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Ruthenium-Catalyzed Propargylic Reduction of Propargylic Alcohols with Silanes**

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Dedicated to Professor Sakae Uemura on the occasion of his 65th birthday

A number of transition-metal complexes are known to promote the hydrosilylation of alkynes with silanes to give the corresponding vinyl silanes, which are versatile building blocks in organic synthesis.[1] The development of highly stereo- and regioselective hydrosilylation reactions of alkynes with silanes is an important subject in organic synthesis.[1] The selectivity in transition-metal-catalyzed hydrosilylation depends on the nature of catalysts, substrates, silanes, and solvents.[2,3] Recently, Trost and co-workers reported a highly selective preparation of α-vinyl silanes from a wide range of

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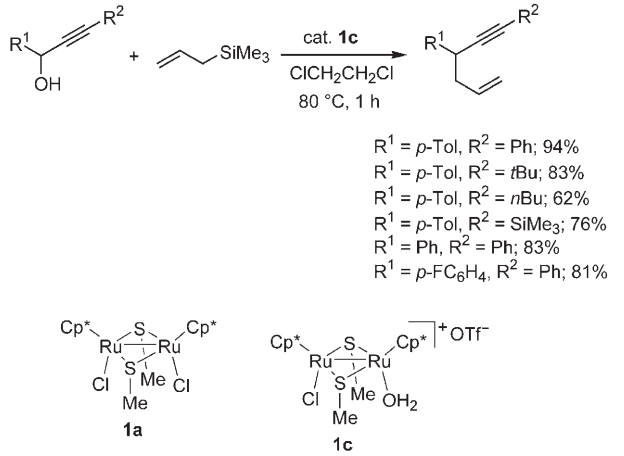
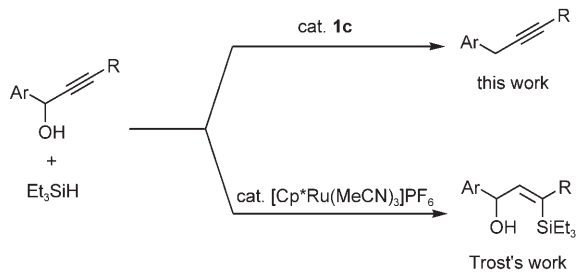
alkynes by catalysis with the cationic ruthenium complex $[Cp^*Ru(MeCN)_3]PF_6$ ($Cp^* = \eta^5$-C_5Me_5).[2a,d,f]

We have recently disclosed a novel catalytic activity of thiolate-bridged diruthenium complexes[4] such as $[\{Cp^*RuCl(\mu_2\text{-}SR)\}_2]$ (R = Me (**1a**), *n*Pr, *i*Pr (**1b**)) and $[Cp^*RuCl(\mu_2\text{-}SMe)_2RuCp^*(OH_2)]OTf$ (**1c**; OTf = OSO_2CF_3). These complexes were shown to be suitable catalysts for the propargylic substitution reactions of propargylic alcohols with a variety of heteroatom- and carbon-centered nucleophiles to give the corresponding propargylic-substituted compounds in high yields with complete selectivity.[5] Some other groups reported the transition-metal-catalyzed propargylic allylation of propargylic alcohols with allyltrimethylsilane to give the corresponding allylated products in good to high yields with high selectivity.[6] These results first prompted us to investigate the ruthenium-catalyzed allylation of propargylic alcohols with allylsilane. As a result, we comfirmed that only cationic thiolate-bridged diruthenium complexes promote the substitution by an allyl group of the hydroxy moiety of propargylic alcohols that bear an internal alkyne, as was expected (Scheme 1).



Scheme 1. Ruthenium-catalyzed propargylic substitution reactions of propargylic alcohols with allyltrimethylsilane.

As an extension of our study on the catalytic reactions with other organosilicon compounds, we have now observed the unexpected and completely chemoselective reduction at the propargylic position of propargylic alcohols that bear an internal alkyne with a variety of silanes to give the corresponding reduction products (substitution of the OH moiety by hydride, referred to herein as propargylic reduction) in good to high yields. This result is in sharp contrast to the recently reported selective formation of (*E*)-vinyl silanes by the hydrosilylation of propargylic alcohols with silanes which was catalyzed by the cationic ruthenium complex $[Cp^*Ru(MeCN)_3]PF_6$ (Scheme 2).[2c,e] Although some transition-metal complexes other than ruthenium are also known to promote the propargylic substitution reactions of propargylic alcohol derivatives with a variety of heteroatom- and carbon-centered nucleophiles to afford the corresponding functionalized propargylic compounds,[6–10] the catalytic propargylic reduction with a hydride has not yet been reported to the best

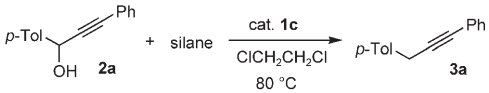


Scheme 2. Diverging pathways in ruthenium-catalyzed transformations of propargylic alcohols with triethylsilane.

of our knowledge. Preliminary results of the ruthenium-catalyzed propargylic reduction of propargylic alcohols with triethylsilane are presented herein. It is noteworthy that the reactions of propargylic alcohols with pinacolborane in the presence of a catalytic amount of **1a** unexpectedly gave the reductive homocoupling products of the propargylic alcohols in good yields with high selectivity.[11]

Treatment of 1-(4-methylphenyl)-3-phenyl-2-propyn-1-ol (**2a**) with triethylsilane in the presence of the cationic diruthenium complex **1c** (5 mol%) in $ClCH_2CH_2Cl$ at 80 °C for one hour afforded the propargylic reduction product 1-phenyl-3-(4-methylphenyl)-1-propyne (**3a**) in 77% yield after isolation (Table 1, entry 1). The reaction also proceeded quite

Table 1: Propargylic reduction of propargylic alcohol **2a** with various silanes in the presence of **1c**.[a]



Entry	Silane (equiv)	*t* [h]	Yield of **3a** [%][b]
1	Et_3SiH (10)	1	77
2	Et_3SiH (5)	1	59
3	$tBuMe_2SiH$ (10)	1	67
4	$PhMe_2SiH$ (10)	1	50
5	iPr_3SiH (10)	3	15
6	Ph_3SiH (10)	3	0
7	Ph_2SiH_2 (10)	1	0
8	$PhMeSiH_2$ (10)	1	0
9	$PhSiH_3$ (10)	1	0
10	$[MeSi(H)O]_n$ (10)[c]	1	0

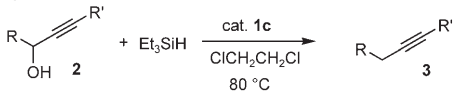
[a] All reactions of **2a** (0.30 mmol) with silane were carried out at 80 °C in the presence of **1c** (0.015 mmol) in $ClCH_2CH_2Cl$ (10 mL). [b] Yield of isolated product. [c] Poly(methylhydrosiloxane) was used.

smoothly at room temperature with a slight decrease of the product yield. This reductive reaction did not proceed at all when either neutral thiolate-bridged diruthenium complexes **1a** and **1b** or mono- and polynuclear ruthenium complexes such as $[(\eta^5\text{-}C_9H_7)RuCl(PPh_3)_2]$, $[\{Cp^*RuCl_2\}_2]$, and $[\{Cp^*RuCl\}_4]$, were employed as catalysts. Although gold-catalyzed propargylic substitution reactions of propargylic alcohols with nucleophiles were reported by Campagne and co-workers,[6b] the present reductive reaction hardly proceeded when $AuCl_3$ was used as a catalyst in place of **1c** under similar conditions. Other silanes such as *tert*-butyldimethylsi-

lane, dimethylphenylsilane, and triisopropylsilane also worked as reducing agents (Table 1, entries 3–5), but triphenylsilane, diphenylsilane, methylphenylsilane, phenylsilane, and poly(methylhydrosiloxane) were not effective (Table 1, entries 6–10).

Reactions of a variety of propargylic alcohols **2** with triethylsilane were subsequently investigated. Typical results are shown in Table 2. The presence of an electron-donating

Table 2: Propargylic reduction of propargylic alcohols **2** with triethylsilane in the presence of **1c**.[a]

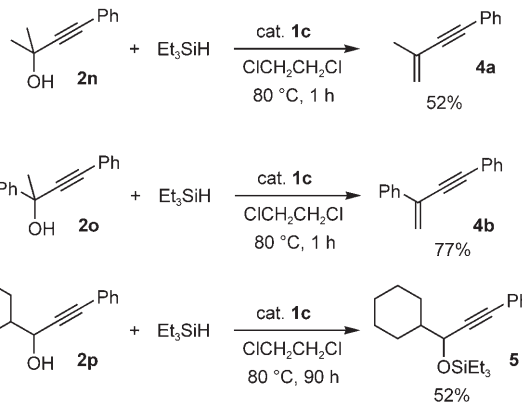


Entry	2			t [h]	Yield of 3 [%][b]
	R	R′			
1	*p*-$MeOC_6H_4$	Ph	(**2b**)	1	97
2	*p*-MeC_6H_4	Ph	(**2a**)	1	77
3	Ph	Ph	(**2c**)	1	43
4	*p*-ClC_6H_4	Ph	(**2d**)	5	42
5	*p*-FC_6H_4	Ph	(**2e**)	5	46
6	*p*-$CF_3C_6H_4$	Ph	(**2f**)	23	0
7	*p*-$MeOC_6H_4$	*n*Bu	(**2g**)	1	94
8	*p*-$MeOC_6H_4$	*t*Bu	(**2h**)	1	93
9	*p*-$MeOC_6H_4$	$SiMe_3$	(**2i**)	1	99
10	1-naphthyl	Ph	(**2j**)	3	66
11	2-naphthyl	Ph	(**2k**)	3	55
12	$Ph_2C{=}CH$	Ph	(**2l**)	1	51[c]

[a] All reactions of **2** (0.30 mmol) with triethylsilane (3.00 mmol) were carried out at 80 °C in the presence of **1c** (0.015 mmol) in $ClCH_2CH_2Cl$ (10 mL). [b] Yield of isolated product. [c] 10 mol % of **1c** was used.

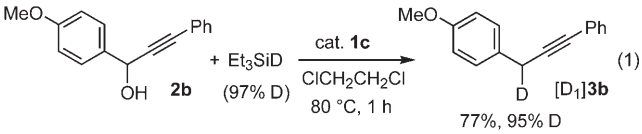
group such as methoxy and methyl on the propargylic benzene ring (**2b** and **2a**) increased the yield of the propargylic reduction product (Table 2, entries 1 and 2; compare with entry 3). In contrast, no improvement of the yield of the reduced products was observed when an electron-withdrawing group such as chloro or fluoro was introduced onto the propargylic benzene ring (**2d** and **2e**; Table 2, entries 4 and 5), and no reduction proceeded at 80 °C even for 23 hours when a trifluoromethyl moiety (**2f**) was introduced (Table 2, entry 6). These results suggest that propargylic cations might be involved as reactive intermediates. In the case of reactions of propargylic alcohols that bear a naphthyl moiety (**2j** and **2k**), the corresponding reduced products were formed in good yields (Table 2, entries 10 and 11). From an alkenyl-substituted propargylic alcohol (**2l**), the corresponding 1,4-enyne compound was obtained in moderate yield (Table 2, entry 12). However, when 1,1,3-triphenyl-2-propyn-1-ol (**2m**), 2-methyl-4-phenyl-3-butyn-2-ol (**2n**), 2,4-diphenyl-3-butyn-2-ol (**2o**), 1-cyclohexyl-3-phenyl-2-propyn-1-ol (**2p**), 1-phenyl-2-propyn-1-ol (**2q**), and 3-phenyl-2-propyn-1-ol (**2r**) were used as substrates, the propargylic reduction did not proceed under the same reaction conditions, and some unexpected reactions occurred (Scheme 3).[12]

To elucidate the mechanism of the propargylic reduction, the following reactions were investigated. When **2b** was treated with [D_1]triethylsilane (97 % D) in the presence of a catalytic amount of **1c**, deuterated 1-phenyl-3-(4-methoxy-

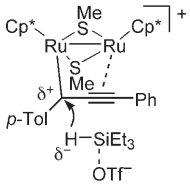


Scheme 3. Ruthenium-catalyzed reactions of propargylic alcohols with triethylsilane.

phenyl)-1-propyne ([D_1]**3b**) was produced with a high deuterium incorporation at the propargylic position (95 % D) [Eq. (1)]. This result indicates that triethylsilane



works as a reduing agent for the reduction at the propargylic position. The pronounced electronic effect of the substituent at the *para* position of the benzene ring in the propargylic alcohol substrate (see above) leads us to propose the presence of a propargylic cation as a reactive intermediate, in which the alkyne moiety may interact with the ruthenium centers of the thiolate-bridged diruthenium complex, although direct evidence of such a reactive intermediate has not yet been obtained. A nucleophilic attack of hydride from the triflate-activated silane on this ruthenium-coordinated propargylic cation might give the corresponding reduction product. A proposed reactive intermediate in the propargylic reduction is shown in Scheme 4. This proposal may be supported by the observation that no reduction occurred in the reactions of allylic alcohols and secondary alcohols such as cinnamyl alcohol and phenylethyl alcohol with triethylsilane under the same reaction conditions.

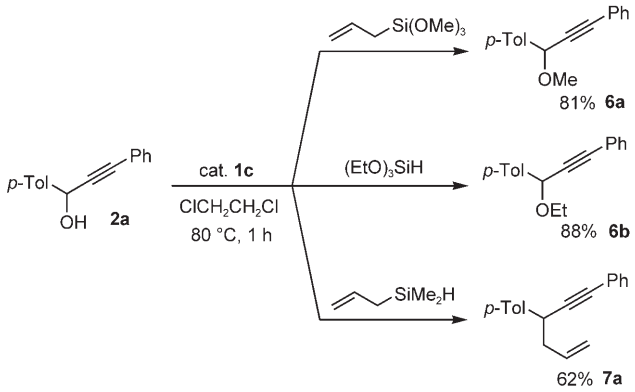


Scheme 4. A proposed reactive intermediate.

Nicholas and Siegel have reported the propargylic reduction of [$Co_2(CO)_6$]-complexed propargylic cations, which were prepared by reactions of propargylic alcohols with a stoichiometric amount of [$Co_2(CO)_8$], with sodium borohydride.[13] In this stoichiometric reaction, several steps were necessary to obtain the corresponding reduction products. However, catalytic and direct reduction of secondary or tertiary alcohols and primary alcohols with silanes to give the corresponding alkanes in high to excellent yields has been reported by Baba and co-workers[14] and by Yamamoto and

co-workers[15] by using indium trichloride and tris(pentafluorophenyl)borane, respectively, as catalysts. During our work, the propargylic reduction of propargylic acetates with triethylsilane by use of a catalytic amount of indium tribromide[16] was reported, in which the propargylic reduction of propargylic alcohols did not proceed smoothly. The reaction described herein provides the first example of the catalytic and direct propargylic reduction of propargylic alcohols to form the corresponding reduced products in good to high yields, although the scope of the reaction is still limited.

Furthermore, we have investigated the ruthenium-catalyzed reactions of propargylic alcohols with organosilicon compounds other than trialkylsilanes under the same reaction conditions. Interestingly, the reactions of **2a** with allyltrimethoxysilane and triethoxysilane at 80 °C for one hour afforded the corresponding ethers **6a** and **6b** in 81 % and 88 % yields, respectively, after isolation (Scheme 5). The reaction of **2a**



Scheme 5. Ruthenium-catalyzed propargylic substitution reactions of propargylic alcohol with organosilicon compounds.

with allyldimethylsilane under the same reaction conditions led to the formation of the allylated compound **7a** in 62 % yield after isolation (Scheme 5).[17] These results indicate that the ability of substituent transfer from a silicon center to the propargylic position has the following trend in these catalytic reactions: alkoxy > allyl > hydride ≫ alkyl, aryl.

In summary, we have observed novel ruthenium-catalyzed propargylic reduction of propargylic alcohols with triethylsilane to give the corresponding alkynes in good to high yields with complete selectivity. The transition-metal-catalyzed propargylic reduction of propargylic alcohols has until now been an unknown reaction system, in contrast to the recently reported transition-metal-catalyzed propargylic substitution reactions of propargylic alcohol derivatives with nucleophiles. Further investigations for elucidating the reaction mechanism in detail and for broadening the synthetic application of this propargylic reduction are currently in progress.

Experimental Section

Typical procedure for the propargylic reduction of propargylic alcohol (**2a**) with triethylsilane, catalyzed by **1c**: Compound **1c** (11.5 mg, 0.015 mmol) was placed in a 20-mL flask under N_2. Distilled and degassed 1,2-dichloroethane (10 mL) was then added to the flask, and **2a** (66.7 mg, 0.30 mmol) and triethylsilane (0.48 mL, 3.00 mmol) were added. The flask was kept at 80 °C for 1 h with magnetic stirring. After the flask had cooled, the solvent was concentrated in vacuo, and the residue was purified by column chromatography on SiO_2 with EtOAc/*n*-hexane (5:95) to give **3a**[16] as a yellow oil (47.6 mg, 0.231 mmol, 77 % yield). ^{1}H NMR: $\delta = 2.33$ (s, 3H), 3.78 (s, 2H), 7.12–7.44 ppm (m, 9H); ^{13}C NMR: $\delta = 21.0$, 25.3, 82.4, 87.8, 123.7, 127.7, 127.8, 128.2, 129.2, 131.6, 133.7, 136.1 ppm.

3l: Brown oil. Yield: 51 %. ^{1}H NMR: $\delta = 3.22$ (d, $J = 7.3$ Hz, 2H), 6.18 (t, $J = 7.3$ Hz, 1H), 7.29–7.36 ppm (m, 15H); ^{13}C NMR: $\delta = 20.6$, 80.9, 88.1, 123.4, 127.3, 127.4, 127.7, 128.1, 128.2, 128.4, 128.6, 128.7, 129.8, 131.6, 139.2, 142.0, 143.3 ppm. HRMS: calcd for $C_{23}H_{18}$: 294.1409; found: 294.1404.

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[12] No reaction occurred when **2m**, **2q**, or **2r** was used as a substrate.
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[17] Separately, we investigated the reaction of **2a** with a mixture of allyltrimethylsilane and triethylsilane in the presence of 5 mol% of **1c** at 80°C for 1 h; only **7a** was isolated in 81% yield.

