breaking of the old carbon-iodide bond. This conclusion is also supported by the comparison of theoretical values of the carbon kinetic isotope effect (Table II) with experimental values $k^{12}/k^{14} = 1.117 \pm 0.011$[2] and $k^{11}/k^{14} = 1.230 \pm 0.0036$.[3] Although these isotope effects were measured at higher temperature, we do not expect any substantial change in the isotope effect over the range of 24 °C. Theoretical dependence of the nitrogen isotope effect on the location of the transition state is much greater for the exploded transition state than for the structures in which the bonding to the central carbon atom is preserved. For the exploded transition state, the observed nitrogen isotope effect would suggest a late or even very late transition state, but this conclusion does not agree with the comparison of observed and calculated deuterium isotope effects, which would suggest a symmetrical transition state. Instead, the isotope effects suggest a symmetrical or slightly late transition state in which the bonding to the central carbon atom is preserved. On the other hand, experimental values of deuterium isotope effects for reaction[8] of methyl iodide with aliphatic amines and pyridine, $k^{H_3}/k^{D_3} = 0.85 - 0.91$, if compared with our theoretical estimates, would suggest a late transition state, as would chlorine kinetic isotope effects[9] in reactions of methyl chloride with aliphatic amines.

Kinetically simple reactions like the one studied here have been the subject of extensive theoretical modeling[10] in the past. These studies have suffered from the arbitrary choice of force field and inconsistency between reactant and transition-state models. For example, for the particular type of reaction under consideration, two different dependences of carbon kinetic isotope effect on the location of the transition state have been postulated. Evidence for bell-shaped dependence[11,12] and for linear dependence without a maximum[13] was obtained from different theoretical calculations. It was finally shown[14] that the problem originates in the reaction coordinate definition. Refined calculations[10] using the BEBOVIB program[15] confirmed the bell-shaped dependence, consistent with what was seen here. An unbiased force field may be obtained from quantum mechanical calculations at the ab initio or semiempirical level. Unfortunately, for ab initio calculations, even a reaction as simple as this one is still prohibitively complex. Semiempirical calculations, on the other hand, can be performed on such systems within a reasonable time limit with readily available computers. The approximations within MNDO or AM1 Hamiltonians appear to be sufficient for reflecting changes of physical properties as small as those introduced by isotopic substitution.

For the reaction in question, values of carbon and deuterium kinetic isotope effects obtained by means of AM1 calculations are in qualitative agreement with previous estimates for analogous reactions on the basis of the BEBOVIB program. In particular, our calculations confirm the bell-shaped dependence of the central carbon kinetic isotope effect on the transition-state location on the reaction coordinate. The dipole moment (8.9 D) and charge developed on the iodide atom ($\delta^- = 0.45$) in the transition state from our calculations are also in excellent agreement with values reported in the literature (8.7 D and 0.43, respectively[16-18]) predicted on the basis of solvent effects on reaction rates. The imaginary frequency of the movement along the reaction coordinate is practically exclusively connected with the asymmetric stretching mode of the N-C-I skeleton. Energetic analysis of the reaction coordinate indicates that the contribution of bending modes of C-H bonds is only a few percent (% c in Table II) regardless of the precise structure of the transition state.

Our results demonstrate the usefulness of semiempirical quantum mechanical methods in evaluation of isotope effects and the usefulness of simultaneous measurement of several isotope effects in the study of transition-state structures.

Acknowledgment. This work was supported by NIH Grant GM43043. Mass spectrometric measurements of the deuterated samples by the Midwest Center for Mass Spectrometry are gratefully acknowledged.

Registry No. p-$MeC_6H_4NMe_2$, 99-97-8; MeI, 74-88-4; N (isotope 15), 14390-96-6; D_2, 7782-39-0.

(8) Willi, A. V. In *Isotopes in Organic Chemistry*; Buncel, E., Lee, C. C., Eds.; Elsevier: Amsterdam, 1977; Vol. 3, p 237.
(9) Swain, C. G.; Hershey, N. D. *J. Am. Chem. Soc.* **1972**, *94*, 1901. Bare, T. M.; Hershey, N. D.; House, H. O.; Swain, C. G. *J. Org. Chem.* **1972**, *37*, 997.
(10) Yamataka, H.; Ando, T. *J. Phys. Chem.* **1981**, *85*, 2281.
(11) Willi, A. V. *Z. Naturforsch. A* **1966**, *21*, 1385.
(12) Sims, L. B.; Fry, A.; Netherton, L. T.; Wilson, J. C.; Reppond, K. D.; Crook, S. W. *J. Am. Chem. Soc.* **1972**, *94*, 1364.
(13) Bron, J. *Can. J. Chem.* **1974**, *52*, 903.
(14) Buddenbaum, W. E.; Shiner, V. J., Jr. In *Isotope Effects on Enzyme-Catalyzed Reactions*; Cleland, W. W., O'Leary, M. H., Northrop, D. B., Eds.; University Park Press: Baltimore, 1977; p 1.
(15) Sims, L. B.; Burton, G.; Lewis, D. E. *QCPE* **1985**, 337.
(16) Abraham, M. H. *Progr. Phys. Org. Chem.* **1974**, *11*, 1.
(17) Abraham, M. H.; Abraham, R. J. *J. Chem. Soc., Perkin Trans. 2* **1975**, 1677.
(18) Abraham, M. H. *Pure Appl. Chem.* **1985**, *57*, 1055.

The Directed Pauson-Khand Reaction†

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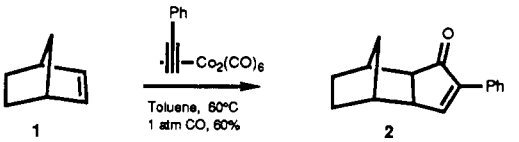
Abstract: The regioselectivity of the cobalt-mediated cocyclization of an alkene, an alkyne, and carbon monoxide has been shown to be directed by the use of a soft atom, either sulfur or nitrogen, tethered to the alkene partner by a carbon chain. Direction from the homoallylic position is more efficient than from the allylic or bishomoallylic position. A rationale is proposed to explain this observation. Studies on the effect of different alkyl groups on the sulfur and nitrogen and other modifications are reported.

Introduction[1c]

The cobalt-catalyzed ene-yne cycloaddition, which yields cyclopentenones, was first reported by Pauson.[2] These cycloaddition reactions were initially carried out with strained alkenes (eq 1), but the reaction has since been extended to include the use of simple alkenes.[3]



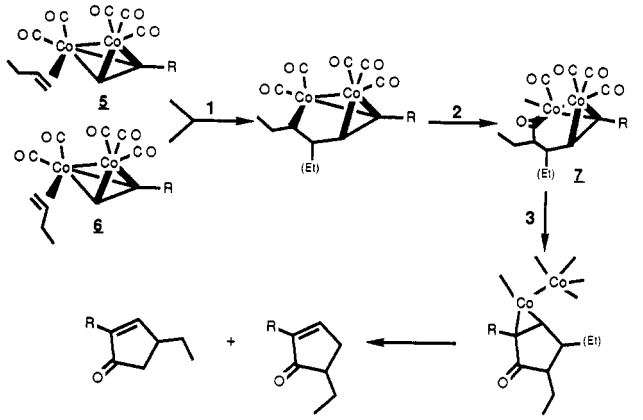
1 2 (1)

Unstrained alkenes are much less reactive than strained alkenes and, as a result, give lower yields of cyclopentenones. In addition,

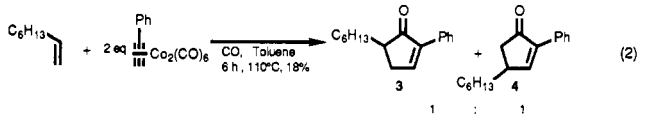
† Dedicated to Professor Peter L. Pauson on the occasion of his retirement.

0002-7863/91/1513-1693$02.50/0

Scheme I

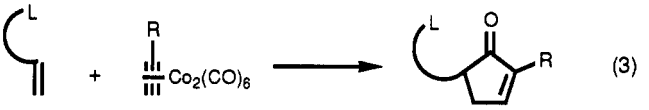


reactions of unsymmetrical olefins with terminal alkynes yield regioisomeric mixtures of cyclopentenones. For example, treatment of 1-octene with (phenylacetylene)hexacarbonyldicobalt gives a 1:1 ratio of isomeric products in 18% yield (eq 2).[4] The



(2)

regioisomers arise from the unsymmetrical substitution pattern on the alkene and not the alkyne. Unsymmetrically substituted acetylenes prefer to react in an orientation that places the larger substituent in the α position of the cyclopentenone. However, when the group at the terminus of the alkyne is small, i.e., methyl, very small amounts of the regioisomeric cyclopentenone have been isolated (vide infra). Our recent results[5] have shown that the previously mentioned problems, isomers and yield, can be overcome by the use of a coordinating heteroatom tethered to the alkene by a carbon chain (eq 3).



(3)

The cycloaddition reaction, referred to as the Pauson–Khand reaction,[3] has attracted much attention due to its potential synthetic utility. Until our report[5] on controlling the regiochemistry in intermolecular reactions, the scope of the reaction was much more limited and most of the synthetic work involved the intramolecular modification[3,6] in order to avoid the aforementioned problems. The synthetic utility of the Pauson–Khand reaction has been demonstrated by incorporation of the cyclopentenone synthesis in the total syntheses of numerous natural products: pentalenene,[7] coriolin,[8] hirsutic acid,[8a] and quadrone,[8b] methylenomycin B,[9] prostaglandin analogues,[10] and PGA_2.[11] In addition, the ene–yne cycloaddition has been used in synthetic approaches to other natural products.[12] The use of silica gel as a medium for the reaction was investigated by Caple and Smit and resulted in an overall improvement in the yield and a significant increase in the reaction rate at lower temperatures.[13] Caple and Smit[14a] and Pauson[14b] have recently reported the use of ultrasound to improve the efficiency of the cycloaddition.

Results and Discussion

A mechanism for the cycloaddition has been proposed,[15] though no intermediates have ever been isolated (Scheme I). Initially, the olefin must coordinate to the cobalt complex.[16] Apparently, a mixture of isomeric complexes **5** and **6** is formed in solution prior to cycloaddition. In step 1, the initial carbon–carbon bond-forming step, it has been proposed that the substituent on the acetylene provides steric interference to the formation of the first bond, causing it to be formed with the less substituted end of the acetylene. However, with terminal alkynes, there seems to be little steric interaction between the unsubstituted end of the alkyne and the alkene substituents; thus, both complexes **5** and **6** are formed. It is apparently this lack of steric control that gives rise to the formation of the regioisomeric cyclopentenones. Therefore, in the reaction of unsymmetrically substituted olefins and terminal acetylenes, regioisomers arise from initial bond formation to either end of the olefin and not to either end of the acetylenic moiety. The regioisomeric ratio of cyclopentenones should be established in step 1. Carbonylation (step 2) to give **7**, reductive coupling (step 3), and decomplexation of the cobalt explain the formation of the observed carbocycles.

(1) (a) Fellow of the A. P. Sloan Foundation, 1989–1991. Camille and Henry Dreyfus Teacher Scholar 1989–1994. (b) Undergraduate Research Participant from Mercer University, Macon, GA, Summer 1989. (c) Presented in part at the Southeastern Regional Meeting of the American Chemical Society, Oct 1987, Orlando, FL; the Gordon Research Conference on Natural Products, July 1987, New Hampton, NH; the Gulf Coast Chemistry Conference, 1987 and 1989, Pensacola, FL; the meeting of the Florida Section of the American Chemical Society, April 1988, Tampa, FL; and the Southeastern Regional Meeting of the American Chemical Society, Oct 1989, Winston-Salem, NC.

(2) Khand, I. U.; Knox, G. R.; Pauson, P. L.; Watts, W. E.; Foreman, M. E. *J. Chem. Soc., Perkin Trans. 1* **1973**, 977.

(3) Pauson, P. L. In *Organometallics in Organic Synthesis*; de Meijere, A., tom Dieck, H., Eds.; Springer-Verlag, Berlin, 1987; p 234. Pauson, P. L. *Tetrahedron* **1985**, *41*, 5855. Pauson, P. L.; Khand, I. U. *Ann. N. Y. Acad. Sci.* **1977**, *295*, 2. See also: Schore, N. E. *Chem. Rev.* **1988**, *88*, 1081. For a recent review on the Pauson–Khand reaction in cyclopentenone synthesis, see: Schore, N. E. *Org. React.*, in press.

(4) Khand, I. U.; Pauson, P. L. *J. Chem. Res., Miniprint* **1977**, 168.

(5) Krafft, M. E. *J. Am. Chem. Soc.* **1988**, *110*, 968.

(6) Schore was the first to demonstrate the intramolecular cycloaddition: Schore, N. E.; Croudace, M. C. *J. Org. Chem.* **1981**, *46*, 5436.

(7) Schore, N. E.; Rowley, E. G. *J. Am. Chem. Soc.* **1988**, *110*, 5224.

(8) (a) Exon, C.; Magnus, P. *J. Am. Chem. Soc.* **1983**, *105*, 2477. Magnus, P.; Exon, C.; Albaugh-Robertson, P. *Tetrahedron* **1985**, *41*, 5861. (b) Magnus, P.; Principe, L. M.; Slater, M. J. *J. Org. Chem.* **1987**, *52*, 1483.

(9) Billington, D. C.; Pauson, P. L. *Organometallics* **1982**, *1*, 1560.

(10) Mulzer, J.; Graske, K.-D.; Kirste, B. *Liebigs Ann. Chem.* **1988**, 891. Magnus, P.; Becker, D. P. *J. Am. Chem. Soc.* **1987**, *109*, 7495. Jaffer, H. J.; Pauson, P. L. *J. Chem. Res., Synop.* **1983**, 244; *J. Chem. Res., Miniprint* **1983**, 2201. Newton, R. F.; Pauson, P. L.; Taylor, R. G. *J. Chem. Res., Miniprint* **1980**, 3501.

(11) Unpublished results: Krafft, M. E.; Wright, C. *Abstracts of Papers*, 198th National Meeting of the American Chemical Society, Miami Beach, FL; American Chemical Society: Washington, DC, 1989; ORGN 256.

(12) For other applications to organic synthesis, see: Knudsen, M. J.; Schore, N. E. *J. Org. Chem.* **1984**, *49*, 5025. Billington, D. C.; Willison, D. *Tetrahedron Lett.* **1984**, *25*, 4041. Schreiber, S. L.; Sammakia, T.; Crowe, W. E. *J. Am. Chem. Soc.* **1986**, *108*, 3128. Schore, N. E.; Knudsen, M. J. *J. Org. Chem.* **1987**, *52*, 569. Caple, R.; Froen, D.; Kraeger, A. *Abstracts of Papers*, 193rd National Meeting of the American Chemical Society, Denver, CO; American Chemical Society: Washington, DC, 1987; ORGN 42. Schore, N. E.; Najdi, S. D. *J. Org. Chem.* **1987**, *52*, 5298. Magnus, P.; Becker, D. P. *J. Am. Chem. Soc.* **1987**, *109*, 7495. Bladon, P.; Khand, I. U.; Pauson, P. L. *J. Chem. Res., Miniprint* **1977**, 153. Sampath, V.; Lund, E. C.; Knudsen, M. J.; Olmstead, M. M.; Schore, N. E. *J. Org. Chem.* **1987**, *52*, 3595. Billington, D. C.; Bladon, P.; Helps, I. M.; Pauson, P. L.; Thomson, W.; Willison, D. *J. Chem. Res., Synop.* **1988**, 326. Saha, M.; Muchmore, S.; Van Der Helm, D.; Nicholas, K. M. *J. Org. Chem.* **1986**, *51*, 1960. For other related cobalt-mediated cycloadditions, see: Vollhardt, K. P. C. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 539 and references cited therein. Iyer, S.; Liebeskind, L. S. *J. Am. Chem. Soc.* **1987**, *109*, 2759. Nicholas, K. M. *Acc. Chem. Res.* **1987**, *20*, 207.

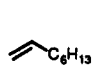
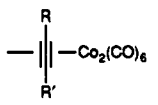
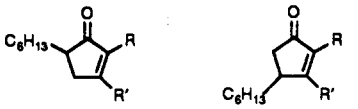
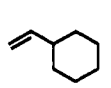
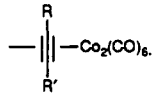
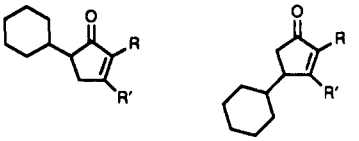
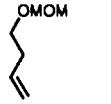
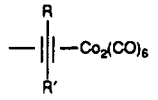
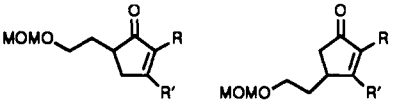
(13) Smit, W. A.; Kireev, S. L.; Nefedov, O. M.; Tarasov, V. A. *Tetrahedron Lett.* **1989**, *30*, 4021. Smit, W. A.; Gybin, A. S.; Shashkov, A. S.; Strychov, Y. T.; Kyzmina, L. G.; Mikaelian, G. S.; Caple, R.; Swanson, E. D. *Tetrahedron Lett.* **1986**, *27*, 1241. Simonian, S. O.; Smit, W. A.; Gybin, A. S.; Shashkov, A. S.; Mikaelian, G. S.; Tarasov, V. A.; Ibragimov, I. I.; Caple, R.; Froen, D. E. *Tetrahedron Lett.* **1986**, *27*, 1245. Smit, W. A.; Simonian, S. O.; Tarasov, V. A.; Mikaelian, G. S.; Gybin, A. S.; Ibragimov, I. I.; Caple, R.; Froen, D. E.; Kreager, A. *Synthesis* **1989**, 472.

(14) (a) See ref 12. (b) Billington, D. C.; Helps, I. M.; Pauson, P. L.; Thomson, W.; Willison, D. *J. Organomet. Chem.* **1988**, *354*, 233.

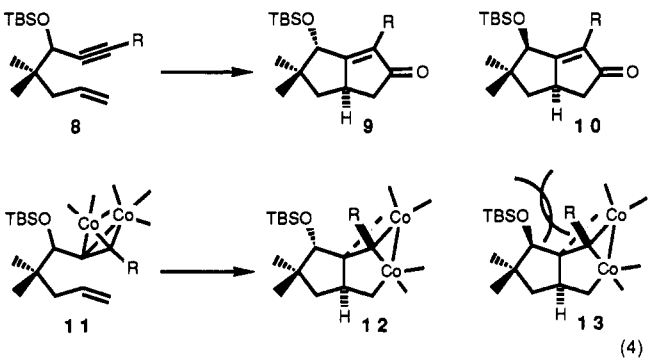
(15) Reference 8a. Magnus, P.; Principe, L. M. *Tetrahedron Lett.* **1985**, *26*, 4851.

(16) Mechanism of ligand exchange: Dickson, R. S.; Fraser, P. *J. Organomet. Chem.* **1974**, *12*, 323. Darensbourg, D. J. *Adv. Organomet. Chem.* **1982**, *21*, 113. Hubel, W. In *Organic Synthesis Via Metal Carbonyls*; Pino, P., Wender, I., Eds.; Wiley Interscience: New York, 1968; Vol 1, p 273.

Table I

entry	alkene	cobalt complex	product(s)	yield (%)
				
1		**14**: R = Bu; R′ = H	**18**[4]:**19**[4] = 1:1	41
2		**15**: R = Ph; R′ = Me	**20**:**21** = 19:1	27
				
3		**16**: R = Ph; R′ = H	**22**:**23** = 2.5:1	47
4		**15**: R = Ph; R′ = Me	**24** (only enone)	22
5		**17**: R = Me; R′ = Me	**25** (only enone)	23
				
6		**14**	**26**:**27** = 3:2	41
7		**17**	**28**:**29** = >40:1	26
8		**15**	**30**:**31** = >40:1	41

Support for the mechanism has been obtained by rationalization of the regiochemical and stereochemical outcome of some highly selective reactions.[17] For example, Magnus observed a very high degree of stereocontrol in an intramolecular cycloaddition reaction that was used as a key step in his synthesis of coriolin.[8a] Ene–yne **8**, upon being warmed with octacarbonyldicobalt, gave rise to a 26:1 ratio of bicyclic products **9** and **10** when R was trimethylsilyl and a 3:1 ratio when R was CH_3 (eq 4).

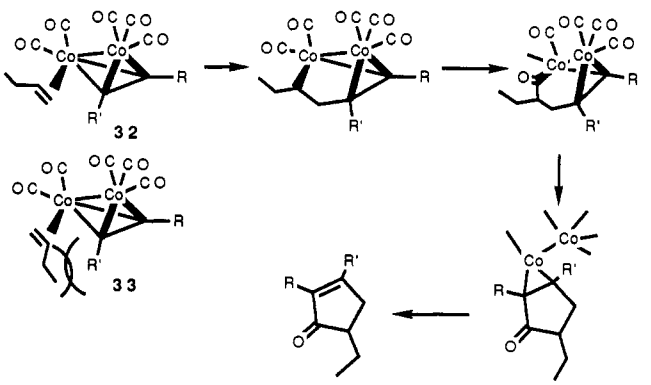


(4)

The stereoselectivity was explained by use of the proposed mechanism. Cycloaddition of cobalt-complexed alkyne **11** can be expected to give two metallacycles **12** and **13**. Assuming the newly formed metallacycle is cis fused, metallacycle **12** minimizes steric interactions present in **13**. The larger R group (TMS vs methyl) gave greater steric control.

We took advantage of the mechanistic rationalization that the alkyl group on a terminal alkyne provides steric control over the cycloaddition leading to cyclopentenones where the substituent from the alkyne always ends up adjacent to the carbonyl. A high degree of regiocontrol over cyclopentenone formation was observed during an investigation of the cyclization reaction using internal alkynes.[18] These results are summarized in Table I. A comparison of the reaction of vinylcyclohexane with (phenylacetylene)hexacarbonyldicobalt (**16**) (entry 3 in Table I) and with

Scheme II



(1-phenyl-1-propyne)hexacarbonyldicobalt (**15**) (entry 4 in Table I) shows the dramatic influence the internal acetylene exerts over the regiochemistry of the cycloaddition. In addition, the bulkier group on the internal alkyne is oriented in the transition state such that it becomes adjacent to the carbonyl in the cyclopentenone (entries 2, 4, and 8). The two groups on the alkyne must be significantly different in size for the steric selection to occur; reaction of the cobalt carbonyl complex of 2-hexyne with 1-octene gave rise to a mixture of four regioisomeric products. However, the cobalt complex of 1-(trimethylsilyl)-1-hexyne was apparently too sterically hindered to react with the unstrained alkene 1-octene. Further comparison of other entries in Table I clearly demonstrates that steric interactions affect the regiochemical outcome of the cycloaddition. In all of the cases cited in Table I, none of the regioisomeric product from the acetylenic partner could be found.

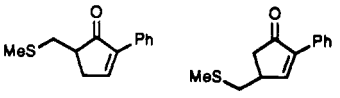
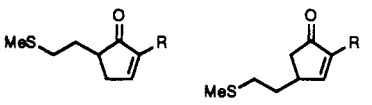
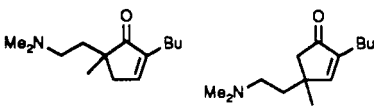
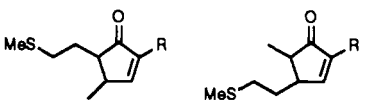
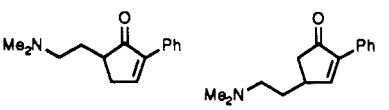
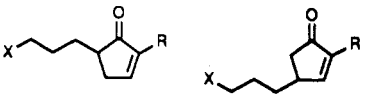
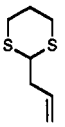
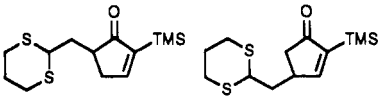
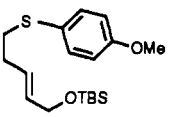
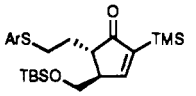
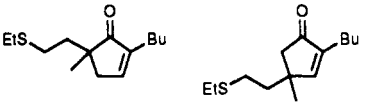
These results can be explained by returning to the mechanistic hypothesis[15] (Scheme II). As previously discussed, with terminal acetylenes (R^1 = H), coordination of the alkene to the cobalt carbonyl complex, prior to cycloaddition, is directed toward the terminal end of the alkyne due to steric interactions with the acetylene substituent.[8,15,19] It is apparent that there is very little steric interaction between the olefin substituents and the terminus of the acetylene; thus, subsequent carbon–carbon bond formation takes place readily from either complex **32** or **33**. When two different alkyne substituents are present, olefin coordination to cobalt must necessarily occur near the smallest acetylene sub-

(17) For examples of regioselective and/or stereoselective cycloaddition reactions, see: ref 8 and Khand, I. U.; Murphy, E.; Pauson, P. L. *J. Chem. Res., Synop.* **1978**, 350. Khand, I. U.; Murphy, E.; Pauson, P. L. *J. Chem. Res., Miniprint* **1978**, 4434. MacWhorter, S. E.; Sampath, V.; Olmstead, M. M.; Schore, N. E. *J. Org. Chem.* **1988**, *53*, 203. LaBelle, B. E.; Knudsen, M. J.; Olmstead, M. M.; Hope, H.; Yanuck, M. D.; Schore, N. E. *J. Org. Chem.* **1985**, *50*, 5215. Sampath, V.; Lund, E. C.; Knudsen, M. J.; Olmstead, M. M.; Schore, N. E. *J. Org. Chem.* **1987**, *52*, 3595.

(18) Krafft, M. E. *Tetrahedron Lett.* **1988**, *29*, 999.

(19) Khand, I. U.; Pauson, P. L. *J. Chem. Soc., Perkin Trans. 1*, **1976**, 30.

Table II

entry	olefin	cobalt complex	product(s)	yield[a] (%)
1		16	 **35**:**36** = 2:1	29
2		14	 **37**:**38** = 8:1; R = Bu	60
3		16	**39**:**40** = 18:1; R = Ph	61
4		14	 **41**:**42** = 20:1	60
5		16	 **43**:**44** = 40 (t:c = 19:1):1; R = Ph	73
6		34	**45**:**46** = 25 (t:c = 20:1):1; R = TMS	65
7		16	 **47**:**48** = 5:1	72
8	 X = NMe_2	16	 **49**:**50** = 3:1; R = Ph	69
9	X = SMe	14	**51**:**52** = 3:1; R = Bu	50
10		34	 **53**:**54** = 35:1	40
11		34	 **55**	79
12		14	 **56**:**57** = 25:1	52

[a] Isolated yields.

stituent (for example, R = Ph and R^1 = CH_3; entries 2, 4, and 8 in Table I). Now, steric interactions between the substituents on the olefin and alkyne seem to be very important, and complex **32** apparently undergoes carbon–carbon bond formation more readily than **33**.

The yields for the Pauson–Khand reaction with internal (acetylene)cobalt complexes typically ranged from 20 to 40%. All of the results are consistent with, and provide support for, the proposed mechanism.

Hence, a partial and limited solution to the problem of regioselectivity in the intermolecular cycloaddition was achieved by taking advantage of steric interactions generated in the transition state. After further consideration of the proposed mechanism, we were confident that a heteroatom, tethered to the olefin by a carbon chain, would coordinate to cobalt and thus control the regiochemical outcome of the reaction (eq 3), which is presumably determined in step 1 of Scheme III. The use of bidentate olefinic ligands was also expected to provide a more stable initial complex and lead to increased yields of products.

As we previously reported,[5] oxygen, nitrogen, and sulfur were investigated for their efficacy as directing ligands. As expected, alcohols, methoxymethyl ethers, and (methoxyethoxy)methyl ethers did not provide any ligand-directed regioselectivity, and essentially 1:1 mixtures of regioisomeric cyclopentenones were obtained. However, the soft ligands sulfur and nitrogen both provided excellent regiocontrol over the cycloaddition, and a number of examples are listed in Table II.

A variety of terminal alkyne complexes were found to participate in the cycloaddition, as illustrated in the table. [(Trimethylsilyl)acetylene]hexacarbonyldicobalt (**34**) is a particularly useful reaction partner since it generates a stable vinylsilane that can then be used in subsequent ipso substitution reactions. However, only low yields of cyclopentenones were obtained from reactions of (trimethylsilyl)acetylene complex **34** and homoallylic amine substrates.

The best results were obtained with homoallylic substrates. Quaternary centers were readily formed via the directed cycloaddition of terminally disubstituted alkenes (entries 4 and 12 in

Scheme III

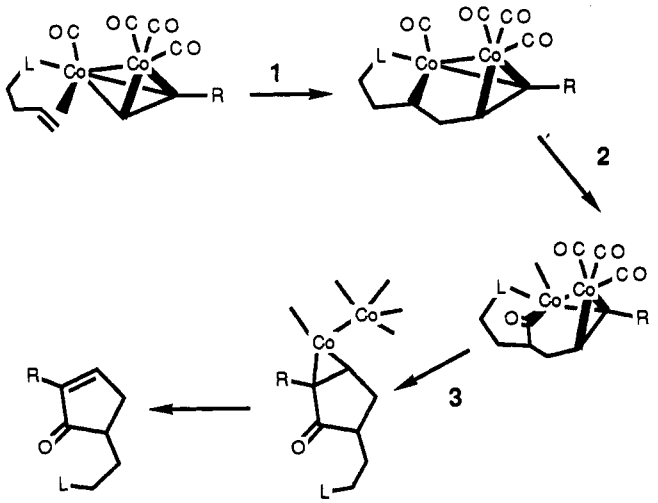
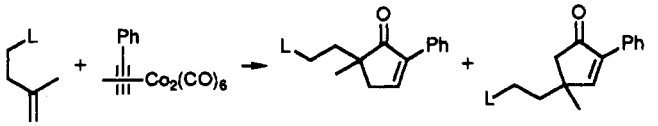
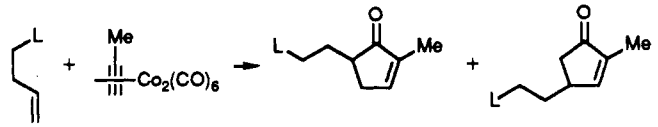


Table III



L	ratio of products	yield (%)
$N(Me)_2$	20:1	60
N(Me)Bu	20:1	40
$N(i\text{-}Pr)_2$		0

Table IV



L	ratio of products	yield (%)
S-Ph	3:1	65
S-(*p*-OMe)Ph	4:1	50
S-*i*-Pr	9:1	60
$S\text{-}C_6H_{13}$	20:1	65

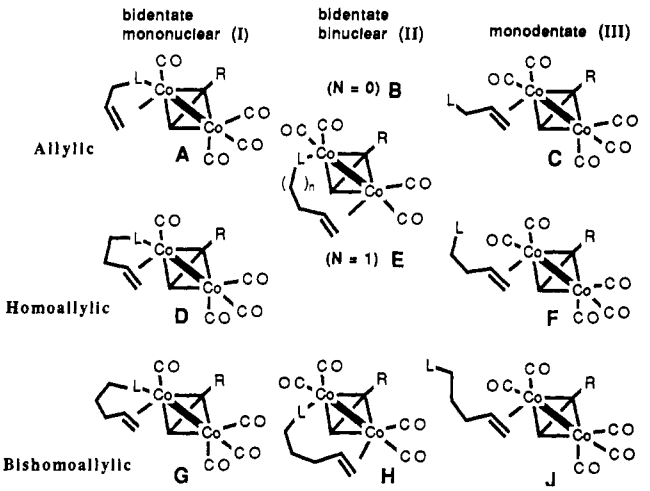
Table II). However, trisubstituted olefins reacted very sluggishly under our conditions and gave rise to only low yields of cyclopentenone adducts. Reaction of allyl methyl sulfide (entry 1) with cobalt complexes **16** (entry 1) or **14** resulted in the formation of regioisomeric cyclopentenones, in low yield, with very little regioselectivity. The analogous reactions of allyldimethylamine were even less successful, and only very minor amounts of cyclopentenones could be isolated. Thioacetals have also been shown to provide a high degree of regiocontrol during cycloaddition (entry 10).

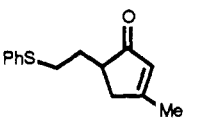
The effect of the steric bulk of the alkyl groups on both nitrogen and sulfur on the cycloaddition regioselectivity was examined. As illustrated in Table III, the steric bulk of the amine ligands seems to have had little effect on the reaction selectivity. While the regioselectivity remained high with straight-chain aliphatic ligands on nitrogen, a minor change in size from dimethylamino to methylbutylamino caused a significant decrease in the yield. Reactions with the branched diisopropylamino directing group were unsuccessful under a variety of reaction conditions.

With sulfides as the directing group, there appears to be a distinct correlation between steric bulk and reaction regiocontrol. These results are listed in Table IV. Very clearly, the straight-chain aliphatic ligands provided the best selectivity.

The observed regioselectivity was essentially the same when either complex **16** or (propyne)hexacarbonyldicobalt (**58**) was used in the cycloaddition. In the reactions with (propyne)hexacarbonyldicobalt, we isolated very small quantities (2–3%) of a regioisomer, for example, **59**, that resulted from initial carbon–

Scheme IV





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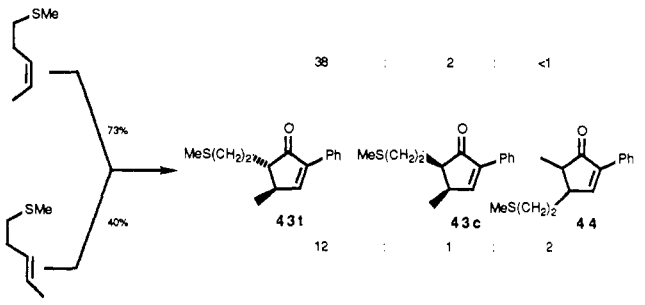
carbon formation taking place at the more substituted end of the alkyne. Small quantities of cyclopentenones with the "abnormal" acetylene regioselectivity have been observed in reactions of internal alkynes, for example, 2-pentyne, where the groups at the two ends of the alkyne are similar in size.[3]

In general, allylic and bishomoallylic substrates gave rise to poor ratios of regioisomeric cyclopentenones, while homoallylic substrates provided the highest ratios. These observations may be explained by reconsideration of the proposed mechanism[15] (Scheme I). Presumably, the regiochemical outcome of the cycloaddition is determined in step 1—the metallacycle-forming step. Thus, we consider the geometrical constraints in the initially formed olefin complex as a very important factor. With this in mind, we envision three different "modes of cycloaddition" or transition-state analogies (Scheme IV). These are (1) bidentate mononuclear (I), which involves the formation of a bidentate olefinic ligand complex with one of the cobalt atoms on the dicobalt acetylene complex, (2) bidentate binuclear (II), which involves the formation of a bidentate olefin ligand complex where the alkene is attached to one cobalt atom of the dicobalt acetylene complex and the directing ligand is attached to the other cobalt atom, and (3) monodentate (III), where the ligand does not exhibit any influence over the regiochemical outcome of the cycloaddition and only the alkene coordinates to the cobalt prior to metallacycle formation. It should be pointed out that the bidentate mononuclear mode of cycloaddition is expected to give the 2,5-disubstituted isomer, the bidentate binuclear mode is expected to yield the 2,4-disubstituted isomer, and the monodentate mode should yield both the 2,4- and 2,5-disubstituted isomers.

With allylic substrates, we believe that the tether between the ligand and the alkene is too short, and therefore, complexes A and B are unlikely to be formed prior to cycloaddition. Reactions of allylic substrates with cobalt alkyne complexes gave low ratios of regioisomeric cyclopentenones, and the monodentate mode of cycloaddition, complex C, is most likely to be the major contributor to the reaction outcome.

Homoallylic substrates gave rise to very good yields of 2,5-disubstituted cyclopentenones. Consequently, it is very likely that the bidentate mononuclear mode of cycloaddition, complex D, is the best mode for these substrates. The tether is apparently of the appropriate length to allow formation of a relatively stable bidentate complex prior to metallacycle formation. Since the results were good with the homoallylic substrates, the bidentate

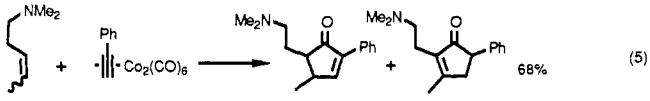
Scheme V



binuclear mode, complex E, is ruled out as a major contributor as it would give rise to the minor regioisomer. Also, molecular models tend to indicate that the tether is too short for mode II, complex E, to be operative. The monodentate mode of cycloaddition, complex F, is eliminated because the increased yields and selectivity suggest that the heteroatom plays an important role in determining the overall regiochemical outcome.

Bishomoallylic substrates, in general, exhibited only a very modest degree of control over the regiochemical outcome of the reaction. As a result, it is likely that both the bidentate mononuclear and bidentate binuclear modes, complexes G and H, respectively, are operative. While we cannot absolutely rule out the monodentate mode of cycloaddition, complex J, the cycloaddition yields with bishomoallylic substrates are higher than with simple olefins, thus supporting a heteroatom-assisted cycloaddition.

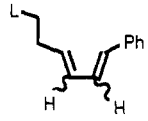
With the regiochemical outcome of the intermolecular cycloaddition under control, we turned our attention to the relationship between the olefin geometry of the homoallylic amine or sulfide and the stereochemistry of the newly formed cyclopentenone. Reaction of either methyl *cis*-3-pentenyl sulfide or methyl *trans*-3-pentenyl sulfide with complex **16** yielded the trans 2,3,5-trisubstituted cyclopentenone **43t** as the major product (Scheme V). While we cannot rule out the possibility of olefin isomerization prior to cycloaddition, we have demonstrated that epimerization can take place after formation of the cyclopentenone. Warming a toluene solution of a 4:1 mixture of **43t** and **43c** for 12 h in the presence of **16** gave rise to an 11:1 ratio of **43t** and **43c** in 95% yield. Longer reaction times, in general, increase the ratio of trans to cis isomers. Reactions of either of the analogous *cis*- or *trans*-3-pentenyldimethylamines with cobalt complex **16** led to formation of the desired cyclopentenones; however, isomerization of the initially formed trisubstituted olefin to the tetrasubstituted isomer was competitive (eq 5).[2]



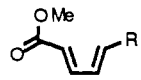
(5)

The reactions were carried out by warming the olefinic amine and the preformed[20] cobalt alkyne complex at 85 → 95 °C in toluene for 4–36 h (depending on the substrate). The cobalt alkyne complexes, in general, undergo some decomposition during prolonged reaction times, and as a result, it is necessary to add excess cobalt complex during the course of the reaction. Our attempts to perform the reactions using a catalytic amount of cobaltoctacarbonyl, under an atmosphere of carbon monoxide, were unsuccessful. The cycloadditions were cleanest when performed under an atmosphere of nitrogen.

When reaction temperatures >100–105 °C were used, dienes **60** were formed in varying amounts. Apparently, the higher reaction temperatures inhibit carbon monoxide insertion, and the presumed cobaltacyclic intermediate undergoes β-elimination followed by reductive elimination to yield the observed dienes. Pauson[21] has observed the formation of analogous dienes **61** from reactions of cobalt alkyne complexes with alkenes that are conjugated with electron-withdrawing groups.



60



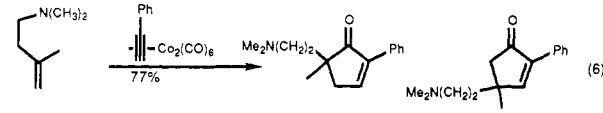
61

We investigated the effect of solvent on the outcome of the cycloaddition. Among those tried, dimethyl sulfoxide decomposed the cobalt complex very rapidly, reactions in dioxane and other ethereal solvents gave many unwanted side-products, and heptane, although giving satisfactory results, resulted in more rapid complex decomposition than toluene. For our examples, the aromatic solvents benzene and toluene gave the best results with a minimization of side products and complex decomposition.[22]

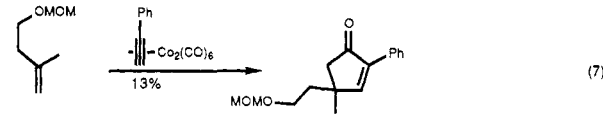
In an additional attempt to improve the efficacy of the cycloaddition, we carried out the reaction in the presence of several additives. In the presence of 2 equiv of trimethylamine *N*-oxide,[23,28] no change in the overall reaction was observed. Tributylphosphine oxide, which has been previously reported to facilitate the ene–yne cycloaddition,[3,14] and hexamethylphosphoramide both slowed the cycloaddition. Tributylphosphine (2 equiv/cobalt complex) completely quenched the desired reaction.

The use of silica gel as a reaction medium has been shown by Caple and Smit[13] to dramatically accelerate intermolecular and intramolecular processes. Our attempts to carry out the ligand-directed cycloaddition on silica gel, under an atmosphere of oxygen, were unsuccessful, and no cyclopentenone adducts were obtained. Under an atmosphere of nitrogen, the ligand-directed cycloaddition in the dry state proceeded, however, in lower yields than under the normal conditions in toluene and other side-products were also formed.

The power that the heteroatom ligand exerts over the reaction outcome is clearly illustrated by comparison of eqs 6 and 7. Under identical experimental conditions, only the ligand-directed reaction (eq 6) proceeded to completion.[24] Thus, the reaction rate appears

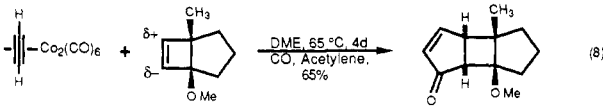


(6)



(7)

to be greatly enhanced by the formation of the bidentate olefin–heteroatom complex prior to cycloaddition. The regiochemical outcome of eq 6 is expected and consistent with the rest of the results described here. However, the regioselectivity observed in eq 7 is not so obvious but is consistent with other results obtained from reactions with 1,1-disubstituted alkenes.[3,13a,17,31] The regiochemical outcome shown for the reaction in eq 7 is supported by several isolated reports of regioselective intermolecular reactions[17] (for example, eq 8). An explanation incorporates both steric and electronic arguments.



(8)

(20) See ref 3. Another method for the formation of (alkyne)hexacarbonyldicobalt complexes was recently reported: Devesagayaraj, A.; Periasamy, M. *Tetrahedron Lett.* **1989**, *30*, 595. Iwashita, Y.; Tamura, F.; Nakamura, A. *Inorg. Chem.* **1969**, *8*, 1179. For a complete description of alkyne–cobalt complexes, see: *Comprehensive Organometallic Chemistry*; Wilkinson, G., Stone, F. G. A., Eds.; Pergamon Press: Oxford, 1982; Vol. 5.

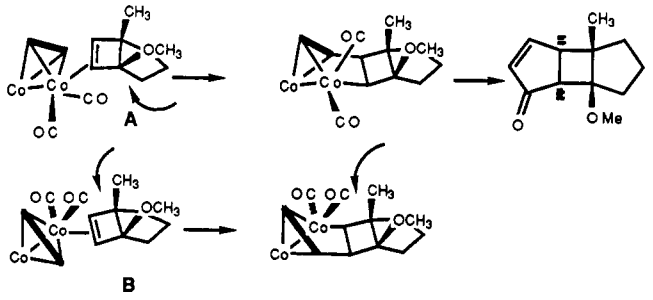
(21) Khand, I. U.; Pauson, P. L. *J. Chem. Soc., Chem. Commun.* **1974**, 379.

(22) Pauson also noted a difference in the reaction outcome when ether or hexane was substituted for benzene. See the first citation in ref 3.

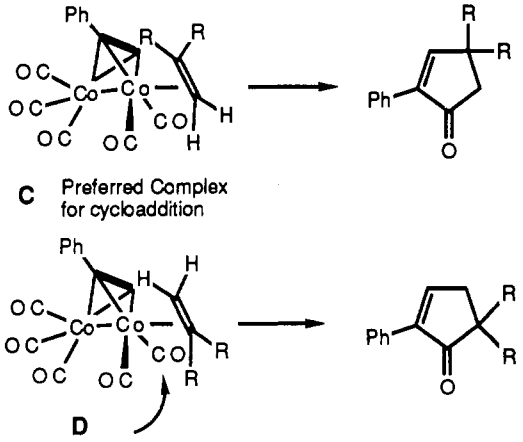
(23) Trimethylamine *N*-oxide is known to remove carbonyl ligands from transition-metal complexes. Shvo, Y.; Hazum, E. *J. Chem. Soc., Chem. Commun.* **1974**, 336.

(24) Pauson reported a similar regioselective reaction; see the first citation in ref 3.

Scheme VI



Scheme VII



With regard to the electronic bias over the cycloaddition, initial carbon–carbon bond formation occurs preferentially at the most electropositive terminus of the alkene.[17] The results of both of the reactions in eqs 7 and 8 are supported by this electronic argument.

A steric argument was used by Schore to explain the selectivity for the reaction shown in eq 8. The explanation is illustrated in Scheme VI. Steric interaction of groups in the allylic position (OCH_3, CH_3) with the carbonyl ligands on the cobalt center (arrows) disfavors B over A. Thus, cycloaddition occurs to put the cobalt, and ultimately the carbonyl in the cyclopentenone, opposite the large group in the allylic position. Olefinic cobalt complex A, which minimizes steric interactions with the carbon monoxide ligands on cobalt, gives rise to the observed product.

The result cited in eq 7 can also be explained by use of an analogous steric argument. As illustrated in Scheme VII, olefin complex C minimizes steric interactions between the carbonyl ligands on cobalt and the olefin substrate (as shown on complex D) and leads, via a lower energy transition state, to the observed product.

In summary, the use of a directing ligand in the Pauson–Khand cycloaddition contributes both to improvement in the yield of the reaction and to control over the regiochemical outcome of the cycloaddition, even to the extent of having to overcome both steric and electronic biases. Further studies on the diastereoselectivity and enantioselectivity of the reaction as well as its utility in natural product synthesis are in progress, and the results will be reported in due course.

Experimental Section

General Procedures. Tetrahydrofuran (THF) and diethyl ether (Et_2O) were distilled from potassium prior to each use. Methylene chloride (CH_2Cl_2) and pyridine were distilled from calcium hydride. Hexane, chloroform ($CHCl_3$), methanol (MeOH), and ethyl acetate (EtOAc) were distilled prior to use. Toluene was distilled from sodium metal prior to use. All reactions were performed under an atmosphere of nitrogen. Infrared spectra (IR) were obtained on either a Perkin-Elmer No. 1320 or a Perkin-Elmer No. 938 infrared spectrophotometer in $CHCl_3$ solutions. ^1H NMR spectra were obtained at 270 MHz on a Bruker W-P270SY instrument, at 300 MHz on a Varian Gemini spectrometer, or at 500 MHz on a Varian VXR500 spectrometer in $CDCl_3$ solutions unless otherwise noted. Carbon spectra were obtained at 75 MHz on a Varian Gemini 300 spectrometer in $CDCl_3$ solutions. Chemical shifts are reported in parts per million downfield relative to tetramethylsilane (δ 0.00); coupling constants are reported in hertz. The following abbreviations are used for the multiplicities: s, singlet; bs, broad singlet; d, doublet; t, triplet; q, quartet; m, multiplet. Low-resolution mass spectra were obtained on a Finnigan 4510 GC/MS instrument. High-resolution mass spectra were obtained on a AEI MS 902 instrument. Mass spectral data are reported as *m/e* (relative intensity). Chromatography refers to flash chromatography as reported by Still.[25] Melting points were taken on a Bristoline hot-stage microscope melting point apparatus or a Meltemp and are uncorrected. Elemental analyses were performed by Galbraith Laboratories, Knoxville, TN.

All of the cobalt alkyne complexes were prepared according to reported procedures.[3,26] Octacarbonyldicobalt obtained from Strem Chemical Co. gave the best results. The yields of the (alkyne)hexacarbonyldicobalt complexes were higher with newer bottles of octacarbonyldicobalt.

Preparation of [(Trimethylsilyl)acetylene]hexacarbonyldicobalt (34). To a solution of 4.0 g (11.7 mmol) of octacarbonyldicobalt in 80 mL of low-boiling petroleum ether at 0–5 °C was slowly added 1.65 mL (11.68 mmol) of (trimethylsilyl)acetylene. The resulting cranberry red solution was stirred for 2–3 h at ambient temperature, then filtered through a pad of Celite, and evaporated to yield a cranberry red oil (4.2 g, 94%) that solidified upon cooling.[28] Carbon monoxide is evolved during the reaction; therefore, the reaction should be performed in a fume hood.

The olefinic amines were prepared by displacement of the corresponding bromide or methanesulfonate ester[27] by a secondary amine.

Preparation of *N*-(3-methyl-3-butenyl)-*N*,*N*-dimethylamine. A solution of 4.9 g (30 mmol) of the methanesulfonate ester of 3-methyl-3-buten-1-ol in 4 mL of ether and 4 mL of anhydrous *N*,*N*-dimethylamine in a resealable tube was stirred for 28 h at room temperature. The resulting slurry was diluted with 30 mL of diethyl ether and washed with 3–4 mL of 15% aqueous potassium carbonate. The aqueous layer was then extracted six times with 8-mL portions of diethyl ether. All of the organic extracts were combined, dried over Na_2SO_4, and distilled at atmospheric pressure. The *N*-(3-methyl-3-butenyl)-*N*,*N*-dimethylamine codistilled with the ether; therefore, the ether distillate was redistilled once to improve the yield (74%, 2.51 g). 300-MHz ^1H NMR: δ 1.73 (s, 3 H, CCH_3), 2.18 (t, J = 7.5, 2 H, CCH_2), 2.23 (s, 6 H, $N(CH_3)_2$), 2.38 (t, J = 7.5, 2 H, CH_2N), 4.70 (apparent q, J = 1, 1 H, olefin), 4.74 (apparent q, J = 1, 1 H, olefin). 75-MHz ^{13}C NMR: δ 22.6, 36.2, 45.7, 58.3, 111.3, 144.7. Mass spectrum, *m/e* (EI): 113 (M^+), 97, 83, 58 (100), 49. Mass spectrum, exact mass for $C_7H_{15}N$: calcd *m/e* 113.1204, obsd *m/e* 113.1202.

All of the sulfides were prepared by displacement of the corresponding bromide or methanesulfonate ester[27] with a mercaptide by standard procedures.

Synthesis of 1-(Methylthio)-3-*trans*-pentene. A slurry of lithium methyl mercaptide (3.5 g, 63 mmol), prepared by the reaction of methanethiol and butyllithium in ether at −78 °C, 1-(mesyloxy)-3-*trans*-pentene (3.55 g, 21.6 mmol), and HMPA (1.0 mL) was warmed in refluxing ethyl ether for 48 h. The resulting mixture was diluted with 100 mL of ether, washed with saturated aqueous $NaHCO_3$, and dried over sodium sulfate. Due to the volatility of the sulfide, the ether was removed by short-path distillation at atmospheric pressure. After removal of the solvent, the sulfide was distilled under aspirator pressure (60–65 °C) to yield 2.03 g (80%) of 1-(methylthio)-3-*trans*-pentene. 300-MHz ^1H NMR: δ 1.65 (d, J = 5, 3 H, CH_3), 2.10 (s, 3 H, SCH_3), 2.26 (d, t, J = 6, 7.5, 2 H, CH_2 allylic), 2.51 (t, J = 7.5, 2 H, CH_2S), 5.43 (d, t, J = 15.2, 6, 1 H, olefin), 5.53 (d, q, J = 15.2, 5, 1 H, olefin). 75-MHz ^{13}C NMR: δ 14.9, 17.3, 31.8, 33.7, 126.3, 129.1. Mass spectrum, *m/e* (EI): 116 (M^+), 84, 61 (100). Mass spectrum exact mass for $C_{16}H_{12}S$: calcd *m/e* 116.0660, obsd *m/e* 116.0672.

Synthesis of 2-Phenyl-3-methyl-5-hexyl-2-cyclopentenone (20) and 2-Phenyl-3-methyl-4-hexyl-2-cyclopentenone (21). A solution of 380 mg (0.945 mmol) of cobalt complex **15** and 53 mg (0.473 mmol) of 1-octene in 3 mL of toluene was warmed to 100–105 °C. After 15 and 24 h, 200 mg of **15** was added. After 36 h, the red-brown solution was cooled to ambient temperature, diluted with 2 mL of EtOAc and 2 mL of hexane, and treated with ca. 0.5 mL of 1,2-ethylenediamine (added slowly due to carbon monoxide evolution). The resulting slurry was stirred for 10–15

(25) Still, W. C.; Kahn, M.; Mitra, A. *J. Org. Chem.* **1978**, *43*, 2923.
(26) Dickson, R. S.; Kirsch, H. P. *Aust. J. Chem.* **1972**, *25*, 1815. Dickson, R. S.; Fraser, P. J. *Adv. Organomet. Chem.* **1974**, *12*, 323.
(27) Crossland, R. K.; Servis, K. L. *J. Org. Chem.* **1970**, *35*, 3195.
(28) Palyi, G.; Varadi, G.; Vizi-Orosz, A.; Marko, L. *J. Organomet. Chem.* **1975**, *90*, 85.
(29) Billington, D. C.; Helps, I. M.; Pauson, P. L.; Thomson, W.; Willison, D. *J. Organomet. Chem.* **1988**, *354*, 233.

min at room temperature and filtered through a plug of silica gel with 25% EtOAc in hexane. Removal of the solvent under reduced pressure yielded a red oil that was chromatographed on silica gel with 10% EtOAc/hexane. Evaporation of the solvent yielded 33 mg (27%) of enone **20**.

20. 300-MHz ^{1}H NMR ($CDCl_3$): δ 0.81 (t, J = 6.5, 3 H, CH_2CH_3), 1.26–1.34 (vbs, 8 H, $(CH_2)_4CH_3$), 1.86 (m, 2 H, 5-CH_2), 2.17 (s, 3 H, 3-CH_3), 2.33 (d, d, d, J = 20, 1, 1, 1 H, 4-H), 2.47 (m, 1 H, 5-H), 2.82 (d, d, d, J = 1, 6.5, 19, 1 H, 4′-H), 7.26–7.50 (m, 5 H, arom). IR ($CHCl_3$) (cm^{-1}): 1140, 1695, 2940. Mass spectrum, m/e (EI): 256 (M^+), 185, 172 (100), 115. 75-MHz ^{13}C NMR: δ 14.2, 18.4, 22.8, 26.3, 27.5, 29.5, 32.0, 39.2, 45.9, 128.1, 128.8, 129.1, 129.7, 140.2, 170.9, 210.0.

21. 270-MHz ^{1}H NMR: δ 0.86 (t, J = 6.5, 3 H, CH_2CH_3), 1.14–1.5 (m, 9 H, $CH(CH_2)_4CH_3$), 1.85 (m, 1 H, 6′-H), 2.13 (s, 3 H, 3-CH_3), 2.25 (d, J = 18, 1 H, 5-H), 2.68 (d, d, J = 18, 6, 1 H, 5′-H), 2.78 (bs, 1 H, 4-H), 7.28–7.45 (m, 5 H, arom). IR ($CHCl_3$) (cm^{-1}): 1145, 1690, 2940. Mass spectrum, m/e (EI): 256 (M^+), 185, 171 (100), 143, 128. Mass spectrum, exact mass for $C_{18}H_{24}O$: calcd m/e 256.1827, obsd m/e 256.1855.

Synthesis of 2-Phenyl-5-cyclohexyl-2-cyclopentenone (22) and 2-Phenyl-4-cyclohexyl-2-cyclopentenone (23). A solution of 190 mg (1.73 mmol) of vinylcyclohexane and 804 mg (2.07 mmol) of complex **16** in 11 mL of toluene was stirred at 98 °C. After 20 h, an additional 600 mg (1.54 mmol) of cobalt complex **16** was added. After 48 h at 98 °C, the reaction mixture was cooled, diluted with EtOAc and hexane (5 mL each), and carefully treated with 2 mL of 1,2-ethylenediamine. Filtration through a plug of silica gel with 25% EtOAc in hexane followed by evaporation of the solvent yielded a red oil. Chromatography on silica gel (8% EtOAc/hexane) gave a 2.5:1 mixture of enones **22** and **23** (47%, 195 mg) as a pale oil. Chromatography of this mixture on silica gel gave the two separate enone isomers.

22. Mp 57.5–59.5 °C. 300-MHz ^{1}H NMR: δ 1.0–1.38 (m, 5 H, cyclohexyl), 1.45 (d, d, d, d, d, J = 12, 6, 4, 2, 2, 1 H, cyclohexyl), 1.62–1.78 (m, 4 H, cyclohexyl), 2.0 (d, d, d, d, d, J = 12, 12, 4, 4, 4, 1 H, cyclohexyl CH), 2.5 (d, d, d, J = 20, 3, 3, 1 H, 4-H), 2.52 (d, d, d, J = 3, 4, 7, 1 H, 5-H), 2.71 (d, d, d, J = 3, 7, 20, 1 H, 4′-H), 7.3–7.41 (m, 3 H, arom), 7.68–7.92 (m, 2 H, arom), 7.8 (t, J = 3, 1 H, 3-H). IR (cm^{-1}): 1140, 1695, 2940. 75-MHz ^{13}C NMR: δ 25.9, 26.1, 26.3, 27.2, 29.4, 30.8, 39.2, 51.8, 127.2, 128.4, 128.5, 131.9, 143.8, 158.3, 210.0. Mass spectrum m/e (EI): 240 (M^+), 158 (100), 115. Anal. Calcd for $C_{17}H_{20}O$: C, 84.96; H, 8.39. Found: C, 84.59; H, 8.20.

23. 300-MHz ^{1}H NMR: δ 1.0–1.32 (m, 5 H, cyclohexyl), 1.47 (d, d, d, d, d, J = 11, 11, 7, 3, 3, 1 H, cyclohexyl CH), 1.66–1.85 (m, 5 H, cyclohexyl), 2.35 (d, d, J = 2.5, 19, 1 H, 5-H), 2.65 (d, d, J = 7, 19, 1 H, 5′-H), 2.78 (d, d, d, d, J = 2.5, 2.5, 7, 7, 1 H, 4-H), 7.29–7.41 (m, 3 H, arom), 7.68–7.71 (m, 2 H, arom), 7.8 (d, J = 2.5, 1 H, 3-H). IR (cm^{-1}): 1140, 1695, 2935. Mass spectrum m/e (EI): 240 (M^+), 158 (100), 128, 83. 75-MHz ^{13}C NMR: δ 26.0, 26.2, 30.5, 30.6, 40.3, 41.9, 44.1, 127.3, 128.5, 128.6, 131.8, 143.3, 161.8, 207.6.

Synthesis of 2-Phenyl-3-methyl-5-cyclohexyl-2-cyclopentenone (24). A solution of 300 mg (2.73 mmol) of vinylcyclohexane and 1.3 g (3.25 mmol) of cobalt complex **15** in 18 mL of toluene was stirred for 48 h at 105 °C. After 36 h, 1.0 g of **15** was added. Upon completion, the resulting brown-red slurry was diluted with 5 mL of EtOAc and 5 mL of hexane, followed by the careful addition of 1.5 mL of 1,2-ethylenediamine. Vacuum filtration through a plug of silica gel gave a red oil that was chromatographed (7% EtOAc/hexane) to yield 152 mg (22%) of **24** as an oil. 300-MHz ^{1}H NMR ($CDCl_3$): δ 0.98–1.37 (m, 5 H, cyclohexyl), 1.46 (d, d, d, d, d, J = 12, 7, 6, 2, 2, 1 H, cyclohexyl), 1.63–1.77 (bm, 4 H, cyclohexyl), 1.98 (d, d, d, d, d, J = 12, 12, 3.3, 3.3, 3.3, 1 H, cyclohexyl CH), 2.17 (s, 3 H, 3-CH_3), 2.45 (d, d, d, J = 20, 2.5, 1, 1 H, 4-H), 2.48 (d, d, d, J = 7.5, 2.5, 3.3, 1 H, 5-H), 2.65 (d, d, bd, J = 20, 7.5, 1, 1 H, 4′-H), 7.25–7.42 (m, 5 H, arom). 75-MHz ^{13}C NMR: δ 18.4, 26.3, 26.6, 26.8, 27.6, 31.4, 35.5, 39.6, 51.2, 111.9, 128.1, 128.8, 129.7, 132.5, 141.1, 171.4, 210.3. Mass spectrum m/e (EI): 256 (M^+) (100), 224, 136, 119. IR ($CHCl_3$) (cm^{-1}): 1140, 1685, 2935. Anal. Calcd for $C_{18}H_{22}O$: C, 84.99; H, 8.71. Found: C, 84.58; H, 8.69.

Synthesis of 2,3-Dimethyl-5-cyclohexyl-2-cyclopentenone (25). A solution of 225 mg (2.04 mmol) of vinylcyclohexane and 834 mg of complex **17** (2.45 mmol) in 13 mL of toluene was warmed to 100 °C. Additional cobalt complex **17** (340 mg, 1.0 mmol) was added after 12 and 24 h. After 36 h at 100 °C, the resulting slurry was cooled, diluted with EtOAc and hexane, carefully treated with 1 mL of 1,2-ethylenediamine, and stirred for 10 min at ambient temperature. Filtration through a plug of silica gel (25% EtOAc/hexane), removal of solvent, and flash chromatography (11% EtOAc/hexane) yielded 90 mg (23%) of enone **25** as a pale yellow oil. 300-MHz ^{1}H NMR: δ 0.96 (d, d, d, J = 2.5, 8, 8, 1 H, cyclohexyl), 1.02–1.34 (m, 5 H, cyclohexyl), 1.64 (s, 3 H, 2-CH_3), 1.6–1.74 (m, 4 H, cyclohexyl), 1.86 (d, d, d, d, d, J = 11.5, 11.5, 3.5, 3.5, 3.5, 1 H, cyclohexyl CH), 2.0 (s, 3 H, 3-CH_3), 2.26 (bd, J = 19, 1 H, 4-H), 2.29 (d, d, d, J = 1, 3.5, 8, 1 H, 5-H), 2.46 (d, d, m, J = 8, 19, 1 H, 4′-H). IR (cm^{-1}): 1140, 1690, 2940. 75-MHz ^{13}C NMR: δ 7.5, 16.8, 25.9, 26.1, 26.3, 27.1, 31.0, 34.7, 38.8, 50.3, 136.6, 169.1, 212.1. Mass spectrum m/e (EI): 192 (M^+), 110, 95. Mass spectrum, exact mass for $C_{13}H_{20}O$: calcd m/e 192.1514, obsd m/e 192.1494. Anal. Calcd for $C_{13}H_{20}O$: C, 81.19; H, 10.48. Found: C, 80.85; H, 10.32.

Synthesis of 2,3-Dimethyl-5-[2-(methoxymethoxy)ethyl]-2-cyclopentenone (28). A solution of 570 mg (1.6 mmol) of complex **17** and 111 mg (0.96 mmol) of the methoxymethyl ether of 3-butenol in 7 mL of toluene was warmed to 95 °C. Complex **17** (340 mg, 1 mmol) was added after 24 h. Stirring was continued for an additional 12 h at 95 °C. The resulting red-brown mixture was cooled to room temperature, diluted with ethyl acetate and hexane (5 mL each), and slowly treated with ca. 1 mL of 1,2-ethylenediamine. Filtration through a plug of silica gel (85% EtOAc/hexane), followed by solvent removal and flash chromatography (60% EtOAc/hexane) yielded 51 mg of enone **28** as a pale yellow oil (26%). 300-MHz ^{1}NMR: δ 1.54 (d, d, d, d, J = 14, 10, 6.5, 6.5, 1 H, OCH_2CH_2), 1.67 (s, 3 H, 2-CH_3), 2.01 (s, 3 H, 3-CH_3), 2.12 (d, d, d, d, J = 14, 4.4, 6.5, 6.5, 1 H, OCH_2CH_2), 2.24 (d, q, m, J = 14, 1, <1, 1 H, 4-H), 2.43 (d, d, d, d, J = 10, 4, 4.4, 1, 1 H, 5-H), 2.71 (d, d, q, J = 14, 4, 1, 1 H, 4′-H), 3.34 (s, 3 H, CH_3O), 3.61 (ab, d, d, J_{ab} = 10, J = 6.5, 6.5, 1 H, OCH_2CH_2, 3.63 (ab, d, d, J_{ab} = 10, J = 6.5, 6.5, 1 H, OCH_2CH_2), 4.60 (s, 2 H, OCH_2O). IR (cm^{-1}): 1040, 1110, 1150, 1645, 1690, 2950. 75-MHz ^{13}C NMR: δ 8.1, 17.2, 31.9, 39.1, 42.7, 55.5, 66.4, 96.8, 136.0, 169.1, 212. Mass spectrum m/e (EI): 198 (M^+), 110, 95, 45. Mass spectrum, exact mass for $C_{11}H_{18}O_3$: calcd m/e 198.1256, obsd m/e 198.1227.

Synthesis of 2-Phenyl-3-methyl-5-[2-(methoxymethoxy)ethyl]-2-cyclopentenone (30). A solution of 261 mg (0.465 mmol) of cobalt complex **15** and 63 mg (0.543 mmol) of the methoxymethyl ether of 3-butenol in 3.5 mL of toluene was warmed to 104 → 106 °C. Complex **15** (300 mg, 0.75 mmol) was added after 24 h. Stirring was continued for an additional 24 h at 105 °C. The resulting red-brown mixture was cooled to room temperature, diluted with ethyl acetate and hexane (5 mL each), and carefully treated with ca. 1 mL of 1,2-ethylenediamine. Filtration through a plug of silica gel (60% EtOAc/hexane) followed by solvent removal and flash chromatography (40% EtOAc/hexane) yielded 58 mg of enone **30** (41%) as a pale yellow oil. 300-MHz ^{1}H NMR: δ 1.68 (d, d, d, d, J = 14, 9, 6.5, 6.5, 1 H, 6-H), 2.17 (s, 3 H, 3-CH_3), 2.22 (d, d, d, d, J = 14, 6.5, 6.5, 5, 1 H, 6′-H), 2.43 (d, d, d, J = 18, 3, 1, 1 H, 4-H), 2.63 (d, d, d, d, J = 9, 7, 5, 3, 1 H, 5-H), 2.87 (d, d, d, J = 18, 7, 1, 1 H, 4′-H), 3.36 (s, 3 H, OCH_3), 3.68 (ab, d, d, J_{ab} = 10, J = 6.5, 6.5, 1 H, OCH_2CH_2), 3.71 (ab, d, d, J_{ab} = 10, J = 6.5, 6.5, 1 H, OCH_2CH_2), 4.63 (s, 2 H, OCH_2O). 75-MHz ^{13}C NMR: δ 18.4, 31.9, 39.3, 43.3, 55.5, 66.4, 96.9, 128.2, 128.8, 129.7, 132.4, 140.0, 170.9, 209.8. IR (cm^{-1}): 1040, 1110, 1150, 1640, 1690, 2950. Mass spectrum m/e (EI): 260.1 (M^+), 228, 198, 172, 129. Mass spectrum, exact mass for $C_{16}H_{20}O_3$, calcd m/e 260.1412, obsd m/e 260.1414.

Synthesis of 2-Phenyl-5-[(methylthio)methyl]-2-cyclopentenone (35) and 2-Phenyl-4-[(methylthio)methyl]-2-cyclopentenone (36). A solution of 184 mg (2.09 mmol) of allyl methyl sulfide and 973 mg of complex **16** (2.5 mmol) in 14 mL of toluene was warmed to 95 °C. Additional cobalt complex **16** (776 mg, 2.0 mmol) was added after 12 h. After 24 h at 95 °C, the resulting slurry was cooled, diluted with EtOAc/hexane (5 mL each), carefully treated with 1 mL of ethylenediamine, and stirred for 10 min at ambient temperature. Filtration through a plug of silica gel (25% EtOAc/hexane), removal of the solvent, and flash chromatography (10% EtOAc/hexane) yielded 83 mg (18%) of enone **35** and 48 mg (11%) of enone **36**.

35. Mp = 55–57.5 °C. 300-MHz ^{1}H NMR: δ 2.14 (s, 3 H, CH_3S), 2.65 (d, d, d, J = 19, 3, 2.7, 1 H, 4-H), 2.66 (d, d, J = 13, 9, 1 H, SCH_2), 2.82 (d, d, d, d, J = 9, 6.5, 4.0, 2.7, 1 H, 5-H), 2.95 (d, d, d, J = 19, 6.5, 2.7, 1 H, 4′-H), 3.07 (d, d, J = 13, 4, 1 H, CH_2S), 7.33–7.42 (m, 3 H, arom), 7.5 (d, d, J = 9, 1, 2 H, arom), 7.85 (t, J = 2.7, 1 H, 3-H). IR (cm^{-1}): 1130, 1300, 1690, 2925. Anal. Calcd for $C_{13}H_{14}OS$: C, 71.52; H, 6.46. Found: C, 71.47; H, 6.43.

36. 270-MHz ^{1}H NMR: δ 2.16 (s, 3 H, SCH_3), 2.42 (d, d, J = 18, 2.5, 1 H, 5-H), 2.72 (d, J = 7, 2 H, SCH_2), 2.8 (d, d, J = 6, 18, 1 H, 5′-H), 3.2 (t, d, d, d, J = 7, 6, 2.5, 2.5, 1 H, 4-H), 7.3–7.45 (m, 3 H, arom), 7.72 (d, d, J = 8, 1.5, 2 H, arom), 7.78 (d, J = 2.5, 1 H, 3-H). IR (cm^{-1}): 1135, 1300, 1590, 2940.

Synthesis of 2-*n*-Butyl-5-[2-(methylthio)ethyl]-2-cyclopentenone (37). A solution of 890 mg (2.4 mmol) of cobalt complex **14** and 112 mg (1.1 mmol) of 3-butenyl methyl sulfide in 7.3 mL of toluene was warmed to 89 °C for 36 h. After 20 h, 200 mg (0.5 mmol) of additional **14** was added. Upon cooling, 1 mL of ethylenediamine was added, and the resulting slurry was filtered through a plug of silica gel with 25% EtOAc/hexane. Removal of the solvent yielded an oil that was chromatographed with 10% EtOAc/hexane. Enone **37** was obtained as a col-

orless oil (60%, 139 mg). 300-MHz ^{1}H NMR: δ 0.89 (t, J = 7.2, 3 H, $CH_3(CH_2)_3$), 1.32 (d, d, q, J = 7.2, 7.2, 7.2, 2 H, $CH_3CH_2(CH_2)_2$), 1.37–1.49 (m, 2 H, $CH_3CH_2CH_2CH_2$), 1.59 (d, d, d, d, J = 14, 9.2, 8.2, 6, 1 H, $CHCH_2$), 2.07 (d, d, d, d, J = 14, 8.8, 9.5, 2.2, 1 H, $CHCH_2$), 2.15 (d, t, J = 9, 1.6, 2 H, $CH_2(CH_2)_2CH_3$), 2.21 (d, d, d, J = 18.3, 4.5, 2.2, 1 H, 4-H), 2.5 (d, d, d, d, J = 9.2, 6.5, 5, 2.2, 1 H, 5-H), 2.57 (ab, d, d, J = 19, 9.5, 8.2, 1 H, CH_2S), 2.60 (ab, d, d, J = 19, 8.8, 6.0, 1 H, CH_2S), 2.77 (d, d, d, t, J = 18.3, 6.6, 3.0, 1.6, 1 H, 4′-H), 7.24 (d, d, t, J = 3.0, 2.2, 1.6, 1 H, 3-H). 75-MHz ^{13}C NMR: δ 14.0, 15.4, 22.6, 24.7, 30.0, 31.1, 32.1, 33.6, 44.6, 146.5, 156.2, 212.0. IR (cm^{-1}): 2915, 1680, 1440. Mass spectrum, m/e (EI): 212 (M^+), 151, 138, 109, 95. Mass spectrum, exact mass for $C_{12}H_{20}OS$: calcd m/e 212.1235, obsd m/e 212.1228.

Synthesis of 2-Phenyl-5-[2-(methylthio)ethyl]-2-cyclopentenone (39). A solution of 380 mg of cobalt complex **14** (1.0 mmol) and 40 mg (0.39 mmol) of 3-butenyl methyl sulfide in 2.5 mL of toluene was warmed to 91 °C. Additional cobalt alkyne complex **14** (150 mg, 0.4 mmol) was added after 12 h. After 26 h, the red solution was cooled, diluted with ethyl acetate and hexane (5 mL each), carefully treated with ca. 1 mL of ethylenediamine, and stirred for 10 min. Filtration through a plug of silica gel with 40% EtOAc in hexane, evaporation of the solvent, and flash chromatography (18% EtOAc/hexane) yielded 55 mg of enone **39** (58%) and 2 mg of enone **40** (3%) as oils.

39. 300-MHz ^{1}H NMR: δ 1.73 (d, d, d, d, J = 13.6, 8.6, 7.2, 4.5, 1 H, $CHCH_2CH_2S$), 2.13 (s, 3 H, SCH_3), 2.21 (d, d, d, d, J = 13.6, 9.5, 8.2, 6, 1 H, $CHCH_2CH_2S$), 2.39 (d, d, d, J = 19, 3, 2.8, 1 H, 4-H), 2.65 (ab, d, d, J = 13.6, 6, 8.2, 1 H, SCH_2), 2.66 (ab, d, d, J = 13.6, 7.2, 8.6, 1 H, SCH_2), 2.72 (d, d, d, d, J = 9.5, 4.5, 7.0, 2.8, 1 H, 5-H), 2.94 (d, d, d, J = 19, 7, 3, 1 H, 4-H), 7.3-7.41 (m, 3 H, arom), 7.68 (d, d, J = 2.2, 3.7, 1 H, arom), 7.7 (d, d, J = 2.2, 2.2, 1 H, arom), 7.79 (d, d, J = 3, 3, 1 H, 3-H). IR (cm^{-1}): 3020, 2920, 2860, 1700, 1140. 75-MHz ^{13}C NMR: δ 15.5, 31.1, 32.2, 33.4, 45.8, 127.6, 129.0, 132.2, 143.4, 157.8, 209.7. Anal. Calcd for $C_{14}H_{16}OS$: C, 72.37; H, 6.94. Found: C, 72.14; H, 7.10. Mass spectrum m/e (EI): 232 (M^+), 171, 158, 128, 115.

Synthesis of 2-Butyl-5-methyl-5-[2-(dimethylamino)ethyl]-2-cyclopentenone (41). A solution of 36 mg (0.318 mmol) of *N*-(3-methyl-3-butenyl)-*N*,*N*-dimethylamine and 234 mg (0.63 mmol) of carbonyl complex **14** in 2 mL of toluene was warmed to 92 °C. After 8 h, 234 mg (0.63 mmol) of cobalt complex **14** was added. The red solution was stirred for 24 h at 92 °C, cooled, diluted with ethyl acetate, and extracted twice with a solution of 10% HCl. The aqueous extracts were neutralized with a solution of 10% NaOH and partitioned into hexane/ethyl acetate. Removal of the solvent, after drying over anhydrous sodium sulfate, yielded 45 mg (62%) of enone **41** as a pale yellow oil. Filtration through a plug of silica gel (10% (10% NH_4OH/MeOH)/$CHCl_3$) yielded **41** as a colorless oil (43 mg, 60%). 500-MHz ^{1}H NMR ($CDCl_3$): δ 0.89 (t, J = 7.3, 3 H, CH_3CH_2), 1.06 (s, 3 H, 5-CH_3), 1.31 (t, q, J = 7.3, 7.3, 2 H, $CH_3CH_2CH_2$), 1.44 (m, 2 H, $CH_3CH_2CH_2CH_2$), 1.58 (d, d, d, J = 10.5, 6.0, 4.5, 1 H, CH_2CH_2N), 1.67 (d, d, d, J = 13.3, 10.5, 5.5, 1 H, CH_2CH_2N), 2.06 (d, d, d, J = 9.5, 9.0, 5.5, 1 H, NCH_2), 2.14 (1 H, NCH_2, obscured), 2.15 (2 H, $CH_2CH_2CH_2CH_3$, obscured), 2.15 (s, 6 H, $N(CH_3)_2$), 2.29 (d, d, d, d, J = 18.8, 2.3, 2.2, 2.2, 1 H, 4-H), 2.54 (d, d, d, d, J = 18.8, 2.3, 2.2, 2.2, 1 H, 4′-H), 7.15 (d, d, d, d, J = 2.3, 2.3, 1.3, 1.3, 1 H, 3-H). 500-MHz ^{1}H NMR (C_6D_6): δ 0.82 (t, J = 7.3, 3 H, CH_2CH_3), 0.98 (s, 3 H, 5-CH_3), 1.20 (d, q, J = 7.3, 7.3, 2 H, $CH_3CH_2CH_2$), 1.39 (m, 2 H, $CH_3CH_2CH_2CH_2$), 1.52 (d, d, d, J = 13.8, 7.3, 6.4, 1 H, CH_2CH_2N), 1.79 (d, d, d, J = 13.8, 7.7, partly obscured, 1 H, CH_2CH_2N), 1.81 (d, d, d, d, J = 18.8, 1.9, 1.8, 1.8, 1 H, 4-H), 1.98 (s, 6 H, $N(CH_3)_2$), 2.05 (d, d, J = 7.3, 7.3, 1 H, CH_2N), 2.05 (d, d, J = 6.4, 6.4, 1 H, CH_2N), 2.17, (m, 2 H, $CH_2CH_2CH_2CH_3$), 2.23 (d, d, d, d, J = 18.8, 1.9, 1.8, 1.8, 1 H, 4′-H), 6.56 (d, d, d, d, J = 2.7, 1.9, 1.4, 1.4, 1 H, 3-H). 75-MHz ^{13}C NMR: δ 13.5, 22.1, 23.8, 24.4, 29.5, 35.5, 40.6, 45.2, 45.4, 55.0, 144.9, 154.4, 213.7. IR (cm^{-1}): 2950, 1690, 1465, 1100, 1010. Mass spectrum m/e (EI): 223 (M^+), 110, 72, 58. Mass spectrum, exact mass for $C_{14}H_{25}NO$: calcd m/e 223.1936, obsd m/e 223.1962.

Synthesis of 2-Phenyl-4-methyl-5-[2-(methylthio)ethyl]-2-cyclopentenone (43) and 2-Phenyl-5-methyl-4-[2-(methylthio)ethyl]-2-cyclopentenone (44). A solution of 40 mg (0.35 mmol) of *cis*-3-pentenyl methyl sulfide and 295 mg (0.76 mmol) of cobalt complex **16** was warmed to 91 °C in 2.3 mL of toluene for 36 h. After 12 h, 295 mg (0.76 mmol) of **16** was added. Upon completion, the red-brown solution was cooled, diluted with 5 mL of EtOAc and 5 mL of hexane, carefully treated with 0.5 mL of ethylenediamine, and filtered through a plug of silica gel using 25% EtOAc in hexane. Removal of the solvent yielded a red oil that was chromatographed with 10% EtOAc in hexane to yield 62 mg of 2-phenyl-4-methyl-5-[2-(methylthio)ethyl]-2-cyclopentenone (**43**) (72%) and 2-phenyl-5-methyl-4-[2-(methylthio)ethyl]-2-cyclopentenone (**44**) (2%) as colorless oils.

43t. 300-MHz ^{1}H NMR ($CDCl_3$): δ 1.31 (d, J = 7.2, 3 H, 4-CH_3), 1.79 (d, d, d, d, J = 14.2, 8.3, 8.3, 6.1, 1 H, CH_2CH), 2.13 (s, 3 H, SCH_3), 2.17 (d, d, d, d, J = 14.2, 8.2, 7.2, 5.0, 1 H, CH_2CH), 2.28 (d, d, d, J = 8.3, 5.0, 2.8, 1 H, 5-H), 2.61–2.73 (m, 3 H, CH_2S, 4-H), 7.3–7.41 (m, 3 H, arom), 7.64 (d, J = 2.7, 1 H, 3-H), 7.7 (d, d, d, J = 7.1, 1.7, 1.7, 2 H, arom). 300-MHz ^{1}H NMR (C_6D_6): δ 0.84 (d, J = 7.1, 4-CH_3), 1.57 (d, d, d, d, J = 13.7, 8.4, 8.3, 6.2, 1 H, CH_2CH), 1.84 (s, 3 H, SCH_3), 2.0–2.07 (m, 2 H, 4-H, 5-H), 2.13 (d, d, d, d, J = 13.7, 8.4, 6.6, 5.4, 1 H, CH_2CH), 2.40 (ab, d, d, J = 13.0, 8.3, 6.6, 1 H, SCH_2), 2.48 (ab, d, d, J = 13.0, 8.4, 6.2, 1 H, SCH_2), 7.06 (d, J = 2.2, 1 H, 3-H), 7.15–7.29 (m, 3 H, arom), 7.93 (d, d, d, J = 7.1, 1.6, 1.6, 2 H, arom). A combination of shift reagents and NOE experiments verified the trans stereochemistry at C-4 and C-5. Irradiation of C-5-H produced an enhancement of the C4 methyl. 75-MHz ^{13}C NMR: δ 15.5, 20.0, 30.4, 32.2, 40.2, 54.2, 127.7, 129.0, 129.0, 132.0, 142.1, 162.7, 209.4. IR (cm^{-1}): 2985, 2930, 2900, 1695, 1450, 1300, 1130. Mass spectrum m/e (EI): 246 (M^+), 198, 185, 172, 129. Anal. Calcd for $C_{15}H_{18}OS$: C, 73.13; H, 7.36. Found: C, 73.34; H, 7.61.

44. 270-MHz ^{1}H NMR: δ 1.28 (d, J = 7.5, 3 H, 5-CH_3), 1.86 (ab, d, d, J = 14, 7, 7, 1 H, $CHCH_2$), 1.93 (ab, d, d, J = 14, 7, 7, 1 H, $CHCH_2$), 2.13 (s, 3 H, SCH_3), 2.2 (d, q, J = 7.5, 3, 1 H, 5-H), 2.67 (t, m, J = 7.5, 3 H, CH_2S and 4-H), 7.3–7.4 (m, 3 H, arom), 7.67–7.71 (m, 3 H, olefin and arom). Mass spectrum m/e (EI): 246 (M^+), 198, 169, 155, 128, 84.

Synthesis of 2-(Trimethylsilyl)-4-methyl-5-[2-(methylthio)ethyl]-2-cyclopentenone (45t). A solution of 40 mg (0.35 mmol) of *trans*-3-pentenyl methyl sulfide and 290 mg (0.75 mmol) of complex **34** in 2.3 mL of toluene was warmed to 93 °C for 36 h. After 24 h, 140 mg (0.36 mmol) of **34** was added. After being cooled to ambient temperature, the resulting red-brown slurry was diluted with 6 mL of a 1:1 mixture of EtOAc/hexane, treated slowly with 0.5 mL of ethylenediamine, stirred for 10 min, and filtered through a pad of silica gel. Removal of the solvent yielded a red oil that was chromatographed (7% EtOAc/hexane) to yield 51 mg (65%) of enone **45t** as a colorless oil. 300-MHz ^{1}H NMR ($CDCl_3$): δ 0.16 (s, 9 H, $Si(CH_3)$), 1.21 (d, J = 7.7, 3 H, 4-CH_3), 1.65 (d, d, d, d, J = 14.5, 12.7, 7.2, 3.2, 1 H, SCH_2CH_2), 1.99–2.11 (m, 2 H, 5-H, SCH_2CH_2), 2.13 (s, 3 H, SCH_3), 2.56–2.67 (m, 3 H, 4-H, CH_2S), 7.55 (d, J = 2.2, 1 H, 3-H). 300-MHz ^{1}H NMR (C_6D_6): δ 0.29 (s, 9 H, $Si(CH_3)$), 0.85 (d, J = 7.7, 3 H, 4-CH_3), 1.55 (d, d, d, d, J = 13.7, 8.8, 8.8, 6, 1 H, SCH_2CH_2), 1.82 (s, 3 H, SCH_3), 1.91 (d, d, d, J = 8.8, 5.5, 3.3, 1 H, 5-H), 2.05–2.18 (m, 2 H, 4-H, SCH_2CH_2), 2.40 (ab, d, d, J = 13, 8.8, 6.6, 1 H, SCH_2), 2.48 (ab, d, d, J = 13, 8.8, 6.0, 1 H, SCH_2), 7.17 (d, J = 2.2, 1 H, olefin). A combination of shift reagents, decoupling, and NOE experiments was used to verify the trans stereochemistry at C-4 and C-5. Irradiation of C-4 methyl produced an enhancement of the C-5 hydrogen. Mass spectrum m/e (EI): 242 (M^+), 181, 165, 152, 124. 75-MHz ^{13}C NMR: δ 2.1, 14.9, 19.3, 29.7, 31.9, 43.8, 53.3, 145.4, 175.7, 214.8. Anal. Calcd for $C_{12}H_{22}OSSi$: C, 59.45; H, 9.15. Found: C, 59.59; H, 9.18.

Preparation of 2-Butyl-5-[3-(methylthio)propyl]-2-cyclopentenone (51) and 2-Butyl-4-[3-(methylthio)propyl]-2-cyclopentenone (52). A solution of 437 mg (1.2 mmol) of cobalt complex **14** and 46 mg (0.4 mmol) of 4-pentenyl methyl sulfide in 2.5 mL of toluene was warmed to 88 °C for 26 h. The resulting red-brown mixture was cooled, diluted with 8 mL of a 1:1 mixture of EtOAc/hexane, carefully treated with 0.5 mL of ethylenediamine, and filtered through a plug of silica gel with 25% EtOAc/hexane. Removal of the solvent in vacuo left a red oil that was chromatographed with 16% EtOAc in hexane. 2-Butyl-5-[3-(methylthio)propyl]-2-cyclopentenone (**51**) (11 mg, 15%) and 2-butyl-4-[3-(methylthio)propyl]-2-cyclopentenone (**52**) (30 mg, 35%) were obtained as colorless oils.

51. 500-MHz ^{1}H NMR: δ 0.91 (t, J = 7.3, 3 H, CH_3), 1.32 (d, d, q, J = 7.3, 7.3, 7.3, 2 H, CH_2CH_3), 1.41–1.48 (m, 3 H, $CHCH_2$ (1 H) and $CH_2CH_2CH_3$ (2 H)), 1.63–1.7 (m, 2 H, CH_2CH_2S), 1.85, (d, d, d, d, J = 13.7, 10.5, 6.4, 4.6, 1 H, $CHCH$), 2.09 (s, 3 H, SCH_3), 2.16, (d, d, d, d, d, J = 7.3, 7.2, 1.8, 1.8, 1.4, 1 H, 2-CH_2), 2.22 (d, d, d, d, J = 18.7, 4.6, 2.2, 2.2, 1 H, 4-H), 2.34 (d, d, d, d, J = 9.2, 6.8, 4.6, 2.2, 1 H, 5-H), 2.48 (ab, d, d, J = 12.9, 8.2, 6.9, 1 H, SCH_2), 2.52 (ab, d, d, J = 12.9, 8.2, 6.9, 1 H, SCH_2), 2.75 (d, d, d, d, d, J = 18.7, 6.5, 1.8, 1.8, 2.8, 1 H, 4′-H), 7.23 (d, d, d, d, J = 4.1, 1.4, 1.4, 1.4, 1 H, 3-H). 75-MHz ^{13}C NMR: δ 14.0, 15.7, 22.6, 24.7, 27.0, 30.0, 30.9, 33.7, 34.3, 45.3, 146.5, 156.4, 212.4. IR (cm^{-1}): 2920, 2865, 1690, 1440, 1220. Mass spectrum m/e (EI): 226 (M^+), 179, 151, 135, 95. Mass spectrum, exact mass for $C_{13}H_{22}OS$: calcd m/e 226.1391, obsd m/e 226.1387.

52. 300-MHz ^{1}H NMR: δ 0.89 (t, J = 7.2, 3 H, CH_3), 1.30 (t, q, J = 7.2, 7.2, 2 H, CH_3CH_2), 1.44 (d, d, t, J = 7.7, 8.6, 7.7, 1 H, $CH_2CHHCH_2CH_3$), 1.45 (d, d, t, J = 8.7, 8.6, 7.1, 1 H, $CH_2CHHCH_2CH_3$), 1.58–1.71 (m, 4 H, 4-CH_2CH_2), 2.02 (d, d, J = 18.6, 2.2, 1 H, 5-H), 2.09 (s, 3 H, SCH_3), 2.15 (d, d, d, d, J = 7.1, 7.1, 1.7, 1.7, 2 H, 2-CH_2), 2.51 (t, J = 7.2, 2 H, CH_2S), 2.58 (d, d, J = 18.6,

6.6, 1 H, 5'-H), 2.80 (m, 1 H, 4-H), 7.2 (d, d, d, J = 2.1, 1.7, 1.7, 1 H, 3-H). 75-MHz ^{13}C NMR: δ 14.0, 15.7, 22.6, 24.5, 27.3, 30.0, 34.4, 38.7, 41.7, 146.7, 161.3, 210.1. IR (cm^{-1}): 2920, 1690, 1050. Mass spectrum m/e (EI): 226 (M^+), 183, 152, 135, 95. Mass spectrum, exact mass for $C_{13}H_{22}OS$: calcd m/e 226.1391, obsd m/e 226.1417.

Synthesis of 5-(1,3-Dithian-2-ylmethyl)-2-(trimethylsilyl)-2-cyclopentenone (53) and 4-(1,3-Dithian-2-ylmethyl)-2-(trimethylsilyl)-2-cyclopentenone (54). A solution of 2-(2-propen-1-yl)-1,3-dithiane (200 mg, 1.25 mmol) and complex **34** (960 mg, 2.5 mmol) in toluene (1.3 mL) was heated at 95 °C for 3 h. The solution was cooled to room temperature, diluted with dichloromethane, and filtered through a plug of silica gel with hexane as the eluent (to remove the remaining complex **34**) followed by ethyl acetate. The ethyl acetate solution was treated with N-methylmorpholine N-oxide, washed with water, and dried over $MgSO_4$. Purification by column chromatography (14% EtOAc in hexane) gave a mixture of enones **53** and **54** (35:1) in 42% yield.

53. Mp (hexane) 114–115 °C. 500-MHz ^{1}H NMR: δ 0.15 (s, 9 H, $Si(CH_3)_3$), 1.70 (ab, d, d, J_{ab} = 14.2, J = 9.2, 6.8, 1 H, 6-H), 1.89 (m, 1 H, $SCH_2CH_{ax}H$), 2.10 (ab, t, t, J_{ab} = 14.1, J = 5.1, 3.2, 1 H, $SCH_2CH_{eq}H$), 2.32 (ab, d, d, J_{ab} = 14.2, J = 7.8, 5.5, 1 H, 6'-H), 2.36 (ab, d, d, J_{ab} = 19.2, J = 3.2, 2.3, 1 H, 4-H), 2.63 (d, d, d, d, J = 9.1, 6.9, 5.5, 3.2, 1 H, 5-H), 2.80–2.90 (m, 4 H, $SCH_2CH_2CH_2S$), 2.94 (ab, d, d, J_{ab} = 19.2, J = 6.9, 2.75, 1 H, 4'-H), 4.22 (d, d, J = 7.8, 6.8, 1 H, SCHS), 7.72 (d, d, J = 2.75, 2.3, 1 H, 3-H). 75-MHz ^{13}C NMR: δ −1.7, 26.1, 29.9, 30.0, 37.3, 37.9, 43.6, 45.9, 147.1, 171.1, 214.8. IR (cm^{-1}): 1685, 1695. Anal. Calcd. for $C_{13}H_{22}OS_2Si$: C, 54.53; H, 7.75. Found: C, 54.32; H, 7.84. Mass spectrum, exact mass for $C_{13}H_{22}OS_2Si$: calcd m/e 286.0881, obsd m/e 286.0851.

54. Mp 82–87 °C. 500-MHz ^{1}H NMR: δ 0.07 (s, 9 H, $Si(CH_3)_3$), 1.77 (ab, d, d, J_{ab} = 14.2, J = 9.2, 6.4, 1 H, 6-H), 1.87 (ab, t, t, J_{ab} = 14.2, J = 11.5, 3.7, 1 H, $SCH_2CH_{ax}H$), 1.98 (ab, d, d, J_{ab} = 14.2, J = 8.25, 9.15, 1 H, 6'-H), 2.02 (ab, d, J_{ab} = 18.8, J = 2.75, 1 H, 5-H), 2.13 (ab, t, t, J_{ab} = 14.2, J = 5.0, 2.3, 1 H, $SCH_2H_{eq}H$), 2.58 (ab, d, J_{ab} = 18.8, J = 6.4, 1 H, 5'-H), 2.80–2.94 (m, 4 H, $SCH_2CH_2CH_2S$), 3.21 (d, d, d, d, J = 9.15, 6.4, 5.95, 2.75, 2.3, 1 H, 4-H), 4.07 (d, d, J = 6.4, 6.25, 1 H, SCHS), 7.64 (d, J = 2.3, 1 H, 3-H). 75-MHz ^{13}C NMR: δ −1.7, 26.0, 30.5, 30.7, 40.1, 40.7, 42.4, 46.0, 147.9, 175.0, 213.1. IR (cm^{-1}): 1690. Mass spectrum, exact mass for $C_{13}H_{22}OS_2Si$: calcd m/e 286.0881, obsd m/e 286.0868.

Preparation of 2-(Trimethylsilyl)-4-[(*tert*-butyldimethylsiloxy)methyl]-5-[2-[(*p*-methoxyphenyl)thio]ethyl]-2-cyclopentenone (55). A solution of 161 mg (0.48 mmol) of *trans*-3-pentenyl-5-(*tert*-butyldimethylsiloxy)-*p*-methoxyphenyl sulfide[30] and 276 mg (0.72 mmol) of complex **34** in 1 mL of toluene was warmed to 93 °C. Additional amounts of cobalt alkyne complex **34** (92 mg, 0.24 mmol) were added after 14 and 22 h. After 30 h, the dark red solution was cooled and chromatographed through a plug of silica gel, eluting with hexane to remove nonpolar impurities, followed by elution with 25% EtOAc/hexane to give crude **55** (200 mg) after removal of the solvent. The crude product was dissolved in CH_2Cl_2 (15 mL), and N-methylmorpholine N-oxide (20–30 mg) was added. The mixture was stirred for 20 min, quenched with brine (10 mL), and extracted with CH_2Cl_2 (2 × 10 mL). The combined organic fractions were dried over Na_2SO_4 and chromatographed (12.5% EtOAc/hexane) to yield 176 mg (79%) of enone **55** as a colorless oil. 300-MHz ^{1}H NMR: δ 0.026 (s, 3 H, $OSiCH_3$), 0.035 (s, 3 H, $OSiCH_3$), 0.15 (s, 9 H, $Si(CH_3)_3$), 0.86 (s, 9 H, $SiC(CH_3)_3$), 1.62 (d, d, d, d, J = 8.8, 13.7, 6.6, 8.2, 1 H, $CHCH_2CH_2$), 1.99 (d, d, d, d, J = 13.7, 8.5, 6.6, 5.5, 1 H, $CHCH_2CH_2$), 2.23 (d, d, d, J = 8.8, 5.5, 2.8, 1 H, 5-H), 2.68 (d, d, d, d, J = 6.1, 6.0, 2.8, 2.2, 1 H, 4-H), 2.91 (d, d, d, J = 19.4, 8.5, 6.6, 1 H, CH_2S), 2.94 (d, d, d, J = 1.9, 8.2, 6.0, 1 H, CH_2S), 3.62 (d, d, J = 9.9, 6.1, 1 H, CH_2O(TBS)), 3.70 (d, d, J = 9.9, 6.0, 1 H, CH_2O(TBS)), 3.79 (s, 3 H, OCH_3), 6.84 (AA'BB', J = 8.8, 2.8, 2 H, arom), 7.35 (AA'BB', J = 8.8, 2.8, 2 H, arom), 7.62 (d, J = 2.2, 1 H, olefin). NOE experiments were used to verify the trans stereochemistry at C-4 and C-5. Irradiation at C-5 H produced an enhancement of the CH_2O(TBS) protons. 75-MHz ^{13}C NMR: δ −5.7, −2.1, 18.0, 25.6, 30.6, 33.6, 48.0, 52.1, 55.2, 64.6, 114.7, 126.2, 133.5, 147.4, 159.2, 172.0, 214.4. IR (cm^{-1}): 1488, 1691, 2950. Anal. Calcd for $C_{24}H_{40}O_3SSi_2$: C, 62.02; H, 8.67. Found: C, 61.66; H, 8.51.

Preparation of 2-*n*-Butyl-5-[2-(ethylthio)ethyl]-5-methyl-2-cyclopentenone (56). A solution of 130 mg (1.00 mmol) of 3-methyl-3-butenyl ethyl sulfide and 464 mg (1.5 mmol) of (hexyne)hexacarbonyldicobalt complex (**14**) in 5 mL of toluene was warmed to 93 °C and stirred for 36 h. The reaction was then cooled, diluted with 10 mL of EtOAc, stirred for 5 min, treated with 1 mL of ethylenediamine, and stirred for 15 min. Filtration through a plug of silica gel (hexane followed by 25% EtOAc in hexane) and evaporation of the 25% EtOAc in hexane eluent gave an oil that was chromatographed (25% EtOAc/hexane) to yield 125 mg of enone (52%) as a pale yellow oil. 500-MHz ^{1}H NMR: δ 0.91 (t, J = 7.3, 3 H, $CH_2CH_2CH_2CH_3$), 1.10 (s, 3 H, 5-CH_3), 1.23 (t, J = 7.3, 3 H, SCH_2CH_3), 1.33 (q, t, J = 7.3, 7.8, 2 H, $CH_2CH_2CH_2CH_3$), 1.46 (m, 2 H, $CH_2CH_2CH_2CH_3$), 1.71 (d, d, d, J = 13.3, 11.9, 4.6, 1 H, $CHHCH_2S$), 1.80 (d, d, d, J = 13.3, 11.4, 5.0, 1 H, $CHHCH_2S$), 2.17 (d, d, d, d, d, J = 8.7, 6.9, 2.3, 1.8, 1.4, 2 H, 2-CH_2), 2.29 (d, d, d, J = 12.8, 11.9, 5.0, 1 H, CH_2CHHS), 2.33 (partly obscured, d, d, d, d, J = 18.8, 2.7, 2.3, 1.8, 1 H, 4-H), 2.41 (partly obscured, d, d, d, J = 12.8, 11.4, 4.6, 1H, CH_2CHHS), 2.52 (q, J = 7.2, 2 H, SCH_2CH_3), 2.55 (obscured, d, d, d, d, J = 18.8, 2.7, 2.3, 1.8, 1 H, 4-H), 7.20 (d, d, d, d, J = 2.7, 2.7, 1.4, 1.4, 1 H, vinyl H). 75-MHz ^{13}C NMR: δ 13.5, 14.4, 22.1, 23.4, 24.4, 25.5, 26.3, 29.6, 37.9, 40.5, 46.5, 145.0, 154.8, 213.4. IR (cm^{-1}): 2955, 2925, 2866, 1690, 1625, 1519, 1450, 1434, 1371, 1345, 1265, 1236, 1010. Anal. Calcd for $C_{14}H_{24}OS$: C, 69.96; H, 10.06. Found: C, 70.08; H, 10.27. Mass spectrum m/e (EI): 240.1 (M^+), 152.2, 110.1, 96.2, 75.0, 55.2. Mass spectrum, exact mass for $C_{14}H_{24}OS$: calcd m/e 240.1548; obsd m/e 240.1549.

Data for compounds in Table III. All compounds were prepared according to the general procedure listed in the following text.

Synthesis of 2-Phenyl-5-[2-(*N*,*N*-dimethylamino)ethyl]-5-methyl-2-cyclopentenone. A solution of 113 mg (1.0 mmol) of *N*,*N*-dimethyl-*N*-(3-methyl-3-butenyl)amine and 582 mg (1.50 mmol) of (phenylacetylene)hexacarbonyldicobalt (**15**) in 12 mL of toluene was warmed to 93 °C. The reaction was cooled after 24 h, diluted with ether, and washed with 10% aqueous HCl solution (6 × 10 mL). The resulting aqueous layer was washed twice with ether and then neutralized with 10% aqueous NaOH solution. Extraction with ethyl acetate (4 × 50 mL), drying over Na_2SO_4, and solvent evaporation yielded an oil that was chromatographed (5% (10% NH_4OH in MeOH) in $CHCl_3$) to yield 156 mg of 2-phenyl-5-[2-(*N*,*N*-dimethylamino)ethyl]-5-methyl-2-cyclopentenone as a yellow oil (68%). 500-MHz ^{1}H NMR: δ 1.19 (s, 3 H, 5-CH_3), 1.68 (d, d, d, J = 13.3, 10.1, 4.6, 1 H, $CHHCH_2N$), 1.84 (d, d, d, J = 13.3, 10.1, 6.0, 1 H, 5-$CHHCH_2N$), 2.17 (s, 6 H, $N(CH_3)_2$), 2.18 (obscured, d, d, d, J = 12.0, 10.1, 6.0, 1 H, $CHHN$), 2.23 (d, d, d, J = 12.0, 10.1, 4.6, 1 H, $CHHN$), 2.46 (d, d, J = 19.7, 2.7, 1 H, 4-H), 2.73 (d, d, J = 19.7, 2.7, 1 H, 4-H), 7.30–7.34 (m, 1 H, arom), 7.35–7.40 (m, 2 H, arom), 7.68–7.73 (m, 3 H, arom and vinyl H). 75-MHz ^{13}C NMR: δ 24.2, 35.8, 40.3, 45.1, 46.6, 54.9, 127.2, 128.4, 128.5, 132.1, 141.9, 155.7, 211.4. IR (cm^{-1}): 2921, 2858, 2820, 2769, 1691, 1487, 1458, 1368, 1302. Mass spectrum m/e (EI): 243 (M^+), 172, 105, 71, 58. Mass spectrum, exact mass for $C_{16}H_{21}NO$: calcd m/e 243.1623, obsd m/e 243.1644.

2-Phenyl-5-[2-(*N*-methyl-*N*-butylamino)ethyl]-5-methyl-2-cyclopentenone. The reaction was stirred at 93 °C for 75 h, with addition of 1 equiv of the cobalt reagent every 24 h, chromatographed (5% (10% NH_4OH/MeOH)/$CHCl_3$) to yield 105 mg of 2-phenyl-5-[2-(*N*-methyl-*N*-butylamino)ethyl]-5-methyl-2-cyclopentenone (37%). 500-MHz ^{1}H NMR: δ 0.89 (t, J = 7.3, 3 H, $NCH_2CH_2CH_2CH_3$), 1.20 (s, 3 H, 5-CH_3), 1.27 (t, q, J = 6.9, 7.3, 2 H, $NCH_2CH_2CH_2CH_3$), 1.39 (t, d, d, J = 8.2, 7.8, 6.9, 2 H, $NCH_2CH_2CH_2CH_3$), 1.70 (d, d, d, J = 13.3, 10.1, 4.6, 1 H, 5-$CHHCH_2N$), 1.85 (d, d, d, J = 13.3, 10.1, 6.0, 1 H, 5-$CHHCH_2N$), 2.18 (s, 3 H, NCH_3), 2.26 (obscured d, d, d, J = 12.4, 10.01, 6.0, 1 H, 5-CH_2CHHN), 2.29 (obscured, d, d, J = 6.8, 6.0, 2 H, $NCH_2CH_2CH_2CH_3$), 2.33 (obscured, d, d, d, J = 12.4, 10.1, 4.6, 1 H, 5-CH_2CHHN), 2.47 (d, d, J = 19.7, 3.2, 1 H, 4-H) 2.78 (d, d, J = 19.7, 3.2, 1 H, 4-H), 7.31–7.36 (m, 1 H, arom), 7.37–7.42 (m, 2 H, arom), 7.71–7.76 (m, 3 H, arom and vinyl H). 75-MHz ^{13}C NMR: δ 13.8, 20.4, 24.3, 29.0, 35.1, 40.3, 41.8, 46.8, 53.1, 57.4, 127.2, 128.5, 128.6, 132.1, 141.8, 156.1, 211.6. IR (cm^{-1}): 2954, 2926, 2866, 2798, 1692, 1594, 1487, 1452, 1369, 1322, 1303. Mass spectrum m/e (EI): 285.0 (M^+), 242, 199, 114, 100. Mass spectrum, exact mass for $C_{19}H_{27}NO$: calcd m/e 285.2093, obsd m/e 285.2074.

Data for Compounds in Table IV. All compounds were prepared according to the general procedure listed in the following text.

Synthesis of 2-Methyl-5-[2-[(*p*-methoxyphenyl)thio]ethyl]-2-cyclopentenone. A solution of 294 mg (1.52 mmol) of 3-butenyl *p*-methoxyphenyl sulfide, 0.3 g of Celite, and 770 mg (2.36 mmol) of cobalt alkyne complex **58** in 8 mL of toluene was warmed to 93 °C. After 24–36 h at that temperature the reaction was cooled, diluted with 10 mL of a 1:1 mixture of EtOAc/hexane, treated with 1 mL of ethylenediamine, and stirred for 10 min. Filtration through a plug of silica gel with 20% EtOAc in hexane yielded an oil that was chromatographed (10% EtOAc/hexane) to yield 88 mg of enone 2-methyl-5-[2-[(*p*-methoxyphenyl)thio]ethyl]-2-cyclopentenone as a pale yellow oil (50%). 300-MHz ^{1}H NMR: δ 1.57 (d, d, d, d, J = 14.3, 8.8, 8.8, 6.1, 1 H, $CHCH_2CH_2S$), 1.73 (d, d, d, J = 2.2, 2.2, 1.6, 3 H, 2-CH_3), 2.04 (d, d, d, d, J = 13.8, 8.8, 7.5, 5.0, 1 H, $CHCH_2CH_2S$), 2.15 (d, d, q, J = 18.7, 2.75, 2.2, 1 H, 4-H), 2.49 (d, d, d, d, J = 8.8, 6.6, 4.9, 2.2, 1 H, 5-H),

(30) Krafft, M. E.; Wright, C. Manuscript in preparation.
(31) Billington, D. C.; Kerr, W. J.; Pauson, P. L.; Farnocchi, C. F. *J. Organomet. Chem.* **1988**, *356*, 213.

2.72 (d, d, d, d, J = 18.7, 6.6, 2.7, 2.2, 1 H, 4′-H), 2.88 (ab, d, d, J = 13.2, 8.2, 7.1, 1 H, CH_2S), 2.93 (ab, d, d, J = 13.2, 8.8, 6.1, 1 H, CH_2S), 3.78 (s, 3 H, OCH_3), 6.83 (AA′BB′, J = 8.8, 3.0, 3.0, 2 H, arom), 7.24 (d, d, q, J = 2.2, 2.2, 1.65, 1 H, 3-H, arom), 7.35 (AA′BB′, J = 8.8, 2.2, 2.2, 2 H, arom). 75-MHz ^{13}C NMR: δ 9.7, 30.9, 33.0, 33.4, 43.5, 55.0, 114.5, 125.9, 143.4, 141.2, 156.5, 159.0, 211.4. IR (cm^{-1}): 2940, 1695, 1445, 1220. Mass spectrum m/e (EI): 262.1 (M^+), 166, 139, 123, 95, 77. Mass spectrum, exact mass for $C_{15}H_{18}O_2S$: calcd m/e 262.1028, obsd m/e 262.1056.

2-Methyl-5-[2-(phenylthio)ethyl]-2-cyclopentenone. 300-MHz ^{1}H NMR ($CDCl_3$): δ 1.66, (d, d, d, d, J = 13.4, 9.2, 8.2, 6.7, 1 H, $CHCH_2CH_2S$), 1.75 (d, d, d, J = 2.2, 2.2, 1.6, 3 H, 2-CH_3), 2.10 (d, d, d, d, J = 13.2, 8.2, 6.4, 4.7, 1 H, $CHCH_2CH_2S$), 2.19 (d, d, d, q, J = 18.7, 2.75, 2.75, 2.2, 1 H, 4-H), 2.5 (d, d, d, d, J = 8.8, 6.6, 5.5, 2.75, 1 H, 5-H), 2.75 (d, d, d, q, J = 18.7, 6.4, 2.75, 2.2, 1 H, 4′-H), 3.0 (ab, d, d, J = 13.5, 8.4, 6.7, 1 H, CH_2S), 3.04 (ab, d, d, J = 13.5, 8.7, 6.4, 1 H, CH_2S), 7.14–7.21 (t, d, d, J = 6.6, 2.2, 2.2, 2 H, arom), 7.24–7.36 (m, 4 H, arom and 3-H). IR (cm^{-1}): 2950, 2880, 1700, 1450, 1340. 75-MHz ^{13}C NMR: δ 9.9, 13.7, 22.2, 28.3, 29.3, 29.6, 31.2, 31.7, 33.1, 43.9, 141.4, 156.7, 211.8. Mass spectrum m/e (EI): 232.0 (M^+), 172, 136, 124, 109, 96, 79, 65. Mass spectrum, exact mass for $C_{14}H_{16}OS$: calcd m/e 232.0922, obsd m/e 232.0916.

2-Methyl-4-[2-(phenylthio)ethyl]-2-cyclopentenone. 300-MHz ^{1}H NMR ($CDCl_3$): δ 1.61 (d, d, d, d, J = 14.3, 8.7, 6.6, 5.4, 1 H, $CHCH_2CH_2S$), 1.67 (s, 3 H, 2-CH_3), 1.79 (d, d, d, d, J = 14.3, 6.4, 8.2, 16.5, 1 H, $CHCH_2CH_2S$), 1.93 (d, d, J = 19.2, 2.2, 1 H, 5-H), 2.5 (d, d, J = 19.2, 6.0, 1 H, 5′-H), 2.86 (ab, d, d, J = 13.2, 8.2, 6.6, 1 H, CH_2S), 2.93 (ab, d, d, J = 13.2, 8.7, 6.4, 1 H, CH_2S), 2.9 (m, 1 H, 4-H), 7.16–7.36 (m, 6 H, arom and 3-H). 500-MHz ^{1}H NMR (C_6D_6): δ 1.23 (d, d, d, d, J = 13.7, 8.7, 8.7, 6.0, 1 H, $CHCH_2CH_2S$), 1.43 (d, d, d, d, J = 13.7, 8.7, 8.7, 6.4, 1 H, $CHCH_2CH_2S$), 1.63 (d, d, J = 18.3, 2.3, 1 H, 5-H), 1.66 (d, d, J = 1.3, 1.3, 3 H, 2-CH_3), 2.17 (d, d, J = 18.3, 6.4, 1 H, 5′-H), 2.34 (d, d, d, d, d, q, J = 8.7, 6.4, 6.4, 2.3, 2.7, 1.3, 1 H, 4-H), 2.49 (ab, d, d, J = 13.1, 8.7, 6.4, 1 H, CH_2S), 2.55 (ab, d, d, J = 13.1, 8.7, 6.0, 1 H, CH_2S), 6.41 (d, q, J = 2.7, 1.3, 1 H, 3-H), 6.91 (d, d, d, d, J = 8.6, 8.6, 1.8, 1.8, 1 H, arom), 7.0 (d, d, d, d, J = 7.8, 7.8, 1.8, 1.8, 2 H, arom), 7.20 (d, d, d, J = 8.6, 3.2, 1.8, 2 H, arom). 75-MHz ^{13}C NMR: δ 10.2, 32.1, 34.6, 38.0, 41.1, 126.8, 129.6, 130.1, 136.5, 142.4, 161.5, 209.9. Mass spectrum m/e (EI): 232 (M^+), 123, 110, 79. Mass spectrum, exact mass for $C_{14}H_{16}OS$: calcd m/e 232.0922, obsd m/e 232.0934.

2-Methyl-5-[2-(hexylthio)ethyl]-2-cyclopentenone. 300-MHz ^{1}H NMR ($CDCl_3$): δ 0.89 (t, J = 7.2, 3 H, hexyl CH_3), 1.26–1.42 (m, 6 H, hexyl chain), 1.53–1.66 (m, 3 H, hexyl CH_2 (2 H) and $CHCHHC$-H_2S (1 H)), 1.77 (d, d, d, J = 2.2, 2.2, 1.65, 3 H, 2-CH_3), 2.09 (d, d, d, d, J = 14, 8.8, 6.9, 4.6, 1 H, $CHCHHCH_2S$), 2.22 (d, d, d, q, J = 18.8, 2.75, 2.75, 2.2, 1 H, 4-H), 2.47–2.54 (m, 1 H, 5-H), 2.52 (t, J = 7.1, 2 H, $SCH_2(CH_2)_4CH_3$), 2.58 (ab, d, d, J_{ab} = 12.8, J = 6.4, 4.6, 1 H, SCH_2), 2.64 (AB, d, d, J_{AB} = 12.8, J = 8.7, 5.1, 1 H, CH_2S), 2.78 (d, d, d, q, J = 18.2, 6.4, 2.75, 2.2, 1 H, 4′-H), 7.26 (d, d, q, J = 2.75, 2.75, 1.65, 1 H, 3-H). IR (cm^{-1}): 2950, 2880, 1700, 1450, 1340. 75-MHz ^{13}C NMR: δ 9.9, 13.7, 22.2, 28.3, 29.3, 29.6, 31.2, 31.7, 33.1, 43.9, 141.4, 156.7, 211.8. Mass spectrum m/e (EI): 240 (M^+), 109, 96. Mass spectrum, exact mass for $C_{14}H_{24}OS$: calcd m/e 240.1548, obsd m/e 240.1528.

2-Methyl-5-[2-(2-propylthio)ethyl]-2-cyclopentenone. 300-MHz ^{1}H NMR ($CDCl_3$): δ 1.25 (d, J = 7.1, 6 H, $CH(CH_3)_2$), 1.59 (d, d, d, d, J = 13.7, 9.3, 8.3, 6.0, 1 H, $CHCH_2CH_2S$), 1.76 (d, d, d, J = 2.2, 2.2, 1.1, 1 H, 2-CH_3), 2.07 (d, d, d, d, J = 13.7, 8.8, 7.1, 5.0, 1 H, $CHCH_2CH_2S$), 2.22 (d, d, d, q, J = 18.7, 2.75, 2.2, 2.2, 1 H, 4-H), 2.49 (d, d, d, d, J = 9.4, 6.6, 4.9, 2.2, 1 H, 5-H), 2.60 (ab, d, d, J_{ab} = 13.2, J = 8.2, 7.1, 1 H, CH_2S), 2.65 (ab, d, d, J_{ab} = 13.2, J = 8.8, 6.0, 1 H, CH_2S), 2.76 (d, d, d, q, J = 18.7, 6.6, 2.75, 2.2, 1 H, 4′-H), 2.94 (septet, J = 7.1, 1 H, $CH(CH_3)_2$), 7.27 (d, d, q, J = 2.7, 2.7, 1.4, 1 H, 3-H). IR (cm^{-1}): 2950, 2990, 1700, 1450, 1220. 75-MHz ^{13}C NMR: δ 9.7, 22.9, 27.8, 31.1, 33.0, 34.0, 43.8, 141.2, 156.5, 211.6. Mass spectrum m/e (EI): 198 (M^+), 109, 96. Mass spectrum, exact mass for $C_{11}H_{18}OS$: calcd m/e 198.1078, obsd m/e 198.1092.

2-Methyl-4-[2-(2-propylthio)ethyl]-2-cyclopentenone. 500-MHz ^{1}H NMR: δ 1.24 (d, 6 H, $CH(CH_3)_2$), 1.64 (d, d, d, d, J = 13.7, 8.9, 8.5, 6.4, 1 H, SCH_2CH_2), 1.75 (d, d, J = 2.3, 1.4, 3 H, CCH_3), 1.80 (m, 1 H, SCH_2CH_2), 2.02 (d, d, J = 18.8, 1.8, 1 H, 5-H), 2.58 (ab, d, d, J_{ab} = 12.8, J = 8.7, 6.4, 1 H, SCH_2), 2.59 (d, d, J = 18.8, 6.4, 1 H, 5′-H), 2.60 (ab, d, d, J_{ab} = 12.8, J = 8.7, 6.4, 1 H, SCH_2), 2.92 (sept, J = 6.9, 1 H, $CH(CH_3)_2$), 2.94 (m, 1 H, 4-H), 7.24 (d, q, J = 2.75, 1.4, 1 H, 3-H).

3-Methyl-5-[2-(phenylthio)ethyl]-2-cyclopentenone (59). 500-MHz ^{1}H NMR (C_6D_6): δ 1.42 (vbs, 3 H, 3-CH_3), 1.52 (d, d, d, q, J = 18.0, 2.8, 1.4, 0.9, 1 H, 4-H), 1.55 (d, d, d, d, J = 14.2, 8.2, 7.8, 7.8, 1 H, $CHCH_2CH_2S$), 1.98 (d, d, d, q, J = 18.0, 6.8, 1.4, 0.9, 1 H, 4′-H), 2.14 (d, d, d, d, J = 14.2, 7.8, 7.8, 5.5, 1 H, $CHCH_2CH_2S$), 2.26 (d, d, d, d, q, J = 8.2, 6.8, 5.5, 2.8, <0.2, 1 H, 5-H), 2.89 (d, d, J = 7.8, 7.8, 2 H, CH_2S), 5.70 (d, d, q, J = 1.4, 1.4, 0.9, 1 H, 3-H), 6.98 (t, d, d, J = 7.5, 1.5, 1.5, 1 H, arom), 7.09 (t, d, d, J = 7.5, 1.5, 1.5, 2 H, arom), 7.39 (t, d, d, J = 7.5, 1.5, 1.5, 2 H, arom). 75-MHz ^{13}C NMR: δ 19.6, 31.3, 31.9, 40.0, 45.9, 126.6, 129.5, 129.9, 130.5, 136.7, 177.8, 211.9. Mass spectrum m/e (EI): 232 (M^+), 136, 123, 109, 96.5. Mass spectrum, exact mass for $C_{14}H_{16}OS$: calcd m/e 232.0922, obsd m/e 232.0932.

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