0, 52.7, 49.7, 30.9; IR (neat) 3280, 2920, 1750, 1710, 1150, 1030 cm^{-1}. Anal. Calcd for $C_7H_8O_3$: C, 59.99; H, 5.75. Found: C, 60.27; H, 5.85.

3-Butynyl-3-oxobutanoate (13): 1.04 g, 96%; ^{1}H-NMR (200 MHz, $CDCl_3$) δ 4.25 (t, J = 6.8 Hz, 2H), 3.47 (s, 2H), 2.55 (td, J = 6.8, 2.8 Hz, 2H), 2.27 (s, 3H), 2.00 (t, J = 2.8 Hz, 1H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 200.0, 167.00, 80.2, 71.2, 62.9, 32.4, 49.9, 18.7; IR (neat) 3280, 2920, 1750, 1710, 1150, 1030 cm^{-1}. Anal. Calcd for $C_8H_{10}O_3$: C, 62.33; H, 6.54. Found: C, 62.55; H, 6.53.

1,1-Dimethyl-2-propynyl-3-oxobutanoate (14): 1.1 g, 92%; ^{1}H-NMR (200 MHz, $CDCl_3$) δ 2.59 (s, 2H), 2.21 (s, 3H), 1.86 (s, 1H), 1.62 (s, 6H); ^{13}C-NMR (50 MHz, $CDCl_3$) δ 200.5, 165.4, 90.2, 84.0, 72.5, 50.8, 30.7, 28.7; IR (neat) 3280, 2920, 1750, 1710, 1150, 1030 cm^{-1}. Anal. Calcd for $C_9H_{12}O_3$: C, 64.27; H, 7.19. Found: C, 64.15; H, 7.27.

V. Preparation of Methyl-2-(1-oxoethyl)-7-phenyl-6-heptynoate (16). At room temperature, under argon, copper(I) iodide (0.016 g; 0.08 mmol; 15 mol%) and tetrakis(triphenylphosphine)palladium(0) (0.063 g; 0.05 mmol; 10 mol %) were added at once to a solution of the ϵ-acetylenic β-keto ester **1** (0.1 g; 0.55 mmol) in benzene (2.5 mL) in the presence of *n*-butylamine (0.27 mL; 2.7 mmol) and iodobenzene (0.23 g; 1.1 mmol). After being stirred for 6 h, the reaction mixture was hydrolyzed with saturated solution of NH_4Cl (8 mL) and extracted with ether (10 mL). The organic layer was washed with a saturated solution of $CuSO_4$ (10 mL) and brine (2 × 10 mL), dried ($MgSO_4$), and concentrated. Purification of the residue by flash chromatography (petroleum ether/ether = 85/15) afforded **16** (0.127 g, 89%): ^{1}H-NMR (400 MHz, $CDCl_3$) δ 7.43−7.27 (m, 5H), 3.76 (s, 3H), 3.53 (t, J = 7.4 Hz, 1H), 2.46 (t, J = 6.9 Hz, 2H), 2.26 (s, 3H), 2.09−2.02 (m, 2H), 1.63 (br quint, J = 7.4 Hz, 2H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 202.9, 170.2, 131.6, 128.3, 127.8, 123.8, 89.1, 81.4, 59.3, 52.5, 28.9, 27.4, 26.5, 19.3; IR (neat) 3240, 2940, 2850, 2200, 1740, 1705, 1635, 1580, 1430 ,1145, 1070, 750, 690 cm^{-1}. MS (m/z) 240, 227, 216, 199, 184, 172, 155, 142, 128, 115, 105, 89, 69, 55, 43.

VI. Preparation of the ϵ-acetylenic β-substituted β-keto Esters 21a−f. 5-(Trimethylsilyl)-4-pentyn-1-ol (18).[34] **18** (4.5 g, 96%) was prepared using the procedure described for **7** and was purified by flash chromatography (petroleum ether/ether = 50/50): ^{1}H-NMR (200 MHz, $CDCl_3$) δ 3.73 (t, J = 6.1 Hz, 2H), 2.32 (t, J = 6.9 Hz, 2H), 1.74 (quint, J = 6.5 Hz, 2H), 0.12 (s, 9H); ^{13}C-NMR (50 MHz, $CDCl_3$) δ 106.7, 85.3, 61.8, 31.2, 16.5, 0.1; IR (neat) 3350, 2960, 2180, 1430, 1250, 1070, 1050 cm^{-1}.

5-(Trimethylsilyl)-4-pentynal (19). Aldehyde **19** (4.3 g, 97%) was prepared using the procedure described for **8** and was purified by flash chromatography (petroleum ether/ether = 50/50): ^{1}H-NMR (400 MHz, $CDCl_3$) δ 9.91 (s, 1H), 2.56 (t, J = 6.7 Hz, 2H), 2.48 (t, J = 6.7 Hz, 2H), 0.10 (s, 9H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 200.4, 104.7, 85.7, 42.5, 13.1, 0.0; IR (neat) 2960, 2900, 2720, 2180, 1730, 1380, 1250, 1050, 840 cm^{-1}.

Methyl 7-(Trimethylsilyl)-2-(1-oxoethyl)-2-hepten-6-ynoate (20). Titanium tetrachloride (4.1 mL; 37 mmol) in CCl_4 (8 mL) was added dropwise at 0 °C to THF (68 mL) and stirred for a few minutes during which time a yellow precipitate appeared. Then, a THF (8 mL) solution of methyl acetoacetate (2.15 g; 18.5 mmol) and a THF (8 mL) solution of **19** (2.85 g; 18.5 mmol) were added. After the mixture was stirred for 75 min at 0 °C, a solution of pyridine (6 mL; 74 mmol) in THF (13 mL) was added by a syring pump over 90 min. The reaction mixture was stirred at 0 °C overnight and then partitioned between ether (200 mL) and water (150 mL). The aqueous phase was extracted with ether (200 mL) and the combined organic layers were washed with brine (300 mL), dried over $MgSO_4$, and concentrated. The residue was purified by flash chromatography (petroleum ether/ether = 20/80) to give **20** as a 1:1 mixture of *E* and *Z* isomers (3.64 g, 75%): ^{1}H-NMR (200 MHz, $CDCl_3$) δ 6.82 (t, J = 7.0 Hz, 1H), 3.72 (s, 3H), 2.40 (td, J = 7.3, 6.3 Hz, 2H), 2.29 (t, J = 6.3 Hz, 2H), 2.21 (s, 3H), 0.02 (s, 9H); ^{13}C-NMR (50 MHz, $CDCl_3$) δ 195.1, 166.4, 146.6, 137.5, 104.9, 86.4, 52.1, 28.9, 26.9, 18.9, 0.0; IR (neat) 2940, 2170, 1730, 1690, 1630, 1430, 1230, 840 cm^{-1}; MS (m/z) 251, 237, 219, 205, 193, 177, 163, 149, 135, 109, 105, 89, 75, 59, 43. Anal. Calcd for $C_{13}H_{20}SiO_3$: C, 61.90; H, 7.94. Found: C, 61.64; H, 7.74.

General Procedure for the Preparation of Compounds 21a-f. (a) To a cooled (−78 °C) THF (40 mL) solution of copper(I) cyanide (1.07 g; 12 mmol) and lithium chloride (1.02 g; 24 mmol) [dried overnight at 100 °C under vacuum 1 mmHg] was added a solution of alkylmagnesium bromide (or chloride) or alkyllithium (6 mmol) in THF (6 mL). After being stirred at −78 °C for 15 min, a THF (6 mL) solution of **20** (3 mmol) and TMSCl (0.76 mL; 6 mmol) was added dropwise. After stirring for 2 h, the reaction mixture was hydrolyzed at −78 °C with a solution of NH_4Cl/NH_4OH (2/1), warmed to room temperature, filtered on Celite, and diluted with ether (100 mL). The organic layer was separated, washed with brine, dried over $MgSO_4$, and concentrated. The crude product was used in the next step without purification. (b) The removal of the trimethylsilyl group followed the procedure b described for **11** except for **21e** whose triple bond is selectively deprotected by $AgNO_3$/KCN (1.2/6 equiv) in a cooled (0 °C) mixture of EtOH:H_2O (3:1).

Methyl 2-(1-oxoethyl)-3-phenyl-6-heptynoate (21a) (R = Ph): 0.85 g, 67%; 1:1 mixture of two inseparable diastereomers; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 7.28 (m, 5H), 7.16 (m, 5H), 3.86 (d, J = 11.0 Hz, 1H), 3.80 (d, J = 11.0 Hz, 1H), 3.76 (s, 3H), 3.53 (m, 2H), 3.39 (s, 3H), 2.31 (s, 3H), 1.98−1.68 (M, 8H), 1.96 (t, J = 2.8 Hz, 2H), 1.90 (s, 3H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 202.1, 201.9, 168.8, 168.2, 139.6, 139.4, 128.9, 128.8, 128.5, 128.1, 128.0, 127.7, 127.4, 127.2, 83.2, 69.1, 69.0, 68.9, 68.6, 52.8, 52.6, 44.5, 44.1, 32.9, 32.5, 29.9, 29.3, 16.2, 16.1; IR (neat) 3300, 3050, 2940, 2100, 1740, 1710, 1430, 1350, 1230, 1150 cm^{-1}; MS (m/z) 258, 240, 226, 216, 198, 184, 156, 141, 128, 115, 91, 77, 59, 51. Anal. Calcd for $C_{16}H_{18}O_3$: C, 74.41; H, 6.98. Found: C, 74.11; H, 7.09.

Methyl 3-methyl-2-(1-oxoethyl)-6-heptynoate (21b) (R = Me): 0.18 g, 76%; 1:1 mixture of two inseparable diastereomers; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 3.66 (s, 3H), 3.65 (s, 3H), 3.29 (d, J = 8.2 Hz, 1H), 3.27 (d, J = 8.2 Hz, 1H), 2.37−2.26 (m, 2H), 2.16 (s, 3H), 2.15 (s, 3H), 2.24−2.05 (m, 4H), 1.91 (t,

J = 2.2 Hz, 1H), 1.90 (t, J = 2.2 Hz, 1H), 1.61−1.48 (m, 2H), 1.37−1.26 (m, 2H), 0.88 (d, J = 10.4 Hz, 3H), 0.87 (d, J = 9.9 Hz, 3H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 202.8, 202.7, 169.3, 77.0, 76.7, 68.9, 68.7, 65.6, 65.1, 52.2, 52.1, 32.7, 32.5, 32.2, 31.8, 29.3, 28.9, 16.4, 16.1, 15.9, 15.8; IR (neat) 3280, 2940, 2120, 1735, 1710, 1430, 1150 cm^{-1}; MS (m/z) 197, 181, 164, 149, 137, 125, 116, 107, 95, 79, 69, 59, 43, 41. Anal. Calcd for $C_{11}H_{16}O_3$: C, 67.35; H, 8.16. Found: C, 67.45; H, 8.21.

Methyl 3-butyl-2-(1-oxoethyl)-6-heptynoate (21c) (R = *n*-Bu): 0.175 g, 62%; 1:1 mixture of two inseparable diastereomers; ^{1}H-NMR (200 MHz, $CDCl_3$) δ 3.70 (s, 3H), 3.69 (s, 3H), 3.51 (d, J = 7.7 Hz, 1H), 3.50 (d, J = 9.3 Hz, 1H), 2.48−2.24 (m, 2H), 2.27−2.10 (m, 4H), 2.20 (s, 6H), 1.90 (t, J = 1.9 Hz, 1H), 1.89 (t, J = 1.8 Hz, 1H), 1.70−1.40 (m, 4H), 1.30−1.10 (m, 12H), 0.82 (t, J = 10.9 Hz, 3H), 0.80 (t, J = 9.8 Hz, 3H); ^{13}C-NMR (50 MHz, $CDCl_3$) δ 203.6, 169.6, 83.7, 83.5, 68.9, 68.7, 62.8, 52.1, 36.8, 36.7, 30.2, 30.0, 29.8, 29.6, 29.5, 29.2, 28.4, 22.8, 22.7, 15.9, 15.8, 13.9; IR (neat) 3290, 2930, 2850, 2225, 1735, 1710, 1430, 1350, 1150, 910, 730 cm^{-1}; MS (m/z) 223, 206, 196, 179, 167, 163, 149, 136, 117, 101, 85, 79, 59, 55, 43. Anal. Calcd for $C_{14}H_{22}O_3$: C, 70.59; H, 9.24. Found: C, 70.53; H, 9.37.

Methyl 3-isopropyl-2-(1-oxoethyl)-6-heptynoate (21d) (R = *i*-Pr): 0.29 g, 52%; 1:1 mixture of two inseparable diastereomers. ^{1}H-NMR (400 MHz, $CDCl_3$) δ 3.72 (s, 3H), 3.71 (s, 3H), 3.54 (d, J = 7.2 Hz, 1H), 3.50 (d, J = 8.8 Hz, 1H), 2.26−2.10 (m, 4H), 2.25 (s, 3H), 2.23 (s, 3H), 1.94 (t, J = 2.8 Hz, 1H), 1.92 (t, J = 2.8 Hz, 1H), 1.77−1.61 (M, 4H), 1.61−1.52 (m, 2H), 1.60−1.42 (m, 2H), 1.40−1.31 (m, 2H), 0.88−0.76 (M, 12H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 203.1 (2C), 169.9, 169.8, 83.9, 83.6, 68.6, 68.5, 62.9, 62.0, 52.2, 52.1, 42.5 (2C), 29.5, 29.3, 29.1, 28.8, 27.4, 27.2, 21.7 (2C), 20.5, 19.7, 18.4, 17.8; IR (neat) 3280, 2940, 2110, 1730, 1630, 1600, 1430, 1240, 1140 cm^{-1}; MS (m/z) 193, 181, 149, 117, 116, 111, 101, 93, 79, 69, 59, 51. Anal. Calcd for $C_{13}H_{20}O_3$: C, 69.61; H, 8.98. Found: C, 69.31; H, 8.87.

Methyl 3-[(trimethylsilyl)methyl]-2-(1-oxoethyl)-6-heptynoate (21e) (R = CH_2SiMe_3): 0.18 g, 76%; 1:1 mixture of two inseparable diastereomers; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 3.68 (s, 3H), 3.67 (s, 3H), 3.52 (d, J = 6.1 Hz, 1H), 3.45 (d, J = 6.1 Hz, 1H), 2.50−2.41 (m, 2H), 2.18 (s, 3H), 2.17 (s, 3H), 2.12−2.11(m, 2H), 1.93 (t, J = 2.6 Hz, 1H), 1.91 (t, J = 2.6 Hz, 1H), 1.59 (m, 4H), 1.56−1.48 (m, 2H), 0.63−0.50 (m, 4H), 0.00 (s, 9H), 0.01 (s, 9H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 203.2 (2C), 169.7 (2C), 83.7, 83.4, 69.2, 68.9, 64.6, 63.4, 52.1 (2C), 33.7, 33.4, 32.1, 31.9, 29.7, 29.5, 19.1, 18.7, 15.5 (2C), −0.8, −0.6; IR (neat) 3280, 2990, 2120, 1780, 1730, 1360, 1330, 1230, 1125, 960, 850 cm^{-1}. Anal. Calcd for $C_{14}H_{24}SiO_3$: C, 62.64; H, 9.01. Found: C, 62.55; H, 8.96.

Methyl 3-*tert*-butyl-2-(1-oxoethyl)-6-heptynoate (21f) (R = *t*-Bu): 0.18 g, 62%, 1:1 mixture of two inseparable diastereomers; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 3.72 (s, 3H), 3.70 (s, 3H), 3.68−3.66 (m, 2H), 2.27−2.26 (m, 2H), 2.24 (s, 3H), 2.23 (s, 3H), 2.13−2.11 (m, 4H), 1.93−1.91 (m, 2H), 1.75−1.65 (m, 4H), 0.90 (s, 9H), 0.89 (s, 9H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 203.6, 170.8, 84.9, 68.7, 60.3, 52.4, 46.7, 34.7, 29.4, 29.3, 28.2, 27.1, 19.2; IR (neat) 3280, 2940, 2110, 1730, 1630, 1600, 1430, 1240, 1140 cm^{-1}; MS (m/z) 223, 206, 196, 181, 167, 163, 149, 135, 116, 107, 91, 79, 59, 57, 43. Anal. Calcd for $C_{14}H_{22}O_3$: C, 70.59; H, 9.24. Found: C, 70.58; H, 9.38.

Ene Type Reactions. General Procedure. $CpCo(CO)_2$ (6 mL; 5 × 10^{-2} mmol) was added to a boiling solution of the ω-acetylenic β-keto ester (1 mmol) in benzene or xylene (15 mL) degassed by three freeze-pump-thaw cycles and was irradiated (light from a projector lamp; ELW, 300W, 50% of its power). The reaction was monitored by TLC and after completion the solvent was removed in vacuo. The residue was purified by flash chromatography to afford the ene cycloadduct.

Methyl 2-methylidene-1-(1-oxoethyl) cyclopentane carboxylate (2): 0.167 g, 92%. ^{1}H-NMR (400 MHz, $CDCl_3$) δ 5.23 (t, J = 2.2 Hz, 1H), 5.16 (t, J = 2.2 Hz, 1H), 3.68 (s, 3H), 2.39 (m, 2H), 2.33 (m, 1H), 2.15 (s, 3H), 2.12 (m, 1H), 1.66 (m, 2H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 203.5, 171.6, 148.6, 112.2, 70.4, 52.6, 35.0, 33.9, 26.6, 24.1; IR (neat) 3080, 2980, 1740, 1710, 1640, 890 cm^{-1}.

Methyl 1-(1-oxoethyl)-2-(phenylmethylidene)cyclopentanecarboxylate (17): 0.191 g, 74 %; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 7.35−7.22 (m, 5H), 6.58 (t, J = 2.5 Hz, 1H), 3.77 (s, 3H), 2.72 (td, J = 7.0, 2.5 Hz, 2H), 2.49−2.16 (m, 2H), 2.25 (s, 3H), 1.82 (q, J = 7.0 Hz, 2H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 204.2, 171.9, 141.6, 137.5, 131.6, 128.7, 128.4, 127.7, 127.1 (2C), 72.4, 52.8, 34.5, 32.2, 26.9, 24.9; IR (neat) 2950, 1735, 1710, 1480, 1430, 1350, 1230, 1120, 690 cm^{-1}; MS (m/z) 259, 240, 227, 216, 199, 184, 167, 155, 141, 129, 115, 102, 91, 77, 63, 43. Anal. Calcd for $C_{16}H_{18}O_3$: C, 74.40; H, 7.02. Found: C, 74.28; H, 7.19.

Methyl 2-Methylidene-1-(1-oxoethyl)-5-phenylcyclopentanecarboxylate (22+23)a (R= Ph): 0.095 g, 69%; 56:44 mixture of inseparable diastereoisomers. **22a**: ^{1}H-NMR (400 MHz, $CDCl_3$) δ 7.29−7.23 (m, 5H), 5.40 (dd, J = 2.7, 1.6 Hz, 1H), 5.36 (dd, J = 2.7, 1.6 Hz, 1H), 4.30 (dd, J = 9.3, 7.1 Hz, 1H), 3.21 (s, 3H), 2.57−2.40 (m, 2H), 2.29 (s, 3H), 2.19−2.11 (m, 2H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 200.9, 170.4, 149.8, 140.9, 128.5, 128.3, 128.0, 127.4, 126.8, 113.0, 75.8, 51.9, 50.3, 33.4, 29.9, 26.8. **23a**: ^{1}H-NMR (400 MHz, $CDCl_3$) δ 7.21−7.14 (m, 5H), 5.26 (dd, J = 2.7, 1.6 Hz, 1H), 5.18 (dd, J = 2.7, 1.6 Hz, 1H), 4.20 (dd, J = 6.6, 5.5 Hz, 1H), 3.81 (s, 3H), 2.76−2.63 (m, 2H), 2.10−2.02 (m, 2H), 1.5 (s, 3H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 204.5, 171.5, 148.9, 138.8, 128.5, 128.3, 128.0, 127.4, 126.8, 111.7, 74.6, 52.7, 51.7, 32.4, 29.9, 28.8. **22a+23a**: IR (neat) 2940, 2220, 1710, 1645, 1430, 1345, 900 cm^{-1}; MS (m/z) 240, 225, 215, 200, 181, 175, 155, 141, 131, 115, 103, 91, 77, 65, 51; Anal. Calcd for $C_{16}H_{18}O_3$: C, 74.40; H, 7.02. Found: C, 74.64; H, 7.35.

Methyl 5-methyl-2-methylidene-1-(1-oxoethyl)cyclopentanecarboxylate (22+23)b (R= Me): 0.135 g, 69%; 77:23 mixture of inseparable diastereomers. **22b**: ^{1}H-NMR (400 MHz, $CDCl_3$) δ 5.27 (t, J = 1.6 Hz, 1H), 5.24 (t, J = 2.2 Hz, 1H), 3.71 (s, 3H), 2.87−2.80 (m, 1H), 2.38−2.24 (m, 2H), 2.22 (s, 3H), 1.49−1.40 (m, 2H), 0.92 (d, J = 6.6 Hz, 3H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 202.0, 171.0, 148.7, 112.7, 73.9, 51.9, 40.7, 32.3, 31.5, 26.9, 16.1. **23b**: ^{1}H-NMR (400 MHz, $CDCl_3$) δ 5.27 (t, J = 1.6 Hz, 1H), 5.23 (t, J = 2.2 Hz, 1H), 3.72 (s, 3H), 2.87−2.80 (m, 1H), 2.53−2.46 (m, 2H), 2.23 (s, 3H), 1.97−1.86 (m, 2H), 0.93 (d, J = 6.6 Hz, 3H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 202.0, 171.0, 148.7, 112.4, 73.9, 52.5, 42.2, 32.3, 31.7, 26.7, 15.6. **22b+23b**: IR (neat) 2950, 2860, 2230, 1710, 1645, 1430, 1240, 910, 730 cm^{-1}; MS (m/z) 164, 154, 139, 137, 122, 111, 107, 95, 79, 67, 59, 43. Anal. Calcd for $C_{11}H_{16}O_3$: C, 67.35; H, 8.16. Found: C, 67.11; H, 8.18.

Methyl 5-butyl-2-methylidene-1-(1-oxoethyl)cyclopentanecarboxylate (22+23)c (R = *n*-Bu): 0.176 g, 74%; 89:11 mixture of inseparable diastereomers. **22c**: ^{1}H-NMR (400 MHz, $CDCl_3$) δ 5.23 (t, J = 2.2 Hz, 1H), 5.17 (t, J = 2.8 Hz, 1H), 3.71 (s, 3H), 2.48−2.46 (m, 1H), 2.25 (s, 3H), 1.96−1.89 (m, 1H), 1.52−1.41 (m, 1H), 1.40−1.10 (M, 6H), 0.86 (t, J = 6.6 Hz, 3H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 202.4, 171.3, 149.6, 111.9, 73.6, 51.9, 46.4, 32.7, 30.4, 30.3, 28.9, 27.3, 22.7, 13.9. **23c**: ^{1}H-NMR (400 MHz, $CDCl_3$) δ 5.18 (t, J = 2.2 Hz, 1H), 5.17 (t, J = 2.8 Hz, 1H), 3.75 (s, 3H), 2.71−2.67 (m, 1H), 2.35−2.26 (m, 1H), 2.14 (s, 3H), 1.52−1.41 (m, 1H), 1.40−1.10 (M, 6H), 0.86 (t, J = 6.6 Hz, 3H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 205.0, 171.8, 149.9, 111.8, 73.3, 52,4, 47.9, 32.4, 30.7, 30.0, 29.7, 29.3, 28.9, 13.9. **22c+23c**: IR (neat) 2940, 2850, 1725, 1710, 1640, 1430, 1350, 1240, 900 cm^{-1}; MS (m/z) 207, 206, 191, 179, 164, 149, 139, 135, 121, 107, 93, 79, 67, 59, 51; Anal. Calcd for $C_{14}H_{22}O_3$: C, 70.59; H, 9.24. Found: C, 70.56; H, 9.44.

Methyl 5-isopropyl-2-methylidene-1-(1-oxoethyl)cyclopentanecarboxylate (22+23)d (R = *i*-Pr): 0.117 g, 52%; 87:13 mixture of inseparable diastereomers. **22d**: ^{1}H-NMR (400 MHz, $CDCl_3$) δ 5.01 (br s, 1H), 4.92 (br t, J = 2.0 Hz, 1H), 3.59 (s, 3H), 2.60−2.53 (m, 1H), 2.40−2.34 (dd, J = 6.5, 6.3 Hz, 1H), 2.25−2.16 (m, 1H), 2.19 (s, 3H), 1.85−1.77 (m, 1H), 1.43−1.34 (m, 1H), 1.36−1.29 (m, 1H), 0.74 (d, J = 6.6 Hz, 3H), 0.72 (d, J = 6.6 Hz, 3H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 203.8, 172.3, 152.0, 111.5, 74.0, 54.5, 52.7, 33.7, 30.9, 28.7, 28.6, 23.4, 21.8. **23d**: ^{1}H-NMR (400 MHz, $CDCl_3$) δ 5.01 (br s, 1H), 4.92 (br t, J = 2.0 Hz, 1H), 3.61 (s, 3H), 2.52−2.40 (m, 1H), 2.40−2.34 (dd, J = 6.5, 6.3 Hz, 1H), 2.25−2.16 (m, 1H), 2.09 (s, 3H), 1.85−1.77 (m, 1H), 1.58−1.45 (m, 1H), 1.36−1.29 (m, 1H), 0.77 (d, J = 4.0 Hz, 3H), 0.72 (d, J = 6.6 Hz, 3H); ^{13}C-

NMR (100 MHz, $CDCl_3$) δ 205.9, 173.4, 152.8, 111.8, 73.3, 56.2, 53.2, 33.0, 31.3, 30.2, 29.2, 23.2, 22.6. **(22+23)d**: IR (neat) 2940, 2845, 1730, 1710, 1640, 1430, 1350, 1230, 900 cm^{-1}. MS (*m*/*z*) 225, 207, 192, 183, 165, 149, 139, 121, 107, 91, 79, 65, 53, 43. Anal. Calcd for $C_{13}H_{20}O_3$: C, 69.61; H, 8.99. Found: C, 69.99; H, 9.18.

Methyl 2-methylidene-1-(1-oxoethyl)-5-[(trimethylsilyl)methyl]cyclopentane carboxylate (22+23)e (R = CH_2SiMe_3): 0.193 g, 72%; 85:15 mixture of inseparable diastereoisomers. **(22+23)e**: ^{1}H-NMR (400 MHz, $CDCl_3$) δ 5.23−5.16 (m, 4H), 3.74 (s, 3H), 3.71 (s, 3H), 2.85−2.77 (m, 2H), 2.58−2.26 (m, 4H), 2.24 (s, 3H), 2.13 (s, 3H), 1.94−1.87 (m, 2H), 1.48−1.41 (m, 2H), 0.36−0.17 (m, ABX, 4H), 0.01 (s, 9H), 0.00 (s, 9H); IR (neat) 2950, 1730, 1710, 1640,1385, 1250, 1080, 890 cm^{-1}. Anal. Calcd for $C_{14}H_{24}SiO_3$: C, 62.6; H, 9.01. Found: C, 62.69; H, 8.97. **22e**: ^{13}C-NMR (100 MHz, $CDCl_3$) δ 206.2, 172.2, 150.2, 112.8, 76.1, 52.8, 44.0, 34.0, 32.2, 28.5, 18.9, 0.0. **23e**: ^{13}C-NMR (100 MHz, $CDCl_3$) δ 203.5, 172.7, 150.3, 112.9, 75.6, 53.3, 45.5, 33.7, 30.6, 28.6, 19.0, −0.01.

Methyl 5-*tert*-butyl-2-methylidene-1-(1-oxoethyl)cyclopentanecarboxylate (22+23)f (R = *t*-Bu): 0.152 g, 64%; 96:4 mixture of inseparable diastereomers. ^{1}H-NMR (200 MHz, $CDCl_3$) δ 5.03 (t, *J* = 2.3 Hz, 2H), 4.92 (t, *J* = 2.7 Hz, 2H), 3.68 (s, 3H), 3.67 (s, 3H), 3.00 (dd, *J* = 7.1, 6.9 Hz, 2H), 2.61−2.30 (m, 4H), 2.39 (s, 3H), 2.38 (s, 3H), 1.89−1.70 (m, 4H), 0.85 (s, 18H); ^{13}C-NMR (50 MHz, $CDCl_3$) δ 203.2, 172.8, 153.0, 109.5, 70.3, 57.6, 51.6, 32.7, 32.5, 28.9, 28.4, 25.6; IR (neat) 2940, 1730, 1710, 1640, 1430, 1350, 1230, 885 cm^{-1}; MS (*m*/*z*) 223, 206, 196, 182, 178, 163, 150, 135, 121, 107, 91, 79, 59, 51, 43. Anal. Calcd for $C_{14}H_{22}O_3$: C, 70.59; H, 9.24. Found: C, 70.82; H, 9.34.

Methyl 5-ethynyl-7-methylene-2-oxobicyclo[3.2.1]octane-1-carboxylate (25): 0.153 g, 70%; white solid; mp 92 °C; ^{1}H-NMR (400 MHz, C_6D_6) δ 5.85 (dd, *J* = 2.7, 2.2 Hz, 1H), 4.84 (br s, 1H), 3.39 (s, 3H), 2.66 (ddd, *J* = 17.0, 4.4, 2.7 Hz, 1H), 2.50 (dd, *J* = 12.6, 3.0 Hz, 1H), 2.29 (ddd, *J* = 17.0, 4.4, 2.2 Hz, 1H), 2.18 (dd, *J* = 12.6, 2.2 Hz, 1H), 2.14 (ddd, *J* = 15.9, 12.1, 9.3 Hz, 1H), 1.85 (s, 1H), 1.84 (ddd, *J* = 15.9, 6.6, 2.2 Hz, 1H), 1.58 (m, 2H); ^{13}C-NMR (100 MHz, C_6D_6) δ 202.4, 169.5, 145.1, 112.8, 87.9, 70.8, 68.9, 52.7, 48.3, 45.4, 38.3, 35.7, 35.6; IR ($CHCl_3$) 3300, 3010, 2100, 1740, 1640, 750 cm^{-1}; HRMS calcd 218.0943, found 218.0948. Anal. Calcd for $C_{13}H_{14}O_3$: C, 71.53; H, 6.46. Found: C, 71.43; H, 6.42.

1-(Methoxycarbonyl)-2-methylidene-1-(1-oxo-6-heptynyl)cyclopentanecarboxylate (27): 0.208 g, 81%; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 5.22 (t, *J* = 2.1 Hz, 1H), 5.14 (t, *J* = 2.1 Hz, 2H), 3.67 (s, 3H), 2.58−2.41 (m, 2H), 2.48 (dt, *J* = 7.1, 2.1 Hz, 2H), 2.32 (t, *J* = 7.1 Hz, 2H), 2.12 (td, *J* = 7.1, 2.6 Hz, 2H), 1.87 (t, *J* = 2.6 Hz, 1H), 1.70−1.48 (M, 4H), 1.49−1.41 (m, 2H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 205.8, 172.1, 148.9, 112.6, 84.5, 70.7, 68.9, 53.0, 38.7, 35.5, 34.3, 28.2, 24.5, 23.6, 18.7; IR (neat) 3300, 2940, 2850, 2250, 1735, 1710, 1640, 1430, 1230, 910, 730 cm^{-1}; MS (*m*/*z*) 249, 217, 199, 189, 171, 161, 147, 139, 131, 122, 109, 95, 81, 65, 53. Anal. Calcd for $C_{15}H_{20}O_3$: C, 72.55; H, 8.12. Found: C, 72.85; H, 8.52.

Application in Synthesis. Methyl 6-[2-(Trimethylsilyl)ethynyl]-2-(1-oxoethyl)-2-nonen-9-(trimethylsilyl)-8-ynoate (29). 29 was prepared using the procedure described for **20**. Compound **29** (4.06 g; 75%) was purified by flash chromatography (petroleum ether/ether = 80/20) and was obtained as a 1:1 mixture of *E* and *Z* isomers: ^{1}H-NMR (400 MHz, $CDCl_3$) δ 6.93 (t, *J* =8.2 Hz, 1H), 6.88 (t, *J* = 7.7 Hz, 1H), 3.83 (s, 3H), 3.78 (s, 3H), 2.54 (m, 2H), 2.45 (m, 2H), 2.40 (m, 2H), 2.39 (m, 2H), 2.38 (s, 3H), 2.37 (dt, *J* = 7.7, 6.5 Hz, 2H), 2.31 (s, 3H), 1.79−1.68 (m, 4H), 0.14 (s, 18H), 0.13 (s, 18H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 200.7, 194.9, 166.7, 164.8, 148.0, 147.9, 137.1, 135.8, 107.2 (2C), 103.6 (2C), 87.3, 87.2, 86.8 (2C), 52.1(2C), 32.5, 32.3, 31.8, 31.7, 27.8 (2C), 27.1, 25.9 (2C), 22.6, 0.04, 0.00; IR (neat) 2950, 2170, 1710, 1690, 1630, 1250, 840 cm^{-1}; MS (*m*/*z*) 361, 303, 264, 249, 231, 199, 159, 131, 96, 89. Anal. Calcd for $C_{20}H_{32}Si_2O_3$: C, 63.78; H, 8.56. Found: C, 63.58; H, 8.76.

Methyl 3-[4-(trimethylsilyl)-3-butynyl]-6-[2-(trimethylsilyl)ethynyl]-2-(1-oxoethyl)-9-(trimethylsilyl)-8-nonyoate (30). Compound **30** was prepared following the general procedure (a) for the preparation of **21a-f**. After flash chromatography (petroleum ether/ether = 90/10), **30** (1.57 g; 94%) was obtained as a mixture of three inseparable diastereomers in equilibrium with the enol forms.^{1}H-NMR (400 MHz, $CDCl_3$) δ 3.70 (s, 3H), 3.69 (s, 3H), 3.68 (s, 3H), 3.54−3.48 (m, 3 × 1H), 2.44−2.39 (m, 3x1H), 2.44−2.31 (M, 3 × 4H), 2.22 (s, 3H), 2.21 (s, 3H), 1.70−1.39 (M, 3 × 7H), 0.11-0.10 (2xs, 3 × 27H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 202.8 (3C), 174.1, 173.7, 169.4, 107.9, 107.8, 107.7, 106.4, 106.0, 103.8 (2C), 86.5, 86.4 (2C), 86.0, 85.2, 84.9, 63.1, 63.0, 62.9, 52.1, 51.0, 36.5, 36.1, 32.0, 31.9, 31.8, 30.0, 29.9, 29.8, 29.5, 29.4, 29.3, 29.2, 29.1, 29.0, 27.3 (2C), 27.2, 25.8, 25.7, 18.1, 17.1, 17.0, 0.0; IR (neat) 2950, 2165, 1740, 1710, 1430, 1245, 840 cm^{-1}; MS (*m*/*z*) 487, 391, 313, 275, 243, 239, 225, 209, 201, 187, 173, 155, 147, 89. Anal. Calcd for $C_{27}H_{46}Si_3O_3$: C, 64.48; H, 9.22. Found: C, 64.54; H, 9.21.

Methyl 3-(3-Butynyl)-6-ethynyl-2-(1-oxoethyl)-8-nonyoate (31). To a cooled (−10 °C) solution of **30** (1.0 g; 2 mmol) in THF (15 mL) was added a THF solution of *n*-Bu_4NF (1 M in THF; 6.4 mL; 3.2 equiv) dropwise. After being stirred for 30 min at −10 °C and an additionnal 3 h at room temperature, the reaction mixture was extracted with ether (50 mL), washed with brine (2 × 20 mL), dried ($MgSO_4$), filtered, and concentrated. The residue was flash chromatographed (petroleum ether−ether = 80/20) affording **31** (0.54 g; 94%) as a mixture of three inseparable diastereomers in equilibrium with the enol forms: ^{1}H-NMR (200 MHz, $CDCl_3$) δ 3.74 (s, 3H), 3.73 (s, 3H), 3.55−3.51 (m, 3 × 1H), 2.51 (m, 3 × 1H), 2.42−2.34 (m, 3 × 4H), 2.24 (s, 3 × 3H), 2.12 (b s, 3 × 1H), 2.05 (t, *J* = 2.2 Hz, 3 × 1H), 1.96 (m, 3 × 1H), 1.80−1.40 (M, 3 × 7H); ^{13}C-NMR (50 MHz, $CDCl_3$) δ 202.8 (3C), 169.5 (3C), 85.4 (3C), 83.4 (3C), 81.4, 81.2, 81.1, 70.6, 70.5, 70.4, 70.3, 70.2, 70.1, 69.1, 68.9, 68.5, 62.8, 62.7, 62.7, 52.3 (3C), 36.5, 36.4, 36.3, 30.9 (3C), 30.8, 30.7, 30.3, 29.6 (3C), 29.4 (3C), 27.8, 27.6, 27.5, 24.5, 24.4, 24.3, 15.9, 15.8, 15.7; IR (neat) 2950, 2850, 2230, 1710, 1640, 1430, 1235, 900 cm^{-1}; MS (*m*/*z*) 243, 215, 211, 187, 183, 173, 169, 149, 129, 116, 101, 91. Anal. Calcd for $C_{18}H_{22}O_3$: C, 75.50; H, 7.74. Found: C, 75.44; H, 7.66.

Methyl 2-(3-Ethynyl-5-hexynyl)-5-methylidene-1-(1-oxoethyl)cyclopentane carboxylate (32). Following the general procedure described above for the ene reaction, **32** was obtained as a mixture of three inseparable diastereomers (0.218 g; 76%): ^{1}H-NMR (400 MHz, $CDCl_3$) δ 5.26 (t, *J* = 2.2 Hz, 3 × 1H), 5.20 (t, *J* = 2.2 Hz, 3 × 1H), 3.79 and 3.73 [(s, **32b**: 14%) and (s, **32a**: 86%), 9H], 2.79−2.72 (m, 3 × 2H), 2.55−2.51 (m, 3 × 1H), 2.46−2.33 (m, 3 × 2H), 2.27 and 2.17 [(s, **32a**: 86%) and (s, **32b**: 14%), 9H], 2.11 (t, *J* = 2.2 Hz, 3 × 1H), 2.04 (m, 3 × 1H), 1.96−1.92 (m, 3 × 1H), 1.74−1.63 (m, 3 × 1H), 1.60-1.40 (M, 3 × 4H), 1.30−1.20 (m, 3 × 1H); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 202.1 (3C), 171.1 (3C), 149.3 112.1 (3C), 85.6 (3C), 81.3 (3C), 76.7 (3C), 70.3 (3C), 70.1 (3C), 52.0 (3C), 46.0 (3C), 32.6 (3C), 32.2 (3C), 30.8(3C), 29.2 (3C), 28.7 (3C), 27.2 (3C), 24.4 (3C); IR (neat) 3280, 2940, 2110, 1720, 1640, 1430, 1160 cm^{-1}; MS (*m*/*z*) 287, 255, 245, 227, 211, 197, 183, 169, 153, 145, 128, 117, 107, 91, 79, 65, 51. Anal. Calcd for $C_{18}H_{22}O_3$: C, 75.50; H, 7.74. Found: C, 75.34; H, 7.80.

Benzocyclobutenes (33). The reaction was carried out under argon in a flame-dried flask, and all the solutions were degassed by three freeze-pump-thaw cycles. A solution of **32** (0.20 g; 0.7 mmol) and $CpCo(CO)_2$ (17 mL; 0.14 mmol) in degassed bis(trimethylsilyl)ethyne (3.4 mL) and xylenes (1 mL) was added dropwise over 20 min to a boiling degassed solution of btmse (7 mL) and $CpCo(CO)_2$ (8.5 mL; 0.07 mmol). Light from a projector lamp (ELW, 300W, 50% of its power) was directed at the reaction mixture during the addition. After the mixture was boiled and irradiated for an additional 15 min, the solvents were removed by vacuum transfer. The crude residue was purified by flash chromatography (petroleum ether/ether = 95/5) to give an inseparable diastereomeric mixture of benzocyclobutenes **33**. **33a+b**: 0.27 g; 84%. ^{1}H-NMR (400 MHz, $CDCl_3$) δ 7.41 (br s, 3 × 1H), 7.38 (br s, 3 × 1H), 5.29−5.20 (m, 3 × 2H), 3.77 and 3.75 [(s, **33b**: 14%) and (s, **33a**: 86%), 9H], 3.47−3.46 (m, 3 × 1H), 3.37−3.33 (m, 3 × 1H), 2.52−2.49 (m, 3 × 1H), 2.37-2.35 (m, 3 × 2H), 2.29 and 2.25 [(s, **33a**: 86%) and (s, **33b**: 14%), 9H], 2.08−1.97 (m, 3 × 1H), 1.80−1.20 (M, 3 × 6H), 0.36 (s, 3 × 9H), 0.35 (s, 3 × 9H); ^{13}C-NMR (100 MHz, C_6D_6) δ 204.7, 204.5, 202.9, 202.7, 171.9

(2C), 171.8 (2C), 150.2, 150.1, 149.9, 149.8, 145.4, 144.7, 144.3 (2C), 137.9, 137.4, 136.6, 132.4 (2C), 132.3, 131.5, 130.1, 129.4, 129.1 (3C), 128.9 (2C), 128.8 (2C), 112.8, 112.7, 112.6, 112.5, 74.4, 74.2, 74.0, 73.9, 52.6, 52.5, 52.4, 53.1, 46.9 (2C), 46.8 (2C), 44.8 (2C), 44.7, 44.6, 37.3 (2C), 37.2 (2C), 33.4, 33.3, 33.1, 30.9, 30.8, 29.9 (2C), 29.7, 29.6 (2C), 28.1 (2C), 27.8 (2C), 2.9 (4C); IR (neat) 3010, 2940, 2395, 1730, 1700, 1430, 1250, 1210, 850, 830 cm^{-1}; MS (*m*/*z*) 456, 353, 301, 281, 265, 251, 219, 207, 187, 167. Anal. Calcd for $C_{26}H_{40}Si_2O_3$: C, 68.37; H, 8.83. Found: C, 68.33; H, 8.86.

Tetracyclic Compounds 35. A degassed solution of benzocyclobutenes **33** (0.24 g; 0.52 mmol) in decane (15 mL) was heated at reflux until TLC indicated that starting material had been consumed (12 h). The solvent was removed by vacuum transfer, and the crude residue was purified by flash chromatography (petroleum ether/ether = 90/10) to afford two compounds **35a** (0.19 g; 79%) and **35b** (0.03 g; 13%). **35a**: ^{1}H-NMR (400 MHz, C_6D_6) δ 7.74 (s, 1H), 7.54 (s, 1H), 3.46 (dd, *J* = 10.4, 5.5 Hz, 1H), 3.27 (s, 3H), 2.76 (ddd, *J* = 12.6, 5.5, 4.9 Hz, 1H), 2.71−2.67 (m, 1H), 2.43 (dt, *J* = 12.6, 5.5 Hz, 1H), 2.29 (ddd, *J* = 12.1, 6.0, 5.5 Hz, 1H), 2.27 (m, 1H), 2.22 (m, 1H), 2.20 (m, 1H), 2.16 (ddd, *J* = 12.6, 5.5, 2.2 Hz, 1H), 1.96 (s, 3H), 1.82 (dt, *J* = 12.1, 4.9 Hz, 1H), 1.60 (ddd, *J* = 9.3, 4.4, 4.4 Hz, 1H), 1.47 (m, 1H), 1.46 (m, 1H), 1.22 (ddd, *J* = 9.9, 4.9, 4.9 Hz, 1H), 0.47 (s, 9H), 0.46 (s, 9H); ^{13}C-NMR (100 MHz, C_6D_6) δ 202.9, 172.2, 142.6, 142.1, 139.5, 136.5, 135.8, 134.7, 74.8, 51.2, 48.9, 42.0, 40.9, 29.4, 29.3, 29.2, 28.1, 27.8, 27.0, 25.1, 2.2, 2.1. **35b**: ^{1}H-NMR (400 MHz, C_6D_6) δ 7.73 (s, 1H), 7.54 (s, 1H), 4.10 (dd, *J* = 11.5, 5.7 Hz, 1H), 3.25 (s, 3H), 2.74−2.66 (m, 1H), 2.72−2.55 (m, 1H), 2.63−2.60 (m, 2H), 2.35−2.23 (m, 1H), 1.93 (s, 3H), 1.68−1.60 (m, 3H), 1.55−1.48 (m, 1H), 1.48−1.38 (m, 1H), 1.38−1.29 (m, 1H), 1.31−1.24 (m, 2H), 0.5 (s, 9H), 0.48 (s, 9H); ^{13}C-NMR (100 MHz, C_6D_6) δ 202.8, 171.1, 142.8, 141.8, 139.9, 136.5, 135.4, 134.5, 73.7, 51.3, 49.0, 42.0, 38.3, 30.6, 30.2, 30.1, 28.9, 27.7, 26.7, 24.8, 2.3, 2.1. **35a**+**35b**: IR (neat) 3010, 2940, 2395, 1730, 1700, 1430, 1250, 1210, 850, 830 cm^{-1}; MS (*m*/*z*) 456, 441, 409, 381, 353, 340, 309, 301, 265, 237, 213, 197, 161, 147, 131. Anal. Calcd for $C_{26}H_{40}Si_2O_3$: C, 68.37; H, 8.83. Found: C, 68.72; H, 9.08.

One-Pot Sequence Procedure. $CpCo(CO)_2$ (7 mL; 5.8×10^{-2} mmol) was added in boiling solution of **31** (0.23 g; 0.5 mmol) in benzene (4 mL) and was irradiated. After 8h, warm btmse (8.5 mL) was quickly added. After being refluxed and irradiated for an additional 30 min, a solution of diphenylphosphinoethane (dppe; 0.06 g; 0.15 mmol) in decane (50 mL) was added. After being heated at reflux for 12h, the solvents were removed in vacuo and the crude residue was purified as above to furnish **35a**+**35b** in 42% yield.

Acknowledgment. Financial support was provided by the CNRS, MRES, and Centre de Recherche des Carrières Rhône-Poulenc. R.S. and P.C. were supported by fellowships from Rhône-Poulenc. The authors are indebted to Dr. O. Convert and Dr. F. Robert, Université P. et M. Curie, respectively, for running ^{1}H-NMR NOE experiments and for carrying out the X-ray structural determination of **35**.

JO9600619