ORGANIC LETTERS

2010
Vol. 12, No. 21
4772−4775

$B(C_6F_5)_3$-Promoted Tandem Silylation and Intramolecular Hydrosilylation: Diastereoselective Synthesis of Oxasilinanes and Oxasilepanes

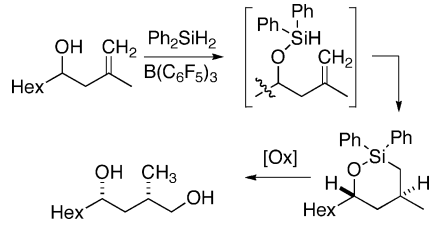
Roman Shchepin,[†] Chunping Xu,[†] and Patrick Dussault*

Department of Chemistry, University of Nebraska-Lincoln, Lincoln, Nebraska 68588-0304, United States

pdussault1@unl.edu

Received August 10, 2010

ABSTRACT



$B(C_6F_5)_3$ promotes regio- and stereoselective cyclizations of unsaturated alkoxysilanes to generate oxasilinanes and oxasilepanes. The same products are available directly from alkenols via tandem silylation and hydrosilylation.

Intramolecular hydrosilylation of alkenes is an important transformation in organic synthesis.[1] Initially investigated for unsaturated silanes,[2] the methodology is now often applied to unsaturated alkoxy- and aminosilanes,[3] where stereospecific oxidative cleavage of the newly formed C−Si bond enables stereodefined synthesis of diols and aminoalcohols.[4,5] The majority of examples involve metal-catalyzed 5-*endo* or 5-*exo* ring closures, although six-membered cyclizations have been reported.[1,3,6] We now report regio- and stereoselective formation of oxasilinanes and oxasilepanes via formation and cyclization of unsaturated alkoxysilanes in the presence of a nonmetal catalyst.

In the course of investigations into the influence of Lewis acids on the ozonolysis of unsaturated silanes, we found that addition of $B(C_6F_5)_3$ to a solution of unsaturated alkoxysilane **1-Pr** resulted in regioselective formation of oxasilinane **2-Pr** with high 3,5-*trans* diastereoselectivity (Table 1).[7,8] The cyclization proceeded efficiently at −78 °C or rt and in the presence of either stoichiometric or catalytic $B(C_6F_5)_3$. Cyclization was also observed for the dimethylsilyl ether (not shown),[9] but the hydrolytic instability of this class of

[†] These authors contributed equally to this work.

(1) (a) Yamamoto, K.; Hayashi, T. In *Transition Metals for Organic Synthesis*, 2nd ed.; Beller, M., Bolm, C., Eds.; Wiley-VCH: Weinheim, 2004; pp 167−191. (b) Marciniec, B. In *Hydrosilylation: A Comprehensive Review on Recent Advances*; Marciniec, B., Ed.; Springer: New York, 2009; pp 3−51.

(2) Benkeser, R. A.; Mozden, E. C.; Muench, W. C.; Roche, R. T.; Siklosi, M. P. *J. Org. Chem.* **1979**, *44*, 1370.

(3) Varchi, G.; Ojima, I. *Curr. Org. Chem.* **2006**, *10*, 1341.

(4) See, for example: (a) Mak, S. Y. F.; Curtis, N. R.; Payne, A. N.; Congreve, M. S.; Francis, C. L.; Burton, J. W.; Holmes, A. B. *Synthesis* **2005**, 3199. (b) Li, F.; Roush, W. R. *Org. Lett.* **2009**, *11*, 2932.

(5) Oxidative cleavage: (a) Jones, G. R.; Landais, Y. *Tetrahedron* **1996**, *52*, 7599. (b) Smitrovich, J. H.; Woerpel, K. A. *J. Org. Chem.* **1996**, *61*, 6044.

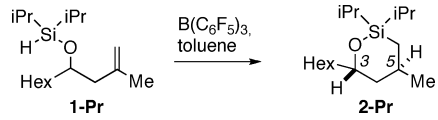
(6) Cyclizations to form six- or seven-membered rings: (a) Widenhoefer, R. A. *Acc. Chem. Res.* **2002**, *35*, 905. (b) Xin, S.; Harrod, J. F. *J. Organomet. Chem.* **1995**, *499*, 181. (c) DeCamp, A. E.; Mills, S. G.; Kawaguchi, A. T.; Desmond, R.; Reamer, R. A.; DiMichele, L.; Volante, R. P. *J. Org. Chem.* **1991**, *56*, 3564. (d) Sibi, M. P. *e-EROS Encyclopedia of Reagents for Organic Synthesis*; John Wiley & Sons: New York, 2001. (e) Widenhoefer, R. A.; Krzyzanowska, B.; Webb-Wood, G. *Organometallics* **1998**, *17*, 5124.

(7) Reviews of $B(C_6F_5)_3$: (a) Piers, W. E. *Adv. Organomet. Chem.* **2005**, *52*, 1. (b) Erker, G. *Dalton Trans.* **2005**, 1883.

(8) Stereochemical assignments are based upon ^3J_H couplings, NOE correlations, and a literature correlation for diol **21**.

10.1021/ol1018757
Published on Web 10/04/2010

Table 1. Cyclization of **1-Pr**[a]

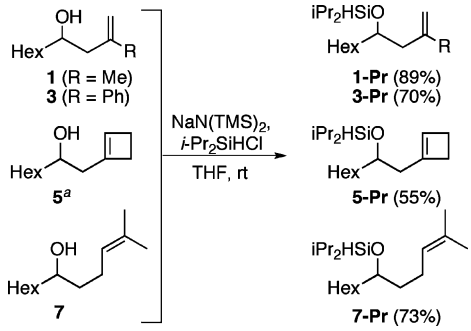


BAr_3 (equiv)	temp (°C)[b]	*t* (h)	yield (%)	*trans* %
1.0	−78	<0.1	82	nd
0.4	rt	<0.1	88	nd
0.1	−78	<0.1	93	nd
0.07	rt	<0.1	84	94[c]

[a] Prepared as illustrated in Scheme 1. [b] Final temperature; reactants mixed at −78 °C. [c] 5% of the *cis*-diastereomer isolated.

reactants led us to abandon this thread following the discovery of the tandem cyclizations discussed later.

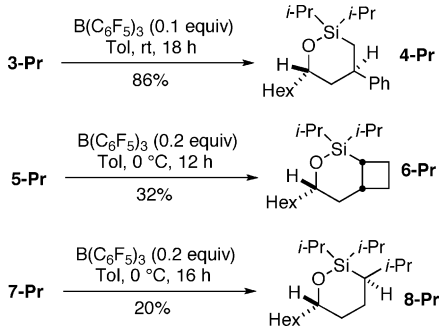
Scheme 1. Preparation of Alkoxysilanes



[a] Inseparable 3:1 mixture with 1-chloro-1-alkylcyclobutane.

The cyclization, apparently the first intramolecular example of a known intermolecular hydrosilylation,[10] was investigated further using alkoxysilanes prepared as illustrated in Scheme 1. 6-*Endo* cyclization onto an α-substituted styrene (**3-Pr**) proceeded slowly but in high yield and with high *trans* selectivity (Scheme 2). Cyclization onto a cyclobutene (**5-Pr**) proceeded much more slowly through a 6-*endo* pathway

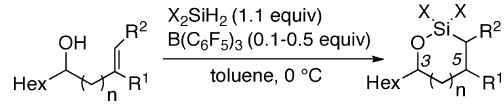
Scheme 2. Additional Cyclizations



to furnish a modest yield of the *cis*-fused adducts (**6-Pr**) as a 5:1 mixture of side chain epimers. A bishomoallyl substrate, **7-Pr**, reacted very slowly through a 6-*exo* pathway to furnish a *trans*-3,6-disubstituted-2-oxa-1-silinane (**8-Pr**).

$B(C_6F_5)_3$ also catalyzes the reductive silylation of alcohols,[11] and we became intrigued by the possibility of tandem silylation/hydrosilylation (Table 2). $B(C_6F_5)_3$-

Table 2. Tandem Silylation/Hydrosilylation



subs	*n*	R^1, R^2	X	*t* (h)	prod	yield (%)	*trans* %[a]
1	1	Me,H	Et	0.1	**2-Et**	47	>90
1	1	Me,H	Ph	0.15	**2-Ph**	80	>90
3	1	Ph,H	Ph			decomp	
5	1	$(CH_2)_2$	Ph			decomp	
9	1	$(CH_2)_4$	Et	0.5	**10-Et**[b]	39	90
9	1	$(CH_2)_4$	Ph	1	**10-Ph**[b]	73	84
11[c]	1	H,Me	Et	0.1	**12-Et**	16	60
11[c]	1	H,Me	Ph	1	**12-Ph**	24	~50
13	2	Me,H	Et	0.1	**14-Et**	73	38

[a] 3,5-Stereochemistry. [b] *cis* ring fusion; see Scheme 3 for structure of **10-Ph**. [c] 3.3:1 mixture of *E*/*Z* isomers.

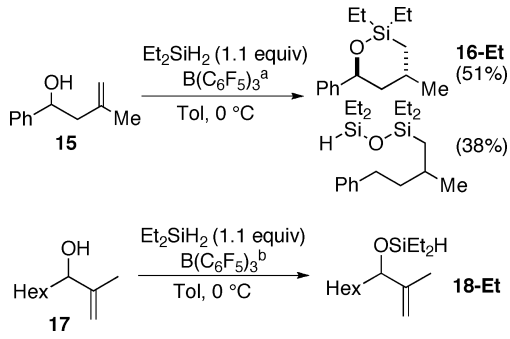
promoted reaction of alkenol **1** with stoichometric Et_2SiH_2 or Ph_2SiH_2 generated oxasilinanes **2-Et** or **2-Ph** with very similar regio- and stereoselection as observed in the stepwise cyclizations. Although alcohols **3** and **5** decomposed under the tandem conditions, cyclohexenol **9** reacted to selectively furnish the 3,5-*trans* diastereomer of *cis*-fused octahydrobenzooxasilinanes **10-Et** and **10-Ph**; the lower yield for the Et_2SiH_2 reaction is likely related to undesired reductive deoxygenation (vida infra). Alkenol **11**, which generates an intermediate siloxane capable of undergoing cyclization through electronically comparable 5-*exo* or 6-*endo* pathways, reacted only through the latter. Bishomoallyl alcohol **13** underwent selective reaction through a 7-*endo* pathway to furnish oxasilepane **14-Et** as a 62:38 *cis*/*trans* mixture.

Reactions employing Et_2SiH_2 often furnished a significant amount of byproducts appearing to result from alcohol deoxygenation.[12] For example, reaction of benzylic alcohol **15** produced oxasilane **16-Et** along with a byproduct identified as a disiloxane on the basis of mass spectrometry and oxidative desilylation (Scheme 3).[13,14]

Application of the one-pot conditions to allylic alcohol **17** resulted only in rapid formation of the diethyl silyl ether.

(9) Tamao, K.; Nakajima, T.; Sumiya, R.; Arai, H.; Higuchi, N.; Ito, Y. *J. Am. Chem. Soc.* **1986**, *108*, 6090.
(10) Rubin, M.; Schwier, T.; Gevorgyan, V. *J. Org. Chem.* **2002**, *67*, 1936.
(11) Blackwell, J. M.; Foster, K. L.; Beck, V. H.; Piers, W. E. *J. Org. Chem.* **1999**, *64*, 4887.
(12) Gevorgyan, V.; Rubin, M.; Benson, S.; Liu, J.-X.; Yamamoto, Y. *J. Org. Chem.* **2000**, *65*, 6179.

Scheme 3. Byproduct Formation

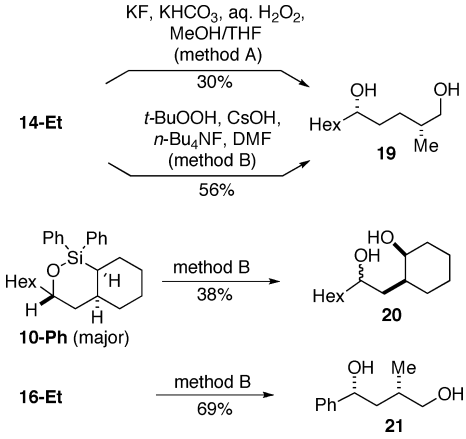


[a] 0.6 equiv. [b] 0.25 equiv.

In general, reactions employing Ph_2SiH_2 proceeded more slowly but generated fewer byproducts; this can be seen, for example, in the formation of **10-Et** versus **10-Ph** (Table 2). The exception was cyclobutene **5**, where decomposition was observed for either silane.

Oxidative desilylation of the hindered siloxanes was initially attempted under Tamao conditions (KF, $KHCO_3$, aq H_2O_2, MeOH/THF).[5] However, as illustrated in Scheme 4, the oxidations were found to proceed in higher yield using

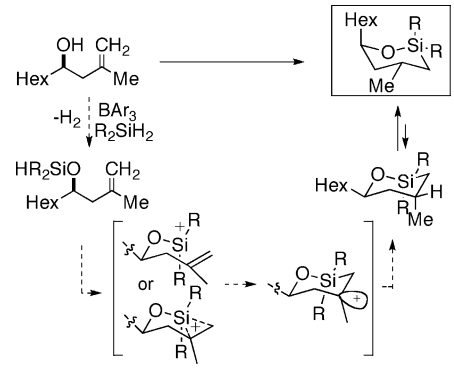
Scheme 4. Oxidative Desilylation



a procedure developed by Woerpel (*t*-BuOOH, $CsOH{\cdot}H_2O$, *n*-Bu_4NF, DMF).[5] The stereochemistry of diols **19**[15] and **21**[16] was determined by comparison with literature reports, establishing (**14-Et**) or confirming (**16-Et**) the stereochemistry of cyclizations.

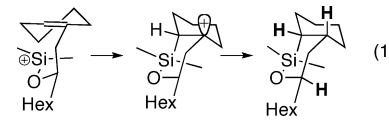
The cyclizations, clearly related to intermolecular $B(C_6F_5)_3$-mediated hydrosilylations[10] and potentially related to cyclizations of unsaturated silanes in the presence of triphenylmethyl cation,[17] almost certainly involve electrophilic attack on an alkene by a silylium-like species derived from interaction of $B(C_6F_5)_3$ with the Si−H (Scheme 5).[18,19]

Scheme 5. Proposed Mechanism



Reduction of the resulting carbocation by the hydridoboron species would furnish the cyclized product and regenerate the Lewis acid catalyst. The selective formation of 3,5-*trans*-disubstituted oxasilinanes can be rationalized by hyperconjugation of the newly formed C−Si bond with the carbocation,[20] with the resulting conformation dictating approach of the hydride. Analogous stereoselectivity has been observed in formation of siloxanes through hydrogen atom delivery to carbon-centered radicals.[21]

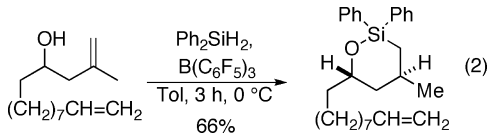
Although 5-*exo* cyclizations are well-established for Pt- or Rh-catalyzed hydrosilylations,[1,3] we observed selective 6-*endo* versus 5-*exo* cyclization with a substrate where either mode would proceed via a secondary carbocation (Table 2, substrate **11**). We also observed very different rates for 6-*exo* and 6-*endo* cyclizations involving electronically similar carbocation intermediates (**7-Pr** vs **1-Pr**). These results point to the importance of interactions between the alkene and the developing silylium-like species. The *cis* selectivity observed for six-membered ring annelations, which complements results from metal-catalyzed cyclizations,[1,3,22] presumably reflects stereoelectronic requirements for trapping of the β-silyl cations.[23] The stereoselectivity of side chain introduction results from cyclization through the low-energy conformer of a chairlike transition state (eq 1).



Several lines of evidence indicate that the tandem and stepwise reactions involve a common hydrosilylation step.

(13) $B(C_6F_5)_3$-promoted formation of disiloxanes: Chojnowski, J.; Rubinsztajn, S.; Cella, J. A.; Fortuniak, W.; Cypryk, M.; Kurjata, J.; Kazmierski, K. *Organometallics* **2005**, *24*, 6077.
(14) Lebel, H.; Ladjel, C. *J. Organomet. Chem.* **2005**, *690*, 5198.
(15) Zhu, G.; Negishi, E.-I. *Org. Lett.* **2007**, *9*, 2771.
(16) Nájera, C.; Yus, M.; Seebach, D. *Helv. Chim. Acta* **1984**, *67*, 289.
(17) Steinberger, H.-U.; Bauch, C.; Mueller, T.; Auner, N. *Can. J. Chem.* **2003**, *81*, 1223.
(18) Larson, G. L.; Fry, J. L. *Org. React.* **2008**, *71*, 1.
(19) Reed, C. A. *Acc. Chem. Res.* **1998**, *31*, 325.
(20) Lambert, J. B. *Tetrahedron* **1990**, *46*, 2677.

Both processes proceed with nearly identical regio- and diastereoselectivity. Furthermore, dialkylsilyl ethers are observed (TLC) as intermediates in some of the slower reactions and become the only product when cyclization is disfavored, as for allylic alcohol **17** (Scheme 3). Finally, a diene substrate reacts selectively across the homoallyl alcohol (eq 2).



(2)

The formation of deoxygenated byproducts is observed mainly in the tandem reactions. The chemoselective deoxygenation of unhindered alcohols by trialkylsilane and $B(C_6F_5)_3$ has been postulated to involve attack of a silylium ate complex on intermediate silyl ethers,[12] suggesting the deoxygenations result from intermolecular reductions directly competing with cyclization.

Overall, the transformation provides a new method for the regio- and stereoselective synthesis of cyclic siloxanes and derived diols. Given that $B(C_6F_5)_3$ has been reported to catalyze the hydrosilylation of ketones and aldehydes,[23] it is likely the method could be extended to allow the synthesis of oxasilacycles from unsaturated aldehydes and ketones.

Acknowledgment. Research support and funding for NMR instrumentation was provided by NSF (CHE-0749916, MRI 0079750, and CHE 0091975). Research was conducted in facilities remodeled with NIH support (RR016544-01). We are grateful for advice from Prof. V. Gevorgyan (University of Illinois at Chicago) and for advice or technical support from S. DiMagno, J. Dumais, J. Belot, C. Schwartz, and S. Basiaga (University of Nebraska-Lincoln).

Supporting Information Available: Details regarding preparation and characterization of new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

OL1018757

(21) Cai, Y.; Roberts, B. P. *J. Chem. Soc., Perkin Trans 1.* **1998**, 467; 3653. In contrast to the results described in this work, we observed a single predominant conformation of oxasilinanes.

(22) Formation of *cis*-oxasilinanes through 6-*exo* cyclization of α-silyloxymethyl radicals: Koreeda, M.; Hamann, L. G. *J. Am. Chem. Soc.* **1990**, *112*, 8175.

(23) Parks, D. J.; Blackwell, J. M.; Piers, W. E. *J. Org. Chem.* **2000**, *65*, 3090. Gevorgyan, V.; Rubin, M.; Liu, J.-X.; Yamamoto, Y. *J. Org. Chem.* **2001**, *66*, 1672.