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Interligand Interactions Dictate the Regioselectivity of *trans*-Hydrometalations and Related Reactions Catalyzed by [Cp*RuCl]. Hydrogen Bonding to a Chloride Ligand as a Steering Principle in Catalysis

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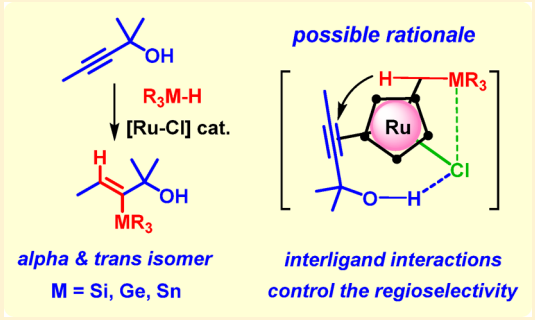
Supporting Information

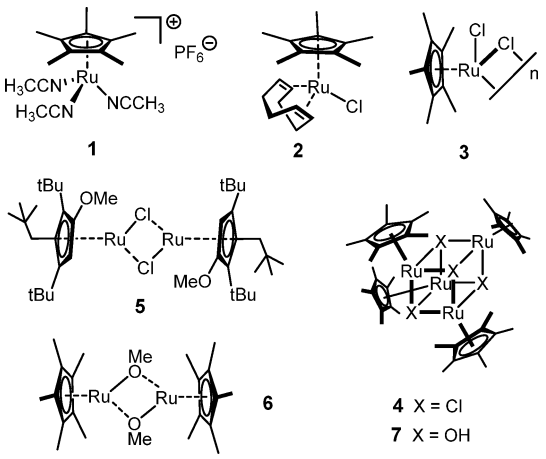
ABSTRACT: Reactions of internal alkynes with R_3M-H (M = Si, Ge, Sn) follow an unconventional *trans*-addition mode in the presence of $[Cp^*Ru(MeCN)_3]PF_6$ (**1**) as the catalyst; however, the regioselectivity is often poor with unsymmetrical substrates. This problem can be solved upon switching to a catalyst comprising a [Ru−Cl] bond, provided that the acetylene derivative carries a protic functional group. The R_3M unit is then delivered with high selectivity to the alkyne-C atom proximal to this steering substituent. This directing effect originates from the ability of the polarized [Ru−Cl] bond to engage in hydrogen bonding with the protic substituent, which helps upload, activate, and lock the alkyne within the coordination sphere. An additional interligand contact of the chloride with the $-MR_3$ center positions the incoming reagent in a matching orientation that translates into high regioselectivity. The proposed secondary interactions within the loaded catalyst are in line with a host of preparative and spectral data and with the structures of the novel ruthenium π-complexes **10** and **11** in the solid state. Moreover, the first X-ray structure of a [Ru(σ-stannane)] complex (**12a**) is presented, which indeed features peripheral Ru−Cl···MR_3 contacts; this adduct also corroborates that alkyne *trans*-addition chemistry likely involves σ-complexes as reactive intermediates. Finally, it is discussed that interligand cooperativity might constitute a more general principle that extends to mechanistically distinct transformations. The presented data therefore make an interesting case for organometallic chemistry that provides inherently better results when applied to substrates containing unprotected rather than protected −OH, −NHR, or −COOH groups.



INTRODUCTION

We have recently communicated that internal alkynes are subject to *trans*-hydrogenation, *trans*-hydroboration, or *trans*-hydrostannation when reacted with H−H, H−B(pin) or H−$SnBu_3$, respectively, in the presence of catalysts comprising a (cationic) [Cp*Ru] template.[1−4] This chemistry extends and generalizes previous work of Trost and co-workers on the *trans*-hydrosilylation of alkynes,[5,6] which has already found widespread use in synthesis.[7−10] These *trans*-addition reactions[11] are intriguing for their unorthodox stereochemical course which formally violates the reigning paradigm of suprafacial delivery of H−X (X = H, BR_2, SiR_3, SnR_3) to the π-system of a given substrate.[12] In any case, they open access to structural motifs that can be difficult to make otherwise and therefore arguably constitute an enabling new methodology.

Irrespective of the stereochemical outcome, however, hydrometalations of unsymmetrical π-bonds are always confronted with problems of regioselectivity.[13] The product ratio often depends on very subtle factors, and the individual isomers are usually difficult to separate; even if so, the formation of product mixtures means an inevitable loss of (precious) material, which can spoil a synthesis and certainly advocates against any late-stage applications as long as this issue cannot be properly addressed.[14] It was therefore gratifying to note that the ruthenium-catalyzed *trans*-hydrostannation gains



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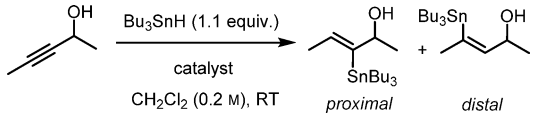
exquisite regioselectivity, provided that internal alkynes bearing protic functionality are reacted with Bu_3SnH in the presence of catalysts containing a [Ru−Cl] motif.[3] The example shown in Table 1 is representative: it illustrates that the outcome is

Table 1. *trans*-Hydrostannation of a Propargylic Alcohol: A Case of Catalyst-Based Regiocontrol



entry	catalyst	loading	proximal:distal	$Z{:}E^a$	yield (%)
1	**1**	5 mol %	74:26	99:1	91
2	**2**	5 mol %	97:3	99:1	73
3	**3**	5 mol %	97:3	99:1	88
4	**4**	1.25 mol %	98:2	99:1	81
5	**5**	2.5 mol %	90:10	99:1	63
6	**6**	2.5 mol %	98:2	99:1	55
7	**7**	1.25 mol %	98:2	99:1	74

[a]Double bond configuration of the major regioisomer, cf. ref 11

largely independent of whether the mononuclear complex [Cp*Ru(cod)Cl] (**2**),[15] the oligomeric material $[Cp^*RuCl_2]_n$ (**3**),[16,17] or the convenient tetramer $[Cp^*RuCl]_4$ (**4**)[15] is used; all of these precatalysts are readily prepared and also commercially available. Even the more elaborate congener **5** exerts a similar effect, although this very electron-rich species is slightly less industrious.[18] Moreover, complexes **6**[19] and **7**[20] comprising [Ru−OR] bonds led to similar results. In all cases, the reactions were highly selective, with the largely dominant isomer featuring an unusual stereochemical and regiochemical pattern of functionalization. This outcome is fully appreciated when compared to the result obtained with the cationic acetonitrile adduct $[Cp^*Ru(MeCN)_3]PF_6$ (**1**):[21] Although this complex had been introduced early on as the preferred catalyst for *trans*-hydrosilylation and had dominated the field ever since,[1−3,5−9] it provides only an inseparable 3:1 mixture of isomers.

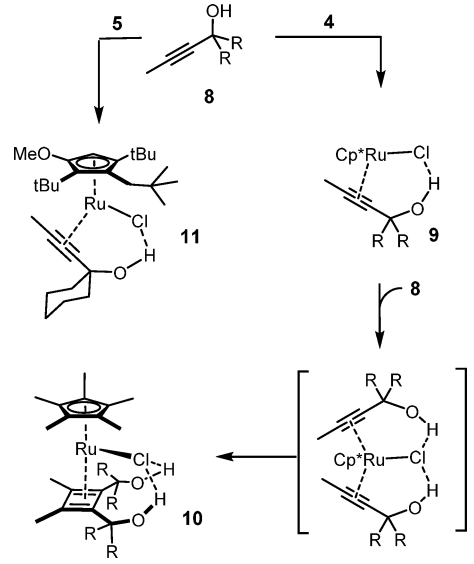
The serendipitous discovery of catalyst-control over the regioselectivity of the *trans*-hydrostannation calls for a more comprehensive investigation. We are now pleased to report that this effect is much more general and certainly pertains to *trans*-hydrosilylation and *trans*-hydrogermylation too.[22] The data outlined below suggest that the hydrogen-bond-acceptor properties of the [Ru−Cl] unit, rather than the metal center itself,[23] are decisive: They likely account for the positioning of the protic alkyne substrate and thereby preorganize the coordination sphere of the active catalyst. Additional contacts between the chloride ligand and the tin (germanium, silicon) center of the reagent may provide further assistance. If such a preorganization by interligand interactions in the periphery of the loaded catalyst is operative, it should allow mechanistically distinct ruthenium-catalyzed transformations to be steered in a similar manner. This phenomenon has only rarely been recognized as such,[24,25] although it might already have been frequently encountered. This notion is supported by an analysis of some literature data.

RESULTS AND DISCUSSION

Hydrogen Bonding as a Steering Principle. The tetrameric complex $[Cp^*RuCl]_4$ (**4**) is a convenient precatalyst in preparative terms and supposedly well suited for mechanistic investigations because no extra ligands are introduced that might compete with the alkyne substrate and/or the tin hydride for the coordination sites on the ruthenium center. **4** is known to be readily disassembled on treatment with bulky neutral donor ligands, leading to the formation of 16-electron complexes of the general type [Cp*Ru(L)Cl].[26] It was therefore assumed that an alkyne substrate would do the same in the first place.

In fact, addition of a propargyl alcohol of type **8** to a solution of **4** in CD_2Cl_2 causes an instant color change from orange-brown to dark red. The ^1H NMR spectrum of the mixture is distinguished by the marked low-field shift of the hydroxyl group from δ_H = 1.97 ppm (CD_2Cl_2) in unbound **8a** (R, R = $(CH_2)_5$) to δ_H = 5.08 ppm in the putative adduct **9a**, which is ascribed to strong hydrogen bonding to the adjacent chloride ligand (Scheme 1);[27] similar results were obtained when the

Scheme 1. Preparation of Hydrogen-Bonded π-Complexes Engaging a [Ru−Cl] Unit[a]



[a]R, R = $(CH_2)_5$.

substrate was used in excess. The ^{13}C NMR spectra show a very significant deshielding of the alkyne C atoms which resonate at 80.0/83.3 ppm in **8a** but at 130.3/154.9 ppm in complex **9a** formed in situ. The very same spectral fingerprints were recorded when **8b** (R = Me) was used (Figure 1). This pronounced and, at the same time, markedly differential downfield shift is fully appreciated if one compares it with the marginal effect observed for the mixture of **8b** and the cationic complex $[Cp^*Ru(MeCN)_3]PF_6$ (**1**). In this case, the alkyne C atoms show almost no visible shift change at ambient temperature (δ_C = 80.4, 83.6 ppm), suggesting that acetonitrile is a competitive ligand. The massive deshielding in **9** speaks for the alkyne serving as a four-electron donor,[28] which in turn implies that the −OH group does not interact with the metal center directly.[29] This interpretation fits to the proposed hydrogen-bonding interaction in the periphery of the complex. In any case, the NMR data are indicative of substantial activation and polarization of the triple bond on complexation to the Ru(+2) center of complex **4**.

Attempts at growing crystals of the putative π-complex **9** suitable for X-ray diffraction have so far met with failure. From the mixture, only single crystals of the corresponding

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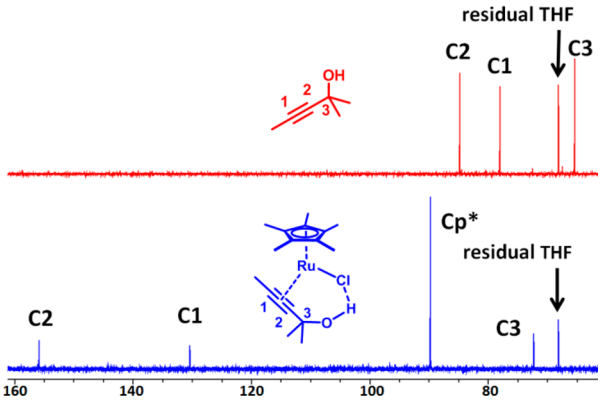

Figure 1. Low-field region of the ^{13}C NMR spectrum (CD_2Cl_2) of the propargyl alcohol **8b** (top) and the putative complex **9b** (bottom), which shows the massive deshielding of the alkyne C atoms upon complex formation; arbitrary numbering scheme as shown.

cyclobutadiene complexes **10** were collected, independent of whether **8a** or **8b** was used as the substrate. The [2 + 2] cycloaddition occurred even at −20 °C and resulted in exclusive head-to-head coupling (Scheme 1).[30−32] This particular connectivity pattern allows both −OH groups to engage in hydrogen bonding to the [Ru−Cl] unit, which obviously outweighs the penalty from placing the bulky cyclohexanol subunits next to each other (Figure 2). In

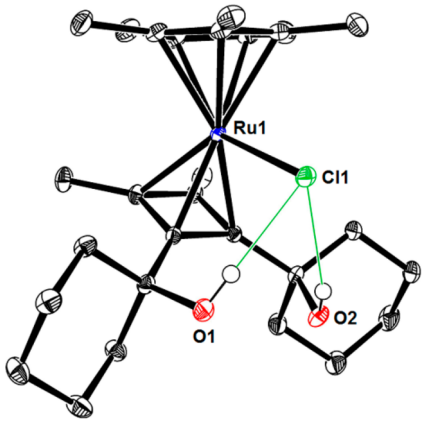

Figure 2. Structure of complex **10a** in the solid state, in which the chloride entertains two short interligand hydrogen bonds. All H atoms, except the ones engaged in hydrogen bonding, are omitted for clarity.

complex **10a**, the −OH···Cl distances are only 2.374 and 2.481 Å long and must therefore both be rated "short" and "strong" according to the categories previously defined in organometallic chemistry.[33,34] Interestingly, the analogous complex **10b** features only one −OH···Cl interligand interaction which, however, is even shorter (2.242 Å); the second −OH proton now forms a tight bridge with O1 (Figure 3). These results showcase that a [RuCl] fragment is apparently capable of precisely positioning two (propargyl) alcohol substrates within the coordination sphere of the metal template either by entertaining two hydrogen bonds itself or by starting a more extended network. In the present cases, the resulting head-to-head arrays evolved via metallacycle formation and reductive elimination to give the cycloadducts of type **10**. It seems likely, however, that this principle has potential implications for

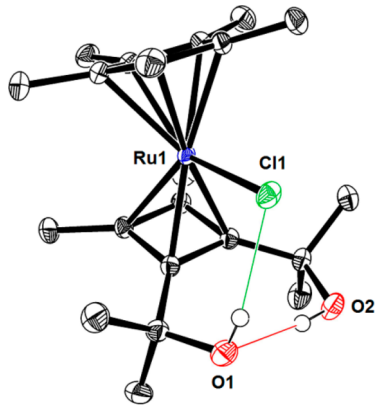

Figure 3. Structure of complex **10b** in the solid state with an extended hydrogen-bonding array. All H atoms, except the ones engaged in hydrogen bonding are omitted for clarity.

mechanistically distinct Ru-catalyzed transformations as well (see below).

Although we were not yet able to suppress the [2 + 2] cycloaddition in our attempts at obtaining an η^4-alkyne complex of type **9** in crystalline form, an arguably very close and valid model for the loaded catalyst implied in the regioselective *trans*-hydrostannation chemistry is shown in Figure 4. Inspired by a

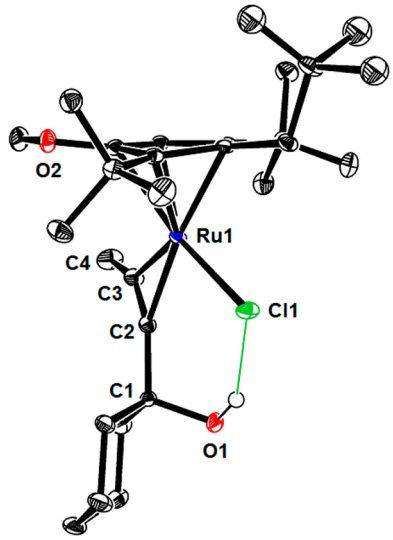

Figure 4. Structure of complex **11** in the solid state. All hydrogen atoms, except the one engaged in hydrogen bonding to the chloride ligand, are omitted for clarity.

literature precedent, we resorted to the encumbered η^5-1-methoxy-2,4-di-*tert*-butyl-3-neopentyl-cyclopentadienyl (Cp^) ligand which disfavors bimolecular pathways on steric grounds;[18] because Cp^ is also arguably more electron donating than the parent Cp* ring, an alkyne coordinated to a Cp^Ru fragment might be less prone to nucleophilic attack. Taken together, these factors should increase the chance to grow crystals of the corresponding 16(18)-electron adducts[29] that retain a formal open coordination site for an incoming reagent. In line with this notion, treatment of the chloride-bridged dimer **5** with **8a** furnished crystals of the corresponding π-complex **11** comprising only a single propargyl alcohol ligand (Scheme 1). Since **5** was shown to be a competent precatalyst (see Table 1), this outcome is deemed relevant for a

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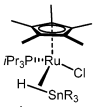
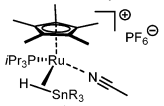
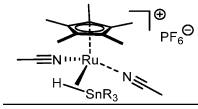
Table 2. Characteristic NMR Data (CD_2Cl_2, −30°C) of R_3SnH and the Derived Ruthenium σ-Stannane Complexes

Compound		^{1}H NMR[a] (ppm)	^{119}Sn NMR (ppm)	$^1J_{Sn,H}$ (Hz)	$^3J_{Sn,P}$ (Hz)
Bu_3SnH		+4.51	+155.6	1535	---
Me_3SnH		+4.51	−100.9	1711	---
	**12a** (R = Bu)[b]	−10.29	+57.0	192	85
	12b (R = Me)[b]	−10.60	+23.2	177	78
	**13a** (R = Bu)[c]	−9.60	+61.4	226	93
	13b (R = Me)	−9.70	nd	284	98
	**14a** (R = Bu)	−6.47	+27.3	383	---
	14b (R = Me)	−6.38	+15.9	441	---

[a]Hydride resonance. [b]The mixture contained 4−7% of free iPr$_3$P; [c]The conversion to **13a** was ca. 80%; nd = not determined

mechanistic discussion. As expected, complex **11** also features a short hydrogen bond between the −OH group and the chloride (2.339 Å) (Figure 4); the O1−H−Cl1 angle (153.7°) falls into the typical range for a hydrogen bond with a metal halide unit.[33] This bridge must persist in CD_2Cl_2 solution, as suggested by the fact that the −OH proton resonates again at very low field (δ_H = 5.26 ppm).[35]

A few additional structural attributes of **11** are noteworthy. Although a [Cp^RuCl] template is certainly more electron rich than the [Cp*RuCl] fragment serving in the actual catalyst, the activation of the alkyne unit is still substantial. This fact is evident from the extended C2−C3 bond length (1.263(2) Å)[36] and the considerable deviation from linearity (C2−C3−C4 145.46(19)°). It is also interesting to note that the bond from the ruthenium center to the C3 atom (Ru1−C3 2.0661(18) Å), to which the hydride would be delivered during a directed *trans*-hydrometalation, is somewhat shorter than the corresponding Ru1−C2 bond (2.0766(18) Å). Overall, these structural attributes are in good agreement with the conclusions drawn from the significant and differential downfield shifts observed in the ^{13}C NMR spectra (the alkyne C atoms resonate at 150.3 and 123.0 ppm), which correspond well to those observed for **8**/[Cp*RuCl]$_4$.

Ruthenium-Stannane σ-Complexes and Possible Additional Preorganization by Cl···Sn Interactions. Although the current understanding of the origin of the high *trans*-selectivity in the addition of H_2 or H−M (M = R_3Si, R_3Sn) to an alkyne is provisional, the available mechanistic information suggests that the reagent is activated upon binding to the ruthenium center via its σ-bond.[37,38] Strong experimental evidence comes from the fact that the cationic σ-hydrogen complex [Cp*Ru(H_2)(cod)]OTf[39] was shown to be a competent *trans*-selective hydrogenation catalyst.[1] In the case of the *trans*-hydrosilylation chemistry, a pathway via σ-silane complexes is substantiated by extensive DFT-calculatuions.[40] Therefore, it is reasonable to assume that the *trans*-hydrostannation involves the analogous σ-stannane complexes at some point.

Stannanes were previously shown to form σ-complexes with various metal centers,[41] but pertinent examples comprising a [Cp*Ru] fragment seem to be unknown. We found that such complexes are readily obtained; they could be fully characterized as long as the coordination sphere of the metal is complemented by adequate ancillary ligands (Table 2). However, they are thermally unstable and must be kept at ≤ −30 °C.

Specifically, the reaction of [Cp*RuCl]$_4$ (**4**), which carries no neutral L-type ligand, with Bu_3SnH gave a major hydride species flanked by tin satellites (δ_H = −11.43 ppm, $^1J_{Sn,H}$ = 203 Hz), but two additional minor resonances were also detected in the crude mixture. Although these data suggest that at least the major compound in solution is a σ-stannane complex of some sort, we were so far unable to obtain it in pure form. In contrast, [Cp*Ru(MeCN)$_3$]PF_6 (**1**), [Cp*Ru(iPr$_3$P)(MeCN)$_2$]PF_6 (**15**) and [Cp*RuCl(iPr$_3$P)] (**16**) all gave single well-defined products (Table 2). They show the same pronounced decrease of the $^1J_{Sn,H}$ from 1535 or 1711 Hz in Bu_3SnH or Me_3SnH, respectively, to values in the range of ca. 170−440 Hz. These data are in excellent accord with the purported σ-complex formation; should a true oxidative insertion of the metal into the Sn−H bond have occurred, smaller $^1J_{Sn,H}$ coupling constants in the range of only ca. 40 Hz are to be expected.[41f] Moreover, the data correspond well to the $^1J_{Sn,H}$ = 270 Hz recorded for the prototype manganese σ-stannane complex [CpMn(CO)$_2$(σ-H−SnPh$_3$)] previously described in the literature.[41a] Finally, it is emphasized that the observed $^1J_{Sn,H}$ values express the likely different degree of Sn−H bond activation; thus, the stannane ligands in the most electron-rich neutral complexes **12** endowed with a phosphine donor ligand are obviously in a more advanced state of activation than that in their cationic congeners **13** and **14**.

This notion is supported by the structure of complex **12a** in the solid state (Figure 5), in which the Sn1−H1 bond length reaches 2.15(6) Å.[42] This appreciable elongation notwithstand-

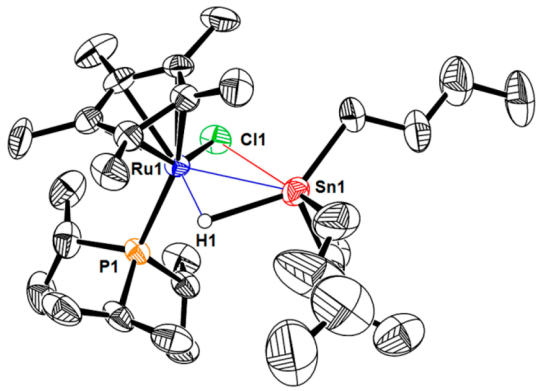


Figure 5. Structure of complex **12a** in the solid state. The position of the hydride ligand has been localized on a difference Fourier map.

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ing, the adduct is definitely a σ-complex as evident from the comparison with the already cited σ-complex [$CpMn(CO)_2(\sigma$-$H{-}SnPh_3)$], which has a Sn−H bond of almost exactly the same length (2.16(4) Å);[41a] moreover, the respective Sn−H distances in true ruthenium hydride species of the type [$Ru(H)(SnR_3)$] are significantly longer (2.636−4.534 Å).[43] The Ru1−H1 distance (1.52(6) Å) also fits well to a σ-stannane species in an advanced state of activation. Adduct formation also affects the Ru1−Cl1 bond in **12a** (2.429(2) Å), which is longer than that in the precursor complex **16** (2.365(2) Å), whereas the corresponding Ru1−P1 bond does not change by much (2.395(2) Å in **12a** versus 2.3741(17) Å in **16**).

A particularly relevant structural attribute is the rather short distance between the chloride ligand and the tin center (3.202 Å), which is well below the sum of the van der Waals radii (4.00 Å). Similar contacts were previously observed in the analogous chlorosilane complex [$Cp^*RuCl(i Pr_3P)(\sigma$-$H{-}SiCl_3)$];[44,45] moreover, interligand Cl···Sn coordination is known from a few other tin complexes.[46]

Although one has to be cautious not to overinterpret this data point, such stabilizing interligand interactions between the [Ru−Cl] bond and the coordinated stannane (silane, germane) reagent might synergize with the hydrogen-bonding array that positions an incoming alkyne substrate endowed with protic functionality. It is tempting to assume the formation of a loaded complex of type **17**, which predisposes the nucleophile for hydride delivery at the alkyne position distal to the protic functionality that is also more deshielded (Figure 6). As a

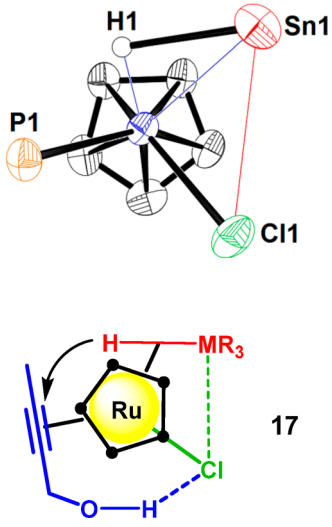

Figure 6. Top: Projection of the core of complex **12a**, illustrating the coordination environment about the ruthenium center. Bottom: Working model for the loaded catalyst of a *trans*-hydrometalation, which mimics the array in this core region in that the phosphine is formally replaced by an alkyne substrate capable of interacting with the chloride ligand via hydrogen bonding; ● = CMe.

consequence, a strong C−Ru-bonding interaction at the proximal site must ensue, which will eventually trap the MR_3 residue (M = Si, Ge, Sn), independent of what the elementary steps of this process might be.

We like to emphasize that we have not yet been able to observe a loaded complex of type **17** by spectroscopic means and therefore cannot rule out that the H−MR_3 reagent is delivered by an outer-sphere process.[47] Even in such a scenario, however, high regioselectivity is expected for the pronounced polarization of the triple bond evident from the NMR data. This issue notwithstanding, the model allows several predictions to be made which can be experimentally probed. Specifically, it suggests that:

(i) Replacement of the chloride-free cationic precatalyst [$Cp^*Ru(MeCN)_3$]$^+$ (**1**) by [$Cp^*RuCl]_4$ (**4**) should not only affect and improve the regioselectivity of the *trans*-hydrostannation, as reported in our preliminary Communication,[3] but also is expected to be a more general principle. In any case, it must pertain to the analogous *trans*-hydrosilylation and *trans*-hydrogermylation reactions,[22] for which such catalyst control has neither been described nor recognized before.

(ii) The steric and electronic properties of the chosen H−MR_3 reagent itself (M = Si, Ge, Sn) are likely of minor importance because the attractive interligand contacts will reign.

(iii) In contrast, the regioselectivity should be correlated with the hydrogen-donor ability of the protic group on the incoming alkyne substrate as well as with the distance between the triple bond and this protic site, which impacts on the rigidity and stability of the ensuing array.

(iv) Likewise, the formal replacement of the [Ru−Cl] motif in the catalyst by less effective hydrogen-bond acceptors units [Ru−X] must result in loss of regioselectivity.

(v) Aprotic nonpolar media will foster the proposed secondary interactions and are therefore expected to be most adequate.

(vi) As hydrogen bonding likely assists π-complex formation, alkynes with a protic group in vicinity might be coordinated preferentially over alkynes devoid of such functionality, thus allowing additional selectivity to be harnessed.

(vii) The favorable predisposition of the reactive components should foster a good functional group tolerance to be expected from a metal-catalyzed hydrometalation anyway.

As will be shown in the following, all of these aspects were found to be valid.

Directed *trans*-Hydrosilylation. As mentioned in the Introduction, the *trans*-hydrosilylation of internal alkynes has been studied in detail in the past and was successfully applied to natural product synthesis.[5−9] Therefore, it is surprising that this chemistry was basically confined to the use of the cationic complex [$Cp^*Ru(MeCN)_3$]PF_6 (**1**) as precatalyst, which engenders preferential silylation at the distal acetylenic C atom of nonterminal propargyl alcohol substrates.[5,6] However, the working hypothesis developed above implies that replacement of **1** by a precatalyst comprising a [Ru−Cl] bond will lead to a different regiochemical outcome, largely independent of the chosen silane reagent. The generally excellent *trans* selectivity of the reaction should not be affected by such a change.

The data summarized in Table 3 confirm these expectations. In line with the literature, we found **1** to engender silyl delivery preferentially at the alkyne C atom distal to the protic site (12:88, Table 3, entry 1), which actually distinguishes the *trans*-hydrosilylation from the analogous *trans*-hydrostannation with the same catalyst that gives roughly the opposite outcome (74:26, Table 1, entry 1). This bias notwithstanding, the use of either [$Cp^*RuCl]_4$ (**4**) or [$Cp^*RuCl(cod)$] (**2**) overrides the

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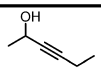
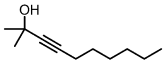
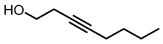
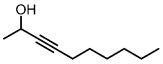
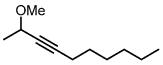
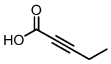
Table 3. Directed *trans*-Hydrosilylation: Catalyst, Solvent, and Silane Screening[a]

Entry	Substrate	Silane	Catalyst	Solvent	Proximal:Distal[b]	Yield (%)
1		Et_3SiH	**1**	CH_2Cl_2	12:88	72
2		Et_3SiH	[Cp*RuI(cod)]	CH_2Cl_2	38:62	85[c]
3		Et_3SiH	[Cp*RuCl(cod)]	CH_2Cl_2	87:13	79
4		Et_3SiH	$[Cp^*RuI_2]_n$	CH_2Cl_2	42:58	86[c]
5		Et_3SiH	**4**	CH_2Cl_2	88:12	96
6		Et_3SiH	**4**	pentane	89:11	81
7		Et_3SiH	**4**	acetone	26:74	83
8		Et_3SiH	**4**	MeOH	15:85	70[d]
9		$BnMe_2SiH$	**4**	pentane	86:14	90
10		Et_3SiH	**1**	CH_2Cl_2	7:93	80
11		Et_3SiH	**4**	pentane	91:9	70
12		$BnMe_2SiH$	**4**	pentane	91:9	84
13		Et_3SiH	**1**	CH_2Cl_2	43:57	86
14		Et_3SiH	**4**	pentane	100:0	99
15		$BnMe_2SiH$	**4**	pentane	100:0	92
16		$(EtO)_3SiH$	**4**	pentane	100:0	86
17		Et_3SiH	**1**	CH_2Cl_2	45:55	99
18		Et_3SiH	**4**	pentane	87:13	83
19		$BnMe_2SiH$	**4**	pentane	88:12	95
20		$(EtO)_3SiH$	**4**	pentane	100:0	76
21		$BnMe_2SiH$	**4**	pentane	24:76	95
22		$(EtO)_3SiH$	**4**	pentane	45:55	68
23		Et_3SiH	**1**	CH_2Cl_2	0:100	77
24		Et_3SiH	**4**	CH_2Cl_2	83:17	75
25		$BnMe_2SiH$	**4**	CH_2Cl_2	71:29	83

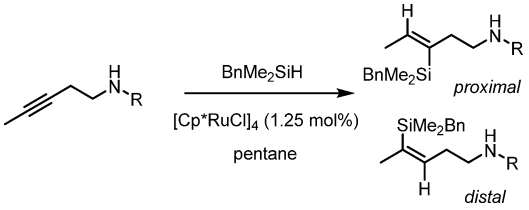
[a]All reactions were carried out with 5 mol % of active ruthenium and 1.2 equiv of the corresponding silane; unless stated otherwise, the selectivity for *trans*-addition was ≥95:5 (major regioisomer). [b]"Proximal" denotes delivery of the silyl group to the alkyne C atom next to the protic group, whereas "distal" refers to the more remote C atom. [c]The major regioisomer was only 67% *trans*-configured. [d]Full conversion could not be reached.

inherent preference, inverts the outcome, and engenders silylation at the proximal C atom with high fidelity. As expected, the choice of silane is of only minor importance, with Et_3SiH, $BnMe_2SiH$, and $(EtO)_3SiH$ leading to similar results in most cases.[48] In conceptual terms, this is a striking example of regio-control by choice of the counterion (PF_6^- versus Cl^-); in preparative terms, it provides a valuable complement to the *trans*-hydrosilylation chemistry known before.

The examples compiled in Table 3 also show that this favorable outcome is contingent upon the cooperativity of a free protic functionality in the alkyne substrate and a chloride ligand in the active catalyst. Indirect evidence for a vital stabilizing interligand interaction between these entities comes from the results obtained with the analogous ruthenium iodide complexes $[Cp^*RuI_2]_n$ and [Cp*RuI(cod)],[49] both of which were unable to reverse the selectivity (entries 2, 4). This finding concurs with literature data which suggest that an [M−I] bond is a much poorer hydrogen-bond acceptor than a [M−Cl] unit.[33] A brief solvent screen provides additional support in that the use of a chloride-containing catalyst has no significant effect when the reaction is carried out in media able to interfere with the proposed interligand hydrogen bonding, such as acetone or MeOH (entries 7, 8). Furthermore, pentane provides slightly better results than CH_2Cl_2, although the poor solubility of the catalysts and/or certain substrates limits its use. Finally, it is pointed out that protection of the propargylic alcohol as the corresponding methyl ether results in a dramatic loss of selectivity (compare entries 19/20 with 21/22), as inferred from the model developed above.[50]

The *trans*-hydrosilylation of a set of homopropargylic amine derivatives provides an arguably even more instructive case in support of the proposed preorganization of the reactants via an interligand hydrogen bond (Table 4). Whereas the acetamide shown in entry 1 as well as the corresponding N-Boc derivative (entry 2) were both poorly selective, the increased acidity of the corresponding trifluoroacetamide (entry 3) and, even more so, trifluorosulfonamide (entry 4) translates into significantly better results.[51] Suffice it to say that the very same trend was observed upon *trans*-hydrostannation of these substrates (see Table 7).

Table 4. Protecting Group Tuning in the *trans*-Hydrosilylation of Homopropargylic Amines[a]



entry	R	proximal:distal	yield (%)
1	$-COCH_3$	52:48	86
2	$-C(O)OtBu$	58:42	94
3	$-COCF_3$	74:26	98
4	$-SO_2CF_3$	92:8	86

[a]Selectivity for *trans*-addition was ≥95:5 in all cases investigated (major regioisomer).

Collectively, these data demonstrate that the use of $[Cp^*RuCl]_4$ (**4**) or [Cp*RuCl(cod)] (**2**)[52] as the preferred catalysts leads to largely unprecedented levels of selectivity in the *trans*-hydrosilylation of internal alkynes endowed with protic functionality.[53] Silyl delivery to the proximal alkyne position is favored, independent of whether the substrate is a primary, secondary, or tertiary propargyl alcohol, a (bis)-homopropargyl alcohol, a propargylic or homopropargylic

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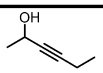
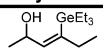
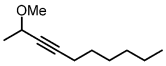
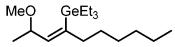
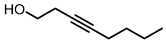
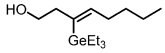
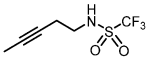
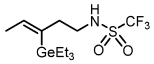
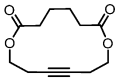
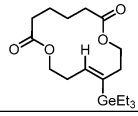
Table 5. Regioselective *trans*-Hydrogermylation of Internal Alkynes[a]

Entry	Substrate	Catalyst	Major Product	proximal:distal	Yield (%)
1		**1**		24:76	83
2		**4**		86:14	78
3		**4**		20:80	88
4		**4**		86:14	96
5		**4**		92:8	78
6		**4**		---	96

[a]The reactions were carried out with 5 mol % of **1** or 1.25 mol % of **4** and 1.2 equiv of Et_3GeH in CH_2Cl_2 as the solvent. The selectivity for *trans*-addition was ≥95:5 in all cases investigated (major regioisomer).

amide, or an acetylene carboxylic acid (Tables 3, 4, and 7). With regard to the generality of the effect, the broad scope, and its convenience, the present method clearly outperforms other known procedures for the regioselective hydrosilylation of such substrates.[53,54] The arguably closest relative is a method using again a chloride-containing catalyst, namely ([*p*-cymene)-$RuCl_2]_2$), which favors proximal delivery but works only for primary and some secondary (homo)propargyl alcohols with a terminal triple bond. In all other cases, this preference is lost.[55,56]

Several additional examples discussed below will further illustrate the excellent coverage and functional group tolerance of this new method. Together with the equally controllable hydrogermylations and hydrostannylations, these results sum up to an interesting case of an organometallic reaction which provides inherently better results when applied to substrates containing protic sites in unprotected rather than protected form.

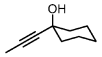
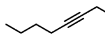
Directed *trans*-Hydrogermylation. The *trans*-hydrogermylation of internal alkynes has received less attention in the past, although it was recognized as a valuable tool for material science.[57,58] The cationic complex $[Cp^*Ru(MeCN)_3]PF_6$ (**1**) seems once again to be the only tested ruthenium catalyst. Therefore, we became interested to see whether the regioselectivity of this reaction can also be reprogrammed by switching to complexes comprising a [Ru−Cl] bond.

In accord with our working hypothesis, this is in fact the case (Table 5). Specifically, the Et_3Ge-residue ends up at the proximal site of the propargylic alcohol shown in entry 2 when $[Cp^*RuCl]_4$ (**4**) was used, whereas the chloride-free catalyst **1** favors the distal adduct (entry 1), much like in the analogous hydrosilylation. Likewise, the selectivity is contingent on the presence of an unprotected −OH group as evident from entry 3. This example also proves that distal delivery is inherently favored, like in the hydrosilylation case, but that this bias is obviously overridden by the preorganization of the reagents via secondary interligand interactions if a free −OH is present. As expected, **4** also led to good results with a homopropargylic alcohol (entry 4) and a sulfonamide substrate (entry 5). An application to a macrocyclic cycloalkyne is meant to show the scope of the procedure, although there is no regioselectivity issue with this symmetrical compound (entry 6).[59] This example merely illustrates that the use of a chloride-containing catalyst is by no means limited to alkyne substrates bearing protic groups. Importantly, the *trans*-selectivity of the hydrogermylation was impeccable (≥95:5) in all cases shown in Table 5.

Comparison with the Directed *trans*-Hydrostannation and Investigations into the Substrate Scope. The stunning cooperativity between a [Ru−Cl]-based catalyst and an internal alkyne endowed with a protic substituent had originally been recognized in our study on *trans*-hydrostannation but was communicated only in preliminary form.[3] With the effect now being generalized and its likely origins elucidated, it was deemed necessary to explore the scope of the reaction in more detail. In addition, a rigorous comparison with the *trans*-hydrosilylation is needed in order to assess if and when the use of toxic tin reagents is justified. Although not all substrates shown in Table 7 were reacted with a silane and a stannane, the compiled data provide a reasonably clear picture.

Before entering into a study of the substrate scope, a short screening assured that the very nature of the chosen stannane has little bearing on the regio- as well as stereochemical outcome (Table 6). In fact, Me_3SnH, Bu_3SnH and Cy_3SnH furnished similar results despite their largely different steric demand, which is obviously overridden by an effective preorganization of the catalyst ligand sphere. This result is gratifying as larger alkyl substituents tend to reduce the acute

Table 6. Comparison of Different Stannanes in *trans*-Hydrostannations Catalyzed by $[Cp^*RuCl]_4$ (4)[a]

Entry	Substrate	Stannane	proximal:distal[b]	*trans:cis*	Yield (%)
1		Me_3SnH	>99:1	99:1	79 (R = Me)
2		Bu_3SnH	98:2	99:1	81 (R = Me)
3		Bu_3SnH	98:2	99:1	84 (R = Et)
4		Cy_3SnH	>99:1	99:1	87 (R = Et)
5		Me_3SnH	>99:1	99:1	89
6		Bu_3SnH	99:1	99:1	97
7		Bu_3SnH	80:20	90:10	79
8		Cy_3SnH	82:18	97:3	89

[a]All reactions were carried out with **4** (1.25 mol %) and 1.1 equiv of R_3SnH in CH_2Cl_2. [b]"Proximal" denotes delivery of the silyl group to the alkyne C atom next to the protic group, whereas "distal" refers to the more remote C atom.

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Table 7. Comparison of *trans*-Hydrosilylation and *trans*-Hydrostannation Catalyzed by 3[17] or 4[a]

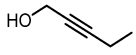
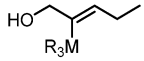
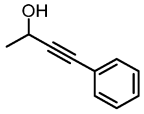
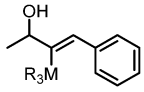
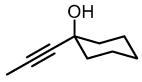
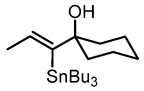
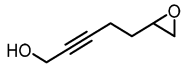
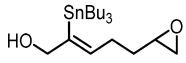
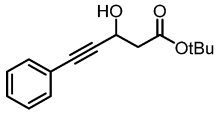
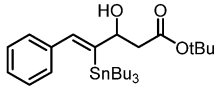
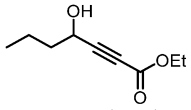
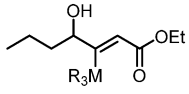
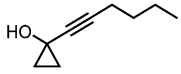
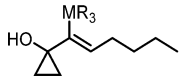
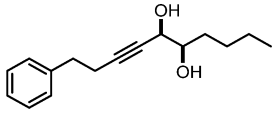
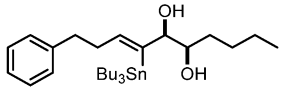
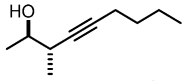
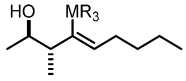
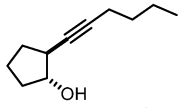
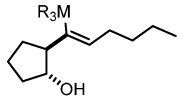
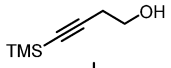
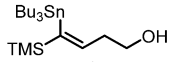
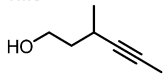
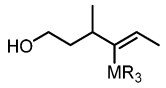
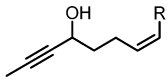
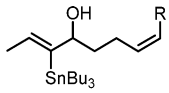
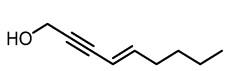
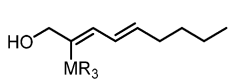
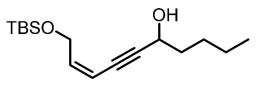
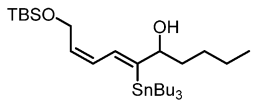
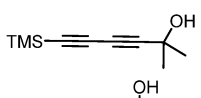
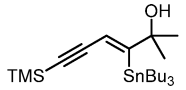
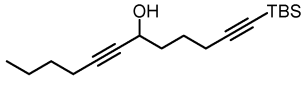
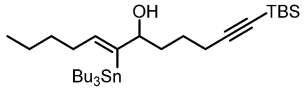
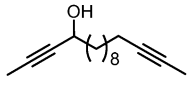
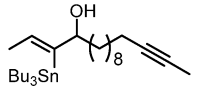
Entry	Substrate	Reagent	Major product	proximal:distal[b]	Yield (%)
1		Bu_3SnH		99:1	40
2		$BnMe_2SiH$		99:1	62-78[c]
3		Bu_3SnH		95:5	83
4		Et_3SiH		91:9	78
5		$BnMe_2SiH$		90:10	92
6		Bu_3SnH		97:3	84
7		$BnMe_2SiH$		84:16	97
8		Bu_3SnH		99:1	97
9		$BnMe_2SiH$		99:1	99
10		Bu_3SnH		90:10	68
11		Bu_3SnH		99:1	85
12		Bu_3SnH		97:3	66
13		$BnMe_2SiH$		99:1	77
14		$(EtO)_3SiH$		99:1	59
15		$BnMe_2SiH$		99:1	66
16		$(EtO)_3SiH$		99:1	61
17		Bu_3SnH		98:2	92
18		Bu_3SnH		94:6	83
19		$BnMe_2SiH$		66:34	72 [d]
20		Bu_3SnH		96:4	88
21		$BnMe_2SiH$		82:18	92
22		$(EtO)_3SiH$		82:18	81
23		Bu_3SnH		7:93	64
24		Bu_3SnH		96:4	83
25		$BnMe_2SiH$		66:34	78
26		Bu_3SnH		97:3	77 (R = H)
27		Bu_3SnH		98:2	72 R = C_5H_{11})
28		Bu_3SnH		99:1[e]	60[g]
29		$BnMe_2SiH$		90:10	53
30		Bu_3SnH		98:2	64
31		Bu_3SnH		99:1	55
32		Bu_3SnH		99:1	87[f]
33		Bu_3SnH		nd	55[h]

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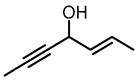
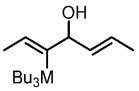
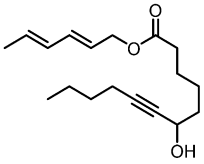
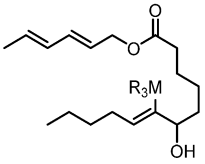
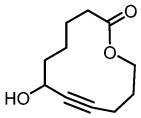
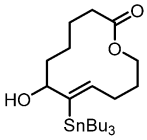
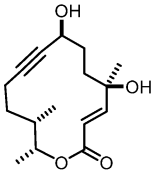
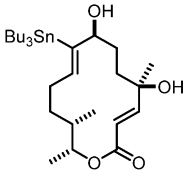
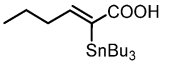
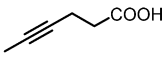
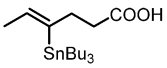
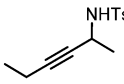
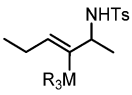
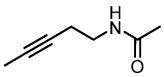
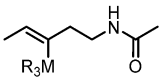
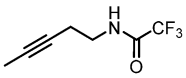
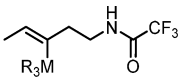
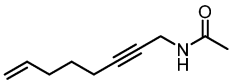
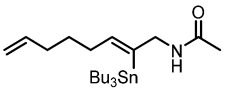
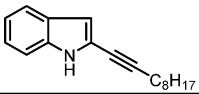
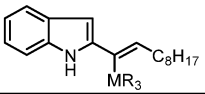
Table 7. continued

Entry	Substrate	Reagent	Major product	proximal:distal[b]	Yield (%)
34		Bu_3SnH		93:7	74
35		$BnMe_2SiH$		60:40	85
36		Bu_3SnH		96:4	37
37		$BnMe_2SiH$		83:17	59
38		Bu_3SnH		95:5	86
39		Bu_3SnH		99:1	83
40		Bu_3SnH		90:10	87
41		Bu_3SnH		93:7	87
42		Bu_3SnH		99:1	90
43		Et_3SiH		86:14	78
44		$BnMe_2SiH$		79:21	82
45		Bu_3SnH		87:13	98
46		$BnMe_2SiH$		52:48	86
47		Bu_3SnH		95:5	90
48		$BnMe_2SiH$		74:26	98
49		Bu_3SnH		89:11	93
50		Bu_3SnH		95:5	81
51		$BnMe_2SiH$		99:1	81

[a]All reactions were carried out with 1.05−1.2 equiv of R_3MH in the presence of either **3** or **4**, such that 5 mol % of Ru were present in the mixture; unless stated otherwise, the selectivity for *trans*-addition was ≥95:5 (major regioisomer). [b]"Proximal" denotes delivery of the R_3M group to the alkyne C atom next to the protic group, whereas "distal" refers to the more remote C atom. [c]ca. 17 mmol scale; in some batches, O-silylation was observed as a side reaction. [d]Crude mixture also contains the *cis*-addition products. [e]*Z*:*E* = 87:13 (major isomer). [f]5−7% of a distannylated product were detected. [g]Yield of the pure (*Z*)-isomer after flash chromatography. [h]Crude mixture contains traces of other isomers which were not assigned; nd = not determined.

and chronic toxicity of tin reagents,[60] although Bu_3SnH continues to dominate the field for its commercial availability.[13,61] At the same time, the data establish Me_3SnH as a valid probe with a simplified spectral footprint for mechanistic studies.

A few trends can be deduced from the results compiled in Table 7. First and foremost it is clear that the directing effect is general and powerful, thus allowing good to excellent levels of regiocontrol to be imposed upon basically all substrates investigated. The data show that the regioselectivity tends to be better for tertiary alcohols than for primary ones (compare entries 5 and 9). Furthermore, the *trans*-hydrostannation usually gives better selectivitites than the analogous *trans*-hydrosilylation. Qualitatively, the difference seems more pronounced whenever the directing group is further remote from the alkyne (compare entries 24/25) and/or when it is less acidic (compare entries 45/46). The reasons for these subtle differences are not clear at this point, but we recall that the inherent bias of the hydrosilylation for distal delivery is higher. In addition, one might speculate that the secondary interaction of the chloride ligand on ruthenium in the loaded complex **17** with the adjacent MR_3 group is stronger in the case of tin, which is softer and more amenable to formation of a transient pentavalent array.[62]

Two cases, however, were found in which the use of a silane was mandatory. Thus, the cyclopropanol derivative shown in entries 15 and 16 was well behaved when reacted with R_3SiH under standard conditions but decomposed with Bu_3SnH as the

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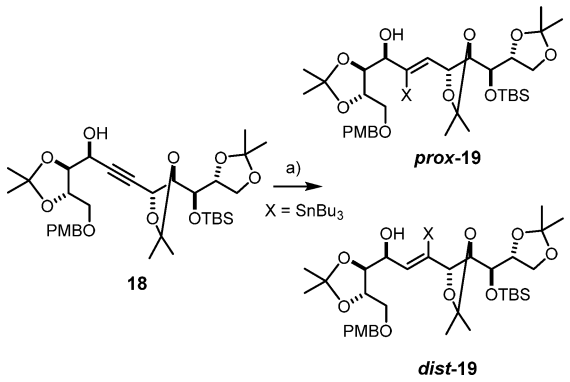
reagent.[63] Likewise, the parent propargyl alcohol performed better in the hydrosilylation manifold, in part for stability reasons (compare entries 1/2). The resulting product is a valuable silylated building block,[64] which is easily made by this new procedure on a multigram scale.

The only notable exception to the otherwise general regioselectivity pattern described herein is the C-silylated homopropargylic alcohol shown in entry 23; in this case, the steric and/or electronic bias of the silylated alkyne could not be outperformed.[3] Another important aspect relates to alkynes with propargylic oxygen substituents on either end, which tend to react unselectively; a representative example is compound **18**[65] shown in Scheme 2. In such cases, interaction of the −OH

Scheme 2[a]

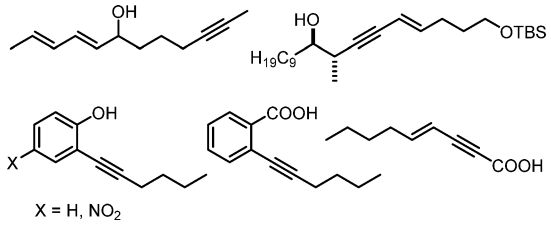


[a]Reagents and conditions: (a) Bu_3SnH, **4** (1.25 mol %), CH_2Cl_2, 69% (*prox*-**19**:*dist*-**19** = 38:62).

on one side with the chloride ligand might have to compete with coordination of the −OR group on the other end with the metal center.[23] This antagonism may well "confuse" the catalyst,[66] especially if steric factors reinforce the effects.

Table 7 deliberately shows a number of substrates that comprise more than one π-system. We had previously noted that even isolated alkenes can be a serious handicap for Ru-catalyzed *trans*-additions when working with the cationic complex **1** as the catalyst.[1−3] It was therefore gratifying to find that the use of **4** largely solves this problem (entries 26, 27, 34, 35, 39, 49). Likewise, we had previously pointed out[1−3,29] that the high affinity of a [Cp*Ru] fragment to (electron rich) arenes[67] as well as to 1,3-dienes[68] is potentially detrimental and can bring such reactions to a halt;[69] likewise, alkynes as part of an 1,3-enyne motif had basically failed to react, probably for the same reason. In view of these shortcomings, it is important to note that a hydroxyl group seems to exert a gentle "activating" effect on a triple bond in vicinity, as evident from the successful *trans*-hydrometalation of two different arylalkyne derivatives (entries 6/7 and 11), two 1,3-enynes (entries 28−30), or a 1,3-diyne (entry 31), all of which gave respectable results. Even a substrate presenting a sterically unhindered 1,3-diene to the catalyst in addition to the propargyl alcohol group was successfully transformed, albeit in only modest yield (entries 36/37). The emerging hydrogen bond between the −OH group and the [Ru−Cl] unit might favor productive binding of an adjacent alkyne and, in doing so, would help outperform coordination of competing donor sites. However, the examples compiled in Chart 1 show that the effect is not totally general; while the failure of the depicted diene-ol derivative fits the

Chart 1. Unreactive or Problematic Substrates



presented logic, the reasons for the inertness of the other shown substrates are less obvious.

The purported "activation" of an alkyne by an adjacent hydroxyl group also transpires from some competition experiments. Thus, substrates comprising a "regular" alkyne as well as a propargyl alcohol unit showed meaningful selectivity for reactions at the latter site (entires 31−33). The ability to distinguish between different π-systems (alkyne/alkene, alkyne/alkyne, alkyne/diene, alkyne/arene, etc.) is arguably an enabling attribute when it comes to applications of this methodology to polyfunctionalized targets.

Although the use of alcohols as directing/activating groups has prevailed in this study, they are by no means the only functionality able to exert a directing effect. As already mentioned in the Directed trans-Hydrosilylation section, carboxylic acids as well as amides, carbamates, and sulfonamides also fall into this category; as expected, their effect pertains to *trans*-hydrostannation as well (see entries 40−49). Even an alkynylated indole was transformed with excellent levels of regio- and stereoselectivity (entries 50/51). This remarkable result holds the promise that this methodology might become a valuable addendum to the repertoire of heterocyclic chemistry as well. Finally, we like to emphasize that cycloalkynes are also covered as long as the resulting *trans*-addition products are not overly strained (entries 38, 39).[70]

DISCUSSION

Spectroscopic, structural, and preparative data all concur in suggesting that the excellent levels of regioselectivity harnessed in *trans*-hydrosilylation, -germylation, or -stannylation reactions of unsymmetrical alkynes carrying nearby protic sites likely originate from interligand interactions rather than from direct coordination of the given functionality onto the catalytically active metal center itself. To this end, the catalyst must contain a [Ru−Cl] unit that serves as an effective hydrogen-bond acceptor. The resulting attractive force favors substrate binding, preorients the unsymmetrical alkyne within the coordination sphere of the catalyst, and probably enhances its electronic bias by polarization of the ligated triple bond, as deduced from the recorded NMR data. A complementary interligand contact between the chloride and the incoming stannane (silane, germane) might further assist the reaction by aligning the reagent in an electronically matching position within the ligand sphere of the nascent active catalyst. The resulting favorable array, as tentatively sketched in **17**, also explains why the reactions are usually fast; in particular, the *trans*-hydrostannations often proceed within minutes at ambient temperature even when carried out on a multigram scale.

Although the templating effect of [M−Cl] fragments has previously been exploited in supramolecular chemistry or crystal engineering and has received some attention in organometallic chemistry too,[33] it has not been advertised

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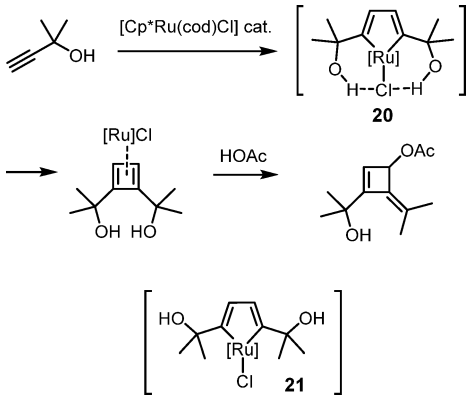
much as a general principle in the context of catalysis, though singular examples are manifest in the literature. In view of the foregoing, however, we are inclined to believe that interligand interactions of the kind discussed above may well be of considerable relevance in other settings too. To underpin this belief, we finish off by reassessing a few selected examples reported by other groups, which deliberately refer to chemistry that is mechanistically distinct from the hydrometalations discussed herein. We emphasize, however, that this discussion is solely based on published data and is therefore tentative; control experiments might be necessary to confirm or refute these views.

As alluded to above, complex **10** was inadvertently formed during attempts at obtaining single crystals of a putative π-complex of type **9** comprising an internal alkyne (Scheme 1). This finding echoes a comprehensive study on ruthenium-catalyzed [2 + 2] cycloadditions of propargyl alcohols containing a terminal triple bond.[30] Depending on the chosen conditions, the resulting products were engaged in further functionalizations as illustrated by the example shown in Scheme 3. In any case, the cycloadducts invariably result from

Scheme 3. Reassessment of a Ruthenium-Catalyzed Cycloaddition That Counterintuitively Leads to Head-to-Head Adducts;[72] [Ru] = Cp*Ru

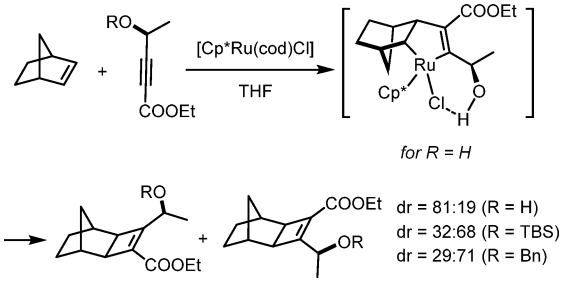


head-to-head coupling. While the authors depicted a metallacycle of type **21** as the reactive intermediate with the −OH groups pointing away from the core, we feel confident to explain the result by a tight hydrogen-bonding array of type **20**;[71] without such an enthalpically favorable interaction, it is not intuitive why the reaction would go against steric effects, since the *tert*-alcohol branches in the cycloadduct clash into each other.

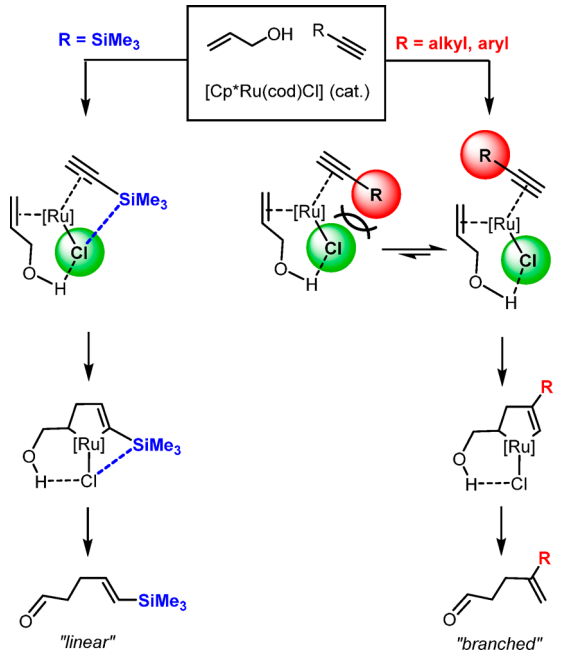
In line with this analysis, Tam and co-workers advocated a hydrogen-bonding array with a [Ru−Cl] unit to explain why acetylene carboxylates bearing an unprotected propargyl alcohol on the other alkyne terminus give the opposite diastereoselectivity than their protected congeners in ruthenium-catalyzed [2 + 2] cycloadditions with norbornene or related strained cycloalkenes (Scheme 4).[24] This proposal was backed up by extensive computations.

Yet another instructive case was reported by Dixneuf and co-workers, who found that allyl alcohol couples with terminal alkynes such that the "branched" rather than the "linear" adducts are favored when the reaction is catalyzed by [Cp*Ru(cod)Cl] in the absence of any extra solvent (Scheme 5).[72] Since our data suggest that the allyl alcohol will initially engage into hydrogen bonding, the formation of the branched

Scheme 4. Diasteroselective [2 + 2] Cycloaddition Benefiting from a Presumed Interligand Hydrogen-Bonded Transition State if R = H



Scheme 5. Interpretation of the Previously Unexplained Observation That Terminal Alkynes Couple with Allyl Alcohol in the Presence of 2 (cat.) to Give Branched Aldehydes Preferentially or Exclusively, Whereas TMS-Acetylene Favors the Linear Product; [Ru] = Cp*Ru



product demands that the substituent R be oriented away from the [Ru−Cl] motif, which is perfectly reasonable on steric grounds. The larger the R group, the higher the selectivity; in fact, *tert*-butylacetylene (R = CMe_3) furnished the branched product exclusively. However, as the only serious exception to this rule, the authors observed that the analogous alkyne with R = $SiMe_3$ favors the opposite outcome and gives the linear adduct with respectable selectivity (73:27). While this striking outlier had remained unexplained,[72] we surmise that the interaction with the chloride on the metal becomes attractive for R = $SiMe_3$, in analogy to the interligand contacts seen between the [Ru−Cl] bond and the tin or silicon moieties of complex **12a** and its relative [Cp*RuCl(iPr$_3$P)(σ-H−$SiCl_3$)] from the silicon series.[44]

More than one additional example from the rich catalytic chemistry of ruthenium seems to lend support for the notion that interligand hydrogen bonds are able to preorganize the reactants of a catalytic transformation.[73] As a final striking piece of evidence we refer to a report from Hoveyda and co-workers, who showed that the ring-opening/cross metathesis of strained

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cycloolefins massively gains in diastereoselectivity with unprotected allylic alcohols as the reaction partners; hydrogen bonding to the −OH group to the chloride ligands of the chosen Grubbs-type carbene catalyst was made accountable for the observed effect.[25]

CONCLUSION

trans-Hydrometalations of unsymmetrical alkynes endowed with protic functionality are distinguished by high levels of regioselectivity, provided they are catalyzed by ruthenium complexes comprising a chloride ligand. A host of spectral, structural, and preparative data suggests that the polarized [Ru−Cl] bond mediates peripheral contacts which result in an effective preorganization of the catalyst's ligand sphere. Hydrogen-bonding arrays between the substrate and the polarized [Ru−Cl] unit seem to be most important. This conclusion makes a compelling case for an organometallic reaction that provides inherently better results when applied to compounds comprising protic sites in unprotected rather than protected form. Moreover, the concept of controlling selectivity via interligand interactions may well apply to mechanistically distinct transformations too. The search for such effects and their use should obviously be extended beyond the realm of ruthenium, as chloride complexes of other catalytically relevant transition metals might obey similar principles for the preorganization of their cargo. Work along these lines is currently in progress in our laboratory.

ASSOCIATED CONTENT

Supporting Information

Experimental part including characterization data, copies of NMR spectra of new compounds, X-ray structure of complex [Cp*RuI(cod)], and supporting crystallographic information. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare the following competing financial interest(s): Patent application filed.

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