# Ti(II)-Mediated Allenyne Cyclization as a New Tool for Generation of Chiral Organotitanium Compounds. Asymmetric Generation of Cyclic Allyltitanium Reagents with No Chiral Auxiliary

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**Abstract:** Treatment of a variety of 1,2-dien-7-ynes with a slight excess of ($\eta^2$-propene)Ti(O-*i*-Pr)$_2$ (**1**), prepared *in situ* from Ti(O-*i*-Pr)$_4$ and 2 equiv of *i*-PrMgCl in ether, afforded 1-alkenyl-2-alkylidenecyclopentanes in moderate to good yields after aqueous workup. The intermediate titanabicycle such as **7** was identified by deuterolysis, which gave $d_2$-**8** with exclusive deuterium incorporation. The use of an optically active allene such as **19** (≤83% ee) realized a highly efficient axial to centered chirality transfer to give **21** (80−83% ee). Analogously, the cyclization of **22** (≤86% ee) with **1** followed by carbonylation (under *ca.* 1 atm of CO) afforded the optically active bicyclic ketone **25** (86% ee). When a homologous 1,2-dien-6-yne **27** was subjected to the cyclization as above, a different type of titanabicycle **28** was generated, which was identified by hydrolysis giving **29** or the following carbonyl addition. Upon reaction with nonanal, **28** afforded the alcohol **32** with very high regio- (with respect to the allylic system), stereo- (the diene moiety), and diastereoselectivities (the hydroxy group). Various 1,2-dien-6-ynes underwent the cyclization followed by the addition to carbonyl compounds in comparable selectivities as above. Chiral 1,2-dien-6-ynes **46** (≤83% ee) achieved a nearly complete chirality transfer to generate a chiral titanabicycle **48**, which, in turn, reacted with nonanal, acetone, or *N*-benzylidenepropylamine to afford the alcohols **51** and **52** (both in 80% ee) or the amine **53** (81% ee) in good yields with a very small loss of the enantiopurity.

## Introduction

Chiral allenes are a versatile intermediate for asymmetric synthesis via the axial to centered chirality transfer and have attracted much attention recently.[1−3] In addition, transition metal-promoted carbon−carbon bond-forming reactions based on allenes, which are of current interest in organic synthesis,[4] allow opportunities to develop novel transformations characteristic of these compounds. In conjunction with our program on the titanium-mediated cyclization,[5] we envisaged that the axial chirality of allene could be transferred to a centered chirality incorporated in the structure of an organometallic moiety that is otherwise difficult to generate. We expected that the treatment of a chiral allenyne such as **2** with ($\eta^2$-propene)-Ti(O-*i*-Pr)$_2$ (**1**)[6−8] would produce optically active titanabicycles such as **4** or **5** *via* **3** (paths a and b in Scheme 1). The objectives of our study centered on (i) the feasibility of both paths, (ii) the choice of the substrates to affect the efficient chirality transfer to **4** or **5**, (iii) the configurational stability of the titanacycle **5** that has an allyltitanium moiety (*vide infra*), and finally (iv) the high degree of chirality transfer from **4** or **5** to the final products. It should be noted that the titanabicycle **5** belongs to a rare class of chiral allyltitanium compounds,[9,10] because it has no extra chiral auxiliary nor chiral ligands to the titanium metal, and, instead, the structure itself is chiral. To

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(1) For reviews, see: (a) Smadja, W. *Chem. Rev.* **1983**, *83*, 263. (b) Pasto, D. J. *Tetrahedron* **1984**, *40*, 2805. (c) Schuster, H. F.; Coppola, G. M. *Allenes in Organic Synthesis*; Wiley: New York, 1984. For a comprehensive survey on the synthetic methods of various allenes, see: (d) Brandsma, L.; Verkruijsse, H. D. *Synthesis of Acetylenes, Allenes and Cumulenes*; Elsevier: Amsterdam, 1981.

(2) For recent examples, see: (a) Shepard, M. S.; Carreira, E. M. *J. Am. Chem. Soc.* **1997**, *119*, 2597. (b) Ikeda, I.; Honda, K.; Osawa, E.; Shiro, M; Aso, M.; Kanematsu, K. *J. Org. Chem.* **1996**, *61*, 2031. (c) Borzilleri, R. M.; Weinreb, S. M.; Parvez, M. *J. Am. Chem. Soc.* **1995**, *117*, 10905. (d) Masse, C. E.; Panek, J. S. *Chem. Rev.* **1995**, *95*, 1293. (e) Ikeda, I.; Kanematsu, K. *J. Chem. Soc., Chem. Commun.* **1995**, 453. (f) Marshall, J. A.; Perkins, J. *J. Org. Chem.* **1994**, *59*, 3509. (g) Carreira, E. M.; Hastings, C. A.; Shepard, M. S.; Yerkey, L. A.; Millward, D. B. *J. Am. Chem. Soc.* **1994**, *116*, 6622. (h) De Schrijver, J.; De Clercq, P. L. *Tetrahedron Lett.* **1993**, *34*, 4369. (i) Matsumoto, Y.; Naito, M.; Uozumi, Y.; Hayashi. T. *J. Chem. Soc., Chem. Commun.* **1993**, 1468. (j) Myers, A. G.; Condroski, K. R. *J. Am. Chem. Soc.* **1993**, *115*, 7926.

(3) Yoshida, Y.; Okamoto, S.; Sato, F. *J. Org. Chem.* **1996**, *61*, 7826.

(4) Trost, B. M.; Kottirsch, G. *J. Am. Chem. Soc.* **1990**, *112*, 2816. Yamamoto, Y.; Al-Masum, M.; Asao, N. *J. Am. Chem. Soc.* **1994**, *116*, 6019. Yamaguchi, M.; Omata, K.; Hirama, M. *Tetrahedron Lett.* **1994**, *35*, 5689. Ma, S.; Negishi, E. *J. Org. Chem.* **1994**, *59*, 4730. Besson, L.; Goré, J.; Cazes, B. *Tetrahedron Lett.* **1995**, *36*, 3853. Besson, L.; Goré, J.; Cazes, B. *Tetrahedron Lett.* **1995**, *36*, 3857. Ahmar, M.; Antras, F.; Cazes, B. *Tetrahedron Lett.* **1995**, *36*, 4417. Bates, R. W.; Rama-Devi, T.; Ko, H.-H. *Tetrahedron* **1995**, *51*, 12939. Doi, T.; Yanagisawa, A.; Nakanishi, S.; Yamamoto, K.; Takahashi, T. *J. Org. Chem.* **1996**, *61*, 2602. Araki, S.; Usui, H.; Kato, M.; Butsugan, Y. *J. Am. Chem. Soc.* **1996**, *118*, 4699.

(5) (a) Urabe, H.; Hata, T.; Sato, F. *Tetrahedron Lett.* **1995**, *36*, 4261. (b) Urabe, H.; Takeda, T.; Sato, F. *Tetrahedron Lett.* **1996**, *37*, 1253. (c) Urabe, H.; Sato, F. *J. Org. Chem.* **1996**, *61*, 6756. (d) Suzuki, K.; Urabe, H.; Sato, F. *J. Am. Chem. Soc.* **1996**, *118*, 8729.

(6) The generation of olefin(derived from the added Grignard reagent)−titanium complexes from Ti(OR)$_4$ and Grignard reagents was first reported by Kulinkovich *et al.* They utilized this complex as 1,2-bis-anionic species, see: Kulinkovich, O. G.; Sviridov, S. V.; Vasilevski, D. A. *Synthesis* **1991**, 234. See also: de Meijere, A.; Kozhushkov, S. I.; Spaeth, T.; Zefirov, N. S. *J. Org. Chem.* **1993**, *58*, 502. Lee, J.; Kim, H.; Cha, J. K. *J. Am. Chem. Soc.* **1995**, 117, 9919. Corey, E. J.; Rao, S. A.; Noe, M. C. *J. Am. Chem. Soc.* **1994**, *116*, 9345.

(7) Similar titanium species having an aryloxy group in place of the alkoxy group is known. Balaich, G. J.; Rothwell, I. P. *J. Am. Chem. Soc.* **1993**, *115*, 1581. Balaich, G. J.; Rothwell, I. P. *Tetrahedron* **1995**, *51*, 4463.

(8) For the initial reports on the use of ($\eta^2$-propene)Ti(O-*i*-Pr)$_2$ prepared *in situ* from Ti(O-*i*-Pr)$_4$ and *i*-PrMgCl as a divalent titanium reagent, see: Kasatkin, A.; Nakagawa, T.; Okamoto, S.; Sato, F. *J. Am. Chem. Soc.*, **1995**, *117*, 3881. Harada, K.; Urabe, H.; Sato, F. *Tetrahedron Lett.* **1995**, *36*, 3203. See also: Okamoto, S.; Kasatkin, A.; Zubaidha, P. K.; Sato, F. *J. Am. Chem. Soc.* **1996**, *118*, 2208. Lee, J.; Kim, H.; Cha, J. K. *J. Am. Chem. Soc.* **1996**, *118*, 4198.

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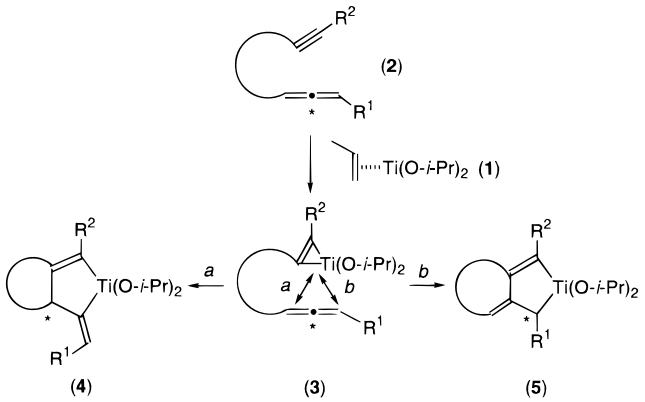
**Scheme 1**




our best knowledge, only one example is recorded for this type of optically active allyltitanium reagent.[11] The difficulty of the access to this allyltitanium compound may arise from the lack of a practical method for its generation and the possibility of spontaneous racemization *via* allylic migration of the metal and *cis*/*trans* isomerization of the allylic system, even if once generated.[12]

As study of early-transition metal-mediated intramolecular cyclizations[13] involving an allene is so far limited and few examples are found in the literature,[14−16] no systematic studies on the feasibility and selectivity of the cyclization have been executed nor were synthetic applications of the intermediate metallacycles explored.[17] Accordingly, we initiated our work to determine what requirements should be fulfilled to realize the above points i−iv. In addition to the solutions to these problems, the full scope and limitation of the present reaction to generate synthetically useful organotitanium compounds will be disclosed.

(9) For reviews on organotitanium reagents, see: Reetz, M. T. *Organotitanium Reagents in Organic Synthesis*; Springer-Verlag: Berlin, 1986. Ferreri, C.; Palumbo, G.; Caputo, R. In *Comprehensive Organic Synthesis*; Trost, B. M., Ed.; Pergamon Press: Oxford, 1991; Vol. 1, p 139. Reetz, M. T. In *Organometallics in Synthesis*; Schlosser, M., Ed.; Wiley: Chichester, 1994; p 195.

(10) For a review on chiral allyltitanium reagents, see: Duthaler, R. O.; Hafner, A. *Chem. Rev.* **1992**, *92*, 807.

(11) Hoppe, D.; Krämer, T. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 160. See also: Zschage, O.; Hoppe, D. *Tetrahedron* **1992**, *48*, 5657.

(12) An allyltitanium compound undergoes the fast allylic migration and *cis*/*trans* isomerization. Duthaler, R. O.; Hafner, A.; Riediker, M. *Pure Appl. Chem.* **1990**, *62*, 631.

(13) For reviews on early transition metal-mediated cyclization of olefins and acetylenes, see: (a) Yasuda, H.; Tatsumi, K.; Nakamura, A. *Acc. Chem. Res.* **1985**, *18*, 120. (b) Buchwald, S. L.; Nielsen, R. B. *Chem. Rev.* **1988**, *88*, 1047. (c) Negishi, E. In *Comprehensive Organic Synthesis*; Trost, B. M., Ed.; Pergamon Press: Oxford, 1991; Vol. 5, p 1163. (d) Negishi, E.; Takahashi, T. *Acc. Chem. Res.* **1994**, *27*, 124. (e) Ohff, A.; Pulst, S.; Lefeber, C.; Peulecke, N.; Arndt, P.; Burkalov, V. V.; Rosenthal, U. *Synlett* **1996**, 111. (f) Sato, F.; Urabe, H. In *Handbook of Grignard Reagents*; Silverman, G. S.; Rakita, P. E., Eds.; Marcel Dekker: New York, 1996; p 23.

(14) Negishi, E.; Holmes, S. J.; Tour, J. M.; Miller, J. A.; Cederbaum, F. E.; Swanson, D. R.; Takahashi, T. *J. Am. Chem. Soc.* **1989**, *111*, 3336.

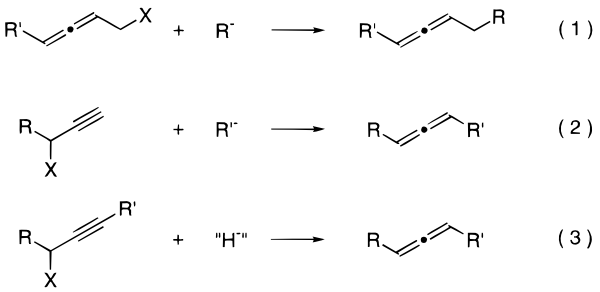
(15) Hicks, F. A.; Kablaoui, N. M.; Buchwald, S. L. *J. Am. Chem. Soc.* **1996**, *118*, 9450.

(16) Portions of this work were orally presented at the 70th Symposium on Organic Synthesis, Japan; November 6−8, 1996, Tokyo (Urabe, H.; Suzuki, K.; Takeda, T.; Hideura, D.; Sato, F. *Abstr. of the Symposium* **1996**, 17) and at the 72nd Annual Meeting of the Chemical Society of Japan; March 27-30, 1997, Tokyo (Hideura, D.; Takeda, T.; Urabe, H.; Sato, F. *Abstr. II* **1997**, 874. Takeda, T.; Urabe, H.; Sato, F. *Abstr. II* **1997**, 875).

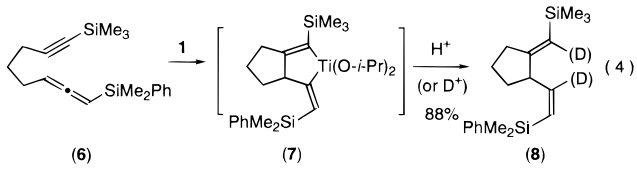
(17) For other transition metal-promoted intramolecular cyclization involving allenes, see: Trost, B. M.; Tour, J. M. *J. Am. Chem. Soc.* **1988**, *110*, 5231. Trost, B. M.; Matsuda, K. *J. Am. Chem. Soc.* **1988**, *110*, 5233. Kent, J. L.; Wan, H.; Brummond, K. M. *Tetrahedron Lett.* **1995**, *36*, 2407. Wender, P. A.; Jenkins, T. E.; Suzuki, S. *J. Am. Chem. Soc.* **1995**, *117*, 1843. Llerena, D.; Aubert, C.; Malacria, M. *Tetrahedron Lett.* **1996**, *37*, 7027. Murakami, M.; Itami, K.; Ito, Y. *J. Am. Chem. Soc.* **1997**, *119*, 2950.

## Results and Discussion

**Preparation of the Starting Materials.** Throughout this study, the starting materials including an allene moiety were conveniently prepared by either alkylation of allenylmethyl halides[1d] with an appropriate carbanioic species (eq 1), a highly $S_N2'$-selective displacement of propargyl alcohol derivatives with organocopper reagents (eq 2),[1d,2c,18] or intramolecular regio- and stereoselective reduction of an acetylenic substrate as shown in eq 3.[2a,19] The R group in these equations has another unsaturated bond such as acetylene so that the bis-unsaturated compounds are obtained ready for the cyclization. As shown in typical procedures in the supporting information, these reactions require standard synthetic operations and generally proceed to give good yields (53−84%). Optically active allenes with defined stereochemistry were accessible according to eqs 2 and 3 starting from optically active propargyl alcohols.




**Cyclization of 1,2-Dien-7-ynes.** A bis-silylated 1,2-octadien-7-yne **6** underwent very clean cyclization with a slight excess of ($\eta^2$-propene)Ti(O-*i*-Pr)$_2$ (**1**), prepared *in situ* from Ti(O-*i*-Pr)$_4$ and *i*-PrMgCl,[8] at −50 °C for 2 h to give product **8** as a single isomer after hydrolytic workup (eq 4).[5] This product apparently arose from the path a in Scheme 1. This regioselection was well explained by the most favorable five-membered ring closure and the accord with the preferential mode of the sterically nonbiased, *inter*molecular cyclization.[20] The stereochemistry of **8** was verified by the $^1$H NMR analysis. Alternatively, deuteration of the reaction mixture afforded exclusively bis-deuterated product $d_2$-**8**, confirming the presence of the intermediate titanacycle **7** in eq 4.



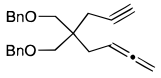
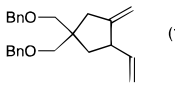
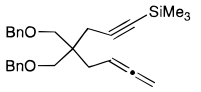
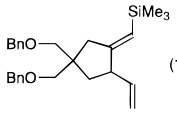
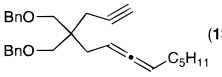
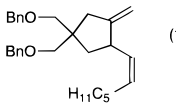
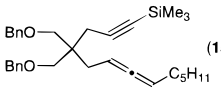
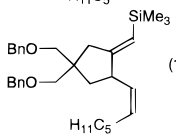
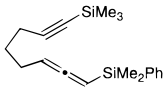
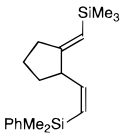
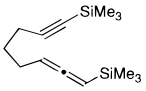
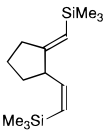

This titanium-mediated intramolecular cyclization seems to be general and other results are summarized in Table 1. The substrates having a terminal allene moiety afforded the desired product in moderate yields (entries 1 and 2). This came from the partial consumption of the starting material by the homocoupling of the terminal allene.[20b,21]

However, terminal acetylenes are acceptable partners in this cyclization (entry 3). The geometry of the newly-formed disubstituted olefinic bond was controlled to *Z* in good selectivities by an alkyl substituent of the starting allene. This *Z* selectivity jumped to an exclusive level by a silyl group apparently owing to its sterically demanding nature (entries 5 and 6).[3] A most plausible reaction course illustrated in eq 5 involves the formation of the titanabicycle **7** from the less

(18) (a) Fleming, I.; Terrett, N. K. *J. Organomet. Chem.* **1984**, *264*, 99. (b) Trost, B. M.; Urabe, H. *J. Am. Chem. Soc.* **1990**, *112*, 4982.

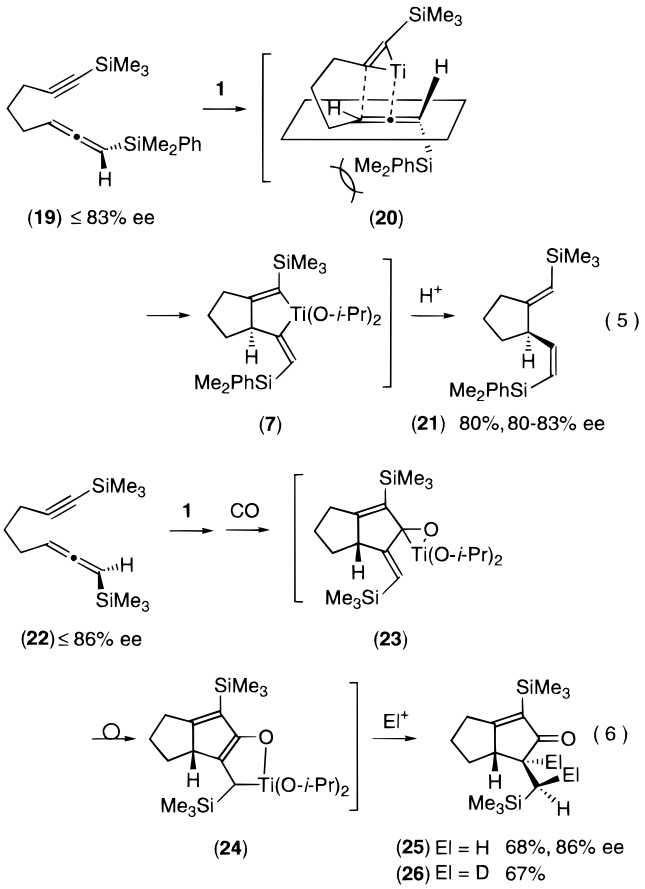
(19) Myers, A. G.; Zheng, B. *J. Am. Chem. Soc.* **1996**, *118*, 4492.

**Table 1.** Cyclization of 1,2-Dien-7-ynes[a]

| Entry | Substrate | | Product[b] | | Yield (%) | *E*/*Z*[c] |
|---|---|---|---|---|---|---|
| 1 |  | (**9**) |  | (**10**) | 45 | -- |
| 2 |  | (**11**) |  | (**12**) | 42 | -- |
| 3 |  | (**13**) |  | (**14**) | 77 | 20:80 |
| 4 |  | (**15**) |  | (**16**) | 98 | 18:82 |
| 5 |  | (**6**) |  | (**8**) | 88 | *Z* only |
| 6 |  | (**17**) |  | (**18**) | 87 | *Z* only |

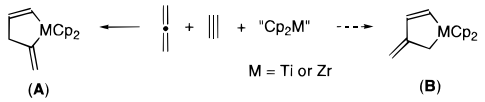
[a]See eq 4. [b]Major isomer is shown. [c]With respect to the newly formed di-substituted double bond.

hindered side of the allene moiety (i. e., *via* **20**, the ligands on the titanium atom were omitted to simplify the structure), which could account for the stereochemistry of the products. To attest the aforementioned chirality transfer to yield the titanabicycle of the type **4** and to show its synthetic advantage, we submitted optically active (*S*)-**19**[22] to the cyclization (eq 5). The product **21** was isolated with nearly complete retention of the enantiomeric excess (ee) of the starting material (≤83% ee), as determined directly by chiral shift study on $^1$H NMR spectroscopy (80% ee)[23] or after derivatization to (1*R*,2*R*)-1-(hydroxymethyl)-2-vinylcyclopentane (83% ee), the absolute stereochemistry of which was established by correlation to an authentic sample. From the synthetic viewpoint, this transformation provides a method for the creation of a chiral, cyclic tertiary carbon center carrying no adjacent functionality such as a carbonyl group[24] with the predictable sense. This chirality transfer was also useful in the carbonylative cyclization[5a] to give optically active bicyclic ketones (eq 6). Cyclization of **22**[22] followed by exposure of the intermediate titanabicycle to carbon monoxide under atmospheric pressure gave an optically active bicyclic ketone **25**, which would result from the rearrangement of the transient oxa(titana)cyclopropane **23** to a titanium homoenolate equivalent **24**.[25,26] The presence of **24** was evidenced by the treatment of the reaction mixture with DCl/$D_2O$ that afforded **26** exclusively, incorporating one deuterium atom at the α and another at the β position to the carbonyl group, both in a stereoselective manner. The enantiomeric purity of **25** was again verified to be as high as the original value of **22** and its stereochemistry was deduced based on the observation in eq 5.




**Cyclization of 1,2-Dien-6-ynes.** 1,2-Dien-6-yne is an interesting substrate to see whether the cyclization proceeds *via* path a or b in Scheme 1 or it does not take place, because path a leads to a stained cyclobutane framework, while path b violates the fulfillment of the intrinsic regiochemical preference observed for the intermolecular cyclization.[20] Treatment of **27** with **1** at −50 °C for 2 h completed the generation of the new titanabicycle **28**,[27] which, upon workup with 1 N HCl, afforded **29** (as an almost equimolar mixture of the positional isomers with respect to the double bond) (Scheme 2). Thus, the cyclization

(20) (a) Maercker, A.; Groos, A. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 210. (b) Yin, J.; Jones, W. M. *Tetrahedron* **1995**, *51*, 4395. (c) Doxsee, K. M.; Juliette, J. J. J.; Zientara, K.; Nieckarz, G. *J. Am. Chem. Soc.* **1994**, *116*, 2147. (d) Yin, J.; Abboud, K. A.; Jones, W. M. *J. Am. Chem. Soc.* **1993**, *115*, 3810. These intermolecular reactions always furnish the metallacycles **A** (rather than **B**) having two alkenyl−metal bonds. Path a in Scheme 1 fulfills this preference.




(21) Schmidt, J. R.; Duggan, D. M. *Inorg. Chem.* **1981**, *20*, 318. Duggan, D. M. *Inorg. Chem.* **1981**, *20*, 1164. Binger, P.; Langhauser, F.; Wedemann, P.; Gabor, B.; Mynott, R.; Krüger, C. *Chem. Ber.* **1994**, *127*, 39.

(22) The ee's of the samples, **19**, **22**, **46**, and **54**, may be somewhat lower than the specified values.

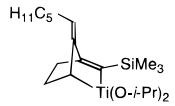
(23) Wenzel, T. J.; Sievers, R. E. *J. Am. Chem. Soc.* **1982**, *104*, 382.

(24) For relevant but alternative approaches, see: Trost, B. M.; Phan, L. T. *Tetrahedron Lett.* **1993**, *34*, 4735. Goeke, A.; Sawamura, M.; Kuwano, R.; Ito, Y. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 662.

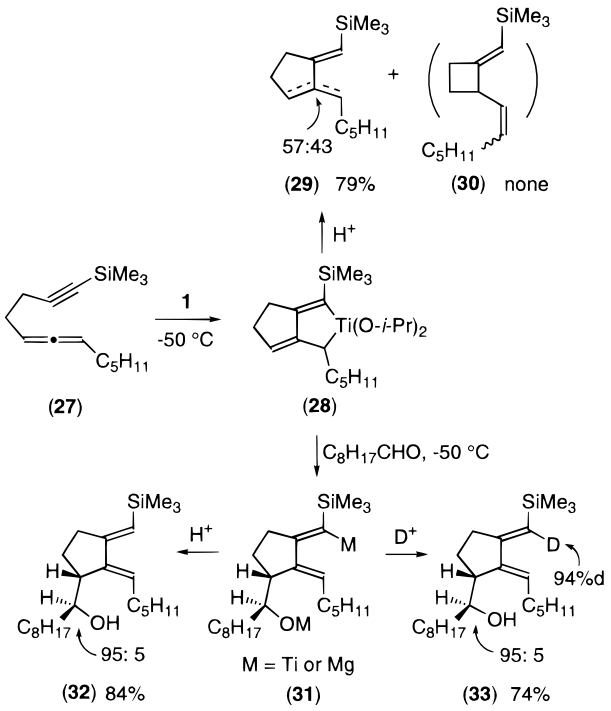
(25) Probert, G. D.; Whitby, R. J.; Coote, S. J. *Tetrahedron Lett.* **1995**, *36*, 4113. Barluenga, J.; Sanz, R.; Fañanás, F. J. *J. Chem. Soc., Chem. Commun.* **1995**, 1009. Mori, M.; Uesaka, N.; Saitoh, F.; Shibasaki, M. *J. Org. Chem.* **1994**, *59*, 5643.

(26) For a review on homoenolates and their equivalents, see: Werstiuk, N. H. *Tetrahedron* **1983**, *39*, 205.

(27) One referee suggested the possibility of another isomer shown below. However, its contribution is much less likely due to the highly strained structure.



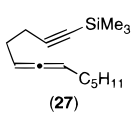
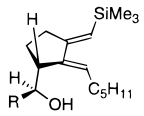
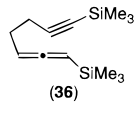
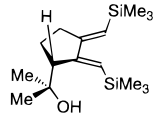
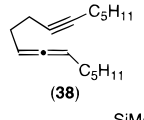
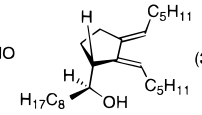
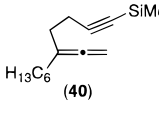
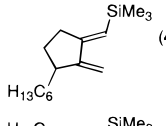
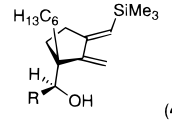
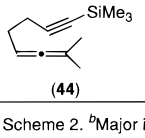
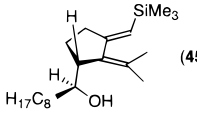
**Scheme 2**




proved to proceed *via* path b, which has not been previously documented in the cyclization of allene and acetylene.[15,16] The regioisomer **30** arising from path a was not seen. The synthetic utility of the titanabicycles such as **28** could be emphasized in the preparation of the substituted cyclopentane ring *via* a highly stereoselective reaction with carbonyl compounds.[9,10] For instance, addition of the titanabicycle **28** to nonanal afforded the alcohol **32** with high diastereoselectivities.[28] The addition selectively took place at the allyltitanium moiety, but not at the vinyl−titanium bond at all.[5b,29] Furthermore, another regioisomer with respect to the allylic system and the stereoisomers of the diene moiety were not observed. The structure of the stereogenic centers in **32** was established by correlation to an authentic sample. In addition, the workup of the reaction mixture with deuteriochloric acid afforded **33** with deuterium at the vinylic position, confirming the presence of the bismetalated species **31**, which may be useful for further synthetic elaboration.

A variety of allenynes and carbonyl compounds participate in the present cyclization and subsequent reaction as summarized in Table 2. Unsaturated aldehydes reacted with the titanabicycle **28** in regio- and stereoselective manner with respect to the diene moiety. However, the diastereoselectivity seems to decrease as compared to saturated aldehydes (entries 2 and 3). The stereochemistry of the benzaldehyde adduct **35** was also independently verified by derivatization. The bis-silyl or bis-alkyl counterparts **36** and **38** behaved similarly to give adducts (entries 4 and 5). 2,2-Bis-substituted allene **40** gave the titanabicycle intermediate, which was led to the single diene **41** upon hydrolysis. The aldehyde addition took place again in a highly regio- and diastereoselective manner to give virtually single adducts **42** and **43**, which serves for the stereoselective construction of a quaternary carbon center incorporated in a cyclopentane ring.[30] The relative configuration of the stereogenic centers was identified by derivatization to an authentic sample. Even with a more congested, trisubstituted allene bond such as that in **44**, the ring closure proved to be still feasible (entry 9). The cyclization and aldehyde addition proceeded under standard reaction conditions to furnish an almost single product. The direct introduction of an isopropylidene group to the product, which is definitely not possible by the existing olefin- and acetylene-based cyclizations, broadens the synthetic application of the metal-mediated cyclization.

**Table 2.** Cyclization of 1,2-Dien-6-ynes and Subsequent Reaction with Electrophiles[a]

| Entry | Substrate | Electrophile | Product[b] | Yield (%) | D.S.[c] |
|---|---|---|---|---|---|
| |  (27) | RCHO |  | | |
| 1 | | R = $C_8H_{17}$ | (32) | 84 | 95: 5 |
| 2 | | $H_{13}C_6$ | (34) | 68 | 80:20 |
| 3 | | Ph | (35) | 98 | 74:26 |
| 4 |  (36) | $Me_2CO$ |  (37) | 69 | -- |
| 5 |  (38) | $C_8H_{17}CHO$ |  (39) | 62 | 93: 7 |
| 6 |  (40) | $H^+$ |  (41) | 75 | -- |
| | | RCHO |  | | |
| 7 | | R = Me | (42) | 73 | >98:2 |
| 8 | | $C_8H_{17}$ | (43) | 40 | >98:2 |
| 9 |  (44) | $C_8H_{17}CHO$ |  (45) | 77 | >95:5 |

[a] See Scheme 2. [b] Major isomer is shown. [c] Diastereoselectivity with respect to the alcohol carbon and the cyclopentane carbon.

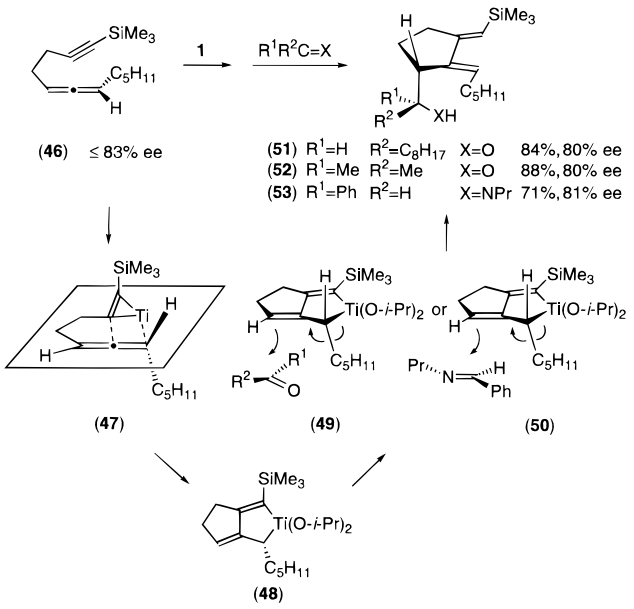
**Generation of a New Type of Chiral Allyltitanium Compounds and Their Reactions.** Having surveyed the titanium-mediated allenyne cyclizations, we were particularly interested in the configurational stability of the intermediate metallacycle **28** (Scheme 2), on the chance that an optically active titanabicycle **48** might be produced in a straightforward manner from optically active allene **46** (Scheme 3). Note that **48** has no additional chiral auxiliary except the allyltitanium moiety itself, which is in marked contrast to other chiral allyltitanium

(28) 1,2-Diastereoselective introduction of a side chain to a ring structure is often necessary transformation. With aldol reactions: Heathcock, C. H. In *Comprehensive Organic Synthesis*; Trost, B. M., Ed.; Pergamon Press: Oxford, 1991; Vol. 2, p 181. With 1,4-additions: Perlmutter, P. *Conjugate Addition Reactions in Organic Synthesis*; Pergamon Press: Oxford, 1992; p 137. With sigmatropy rearrangements: Hill, R. K. In *Comprehensive Organic Synthesis*; Trost, B. M., Ed.; Pergamon Press: Oxford, 1991; Vol. 5, p 785. Wipf, P. In *Comprehensive Organic Synthesis*; Trost, B. M., Ed.; Pergamon Press: Oxford, 1991; Vol. 5, p 827. Wilson, S. R. In *Organic Reactions*; Paquette, L. A., Ed.; Wiley: New York, 1993; Vol. 43, p 93. With radical reactions: Curran, D. P. *Synthesis* **1988**, 417.

(29) See also: Negishi, E.; Miller, S. R. *J. Org. Chem.* **1989**, *54*, 6014. Dimmock, P. W.; Whitby, R. J. *J. Chem. Soc., Chem. Commun.* **1994**, 2323. Hanzawa, Y.; Harada, S.; Nishio, R.; Taguchi, T. *Tetrahedron Lett.* **1994**, *35*, 9421. Luker, T.; Whitby, R. J. *Tetrahedron Lett.* **1994**, *35*, 9465. Ordinary alkenyltitanium species were reported to react with aldehydes. Boeckman, R. K., Jr.; O'Connor, K. J. *Tetrahedron Lett.* **1989**, *30*, 3271. Schick, H.; Spanig, J.; Mahrwald, R.; Bohle, M.; Reiher, T.; Pivnitsky, K. K. *Tetrahedron* **1992**, *48*, 5579.

(30) Martin, S. F. *Tetrahedron* **1980**, *36*, 419.

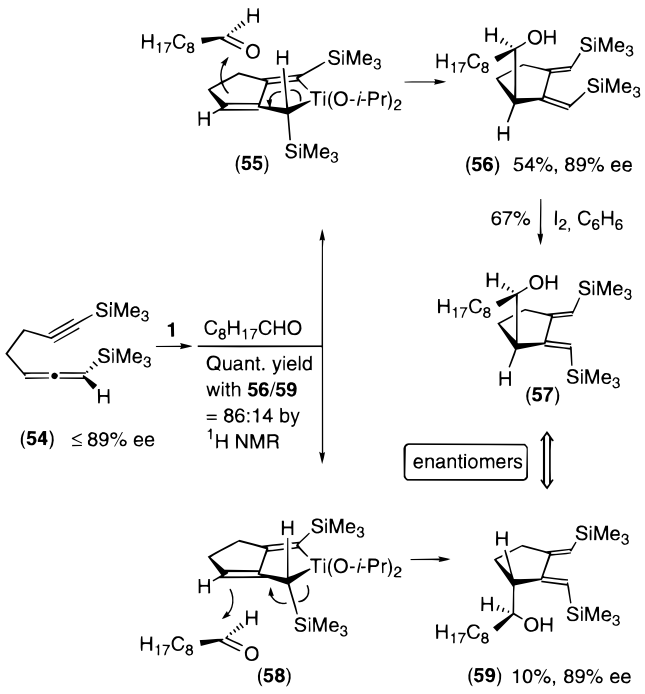
**Scheme 3**




reagents.[10,31] There have been no more than a few relevant reports dealing with an allyltitanium compound of the former type fairly stable against the racemization,[11] nor has there been any firm information on the (configurational) stability of the titanabicycles.[12,32] When *R*-allene **46**[22] was treated with **1** (−50 °C, 2 h) and subsequently with nonanal (−50 °C, 30 min) as above, optically active adduct **51** was, in fact, obtained (Scheme 3). $^1$H NMR analysis of the Mosher ester of **51** disclosed that this alcohol nearly completely retains the original ee value of the starting allene. In addition, this analysis correctly predicted the absolute stereochemistry of the alcohol carbon of **51** based on the well precedented protocol.[33] Eventually, the absolute as well as relative stereochemistry of **51** was unambiguously established by correlation to an authentic sample. Considering the structures of the starting allene **46** and the product **51**, we postulated the stereochemistries of the most likely intermediates **47**−**49** as shown in Scheme 3. In **49**, the aldehyde approaches to the allyltitanium moiety with the least hindered orientation that places the aldehyde hydrogen at the most encumbered and the carbonyl oxygen at the next hindered positions to furnish the observed consecutive stereocenters, while the pentyl side chain of the titanabicycle rotates out from the ring to form the *E*-double bond, which minimizes the steric repulsion in the product. Thus, the overall process could be expressed in terms of the *syn*-$S_E2'$ attack of the electrophile to the allyltitanium moiety. This pattern of the reaction is well accepted in the six-membered transition state for many allyltitanium additions to carbonyl compounds,[9−11] even though, in the present case, this cyclic transition state is definitely not possible due to the remote location of the titanium metal and the reaction center. The same reaction with acetone (−50 °C, 1.5 h) afforded a single adduct **52** again without any significant loss of the enantiopurity.

Imines may be used equally well as the carbonyl compounds.[34] The same addition of the titanabicycle **48** to *N*-benzylidenepropylamine did not take place at −50 °C, but it did proceed slowly at 0 °C during 1 h (by TLC monitoring), eventually affording a virtually single amine **53** (diastereoselectivity >97:<3). The relative stereochemistry of the product was confirmed by correlation to the benzaldehyde adduct **35**, and the absolute stereochemistry was deduced on the assumption that the reaction, which again afforded only the *E*,*E*-diene product, proceeded in the same sense as observed for **51**. It would be reasonable that the phenyl group of the imine is located at the least hindered position in **50**, which well accounts for the observed stereochemistry. The enantiopurity of **53** again showed only a negligible decrease, which clearly shows that *the absolute configuration of the allyltitanium moiety in the titanabicycle such as **48** is stable up to 0 °C!*

**Scheme 4**




In the above cyclization and aldehyde (or imine) addition of the substrates carrying both allenyl and acetylenic substituents, the formation of the *E*,*E*-diene moiety was always observed in the products as evidenced by $^1$H NMR analysis (Table 2). However, we encountered one exception wherein the product having an *E*,*Z*-diene portion became a major constituent. Thus, the reaction of bis-silylated allenyne **54**[22] with **1** and then with nonanal proceeded in an anomalous way to give **56** having an *E*,*Z*-diene as the major product together with a small amount of **59** with an *E*,*E*-diene moiety (Scheme 4). This phenomenon does not mean the characteristic nature of this particular substrate **54**, because the reaction of **36** (= racemic form of **54**) reacted with acetone in the usual manner as shown in entry 4 in Table 2. The olefin geometries for **56** and **59** are unambiguously determined by NOE studies of $^1$H NMR spectroscopy and are also supported by the following chemical correlation. A catalytic amount of iodine in benzene[35] converted the *E*,*Z*-isomer **56** to the more thermodynamically stable *E*,*E*-isomer **57**, which is identical in all respects with the minor isomer **59** except their chiralities as described below. In addition, this transformation clearly shows that the relative

(31) Urabe, H.; Yoshikawa, K.; Sato, F. *Tetrahedron Lett.* **1995**, *36*, 5595.

(32) For the issue on configurational stability of metallacycles which effects the transmission of the starting olefin geometry to the product, see and compare: reference 15. Negishi, E.; Choueiry, D.; Nguyen, T. B.; Swanson, D. R. *J. Am. Chem. Soc.* **1994**, *116*, 9751.

(33) Ohtani, I.; Kusumi, T.; Kashman, Y.; Kakisawa, H. *J. Am. Chem. Soc.* **1991**, *113*, 4092. Zeng, L.; Ye, Q.; Oberlies, N. H.; Shi, G.; Gu, Z.-M.; He, K.; McLaughlin, J. L. *Nat. Prod. Rep.* **1996**, 281. Dale, J. A.; Mosher, H. S. *J. Am. Chem. Soc.* **1973**, *95*, 512.

(34) For allyl addition to imines, see: Gao, Y.; Sato, F. *J. Org. Chem.* **1995**, *60*, 8136. Yamamoto, Y.; Asao, N. *Chem. Rev.* **1993**, *93*, 2207. Roush, W. R. In *Comprehensive Organic Synthesis*; Trost, B. M., Ed.; Pergamon Press: Oxford, 1991; Vol. 2, p 1.

(35) Crimmins, M. T.; Al-awar, R. S.; Vallin, I. M.; Hollis, W. G., Jr.; O'Mahony, R.; Lever, J. G.; Bankaitis-Davis, D. M. *J. Am. Chem. Soc.* **1996**, *118*, 7513.

stereochemistries between the alcohol carbon and the cyclopentane carbon in **56** and **59** are the same. The $^1$H NMR analysis of the MTPA ester derived from **56** and **59** determined not only the ee values for both products (89% ee) but also their absolute stereochemistries with respect to the alcohol carbon to be *R* and *S*.[33] This assignment was readily counterchecked by the $^1$H NMR analysis of the MTPA esters derived from **57** and **59**, which revealed that these are enantiomers with each other. These observations show that the rule of the addition of the cyclic allyltitanium intermediate (*syn*-$S_E2'$ fashion, most likely, as discussed above) strictly makes the *E*,*Z*-diene product have the *R* configuration with respect to the alcohol carbon and the *E*,*E*-diene product accompany the *S* alcohol carbon. As far as the issue of which factor distributes the reaction paths to produce either the *E*,*E*- or *E*,*Z*-diene product is concerned, we can not offer any clear-cut explanation at present.

## Conclusion

The cyclization followed by the selective reaction of the resultant titanbicycle with an electrophile described herein is a useful entry to the metal-promoted intramolecular cyclizations of bis-unsaturated compounds. The characteristic feature of the allene functionality was amply utilized in the efficient chirality transfer and the generation of the hitherto unknown titanabicycles which are useful organotitanium intermediates for the stereoselective addition to carbonyl compounds. In conjunction with the recent developments in the preparation of chiral allenes with predictable absolute stereochemistry and optical purity,[2ac,18a,19,36] this method would become attractive in the construction of optically active, substituted cyclopentanes, which are possible precursors for the synthesis of naturally occurring products having five-membered carbocycles.[37] Application of the present transformation along this line will be reported in due course.

## Experimental Section

**General.** $^1$H and $^{13}$C NMR spectra were taken on a Varian Gemini-300 spectrometer at 300 and 75 MHz, respectively. $CDCl_3$ was used as the solvent unless otherwise noted. Chemical shifts are reported in parts per million shift ($\delta$ value) from $Me_4Si$ ($\delta = 0$ ppm for $^1$H) or based on the middle peak of the solvent ($CDCl_3$) ($\delta = 77.00$ ppm for $^{13}$C NMR) as an internal standard. When $^1$H NMR spectra were taken in $C_6D_6$, the peak of the residual proton of the solvent is the internal standard ($\delta = 7.20$ ppm). Signal patterns are indicated as br, broad; s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet. Coupling constants (*J*) are given in hertz. Infrared (IR) spectra were recorded on a JASCO FT/IR-230 spectrometer. Broad or shoulder peaks were specified as br or sh. Optical rotation was measured on JASCO DIP-370 digital polarimeter. All reactions were performed under nitrogen or argon. Solvents and chemicals were purified or dried in a standard manner.

**8-(Phenyldimethylsilyl)-1-(trimethylsilyl)-6,7-octadien-1-yne (6).** This is a racemic form of **19**. For physical properties, see those of **19**.

**1-[2-(*Z*)-(Phenyldimethylsilyl)vinyl]-2-[(*E*)-(trimethylsilyl)methylene]cyclopentane (8).** This is a racemic form of **21**. For physical properties, see those of **21**.

**5,5-Bis([(benzyloxy)methyl])-1,2-octadien-7-yne (9).** This was prepared according to eq 1.[38] $^1$H NMR $\delta$ 1.93 (t, $J = 2.6$ Hz, 1 H), 2.20 (dt, $J = 9.0$, 3.0 Hz, 2 H), 2.33 (d, $J = 2.6$ Hz, 2 H), 3.42 (s, 4 H), 4.49 (s, 4 H), 4.62 (dt, $J = 6.5$, 3.0 Hz, 2 H), 5.05 (tt, 1 H, $J = 6.5$, 9.0 Hz, 1 H), 7.30 (m, 10 H); $^{13}$C NMR $\delta$ 22.22, 31.51, 42.43, 70.16, 71.81, 73.33, 73.66, 81.18, 85.03, 127.37 (6 carbons), 128.22 (4 carbons), 138.70 (2 carbons), 210.00; IR (neat) 3060, 3030, 2860, 2370, 2120, 1950, 1500, 1450, 1360, 1210, 1100, 1030, 840, 740, 700 cm$^{-1}$. Anal. Calcd for $C_{24}H_{26}O_2$: C, 83.20; H, 7.57. Found: C, 83.31; H, 7.85.

**1,1-Bis([(benzyloxy)methyl])-3-vinyl-4-methylenecyclopentane (10):** $^1$H NMR $\delta$ 1.33 (dd, $J = 9$, 12 Hz, 1 H), 1.91 (dd, $J = 8$, 12 Hz, 1 H), 2.21 (d, $J = 15$ Hz, 1 H), 2.27 (d, $J = 15$ Hz, 1 H), 3.03 (m, 1 H), 3.27−3.36 (m, 4 H), 4.38−4.46 (m, 4 H), 4.67 (br s, 1 H), 4.81 (br s, 1 H), 4.92 (d, $J = 12$ Hz, 1 H), 4.93 (d, $J = 15$ Hz, 1 H), 5.56 (ddd, $J = 9$, 12, 15 Hz, 1 H), 7.20−7.30 (m, 10 H); $^{13}$C NMR $\delta$ 38.57, 39.52, 46.25, 47.33, 71.83, 72.93, 73.23 (2 carbons), 106.94, 114.65, 127.35 (6 carbons), 128.25 (4 carbons), 138.88 (2 carbons), 140.83, 143.81; IR (neat) 3060, 3030, 2860, 1650, 1500, 1450, 1360, 1260, 1200, 1100, 1030, 910, 800, 730, 700 cm$^{-1}$. Anal. Calcd for $C_{24}H_{28}O_2$: C, 82.72; H, 8.04. Found: C, 82.90; H, 8.25.

**5,5-Bis([(benzyloxy)methyl])-8-(trimethylsilyl)-1,2-octadien-7-yne (11):**[38] $^1$H NMR $\delta$ 0.12 (s, 9 H), 2.19 (dt, $J = 9.0$, 3.0 Hz, 2 H), 2.33 (s, 2 H), 3.42 (s, 4 H), 4.49 (s, 4 H), 4.62 (dt, $J = 6.5$, 3.0 Hz, 2 H), 5.05 (tt, $J = 6.5$, 9.0 Hz, 1 H), 7.30 (m, 10 H); $^{13}$C NMR $\delta$ 0.13, 23.61, 31.65, 42.61, 71.95, 73.40, 73.59, 85.13, 86.69, 104.16, 127.36 (6 carbons), 128.23 (4 carbons), 138.76 (2 carbons), 210.00; IR (neat) 3060, 3030, 2860, 2370, 2170, 1950, 1500, 1450, 1360, 1250, 1200, 1100, 1030, 840, 730, 700 cm$^{-1}$. Anal. Calcd for $C_{27}H_{34}O_2Si$: C, 77.46; H, 8.19. Found: C, 77.74; H, 8.29.

**1,1-Bis([(benzyloxy)methyl])-3-vinyl-4-[(*E*)-(trimethylsilyl)methylene]cyclopentane (12):** $^1$H NMR $\delta$ 0.10 (s, 9 H), 1.40 (m, 1 H), 1.99 (m, 1 H), 2.23−2.49 (m, 2 H), 3.11 (br q-like m, 1 H), 3.37−3.42 (m, 4 H), 4.44−4.52 (m, 4 H), 5.00 (d, $J = 16.8$ Hz, 1 H), 5.05 (d, $J = 10$ Hz, 1 H), 5.27 (br s, 1 H), 5.58 (ddd, $J = 8.1$, 9.9, 16.8 Hz, 1 H); $^{13}$C NMR $\delta$ 0.15, 37.85, 39.00, 46.55, 50.33, 71.94, 73.22, 73.33, 73.37, 115.05, 120.41, 127.39 (6 carbons), 128.31 (4 carbons), 138.78, 138.86, 141.08, 162.68; IR (neat) 3060, 3030, 2950, 2930, 2860, 1620, 1500, 1360, 1250, 1200, 1100, 1030, 840, 730, 700 cm$^{-1}$. Anal. Calcd for $C_{27}H_{36}O_2Si$: C, 77.09; H, 8.63. Found: C, 77.09; H, 8.81.

**4,4-Bis([(benzyloxy)methyl])-6,7-tridecadien-1-yne (13):**[38] $^1$H NMR $\delta$ 0.87 (t, $J = 6.0$ Hz, 3 H), 1.24−1.32 (m, 4 H), 1.32−1.42 (m, 2 H), 1.91 (brs, 1 H), 1.94 (m, 2 H), 2.19 (m, 2 H), 2.32 (d, $J = 1.5$ Hz, 2 H), 3.39 (d, $J = 10.6$ Hz, 1 H), 3.44 (d, $J = 10.6$ Hz, 1 H), 4.50 (s, 4 H), 5.02 (m, 2 H), 7.32 (m, 10 H); $^{13}$C NMR $\delta$ 14.06, 22.23, 22.51, 28.92, 28.99, 31.34, 32.20, 42.37, 70.08, 71.91, 71.94, 73.34 (2 carbons), 81.34, 85.60, 90.04, 127.35 (6 carbons), 128.22 (4 carbons), 138.82 (2 carbons), 205.68; IR (neat) 3060, 3030, 2930, 2860, 2120, 1960, 1500, 1450, 1360, 1270, 1200, 1100, 1030, 880, 730, 700 cm$^{-1}$. Anal. Calcd for $C_{29}H_{36}O_2$: C, 83.61; H, 8.71. Found: C, 83.42; H, 8.74.

**An 80:20 mixture of 1,1-bis([(benzyloxy)methyl])-3-(1(*Z*)-hepten-1-yl)-4-methylenecyclopentane and 1,1-bis([(benzyloxy)methyl])-3-(1(*E*)-hepten-1-yl)-4-methylenecyclopentane (14):** $^1$H NMR $\delta$ 0.88 (t, $J = 5.8$ Hz, 3 H), 1.20−1.38 (m, 7 H), 1.92−2.07 (m, 3 H), 2.28 (d, $J = 15$ Hz, 1 H), 2.36 (d, $J = 15$ Hz, 1 H), 3.04 (br q-like m, 1 H, *E*-isomer), 3.29 (m, 1 H, *Z*-isomer), 3.35 (d, $J = 9$ Hz, 1 H), 3.39 (d, $J = 9$ Hz, 1 H), 3.42 (s, 2 H), 4.40−4.58 (m, 4 H), 4.69 (m, 1 H, *Z*-isomer), 4.73 (m, 1 H, *E*-isomer), 4.82 (br s, 1 H, *Z*-isomer), 4.85 (br s, 1 H, *E*-isomer), 5.15 (t, $J = 10$ Hz, 1 H, *Z*-isomer), 5.20 (m, 1 H, *E*-isomer), 5.41 (m, 1 H, *E*-isomer), 5.45 (dt, $J = 10$, 6.8 Hz, 1 H, *Z*-isomer), 7.23−7.37 (m, 10 H); IR (neat) 3030, 2930, 2850, 2360, 1650, 1500, 1450, 1360, 1260, 1210, 1100, 1030, 880, 730, 700 cm$^{-1}$ for an 80:20 mixture of the *Z*- and *E*-isomers. Anal. Calcd for $C_{29}H_{38}O_2$: C, 83.20; H, 9.15. Found: C, 83.06; H, 9.52 for an 80:20 mixture of the *Z*- and *E*-isomers.

**4,4-Bis([(benzyloxy)methyl])-1-(trimethylsilyl)-6,7-tridecadien-1-yne (15):**[38] $^1$H NMR $\delta$ 0.12 (s, 9 H), 0.88 (t, $J = 7.5$ Hz, 3 H), 1.28 (m, 4 H), 1.38 (q, $J = 7$ Hz, 2 H), 1.94 (m, 2 H), 2.18 (m, 2 H), 2.34 (s, 2 H), 3.39 (d, $J = 10.6$ Hz, 1 H), 3.41 (s, 2 H), 3.43 (d, $J = 10.6$ Hz, 1 H), 4.47 (s, 4 H), 5.01 (m, 2 H), 7.32 (m, 10 H); $^{13}$C NMR $\delta$ 0.16, 14.07, 22.50, 23.59, 28.92, 28.98, 31.35, 32.28, 42.55, 72.01 (2 carbons), 73.36 (2 carbons), 85.71, 86.57, 89.95, 104.32, 127.33 (6

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carbons), 128.22 (4 carbons), 138.82 (2 carbons), 205.66; IR (neat) 3050, 3040, 2960, 2920, 2180, 1960, 1500, 1460, 1360, 1250, 1100, 850, 690 $cm^{-1}$. Anal. Calcd for $C_{32}H_{44}O_2Si$: C, 78.63; H, 9.07. Found: C, 78.21; H, 9.07.

**An 82:18 mixture of 1,1-bis([(benzyloxy)methyl])-3-(1(*Z*)-hepten-1-yl)-4-[(*E*)-(trimethylsilyl)methylene]cyclopentane and 1,1-bis([(benzyloxy)methyl])-3-(1(*E*)-hepten-1-yl)-4-[(*E*)-(trimethylsilyl)-methylene]cyclopentane (16):** $^1$H NMR $\delta$ 0.04 (s, 9 H), 0.87 (t, $J$ = 7.5 Hz, 3 H), 1.20−1.37 (m, 7 H), 1.90−2.04 (m, 3 H), 2.30 (d, $J$ = 15 Hz, 1 H), 2.36 (d, $J$ = 15 Hz, 1 H), 3.02 (br q-like m, 1 H, *E*-isomer), 3.34 (d, $J$ = 10 Hz, 1 H), 3.35 (m, 1 H, *Z*-isomer), 3.38 (d, $J$ = 10 Hz, 1 H), 3.41 (s, 2 H), 4.49 (s, 2 H), 4.49 (d, $J$ = 10.6 Hz, 1 H), 4.53 (d, $J$ = 10.6 Hz, 1 H), 5.11 (dd, $J$ = 9.6, 10.8 Hz, 1 H, *Z*-isomer), 5.15 (m, 1 H, *E*-isomer), 5.19 (q, $J$ = 1.9 Hz, 1 H, *Z*-isomer), 5.23 (q, $J$ = 1.9 Hz, 1 H, *E*-isomer), 5.36 (m, 1 H, *E*-isomer), 5.46 (dt, $J$ = 10.8, 7.7 Hz, *Z*-isomer), 7.23−7.37 (m, 10 H); IR (neat) 3030, 2950, 2930, 2860, 2320, 1620, 1500, 1450, 1360, 1250, 1200, 1100, 1030, 870, 840, 730, 700 $cm^{-1}$ for an 82:18 mixture of the *Z*- and *E*-isomers. Anal. Calcd for $C_{32}H_{46}O_2Si$: C, 78.31; H, 9.45. Found: C, 78.36; H, 9.40 for an 82:18 mixture of the *Z*- and *E*-isomers.

**1,8-Bis(trimethylsilyl)-6,7-octadien-1-yne (17).** This is a racemic form of **22**. For physical properties, see those of **22**.

**A Typical Procedure for the Cyclization of 1,2-Dien-7-ynes. 1-[2(*Z*)-(Trimethylsilyl)vinyl]-2-[(*E*)-(trimethylsilyl)methylene]cyclopentane (18).** To a mixture of allenyne **17** (51.2 mg, 0.227 mmol) and Ti(O-*i*-Pr)$_4$ (0.0829 mL, 0.283 mmol) in 2 mL of $Et_2O$ was added *i*-PrMgCl (0.539 mL of a 1.16 M ether solution, 0.625 mmol) at −78 °C. After stirring at −78 °C for 30 min, the solution was allowed to warm to −50 °C over 30 min, and it was further stirred at the same temperature for 2 h. After 3 N HCl was added to the reaction mixture, the organic layer was separated and the aqueous layer was extracted with ether. Combined organic layers were washed successively with 1 N HCl and aqueous $NaHCO_3$ solution, dried, and concentrated to an oil, which was chromatographed on silica gel to give the title compound (44.3 mg, 87%): $^1$H NMR $\delta$ 0.09 (s, 9 H), 0.14 (s, 9 H), 1.38 (dt, $J$ = 6.4, 10.7 Hz, 1 H), 1.59 (m, 1 H), 1.81 (m, 1 H), 2.29 (m, 1 H), 2.46 (m, 2 H), 3.09 (m, 1 H), 5.22 (q, $J$ = 3.0 Hz, 1 H), 5.64 (d, $J$ = 13.5 Hz, 1 H), 6.01 (dd, $J$ = 9.4, 13.5 Hz, 1 H); $^{13}$C NMR $\delta$ 0.35, 0.40, 25.1, 32.49, 33.84, 52.20, 119.91, 129.34, 151.01, 163.75; IR (neat) 2950, 1620, 1600, 1410, 1250, 840, 760, 690 $cm^{-1}$. Anal. Calcd for $C_{14}H_{28}Si_2$: C, 66.53; H, 11.09. Found: C, 66.65; H, 11.30.

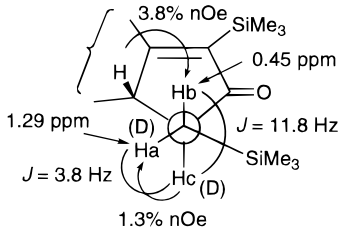
**(*S*)-8-(Phenyldimethylsilyl)-1-(trimethylsilyl)-6,7-octadien-1-yne (19) (≤83% ee).** This was prepared according to eq 2.[38] $^1$H NMR $\delta$ 0.13 (s, 9 H), 0.35 (s, 6 H,), 1.58 (quintet, $J$ = 7 Hz, 2 H), 2.07 (dq, $J$ = 3.1, 7 Hz, 2 H), 2.24 (t, $J$ = 6.8 Hz, 2 H), 4.82 (q, $J$ = 6.8 Hz, 1 H), 5.07 (dt, $J$ = 6.8, 3.1 Hz, 1 H), 7.35 (m, 3 H), 7.51 (m, 2 H); $^{13}$C NMR $\delta$ −2.44, −2.37, 0.03, 19.22, 26.79, 28.48, 81.37, 83.08, 84.67, 107.23, 127.86, 129.17, 133.78, 138.70, 211.38; IR (neat) 3070, 3050, 3015, 2960, 2170, 1940, 1430, 1250, 1115, 840, 820, 780, 760, 730, 700 $cm^{-1}$. $[\alpha]^{23}_D$ +88.5 (*c* 1.20, $CHCl_3$) for a sample of *ca.* 83% ee. Anal. Calcd for $C_{19}H_{28}Si_2$: C, 73.00; H, 9.03. Found: C, 72.65; H, 9.06.

**(*R*)-1-[2(*Z*)-(Phenyldimethylsilyl)vinyl]-2-[(*E*)-(trimethylsilyl)-methylene]cyclopentane (21) (80−83% ee).** To a mixture of the allene **19** (48 mg, 0.154 mmol, ≤83% ee) and Ti(O-*i*-Pr)$_4$ (0.060 mL, 0.192 mmol) in 2 mL of $Et_2O$ was added *i*-PrMgCl (1.44 M in ether, 0.300 mL, 0.432 mmol) dropwise at −78 °C under nitrogen. After stirring for 30 min, the solution was warmed to −50 °C over 30 min and kept at this temperature for an additional 2 h. The reaction was terminated by the dropwise addition of 3 N HCl (2 mL). The organic layer was separated, washed with aqueous $NaHCO_3$ solution, dried ($MgSO_4$), and concentrated to an oil, which was chromatographed on silica gel (hexane−ether) to afford the title compound (38.2 mg, 80%, 80−83% ee): $^1$H NMR $\delta$ 0.08 (s, 9 H), 0.39 (s, 3 H), 0.40 (s, 3 H), 1.25−1.40 (m, 1 H), 1.40−1.57 (m, 1 H), 1.76 (m, 2 H), 2.26 (dt, $J$ = 14.0, 7.5 Hz, 1 H), 2.41 (dd, $J$ = 8.3, 14.0 Hz, 1 H), 3.05 (q, $J$ = 9.3 Hz, 1 H), 5.21 (br s, 1 H), 5.75 (d, $J$ = 13.0 Hz, 1 H), 6.17 (dd, $J$ = 9.3, 13.0 Hz, 1 H), 7.34 (m, 3 H), 7.56 (m, 2 H). The vinylic coupling constant ($J$ = 13 Hz) shows that the stereochemistry of the vinylsilane moiety is *Z*. In addition, the following NOE study confirmed the stereochemical assignment to the tri-substituted olefin moiety. Irradiation of the proton at $\delta$ 3.05 ppm (C*H*CH=CHSiMe$_2$Ph) showd 2%, 2%, and 2.5% enhancements to the peaks at $\delta$ 5.21 (C=C*H*SiMe$_3$), 6.17 (C*H*=CHSiMe$_2$Ph), and 1.76 ppm (one of cyclopentane $CH_2$). $^{13}$C NMR $\delta$ −0.82, −0.62, −0.52, 24.94, 32.33, 33.40, 52.29, 120.06, 127.19, 127.77, 128.86, 133.87, 139.98, 152.83, 163.65; IR (neat) 3070, 2950, 2350, 1600, 1430, 1250, 1110, 840, 780, 730, 700 $cm^{-1}$. $[\alpha]^{23}_D$ −116 (*c* 0.28, $CHCl_3$) or −128 (*c* 1.4, hexane) for a sample of 80−83% ee. Anal. Calcd for $C_{19}H_{30}Si_2$: C, 72.54; H, 9.61. Found: C, 72.44; H, 9.58. The enantiomeric excess was determined by $^1$H NMR chiral shift study with (+)-Eu(hfc)$_3$-Ag(fod) (1:1) to be 80% ee.[23] The following separation of the peak (C*H*=CHSiMe$_2$Ph) was observed. $^1$H NMR (C*H*=CHSiMe$_2$Ph): $\delta$ 0 mol%: 6.17. 30 mol%: major, 6.167; minor 6.164. 40 mol%: major, 6.168; minor, 6.162. 50 mol%: major, 6.168; minor, 6.160 ppm. Alternatively, the enantiopurity of **21** was determined by $^1$H NMR analysis of the MTPA ester of the derived (1*R*,2*R*)-1-(hydroxymethyl)-2-vinylcyclopentane to be 83% ee. The absolute stereochemistry of **21** was unambiguously assigned based on the correlation to an authentic sample.[38]

**(*R*)-1,8-Bis(trimethylsilyl)-6,7-octadien-1-yne (22) (≤86% ee).** This was prepared according to eq 3.[38] $^1$H NMR $\delta$ 0.10 (s, 9 H), 0.15 (s, 9 H), 1.61 (m, 2 H), 2.26 (m, 2 H), 2.27 (t, $J$ = 7.5 Hz, 2 H), 4.75 (q, $J$ = 6.8 Hz, 1 H) 4.92 (dt, $J$ = 6.8, 3.1 Hz, 1 H); $^{13}$C NMR $\delta$ −0.93, 0.16, 19.31, 26.90, 28.61, 82.46, 82.83, 84.60, 107.21, 210.03; IR (neat) 2960, 2900, 2860, 2180, 1940, 1410, 1250, 1050, 840, 760, 700, 640 $cm^{-1}$. $[\alpha]^{23}_D$ −82.3 (*c* 2.24, $CHCl_3$) for a sample of *ca.* 86% ee. Anal. Calcd for $C_{14}H_{26}Si_2$: C, 67.11; H, 10.46. Found: C, 66.85; H, 10.23.

**A Typical Procedure for the Cyclization and Carbonylation of 1,2-Dien-7-ynes. (4*S*,5*S*)-2-(Trimethylsilyl)-4-[(trimethylsilyl)methyl]-1-bicyclo[3.3.0]octen-3-one (25) (86% ee).** To a mixture of the allene **22** (103 mg, 0.453 mmol, ≤86% ee) and Ti(O-*i*-Pr)$_4$ (0.170 mL, 0.565 mmol) in 5 mL of $Et_2O$ was added *i*-PrMgCl (1.61 M in ether, 0.770 mL, 1.24 mmol) dropwise at −78 °C under nitrogen. After stirring for 30 min, the solution was warmed to −50 °C over 30 min and kept at this temperature for an additional 2 h. The cold solution (−50 °C) was exposed to carbon monoxide (*ca.* 1 atm) with the aid of a balloon. After the mixture was allowed to warm from −50 °C to room temperature over 2 h with stirring under CO, 3 N HCl (4 mL) was slowly introduced to the cold solution (0 °C). The organic layer was separated, washed with aqueous $NaHCO_3$ solution, dried ($MgSO_4$), and concentrated to an oil, which was chromatographed on silica gel (hexane−ether) to afford the title compound (78.0 mg, 68%, 86% ee): $^1$H NMR $\delta$ 0.02 (s, 9 H), 0.17 (s, 9 H), 0.45 (dd, $J$ = 11.8, 15.8 Hz, 1 H), 1.12 (m, 1 H), 1.29 (dd, $J$ = 3.8, 15.8 Hz, 1 H), 1.91−1.99 (m, 2 H), 2.02 (m, 1 H), 2.21 (dt, $J$ = 15.0, 7.5 Hz, 1 H), 2.40 (m, 1 H), 2.58 (m, 2 H). The following assignments to the protons were supported by decoupling and NOE experiments. The NOE study also determined the relative stereochemistry of this product. Protons at $\delta$ 1.12 ($CH_2CH_2CH_2$), 2.02 ($CH_2CH_2CH_2$), and 2.21 ($CH_2CH$) ppm proved to be vicinal or geminal by a decoupling experiment. Irradiation of the proton at $\delta$ 2.40 ppm (m, 1 H, C*H*CHCH$_2$SiMe$_3$) showed a 3.8% NOE enhancement to that at $\delta$ 0.45 ppm (C$H_2$SiMe$_3$). Irradiation of the proton at $\delta$ 1.91−1.99 ppm (C*H*CH$_2$SiMe$_3$, C$H_2$CH) showed a 1.3% NOE enhancement to that $\delta$ 1.29 ppm (C$H_2$SiMe$_3$) and a 3.3% NOE enhancement to the one at $\delta$ 1.12 ppm ($CH_2CH_2CH_2$).

Furthermore, in order to determine the stereochemistry of the deuteration (*vide infra*), the peak assignment to both methylene protons in the $Me_3SiCH_2$ group is crucial. The following figure shows a Newman projection (view from the methylene carbon of $Me_3SiCH_2$ to the ring carbon) of the most stable conformer of **25**. Both protons Ha and Hb α to the silyl group ($\delta$ 0.45 and $\delta$ 1.29 ppm) were distinguished from each other based on the following: (i) the upfield shift for Hb as compared to Ha owing to the shielding effect of the nearby olefinic bond, (ii) the fact that the coupling constants observed between Ha/Hc and Hb/Hc shown in the figure satisfy the calculated values by the Karplus equation based on a molecular model, and (iii) the NOE enhancements observed between the proton Hb and the bridgehead proton and between Ha and the ketone α-proton (Hc). On deuterolysis, protons Ha ($\delta$ 1.29 ppm) and Hc were exclusively exchanged to deuteriums to give **26** (*vide infra*).




$^{13}$C NMR $\delta$ −1.18, −0.94, 16.55, 25.75, 27.47, 31.17, 51.16, 56.95, 133.75, 195.71, 216.96; IR (neat) 2950, 2900, 2345, 1690, 1610, 1450, 1410, 1250, 1220, 1130, 1110, 1050, 840, 760, 690 cm$^{-1}$. $[\alpha]^{23}_{D}$ −95.8 (*c* 1.56, $CHCl_3$) for a sample of 86% ee. Anal. Calcd for $C_{15}H_{28}OSi_2$: C, 64.21; H, 10.06. Found: C, 63.91; H, 10.08.

The absolute stereochemistry was deduced based on the stereochemical outcome **19** → **21** (eq 5). The enantiomeric excess of this compound was determined by a chiral shift study ((+)-Eu(hfc)$_3$) of its derivative.[38]

**(4*S*,5*S*)-2-(Trimethylsilyl)-4-deuterio-4-[(*R*)-(trimethylsilyl)(deuterio)methyl]-1-bicyclo[3.3.0]octen-3-one (26):** $^1$H NMR $\delta$ 0.02 (s, 9 H), 0.17 (s, 9 H), 0.45 (br s, 1 H), 1.12 (m, 1 H), 1.91−1.99 (m, 1 H), 2.02 (m 1 H), 2.21 (dt, *J* = 15.0, 7.5 Hz, 1 H), 2.40 (m, 1 H), 2.58 (m, 2 H). Note that peaks at $\delta$ 1.29 and 1.91−1.99 ppm of **25** disappeared. For the stereochemical assignment to the deuterated positions, see **25**.

**(±)-1-(Trimethylsilyl)-5,6-dodecadien-1-yne (27).** This is a racemic form of **46**. See **46** for spectral properties.

**A 57:43 Mixture of 1-Hexyl-5-[(*E*)-(trimethylsilyl)methylene]-1-cyclopentene and 1-((*E*)-Hexylidene)-2-[(*E*)-(trimethylsilyl)methylene]cyclopentane (29). 1-Hexyl-5-[(*E*)-(trimethylsilyl)methylene]-1-cyclopentene:** 1H NMR $\delta$ 0.12 (s, 9 H), 0.88 (t, J = 7 Hz, 3 H), 1.22−1.55 (m, 8 H), 2.06 (m, 2 H), 2.34 (br t, J = 8 Hz, 2 H), 2.42 (m, 2 H), 5.22 (s, 1 H), 5.93 (br s, 1 H).

**1-((*E*)-Hexylidene)-2-[(*E*)-(trimethylsilyl)methylene]cyclopentane:** $^1$H NMR $\delta$ 0.12 (s, 9 H), 0.88 (t, *J* = 7 Hz, 3 H), 1.22−1.55 (m, 6 H), 1.70 (quintet, *J* = 7.7 Hz, 2 H), 2.06 (m, 2 H), 2.42 (m, 2 H,), 2.59 (m, 2 H), 5.82 (t, *J* = 2 Hz, 1 H), 5.88 (tt, *J* = 2, 7 Hz, 1 H).

IR (neat) 3040, 2955, 2855, 1595, 1460, 1245, 835, 770, 735, 690 cm$^{-1}$ for the above mixture of isomers. Anal. Calcd for $C_{15}H_{28}Si$: C, 76.19; H, 11.93. Found: C, 76.13; H, 11.86 for the above mixture of isomers.

**(±)-(1*RS*)-1-[(1*RS*)-2-((*E*)-1-Hexylidene)-3-[(*E*)-(trimethylsilyl)methylene]cyclopent-1-yl]-1-nonanol (32).** This is a racemic form of **51**. See **51** for spectral properties and structural determination.

**(1*RS*)-1-[(1*RS*)-2-((*E*)-1-Hexylidene)-3-[(*E*)-(trimethylsilyl)(deuterio)methylene]cyclopent-1-yl]-1-nonanol (33):** $^1$H NMR $\delta$ 0.11 (s, 9 H), 0.90 (t, *J* = 6.8 Hz, 6 H), 1.21−1.37 (m, 18 H), 1.38 (m, 2 H), 1.61 (d, *J* = 3.8 Hz, 1 H), 1.72 (m, 2 H), 2.16 (m, 2 H), 2.43 (m, 2 H), 2.80 (t, *J* = 6.8 Hz, 1 H), 3.34 (t, *J* = 7.2 Hz, 1 H), 6.04 (t, *J* = 7.6 Hz, 1 H). Note that peak at 5.85 ppm of **32** disappeared to show 94% deuterium incorporation.

**(1*RS*)-1-[(1*RS*)-2-(1-(*E*)-Hexylidene)-3-[(*E*)-(trimethylsilyl)methylene]cyclopent-1-yl]-2-(*E*)-nonen-1-ol (34):** $^1$H NMR major isomer: $\delta$ 0.11 (s, 9 H), 0.87 (t, *J* = 6.5 Hz, 6 H), 1.20−1.37 (m, 14 H), 1.63 (m, 1 H), 1.76 (m, 1 H), 2.03 (m, 2 H), 2.08 (s, 1 H), 2.20 (m, 2 H), 2.42 (m, 2 H), 2.87 (t, *J* = 6.8 Hz, 1 H), 3.83 (t, *J* = 6.6 Hz, 1 H), 5.42 (dt, *J* = 6.2, 15.6 Hz, 1 H), 5.63 (dd, *J* = 6.6, 15.6 Hz, 1 H), 5.83 (s, 1 H), 6.02 (t, *J* = 7.2 Hz, 1 H). The following NOE study confirmed the stereochemical assignment to the diene moiety of the major isomer. Irradiation of the proton at $\delta$ 6.02 ppm (C═C*H*C$_5$H$_{11}$) showed a 15% enhancement to that at $\delta$ 5.83 ppm (C═C*H*SiMe$_3$). $^1$H NMR minor isomer (only characteristic peaks are shown): $\delta$ 1.67 (d, *J* = 3.0 Hz, 1 H), 4.11 (m, 1 H), 5.80 (s, 1 H), 5.94 (t, *J* = 6.8 Hz, 1 H). These peak positions showed that the minor isomer also has an *E*,*E*-diene moiety. Thus, the minor isomer should be another diastereoisomer of the major one (with respect to the alcohol configuration). $^{13}$C NMR major isomer: $\delta$ −0.37, 14.04, 22.61, 25.02, 25.60, 28.90, 29.14, 29.54, 30.20, 31.10, 31.59, 31.67, 31.73, 32.38, 47.65, 74.94, 115.19, 125.02, 130.49, 133.44, 142.13, 156.88; IR (neat) 3421 (br), 2956, 2925, 2856, 1591, 1460, 1379, 1248, 1095, 968, 908, 862, 841, 735, 688 cm$^{-1}$ for an 80:20 mixture of the diastereoisomers. Anal. Calcd for $C_{24}H_{44}OSi$: C, 76.52; H, 11.77. Found: C, 76.76; H, 11.95 for an 80:20 mixture of the diastereoisomers. The relative stereochemistry was deduced as depicted provided that the reaction proceeded in the same sense as the case of **32** and **35**.

**(1*RS*)-[(1*SR*)-2-(1-(*E*)-Hexylidene)-3-[(*E*)-(trimethylsilyl)methylene]cyclopent-1-yl](phenyl)methanol (35):** $^1$H NMR major isomer: $\delta$ 0.10 (s, 9 H), 0.88 (t, *J* = 7.9 Hz, 3 H,), 1.27 (m, 4 H), 1.32 (m, 2 H), 1.53 (m, 2 H), 2.08 (s, 1 H), 2.27 (m, 2 H), 2.38 (m, 2 H), 3.10 (m, 1 H), 4.37 (d, *J* = 4.6 Hz, 1 H), 5.88 (s, 1 H), 6.10 (t, *J* = 7.6 Hz, 1 H), 7.32−7.88 (m, 5 H). The following NOE study confirmed the stereochemical assignment to the diene moiety of the major isomer. Irradiation of the proton at $\delta$ 6.10 ppm (C═C*H*C$_5$H$_{11}$) showed a 21% enhancement to that at $\delta$ 5.88 ppm (C═C*H*SiMe$_3$). $^1$H NMR minor isomer (only characteristic peaks are shown): $\delta$ 1.82 (d, *J* = 3.0 Hz, 1 H), 4.73 (dd, *J* = 3.0, 5.3 Hz, 1 H), 5.83 (s, 1 H), 5.88 (t, *J* = 7.6 Hz, 1 H). These peak positions showed that the minor isomer also has an *E*,*E*-diene moiety. Thus, the minor isomer should be another diastereoisomer of the major one (with respect to the alcohol configuration), which was finally verified by the derivatization. $^{13}$C NMR major isomer: $\delta$ −0.43, 13.98, 22.60, 25.92, 29.51, 30.23, 30.60, 31.68, 49.34, 75.33, 115.58, 125.60, 126.16, 126.94, 128.20, 134.34, 142.39, 156.48; $^{13}$C NMR minor isomer (only characteristic peaks are shown): $\delta$ −0.32, 14.04, 49.04, 75.48, 114.46, 126.58, 142.68, 158.20; IR (neat) 3446 (br), 3062, 3030, 2954, 2927, 2871, 1707, 1593, 1493, 1456, 1377, 1248, 1201, 1022, 960, 841, 758, 700 cm$^{-1}$ for a 74:26 mixture of the diastereoisomers. Anal. Calcd for $C_{22}H_{34}OSi$: C, 77.13; H, 10.00. Found: C, 76.79; H, 10.13 for a 74:26 mixture of the diastereoisomers.

The relative stereochemistry of diastereoisomers was determined by correlation to an authentic sample.[38]

**1,7-Bis(trimethylsilyl)-5,6-heptadien-1-yne (36).** This is a racemic form of **54**. For physical properties, see those of **54**.

**2-[2,3-Bis[(*E*)-(trimethylsilyl)methylene]cyclopent-1-yl]-2-propanol (37):** $^1$H NMR $\delta$ 0.12 (s, 9 H), 0.17 (s, 9 H), 1.02 (s, 3H), 1.27 (s, 3 H), 1.58 (s, 1 H), 1.82 (m, 2 H), 2.47 (m, 2 H), 2.83 (d, *J* = 7.5 Hz, 1 H), 5.98 (t, *J* = 2.5 Hz, 1 H), 6.08 (s, 1 H). The following NOE study confirmed the stereochemical assignment to the diene moiety. Irradiation of the proton at $\delta$ 6.08 ppm (CHC═C*H*SiMe$_3$) showed a 6.0% enhancement to that at $\delta$ 5.98 ppm ($CH_2$C═C*H*SiMe$_3$). $^{13}$C NMR $\delta$ −0.67, 0.15, 25.70, 25.95, 28.54, 30.19, 53.46, 72.39, 117.98, 123.62, 158.40, 159.45; IR (neat) 3480 (br), 2950, 2900, 1730, 1610, 1470, 1370, 1340, 1250, 1170, 1140, 1100, 1020, 950, 840, 690 cm$^{-1}$. Anal. Calcd for $C_{16}H_{32}OSi_2$: C, 64.79; H, 10.87. Found: C, 64.79; H, 10.87.

**6,7-Heptadecadien-11-yne (38).** This was prepared according to eq 2.[38] $^1$H NMR $\delta$ 0.880 (t, *J* = 5.7 Hz, 3 H), 0.885 (t, *J* = 5.7 Hz, 3 H), 1.25−1.34 (m, 8 H), 1.37 (quintet, *J* = 6.1 Hz, 2 H), 1.47 (quintet, *J* = 7.2 Hz, 2 H), 1.96 (dq, *J* = 2.3, 7.6 Hz, 2 H), 2.12 (m, 2 H), 2.13 (m, 2 H), 2.23 (m, 2 H), 5.12 (m, 2 H); $^{13}$C NMR $\delta$ 13.94, 14.02, 18.76, 18.85, 22.23, 22.49, 28.86, 28.90 (3 carbons), 31.10, 31.35, 79.52, 80.66, 89.69, 91.69, 203.93; IR (neat) 2956, 2927, 2858, 2033, 1961, 1466, 1379, 1333, 1286, 1119, 910, 872, 735 cm$^{-1}$. Anal. Calcd for $C_{17}H_{28}$: C, 87.86; H, 12.14. Found: C, 87.68; H, 12.42.

**(1*RS*)-1-[(1*RS*)-2,3-Bis(1-(*E*)-hexylidene)cyclopent-1-yl]-1-nonanol (39):** $^1$H NMR major isomer: $\delta$ 0.86 (t, *J* = 6.1 Hz, 9 H), 1.20−1.37 (m, 24 H), 1.38 (m, 2 H), 1.70 (s, 1 H), 1.73 (m, 2 H), 2.03 (q, *J* = 7.6 Hz, 2 H), 2.16 (m, 2 H), 2.37 (m, 2 H), 2.80 (t, *J* = 7.2 Hz, 1 H), 3.32 (t, *J* = 7.6 Hz, 1 H), 5.73 (m, 1 H), 5.87 (t, *J* = 7.2 Hz, 1 H). The following NOE study confirmed the stereochemical assignment to the diene moiety of the major isomer. Irradiation of the proton at $\delta$ 5.87 ppm (C═C*H*C$_5$H$_{11}$) showed an 11.5% enhancement to that at $\delta$ 5.73 ppm (C═C*H*C$_5$H$_{11}$). $^1$H NMR minor isomer (only characteristic peaks are shown): $\delta$ 5.68 (m, 1 H, C═C*H*C$_5$H$_{11}$). Another vinylic proton possibly overlaps with the peak of the major isomer ($\delta$ 5.73 ppm). These peak positions showed that the minor isomer also has an *E*,*E*-diene moiety. Thus, the minor isomer should be another diastereoisomer of the major one (with respect to the alcohol configuration). $^{13}$C NMR major isomer: $\delta$ 14.06 (3 carbons), 22.60, 22.66, 26.01, 26.25, 27.69, 29.15, 29.32, 29.58, 29.64, 29.73, 29.82 (the peaks in the area $\delta$ 29.15−29.82 may contain 2 types of carbons), 30.05, 31.63, 31.69, 31.90, 34.54, 48.66, 72.54, 119.42, 122.22, 139.94, 142.42; IR (neat) 3431 (br), 2956, 2925, 2856, 2245, 1657, 1466, 1377, 1261, 1136, 1066, 908, 852, 735 cm$^{-1}$ for a 93:7 mixture of the diastereoisomers. Anal. Calcd for $C_{26}H_{48}O$: C, 82.91; H, 12.84. Found: C, 82.72; H, 12.64 for a 93:7 mixture of the diastereoisomers. The relative

stereochemistry was deduced as depicted provided that the addition proceeded in the same sense as the case of **32** and **35**.

**3-Hexyl-7-(trimethylsilyl)-1,2-heptadien-6-yne (40):**[38] $^1$H NMR $\delta$ 0.14 (s, 9 H), 0.88 (t, $J$ = 6.8 Hz, 3 H), 1.23−1.30 (m, 6 H), 1.40 (m, 2 H), 1.94 (m, 2 H), 2.16 (m, 2 H), 2.322 (dd, $J$ = 6.6, 8.4 Hz, 1 H), 2.325 (dd, $J$ = 6.6, 8.4 Hz, 1 H), 4.68 (quintet, $J$ = 3.2 Hz, 1 H); $^{13}$C NMR $\delta$ −0.02, 13.97, 18.44, 22.53, 27.34, 28.85, 31.08, 31.62, 32.00, 76.40, 84.48, 102.33, 107.32, 205.75; IR (neat) 2956, 2927, 2856, 2175, 1957, 1458, 1250, 1041, 843, 760, 735, 698 cm$^{-1}$. Anal. Calcd for $C_{16}H_{28}Si$: C, 77.34; H, 11.36. Found: C, 77.27; H, 11.43.

**3-Hexyl-2-methylene-1-[(*E*)-(trimethylsilyl)methylene]cyclopentane (41):** $^1$H NMR $\delta$ 0.13 (s, 9 H), 0.89 (t, $J$ = 6.8 Hz, 3 H), 1.23−1.42 (m 10 H), 1.93 (m, 2 H), 2.25−2.58 (br m, 3 H), 4.79 (d, $J$ = 2.1 Hz, 1 H), 5.39 (d, $J$ = 2.7 Hz, 1 H), 5.96 (t, $J$ = 2.4 Hz, 1 H). The following NOE study confirmed the stereochemical assignment of the diene moiety. Irradiation of the proton at $\delta$ 5.39 ppm (C=C*H*$_2$) showed a 27% enhancement to that at $\delta$ 4.79 ppm (C=C*H*$_2$) and an 11% enhancement to that at $\delta$ 5.96 ppm (C=C*H*SiMe$_3$). $^{13}$C NMR $\delta$ −0.54, 14.00, 22.57, 27.42, 29.49, 30.20, 31.52, 31.83, 33.88, 44.04, 103.10, 117.00, 154.49, 157.25; IR (neat) 2954, 2925, 2856, 1597, 1458, 1412, 1379, 1248, 1047, 870, 843, 766, 690 cm$^{-1}$. Anal. Calcd for $C_{16}H_{30}Si$: C, 76.72; H, 12.07. Found: C, 76.63; H, 12.32.

**(1*RS*)-1-[(1*RS*)-1-Hexyl-2-methylene-3-[(*E*)-(trimethylsilyl)methylene]cyclopent-1-yl]ethanol (42).** To a stirred mixture of **40** (150 mg, 0.604 mmol) and Ti(O-*i*-Pr)$_4$ (0.223 mL, 0.755 mmol) in 9 mL of Et$_2$O was added *i*-PrMgCl (1.36 M in ether, 1.22 mL, 1.66 mmol) dropwise at −78 °C under argon. After stirring for 30 min, the solution was warmed to −50 °C over 30 min and kept at this temperature for another 2 h. Acetaldehyde (0.051 mL, 0.906 mmol) was added, and the reaction mixture was stirred at this temperature for an additional 30 min. The reaction was terminated by the addition of aqueous 1 N HCl at −50 °C. The organic layer was separated, washed with aqueous NaHCO$_3$ solution, dried (Na$_2$SO$_4$), and concentrated to an oil. $^1$H NMR analysis of this crude material revealed that the product was virtually single and only a trace amount (<1−2%) of another diastereoisomer may be present. Chromatography on silica gel (hexane−ether) afforded the title compound (129 mg, 73%) as a colorless oil and as a >98:<2 mixture of diastereoisomers with respect to the hydroxy group. $^1$H NMR $\delta$ 0.12 (s, 9 H), 0.88 (t, J = 6.8 Hz, 3 H), 1.13 (d, $J$ = 6.3 Hz, 3 H), 1.22−1.35 (m, 10 H), 1.56 (s, 1 H), 1.72 (m, 2 H), 2.43 (ddd, $J$ = 2.4, 6.6, 11.2 Hz, 2 H), 3.61 (m, 1 H), 4.70 (s, 1 H), 5.60 (s, 1 H), 5.96 (t, $J$ = 2.4 Hz, 1 H). The following NOE study confirmed the stereochemical assignment of the diene moiety. Irradiation of the proton at $\delta$ 5.60 ppm (C=C*H*$_2$) showed a 30% enhancement to that at $\delta$ 4.70 ppm (C=C*H*$_2$) and a 16% enhancement to that at $\delta$ 5.96 ppm (C=C*H*SiMe$_3$). $^{13}$C NMR $\delta$ −0.58, 14.00, 22.55, 22.60, 23.79, 30.04, 30.16, 30.49, 31.51, 31.74, 53.61, 76.19, 105.79, 118.21, 151.22, 157.61; IR (neat) 3400 (br), 2960, 2925, 2850, 1628, 1589, 1468, 1378, 1248, 1080, 910, 867, 842, 765, 737, 690 cm$^{-1}$. Anal. Calcd for $C_{18}H_{34}OSi$: C, 73.40; H, 11.63. Found: C, 73.39; H, 11.58.

The relative stereochemistry was determined by correlation to an authentic sample.[38]

**(1*RS*)-1-[(1*RS*)-1-Hexyl-2-methylene-3-[(*E*)-(trimethylsilyl)methylene]cyclopent-1-yl]-1-nonanol (43):** $^1$H NMR $\delta$ 0.12 (s, 9 H), 0.86 (br m, 6 H), 1.21−1.38 (m, 24 H), 1.56 (s, 1 H), 1.73 (m, 2 H), 2.41 (dt, $J$ = 2.5, 7.7 Hz, 2 H), 3.31 (m, 1 H), 4.69 (s, 1 H), 5.58 (s, 1 H), 5.95 (t, $J$ = 2.5 Hz, 1 H). The following NOE study confirmed the stereochemical assignment of the diene moiety to the product. Irradiation of the proton at $\delta$ 5.58 ppm (C=C*H*$_2$) showed a 29% enhancement to that at $\delta$ 4.69 ppm (C=C*H*$_2$) and a 25% enhancement to that at $\delta$ 5.95 ppm (C=C*H*SiMe$_3$). $^{13}$C NMR $\delta$ −0.58, 13.99 (2 carbons), 22.57, 23.75, 27.41, 29.22, 29.53, 29.62, 30.08, 30.16, 30.47, 31.31, 31.51, 31.74, 31.80, 33.78, 53.76, 76.02, 105.68, 118.13, 154.14, 157.66; IR (neat) 3467 (br), 2975, 2925, 2856, 1589, 1466, 1379, 1248, 1053, 868, 843, 735, 690 cm$^{-1}$. Anal. Calcd for $C_{25}H_{48}OSi$: C, 76.46; H, 12.32. Found: C, 76.32; H, 12.36. The relative stereochemistry was deduced as depicted provided that the reaction proceeded in the same sense as the case of **42**.

**7-Methyl-1-(trimethylsilyl)-5,6-octadien-1-yne (44):**[38] $^1$H NMR $\delta$ 0.14 (s, 9 H), 1.68 (d, $J$ = 3.0 Hz, 6 H), 2.154 (ddd, $J$ = 6.0, 6.6, 8.4 Hz, 1 H), 2.158 (ddd, $J$ = 6.0, 6.6, 8.4 Hz, 1 H), 2.300 (dd, $J$ = 6.6, 8.4 Hz, 1 H), 2.302 (dd, $J$ = 6.6, 8.4 Hz, 1 H), 5.00 (septet/t, $J$ = 3.0, 6.0 Hz, 1 H); $^{13}$C NMR $\delta$ 0.02, 19.59, 20.59 (2 carbons), 28.41, 84.41, 87.39, 96.03, 107.19, 201.97; IR (neat) 2960, 2910, 2860, 2175, 1981, 1446, 1363, 1323, 1250, 1041, 895, 841, 760, 698, 640 cm$^{-1}$. Anal Calcd for $C_{12}H_{20}Si$: C, 74.92; H, 10.48. Found: C, 74.87; H, 10.41.

**(1*RS*)-1-[(1*RS*)-2-(Isopropylidene)-3-[(*E*)-(trimethylsilyl)methylene]cyclopent-1-yl]-1-nonanol (45).** To a stirred mixture of **44** (100 mg, 0.520 mmol) and Ti(O-*i*-Pr)$_4$ (0.192 mL, 0.650 mmol) in 7 mL of Et$_2$O was added *i*-PrMgCl (1.60M in ether, 0.893 mL, 1.43 mmol) dropwise at −78 °C under argon. After stirring for 30 min, the solution was warmed to −50 °C over 30 min, and kept at this temperature for another 2 h. Nonanal (0.107 mL, 0.624 mmol) was added, and the reaction mixture was stirred at this temperature for an additional 30 min. The reaction was terminated by the addition of aqueous 1 N HCl at −50 °C. The organic layer was separated, washed with aqueous NaHCO$_3$ solution, dried (Na$_2$SO$_4$), and concentrated to an oil, which was analyzed by $^1$H NMR spectroscopy to be a ≥95:≤5 mixture of diastereoisomers. Chromatography on silica gel (hexane−ether) afforded the title compound (134 mg, 77%) as a colorless oil.

**Major Isomer.** $^1$H NMR $\delta$ 0.11 (s, 9 H), 0.88 (t, $J$ = 6.9 Hz, 3 H), 1.23−1.34 (br m, 14 H), 1.56 (s, 1 H), 1.72 (m, 2 H), 1.86 (s, 3 H), 1.97 (s, 3 H), 2.42 (m, 2 H), 2.79 (t, $J$ = 7.8 Hz, 1 H), 3.29 (t, $J$ = 6.3 Hz, 1 H), 5.56 (s, 1 H). The following NOE study confirmed the stereochemical assignment of the olefin moiety. Irradiation of the proton at $\delta$ 5.56 ppm (C=C*H*SiMe$_3$) showed a 2.9% enhancement to that at $\delta$ 1.97 ppm (C=C*Me*$_2$). The relative stereochemistry was deduced as depicted provided that the reaction proceeded in the same sense as that of other allenynes. $^{13}$C NMR $\delta$ −0.38, 14.00, 22.27, 22.57, 24.12, 25.07, 26.07, 29.24, 29.53, 29.78, 30.98, 31.82, 34.36, 48.75, 73.11, 124.43, 131.76, 138.22, 156.39; IR (neat) 3448 (br), 2960, 2925, 2854, 1587, 1458, 1369, 1246, 1065, 856, 840, 735, 690 cm$^{-1}$ for a ≥95:≤5 mixture of the diastereoisomers. Anal. Calcd for $C_{21}H_{40}OSi$: C, 74.93; H, 11.98. Found: C, 74.92; H, 12.04 for a ≥95:≤5 mixture of the diastereoisomers.

**Minor Isomer.** $^1$H NMR (only a characteristic peak is shown) $\delta$ 5.48 (s, 1 H). This peak position supports that the minor isomer also has an *E*-trisubstituted olefin. Thus, these two isomers should be diastereoisomers with respect to the hydroxy group.

**(*R*)-1-(Trimethylsilyl)-5,6-dodecadien-1-yne (46) (≤83% ee).** This was prepared according to eq 3.[38] $^1$H NMR $\delta$ 0.15 (s, 9 H), 0.91 (t, $J$ = 6.9 Hz, 3 H), 1.22−1.33 (m, 4 H), 1.38 (quintet, $J$ = 7.2 Hz, 2 H), 1.97 (m, 2 H), 2.20 (m, 2 H), 2.31 (t, $J$ = 7.2 Hz, 2 H), 5.14 (m, 2 H); $^{13}$C NMR $\delta$ 0.12, 14.01, 19.82, 22.50, 28.35, 28.91 (2 carbons), 31.34, 84.63, 89.38, 91.95, 106.83, 203.91; IR (neat) 2958, 2927, 2856, 2175, 1963, 1458, 1379, 1329, 1250, 1043, 893, 843, 760, 698 cm$^{-1}$. $[\alpha]^{23}_D$ −37.7 (*c* 1.03, CHCl$_3$) for a sample of *ca.* 83% ee. Anal. Calcd for $C_{15}H_{26}Si$: C, 76.84; H, 11.18. Found: C, 76.81; H, 11.10.

**A Typical Procedure for the Cyclization of 1,2-Dien-6-ynes and the Addition to Carbonyl Compounds. (1*S*)-1-[(1*S*)-2-((*E*)-1-Hexylidene)-3-[(*E*)-(trimethylsilyl)methylene]cyclopent-1-yl]-1-nonanol (51) (80% ee).** To a stirred mixture of **46** (100 mg, 0.427 mmol, ≤83% ee) and Ti(O-*i*-Pr)$_4$ (0.157 mL, 0.533 mmol) in 5.4 mL of Et$_2$O was added *i*-PrMgCl (1.60 M in ether, 0.733 mL, 1.18 mmol) dropwise at −78 °C under argon. After stirring for 30 min, the solution was warmed to −50 °C over 30 min and kept at this temperature for another 2 h. Nonanal (0.110 mL, 0.640 mmol) was added, and the reaction mixture was stirred at this temperature for an additional 30 min. The reaction was terminated by the addition of aqueous 1 N HCl at −50 °C. The organic layer was separated, washed with aqueous NaHCO$_3$ solution, dried (Na$_2$SO$_4$), and concentrated to an oil, which was analyzed by $^1$H NMR spectroscopy to be a 95:5 mixture of diastereoisomers. Chromatography on silica gel (hexane−ether) afforded the title compound (136 mg, 84%, 80% ee) as a colorless oil of the same diastereomer composition. $^1$H NMR major isomer: $\delta$ 0.11 (s, 9 H), 0.90 (t, $J$ = 6.8 Hz, 6 H), 1.21−1.37 (m, 18 H), 1.38 (m, 2 H), 1.61 (d, $J$ = 3.8 Hz, 1 H), 1.72 (m, 2 H), 2.16 (m, 2 H), 2.43 (m, 2 H), 2.80 (t, $J$ = 6.1 Hz, 1 H), 3.34 (t, $J$ = 6.8 Hz, 1 H), 5.85 (s, 1 H), 6.04 (t, $J$ = 7.6 Hz, 1 H). The following NOE study confirmed the stereochemical assignment of the diene moiety to the major isomer. Irradiation of the proton at $\delta$ 6.04 ppm (C=C*H*C$_5$H$_{11}$) showed a 16% enhancement to that at $\delta$ 5.85 ppm (C=C*H*SiMe$_3$). $^1$H NMR minor isomer (only characteristic peaks are shown): $\delta$ 5.79 (s, 1 H), 5.94 (t, $J$ = 7.6 Hz, 1 H). These peak positions showed that the minor isomer also has an *E*,*E*-diene

moiety. Thus, the minor isomer should be another diastereoisomer of the major one (with respect to the alcohol configuration). $^{13}$C NMR major isomer: $\delta$ −0.37, 14.00, 14.07, 22.61, 22.66, 26.24, 26.31, 29.30, 29.53, 29.62, 29.81, 30.27, 31.10, 31.65, 31.90, 34.63, 47.85, 72.62, 115.25, 125.30, 142.30, 156.88; IR (neat) 3402 (br), 2924, 2854, 1593, 1466, 1377, 1246, 1122, 1066, 862, 841, 766, 723, 688 cm$^{-1}$ for a 95:5 mixture of the diastereoisomers. $[\alpha]^{22}_D$ −66.9 (*c* 0.242, $CHCl_3$) for a sample of 80% ee and a 95:5 mixture of the diastereoisomers. Anal. Calcd for $C_{24}H_{46}OSi$: C, 76.12; H, 12.24. Found: C, 75.87; H, 11.97 for a 95:5 mixture of the diastereoisomers.

The enantiomeric excess of the title compound **51** was determined by $^1$H NMR analysis of the derived MTPA ester. Several separated peaks were observed. The peak assignments were verified by decoupling experiments, where necessary.

The (*S*)-MTPA ester from **51** and (*R*)-MTPA-Cl: $^1$H NMR $\delta$ 0.13 (s, 9 H, $Me_3Si$), 1.42 (m, 2 H, C*H*$_2$CH(OH)), 1.68 (m, 2 H, cyclopentane-C*H*$_2$), 3.30 (t, *J* = 6.8 Hz, 1 H, C*H*C═CHC$_5$H$_{11}$), 5.82 (s, 1 H, C═C*H*SiMe$_3$), 5.93 (t, *J* = 7.6 Hz, 1 H, C═C*H*C$_5$H$_{11}$).

The (*R*)-MTPA ester from **51** and (*S*)-MTPA-Cl: $^1$H NMR $\delta$ 0.11 (s, 9 H, $Me_3Si$), 1.50 (m, 2 H, CH$_2$CH(OH)), 1.68 (m, 2 H, cyclopentane-CH$_2$), 3.23 (t, *J* = 6.8 Hz, 1 H, C*H*C═CHC$_5$H$_{11}$), 5.77 (s, 1 H, C═C*H*SiMe$_3$), 5.86 (t, *J* = 7.6 Hz, 1 H, C═C*H*C$_5$H$_{11}$).

The integration of peak areas at $\delta$ 5.82 and 5.77 ppm (C═C*H*SiMe$_3$) determined the ee to be 80%. It should be noted that an empirical means, the modified Mosher's method,[33] correctly predicts the absolute configuration of the hydroxy group to be *S*.[38] The absolute as well as relative stereochemistry of the major isomer was unambiguously established by correlation to an authentic sample.[38]

**2-[(1*S*)-2-(1(*E*)-Hexylidene)-3-[(*E*)-(trimethylsilyl)methylene]cyclopent-1-yl]-2-propanol (52) (80% ee).** The reaction was carried out according to the preparation of **51** except that the addition to acetone was performed at −50 °C for 1.5 h. $^1$H NMR $\delta$ 0.12 (s, 9 H), 0.88 (t, *J* = 6.2 Hz, 3 H), 1.12 (s, 3 H), 1.21 (s, 3 H), 1.30 (m, 6 H), 1.56 (s, 1 H), 1.80 (m, 2 H), 2.17 (m, 2 H), 2.47 (m, 2 H), 2.78 (d, *J* = 3.8 Hz, 1 H), 5.78 (s, 1 H), 5.96 (t, *J* = 7.5 Hz, 1 H). The following NOE study confirmed the stereochemical assignment to the diene moiety. Irradiation of the proton at $\delta$ 5.96 ppm (C═C*H*C$_5$H$_{11}$) showed a 16.6% enhancement to that at $\delta$ 5.78 ppm (C═C*H*SiMe$_3$). $^{13}$C NMR $\delta$ −0.50, 14.00, 22.60, 25.94, 26.97, 28.22, 29.44, 30.63, 30.96, 31.65, 51.42, 74.30, 114.68, 126.34, 143.33, 159.41; IR (neat) 3448 (br), 2954, 2927, 2856, 1593, 1466, 1377, 1246, 1169, 951, 931, 864, 839, 735, 688 cm$^{-1}$. $[\alpha]^{23}_D$ −105 (*c* 0.298, $CHCl_3$) for a sample of 80% ee. Anal. Calcd for $C_{18}H_{34}OSi$: C, 73.40; H, 11.63. Found: C, 72.97; H, 11.84. The enantiomeric excess of this sample was determined by $^1$H NMR chiral shift analysis with (+)-Eu(hfc)$_3$ to be 80% ee. $^1$H NMR $\delta$ 0 mol %: 0.12 (s, 9 H, $Me_3Si$), 2.78 (d, 1 H, CHC(OH)). 10 mol %: major, 0.19, 3.74; minor, 0.18, 3.73. 20 mol %: major, 0.22, 4.40; minor, 0.20, 4.30. 30 mol %: major, 0.234, 4.88; minor, 0.211, 4.73 ppm. The integration of peak areas at $\delta$ 0.234 and 0.211 ppm ($Me_3Si$) at 30 mol % Eu(hfc)$_3$ determined the ee to be 80%. The absolute stereochemistry was deduced as depicted provided that the reaction proceeded in the same sense as the case of **51**.

**A Typical Procedure for the Cyclization of 1,2-Dien-6-ynes and the Addition to Imines. (*S*)-*N*-Propyl-[(1*S*)-2-((*E*)-1-hexylidene)-3-[(*E*)-(trimethylsilyl)methylene]cyclopent-1-yl](phenyl)methylamine (53) (81% ee).** To a stirred mixture of **46** (50 mg, 0.213 mmol, ≤83% ee) and Ti(O-*i*-Pr)$_4$ (0.079 mL, 0.267 mmol) in 2.7 mL of Et$_2$O was added *i*-PrMgCl (1.60 M in ether, 0.367 mL, 0.586 mmol) dropwise at −78 °C under argon. After stirring for 30 min, the solution was warmed to −50 °C over 30 min and kept at this temperature for 2 h. *N*-Benzylidenepropylamine (47 mg, 0.320 mmol) in 0.5 mL of ether was then added, and the reaction mixture was stirred for 20 min at the same temperature. After this period, the addition to the imine was not observed. Then the mixture was rapidly warmed to 0 °C and kept at this temperature for 1 h, during which the reaction slowly proceeded to almost completion by TLC analysis. After the addition of $H_2O$ to the reaction mixture at 0 °C, the organic layer was separated, dried ($Na_2SO_4$), and concentrated to an oil. $^1$H NMR analysis of this crude material revealed that the product was virtually single and only a small amount (≤3%) of another diastereoisomer may be present. Purification on silica gel (hexane−ether) afforded the title compound (58.3 mg, 71%, 81% ee, a ≥97:≤3 mixture of diastereoisomers with respect to the amino group) as a colorless oil: $^1$H NMR $\delta$ 0.11 (s, 9 H), 0.86 (t, *J* = 7 Hz, 3 H), 0.88 (t, *J* = 6 Hz, 3 H), 1.35 (m, 8 H), 1.55 (br m, 1 H), 1.73 (m, 2 H), 2.00 (m, 2 H), 2.27 (m, 2 H), 2.40 (m, 2 H), 2.93 (t, *J* = 7 Hz, 1 H), 3.68 (d, *J* = 5.9 Hz, 1 H), 5.88 (s, 1 H), 5.89 (t, *J* = 7.6 Hz, 1 H), 7.28−7.88 (m, 5 H); $^{13}$C NMR $\delta$ −0.33, 11.71, 14.02, 22.56, 23.35, 25.54, 29.31, 29.41, 31.32, 31.72, 48.52, 50.07, 65.63, 114.32, 124.23, 126.49, 127.75, 127.85, 128.97, 143.34, 158.55; IR (neat) 3070, 3030, 3000 (br), 2954, 2858, 1707, 1595, 1458, 1246, 1201, 839, 750, 702 cm$^{-1}$ for a ≥97:≤3 mixture of the diastereoisomers. $[\alpha]^{22}_D$ −61.0 (*c* 0.404, $CHCl_3$) for a sample of 81% ee and a ≥97:≤3 mixture of the diastereoisomers. Anal. Calcd for $C_{25}H_{41}NSi$: C, 78.26; H, 10.77; N, 3.65. Found: C, 78.11; H, 10.96; N, 3.61.

The enantiomeric excess (81% ee) of the title amine **53** was determined by $^1$H NMR analysis of its mandelic acid salt.[39] Several peaks were separated as follows. **53** with (+)-mandelic acid: $^1$H NMR $\delta$ 0.10 (s, $Me_3Si$), 3.18 (m, C*H*CH(Ph)NH), 3.61 (d, NHC*H*(Ph)), 5.54 (t, C═C*H*SiMe$_3$), 5.71(C═C*H*C$_5$H$_{11}$). **53** with (−)-mandelic acid: $^1$H NMR $\delta$ 0.13 (s, $Me_3Si$), 3.07 (m, C*H*CH(Ph)NH), 3.58 (d, NHC*H*(Ph)), 5.56 (t, C═C*H*SiMe$_3$), 5.72 (C═C*H*C$_5$H$_{11}$). The integration of peak areas at $\delta$ 3.18 and 3.07 ppm (C*H*CH(Ph)NH) determined the ee to be 81%. The stereochemistry of the diene moiety and the relative configuration were correlated to those of the major isomer of the benzaldehyde adduct **35**.[38]

**(*R*)-1,7-Bis(trimethylsilyl)-5,6-heptadien-1-yne (54).** This was prepared according to the synthesis of **22**.[38] $^1$H NMR $\delta$ 0.09 (s, 9 H), 0.15 (s, 9 H), 2.20 (m, 2 H), 2.30 (m, 2 H) 4.83 (q, *J* = 7.0 Hz, 1 H), 4.95 (dt, *J* = 7.0, 3.4 Hz, 1 H); $^{13}$C NMR $\delta$ 0.16, 0.93, 20.35, 27.38, 81.13, 83.49, 84.74, 106.93, 209.70; IR (neat) 2960, 2900, 2860, 2180, 1940, 1410, 1320, 1250, 1190, 1040, 840, 760, 700, 640 cm$^{-1}$. $[\alpha]^{23}_D$ −79.6 (*c* 1.52, $CHCl_3$) for a sample of *ca.* 89% ee. Anal. Calcd for $C_{13}H_{24}Si_2$: C, 65.95; H, 10.15. Found: C, 66.13; H, 10.20.

**An 86:14 Mixture of (1*R*)-1-[(1*R*)-2-[(*Z*)-(trimethylsilyl)methylene]-3-[(*E*)-(trimethylsilyl)methylene]cyclopent-1-yl]-1-nonanol (56) and (1*S*)-1-[(1*S*)-2-[(*E*)-(trimethylsilyl)methylene]-3-[(*E*)-(trimethylsilyl)methylene]cyclopent-1-yl]-1-nonanol (59).** To allenyne **54** (36.2 mg, 0.170 mmol, ≤89% ee) and Ti(O-*i*-Pr)$_4$ (0.0624 mL, 0.213 mmol) in 2 mL of ether was added *i*-PrMgCl (0.405 mL of a 1.16 M ether solution, 0.468 mmol) at −78 °C. After 30 min, the solution was gradually warmed to −50 °C over 30 min and was stirred at this temperature for an additional 2 h. Nonanal (0.0440 mL, 0.255 mmol) in 1 mL of ether was added to this solution at −50 °C, and the mixture was gradually warmed to 0 °C. After stirring at this temperature for 20 min, the reaction was terminated by the addition of 1 N HCl and ether. The organic layer was separated, and the aqueous layer was extracted with ether. Combined organic layers were washed with aqueous $NaHCO_3$ solution and concentrated to an oil, $^1$H NMR analysis of which showed the formation of the major and minor isomers in a ratio of 86:14 and in a quantitative yield. Careful chromatography on silica gel afforded the major isomer **56** (31.6 mg, 54%) as a more polar constituent on analytical TLC (Merck No. 1.05554, ethyl acetate in hexane), the minor isomer **59** (6 mg, 10%, contaminated with a small amount of **56**) as a less polar constituent, and a portion of the mixture of **56** and **59**.

**Major Isomer. (1*R*)-1-[(1*R*)-2-[(*Z*)-(Trimethylsilyl)methylene]-3-[(*E*)-(trimethylsilyl)methylene]cyclopent-1-yl]-1-nonanol (56):** $^1$H NMR $\delta$ 0.11 (s, 9 H), 0.15 (s, 9 H), 0.88 (t, *J* = 7.5 Hz, 3 H), 1.21−1.39 (m, 12 H), 1.55 (m, 3 H), 1.80 (d, *J* = 3.0 Hz, 1 H), 1.84−1.93 (m, 1 H), 2.37−2.47 (m, 3 H), 3.34 (br t, *J* = 7.5 Hz, 1 H), 5.48 (s, 1 H), 5.88 (t, *J* = 2.3 Hz, 1 H). The following NOE study confirmed the stereochemical assignment to the diene moiety. Irradiation of the proton at $\delta$ 2.37−2.47 ppm (C*H*$_2$C═CHSiMe$_3$ and C*H*C═CHSiMe$_3$) showed a 10.8% enhancement to that at $\delta$ 5.48 ppm (CHC═C*H*SiMe$_3$) and no enhancement to that at $\delta$ 5.88 ppm (CH$_2$C═C*H*SiMe$_3$). Contrarily, no NOE enhancements were observed between the vinylic protons at $\delta$ 5.48 and 5.88 ppm. $^{13}$C NMR $\delta$ −0.61, 0.10, 14.08, 22.67, 25.57, 26.02, 29.30, 29.59, 29.75, 31.05, 31.91, 34.21, 54.02, 72.50, 125.11 (2 carbons), 156.53, 161.83; IR (neat) 3500 (br), 2950, 2930, 2850, 2360, 1610, 1460, 1250, 1020, 840, 750, 690 cm$^{-1}$. $[\alpha]^{23}_D$ 35.2 (*c* 0.32, $CHCl_3$) for a sample of *ca.* 89% ee. Anal. Calcd for $C_{22}H_{44}OSi_2$: C, 69.39; H, 11.65. Found: C, 69.88; H, 11.89.

(39) Benson, S. C.; Cai, P.; Colon, M.; Haiza, M. A.; Tokles, M.; Snyder, J. K. *J. Org. Chem.* **1988**, *53*, 5335.

The MTPA esters of this alcohol showed separation of several peaks on $^1$H NMR spectrum. The (*S*)-MTPA ester from (*R*)-MTPA-Cl: $^1$H NMR $\delta$ 0.10 (s, $SiMe_3$), 1.24 (m, $(CH_2)_6$), 2.31 (m, C*H*$_2$C═C$SiMe_3$), 2.94 (q-like m, C*H*CH(OMTPA)$CH_2$), 5.45 (d, $J$ = 2 Hz, CHC═C*H*$SiMe_3$), 5.83 (t, $J$ = 2.3 Hz, $CH_2$C═C*H*$SiMe_3$). The (*R*)-MTPA ester from (*S*)-MTPA-Cl: $^1$H NMR $\delta$ 0.12 (s, $SiMe_3$), 1.20 (m, $(CH_2)_6$), 2.40 (m, C*H*$_2$C═C$SiMe_3$), 2.99 (q-like m, C*H*CH(OMTPA)-$CH_2$), 5.49 (d, $J$ = 2 Hz, CHC═C*H*$SiMe_3$), 5.85 (t, $J$ = 2.3 Hz, $CH_2$C═C*H*$SiMe_3$). The enantiomeric excess was determined by integration of the peaks at $\delta$ 5.45 and 5.49 ppm (CHC═C*H*$SiMe_3$) to be 89% ee. The absolute configuration (of the hydroxy group) was determined by the modified Mosher's method.[33,38]

The relative and absolute stereochemistry of the major isomer **56** was further correlated to that of the minor isomer **59** based on the iodine-catalyzed isomerization of dienes.[35] An iodine solution was prepared with one crystal of iodine and 4 mL of dry benzene. To a solution of **56** (6.0 mg, 0.017 mmol) in benzene (2 mL) was added the iodine solution to allow the light pink color to be retained. Upon completion of the reaction by TLC analysis, the reaction mixture was quenched with aqueous $Na_2S_2O_3$ and the aqueous layer was extracted with ether. The combined organic extracts were washed with brine, dried over $MgSO_4$, filtered, and concentrated in vacuo. Purification on silica gel (hexane−ether) afforded **57** (4.0 mg, 67%) as a colorless oil. Its spectral properties and mobility on analytical TLC were identical with those of the minor isomer **59**. However, the MTPA ester of **57** showed the reversal of the peak positions as compared to that derived from minor isomer **59** (*vide infra*).

**Minor Isomer. (1*S*)-1-[(1*S*)-2-[(*E*)-(Trimethylsilyl)methylene]-3-[(*E*)-(trimethylsilyl)methylene]cyclopent-1-yl]-1-nonanol (59):** $^1$H NMR $\delta$ 0.10 (s, 9 H), 0.17 (s, 9 H), 0.88 (t, $J$ = 7.5 Hz, 3 H), 1.21−1.39 (m, 12 H), 1.56 (br s, 1 H), 1.60 (m, 3 H), 1.75 (m, 1 H), 2.40 (m, 2 H), 2.75 (m, 1 H), 3.27 (br t, $J$ = 7.5 Hz, 1 H), 6.01 (t, $J$ = 2.3 Hz, 1 H), 6.09 (s, 1 H); IR (neat) 3500 (br), 2950, 2930, 2850, 2360, 1610, 1460, 1250, 1020, 840, 750, 690 cm$^{-1}$. The following NOE study confirmed the stereochemical assignment to the diene moiety. Irradiation of the proton at $\delta$ 6.09 ppm (CHC═C*H*$SiMe_3$) showed a 12.5% enhancement to that at $\delta$ 6.01 ppm ($CH_2$C═C*H*$SiMe_3$).

The MTPA esters of this alcohol showed separation of several peaks on $^1$H NMR spectrum. The (*S*)-MTPA ester from (*R*)-MTPA-Cl: $^1$H NMR $\delta$ 1.69 (m, C*H*$_2$CH(OMTPA)), 3.22 (m, C*H*CH(OMTPA)$CH_2$), 5.97 (t, $J$ = 2.3 Hz, $CH_2$C═C*H*$SiMe_3$), 6.11 (s, CHC═C*H*$SiMe_3$). The (*R*)-MTPA ester from (*S*)-MTPA-Cl: $^1$H NMR $\delta$ 1.71 (m, C*H*$_2$CH-(OMTPA)), 3.15 (m, C*H*CH(OMTPA)$CH_2$), 5.95 (t, $J$ = 2.3 Hz, $CH_2$C═C*H*$SiMe_3$), 6.05 (s, CHC═C*H*$SiMe_3$). The enantiomeric excess was determined by integration of the peaks at $\delta$ 6.11 and 6.05 ppm (CHC═C*H*$SiMe_3$) to be 89% ee. The absolute configuration (of the hydroxy group) was determined by the modified Mosher's method.[33,38]

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**Supporting Information Available:** Preparation of representative starting materials and structural determination of several key compounds (13 pages). See any current masthead page for ordering and Internet access instructions.

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