Highly Regio- and Stereoselective [3+2] Cyclopentanone Annulation Using a 3-(Alkylthio)-2-siloxyallyl Cationic Species

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Abstract: A new synthetic method for functionalized cyclopentanones was developed on the basis of a [3+2] cycloaddition reaction of a 1-(methylthio)-2-siloxyallyl cationic species and olefins. Allyl acetates **1a** and **1b**, which are the precursors of the allyl cationic species, are easily prepared in three or four steps from commercially available compounds. Under the influence of $EtAlCl_2$ or $AlCl_3$, **1a** or **1b** reacted with various kinds of olefins such as enol ethers, vinyl sulfides, styrenes, and trialkylolefins to afford the corresponding cyclopentanones in good yields. It is noteworthy that the sterically more hindered regioisomer was predominantly formed in every case. Furthermore, the reactions of **1b** with vinyl sulfides exhibited surprisingly high stereoselectivity, which can be rationalized by the six-membered transition state models involving an orbital interaction between the sulfur atom of the vinyl sulfide and the α-carbon of the allyl cation.

Introduction

Cyclopentanoid compounds are found in a wide range of natural products,[1] and various kinds of synthetic methods have been explored.[2] While intramolecular ring closure of an acyclic compound is generally applicable to cyclopentane synthesis, a [3+2] cycloaddition approach which produces two C−C bonds in one stage is advantageous from the viewpoint of efficiency.[3] The utility of a cycloaddition reaction is critically dependent on regioselectivity as well as diastereoselectivity, which can be seen in Diels−Alder reactions. In this regard, much less attention has been given to the [3+2] cycloaddition approach in cyclopentane synthesis, whereas a variety of three-carbon units have been reported.[4]

Use of a 2-oxyallyl cationic species[5] as a three-carbon unit seems to be advantageous for natural product synthesis, because it gives cyclopentanone derivatives which are suitable for further functionalizations. However, this type of cyclopentanone annulation has considerable limitations arising from the stepwise mechanism, in contrast with the [4+3] cycloaddition reactions of a 2-oxyallyl cationic species with dienes which have found widespread use in organic synthesis.[5,6] On the other hand, in connection with the vinyl sulfide chemistry previously described,[7] we are intrigued with the high reactivity as well as the appropriate stability of thionium ion intermediates. In certain cases, a sulfur atom also plays an important role in controlling the regio- and stereochemistry of the products.[7f,i] These characteristic features of sulfur led us to design 1-(alkylthio)-2-siloxyallyl cationic species **A** as a new three-carbon unit with a view to inducing regio- and stereoselective [3+2] cyclopentanone annulation reactions (Scheme 1). Thus, the reaction of cationic species **A** with a nucleophilic olefin would afford intermediate **B** or **C** having an enol silyl ether moiety and a cationic carbon, which would undergo intramolecular cyclization to give cyclopentanone **D** or **E**, respectively.

(1) For reviews, see: (a) *Cyclopentanoid Terpene Derivatives*; Taylor, W. I., Battersby, A. R., Eds.; M. Dekker: New York, 1969. (b) Paquette, L. A. *Top. Curr. Chem.* **1984**, *119*, 1. (c) Paquette, L. A.; Doherty, A. M. *Polyquinane Chemistry: Synthesis and Reactions*; Springer-Verlag: Berlin, 1987. (d) Hudlicky, T.; Rulin, F.; Lovelace, T. C.; Reed, J. W. In *Studies in Natural Products Chemistry*; Atta-ur Rahman, Ed.; Elsevier: Oxford, 1989; Vol. 3, Part B, pp 3−72. (e) Mehta, G.; Srikrishna, A. *Chem. Rev.* **1997**, *97*, 671.

(2) For reviews of cyclopentane synthesis, see: (a) Ramaiah, M. *Synthesis* **1984**, 529. (b) Hudlicky, T.; Price, J. D. *Chem. Rev.* **1989**, *89*, 1467.

(3) For reviews of [3+2] cycloaddition reactions, see: (a) Little, R. D. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon: Oxford, 1991; Vol. 5, Chapter 3.1, pp 239−270. (b) Chan, D. M. T. in *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon: Oxford, 1991; Vol. 5, Chapter 3.2, pp 271−314.

(4) For examples, see: (a) Trost, B. M. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 1 and references therein. (b) Danheiser, R. L.; Carini, D. J.; Fink, D. M.; Basak, A. *Tetrahedron* **1983**, *39*, 935. (c) Marino, J. P.; Laborde, E. *J. Am. Chem. Soc.* **1985**, *107*, 374. (d) Cekovic, Z.; Saicic, R. *Tetrahedron Lett.* **1986**, *27*, 5893. (e) Boger, D. L.; Brotherton, C. E. *J. Am. Chem. Soc.* **1986**, *108*, 6695. (f) Beal, R. B.; Dombroski, M. A.; Snider, B. B. *J. Org. Chem.* **1986**, *51*, 4391. (g) Curran, D. P.; Chen M.-H. *J. Am. Chem. Soc.* **1987**, *109*, 6558. (h) Gray, B. D.; McMillan, C. M.; Miller, J. A.; Ullah, G. M. *Tetrahedron Lett.* **1987**, *28*, 689. (i) Feldman, K. S.; Romanelli, A. L.; Ruckle, R. E., Jr.; Miller, R. F. *J. Am. Chem. Soc.* **1988**, *110*, 3300. (j) Beak, P.; Burg, D. A. *J. Org. Chem.* **1989**, *54*, 1647. (k) Rosenblum, M.; Watkins, J. C. *J. Am. Chem. Soc.* **1990**, *112*, 6316. (l) Singleton, D. A.; Church, K. M. *J. Org. Chem.* **1990**, *55*, 4780. (m) Herndon, J. W.; Wu, C.; Harp, J. J.; Kreutzer, K. A. *Synlett* **1991**, 1. (n) Ejiri, S.; Yamago, S.; Nakamura, E. *J. Am. Chem. Soc.* **1992**, *114*, 8707. (o) Panek, J. S.; Jain, N. F. *J. Org. Chem.* **1993**, *58*, 2345. (p) Knölker, H.-J.; Graf, R. *Synlett* **1994**, 131. (q) Ghera, E.; Yechezkel, T.; Hassner, A. *J. Org. Chem.* **1996**, *61*, 4959. See also refs 5a and 5b.

(5) (a) Noyori, R.; Hayakawa, Y. *Org. React.* **1983**, *29*, 163. (b) Hoffmann, H. M. R. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 1. (c) Mann. J. *Tetrahedron* **1986**, *42*, 4611. (d) Hardinger, S. A.; Bayne, C.; Kantorowski, E.; McClellan, R.; Larres, L.; Nuesse, M.-A. *J. Org. Chem.* **1995**, *60*, 1104. (e) Harmata, M. *Tetrahedron* **1997**, *53*, 6235 and references therein.

(6) For a review of [4+3] cycloaddition reactions, see: Hosomi, A.; Tominaga, Y. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon: Oxford, 1991; Vol. 5, Chapter 5.1, pp 593−615.

(7) (a) Tanino, K.; Nakamura, T.; Kuwajima, I. *Tetrahedron Lett.* **1990**, *31*, 2165. (b) Tanino, K.; Shoda, H.; Nakamura, T.; Kuwajima, I. *Tetrahedron Lett.* **1992**, *33*, 1337. (c) Nakamura, T.; Tanino, K.; Kuwajima, I. *Chem. Lett.* **1992**, 1425. (d) Nakamura, T.; Tanino, K.; Kuwajima, I. *Tetrahedron Lett.* **1993**, *34*, 477. (e) Adachi, A.; Masuya, K.; Tanino, K.; Kuwajima, I. *J. Org. Chem.* **1993**, *58*, 4189. (f) Takayanagi, M.; Tanino, K.; Kuwajima, I. *J. Am. Chem. Soc*. **1993**, *115*, 12635. (g) Tohyama, Y.; Tanino, K.; Kuwajima, I. *J. Org. Chem.* **1994**, *59*, 518. (h) Masuya, K.; Tanino, K.; Kuwajima, I. *Tetrahedron Lett.* **1994**, *35*, 7965. (i) Takayanagi, M.; Tanino, K.; Kuwajima, I. *Synlett* **1995**, 173. (j) Sato, K.; Koga, T.; Masuya, K.; Tanino, K.; Kuwajima, I. *Synlett* **1996**, 751.

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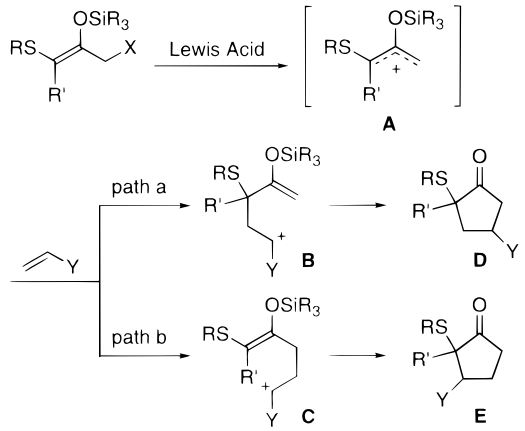
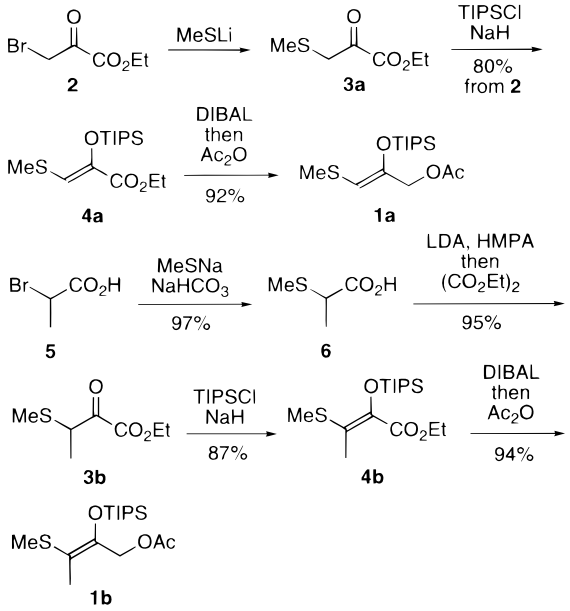
Scheme 1



Scheme 2

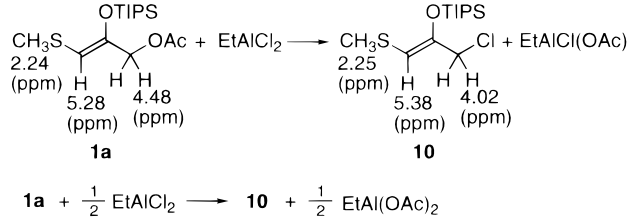


Although selectivity in such processes may be unpredictable, the sulfur substituent is expected to have some influence on the regio- and stereochemical outcome.[8] To clarify this aspect, we examined the reaction of acetate **1** with olefins in the presence of Lewis acids.[9]

Results

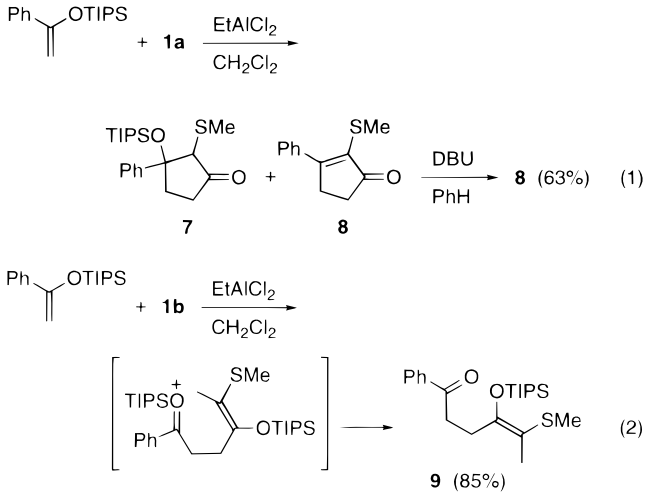
The starting materials were readily prepared as shown in Scheme 2. Commercially available ethyl bromopyruvate (**2**) was converted into the corresponding sulfide **3a** under the influence of lithium methanethiolate. Ethyl 3-(methylthio)-2-oxobutanoate (**3b**) was also prepared by Claisen condensation between the dianion of 2-(methylthio)propionic acid (**6**) and diethyl oxalate followed by decarboxylation.[10] The reactions of esters **3** with TIPSCl and NaH resulted in stereoselective formation of the (*Z*)-enol silyl ethers **4**, which were successively

Scheme 3



treated with DIBAL and acetic anhydride to yield allyl acetates **1a** and **1b**, respectively.[11]

Initially, the reactions of **1a** with 1-(triisopropylsiloxy)styrene were examined in the presence of several Lewis acids. Although the use of $TiCl_4$ and TMSOTf led to complex results, $EtAlCl_2$ effected the desired annulation reaction to afford a mixture of cyclopentanone **7** and enone **8**. Since treatment of the crude mixture with DBU afforded enone **8** as the sole product, the annulation reaction proved to proceed through path b predominantly (eq 1). On the other hand, the reaction of **1b** with the enol silyl ether gave acyclic compound **9** rather than a cyclopentanone. In this case, the silyl oxonium ion intermediate undergoes desilylation probably because the alternative cyclization pathway suffers from the steric repulsion between the adjacent tertiary carbon centers (eq 2).



It should be noted that the enol silyl ether moiety of **9** completely retains the geometry of **1b**,[11] which suggests that the 1-(methylthio)-2-siloxyallyl cationic species rigorously maintains the geometry of the double bond. To obtain information on the reactive cationic species, the reaction of **1a** with $EtAlCl_2$ in $CDCl_3$ at room temperature was checked by ^1H NMR experiments. Although a 1:1 mixture of **1a** and $EtAlCl_2$ quickly decomposed to give a complex mixture, a 2:1 mixture led to quantitative formation of the corresponding (*Z*)-allyl chloride **10** after 1 min, which underwent decomposition after 15 min. These results indicate that treatment of **1a** with $EtAlCl_2$ readily yields **10** which is in equilibrium with a labile allyl cation in the presence of the aluminum reagent. Thus, EtAlCl(OAc) effects fast decomposition of the allyl chloride at room temperature, while the much less Lewis acidic $EtAl(OAc)_2$ induces slower reaction (Scheme 3).

In contrast with the enol silyl ether, alkyl enol ethers as well as vinyl sulfides were found to serve as efficient two-carbon

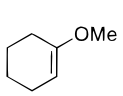
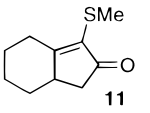
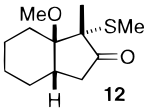
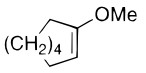
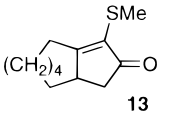
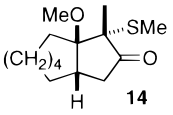
(8) It is reported that the C−C bond formation reaction between an enol silyl ether and a 1-(phenylthio)allyl cation occurs at the γ-position of sulfur: Hunter, R.; Simon, C. D. *Tetrahedron Lett.* **1986**, *27*, 1385.

(9) For a preliminary report of a part of this work, see: Masuya, K.; Domon, K.; Tanino, K.; Kuwajima, I. *Synlett* **1996**, 157. A similar methylenecyclopentane annulation could also be effected by using the substrate having a TMS-methyl group in place of TIPSO of **1**: Takahashi, Y.; Tanino, K.; Kuwajima, I. *Tetrahedron Lett.*, **1996**, *37*, 5943.

(10) Hangauer, D. G., Jr. *Tetrahedron Lett.* **1981**, *22*, 2439.

(11) The (*Z*)-configuration of the products was determined by observation of NOE between the allylic proton and the olefinic proton or the other allylic proton.

Table 1. Annulation Reactions with Enol Ethers[a]

entry	olefin	enophile	product	yield	ratio[b]
1		**1a**	 **11**	86%[c]	
2		**1b**	 **12**	95%	>99 : <1
3		**1a**	 **13**	73%[c]	
4		**1b**	 **14**	44%	82 : 18

[a] The olefins were treated with 1.1 equiv of **1a** or **1b** and 1.1 equiv of $EtAlCl_2$ in CH_2Cl_2. [b] Diastereomeric ratio determined by ^1H NMR analysis. [c] The crude product was treated with DBU to afford the corresponding enone.

units for the [3+2] cycloaddition reaction with both **1a** and **1b**. Since **1a** usually gave a mixture of the cyclopentanones and the corresponding cyclopentenones, the products were isolated as the enones after treating the crude mixture with DBU. Typical examples are shown in Tables 1 and 2.

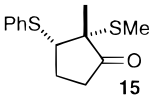
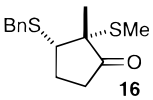
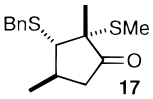
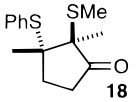
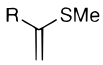
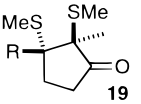
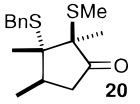
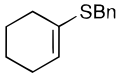
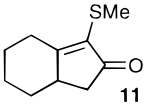
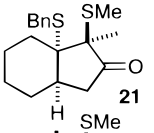
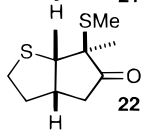
To extend the synthetic possibilities of the cylopentanone annulation, we attempted the reactions of olefins without heteroatom substituents. While styrenes afforded the corresponding adducts in acceptable yields (Table 3), the reactions of simple trisubstituted olefins were very sluggish. However, combined use of $AlCl_3$ and proton sponge (1,8-bis(dimethylamino)naphthalene)[12] in place of $EtAlCl_2$ was found to effect the desired transformation smoothly (Table 4). Proton sponge plays an important role to increase the product yields by trapping hydrogen chloride which causes the side reactions with the olefins.

Discussion

Regioselectivity. Several remarkable features of these transformations have also been disclosed by the present study. The first is the almost complete regioselection to yield the sterically more hindered regioisomer. These results indicate that the initial C−C bond formation between an olefin and the 1-(methylthio)-2-siloxyallyl cationic intermediate predominantly occurred at the γ-position of sulfur (path b in Scheme 1).[8] To understand the regioselectivities, we performed PM3[13] calculations on the allyl cationic species (Figure 1). However, the results indicated the α-carbon of sulfur has both the largest LUMO coefficient and electropositive charge, which means that mechanisms involving the usual kinetic orbital or charge control do not agree with the observations.

On the other hand, the relative stability of the cationic intermediates **B** and **C** in Scheme 1 was found to reflect the observed regioselectivity. Thus, PM3 calculations on the corresponding models of **B** and **C** were performed in order to estimate the energy difference between them (Figure 2). The results indicated that the isomer arising from path b, which involves the conjugation of the methylthio group and the double bond, is much more stable than the other. Although there is no evidence for a reversal of the first C−C bond formation step, the regiochemistry of the cyclopentanone annulation reaction could be rationalized by thermodynamic control.[14]

Table 2. Annulation Reactions with Vinyl Sulfides[a]

entry	olefin	enophile	product	yield	ratio[b]
1		**1b**	 **15**	82%	>99 : <1
2		**1b**	 **16**	86%	>99 : <1
3		**1b**	 **17**	84%	95 : 5
4		**1b**	**17**	66%	96 : 4
5		**1b**	 **18**	89%	>99 : <1
6[c]		**1b**	 **19**	72%	>99 : <1
7		**1b**	 **20**	78%	>99 : <1
8		**1b**	**20**	82%	94 : 6
9		**1a**	 **11**	79%[d]	
10		**1b**	 **21**	95%	>99 : <1
11		**1b**	 **22**	76%	>99 : <1

[a] The olefins were treated with 1.1 equiv of **1a** or **1b** and 1.1 equiv of $EtAlCl_2$ in CH_2Cl_2. [b] Diastereomeric ratio determined by ^1H NMR analysis. [c] R = $TBSO(CH_2)_2$. [d] The crude product was treated with DBU to afford the corresponding enone.

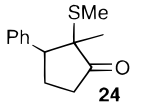
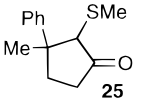
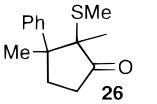
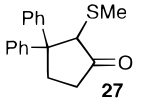
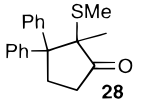
Diastereoselectivity. In addition to such regiochemical features, the reactions of **1b** with vinyl sulfides exhibited surprisingly high stereoselectivity. Although direct assignment of the configuration of the cyclopentanones was quite difficult, we found that the NOE experiments of the corresponding enol

(12) Alder, R. W.; Bowman, P. S.; Steele, W. R. P.; Winterman, D. R. *Chem. Commun.* **1968**, 723.

(13) (a) Stewart, J. J. P. *J. Comput. Chem.* **1989**, *10*, 209. (b) Stewart, J. J. P. *J. Comput. Chem.* **1989**, *10*, 211.

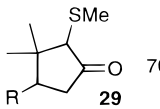
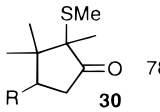
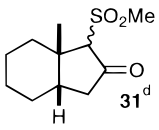
(14) One of the reviewers suggested that the Hammond postulate might be used to rationalize the results. Thus, the first C−C bond-forming step, in which both the reactant and product are cations, is probably not very exothermic and might have a late (or at least not early) transition state. Therefore, in the context of the Hammond postulate, energy differences in product stability may be reflected in the transition states, favoring the intermediate leading to the observed regioisomer.

Table 3. Annulation Reactions with Styrenes[a]

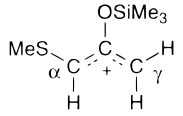
entry	olefin	enophile	product	yield	$E:Z$[b]
1		**1a**	 **23**	66%	50 : 50
2		**1b**	 **24**	95%	>99 : <1
3		**1a**	 **25**	79%	84 : 16
4		**1b**	 **26**	86%	74 : 26
5		**1a**	 **27**	77%	
6		**1b**	 **28**	99%	

[a] The olefins were treated with 1.1 equiv of **1a** or **1b** and 1.1 equiv of $EtAlCl_2$ in CH_2Cl_2. [b] Determined by ^1H NMR analysis.

Table 4. Annulation Reactions with Trialkylolefins[a]

entry	olefin	enophile	product	yield	ratio[b]
1[c]		**1a**	 **29**	70%	54 : 46
2[c]		**1b**	 **30**	78%	72 : 28
3		**1a**	 **31**[d]	64%	54 : 46

[a] The olefins were treated with 1.2 equiv of **1a** or **1b** and 3.0 equiv of $AlCl_3$ in the presence of 0.2 equiv of proton sponge in CH_2Cl_2. [b] Diastereomeric ratio determined by ^1H NMR analysis. [c] R = $Ph(CH_2)_4$. [d] The adduct was isolated as the corresponding sulfone after treating the crude product with oxone.



	Coefficient	Atom Charge
Cα	0.7020	+0.3214
Cγ	0.4744	-0.0599

Figure 1. Coefficients and atom charges of the molecular orbital of a model compound calculated by the PM3 Method.

silyl ethers give useful information to determine the stereochemistry as shown in Figure 3.

Several stereochemical features of the reactions of **1b** with vinyl sulfides have been noted.

(1) The configurational relationship between the C-2 and C-3 positions of the cycloadduct is highly dependent on the substituent at the α-position of a vinyl sulfide. Thus, vinyl sulfides with an olefinic hydrogen at this position always afford cyclopentanones in which the two alkylthio groups are cis to each other (eq 3). On the other hand, the opposite diastereoselectivity was observed in the reactions of vinyl sulfides having an α-alkyl group (eq 4).

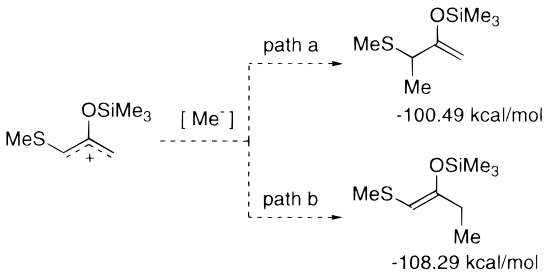
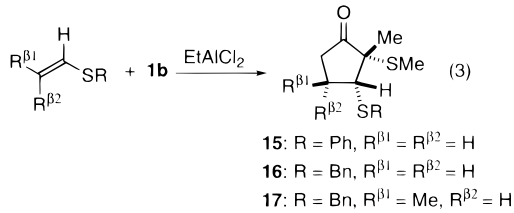
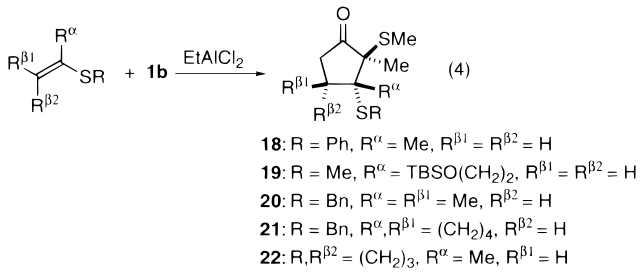


Figure 2. Heat of formation of model compounds for path a and path b calculated by the PM3 method.





(2) A vinyl sulfide containing a β-substituent gives a cyclopentanone with three continuous stereogenic centers. While a concerted cycloaddition reaction affords an adduct which retains the relative stereochemistry of the substituents in the olefin, a mixture of diastereomers may be obtained by a stepwise annulation reaction. It is noteworthy that the [3+2] cycloaddition of 1-(benzylthio)cyclohexene and 2-methyl-4,5-dihydrothiophene gave cyclopentanones **21** and **22** in diastereomerically pure form (entries 10 and 11 in Table 2), in which the stereochemistry at the C-3 and C-4 positions is consistent with the geometry of the vinyl sulfides.

(3) However, this is not the case for the acyclic vinyl sulfides. Thus, both of the geometrical isomers of 2-(benzylthio)-2-butene afforded the same diastereomer **20** as a major product (entries 7 and 8 in Table 2), and similar behavior was observed in the reactions of 1-(benzylthio)-1-propene (entries 3 and 4 in Table 2). These results suggested that the acyclic vinyl sulfides may rapidly undergo isomerization of geometry under the reaction conditions. Indeed, treatment of (*Z*)-2-(benzylthio)-2-butene with $EtAlCl_2$ afforded a mixture of geometrical isomers even at −78 °C. Judging from the stereochemistry at the C-3 and C-4 positions, cyclopentanones **17** and **20**, which have a configuration similar to that of **21**, seem to arise from the (*E*)-vinyl sulfide.

Since the [3+2] cycloaddition reaction proceeds through an ionic stepwise mechanism, such high selectivities should be remarkable enough to attract much attention from both synthetic and mechanistic viewpoints. In this connection, we have already reported a diastereoselective conjugate addition reaction of vinyl sulfides with α,β-unsaturated carbonyl compounds.[7i] In that paper, we suggested that the almost complete regio- and

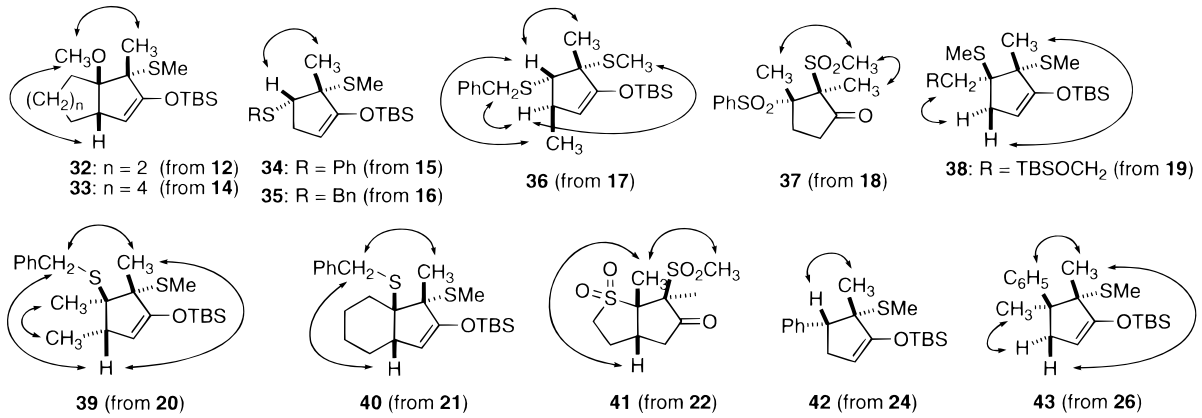
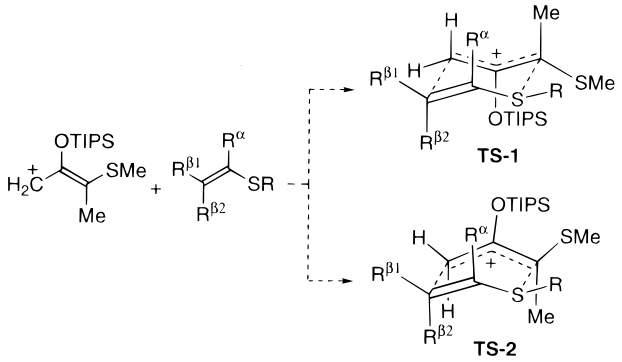
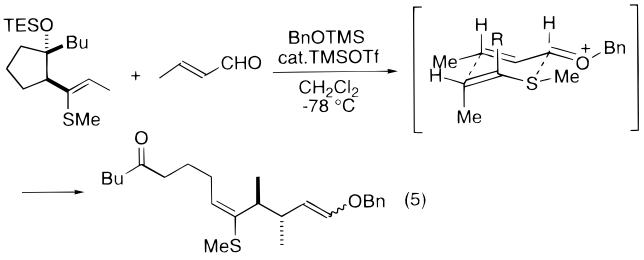


Figure 3. Determination of the stereochemistry by NOEs.

Scheme 4



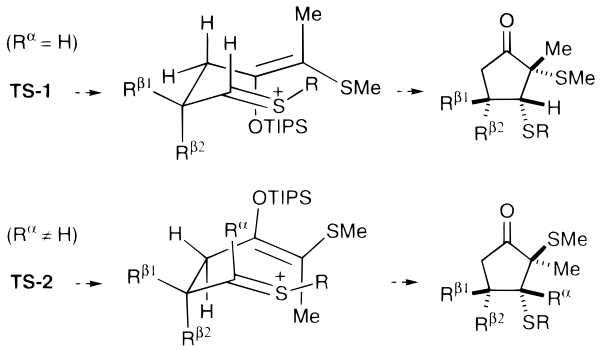
diastereoselection would come from a significant orbital interaction between the sulfur atom and the carbonyl carbon to fix the transition state as shown in eq 5.[15]



The characteristic features of the [3+2] cycloaddition reaction could also be accounted for by assuming similar cyclic transition state models in the first C−C bond formation step. At this initial stage, the allyl cation intermediate which retains the geometry of **1b** (vide supra) and a vinyl sulfide arrange themselves in parallel planes. PM3 calculations on a model of the allyl cation intermediate indicated that the α-carbon of the methylthio group has the largest LUMO coefficient, while a vinyl sulfide was found to have the largest HOMO coefficient at the sulfur atom.[7i] Taking into account an orbital interaction between these two atoms, six-membered cyclic transition state models **TS-1** (chairlike form) and **TS-2** (boatlike form) are assumed (Scheme 4). It should be noted that the regiochemistry of the cycloaddition products is exactly consistent with these transition state models.

(15) A similar six-membered transition state model has been suggested for [2+2] cycloaddition reactions of vinyl selenides and enones: (a) Yamazaki, S.; Fujitsuka, H.; Yamabe, S.; Tamura, H. *J. Org. Chem.* **1992**, *57*, 5610. (b) Yamazaki, S.; Fujitsuka, H.; Takara, F.; Inoue, T. *J. Chem. Soc., Perkin Trans. 1* **1994**, 695. (c) Yamazaki, S.; Tanaka, M.; Yamaguchi, A.; Yamabe, S. *J. Am. Chem. Soc.* **1994**, *116*, 2356.

Scheme 5



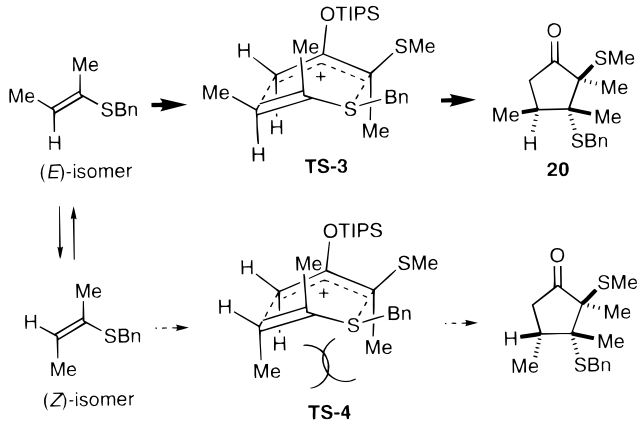
The first C−C bond formation through the cyclic transition state leads to a thionium ion intermediate which already has an almost suitable conformation to undergo the second C−C bond formation. Since there is no requirement for rotation of the cationic center or the enol silyl ether moiety of the thionium ion intermediate at this stage, the configuration of **TS-1** or **TS-2** would ultimately correspond to the stereochemistry of the cyclopentanone. Therefore, the stereochemical outcome of the cycloaddition reaction mentioned before could be rationalized as follows.

(1) **TS-1** would lead to a cyclopentanone in which the two alkylthio groups are cis to each other, while the corresponding C-2 epimer would be produced through **TS-2** (Scheme 5). In general, chairlike transition state **TS-1** may be more favored, and this is the case for the reactions of vinyl sulfides without an alkyl substituent at the α-position (R^α = H). On the other hand, vinyl sulfides having an α-alkyl group ($R^\alpha \neq$ H) would prefer **TS-2**, because **TS-1** suffers from the severe 1,3-diaxial steric repulsion between R^α of the vinyl sulfide and the methyl group of the allyl cation. Consequently, the α-substituent of a vinyl sulfide significantly influences the transition state and controls the relative configuration between the C-2 and C-3 positions of the cyclopentanone.

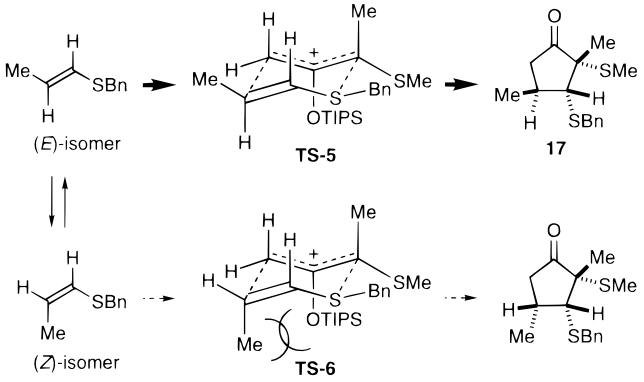
(2) The stereospecific cycloaddition reactions of cyclic vinyl sulfides could be explained by continuous C−C bond formation through **TS-2** without rotation of the cationic center or the enol silyl ether moiety of the thionium ion intermediate.

(3) Both of the geometrical isomers of 2-(benzylthio)-2-butene afforded the same diastereomer **20** as a major product, probably because of the rapid isomerization of geometry under the reaction conditions. The transition state models (**TS-3** and **TS-4**) for both of the geometrical isomers are depicted on the basis of **TS-2** (Scheme 6). Since **TS-4** contains the 1,4-diaxial steric repulsion between the β-methyl group of the vinyl sulfide and

Scheme 6



Scheme 7



the methyl group of the allyl cation, the cycloaddition reaction of (*Z*)-2-(benzylthio)-2-butene would be much more sluggish than that of the (*E*)-isomer. Therefore, not only the (*E*)-isomer but also the (*Z*)-isomer undergoes cycloaddition reaction through **TS-3** to give **20** as a major product.[16]

A similar mechanism involving fast isomerization of geometry can be applied to the reactions of 1-(benzylthio)-1-propene. In these cases, chairlike transition state models should be employed because this vinyl sulfide contains the olefinic hydrogen at the α-position, and preferential formation of **17** is attributable to the 1,3-diaxial steric repulsion between the *β*-methyl group of the vinyl sulfide and the siloxy group in **TS-6** (Scheme 7).

These transition state models are, of course, applicable only to the reactions of vinyl sulfides. On the other hand, moderate to high stereoselectivities were also observed in the reactions of enol ethers and styrenes. These results may suggest certain attractive interactions between the alkoxy group or phenyl group and the α-carbon of the allyl cation intermediate, although the origin of the interaction is not clear at the present stage.

Conclusion

In conclusion, an efficient [3+2] cyclopentanone annulation reaction was developed by employing 1-(methylthio)-2-siloxyallyl acetates **1a** and **1b** as new three-carbon units. Under the influence of $EtAlCl_2$ or $AlCl_3$, **1a** or **1b** reacted with various kinds of olefins to afford the corresponding cyclopentanones in almost complete regioselectivity. Furthermore, extremely high stereoselectivity was observed in the reactions of **1b** with vinyl sulfides, which can be rationalized by the six-membered transition state models involving an orbital interaction between the sulfur atom of the vinyl sulfide and the α-carbon of the allyl cation. The wide range of applicability as well as the high selectivities of this transformation would have advantages for natural product synthesis. Indeed, we have already demonstrated the utility of the present methodology in total synthesis of coriolin,[17] and synthetic studies on other natural products are now in progress.

Experimental Section

General Methods. All reactions were carried out under a positive pressure of dry nitrogen or argon. Diethyl ether and tetrahydrofuran were distilled from sodium and benzophenone immediately before use. CH_2Cl_2 was distilled successively from P_2O_5 and K_2CO_3 under nitrogen and stored over molecular sieves. Hexane was distilled from $LiAlH_4$ under nitrogen and stored over potassium mirror. HMPA and diisopropylamine were distilled from CaH_2 under nitrogen and stored over molecular sieves. Flash chromatography was performed using 40−100 *μ*m mesh KANTO (silica gel 60N, spherical, neutral) or 100 *μ*m mesh Fuji Silysia (FL100DX, spherical, basic) silica gel. Analytical TLC was carried out on 250-*μ*m Merck (Kiesegel 60F-254) silica gel plates. Melting points are corrected. ^1H and ^{13}C NMR spectra were recorded at 270 or 300 MHz (^1H) using $CDCl_3$ with tetramethylsilane as the internal standard.

Preparation of 1a and 1b: Ethyl (*Z*)-3-(Methylthio)-2-(triisopropylsiloxy)-2-propenoate (4a). To a solution of dimethyl disulfide (7.6 mL, 84 mmol) in hexane (155 mL) was added a 1.03 M ethereal solution of methyllithium (78 mL, 80 mmol) at 0 °C. After being stirred for 30 min at 0 °C, the solution was cooled to −78 °C, and ethyl bromopyruvate (**2**) (10 mL, 72 mmol) was added. After being stirred for 80 min, the reaction mixture was poured into saturated aqueous NH_4Cl solution. The mixture was separated, and the aqueous layer was extracted with ether. The combined organic layer was washed with brine, and dried over $MgSO_4$. Concentration under reduced pressure afforded crude ketoester **3a** which was used for the next step without purification. To a mixture of NaH (2.5 g, 105 mmol) and TIPSCl (18 mL, 84 mmol) in THF (80 mL) was added a solution of **3a** in THF (30 mL) at 0 °C. After being stirred for 13 h at 0 °C, the reaction mixture was poured into a saturated aqueous $NaHCO_3$ solution. The mixture was separated, and the aqueous layer was extracted with ether. The combined organic layer was washed with brine, and dried over $MgSO_4$. Concentration under reduced pressure followed by purification by flash column chromatography afforded **4a** (18.4 g, 57.8 mmol, 80% from ethyl bromopyruvate) as a colorless oil: IR (neat) 1720, 1640 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) *δ* 1.03−1.38 (m, 24 H), 2.36 (s, 3 H), 4.20 (q, 2 H, $J = 7.1$ Hz), 6.63 (s, 1 H); ^{13}C NMR ($CDCl_3$, 75 MHz) *δ* 13.56, 14.30, 16.88, 18.03, 60.83, 68.50, 123.60, 137.75, 162.71. Anal. Calcd for $C_{15}H_{30}O_3SSi$: C, 56.55; H, 9.49; S, 10.06. Found: C, 56.46; H, 9.50; S, 9.98.

(*Z*)-3-Acetoxy-1-(methylthio)-2-(triisopropylsiloxy)-1-propene (1a). A mixture of **4a** (2.1 g, 6.5 mmol) and a 0.93 M hexane solution of diisobutylaluminum hydride (17.4 mL, 16 mmol) in CH_2Cl_2 (35 mL) was stirred at −78 °C for 1 h. To this were added acetic anhydride (2.5 mL, 26 mmol) and 4-(dimethylamino)pyridine (3.2 g, 26 mmol), and the mixture was stirred for 30 min at room temperature. The mixture was poured into a saturated aqueous $NaHCO_3$ solution. The mixture was separated, and the aqueous layer was extracted with ether. The combined organic layer was washed with brine, and dried over $MgSO_4$. Concentration under reduced pressure followed by purification by flash column chromatography afforded **1a** (1.9 g, 6.0 mmol, 92%) as a colorless oil: IR (neat) 1740 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) *δ* 1.08−1.30 (m, 21 H), 2.08 (s, 3 H), 2.24 (s, 3 H), 4.48 (s, 2 H), 5.29 (s, 1 H); ^{13}C NMR ($CDCl_3$, 67.5 MHz) *δ* 13.17, 16.81, 17.90, 20.94,

(16) In this connection, a 1:1:1 mixture of (*Z*)-2-(benzylthio)-2-butene, 3-methyl-2-(benzylthio)-2-butene, and **1b** was treated with $EtAlCl_2$ at −45 °C, and preferential formation of cyclopentanone **20** (69%) over 3-(benzylthio)-2,3,4,4-tetramethyl-2-(methylthio)cyclopentanone (6%) was observed. The lower reactivity of the tetrasubstituted vinyl sulfide suggests that cycloaddition reaction through **TS-2** suffers from the 1,4-diaxial steric repulsion between $R^{\beta 2}$ of the vinyl sulfide and the methyl group of the allyl cation which can also be found in **TS-4**.

(17) Domon, K.; Masuya, K.; Tanino, K.; Kuwajima, I. *Tetrahedron Lett.* **1997**, *38*, 465.

65.83, 110.29, 143.64, 170.55. Anal. Calcd for $C_{15}H_{30}O_3SSi$: C, 56.55; H, 9.49; S, 10.06. Found: C, 56.27; H, 9.35; S, 9.81.

2-(Methylthio)propionic Acid (6). An aqueous solution of sodium 2-bromopropionate was prepared from 2-bromopropionic acid (**5**) (15 mL, 167 mmol), $NaHCO_3$ (14 g, 167 mmol), and 35 mL of water. To this was slowly added a 15% aqueous solution of MeSNa (82 mL, 175 mmol) at room temperature, and the mixture was stirred for 1 h. The reaction mixture was acidified by dropwise addition of concentrated hydrochloric acid using Congo Red as an indicator. The solution was extracted with ether, and the organic layer was washed with brine, and dried over $MgSO_4$. Concentration followed by distillation under reduced pressure (bp 78 °C, 1.5 mmHg) afforded **6** (19.4 g, 162 mmol, 97%) as a colorless oil: IR (neat) 3100, 1710 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ 1.47 (d, 3 H, J = 7.6 Hz), 2.21 (s, 3 H), 3.36 (q, 1 H, J = 7.6 Hz), 11.81 (br s, 1 H); ^{13}C NMR ($CDCl_3$, 67.5 MHz) δ 14.09, 16.09, 41.72, 179.33. Anal. Calcd for $C_4H_8O_2S$: C, 39.98; H, 6.71; S, 26.68. Found: C, 39.68; H, 6.54; S, 26.91.

Ethyl 3-(Methylthio)-2-oxobutyrate (3b). To an ice-cooled solution of diisopropylamine (20.4 mL, 144 mmol) in THF (145 mL) was added a 1.60 M hexane solution of butyllithium (90 mL, 144 mmol). After 10 min, acid **6** (6.4 mL, 60 mmol) and HMPA (48 mL) were added, and the solution was stirred for 2 h. The mixture was cooled to −23 °C, and diethyl oxalate (9.8 mL, 72 mmol) was added. After being stirred for 2 h at 0 °C, the mixture was acidified by dropwise addition of diluted hydrochloric acid. The mixture was separated, and the aqueous layer was extracted with ether. The combined organic layer was washed with a saturated aqueous $NaHCO_3$ solution followed by brine, and dried over $MgSO_4$. Concentration under reduced pressure followed by purification by flash column chromatography afforded **3b** (10.1 g, 57 mmol, 95%) as a colorless oil: IR (neat) 1740, 1720 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ 1.38 (t, 3 H, J = 7.1 Hz), 1.43 (d, 3 H, J = 6.9 Hz), 1.85 (s, 3 H), 4.17 (q, 1 H, J = 6.9 Hz), 4.36 (q, 2 H, J = 7.1 Hz); ^{13}C NMR ($CDCl_3$, 67.5 MHz) δ 10.11, 12.43, 13.93, 41.51, 62.50, 162.29, 184.43.

Ethyl (*Z*)-3-(Methylthio)-2-(triisopropylsiloxy)-2-butenoate (4b). According to the procedure for preparation of **4a**, **3b** (10.1 g, 57 mmol) was treated with NaH (2.1 g, 86 mmol) and TIPSCl (14.6 mL, 68.4 mmol) to afford **4b** (16.6 g, 49.8 mmol, 87%) as a colorless oil: IR (neat) 1700, 1630, 1555 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ 1.04−1.16 (m, 21 H), 1.33 (t, 3 H, J = 7.0 Hz), 2.11 (s, 3 H), 2.25 (s, 3 H), 4.25 (q, 2 H, J = 7.0 Hz); Anal. Calcd for $C_{16}H_{32}O_3SSi$: C, 57.78; H, 9.70; S, 9.64. Found: C, 57.56; H, 9.89; S, 9.84.

(*Z*)-1-Acetoxy-3-(methylthio)-2-(triisopropylsiloxy)-2-butene (1b). According to the procedure for preparation of **1a**, **4b** (16.6 g, 49.8 mmol) was treated with diisobutylaluminum hydride followed by acetic anhydride and 4-(dimethylamino)pyridine to afford **1b** (15.6 g, 46.8 mmol, 94%) as a colorless oil: IR (neat) 1740, 1625 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ 1.05−1.25 (m, 21 H), 2.03 (s, 3 H), 2.09 (s, 3 H), 2.17 (s, 3 H), 4.95 (s, 2 H); ^{13}C NMR ($CDCl_3$, 67.5 MHz) δ 13.36, 14.11, 15.59, 16.46, 17.88, 60.67, 127.03, 137.55, 164.72. Anal. Calcd for $C_{16}H_{32}O_3SSi$: C, 57.78; H, 9.70; S, 9.64. Found: C, 57.51; H, 9.81; S, 9.42.

General Procedure for the [3+2] Cycloaddition Reaction of 1a with Enol Ethers, Vinyl Sulfides, or Styrenes (Method A). To a mixture of **1a** (0.33 mmol) and an alkene (0.3 mmol) in CH_2Cl_2 (0.6 mL) was added a 1.0 M hexane solution of $EtAlCl_2$ (0.33 mL, 0.33 mmol) at −45 °C. After the mixture was stirred at adequate temperature until disappearance of the alkene (monitored by TLC), a saturated aqueous $NaHCO_3$ solution was added. The mixture was separated, and the aqueous layer was extracted with ether. The combined organic layer was washed with brine, dried over $MgSO_4$, and concentrated under reduced pressure. The crude product was treated with 1,8-diazabicyclo-[5.4.0]undec-7-ene (DBU) (0.13 mL, 0.9 mmol) in benzene (1.3 mL) for 1 day at room temperature. The mixture was poured into a saturated aqueous NH_4Cl solution. The mixture was separated, and the aqueous layer was extracted with ether. The combined organic layer was washed with brine, and dried over $MgSO_4$. Concentration under reduced pressure followed by purification by flash column chromatography (silica gel 60N, spherical, neutral) afforded the desired product.

General Procedure for the [3+2] Cycloaddition Reaction of 1b with Enol Ethers, Vinyl Sulfides, or Styrenes (Method B). To a mixture of **1b** (0.33 mmol) and an alkene (0.3 mmol) in CH_2Cl_2 (0.6 mL) under a nitrogen atmosphere was added a 1.0 M hexane solution of $EtAlCl_2$ (0.33 mL, 0.33 mmol) at −45 °C. After the mixture was stirred at adequate temperature until disappearance of the alkene (monitored by TLC), a saturated aqueous $NaHCO_3$ solution was added. The mixture was separated, and the aqueous layer was extracted with ether. The combined organic layer was washed with brine, and dried over $MgSO_4$. Concentration under reduced pressure followed by purification by flash column chromatography (silica gel 60N, spherical, neutral) afforded the desired product.

9-(Methylthio)bicyclo[4.3.0]non-1(9)-en-8-one (11): IR (neat) 1700, 1600, 1450, 1200, 950 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ 1.00−1.60 (m, 3 H), 1.78−2.22 (m, 5 H), 2.30 (s, 3 H), 2.56−2.66 (m, 2 H), 3.10−3.18 (m, 1 H); ^{13}C NMR ($CDCl_3$, 67.5 MHz) δ 15.37, 25.27, 26.56, 29.60, 34.92, 40.68, 41.44, 131.52, 182.01, 205.12. Anal. Calcd for $C_{10}H_{14}OS$: C, 65.89; H, 7.74; S, 17.59. Found: C, 66.18; H, 7.88; S, 17.29.

(1*R,6*S**,9*S**)-1-Methoxy-9-methyl-9-(methylthio)bicyclo[4.3.0]-nonan-8-one (12):** IR (neat) 1740, 1440, 1200, 1090 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ 1.20−1.68 (m, 10 H, involving a singlet at 1.40), 1.76−1.90 (m, 1 H), 2.24−2.42 (m, 6 H, involving a singlet at 2.26), 3.42 (s, 3 H); ^{13}C NMR ($CDCl_3$, 67.5 MHz) δ 12.44, 17.73, 19.98, 21.31, 23.86, 25.09, 37.24, 39.15, 50.98, 60.67, 82.78, 215.62. Anal. Calcd for $C_{12}H_{20}O_2S$: C, 63.11; H, 8.83; S, 14.04. Found: C, 63.40; H, 9.10; S, 14.30.

(2*R,3*S**,4*R**)-3-(Benzylthio)-2,4-dimethyl-2-(methylthio)cyclo-pentanone (17):** IR ($CDCl_3$) 1720, 1600, 1450, 1380, 1100, 1070 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ 1.06 (d, 3 H, J = 6.2 Hz), 1.22 (s, 3 H), 1.72−1.84 (m, 1 H), 1.91 (s, 3 H), 2.40−2.50 (m, 2 H), 2.78−2.90 (m, 1 H), 3.80 (d, 1 H, J = 12.2 Hz), 3.86 (d, 1 H, J = 12.2 Hz), 7.20−7.35 (m, 5 H); ^{13}C NMR ($CDCl_3$, 67.5 MHz) δ 10.49, 17.64, 18.19, 34.45, 37.96, 43.25, 58.68, 59.95, 127.29, 128.49, 129.26, 137.97, 206.93. Anal. Calcd for $C_{15}H_{20}OS_2$: C, 64.24; H, 7.19; S, 22.87. Found: C, 64.54; H, 7.34; S, 22.91.

(2*S,3*S**,4*R**)-3-(Benzylthio)-2,3,4-trimethyl-2-(methylthio)cyclo-pentanone (20):** IR (neat) 1730, 1500, 1450, 1380, 1240, 1050, 710 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ 1.32 (d, 3 H, J = 7.6 Hz), 1.49 (s, 3 H), 1.55 (s, 3 H), 2.05 (s, 3 H), 2.35 (dd, 1 H, J = 5.4, 18.4 Hz), 2.50−2.64 (m, 1 H), 2.71 (dd, 1 H, J = 9.5, 18.4 Hz), 3.80 (d, 1 H, J = 12.2 Hz), 3.89 (d, 1 H, J = 12.2 Hz), 7.20−7.35 (m, 5 H); ^{13}C NMR ($CDCl_3$, 67.5 MHz) δ 13.56, 17.56, 18.17, 18.54, 18.78, 34.09, 36.77, 41.64, 60.65, 127.15, 128.59, 129.03, 137.19, 210.56. Anal. Calcd for $C_{16}H_{22}OS_2$: C, 65.26; H, 7.53; S, 21.78. Found: C, 65.06; H, 7.76; S, 21.62.

(1*S,5*R**,8*S**)-8-Methyl-8-(methylthio)-2-thiabicyclo[3.3.0]octan-7-one (22):** mp 70 °C; IR (neat) 1720, 1710, 1450, 1220, 1070 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ 1.45 (s, 3 H), 1.56 (s, 3 H), 1.82−1.96 (m, 4 H, involving a singlet at 1.94), 2.10−2.32 (m, 2 H), 2.78−3.06 (m, 4 H); ^{13}C NMR ($CDCl_3$, 67.5 MHz) δ 11.97, 17.41, 23.72, 30.41, 32.38, 37.64, 46.43, 62.30, 69.85, 206.34. Anal. Calcd for $C_{10}H_{16}OS_2$: C, 55.51; H, 7.45; S, 29.64. Found: C, 55.35; H, 7.74; S, 29.40.

(2*S,3*R**)-2-Methyl-2-(methylthio)-3-phenylcyclopentanone (24):** mp 70 °C; IR (CH_2Cl_2) 1710, 1600, 1360, 1220, 710 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ 1.38 (s, 3 H), 1.84 (s, 3 H), 2.47−2.60 (m, 2 H), 2.78−2.89 (m, 1 H); ^{13}C NMR ($CDCl_3$, 67.5 MHz) δ 10.02, 18.04, 22.96, 35.04, 53.89, 55.96, 127.53, 128.03, 128.96, 136.91, 209.11. Anal. Calcd for $C_{13}H_{16}OS$: C, 70.87; H, 7.32; S, 14.55. Found: C, 70.81; H, 7.62; S, 14.29.

(2*R,3*S**)-3-Methyl-2-(methylthio)-3-phenylcyclopentanone (25).** This compound contains 16% of the minor diastereomer: IR (neat) 1730, 1380, 1260, 1150, 1070, 760, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ 1.36 (s, 3 H), 2.02 (s, 3 H), 2.10−2.82 (m, 4 H), 3.16 (s, 1 H), 7.20−7.40 (m, 5 H) with peaks due to the minor isomer at 1.44 (s), 2.16 (s), and 3.42 (s); ^{13}C NMR ($CDCl_3$, 67.5 MHz) δ 14.34, 30.17, 30.23, 33.14, 47.46, 60.36, 125.71, 126.65, 128.28, 144.58, 209.45. Anal. Calcd for $C_{13}H_{16}OS$: C, 70.87; H, 7.32; S, 14.55. Found: C, 70.60; H, 7.49; S, 14.37.

General Procedure for the [3+2] Cycloaddition Reaction of 1a or 1b with Trisubstituted Alkenes (Method C). To a mixture of aluminum chloride (120 mg, 0.9 mmol) and 1,8-bis(dimethylamino)-naphthalene (19.8 mg, 0.09 mmol) in CH_2Cl_2 (0.9 mL) was added a

solution of **1a** or **1b** (0.33 mmol) and a trisubstituted alkene (0.3 mmol) in CH_2Cl_2 (0.9 mL) at −45 °C. After the mixture was stirred at adequate temperature until disappearance of the alkene (monitored by TLC), a saturated aqueous $NaHCO_3$ solution was added. The mixture was separated, and the aqueous layer was extracted with ether. The combined organic layer was washed with brine, and dried over $MgSO_4$. Concentration under reduced pressure followed by purification by flash column chromatography (silica gel 60N, spherical, neutral) afforded the desired product.

2,3,3-Trimethyl-2-(methylthio)-4-(4-phenylbutyl)cyclopentanone (30). This compound was obtained as a 72:28 mixture of diastereomers: IR (neat) 1720, 1450, 1250, 1080, 760, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ 0.76 (s, 3 H), 1.02−1.90 (m, 15 H, involving singlets at 1.08, 1.18, and 1.88), 2.22−2.56 (m, 2 H), 2.62 (td, 2 H, J = 2.7, 7.8 Hz), 2.75 (dd, 1 H, J = 8.6, 18.9 Hz), 7.10−7.35 (m, 5 H) with peaks due to the minor isomer at 0.98 (s), 1.02 (s), 1.22 (s), and 2.01 (s); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 10.77, 11.74, 12.83, 13.19, 16.23, 16.46, 17.96, 18.03, 19.28, 19.48, 20.36, 26.78, 28.47, 28.75, 29.74, 31.50, 31.66, 32.06, 35.83, 39.77, 39.84, 41.40, 43.43, 44.94, 60.55, 62.11, 125.63, 128.22, 128.32, 142.44, 208.94, 213.62. Anal. Calcd for $C_{19}H_{28}OS$: C, 74.95; H, 9.27; S, 10.53. Found: C, 74.66; H, 9.42; S, 10.33.

General Procedure for Preparation of Enol Silyl Ethers 32, 33, 34, 35, 36, 38, 39, 40, 42, and 43. To an ice-cooled solution of a cyclopentanone derivative (0.1 mmol) and 2,6-lutidine (0.6 mmol) in CH_2Cl_2 (0.6 mL) was added *tert*-butyldimethylsilyl trifluoromethanesulfonate (69 μL, 0.3 mmol). After the mixture was stirred at room temperature until disappearance of the ketone (monitored by TLC), a saturated aqueous $NaHCO_3$ solution was added. The mixture was separated, and the aqueous layer was extracted with ether. The combined organic layer was washed with brine, and dried over $MgSO_4$. Concentration under reduced pressure followed by purification by flash column chromatography afforded the corresponding enol silyl ethers.

(1*R,6*S**,9*S**)-8-(*tert*-Butyldimethylsiloxy)-1-methoxy-9-methyl-9-(methylthio)bicyclo[4,3,0]non-7-ene (32).** This compound was prepared from **12** in 92% yield: IR (neat) 1640, 1460, 1300, 1250, 1110, 1090 cm^{-1}; ^1H NMR ($CDCl_3$, 270 MHz) δ 0.18 (s, 3 H), 0.22 (s, 3 H), 0.96 (s, 9 H), 1.18−1.64 (m, 10 H, involving a singlet at 1.38), 2.16 (s, 3 H), 2.28 (d, 1 H, J = 14.6 Hz), 2.67 (br s, 1 H), 3.48 (s, 3 H), 4.28 (bs, 1 H); ^{13}C NMR ($CDCl_3$, 67.5 MHz) δ −4.89, −4.56, 13.26, 17.36, 18.22, 21.28, 22.07, 25.20, 25.38, 25.72, 43.88, 51.36, 61.67, 85.64, 102.28, 156.62. Anal. Calcd for $C_{18}H_{34}O_2SSi$: C, 63.10; H, 10.00; S, 9.36. Found: C, 63.34; H, 10.29; S, 9.21.

(3*S,4*R**,5*R**)-4-(Benzylthio)-1-(*tert*-butyldimethylsiloxy)-3,4,5-trimethyl-5-(methylthio)cyclopentene (39).** This compound was prepared from **20** in 87% yield: IR (neat) 1640, 1240, 1080, 840 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.00 (s, 3 H), 0.04 (s, 3 H), 0.77 (s, 9 H), 0.90 (d, 3 H, J = 9.0 Hz), 1.36 (s, 3 H), 1.96 (s, 3 H), 2.44−2.54 (m, 1 H), 3.67 (d, 1 H, J = 6.0 Hz), 3.83 (d, 1 H, J = 6.0 Hz), 4.22 (d, 1 H, J = 1.9 Hz), 7.00−7.20 (m, 5 H); ^{13}C NMR ($CDCl_3$, 67.5 MHz) δ −5.05, −4.59, 14.09, 15.67, 18.14, 20.01, 22.02, 25.64, 33.71, 44.10, 61.87, 63.49, 103.92, 126.77, 128.43, 129.03, 138.40, 156.23. Anal. Calcd for $C_{22}H_{36}OS_2Si$: C, 64.65; H, 8.88; S, 15.69. Found: C, 64.55; H, 9.00; S, 15.95.

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Supporting Information Available: Preparation of the vinyl sulfides in Table 2 and 3-methyl-2-(benzylthio)-2-butene and characterization data for **8**, **9**, **13**−**16**, **18**, **19**, **21**, **23**, **26**−**29**, **31**, **33**−**38**, **40**−**43**, and 3-(benzylthio)-2,3,4,4-tetramethyl-2-(methylthio)cyclopentanone (8 pages). See any current masthead page for ordering information and Web access instructions.

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