JOC Article

Silylstannylation of Allenes and Silylstannylation−Cyclization of Allenynes. Synthesis of Highly Functionalized Allylstannanes and Carbocyclic and Heterocyclic Compounds

Ramaiah Kumareswaran, Seunghoon Shin,† Isabelle Gallou, and T. V. RajanBabu*

Department of Chemistry, The Ohio State University, 100 West 18th Avenue, Columbus, Ohio 43210

rajanbabu.1@osu.edu

Received June 11, 2004

Catalyzed by Pd(0), trialkylsilyltrialkylstannane ($R_3Si-SnR'_3$) reagents undergo highly selective additions to 1,2-dien-7-ynes and 1,2-dien-8-ynes to give 2-vinylalkylidenecyclopentanes with silicon and tin substituents on the double bonds. Similar additions of distannanes and borostannanes show that the reactions with silylstannanes are superior in terms of ease of handling of the bifunctional reagents and the isolation of the products after the reaction. The chemo- and regioselectivities are controlled by the enhanced reactivity of the allene unit, while the (*Z*)-geometry of the exocyclic stannylvinylidene is a consequence of the syn-carbometalation and subsequent reductive elimination from Pd with retention of configuration at the vinyl carbon. Synthesis of highly functionalized pyrrolidines and indolizidines and the reluctance of certain kinds of allenynes and silicon−tin reagents to undergo the cyclization illustrate the scope and limitations of the reaction. Based on the isolation of intermediates, a mechanism for the formation of the cyclic compounds is proposed. Model transition states to explain the stereoselectivity in cyclization of substituted allenynes are provided. Further elaboration using the vinyltin and vinylsilane moieties should lead to highly functionalized carbocyclic and heterocyclic compounds. Under similar conditions, addition of silylstannanes to highly functionalized allenes gives *E*-allylstannanes with high stereoselectivity. Functional groups such as THP- and silyl-ethers, lactones, β- and γ-lactams, α,β-unsaturated esters, olefins, and substituted acetylenes are tolerated under the reaction conditions.

Introduction

Many traditional methods of cyclization are limited by the fact that often functional groups are depleted in the ring-forming event.[1] Several strategies have been designed to overcome this problem, including invention of methods that incorporate elements of various bifunctional reagents (e. g., R_3SiH, R_3SnH, $R_3Si-SiR'_3$, $R_3Si-SnR'_3$, $R_3Si-BR'_2$, and $R_3Sn-BR'_2$) concurrent with the cyclization reaction.[2] We have been interested in the use of readily available, air- and moisture-stable trialkylsilyltrialkylstannanes[3] in the cyclization reactions of diynes[4] and allenynes.[5] We recently reported the details of silylstannylation cyclization of diynes in which helically chiral (*ZZ*)-1,2-bis-alkylidenecyclopentanes are produced (eq 1). These fascinating molecules have very low activation barriers for enantiomerization (<60 kJ mol^{-1}) irrespective of the size of the silicon and tin groups.[6] As expected, the dienes undergo highly selective reactions such as protodestannylation, Sn−halogen exchange, Stille-coupling, and Diels−Alder reactions (after destannylation). However, reactions of unsymmetrical diynes (R ≠ H in

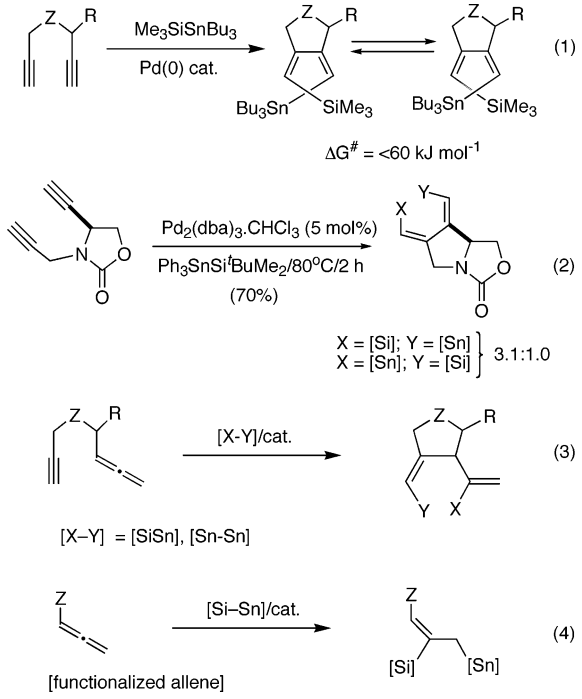
† Current address: Department of Chemistry, Hanyang University, Seoul 133-791, Korea.

(1) For recent reviews on transition-metal-catalyzed cyclization reactions, see: (a) Tamao, K.; Kobayashi, K.; Ito, Y. *Synlett* **1992**, 539. (b) Lautens, M.; Klute, W.; Tam, W. *Chem. Rev.* **1996**, *96*, 49. (c) Negishi, E.-i.; Copéret, C.; Ma, S.; Liou, S.-Y.; Liu, F. *Chem. Rev.* **1996**, *96*, 365. (d) Ojima, I.; Tzamarioudaki, M.; Li, Z.; Donovan, R. J. *Chem. Rev.* **1996**, *96*, 635. (e) Grubbs, R. H.; Chang, S. *Tetrahedron* **1998**, *54*, 4413. (f) Trost, B. M.; Krische, M. J. *Synlett* **1998**, 1. (g) Sato, F.; Urabe, H.; Okamoto, S. *Chem. Rev.* **2000**, *100*, 2835. (h) Brummond, K. A.; Kent, J. L. *Tetrahedron* **2000**, *56*, 3263.

(2) For recent review articles, see: (a) Suginome, M.; Ito, Y. *Chem. Rev.* **2000**, *100*, 3221. (b) Smith, N. D.; Mancuso, J.; Lautens, M. *Chem. Rev.* **2000**, *100*, 3257. (c) Itoh, K.; Matsuda, I.; Yamamoto, K. *J. Synth. Org. Chem. Jpn.* **1999**, *57*, 912. For recent representative publications that deal with R_3SiH and R_3SnH, see: (d) Ojima, I.; Vu, A. T.; Lee, S.-Y.; McCullah, J. V.; Moralee, A. C.; Fujiwara, M.; Hoang, T. H. *J. Am. Chem. Soc.* **2002**, *124*, 9164 and references therein. (d) Kisanga, P.; Widenhoefer, R. A. *J. Am. Chem. Soc.* **2000**, *122*, 10017. (e) Lautens, M.; Mancuso, J. *Org. Lett.* **2000**, *2*, 671. (f) R_3Si-BR_2: Onozawa, S.; Hatanaka, Y.; Tanaka, M. *J. Chem. Soc., Chem. Commun.* **1997**, 1229. Suginome, M.; Matsuda, T.; Ito, Y. *Organometallics* **1998**, 5233. (g) R_3SnBR_2: Onozawa, S.; Hatanaka, Y.; Choi, N.; Tanaka, M. *Organometallics* **1997**, *16*, 5389. (h) $R_3SiSiR_3/R_3SnSnR_3/R_3SiSnR_3$: Obora, Y.; Tsuji, Y.; Kakehi, T.; Kobayashi, M.; Shinkai, Y.; Ebihara, M.; Kawamura, T. *J. Chem. Soc., Perkin Trans. 1* **1995**, 599. [SiSn]-mediated cyclization of enynes: (i) Mori, M.; Hirose, T.; Wakamatsu, H.; Imakuni, N.; Sato, Y. *Organometallics* **2001**, *20*, 1907. (k) Of bis-allenes: Kang, S.-K.; Baik, T.-G.; Kulak, A. N.; Ha, Y.-H.; Lim, Y.; Park, J. *J. Am. Chem. Soc.* **2000**, *122*, 11529. (l) allene-aldehydes: Kang, S.-U.; Ha, Y.-H.; Ko, B.-S.; Lim, Y.; Jung, J. *Angew. Chem., Int. Ed.* **2002**, *41*, 343. (m) Pauson−Khand-type reactions: Shibata, T.; Kadowaki, S.; Hirase, M.; Takagi, K. *Synlett* **2003**, 573. Brummond, K. M.; Chen, Y.; Sill, P.; You, L. *J. Am. Chem. Soc.* **2002**, *124*, 15186. (n) Stoichiometric Ti(II)-mediated cyclization of allenynes: Urabe, H.; Takeda, T.; Hideura, D.; Sato, F. *J. Am. Chem. Soc.* **1997**, *119*, 11295.

10.1021/jo049010z CCC: $27.50
Published on Web 09/17/2004

eq 1) give a mixture of products arising from incorporation of Si and Sn at either of the two termini (eq 2), and alternate methods have to be resorted to for controlling the regiochemistry of the silylstannylation. In an attempt to circumvent this problem, and to probe the scope of the cyclization reactions in other related π-unsaturated systems, we investigated allenynes (eq 3), in which high chemoselectivity was expected to prevail due to the increased reactivity of the allene in the Pd-catalyzed addition reactions.[7] Structural features of the allenyne substrates and the nature of the Si−Sn reagents sometimes prevented the cyclization, even though the initial addition to the allene (eq 4) proceeded with excellent regio- and stereoselectivity. Thus, a parallel study to define the scope, limitations, and functional group compatibility of the silylstannylation and distannylation of these and other highly functionalized allenes (eq 4) was also undertaken. Simple allenes have been subjected to the silylstannylation reaction under different conditions by Mitchell.[8] As recorded later in this paper, the regio- and stereoselectivity and tolerance to various functional groups appear to be significantly better under our modified conditions. The details of these investigations are disclosed in this paper.



Results and Discussion

A. Silylstannylation−Cyclization of Allenynes. Synthesis of Substrates for Cyclization. A set of

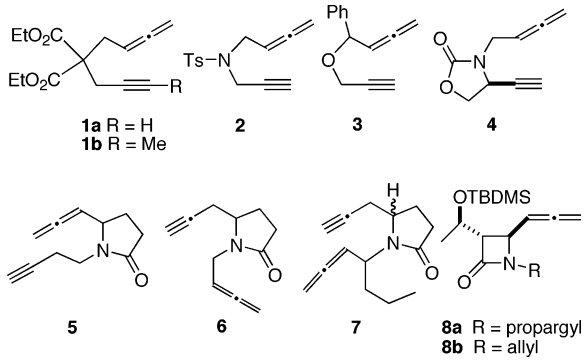
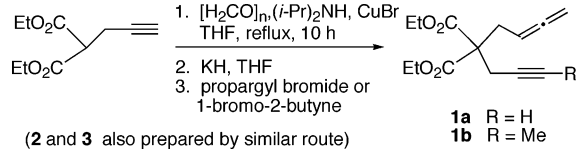
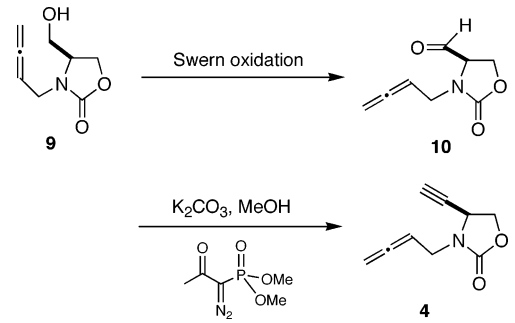


FIGURE 1. Allenynes used for silylstannylation studies.

SCHEME 1. Synthesis of Allenynes 1−3



SCHEME 2. Synthesis of Substrate 4



allenynes, shown in Figure 1, was chosen to illustrate the various approaches for their preparation, functional group compatibility of the cyclization reaction, and the potential utility of the products in synthesis. Particularly appealing are applications for the synthesis of *N*-heterocyclic compounds such as pyrrolidines, pyrrolizidines, and indolizidines prepared from allenynes such as **5**−**7**.

The substrates **1**−**3** were prepared by propargylation of the allenyl derivatives, which in turn were prepared by Crabbe reaction[9] (Scheme 1).

Scheme 2 describes the synthesis of the substrate **4** starting with the known allenyl alcohol **9**.[10] Swern oxidation of **9** proceeds uneventfully to give the aldehyde **10**, which can be transformed into the allenyne **4** in overall 56% yield in two steps. The aldehyde **10** is also useful in the preparation of other allene derivatives (vide infra).

Substrates **5** and **6** were prepared from succinimide (Schemes 3 and 4). For the preparation of **5**, succinimide was reacted with 3-butynol under Mitsunobu conditions[11]

(3) (a) Chenard, B. L.; Laganis, E. D.; Davidson, F.; RajanBabu, T. V. *J. Org. Chem.* **1985**, *50*, 3666. See also: (b) Mitchell, T. N.; Killing, H.; Dicke, R.; Wickenkamp, R. *J. Chem. Soc., Chem. Commun.* **1985**, 354.

(4) Gréau, S.; Radetich, B.; RajanBabu, T. V. *J. Am. Chem. Soc.* **2000**, *122*, 8579.

(5) Shin, S.; RajanBabu, T. V. *J. Am. Chem. Soc.* **2001**, *123*, 8416.

(6) Warren, S.; Chow, A.; Fraenkel, G.; RajanBabu, T. V. *J. Am. Chem. Soc.* **2003**, *125*, 15402.

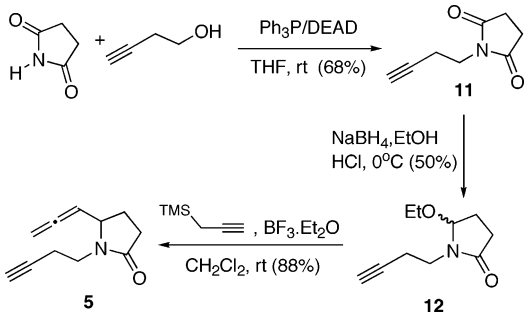
(7) For a review of Pd-catalyzed reactions of allenes, see: Zimmer, R.; Dinesh, C. U.; Nandanan, E.; Khan, F. A. *Chem. Rev.* **2000**, *100*, 3067.

(8) Mitchell, T. N.; Schneider, U. *J. Organomet. Chem.* **1991**, *407*, 319.

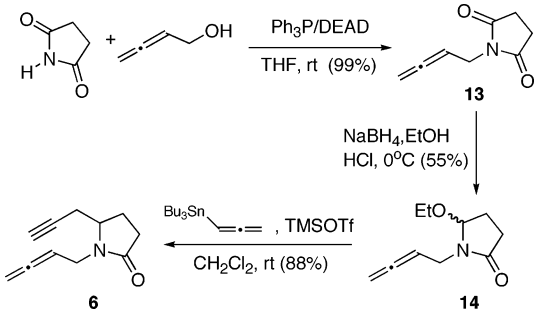
(9) Starting materials: (a) Woo, L. W. L.; Smith, H. J.; Barrell, K. J.; Nicholls, P. J. *J. Chem. Soc., Perkin Trans. 1* **1993**, 2549. (b) Djahanbini, D.; Cazes, B.; Gore, J. *Tetrahedron* **1987**, *43*, 3441. (c) Oppolzer, W.; Ruiz-Montes, J. *Helv. Chim. Acta* **1993**, *76*, 1266. (d) Urabe, H.; Takeda, T.; Hideura, D.; Sato, F. *J. Am. Chem. Soc.* **1997**, *119*, 11295. (f) Brandsma, L.; Verkruijsse, H. D. *Synthesis of Acetylenes, Allenes and Cumulenes: A Laboratory Manual*; Elsevier Scientific: New York, 1981.

(10) Chevliakov, M. V.; Montgomery, J. *J. Am. Chem. Soc.* **1999**, *121*, 11139.

SCHEME 3. Synthesis of Allenyne 5



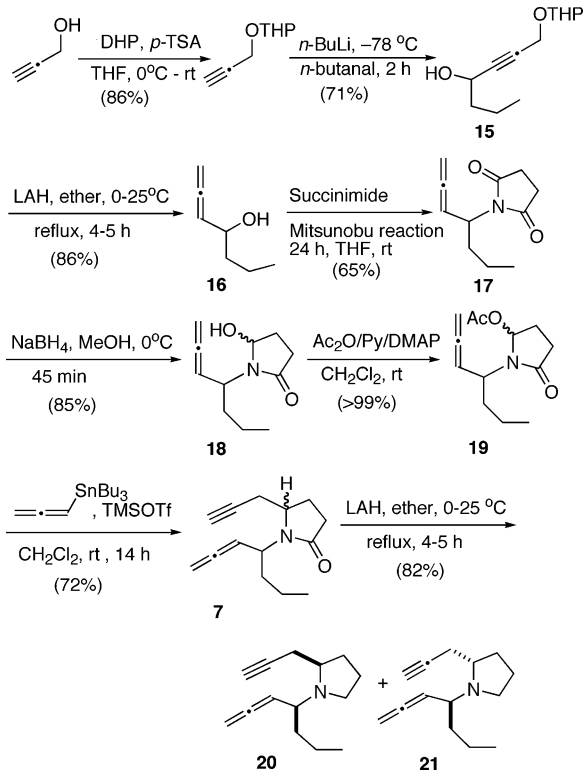
SCHEME 4. Synthesis of Allenyne 6



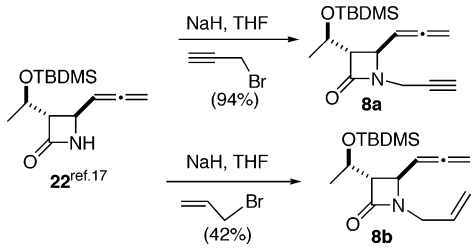
to give the *N*-(3-butynyl) derivative **11**, which was reduced with $NaBH_4$ in ethanol under conditions described by Hart et al.[12] to get the 4-ethoxypyrrolidone **12**. Lewis acid-assisted addition of propargyltrimethylsilane afforded the allenyne substrate **5** in overall 30% yield starting from succinimide. Likewise, allenyne **6** was prepared from succinimide in 48% yield by the route shown in Scheme 4. The propargylation of the acyliminium ion[13] derived from **14** with tri-*n*-butylstannylallene proceeds in excellent yield in the presence of trimethylsilyl triflate to give the allenyne **6**.

One of our goals in this project is to develop generally applicable synthesis of highly functionalized pyrrazolidines, indolizidines, and quinolizidines.[14] In an initial attempt to explore the viability of these methods for the synthesis of these condensed heterocyclic compounds, we prepared substrate(s) **7** as shown in Scheme 5. The synthesis starts from propargyl alcohol **15**, which was converted into allenol **16**[15] in multigram scale. Mitsunobu reaction of this alcohol with succinimide gave 65% yield

SCHEME 5. Synthesis of Allenyne 7



SCHEME 6. Synthesis of Substrates 8a and 8b



of **17**. Controlled reduction of **17** produced the hydroxylactam in high yield as a mixture of two diastereomers. Reduction of the imide **17** in ethanol under acidic conditions to get the ethoxy lactam gave unexpected olefinic side products in the present example.[12] The alcohol(s) **18** were converted into acetoxylactam(s) **19**. Under optimized conditions, reaction of **19** with allenyltributylstannane[16] using TMSOTf as a Lewis acid afforded the required allenyne **7** as a chromatographically inseparable mixture of isomers in 1:1 ratio. However, reduction of the lactam function in **7** led to the pyrrolidines **20** and **21**, which were easily separated by chromatography.

Synthesis of two other highly functionalized allenes carrying a β-lactam functionality is shown in Scheme 6. These compounds were prepared from previously known allenyl derivative **22**[17] to test the limits of tolerance of a number of sensitive functional groups to the Pd-catalyzed reaction conditions and as potential precursors for pharmaceutically relevant bicyclic β-lactams.[18]

(11) Mitsunobu, O.; Wada, M.; Sano, T. *J. Am. Chem. Soc.* **1972**, *94*, 679.

(12) (a) Burnett, D. A.; Choi, J.-K.; Hart, D. J.; Tsai, Y.-M. *J. Am. Chem. Soc.* **1984**, *106*, 8201. (b) See also: Hubert, J. C.; Wijnberg, J. B. P. A.; Speckamp, W. N. *Tetrahedron* **1975**, *31*, 1437.

(13) For a recent review of acyliminium ion chemistry, see: (a) Maryanoff, B. E.; Zhang, H.-C.; Cohen, J. H.; Turchi, I. J.; Maryanoff, C. J. *Chem. Rev.* **2004**, *104*, 1431. (b) Hart, D. J. *Alkaloids: Chem. Biol. Perspect.* **1988**, *6*, 227. (c) Hiemstra, H.; Speckamp, W. N. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon: Oxford, 1991; Vol. 2, pp 1047−1082.

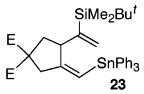
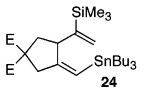
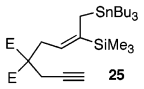
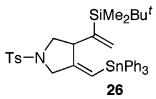
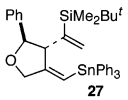
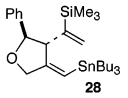
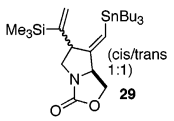
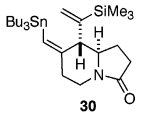
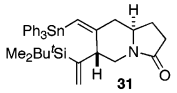
(14) Recent general reviews on pyrrolizidines, indolizidines, and quinolizidine alkaloids: (a) Daly, J. W.; Garraffo, H. M.; Spande, T. F. Alkaloids from amphibian skins. In *Alkaloids: Chemical and Biological Perspectives*; Pelletier, S. W., Ed.; Pergamon Press: Oxford, 1998; Vol. 13, pp 1−161. (b) Colegate, S. M.; Dorling, P. R. In *Handbook of Plant and Fungal Toxicants*; D'Mello, J. P. F., Ed.; CRC Press: Boca Raton, 1997; Chapter 1, pp 1−18. (c) Nash, R. J.; Watson, A. A.; Asano, N. In *Alkaloids: Chemical and Biological Perspectives*; Pelletier, S. W., Ed.; Pergamon Press: Oxford, 1996; Vol. 11, pp 345−375. (d) Daly, J. W. *J. Nat. Prod.* **1998**, *61*, 162. (e) Michael, J. P. Indolizidine and Quinolizidine Alkaloids. *Nat. Prod. Rep.* **1997**, *14*, 630; **1998**, *15*, 571; **1999**, *16*, 675; **2000**, *17*, 579.

(15) Kimura. M.; Tanaka, S.; Tamaru, Y. *Bull. Chem. Soc. Jpn.* **1995**, *68*, 1687.

(16) Boaretto, A.; Marton, D.; Tagliavini, G. *J. Organomet. Chem.* **1985**, *297*, 149.

(17) Prasad, J. S.; Liebeskind, L. S. *Tetrahedron Lett.* **1988**, *29*, 4253.

TABLE 1. Cyclization of Allenynes Mediated by $R_3SiSnR'_3$

Entry	Substrate	[SiSn] reagent	Conditions[a]	Product(s)	Yield(%)[b]
1.	**1a**	$Me_2Bu^tSiSnPh_3$	rt, 17 h, **A**	 **23**	80 (>95)
2.	**1a**	$Me_3SiSnBu_3$	45 °C, 48 h, **A**	 **24**	71 (>95)
3.	**1a**	$Me_3SiSnBu_3$	rt, 2 h, **A**	 **25**	81 (>90)[c]
4.	**2**	$Me_2Bu^tSiSnPh_3$	rt, 24 h, **A**	 **26**	41 (>90)
5.	**3**	$Me_2Bu^tSiSnPh_3$	rt, 12 h, **B**	 **27**	61 (>80)
6.	**3**	$Me_3SiSnBu_3$	80 °C, 5 h, **B**	 **28**	72 (>95)
7.	**4**	$Me_3SiSnBu_3$	80 °C, 12 h, C_6D_6, **A**	 (cis/trans 1:1) **29**	76
8.	**5**	$Me_3SiSnBu_3$	60 °C, C_6H_6, **A** 18 h	 **30**	41 (~100% by NMR)
9.	**6**	$Me_2Bu^tSiSnPh_3$	40 °C, C_6H_6, **A** 18 h	 **31**	41 (~100% by NMR)
10.	**7**	$Me_2Bu^tSiSnPh_3$	45 °C, C_6H_6, 24 h, **A**	(see eq **5**, **32**, **33**)	78
11.	**1b**	$Me_3SiSnBu_3$	80 °C, C_6D_6, 48 h, **A**	Acyclic products (**36**, see eq 8)	--
12.	**6**	$Me_3SiSnBu_3$	rt, C_6H_6, **A**	Acyclic products (**37**, see eq 9)	88
13.	**8a** (R = propargyl) **8b** (R = allyl)	$Me_3SiSnBu_3$	rt, benzene, **A**	Acyclic products (**62**, see eq 11)	23 (**62a**) (from **8a**) 82 (**62b**) from **8b**

[a] Key: (A) 5 mol % $Pd_2(dba)_3$ with 10 mol % $P(C_6F_5)_3$; (B) 5 mol % $Pd(PhCN)_2Cl_2$ with 10 mol % $P(C_6F_5)_3$. [b] Isolated yields; yields determined by NMR in parentheses. [c] Isolated material contained 5% cyclic product **24** (entry 2).

Silylstannylation−Cyclization of Allenynes. The results of cyclization of various allenynes (Figure 1) mediated by silylstannane reagents are shown in Table 1. A typical substrate **1a**, in the presence of Ph_3Sn-

SCHEME 7. Silylstannylatin−Cyclization of a Prototypical Allenyne

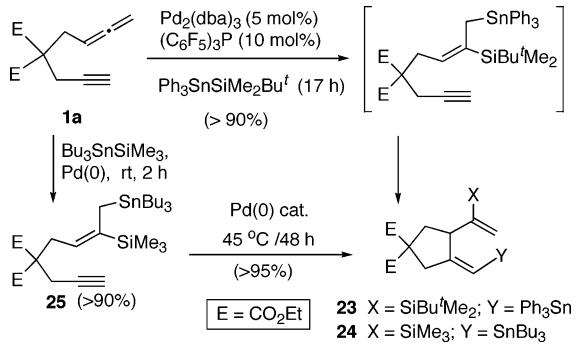


TABLE 2. Effect of Phosphine Ligands on Formation of 23 (See Scheme 7)

entry	ligand	% conversion (12 h)[a]	% conversion (48 h)
1	$P(C_6F_5)_3$	61	>90
2	$P(3,5\text{-}Me_2\text{-}C_6H_3)_3$	39	>90
3	PPh_3	<10	>60
4	PBu_3	<10	>60
5	P^tBu_3	<10	81

[a] Conversions based on in situ NMR; no side products were detected. For conditions see the text.

$SiMe_2Bu^t$ (1.1 equiv), $Pd_2(dba)_3{\cdot}CHCl_3$ (5 mol % in Pd), and $P(C_6F_5)_3$ (10 mol %) in 1 mL of C_6D_6, undergoes an exceptionally clean reaction (by NMR: >90% conversion to the product, rest starting material) at room temperature to give the cyclic product **23** in 80% isolated yield (Scheme 7). The lower preparative yield of the product is an indication of the instability of this relatively sensitive material, which was isolated by column chromatography on silica gel using hexane containing 5% Et_3N. The structure and configuration of **23** were unambiguously established by NMR spectroscopy (^1H, ^{13}C, COSY, NOE difference spectra) and elemental analysis. The identity of the SnC-*H* and the geometry of the double bond is clear from the coupling pattern (δ 6.40; d, $^1J_{Sn-H}$ = 74 Hz) and the NOE difference spectrum (Figure 1, Supporting Information). Among the large number of monophosphine ligands that were screened for the reaction (Table 2) only $P(3,5\text{-}Me_2\text{-}C_6H_3)_3$ and $(C_6F_5)_3P$) gave any appreciable reaction after 12 h at room temperature (39% and 61%, respectively). The source of Pd, while not as critically important, showed a definite trend in reactivity when used in conjunction with $(C_6F_5)_3P$: $(PhCN)_2PdCl_2$ > $[Pd(allyl)Cl]_2$/AgOTf ~ $Pd_2(dba)_3{\cdot}CHCl_3$ ≫ $PdCl_2(Ph_3P)_2$ ~ $Pd(PPh_3)_4$.

When the reaction was repeated with a less reactive silylstannane, $Bu_3SnSiMe_3$, we were able to isolate an uncyclized adduct **25** in excellent yield (81% isolated, rest cyclized product **24**) and stereochemical purity (Scheme 7). On prolonged heating (45 °C, 48 h) the intermediate allylstannane **25** is quantitatively converted into the cyclic product **24**. Presumably, the corresponding allyltriphenylstannane is too reactive to accumulate in solution to any appreciable degree. The acyclic intermediate **25** was fully characterized by ^1H, NOE difference, ^{13}C, ^{119}Sn, and IR spectra and HRMS.

(18) Kant, J.; Walker, D. G. In *Organic Chemistry of β-Lactams*; George, G. I., Ed.; VCH: New York, 1993; pp 121−196.

Table 1 shows the generality of the cyclization reaction. Reaction of $Ph_3Sn-SiMe_2Bu^t$ with *N*-tosylallenyne **2** gives the cyclic product **26** in >90% yield at room temperature, whereas the oxygenated derivative **3** gives the products **27** and **28** as single diastereomers under the conditions cited (entries 5 and 6). The less reactive trimethylsilyltributylstannane takes 5 h at 80 °C to complete the cyclization of **3** to give the product **28**. When **3** is treated with trimethylsilyltributylstannane at room temperature in the presence of $(PhCN)_2PdCl_2$ and $(C_6F_5)_3P$, a mixture of an allylstannane and the cyclic product **28** (1:3) is obtained.

Structures of the cyclic products **27** and **28** were confirmed by IR, ^1H, NOE difference, and ^{13}C NMR spectroscopy, HMQC, COSY, HRMS, and elemental analysis.[19] For the NOE data, while consistent with the assigned configuration of the THF derivatives **27** and **28**, it should be stressed that in five-membered carbocyclic and heterocyclic compounds this method is usually not reliable in assigning vicinal stereochemistry. However, this configuration is assigned to the vinylstannanes based on a reasonable model for the cyclization (vide infra, under Mechanism and Stereoselectivity, Figure 3) and the fact that only a single diastereomer is produced in the reaction.

The adduct **27** is cleanly converted into the corresponding bromo compound in 74% yield by treatment with NBS in CH_2Cl_2 at room temperature.[19] Reaction with formic acid in CH_2Cl_2 leads to protodestannylation (78%).[19]

Synthesis of Pyrrolidines and Indolizidines. Allenyne **4** would represent an advanced intermediate for the synthesis of highly functionalized pyrrolidines such as kainic acids or its congeners.[20] When **4** was treated with $Me_3Si-SnBu_3$ (1.1 equiv), a Pd precursor (5 mol %) and ligand (10 mol %) in C_6D_6 at 80 °C, an efficient conversion into a mixture of products, **29-*cis*** and **29-*trans***, was observed (Table 1, entry 7). Use of $Pd(PhCN)_2Cl_2$ was less efficient compared to $Pd_2(dba)_3$ in this case. The 1,3-diastereoselctivity (1:1) remains the same in both instances or when different Si−Sn reagents were used. Sterically less encumbered $Me_3SiSnBu_3$ gave higher yield (76%) and cleaner conversion compared with $Me_2Bu^tSiSnPh_3$ (50% yield).

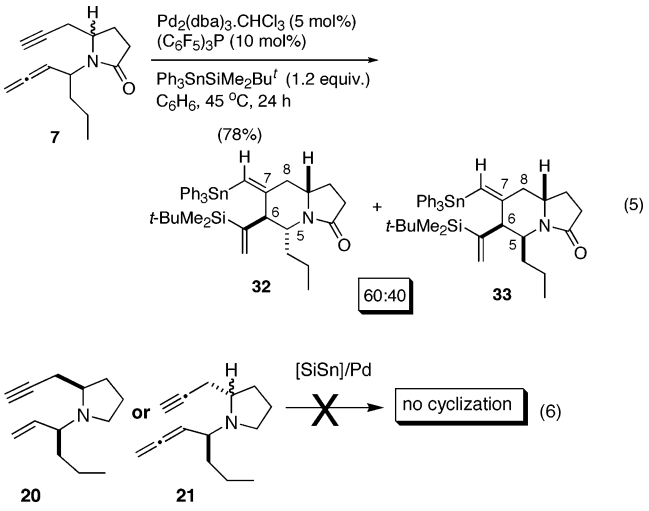
Cyclization of allenynes derived from readily available *N*-acyliminium ions[13] should provide an expeditious entry into highly functionalized bicyclic *N*-heterocyclic compounds. Two examples are shown in entries 8 and 9 in Table 1. The allenyne **5**, prepared in three steps from succinimide and 3-butynol (Scheme 3), gave the product indolizidine (**30**) as a single isomer. The relative stereochemistry of the vicinal appendages has been assigned as trans on the basis of NMR experiments, models for the cyclization, and the results described in the next

(19) See the Supporting Information for details.

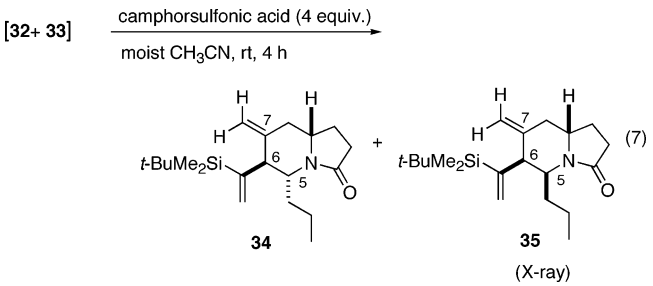
(20) (a) *Kainic Acid a Tool in Neurobiology*; McGeer, E. G., Olney, J. W., McGeer, P. L., Eds.; Raven Press: New York, 1978. (b) Hollmann, M.; Heinemann, S. Cloned Glutamate Receptors. *Annu. Rev. Neurosci.* **1994**, *17*, 31. (c) Shinozaki, H. In *Excitatory Amino Acid Receptors. Design of Agonists and Antagonists*; Krogsgaard-Larsen, P., Hansen, J. J., Eds.; Ellis Horwood: New York, 1992; p 261. (d) Parsons, A. F. Recent developments in kainoid amino acid chemistry. *Tetrahedron* **1996**, *52*, 4149. (e) Moloney, M. G. Excitatory Amino Acids. *Nat. Prod. Rep.* **1998**, 205. (f) Moloney, M. G. Excitatory Amino Acids. *Nat. Prod. Rep.* **1999**, 485 and references therein.

section where in a related system unambiguous relative stereochemical assignments were made on the basis of solid-state structure derived from X-ray crystallographic analysis. Relative juxtaposition of the allene and acetylene are reversed in the substrate **6**, and an alternate substitution pattern of the indolizidine (**31**) results upon cyclization.

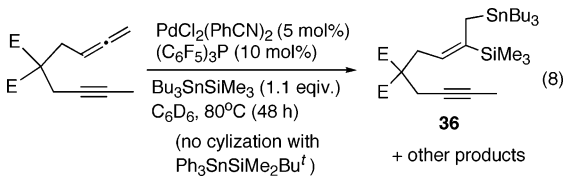
Indolizidines with multiple alkyl substituents, exemplified by indolizidine-223A,[21] are a class of compounds that has attracted some recent attention. Our approach to the synthesis of this class of compounds which relies upon the allenyne cyclization is shown in eq 5. The synthesis of the starting allenyne is shown in Scheme 5. Cyclization of allenyne **7** proceeds stereoselectively with respect to the newly created stereogenic center (only 6-β). The diastereomeric ratio reflects nearly the isomeric ratio of the starting material **7** at C_5. The 1:1 ratio of two isomers **32** and **33** is evident in the ^{13}C NMR spectrum in which two signals were observed for each carbon atom even though the two compounds could not be separated by column chromatography. The confirmation of the stereochemistry of the products came from the corresponding destannylated products **34** and **35** (vide infra). A strong cross-peak between the $Ph_3Sn-CH{=}CR_2$ and the allylic hydrogens (C_8) in the 2D NOSY spectrum of **32**/**33** clearly indicates the double-bond geometry shown. Incidentally, the free amines **20** or **21** (Scheme 5) derived from the lactams failed to undergo the cyclization (eq 6).



Selective Destannylation of 32 and 33 and Relative Configuration of the Cyclization Products. Protodesilylation[22] and protodestannylation[23] of vinylsilanes and vinylstannanes are known to proceed in the presence of strong acids such as trifluoroacetic acid (TFA) and hydrofluoric acid in various organic solvents. However, all our efforts to carry out this transformation on a mixture of **32** and **33** using various acids such as camphorsulfonic acid (CSA), TFA, HF, and HI led only to a selective destannylation to get a mixture of products **34** and **35** (eq 7). The bulk of the *tert*-butyldimethylsilyl group, along with the reluctance to the formation of a primary carbonium ion, should be responsible for this unusual result. The structures of the two products were unambiguously established by a combination of 1D and 2D NMR studies (see the Experimental Section for details) and X-ray crystallographic analysis. The C_5-hydrogens from the two isomers were carefully identified in the ^1H NMR with the help of the 2D-COSY spectrum. This peak appears as a doublet of triplet (J = 12, 4.5 Hz) in **34** and as a doublet of doublet (J = 8, 8 Hz) in **35**. The ratio of the two products was found to depend on the strength of the acid used, and the reaction conditions, suggesting some form of equilibration or selective loss of one of the indolizidines under the reaction conditions. The product, when recrystallized from mixture of methylene chloride and hexane (2:5) as a solvent, gave a well-behaved solid, still as a mixture of **34** and **35**. This mixture showed a moderately sharp melting point of 56−58 °C. A randomly picked, suitable crystal was subjected to X-ray crystallographic analysis. An ORTEP representation of the structure is shown in Figure 2.[19] This solid was identified as the minor component (**35**) of the mixture by NMR methods. This, in combination with the extensive NMR studies, corroborates the structures of the two indolizidines **34** and **35** and, thus, the stereoselective nature of the cyclization (i.e., exclusive formation of the C_6-β-vinyl derivative).



Limitations of the Reaction. Formation of Acyclic Adducts. The cyclization appears to be limited to allenynes with terminal acetylenes. For example, substrate **1b**, an internal acetylene, failed to undergo the cyclization reaction even under forcing conditions (eq 8). While *t*-$BuMe_2SiSnPh_3$ failed to react, $Me_3SiSnBu_3$ gave only an acyclic adduct **36** under the standard conditions. Attempts to cyclize this adduct under more forcing conditions lead to decomposition of the material.



For some substrates, the success of the reaction also depends on the choice of the silylstannane reagent. For example, substrate **6**, which underwent smooth cyclization with $BuMe_2SiSnPh_3$, gave only acyclic product **37** with $Me_3SiSnBu_3$ (Table 1, entries 9 and 12, and eq 9). Under similar conditions, **5** also gave acyclic product **38** (eq 10). Likewise, the β-lactam substrates **8a** and **8b** gave

(21) Garraffo, H. M.; Jain, P.; Spande, T. F.; Daly, J. W. *J. Nat. Prod.* **1997**, *60*, 2. IND 223A. See also ref 14.

(22) Protodesilylation: (a) Utimoto, K.; Kitai, M.; Nozaki, H. *Tetrahedron Lett.* **1975**, 2825. (b) Chan, T. H.; Fleming, I. *Synthesis* **1979**, 761.

(23) Protodestannylation: Stork, G.; Mook, R., Jr. *J. Am. Chem. Soc.* **1987**, *109*, 2829.

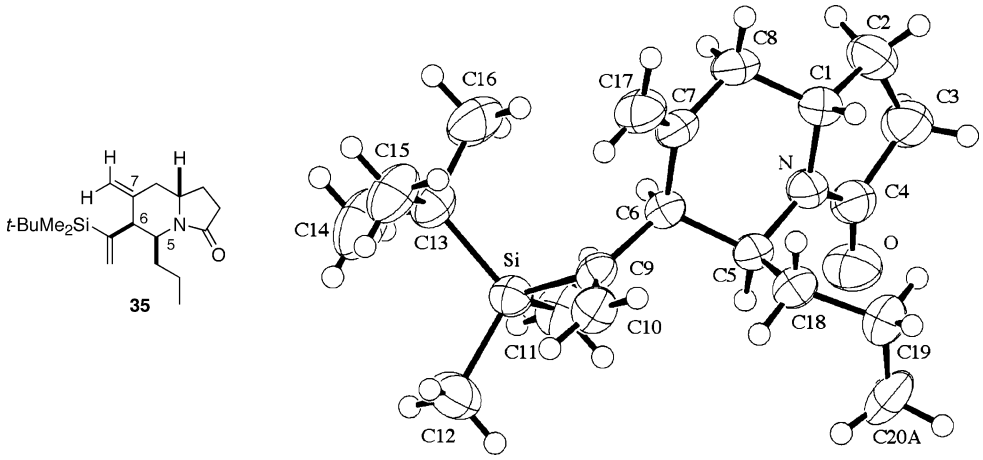
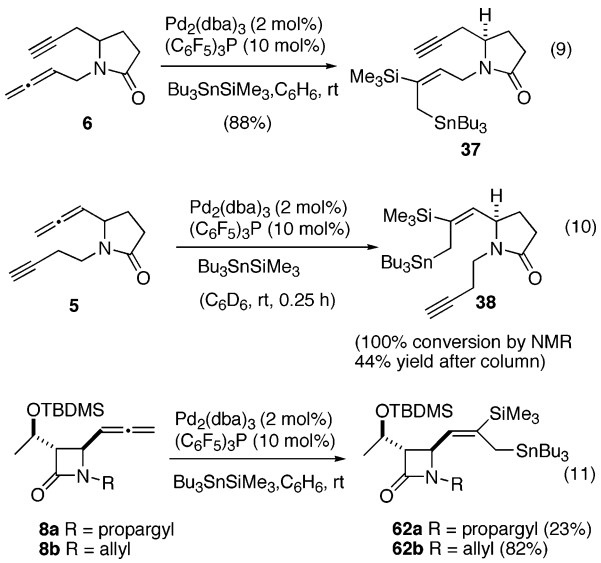


FIGURE 2. Solid-state structure and ORTEP diagram of indolizidine **35**.

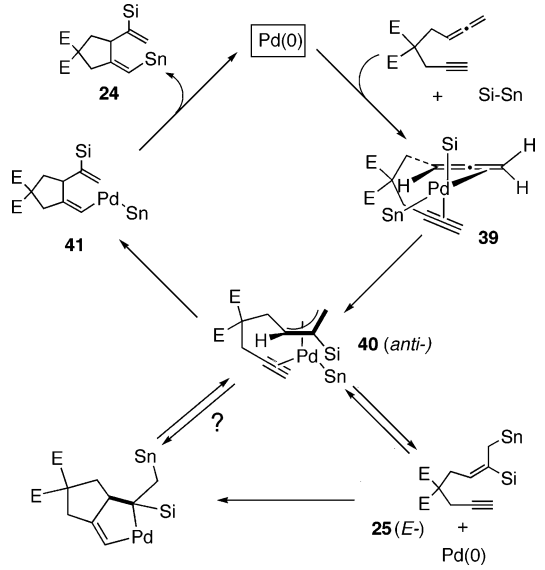
only acyclic allylstannanes **62a** and **62b** under the standard reaction conditions (entry 13, and eq 11).



Mechanism and Stereoselectivity. Details of the mechanism of silyl-stannylation and the ensuing cyclization remains unknown. A unified mechanism that accounts for the observed results is shown in Scheme 8. Coordination of the Pd^{2+} on the terminal π-bond on the sterically more accessible face (**39**) would lead to an anti π-allyl Pd-complex **40**, which upon reductive elimination with formation of the less congested allylstannane and regeneration of Pd(0) would give the primary product **25**. A more energetically demanding insertion of the acetylene into this π-allyl Pd complex takes place at a higher temperature leading to the cyclic product **24** via **41**.[24] In support of such a mechanism, we have observed that isolated **25** can be converted into **24** using Pd(0) and $(C_6F_5)_3P$ at elevated temperatures. Support for the oxidative addition of allylstannanes comes largely from experimental observations on the allylstannane additions to acetylenes published by Shirakawa et al.[24c,d]

Reversibility of C−Sn bond formation is also implied in Mitchell's original studies on additions of stannanes to allenes.[8] The carbometalation of the Pd-allyl intermediate **40** is expected to be a syn-addition and this will be followed by a reductive elimination of Pd(0) from **41** with retention of configuration. These processes result in the exquisite stereoselectivity seen in these reactions.

SCHEME 8. Possible Mechanism of Silylstannylation/Cyclization of an Allenyne



Inspection of models suggests that in the cyclization of **3**, of the two transition states (leading to the *trans*-**27** and *cis*-**27**) the one leading to the former is relatively strain-free (Figure 3). This model assumes, that the anti-configuration for the π-allyl-Pd-intermediate would be more stable resulting in an anti-orientation of the vinyl-R_3Si group and the C_3-substituent. Note that the favorable TS has a quasi-chairlike appearance while the other one has "boatlike" features.

(24) (a) A theoretical study of silylstannylation: Hada, M.; Tanaka, Y.; Ito, M.; Murakami, M.; Amii, H.; Ito, Y.; Nakatsuji, H. *J. Am. Chem. Soc.* **1994**, *116*, 8754. (b) For a metal-catalyzed carbocyclization by intramolecular reactions of allylsilanes and allylstannanes with alkynes, see: Fernández-Rivas, C.; Méndez, M.; Echavarren, A. M. *J. Am. Chem. Soc.* **2000**, *122*, 1221. This reaction in which the trialkyltin moiety is lost is mechanistically different from latter stages of the silylstannylation/cyclization. For intermolecular allylstannane additions to acetylenes catalyzed by Ni and Pd, see: (c) Shirakawa, E.; Yamasaki, K.; Yoshida, H.; Nakao, Y.; Hiyama, T. *J. Am. Chem. Soc.* **1999**, *121*, 10221. (d) Shirakawa, E.; Yoshida, H.; Nakao, Y.; Hiyama, T. *Org. Lett.* **2000**, *2*, 2209. (e) A less likely alternate mechanism involving a palladacyle cannot be ruled out at this time.

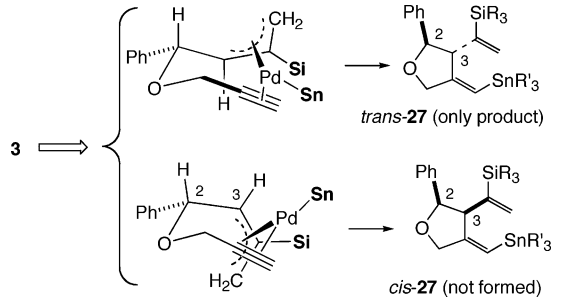


FIGURE 3. Relatively strain-free transition state leading to *trans*-**27**.

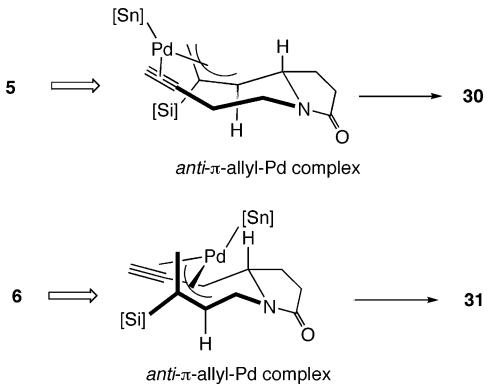


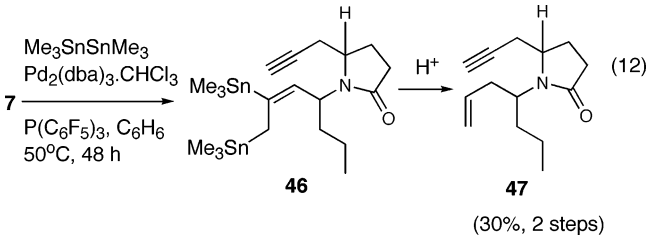
FIGURE 4. Favored transition states in the cyclization of **5** and **6**.

The stereoselectivity in the cyclization of **5** and **6** can also be explained on the basis of the most favorable conformation of the putative intermediate π-allyl Pd complexes shown in Figure 4. As in the case of the cyclization of **3** (Figure 3), the steric interactions in the anti-π-allyl Pd-complex undergoing the cyclization would satisfactorily account for the observed stereochemical result.

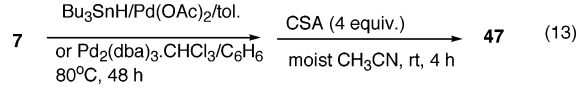
In the case of the cyclization of **4** (Table 1, entry 7), such analysis does not easily explain why the stereoselectivity is completely lost.

B. Allenyne Cyclization using Other X−Y Reagents. Comparison of Silylstannylation with Other Similar Reagents. The silyltin reagents are generally superior to other bis-functionalization reagents in this type of cyclizations. For comparison, cyclization reactions of **1a**, **3**, and **7** with a boron−tin reagent and ditin reagents were carried out, and the results are shown in Table 3. The borostannylation is a relatively poor reaction giving **42** from **1a** as the major cyclic product in no more than 50% yield upon isolation (entry 1). Judged by "in situ" NMR analysis, the distannylation reaction proceeds to give a good yield of **43** (entry 2) at 45 °C, and the corresponding acyclic adduct **44** at room temperature. Typical results for substrates **3** and **7** are shown in entries 4 and 5. Isolation of the Sn−Sn and Sn−B compounds presents significant problems, and upon chromatography severe losses are encountered. The distannylated products are best isolated after protodestannylation with CSA in moist acetonitrile as shown in eq 12 for **46**.

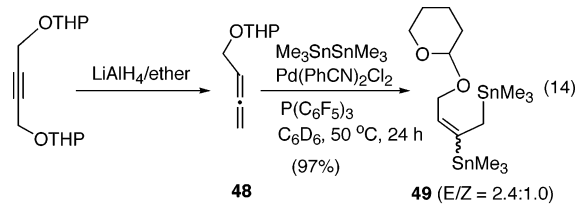
Recently, Lautens et al. reported cyclization of 1,6-diynes and 1,6-enynes using catalytic amounts of Pd(0)

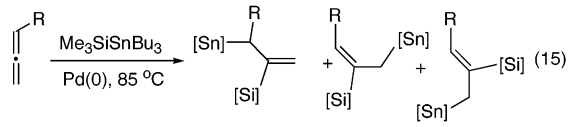


and *n*-Bu_3SnH.[25] Under these conditions, only hydrostannylation of the allene in **7** resulted and the product was identified as the enyne **47** (eq 13) after protodestannylation by the same procedure shown in eq 12.



C. Silylstannylation of Highly Functionalized Allenes Under New Protocols. Mitchell first reported the reactions of distannanes and silylstannanes with allenes.[3b,8] The addition of ditin reagent is apparently reversible, and under catalysis of Pd(0), a thermodynamic mixture of products is obtained. The more useful addition of silylstannanes under the reaction conditions reported by Mitchell [(1:1 allene and $Me_3SiSnMe_3$ or $Me_3SiSnBu_3$, 1 mol % $Pd(PPh_3)_4$] leads to a mixture of products, typical examples of which are shown in eqs 14 and 15. Compared to these reactions and the corresponding Pt-catalyzed diboronation[26] of allenes, we find that our modified conditions give more stereoselective reactions. Since allylstannanes are useful intermediates in their own right we have expanded the synthesis of functionalized allylstannanes by this route.





R	yield			
n-Bu	(67)	--	75	23
t-Bu	(62)	95	5	--
Ph	(63)	--	95	5
CH_2CO_2Et	(62)	90	10	--

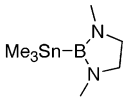
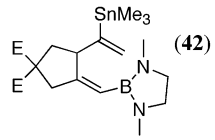
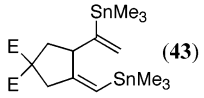
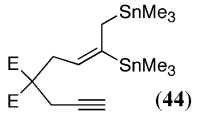
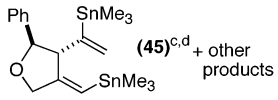
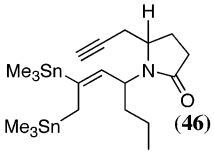
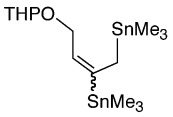
The 4-(2-tetrahydropyranyloxy)-1,2-butadiene (**48**) was prepared as shown in eq 14.[27] Syntheses of additional

(25) (a) Lautens, M.; Smith, N. D.; Ostrovsky, D. *J. Org. Chem.* **1997**, *62*, 8970. (b) Lautens, M.; Mancuso, J. *Org. Lett.* **2000**, *2*, 671.

(26) Ishiyama, T.; Kitano, T.; Miyaura, N. *Tetrahedron Lett.* **1998**, *39*, 2357. For a $R_3SiSnR'_3$-mediated addition of aryl iodides and vinyl iodides to allenes, see: Yang, F.-U.; Cheng, C.-H. *J. Am. Chem. Soc.* **2001**, *123*, 761.

(27) Preparation of **48**: Brandsma, L.; Verkruijsse, H. D. *Synthesis of Acetylenes, Allenes and Cumulenes: A Laboratory Manual*; Elsevier Scientific: New York, 1981.

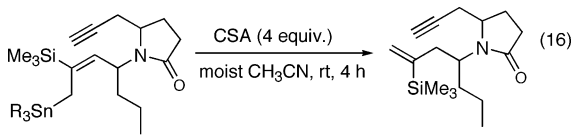
TABLE 3. Cyclization of Allenynes Mediated by Boron−Tin and Tin−Tin Reagents

entry	[XY] reagent	substrate	conditions[a]	product(s)	yield(%)[b]
1.		**1a**	80 °C, 1 h, **A**	 (**42**)	(>80)
2.	$Me_3SnSnMe_3$	**1a**	45 °C, 48 h, **A**	 (**43**)	46 (>90)
3.	$Me_3SnSnMe_3$	**1a**	rt, 22 h, **A**	 (**44**)	(>90)
4.	$Me_3SnSnMe_3$	**3**	65 °C, 8 h, **B**	 (**45**)[c,d] + other products	42
5.	$Me_3SnSnMe_3$	**7**	50 °C, 48 h, **A**	 (**46**)	30[e,f]
6.	$Me_3SnSnMe_3$	**48**	50°C, 24 h, **B**,	 **49** (E/Z = 2.4:1.0)	97

[a] Key: (A) 5 mol % $Pd_2(dba)_3$ with 10 mol % $P(C_6F_5)_3$; (B) 5 mol % $Pd(PhCN)_2Cl_2$ with 10 mol % $P(C_6F_5)_3$. [b] Yields determined by NMR in parentheses. [c] Not isolated due to instability on column chromatography. [d] Configuration of **45** tentative, assigned by analogy to entries 4−6 of Table 1. [e] Major side product acyclic bis-adduct (**45a**). [f] Isolated as **47** after double-destannylation with CSA, CH_3CN, rt, 4 h (see eq 12).

allenes used in this study are shown in Scheme 9. The *N*-allenyl derivative **55** was prepared from the known propargyl compound **54**,[28] which is produced in situ by treatment of the serinol derivative with excess NaH. The sodium benzylate that is produced in the medium catalyzes the isomerization of the propargyl derivative into the allenyl derivative **55**. Substrates **59** and **60** were also prepared from serine by established chemistry via intermediate **9**[10] shown in Scheme 9.

Typical examples of silylstannylation of allenes are shown in Table 4. The allenynes **1a**,**b**, **3**, and **5**−**7** have been discussed previously in connection with the silylstannylation−cyclization reaction. These substrates give addition to the allene *without* cyclization under mild conditions. The inevitable byproducts in these reactions, formed to varying degrees, are the cyclic products. By careful monitoring of the reaction by NMR spectroscopy, the reaction can be optimized to get maximum yields of the expected allylstannanes, which are formed with excellent regio- and stereoselectivity. As shown in the case of **1a** (Scheme 7), the reaction can also be controlled by the use of different silylstannanes. In some instances, different silylstannanes show dramatic difference in reactivity and monitoring of the reaction is not needed. For example, substrate **7,** which gave an excellent yield of the indolizidines **32** and **33** with $Me_2Si(t\text{-}Bu)SnPh_3$ (eq 8), gave only acyclic adducts (**51** and **52**) under a variety of reaction conditions with $Me_3SiSnBu_3$ and $Me_3SiSnPh_3$ respectively. These adducts were conveniently identified after destannylation with CSA and moist acetonitrile (eq 16).



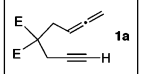
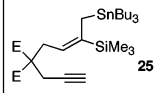
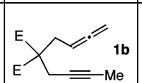
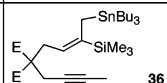
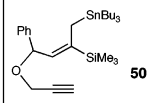
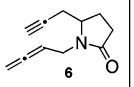
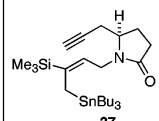
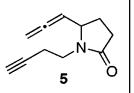
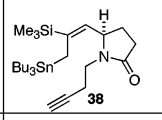
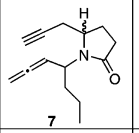
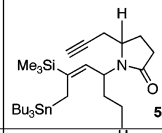
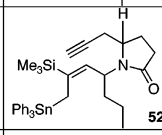
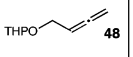
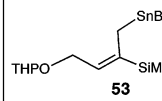
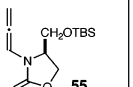
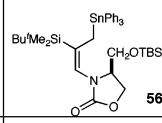
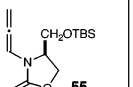
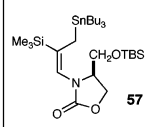
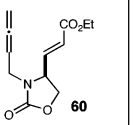
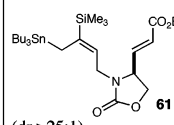
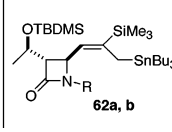
R = Bu **51**
R = Ph **52**

63

Note that the silylstannylation of allenes gives clean (*E*)-allylstannanes (e.g., **48**−**53)**, whereas distannylation gives a mixture of (*E*)- and (*Z*)-products (compare eq 14 and entry 8, Table 4). Other successful substrates include

(28) Hanessian, S.; Ninkovic, S. *J. Org. Chem.* **1996**, *61*, 5418.

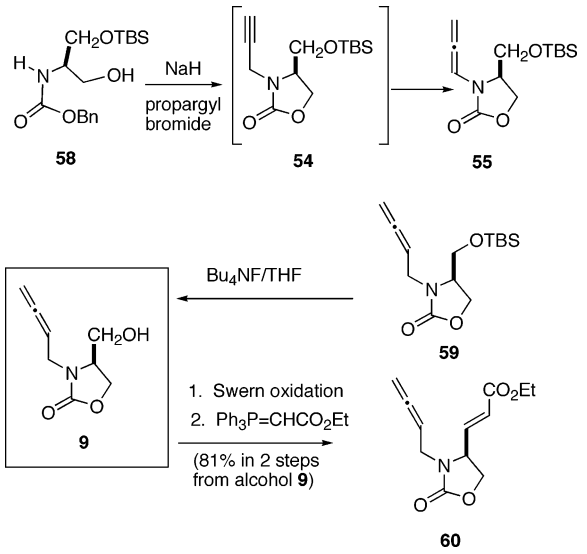
TABLE 4. Silylstannylation of Functionalized Allenes

no.	allene	[SiSn]	Conditions[a]	product	Yield[b]
1.	 **1a**	$Me_3SiSnBu_3$	$Pd_2(dba)_3$. $CHCl_3$, C_6H_6, rt, 2 h	 **25**	**81** (>90)[c]
2.	 **1b**	$Me_3SiSnBu_3$	$Pd(PhCN)_2Cl_2$ (5 mol%), $P(C_6F_5)_3$ (10 mol%) C_6D_6, 80 °C, 2 d	 **36**	(50)[d]
3.	**3**	$Me_3SiSnBu_3$	rt, 12 h, **B**	 **50**	**50**:**28** = 1:3 by NMR
4.	 **6**	$Me_3SiSnBu_3$	rt, C_6H_6, **A**	 **37**	88
5.	 **5**	$Me_3SiSnBu_3$	rt, C_6D_6, **A**, 15 min	 **38**	44
6.	 **7**	$Me_3SiSnBu_3$	C_6H_6, 45°C, 48 h, **A**	 **51**	(63)[e]
7.	**7**	$Me_3SiSnPh_3$	C_6H_6, 45°C, 48 h, **A**	 **52**	(75)[e]
8.	 **48**	$Me_3SiSnBu_3$	$Pd(PhCN)_2Cl_2$ (5 mol%), $P(C_6F_5)_3$ (10 mol%) rt, 12 h	 **53**	92 (>95) E/Z:>95/<5
9.	 **55**	$Me_2BuSiSnPh_3$	$Pd(PhCN)_2Cl_2$ (5 mol%), $P(C_6F_5)_3$ (10 mol%) rt, 8 h	 **56**	60 (>95) E only
10.	 **55**	$Me_3SiSnBu_3$	$Pd(PhCN)_2Cl_2$ (5 mol%), $P(C_6F_5)_3$ (10 mol%) rt, 12 h	 **57**	47 (>95) E/Z:>99/<1
11.	 **60**	$Me_3SiSnBu_3$	$Pd_2(dba)_3$. $CHCl_3$, C_6H_6, rt, 20 min	 **61** (dr >25:1)	84
12.	**8a** (R = propargyl) **8b** (R = allyl)	$Me_3SiSnBu_3$	rt, benzene, **A**	 **62a, b**	23 (**62a**) (from **8a**) 82 (**62b**) from **8b**

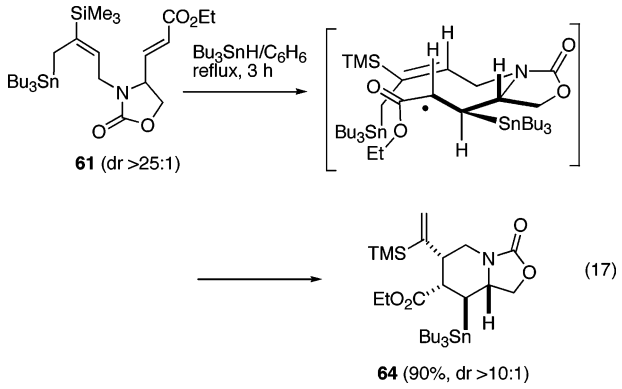
[a] Key: (A) 5 mol % $Pd_2(dba)_3$ with 10 mol % $P(C_6F_5)_3$; (B) 5 mol % $Pd(PhCN)_2Cl_2$ with 10 mol % $P(C_6F_5)_3$. [b] Isolated yields; yields determined by NMR in parentheses. [c] Isolated material contained 8% cyclic product **24** (Scheme 7). [d] Conversion based on NMR. [e] Identified as **63**, the destannylated product (~40%; see eq 16).

N-alleneoxazolidinone **55** and, surprisingly, **60**, which carries a reactive α,β-unsaturated ester moiety. The silylstannylation of **60** gives a substrate **61**, which is useful for further annulation reactions. An example of a

SCHEME 9. Synthesis of Functionalized Allenes (Table 4)



novel radical cyclization to form a highly substituted piperidine is shown in eq 17. Other similar protocols for cyclization including Lewis acid and transition metal-mediated processes[24b] can be envisioned for these highly functionalized molecules. Nucleophilic reactions of the *E*-allylstannanes with electrophiles such as carbonyl compounds would also expand the utility of these intermediates. Such studies are in progress.



Conclusion

Trialkylsilyltrialkylstannane ($R_3Si-SnR'_3$) reagents undergo highly selective Pd-catalyzed additions to 1,2-dien-7-ynes and 1,2-dien-8-ynes to give 2-vinylalkylidenecyclopentanes with silicon and tin substituents on the double bonds. Similar additions of distannanes and borostannanes show that the reactions with silylstannanes are superior in terms of ease of handling of the bifunctional reagents and the isolation of the products after the reaction. The chemo- and regioselectivities are controlled by the enhanced reactivity of the allene unit vis-à-vis the acetylene. The (*Z*)-geometry of the exocyclic stannylvinylidene is a consequence of the syn-carbometalation and subsequent reductive elimination from Pd with retention of configuration at the vinyl carbon. This method is particularly useful for the synthesis of highly functionalized pyrrolidines and indolizidines. Reluctance of certain kinds of allenynes (especially with internal acetylenes, or with less reactive trialkylsilyltrialkylstannane reagents) to undergo the cyclization illustrates limitations of the reaction. However, in these instances, the intermediate allylstannanes, resulting from the initial addition to the allenes, can be isolated. Based on the isolation of these intermediates, and their subsequent conversion to the cyclic products under more forcing conditions, a mechanism for the reaction is proposed. Model transition states to explain the stereoselectivity in the cyclization of substituted allenynes are provided. Further elaboration using the vinyltin and vinylsilane moieties should lead to highly functionalized carbocyclic and heterocyclic compounds. Examples of Sn−halogen exhange and protodestannylation are illustrated. Under similar conditions, addition of silylstannanes to highly functionalized allenes give (*E*)-allylstannanes with high stereoselectivity. Functional groups such as THP and silyl ethers, lactones, β- and γ-lactams, α-β-unsaturated esters, olefins, and substituted acetylenes are tolerated under the reaction conditions.

Experimental Section

Silylstannylation−Cyclization of Allenynes. Synthesis of prototypical substrates **4** and **7** and silylstannane-mediated cyclization of these compounds will be described here. For the details of the syntheses of other substrates **1a**,**b**, **2**, **3**, **5**, **6**, **20**, **21**, and **55**, procedures for reactions with silylstannane, distannane, and borostannane reagents, and characterization of the products, see the Supporting Information.

The syntheses of the silylstannane[3a,6] and borostannane[29] reagents have been described before.

Synthesis of (*S*)-3-(Buta-2,3-dienyl)-4-ethynyloxazolidin-2-one (4) (Scheme 2). To a solution of DMSO (0.35 mL, 4.9 mmol) in 4 mL of CH_2Cl_2 was added $(COCl)_2$ (0.21 mL, 2.2 mmol) dropwise at −60 °C. After 5 min, a solution of alcohol (*S*)-3-(buta-2,3-dienyl)-4-(hydroxymethyl)oxazolidin-2-one **(9)**[10] (345 mg, 2.04 mmol) in 4 mL of CH_2Cl_2 was added dropwise over 8 min. After the mixture was stirred for 15 min at −60 °C, Et_3N (0.57 mL, 4.1 mmol) was added, the mixture was warmed slowly to −15 °C over 20 min, and the solvent was evaporated to dryness. The crude mixture of the resulting (*R*)-3-(buta-2,3-dienyl)-2-oxooxazolidin-4-carbaxaldehyde **10** was dissolved in MeOH (5 mL) at 0 °C ,and to this solution were added Seyferth−Gilbert[30] reagent (735 mg, 4.08 mmol) and K_2CO_3 (564 mg, 4.08 mmol). The resulting mixture was stirred at rt for 20 h. The reaction mixture was poured into brine (40 mL), and the aqueous layer was extracted with ether (40 mL × 4). The combined organic layer was dried ($MgSO_4$) and evaporated, and the residue was subjected to flash chromatography (EtOAc/Hex = 1/2) to get 187 mg (56%) of **4** as an oil: IR (neat, NaCl) 3288, 3065, 2984, 2920, 2118, 1957, 1748, 1479, 1416, 1372, 1217, 1183, 1084, 1024 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 2.50 (d, J = 2.1 Hz, H, CC*H*), 3.71 (dddd, J = 2.0, 3.5, 7.6, 15.2 Hz, H, NCH_2), 4.18−4.24 (m, H, NCH_2), 4.22−4.28 (m, H, OCH_2), 4.46 (td, J = 1.2, 8.5 Hz, H, OCH_2), 4.59 (ddd, J = 2.0, 6.2, 8.5 Hz, H, *NCH*), 4.81−4.88 (m, 2H, C=C=CH_2), 5.08−5.14 (m, H, C*H*=C=C); ^{13}C NMR (125 MHz, $CDCl_3$) δ 41.3, 46.9, 67.4, 75.7, 77.6, 78.8, 85.6, 157.2, 209.7; HRMS calcd for [M + Na] 186.0525, found 186.0538.

Synthesis of Allenyne 7 (Scheme 5). (a) Preparation of 1-(Hepta-1,2-dien-4-yl)pyrrolidine-2, 5-dione 17 by a Mitsunobu Reaction. In a 250 mL two-necked, round-

(29) (a) Wong, T.-T.; Busse, P. J.; Niedenzu, K. *Inorg. Chem.* **1970**, *9*, 2150. (b) Bradley, E. B.; Herber, R. H.; Busse, P. J.; Niedenzu, K. *J. Organomet. Chem.* **1973**, *52*, 297.

(30) (a) Gilbert, J. C.; Weerasooriya, U. *J. Org. Chem.* **1982**, *47*, 1837. (b) Muller, S.; Liepold, B.; Roth, G. J.: Bestman, H. J. *Synlett* **1996**, 521.

bottomed flask equipped with an addition funnel, stirring bar, and N_2 inlet were placed allenol **16** (44.6 mmol, 5 g), succinimide (44.6 mmol, 3.79 g), and PPh_3 (44.6 mmol, 11.68 g) in 70 mL of THF at rt. A THF (20 mL) solution of diethyl azodicarboxylate (44.6 mmol, 7.76 g) was added dropwise at rt over a period of 40 min, and the resultant dark mixture was stirred for 24 h. Analysis of the reaction by TLC indicated a complete consumption of the allenol. The reaction mixture was concentrated to dryness on a rotary evaporator, and the residue was triturated with 30% EtOAc in hexanes (3 × 50 mL). The combined washings was concentrated to give a crude product which upon flash column chromatography (15% EtOAc in hexanes) afforded **17** (5.59 g, 65%) as a thick pale yellowish oil: ^{1}H NMR (400 MHz) δ 5.44 (q, J = 7 Hz, 1H), 4.77 (dt, J = 7, 3 Hz, 2H), 4.68−4.63 (m, 1H), 1.94−1.88 (m, 1H), 1.84−1.78 (m, 1H), 1.31−1.21 (m, 2H), 0.89 (t, J = 7.5 Hz, 3H); ^{13}C NMR (100 MHz) δ 208.6, 177.1, 89.3, 77.1, 51.2, 33.9, 28.2, 19.9, 13.7.

(b) Reduction of 17 to 1-(Hepta-1, 2-dien-4-yl)-5-hydroxypyrrolidin-2-one (18). In a 100 mL two-necked, round-bottomed flask equipped with a rubber septum, stirring bar, and N_2 inlet was placed **17** (5 mmol, 965 mg) in 30 mL of methanol at 0 °C. Sodium borohydride (10 mmol, 380 mg) was added as three approximate portions, and the resultant mixture was stirred at the same temperature for 40 min. Water (3 mL) was added to quench the reaction and concentrated on a rotary evaporator. The residue was extracted with CH_2Cl_2 (3 × 25 mL). The combined organic part was washed with brine, dried ($MgSO_4$), and concentrated. Purification by flash column chromatography (60% EtOAc in hexanes) afforded a thick colorless oil which was found to be the desired **18** (829 mg, 85%) as a mixture of ∼1:1 diastereomers: ^{1}H NMR (500 MHz) δ 5.35 and 5.2 (2q, J = 6.5 Hz, 1H), 5.32 and 5.27 (2t, J = 4 Hz, 1H), 4.8−4.77 (m, 2H), 4.5−4.7 (m, 1H), 3.99 and 3.79 (2d, J = 7 Hz, 1H, exchangeable with D_2O), 2.64−2.56 (m, 1H), 2.27−2.2 (m, 2H), 1.92−1.88 (m,1H), 1.77−1.64 (m, 2H), 1.37−1.2 (m, 2H), 0.89 and 0.87 (2t, J = 6 Hz, 3H); ^{13}C NMR (125 MHz) δ 208.9 and 208.2, 175.5 and 175.3, 92.1 and 90.4, 82.9 and 82.2, 77.3 and 77.3, 51.2 and 50.3, 36.4 and 33.8, 29.4, 29.2 and 28.9, 20.1 and 19.8, 14.1 and 13.9.

(c) Conversion of 18 into 1-(Hepta-1, 2-dien-4-yl)-5-oxopyrrolidin-2-yl Acetate (19). In a 100 mL single-necked flask equipped with a stirring bar and a ground glass jointed one way stopcock connected to N_2 was placed **18** (20 mmol, 3.9 g) in 50 mL of CH_2Cl_2 at rt. Acetic anhydride (25 mmol, 2.36 mL), pyridine (25 mmol, 2.02 mL), and 50 mg of DMAP were added successively. The reaction flask was evacuated and refilled with N_2. Analysis by TLC after stirring for 3 h indicated a total disappearance of the starting material while showing a nonpolar spot. The reaction mixture was diluted with 50 mL of CH_2Cl_2, transferred into a separatory funnel, and washed with water and then brine. The organic part was dried ($MgSO_4$), concentrated on a rotary evaporator, and dried (0.1 mmHg at 40−50 °C for 30 min) to get a viscous oil (3.97 g). Analysis of the product by NMR indicated it to be a mixture of 1:1 diastereomers and also pure enough to proceed for the next step without further purification: ^{1}H NMR (500 MHz) δ 6.28 (dd, J = 13 Hz, 1H), 5.12 (qd, J = 6.5, 1.5 Hz, 1H), 4.81−4.74 (m, 2H), 4.57−4.49 (m, 1H), 2.58 (dt, J = 16.5 Hz, 9 Hz, 1H), 2.35−2.2 (m, 2H), 2 and 1.99 (2s, 3H), 1.98−1.93 (m, 1H), 1.67−1.62 (m,1H), 1.54−1.51 (m, 1H), 1.36−1.22 (m, 2H), 0.878 and 0.875 (2t, J = 7.5 Hz, 3H); ^{13}C NMR (125 MHz) δ 208.9 and 208.1, 176.1 and 176.1, 170.5 and 170.4, 91.1 and 90.2, 84.4 and 82.8, 77.8 and 77.6, 50.7 and 49.7, 35.6 and 33.2, 28.9, 27.3 and 27.1, 21.6 and 21.5, 19.8 and 19.7, 14.1 and 13.9.

(d) Propargylation of 19 to 1-(Hepta-1,2-dien-4-yl)-5-(prop-2-ynyl)pyrrolidin-2-one (7). In a 250 mL two-necked, round-bottomed flask equipped with a stirring bar, rubber septum, and N_2 inlet were placed **19** (15 mmol, 3.555 g) and allenyltributylstannane (45 mmol, 14.81 g) in 60 mL of CH_2Cl_2 at 0 °C. Trimethylsilyl trifluoromethanesulfonate (37.5 mmol, 6.78 mL) was added dropwise through a syringe. The ice bath was removed, and the reaction mixture was stirred overnight. Saturated aq $NaHCO_3$ was added to quench the reaction and the mixture extracted with CH_2Cl_2 (3 × 30 mL). The combined organic part was washed with brine, dried ($MgSO_4$), and concentrated on a rotary evaporator to get a crude product which was purified by flash column chromatography to obtain **7** (2.3 g, 72%) as a colorless viscous oil. Analysis of the product by NMR indicated that it is a mixture of two diastereomers in nearly 1:1 ratio: ^{1}H NMR (500 MHz) δ 5.27 and 5.24 (2q, J = 5.5 Hz, 1H), 4.82−4.73 (m, 2H), 4.58−4.53 and 4.37−4.33 (2m, 1H), 3.82−3.77 and 3.74−3.7 (2m, 1H), 2.58−2.34 (m, 3H), 2.3−2.13 (m, 2H), 1.99−1.93 (m, 2H), 1.73−1.57 (m, 2H), 1.37−1.2 (m, 2H), 0.89 and 0.88 (2t, J = 7.5 Hz, 3H); ^{13}C NMR (125 MHz) δ 208.9 and 208.2, 175.7 and 175.5, 92.1 and 90.1, 80.4 and 80.3, 77.5 and 77.3, 71.2, 57.0 and 55.3, 52.2 and 49.9, 35.8 and 32.8, 30.6 and 30.3, 25.4 and 25.3, 24.5 and 24.4, 20.3 and 19.9, 14.0 and 13.98; HRMS (EI/CI) calcd for $C_{14}H_{19}NONa^+$ 240.135882, found 240.135242.

Cyclization of 1a (Table 1, Entry 1). (*Z*)-Diethyl 3-(1-(*tert*-butyldimethylsilyl)vinyl)-4-((triphenylstannyl)-methylene)cyclopentane-1,1-dicarboxylate (23). To a solution of $Pd_2(dba)_3$·$CHCl_3$ (1.3 mg, 0.0025 mmol Pd), $P(C_6F_5)_3$ (2.7 mg, 0.0050 mmol), and $Ph_3Sn-SiMe_2Bu^t$ (26 mg, 0.055 mmol) in 1 mL of C_6D_6 at rt was added allenyne **1a** (12.5 mg, 0.050 mmol), and the reaction mixture was kept in an NMR tube. Progress of the reaction was followed by ^{1}H NMR. After 2 days at rt, the contents of the NMR tube was evaporated and the residual oil was purified by flash chromatography (Hex/Et_3N = 95/5) to get 29 mg (80%) of product as a colorless oil. **23**: ^{1}H NMR (400 MHz, C_6D_6) δ −0.24 (s, 3H), −0.16 (s, 3H), 0.77 (s, 9H), 0.90 (t, J = 7.1 Hz, 3H, C*H*$_3$CH$_2$O), 0.93 (t, J = 7.1 Hz, 3H, C*H*$_3$CH$_2$O), 2.30 (dd, J = 5.5, 13.0 Hz, H, C*H*$_2$-CH), 3.16 (dd, J = 9.1, 13.0 Hz, H, C*H*$_2$CH), 3.22 (d, J = 15.5 Hz, H, C*H*$_2$C=C), 3.70−3.75 (m, 2H, CH$_2$C*H*, C*H*$_2$C=C), 3.90−4.05 (m, 4H, CH$_3$C*H*$_2$O), 5.36 (t, J = 1.6 Hz, H, SiC=C*H*$_2$), 5.95 (t, J = 1.8 Hz, SiC=C*H*$_2$) together 2H, 6.40 (s, J_{Sn-H} = 74 Hz, 1H), 7.25−7.35 (m, 9H), 7.68−7.85 (m, 6H); Figure 1 in the Supporting Information shows in detail all the NOE contacts from which the configurations of the double bonds were established; ^{13}C NMR (100 MHz, C_6D_6) δ −6.1, −4.4, 13.4, 13.6, 26.9, 41.1, 46.4, 50.1, 59.0, 60.9, 61.0, 119.6, 126.8, 128.3 (J_{Sn-C} = 50 Hz), 128.6, 137.0 (J_{Sn-C} = 38 Hz), 138.9, 151.1, 163.6, 170.5, 171.1. Anal. Calcd for $C_{38}H_{48}O_4SiSn$: C, 63.78; H, 6.76. Found: C, 64.16, H, 6.74.

Screening for Optimal Ligand for Cyclization (Table 2). To a solution of $Pd_2(dba)_3$·$CHCl_3$ (1.3 mg, 0.0025 mmol Pd), phosphine ligand (0.0050 mmol), and $Ph_3Sn-SiMe_2Bu^t$ (26 mg, 0.055 mmol) in 1 mL of C_6D_6 at rt was added allenyne **1a** (12.5 mg, 0.050 mmol), and the reaction mixture was kept in an NMR tube. Progress of the reaction was followed by ^{1}H NMR. The reaction gave a clean conversion into the cyclic product, and no discernible side product was observed except starting material. The conversions are based on the amount of product and starting material left at the end of the prescribed time in solution as estimated by NMR spectroscopy.

Screening for the Pd Precursor for the Cyclization in Scheme 7. To a solution of Pd precursor (0.0025 mmol Pd), $P(C_6F_5)_3$ (2.7 mg, 0.0050 mmol), and $Ph_3Sn-SiMe_2Bu^t$ (26 mg, 0.055 mmol) in 1 mL of C_6D_6 at rt was added allenyne **1a** (12.5 mg, 0.050 mmol), and the reaction mixture was kept in an NMR tube. Progress of the reaction was followed by ^{1}H NMR. The reaction gave clean conversion into the cyclic product, and no discernible side product was observed except starting material.

Cyclization of Substrate 4 (Entry 7, Table 1). To a solution of $Pd_2(dba)_3$·$CHCl_3$ (2.6 mg, 0.0050 mmol Pd) and $P(C_6F_5)_3$ (5.3 mg, 0.010 mmol) in C_6D_6 (1 mL) were added $Bu_3Sn-SiMe_3$ (40.0 mg, 0.110 mmol) and the starting allenyne **4** (16.3 mg, 0.100 mmol). The progress of the reaction was monitored by ^{1}H NMR spectroscopy. After 4 h at 80 °C, the ^{1}H NMR spectrum indicated a mixture of the acyclic adduct and cyclic product **29** (1:3), and after 12 h at 80 °C, the conversion was

TABLE 5. Silylstannylation−Cyclization of Substrate 4

entry	Pd source	[Si−Sn]	conditions	yield[a] (%)	cis/trans
1	$Pd(PhCN)_2Cl_2$	$Ph_3SnSiMe_2Bu^t$	80 °C/3 h	0	N/A
2	$Pd(PhCN)_2Cl_2$	$Bu_3SnSiMe_3$	80 °C/3 h	59	1:1
3	$Pd_2(dba)_3{\cdot}CHCl_3$	$Ph_3SnSiMe_2Bu^t$	55 °C/1 h	(50)	1:1
4	$Pd_2(dba)_3{\cdot}CHCl_3$	$Bu_3SnSiMe_3$	55 °C/1 h	76	1:1

[a] Isolated; values estimated by NMR are shown in parentheses.

complete. The ratio of *cis*-(*E*,6*S*,7a*R*)-tetrahydro-6-(1-(trimethylsilyl)vinyl)-7-((triphenylstannyl)methylene)pyrrolo[1,2-*c*]oxazol-3(*1H*)-one (**29-*cis***) and *trans*-(*E*,6*R*,7a*R*)-tetrahydro-6-(1-(trimethylsilyl)vinyl)-7-((triphenylstannyl)methylene)pyrrolo[1,2-c]oxazol-3(*1H*)-one (**29-*trans***) was 1:1 as identified by the ^{1}H NMR spectrum of the crude mixture. The solvent was removed, and the resulting residue was subjected to column chromatography (Et_3N/Hex = 5/95). Careful separation of diastereomers gave **29-*cis*** (23 mg, 44%) and **29-*trans*** (15 mg, 29%) both as colorless oils. **29-*cis***: IR (neat, NaCl) 2955, 2923, 1760, 1619, 1461, 1387, 1296, 1250, 1201, 1150, 1073, 1023 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ 0.20 (s, 9H), $SnBu_3$ peaks were omitted, 3.34 (dd, J = 6.8, 11.6 Hz, H, NCH_2), 3.39 (br d J = 6.3 Hz, H, ring CHC(Si)=CH_2), 3.81 (d, J = 11.6 Hz, H, NCH_2), 4.26 (dd, J = 3.8, 8.6 Hz, H, OCH_2), 4.39 (ddd, J = 1.9, 3.8, 8.8 Hz, H, NC*H*), 4.62 (t, J = 8.8 Hz, H, OCH_2), 5.57 (t, J = 1.8 Hz, H, C(Si)=CH_2 cis to Si), 5.71 (t, J = 1.9 Hz, H, C(Si)=CH_2, trans to Si), 6.19 (s, J_{Sn-H} = 50 Hz, H, C=C*H*(Sn); ^{13}C NMR (125 MHz, $CDCl_3$): δ −0.1, 10.4, 14.1, 27.7, 29.5, 52.7, 52.8, 63.7, 69.6, 126.6, 127.6, 152.7, 161.1, 162.5; HRMS calcd for $C_{24}H_{45}NO_2SiSn$ [(M + Na)$^+$] 550.2134, found 550.2160.

29-*trans*: IR (neat, NaCl) 2956, 1766, 1621, 1464, 1392, 1301, 1249, 1199, 1150, 1085, 1029 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.15 (s, 9H), $SnBu_3$ peaks were omitted, 2.93 (dd, J = 6.2, 11.7 Hz, H, NCH_2, anti), 3.56 (br t, J = 7.6 Hz, H, ring CHC(Si)=CH_2), 4.15 (dd, J = 9.1, 11.7 Hz, H, NCH_2, syn), 4.24 (dd br, J = 1.8, 7.6 Hz, H, NC*H*), 4.35 (dd, J = 2.6, 8.7 Hz, H, OCH_2, anti), 4.56 (dd, J = dd, J = 7.8, 8.6 Hz, H, OCH_2, syn), 5.45 (dd, J = 1.3, 2.2 Hz, H, C(Si)=CH_2 cis to Si), 5.71 (t, J = 1.9 Hz, H, C(Si)=CH_2, trans to Si), 6.08 (t, J = 1.9 Hz, J_{Sn-H} = 46 Hz, H, C=C*H*(Sn)); ^{13}C NMR (125 MHz, $CDCl_3$) δ −0.2, 10.5, 14.1, 27.7, 29.5, 51.3, 53.3, 63.3, 68.0, 123.7, 125.4, 153.1, 157.3, 161.9; HRMS calcd for $C_{24}H_{45}NO_2SiSn$ [(M + Na)$^+$] 550.2134, found 550.2130.

The structural assignments of **29-*cis*** and **29-*trans*** were made by NOE experiments (see Figure 1 in the Supporting Information for details), as well as a full characterization by ^{1}H, ^{13}C, COSY, HMQC, IR, and high-resolution MS.

The more polar isomer was assigned as the **29-*cis*** structure: based on the strong H_b-H_c NOE contact, α and β OCH_2 protons can be assigned as H_c and H_d, respectively. A long-range NOE contact from H_e to H_d (β) would be possible because of the concave geometry and observation of this H_e-H_d contact supports 2,4-cis stereochemistry. Likewise, the less polar component was assigned to **29-*trans*** structure: strong H_c-H_b NOE contact indicates that α and β OCH_2 protons can be assigned as H_c and H_d, respectively. The absence of H_e-H_c/H_d is a good indication that the (Si)C=CH_2 substituent is on the convex side (or pseudoequatorial) of the bicyclic system. The observation of H_e-H_b contact also supports these assignments.

The cyclization reaction was carried out with different Pd sources and Si−Sn reagents and the results are shown in Table 5.

Cyclization of 7 to Isomeric (*Z*)-6-(1-(*tert*-Butyldimethylsilyl)vinyl)hexahydro-7-triphenylstannyl)methylene)-5-propylindolizin-3(5*H*)-one 32 and 33 (Table 1, Entry 10, Eq 5). In a two-necked, round-bottomed flask equipped with a reflux condenser, stirring bar, rubber septum, and N_2 inlet were placed $Pd_2(dba)_3{\cdot}CHCl_3$ (0.25 mmol, 259 mg) and $P(C_6F_5)_3$ (0.5 mmol, 266 mg). A solution of allenyne **7** (5 mmol, 1.085 g) in 30 mL of benzene followed by *t*-$BuMe_2Si-SnPh_3$ (5.5 mmol, 2.558 g) were added. The rubber septum was quickly replaced with a glass stopper, and the dark mixture was heated at 45 °C for 24 h. Analysis by TLC indicated the completion of the reaction. The reaction mixture was concentrated, and the residue was purified by flash column chromatography (15% EtOAc in hexanes) to afford a sticky solid (2.66 g, 78%) which was found to be the desired product as a mixture of **32** and **33**. Major isomer **32**: ^{1}H NMR (500 MHz) δ 7.56−7.5 (m, 6H), 7.37−7.33 (m, 9H), 5.99 (t, J = 35 Hz, 1H), 5.87 (t, J = 1 Hz, 1H), 5.47 (d, J = 0.5 Hz, 1H), 4.31 (ddd, J = 16, 7.5, 3.5 Hz, 1H), 3.97−3.92 (m, 1H), 3.69 (d, J = 7.5 Hz, 1H), 3.09 (dd, J = 13, 7 Hz, 1H), 2.45−2.4 (m, 2H), 2.3 (dd, J = 13, 3.5 Hz, 1H), 2.18−2.13 (m, 1H), 1.8−1.74 (m, 1H), 1.6−1.56 (m, 1H), 1.38−1.35 (m, 1H), 1.23−1.18 (m, 2H), 0.87 (t, J = 7.5 Hz, 3H), 0.6 (s, 9H), 0.16 (s, 3H), −0.51 (s, 3H); ^{13}C NMR (125 MHz) δ 173.6, 157.7, 149.5, 139.9, 139, 137.5, 137.3, 129, 128.9, 125.5, 54.2, 53.5, 50.5, 45.4, 31.6, 27.4, 25.9, 20.4, 17.7, 14.3, −5.2, −5.6; HRMS (EI/CI) calcd for $C_{29}H_{55}NOSiSnNa^+$ 604.296929, found 604.29609.

Destannylation of Indolizidines 32 and 33 to 6-(1-(*tert*-Butyldimethylsilyl)vinyl)hexahydro-7-methylene-5-propylindolizin-3(5*H*)-one 34 and 35 (Eq 7). In a single-necked flask equipped with a stirring bar and a ground glass jointed one-way stopcock attached to N_2 was placed indolizidine mixture **32** and **33** (2 mmol, 1.364 g) in 30 mL of CH_3CN and 0.5 mL of water. Camphorsulfonic acid (8 mmol, 1.856 g) was added at rt in one portion, and the mixture was stirred for 4 h to see a complete consumption of the starting material while showing a slightly polar spot on TLC analysis. The reaction mixture was concentrated to dryness, dissolved in 100 mL of CH_2Cl_2, and transferred into a separatory funnel. Successive washings with satd aq $NaHCO_3$ and brine, drying ($MgSO_4$), and concentration gave a crude product which was purified by flash column chromatography (20% EtOAc in hexanes) to afford an inseparable mixture of **34** and **35** (573 mg, 86%) as a solid: mp 56−58 °C. Indolizidine **34**: ^{1}H NMR (500 MHz) δ 5.05 (d, J = 1.5 Hz, 1H), 4.99 (t, J = 2 Hz, 2H), 4.91 (br s, 1H), 4.22 (dt, J = 12, 4.5 Hz, 1H), 3.68−3.63 (m, 1H), 3.15 (br s, 1H), 2.52 (dd, J = 13, 4 Hz, 1H), 2.42 (ddd, J = 12, 6, 4 Hz, 1H), 2.23−2.12 (m, 1H), 1.95 (t, J = 13 hz, 1H), 1.66−1.58 (m, 1H), 1.5−1.44 (m, 1H), 1.4−1.22 (m, 2H), 1.2−1.12 (m, 2H), 0.89 (t, J = 7.5 Hz, 3H), 0.84 (s, 9H), 0.06 (s, 3H), 0.05 (s, 3H); ^{13}C NMR (125 MHz) δ 173.6, 145.6, 142.1, 132.3, 112.8, 53.7, 52.1, 50.5, 44.1, 30.0, 28.4, 27, 24.8, 19.3, 17.6, 14.4, −4.9. **35**: ^{1}H NMR (500 MHz) δ 5.91 (br s, 1H), 5.84 (br s, 2H), 5.49 (br s, 1H), 4.38 (dd, J = 8.5, 6.5 Hz, 1H), 3.6−3.54 (m, 1H), 3 (br s, 1H), 2.37 (dd, J = 10.5, 2 Hz, 1H), 2.42 (ddd, J = 12, 6, 4 Hz, 1H), 2.23−2.2 (m, 1H), 2.15 (t, J = 12.5 Hz, 1H), 1.66−1.58 (m, 1H), 1.5−1.44 (m, 1H), 1.4−1.22 (m, 2H), 1.2−1.12 (m, 2H), 0.89 (t, J = 7.5 Hz, 3H), 0.85 (s, 9H), 0.13 (s, 3H), 0.05 (s, 3H); ^{13}C NMR (125 MHz) δ 173.8, 149.9,143.7, 127.9, 114.6, 55.7, 53.1, 50.5, 38.8, 34.6, 31, 27.4, 25.6, 19.6, 17.4, 14.3, −3.9; HRMS (EI/CI) calcd for $C_{20}H_{35}NOSiNa^+$ 356.238009, found 356.23704.

Recrystallization of the mixture from methylene chloride and hexane gave crystals suitable for X-ray analysis, and the ORTEP diagram is shown in Figure 2.

Stereoselective Silylstannylation of Highly Functionalized Allenes. Synthesis of Allyl Stannanes. Addition of silylstannanes under the new protocol to allenes **6** and **55** are described. For other examples, see the Supporting Information.

Addition of Trimethylsilyltributylstannane to 6. 5-(2-Propynyl)-1-((2*E*)-4-tri-*n*-butylstannyl-3-trimethylsilyl-butenyl)-2-pyrrolidinone (37) (Table 4, Entry 4, Eq 9). To a solution of 1-(2,3-butadienyl)-5-(2-propynyl)-2-pyrrolidinone (20 mg, 0.11 mmol) in 1 mL C_6D_6 were added $Bu_3SnSiMe_3$ (36 μL, 0.11 mmol, 1 equiv), $Pd_2(dba)_3$ (2 mg, 0.002 mmol, 2 mol %), and $P(C_6F_5)_3$ (6 mg, 0.011 mmol, 10 mol %). The reaction was monitored by ^{1}H NMR. After 4 h at room temperature, the reaction was complete (100% yield by NMR). The solvent was evaporated and the crude mixture purified by column chromatography (SiO_2: hexanes/diethyl ether 2/1) to give 46 mg (80% isolated yield) of a colorless oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.27 (dd, J = 6.5, 5.5, 1 H, NCH_2CH), 4.08 (dd, J = 15.9, 5.3, 1 H, NCH_2), 3.71−3.64 (m overlapping dd, J = 16.2, 6.1, 1 + 1 H, $NCH_2 + H^5$), 2.52 (m, 1 H, H^4), 2.40 (m, 2 H, CH^4CH_2), 2.35 (m, 1 H, H^4), 2.15 (m, 1 H, H^3), 1.95 (m, 2 H, H^3 + CCH), 1.86 (d, J = 11.4, J_{Sn-H} = 32.9, 2 H, $SnCH_2CSi$), 1.63 (m, 6 H, $SnCH_2$), 1.40 (m, 6 H, $SnCH_2CH_2$), 1.00 (m, 15 H, $Sn(CH_2)_2CH_2CH_3$), 0.16 (s, 9 H, $SiCH_3$); NOE $NCH_2CH \rightarrow SiMe_3$: 2%, $NCH_2CH \rightarrow SnCH_2CSi$: 0%; ^{13}C NMR (125 MHz, C_6D_6) δ 173.5, 144.8, 128.6, 79.8, 71.2, 56.2, 39.5, 29.9, 29.7, 29.6, 27.8, 23.7, 13.9, 13.6, 10.6, −1.4; ^{119}Sn (186 MHz, $CDCl_3$) δ −17.8; IR (film) 3312, 1695 cm^{-1}; HRMS calcd for $C_{26}H_{49}NOSiSnNa$ $M^{\bullet+}$ = 562.24977, found 562.24654.

Table 4, Entry 9. (*E*)-4-(*tert*-Butyldimethylsilanyloxymethyl)-3-[2-(*tert*-butyldimethylsilanyl)-4-triphenylstannanylprop-2-enyl]oxazolidin-2-one (56). To a solution of $Pd(PhCN)_2Cl_2$ (1.9 mg, 0.0050 mmol Pd), $P(C_6F_5)_3$ (5.3 mg, 0.010 mmol), and $Ph_3Sn-SiMe_2Bu^t$ (51 mg, 0.110 mmol) in 1 mL of C_6D_6 at rt was added allene **55** (26.9 mg, 0.100 mmol), and the mixture was kept in an NMR tube at rt. After 8 h at rt, the ^{1}H NMR spectrum indicated a clean conversion into the desired product **56**. Solvent was evaporated from the contents of the NMR tube, and the residual oil was purified by flash chromatography (Hex/Et_3N = 95/5) to get 44 mg (60%) of product as an off-white solid (mp 144−146 °C). **56**: IR (thin film) 3049, 2953, 2927, 2895, 2856, 2252, 1748, 1605 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ −0.15 (s, 3H), −0.10 (s, 3H), −0.01 (s, 3H), 0.00 (s, 3H), 0.84 (s, 9H), 0.86 (s, 9H), 2.35 (dd, J_{Sn-H} = 90 Hz, J = 1.8, 12.2 Hz, H, CH_2SnBu_3), 2.46 (d, J_{Sn-H} = 90 Hz, J = 12.2 Hz, H, CH_2SnBu_3), 3.00 (t, J = 8.0 Hz, H, CH_2-OTBS), 3.44 (dd, J = 2.2, 10.3 Hz, H, OCH_2CH), 3.52 (dd, J = 5.1, 10.5 Hz, H, OCH_2CH), 3.82 (dd, J = 2.9, 10.5 Hz, H, CH_2-OTBS), 3.85 (m, H, OCH_2CH), 6.02 (d, J_{Sn-H} = 38 Hz, J = 1.8 Hz, H, NCH=CSi), 7.32−7.42 (m, 9H), 7.45−7.62 (m, 6H); see Figure 1 (Supporting Information) for NOE data; ^{13}C NMR (125 MHz, $CDCl_3$) δ −6.2, −5.5, −5.1, 16.2, 17.8, 18.4, 26.0, 27.2, 57.0, 61.5, 65.3, 126.6, 126.8, 129.0 (J_{Sn-C} = 48 Hz), 129.5, 137.5 (J_{Sn-C} = 34 Hz), 139.0, 157.4.Anal. Calcd for $C_{37}H_{53}NO_3Si_2Sn$: C, 60.49; H, 7.27; N, 1.91. Found: C, 60.57; H, 7.19; N, 1.88.

Acknowledgment. Financial assistance by the U.S. National Science Foundation (CHE-0079948 and CHE-0308378) is gratefully acknowledged.

Supporting Information Available: Full experimental details for the preparation of staring materials not listed in the printed version, silylstannylation, distannylation, and related reactions of these substrates, and spectroscopic and chromatographic data for characterization of compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

JO049010Z