26.3, 28.9, 31.5, 34.0, 35.4 (CH_2), 77.3, 86.3 (=CH), 93.4, 103.8, 128.8, 135.3 (=C), 140.7 (=CH), 149.3 (=C); IR (nujol): $\tilde{\nu} = 844$, 1561, 1630, 3103 cm^{-1}; elemental analysis calcd (%) for $C_{26}H_{36}RuClPF_6$: C 49.57, H 5.76, Cl 5.63; found: C 49.23, H 5.50, Cl 6.27. Microcrystals of complex **12b** were obtained in a dichloromethane/diethyl ether biphasic system.

Received: March 15, 2001 [Z16777]

[1] a) R. W. Aben, H. W. Scheeren, *J. Chem. Soc. Perkin Trans. 1* **1979**, 3132 – 3138; b) W. J. Leigh, J. A. Postigo, P. C. Vennerie, *J. Am. Chem. Soc.* **1995**, *117*, 7826 – 7827.

[2] a) A. Ichihara, R. Kimura, S. Yamada, S. Sakamura, *J. Am. Chem. Soc.* **1980**, *102*, 6353 – 6355; b) M. E. Jung, K. M. Halweg, *Tetrahedron Lett.* **1981**, *22*, 2735 – 2738.

[3] K. P. C. Vollhardt, *Angew. Chem.* **1984**, *96*, 539 – 541; *Angew. Chem. Int. Ed. Engl.* **1984**, *23*, 539 – 556.

[4] a) M. L. Randall, J. A. Tallarico, M. L. Snapper, *J. Am. Chem. Soc.* **1995**, *117*, 9610 – 9611; b) J. A. Tallarico, M. L. Randall, M. L. Snapper, *Tetrahedron* **1997**, *53*, 16511 – 16520; c) B. R. Maughon, M. Weck, B. Mohr, R. H. Grubbs, *Macromolecules* **1997**, *30*, 257 – 265.

[5] a) J. H. Kwon, S. J. Lee, S. C. Shim, *Tetrahedron Lett.* **1991**, *32*, 6719 – 6722; b) S. Aurrichio, A. Selva, A. M. Truscello, *Tetrahedron* **1997**, *53*, 17407 – 17416.

[6] a) B. B. Snider, D. J. Rodini, R. S. E. Conn, S. Sealfon, *J. Am. Chem. Soc.* **1979**, *101*, 5283 – 5293; b) B. B. Snider, D. M. Roush, D. J. Rodini, D. Gonzalez, D. Spindell, *J. Org. Chem.* **1980**, *45*, 2773 – 2785; c) L. Birkofer, D. Eichstädt, *J. Organomet. Chem.* **1986**, *307*, 279 – 284.

[7] a) K. Narasaka, Y. Hayashi, H. Shimadzu, S. Niihata, *J. Am. Chem. Soc.* **1992**, *114*, 8869 – 8885; Ru: b) A. Mitsudo, K. Kokuryo, Y. Takegami, *J. Chem. Soc. Chem. Commun*. **1976**, 722 – 723; c) T.-a. Mitsudo, K. Kokuryo, T. Shinsugi, Y. Nakagawa, Y. Watanabe, Y. Takegami, *J. Org. Chem.* **1979**, *44*, 4492 – 4496; d) T.-a. Mitsudo, H. Naruse, T. Kondo, Y. Ozaki, Y. Watanabe, *Angew. Chem.* **1994**, *106*, 595 – 597; *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 580 – 581; e) B. N. Warrener, G. Abbenante, C. H. L. Kennard, *J. Am. Chem. Soc.* **1994**, *116*, 3645 – 3646.

[8] K. Kasai, Y. Liu, R. Hara, T. Takahashi, *Chem. Commun.* **1998**, 1989 – 1990.

[9] L. Trabert, H. Hopf, *Liebigs Ann. Chem.* **1980**, 1786 – 1800.

[10] E. Piers, E. M. Boehringer, J. G. K. Yee, *J. Org. Chem.* **1998**, *63*, 8642 – 8643.

[11] J. Le Paih, S. Dérien, P. H. Dixneuf, *Chem. Commun*. **1999**, 1437 – 1438.

[12] P. J. Fagan, W. S. Mahoney, J. C. Calabrese, I. D. Williams, *Organometallics* **1990**, *9*, 1843 – 1852.

[13] S. Dérien, L. Ropartz, J. Le Paih, P. H. Dixneuf, *J. Org. Chem.* **1999**, *64*, 3524 – 3531.

[14] The NMR spectra with a single resonance (^1H) at $\delta = 3.42$ and a single resonance (^{13}C) at $\delta = 69.8$ for the alkenyl unit of the cycle show the symmetry of the complex **11**.

[15] Crystal structure analysis: $RuClC_{26}H_{36} \cdot PF_6$, $M_r = 630.04$, monoclinic, *I2/a*, $a = 22.704(1)$, $b = 11.221(1)$, $c = 23.530(2)$ Å, $\beta = 114.57(1)$, $V = 5451.8(7)$ $Å^{-3}$, $Z = 8$, $\rho = 1.535$ $Mg\,m^{-3}$, $\lambda(Mo_{K\alpha}) = 0.71073$ Å, $\mu = 7.86$ cm^{-1}, $F(000) = 2576$, $T = 293$ K. The crystal, dimensions $0.37 \times 0.27 \times 0.23$ mm was studied on a NONIUS Kappa CCD diffractometer with graphite monochromatized $Mo_{K\alpha}$ radiation. The cell parameters are obtained with 10 frames (psi rotation: 1° per frame). The data collection (Nonius, 1999) ($2\theta_{max} = 60°$, 176 frames (117 via 1.6° phi rotation and 16 s per frame, 52 via 1.6° omega rotation) range *hkl*: *h* −25.29, *k* 0.14, *l* −25.30) gives 22884 reflections. The data reduction leads to 6103 independent reflections from which 4681 with $I > 2.0\sigma(I)$. The absorption correction is made with a faces indexed crystal. The structure was solved with SIR-97 which reveals the non-hydrogen atoms of the cation and the anion. One atom (C19) of the cyclohexene ring appears disordered between two positions. After anisotropic refinement, many hydrogen atoms may be found with a Fourier Difference. The whole structure was refined with SHELXL 97 by the full-matrix least-square techniques (use of F^2 magnitude; *x*, *y*, *z*, β_{ij} for Ru, Cl, P, C, and F atoms, *x*, *y*, *z* in riding mode for H atoms ; 316 variables and 4681 observations with $I > 2.0\sigma(I)$; calcd $w = 1/[\sigma^2(F_o^2) + (0.122\,P)^2 + 10.23\,P]$ where $P = (F_o^2 + 2\,F_c^2)/3$ with the resulting $R = 0.058$, $R_w = 0.169$ and $S_w = 1.024$ (residual $\Delta\rho < 1.37$ e $Å^{-3}$). Crystallographic data (excluding structure factors) for the structure reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-160045. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: (+44) 1223-336-033; e-mail: deposit@ccdc.cam.ac.uk).

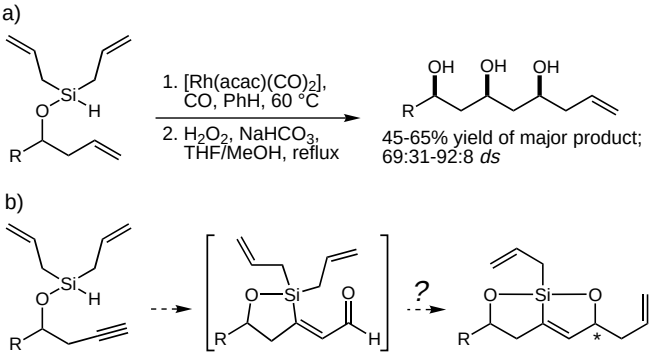
[16] P. J. Ridgwell, P. M. Bailey, S. N. Wetherell, E. A. Kelley, P. M. Maitlis, *J. Chem. Soc. Dalton Trans.* **1982**, 999 – 1004.

Tandem Intramolecular Alkyne Silylformylation – Allylsilylation: A Case of Remote 1,5-Asymmetric Induction**

Steven J. O'Malley and James L. Leighton*

Dedicated to Professor David A. Evans on the occasion of his 60th birthday

As part of a program dedicated to the development of stereoselective catalytic methods for the synthesis of polyols, we have recently reported the tandem intramolecular silylformylation – allylsilylation of alkenes (Scheme 1a).[1, 2] Alkynes are well-known substrates for silylformylation,[3] and it seemed plausible that tandem allylsilylation of the resultant unsaturated aldehydes might occur as well (Scheme 1b). Interestingly, in this system the silicon-substituted carbon atom is no longer stereogenic. Thus, any diastereoselectivity



Scheme 1. a) Tandem alkene silylformylation – allylsilylation and b) proposed tandem alkyne silylformylation – allylsilylation. Hacac = acetylacetone.

[*] Prof. J. L. Leighton, S. J. O'Malley
Department of Chemistry, Columbia University
New York, NY 10027 (USA)
Fax: (+1) 212-932-1289
E-mail: leighton@chem.columbia.edu

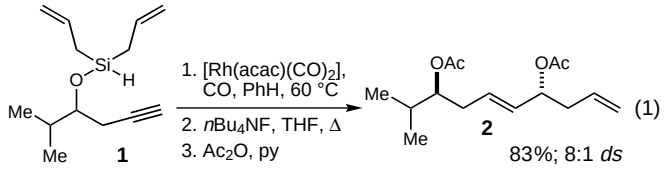
[**] Financial support was provided by the National Institutes of Health (National Institute of General Medical Sciences, GM58133). We are grateful to Bristol-Myers Squibb for generous financial support in the form of an Unrestricted Grant in Synthetic Organic Chemistry to J.L.L. We thank Merck Research Laboratories and DuPont Pharmaceuticals for generous financial support.

Supporting information for this article is available on the WWW under http://www.angewandte.com or from the author.

  1433-7851/01/4015-2915 $ 17.50+.50/0

in the allylsilylation would have to derive from the original homopropargylic stereocenter, and would constitute an example of remote 1,5-stereoinduction.[4]

Our study commenced with diallylsilyl ether **1** [Eq. (1)]. Treatment of this silane with 1.0 mol% of $[Rh(acac)(CO)_2]$ and 6.9 MPa (1000 psi) of CO in benzene at 60 °C in a



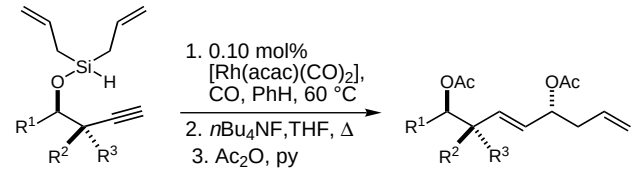
(1)

high-pressure reactor produced a yellow oil upon concentration. The unpurified material was subjected to protodesilylation (nBu$_4$NF, THF, reflux) and peracetylation (Ac_2O, pyridine (py)) to provide an 8:1 mixture of diacetate **2** and its *syn* diastereomer in 83% overall yield.[5, 6] Thus, the allylsilylation proceeded with good 1,5-diastereoselectivity, providing the 1,5-*anti* product as the major diastereomer, a result which is opposite to that observed with alkene substrates.

Optimization of the reaction conditions revealed that the catalyst loading could be reduced to 0.1 mol% with no decrease in efficiency. At significantly lower CO pressures, and/or at significantly lower temperatures there was a small improvement in the diastereoselectivity, accompanied, however, by a significant drop in reaction rate. We therefore settled on 6.9 MPa of CO in benzene at 60 °C as the standard reaction conditions.

With optimal reaction conditions identified, we set out to investigate the scope of the reaction with regard to homopropargylic and propargylic substituents (Table 1). Entries 1–6 clearly establish a direct correlation between the steric size of the homopropargylic substituent and the diastereoselectivity of the reaction, as well as a tolerance for alkyne and silyloxy functional groups. The superior diastereoselectivity shown in entry 7 indicates the stereochemically reinforcing

Table 1. Tandem alkyne silylformylation–allylsilylation.

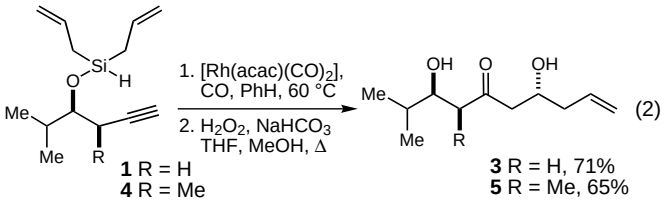


Entry	R^1	R^2	R^3	*ds*[a]	Yield [%][b]
1	*n*Pr	H	H	4:1	68
2	$HC{\equiv}CCH_2$	H	H	4:1	63
3[c]	$TBSOCH_2CH_2$	H	H	5:1	63
4	*i*Pr	H	H	8:1	83
5	Ph	H	H	7:1	83
6	*t*Bu	H	H	10:1	66
7	*i*Pr	Me	H	23:1	70
8	*i*Pr	H	Me	7:1	70

[a] 1,5-*anti*:1,5-*syn*; measured by gas chromatography. [b] Yield of the isolated purified mixture of diastereomers. [c] The *tert*-butyldimethylsilyl (TBS) group is cleaved during the protodesilylation step and the triacetate is isolated.

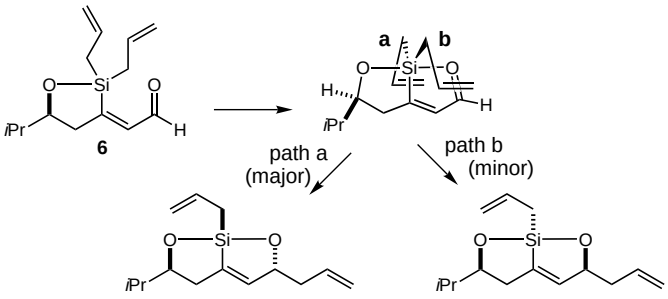
nature of a *syn* propargylic methyl group, whereas with an *anti* propargylic methyl group (entry 8) useful diastereoselectivity is still observed.

As an alternative to the protodesilylative workup of Table 1, we have also investigated an oxidative workup to provide β,β'-dihydroxyketone products. Subjection of silanes **1** and **4** to the standard tandem silylformylation–allylsilylation conditions, followed by evaporation of the solvent and subjection of the residue to the conditions of the Tamao oxidation[7] (H_2O_2, $NaHCO_3$, THF/MeOH, reflux) led to oxodiols **3** and **5** in 71 and 65% yields, respectively, and with identical diastereoselectivities to entries 4 and 7 in Table 1 [Eq. (2)]. The oxidative workup is noteworthy in the context of polyol synthesis in that diastereoselective ketone reductions would allow access to stereochemically diverse triol arrays.



(2)

Based on arguments previously advanced,[1] and in analogy to the corresponding reactions of alkenes, we propose an uncatalyzed allylsilylation of the presumed aldehyde intermediates.[8] Binding of the aldehyde by the Lewis acidic silicon atom[9] is followed by intramolecular allylsilylation as depicted for aldehyde **6** (Scheme 2). In this model, the diastereoselectivity is determined by the relative rates at which the



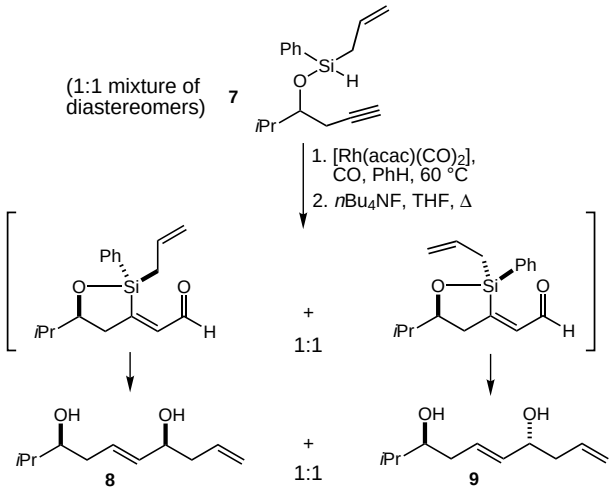
Scheme 2. Proposed model for remote 1,5-stereoinduction.

diastereotopic allyl groups transfer (path a vs. path b). A simple working hypothesis for the observed preference for path a would invoke a destabilizing steric interaction between the 2-propyl group and the allyl group **b**. The correlation between steric size of the homopropargylic substituent and the selectivity observed in entries 1–6 of Table 1 is consistent with this hypothesis as is the high selectivity observed in entry 7. The nearly identical selectivity observed in entries 4 and 8 is less well rationalized by this model and is suggestive of more subtle stereoelectronic effects.

A key feature of this model is that both of the diastereotopic allyl groups can transfer and each leads to a different product diastereomer. It could therefore be surmised that selective replacement of either allyl group with a nontrans-

  1433-7851/01/4015-2916 $ 17.50+.50/0

ferable group would lead to a stereospecific reaction. To gain support for this hypothesis we prepared silane **7** as a 1:1 mixture of diastereomers. Subjection of this mixture to the standard reaction conditions led, presumably by way of the illustrated 1:1 mixture of aldehydes, to a 1:1 mixture of diol diastereomers **8** and **9** (Scheme 3). The clear implication of this experiment is that either product diastereomer could be selected for, based only on the availability of the starting chiral silanes in diastereomerically pure form.



Scheme 3. Evidence for the stereochemical model.

The reactions reported here should find broad application in organic synthesis. The entire sequence (homopropargylic alcohol to 1,5-diol or oxodiol) can be carried out in a day and requires only readily available reagents ($HSiCl_3$, AllylMgBr, CO, nBu$_4$NF or H_2O_2). In the tandem silylformylation – allylsilylation reaction two new C–C bonds are formed as well as a remote stereocenter. Further studies to extend the synthetic utility of this process are in progress.

Experimental Section

Preparation of the diallylsilyl ethers: To a solution of the homopropargylic alcohol (10.0 mmol) in Et_2O (20 mL) is added trichlorosilane (20.0 mmol). The solution is heated at reflux for 2 h, and then concentrated (**Caution!** HCl evolution). The residue is redissolved in Et_2O (20 mL) and the solution is cooled to 0 °C. Allylmagnesium bromide (20.0 mL, 20.0 mmol, 1.0 M in Et_2O) is then added with vigorous stirring. The reaction mixture is warmed to room temperature and diluted with pentane. The mixture is filtered through a pad of Celite and the filtrate is concentrated. The residue is treated with pentane, and the mixture is filtered through a pad of Celite. The filtrate is concentrated and the residue is typically purified by distillation under vacuum (< 1.0 Torr).

Tandem Silylformylation – Allylsilylation: A glass liner for a stainless steel 45 mL Parr high-pressure reactor equipped with a stir bar and septum is charged with a solution of the diallylsilyl ether substrate (2.0 mmol) in benzene (6.0 mL). The solution is cooled to −78 °C and [Rh(acac)(CO)$_2$] (0.5 mg, 0.002 mmol) is added. The liner is inserted into the Parr reactor, and the pressure gauge and gas inlet assembly is attached. The reactor is charged to 3.4 MPa (500 psi) with CO, and vented. The reactor is then charged to 6.9 MPa (1000 psi) with CO and immersed (~2.5 cm) in an oil bath at 60 °C. After 2 – 3 h, the reactor is cooled to 0 °C and then vented. The solution is concentrated and the residue is immediately subjected to either workup procedure without further purification.

Protodesilylation: To a solution of the residue from the tandem silylformylation – allylsilylation in THF (10.0 mL) is added tetra-*n*-butylammonium fluoride (6.0 mL, 6.0 mmol, 1.0 M in THF). The solution is heated at reflux for 2 h, and then cooled. Saturated aqueous NH_4Cl is added, and the mixture is extracted with Et_2O. The combined organic layers are dried ($MgSO_4$), filtered and concentrated. The resulting diols may be purified by chromatography on silica gel.

Tamao oxidation: To a solution of the residue from the tandem silylformylation – allylsilylation in THF (3.0 mL) and MeOH (3.0 mL) is added $NaHCO_3$ (0.15 g, 1.8 mmol) and H_2O_2 (1.5 mL, 35 % in H_2O). The solution is heated at reflux for 3 h, and then cooled. Saturated aqueous NaCl is added, followed by saturated aqueous $Na_2S_2O_3$, and the mixture is extracted with Et_2O. The combined organic layers are dried ($MgSO_4$), filtered and concentrated. The resulting oxodiols may be purified by chromatography on silica gel.

Received: April 5, 2001 [Z16904]

[1] M. J. Zacuto, J. L. Leighton, *J. Am. Chem. Soc.* **2000**, *122*, 8587 – 8588.

[2] A conceptually similar tandem hydroformylation – allylboration reaction was earlier reported by Hoffmann et al., see: a) R. W. Hoffmann, D. Brückner, V. J. Gerusz, *Heterocycles* **2000**, *52*, 121 – 124; b) R. W. Hoffmann, J. Krüger, D. Brückner, *New J. Chem.* **2001**, *25*, 102 – 107; c) R. W. Hoffmann, D. Brückner, *New J. Chem.* **2001**, *25*, 369 – 373.

[3] a) I. Matsuda, A. Ogiso, S. Sato, Y. Izumi, *J. Am. Chem. Soc.* **1989**, *111*, 2332 – 2333; b) I. Ojima, P. Ingallina, R. J. Donovan, N. Clos, *Organometallics* **1991**, *10*, 38 – 41; c) I. Ojima, R. J. Donovan, W. R. Shay, *J. Am. Chem. Soc.* **1992**, *114*, 6580 – 6582; d) I. Ojima, M. Tzamarioudaki, C.-Y. Tsai, *J. Am. Chem. Soc.* **1994**, *116*, 3643 – 3644; e) F. Monteil, I. Matsuda, H. Alper, *J. Am. Chem. Soc.* **1995**, *117*, 4419 – 4420; f) I. Ojima, E. Vidal, M. Tzamarioudaki, I. Matsuda, *J. Am. Chem. Soc.* **1995**, *117*, 6797 – 6798; g) I. Ojima, J. V. McCullagh, W. R. Shay, *J. Organomet. Chem.* **1996**, *521*, 421 – 423.

[4] For examples of 1,5-stereoiduction in C–C bond forming reactions, see: a) J. Fujiwara, Y. Fukutani, M. Hasegawa, K. Maruoka, H. Yamamoto, *J. Am. Chem. Soc.* **1984**, *106*, 5004 – 5005; b) T. Harada, T. Hayashi, I. Wada, N. Iwaake, A. Oku, *J. Am. Chem. Soc.* **1987**, *109*, 527 – 532; c) K. Tomooka, T. Okinaga, K. Suzuki, G.-I. Tsuchihashi, *Tetrahedron Lett.* **1987**, *28*, 6335 – 6338; d) A. H. McNeill, E. J. Thomas, *Tetrahedron Lett.* **1990**, *31*, 6239 – 6242; e) G. Erker, F. Sosna, P. Betz, S. Werner, C. Krüger, *J. Am. Chem. Soc.* **1991**, *113*, 564 – 573; f) M. Nishida, E. Ueyama, H. Hayashi, Y. Ohtake, Y. Yamaura, E. Yanaginuma, O. Yonemitsu, A. Nishida, N. Kawahara, *J. Am. Chem. Soc.* **1994**, *116*, 6455 – 6456; g) M. P. Sibi, J. Ji, J. B. Sausker, C. P. Jasperse, *J. Am. Chem. Soc.* **1999**, *121*, 7517 – 7526; h) L. F. Tietze, C. Schünke, *Eur. J. Org. Chem.* **1998**, 2089 – 2099; i) D. Badone, J.-M. Bernassau, R. Cardamone, U. Guzzi, *Angew. Chem.* **1996**, *108*, 575 – 578; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 535 – 538. j) I. Paterson, K. R. Gibson, R. M. Oballa, *Tetrahedron Lett.* **1996**, *37*, 8585 – 8588; k) D. A. Evans, P. J. Coleman, B. Côté, *J. Org. Chem.* **1997**, *62*, 788 – 789; l) L. N. Pridgen, K. Huang, S. Shilcrat, A. Tickner-Eldridge, C. DeBrosse, R. C. Haltiwanger, *Synlett* **1999**, 1612 – 1614; m) E. Nicolás, K. C. Russell, V. J. Hruby, *J. Org. Chem.* **1993**, *58*, 766 – 770 .

[5] Although the diols can be cleanly isolated, a quantitative assay of the diastereoselectivity (by gas chromatography) was best performed with the derived diacetates.

[6] See the Supporting Information for a description of the stereochemical proofs.

[7] For a review on the Tamao and Fleming oxidations, see: G. R. Jones, Y. Landais, *Tetrahedron* **1996**, *52*, 7599 – 7662.

[8] We are aware of only one other example of an uncatalyzed/unpromoted allylsilylation of aldehydes using a tetracoordinate allylsilane, see: K. Matsumoto, K. Oshima, K. Utimoto, *J. Org. Chem.* **1994**, *59*, 7152 – 7155.

[9] This is believed to be an example of ring strain-induced Lewis acidity. See ref. [1] and: a) E. F. Perozzi, R. S. Michalak, G. D. Figuly, W. H. Stevenson III, D. B. Dess, M. R. Ross, J. C. Martin, *J. Org. Chem.* **1981**, *46*, 1049 – 1053; b) S. E. Denmark, R. T. Jacobs, G. Dai-Ho, S. Wilson, *Organometallics* **1990**, *9*, 3015 – 3019; c) A. G. Myers, S. E. Kephart, H. Chen, *J. Am. Chem. Soc.* **1992**, *114*, 7922 – 7923; d) S. E. Denmark, B. D. Griedel, D. M. Coe, M. E. Schnute, *J. Am. Chem. Soc.* **1994**, *116*, 7026 – 7043; e) K. Omoto, Y. Sawada, H. Fujimoto, *J. Am. Chem. Soc.* **1996**, *118*, 1750 – 1755.

  1433-7851/01/4015-2917 $ 17.50+.50/0