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Non-Pd transition metal-catalyzed hydrostannations: Bu_3SnF/PMHS as a tin hydride source

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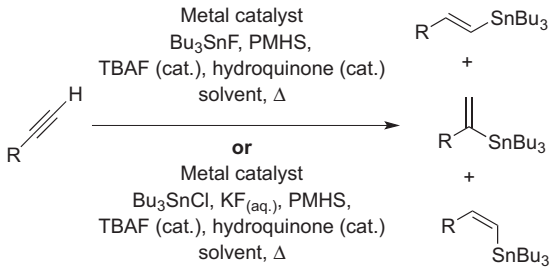
ABSTRACT

Molybdenum, cobalt, nickel, ruthenium, and rhodium catalyzed alkyne hydrostannations using in situ generated Bu_3SnH were studied. In most cases, Bu_3SnF+polymethylhydrosiloxane (PMHS) performed well as the in situ source of Bu_3SnH. In contrast, the combination of Bu_3SnCl/KF_{aq}/PMHS, which had witnessed earlier success in Pd-catalyzed hydrostannation reactions, proved less employable in alkyne hydrostannations mediated by these metals.

1. Introduction

Bu_3SnCl and polymethylhydrosiloxane (PMHS) in the presence of aqueous KF can serve as an in situ source of Bu_3SnH in conjunction with free radical or palladium catalyzed alkyne hydrostannations.[1] Quite recently, we demonstrated that Bu_3SnCl, PMHS, KF, and 18-crown-6 provide an efficient alternative to the aqueous protocols where terminal alkynes are efficiently hydrostannylated with in situ generated organotin hydride under nickel, cobalt, and molybdenum catalysts.[2] These protocols, which likely proceed through organotin fluoride intermediates,[3] help to minimize the cost, toxicity,[4,5] and storage issues commonly associated with using Bu_3SnH (or Bu_3SnCl) directly. We have also shown that the Bu_3SnF, PMHS, and catalytic quantities of tetrabutylammonium fluoride (TBAF) make for another efficient anhydrous version of this chemistry.[1] Pd-catalyzed hydrostannations employing both the Bu_3SnCl and Bu_3SnF methods for the in situ generation of Bu_3SnH have proven viable with a wide array of alkynes, affording comparable yields and regioselectivities to when Bu_3SnH is used directly.[1]

The Bu_3SnX/PMHS/fluoride mix is also mild enough to allow the vinylstannanes prepared in this way to be further reacted as part of various one-pot synthetic schemes. Most often, such one-pot processes have come in the form of hydrostannation/cross-coupling cascades, where both steps were catalyzed by palladium.[6,7] Of course, it is not hard to imagine employing the vinyltins in other in situ reactions that are mediated by metals other than palladium. To help build a foundation for such future studies, a survey of both the Bu_3SnCl/PMHS/KF and the Bu_3SnF/PMHS conditions against a variety of known hydrostannation catalysts was deemed worthwhile (Scheme 1).



Scheme 1. General reaction protocol.

2. Results and discussions

2.1. Molybdenum-catalyzed hydrostannations

We began our study by looking at Molybdenum-catalyzed hydrostannations. In 1990, Guibé and co-workers found $MoBr(allyl)(CO)_2(CH_3CN)_2$ suitable for the hydrostannation of propargylic

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alcohol derivatives, albeit with poor regioselectivity.[8] This problem was nicely solved by Kazmaier and co-workers when they established that catalysis by $Mo(CO)_3(CN^tBu)_3$ (a.k.a. $MoBI_3$) promoted the hydrostannations of variety of oxo-substituted alkynes with high selectivity for the proximal regioisomer.[9–11] Owing to the fact that the hetero-atoms present in their substrates likely played a directing role in these Mo-catalyzed reactions (vide infra), we were both curious and apprehensive as to how our aqueous KF/Bu_3SnCl/PMHS conditions would fare in $MoBI_3$-catalyzed hydrostannations. As Kazmaier recovered fully active $MoBI_3$ after column chromatography, we hoped $MoBI_3$'s robustness would bode well for our hydrostannations. Unfortunately, though not entirely unexpectedly, it did not, and no vinyltins were ever observed. Control experiments revealed water to be the offending element in these failures and no variation of reaction times, temperatures, substrates, concentrations or catalyst loads changed the outcome.

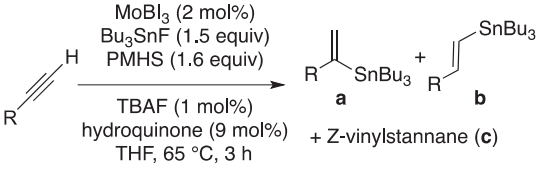
In contrast, switching to the anhydrous Bu_3SnF/PMHS conditions provided positive results. As shown in Table 1, a variety of alkynes were exposed to 1.5 equiv Bu_3SnF, 1.6 equiv PMHS, TBAF (1 mol %), and $MoBI_3$ (2 mol %) in THF (conditions A). Per Kazmaier's procedure, catalytic quantities of hydroquinone were added to suppress any free radical processes.[9–11] After heating the resulting mixtures at 60–65 °C, the corresponding vinylstannanes were obtained after 3 h. With some notable exceptions, the yields and regioselectivities generally mimicked those observed when the same substrates were hydrostannated with premade Bu_3SnH (conditions B). That said, the hydrostannations with in situ generated Bu_3SnH (conditions A) held certain advantages over standard protocols (conditions B). For example, the Bu_3SnF/PMHS reactions were typically completed in less time (3 versus 12 h) and could be run with half the amount of organotin used by Kazmaier.

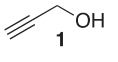
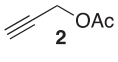
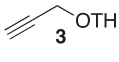
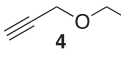
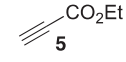
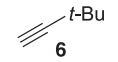
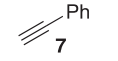
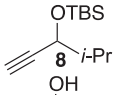
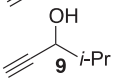
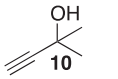
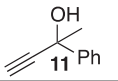
As mentioned above, a few substrates responded quite differently to the two sets of conditions. For example, ethyl propiolate (entry 5) gave the *Z*-stannane as the major product under conditions A, where as the internal isomer predominated under conditions B. The regiochemical results for this substrate were largely unchanged when the reaction was stopped at low conversion and with newly purchased hydroquinone. Thus this divergence of regiochemical outcomes does not appear to be a consequence of isomerization or adventitious free radicals under the Bu_3SnF/PMHS conditions. At this point the root cause of these contrasting results remains unclear. However, these by-products could be the result of β-hydride elimination followed by readdition–reductive elimination of the M–H species (Scheme 2).[12] It is interesting to note that, in our hands,[13] both ethyl propiolate and phenylacetylene afforded *Z*-products, suggesting that $MoBI_3$ catalyzed hydrostannations of conjugated alkynes may be prone to proceed through an admixture of mechanistic pathways.

We also took the opportunity to answer some global questions surrounding substrate scope and $MoBI_3$ catalysis. To the best of our knowledge, $MoBI_3$-catalyzed hydrostannations of alkynes bearing non-heteroatom containing substituents at the propargylic positions have not been previously described. When 3,3-dimethyl propyne (entry 6) was subjected to the reaction conditions A and B, the distal (*E*) vinylstannanes were the major products. As discussed earlier, reaction of phenylacetylene (entry 7) produced a mixture of proximal and distal (*E* and *Z*) isomers under conditions A and B with the *E* stannane being the major product under both the protocols. These results are inconsistent with Kazmaier's model for $MoBI_3$ catalyzed hydrostannations and again indicate a more complex mechanistic pathway(s).

Owing in part to the ethyl propiolate results, the hydrostannation of substituted alkynyl esters were also explored under our conditions (Table 2). While Kazmaier has reported[10] on the hydrostannation of disubstituted alkynes, none of his examples

Table 1
$MoBI_3$-catalyzed hydrostannations of terminal alkynes



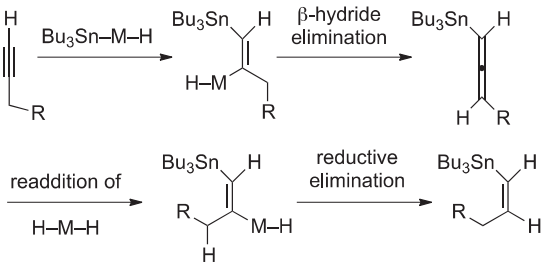
Entry	Alkyne	Yields[a] Bu_3SnF/PMHS (Conditions A)	Yields[a] Bu_3SnH (Conditions B)
1	 **1**	90% Int/E (5/1)	94%[b] Int/E (8.1/1) **17a/17b**
2	 **2**	75%[d] Int/E (18/1)	91%[b] Int/E (24/1) **18a/18b**
3	 **3**	85% Int/E (19/1)	98%[b] Int/E (>19/1) **19a/19b**
4	 **4**	43%[c] Int/E (10/1)	43%[b] Int/E (>19/1) **20a/20b**
5	 **5**	73%[c] Int/E/Z (1.1/1/4.9)	98% Int/E/Z (10/1/1.5) **21a/21b/21c**
6	 **6**	54%[c] Int/E (1/2.5)	93%[c] Int/E (1/2.1) **22a/22b**
7	 **7**	98%[c,d] Int/E/Z (1/3.9/1.5)	97%[c,d] Int/E/Z (1/4.5/2.3) **23a/23b/23c**
8	 **8**	49%[d] Int/E (2.9/1)	58% Int/E (1.4/1) **24a/24b**
9	 **9**	51%[d] Int/E (4.1/1)	86% Int/E (4/1) **25a/25b**
10	 **10**	79% Int/E (6/1)	81% Int/E (2.3/1) **26a/26b**
11	 **11**	92% Int/E (3.7/1)	99% Int/E (3/1) **27a/27b**

[a]Yields refer to spectroscopically pure products. Yields and isomeric ratios are averaged over two runs unless otherwise stated.

[b]Taken from Ref. 10.

[c]Yields and isomeric ratio are calculated from ^{1}H-NMR of crude samples using hexamethyldisiloxane as an internal standard.

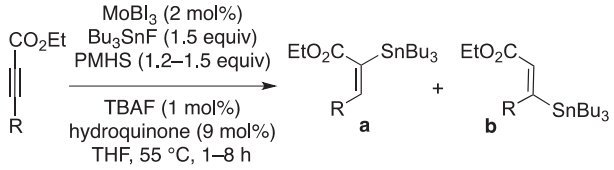
[d]Yields and isomeric ratio are averaged over three runs.



A generic mechanism for the formation of the internal and E isomers can be found in reference 12

Scheme 2. Possible mechanism of *Z*-isomer formation.

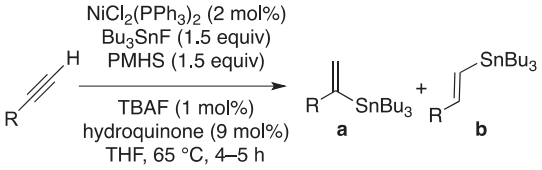
Table 2
$MoBI_3$-catalyzed hydrostannations of alkynyl esters



Entry	Alkyne R =	Time (h)	Yields[a] Bu3SnF/PMHS (Conditions C)	Yields[a] Bu3SnH (Conditions D)
1	–$(CH_2)_4$OTBS **12**	1	88% a/b (3.3/1) **28a/28b**	79% a/b (3.7/1)
2	–$(CH_2)_4$OH **13**	1	64% a/b (3.4/1) **29a/29b**	92% a/b (3.8/1)
3	–$(CH_2)_3$-C≡C-TMS **14**	8	79% a/b (2.5/1) **30a/30b**	67% a/b (2.8/1)

[a]Yields refer to spectroscopically pure products. Yield and isomeric ratio are averaged over two runs.

Table 3
$NiCl_2(PPh_3)_2$-catalyzed hydrostannation of terminal alkynes



Entry	Alkyne	Yields[a] Bu3SnF/PMHS (Conditions E)	Yields[a] Bu3SnH (Conditions F)
1	OH **1**	70% Int/E (2.4/1) **17a/17b**	59%[e] Int/E (4.3/1)
2	OTHP **3**	61% Int/E (1.7/1) **19a/19b**	49% Int/E (7.1/1)
3[b]	OH **15** Ph	86% Int/E (2/1) **31a/31b**	72%[e] Int/E (1.4/1)
4	OH **11** Ph	66% Int/E (1/1.8) **27a/27b**	47%[e] Int/E (1/4)
5	OTBS **16**	40% Int/E (2.3/1) **32a/32b**	52% Int/E (4/1)
6	*t*-Bu **6**	83% Int/E (1/22) **22a/22b**	100%[d] Int/E (1/4.3)
7	Ph **7**	83%[d] Int/E/Z (4.6/3.8/1) **23a/23b/23c**	80%[c] Int/E/Z (9/10/1)

[a]Yields refer to spectroscopically pure products. Yield and isomeric ratio are averaged over two runs unless otherwise stated.

[b]Trace amounts of *Z*-stannane were observed. For a mechanistic explanation see Ref. 12.

[c]Data taken from Ref. 16.

[d]Yield was calculated from ^{1}H-NMR of crude samples using hexamethyldisiloxane as an internal standard.

[e]Yield and isomeric ratio are averaged over three runs.

contained functionality on both alkyne substituents. For these substrates, the α and β hydrostannation products were determined by presence of a triplet and a singlet vinyl proton resonance, respectively. Using this method, we determined that hydrostannation preferentially occurred proximal to the ester and no *Z*-isomers were observed. Bu_3SnF/PMHS (conditions C) was comparable to Bu_3SnH (conditions D) in terms of isomeric product ratios and yields.[10,11] Stannane isomeric ratios were not affected by the presence of oxygen containing groups in the alkyl chain coming off the alkyne (Table 2, entries 1 and 2). These results complement higher order cuprate mediated stannyl metalations of alkynyl esters, which predominantly lead to formation of vinylstannanes distal to the ester.[14]

2.2. Nickel catalyzed hydrostannations

Driven by part by the ability of nickel to catalyze cross-couplings,[15] we next applied the conditions to hydrostannations catalyzed by $NiCl_2(PPh_3)_2$. With this catalyst, the Bu_3SnF/PMHS conditions again produced the corresponding vinylstannanes in moderate to good yields (Table 3, conditions E). Use of this catalyst in hydrostannation reactions was previously documented by Kikukawa in 1988.[16] Hydrostannation of the propargylic alcohols (entry 1 and 3) and their derivatives (entry 2 and 5) favored the proximal isomer. However, when the propargylic position was too sterically congested (entry 4) or the oxygen functionality at the propargylic position was removed (entry 6), the selectivity switched to favor the distal *E*-isomer. Ni-catalyzed hydrostannation of phenylacetylene also showed lack of selectivity in stannane formation. This result, however, is consistent with the reported hydrostannation of the same alkyne with premade Bu_3SnH (Conditions F, entry 7).[16] It is important to mention that in most cases, trace amounts of the *Z*-isomer were also observed.

2.3. Cobalt-catalyzed hydrostannations

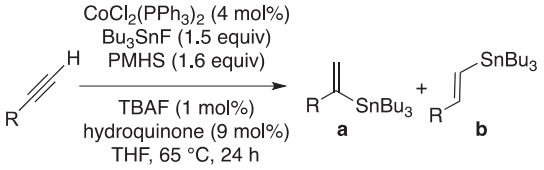
Next we looked at the use of $CoCl_2(PPh_3)_2$ first put forth by Kikukawa (Table 4).[16] Like the molybdenum and nickel catalysts, this Co-catalyst generally gave good results under our protocol with three functionally and sterically diverse alkynes. Unfortunately, consistency was not the hallmark of these reactions. While the cause of the inconsistency was not clear, it was easy to identify when a reaction was not progressing properly as in those instances the reaction would fail to produce its typical blue color.

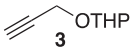
2.4. Rh- and Ru-catalyzed hydrostannations

Kikukawa and co-workers found that Rh complexes, especially $[RhCl(COD)]_2$, catalyzed the hydrostannations of terminal acetylenes to give the internal isomer regioselectively with good yields.[16] In contrast, under our methodology this catalyst behaved poorly (Table 5) producing trace amount of product with no detectable isomeric priority when THP propargylic ether was used. For the alkynes tested, utilization of $RhCl(CO)(PPh_3)_2$ produced mixtures of *E*- and internal vinylstannanes in variable yields with the Bu_3SnF/PMHS conditions affording modest selectivity for the *E*-vinylstannanes. The use of $RuCl_2(PPh_3)_4$ was attempted with little success and a complex mixture was obtained when THP propargylic ether was used as the substrate.

Finally, all the catalysts proved less effective under aqueous KF/Bu_3SnCl/PMHS conditions (Scheme 1). KF/Bu_3SnCl/PMHS reactions were either very slow, did not go at all, or generated irreproducible results with poor yields. However, as noted earlier, anhydrous Bu_3SnCl/KF/18-crown-6 conditions could be successfully employed in Ni, Co, and Mo catalyzed hydrostannations.[2]

Table 4
$CoCl_2(PPh_3)_2$-catalyzed hydrostannation of terminal alkynes



Entry	Alkyne	Yields[a]	
		Bu_3SnF/PMHS (Conditions G)	Bu_3SnH (Conditions H)
1	 **3**	65%[a,b] Int/E (1.5/1) **19a/19b**	84%[a,f] Int/E (1.3/1)
2	 **6**	91%[d,e] Int/E (1/99) **22a/22b**	100%[d,f] Int/E (1/5.3)[c]
3	 **7**	98%[b,d] Int/E/Z (2.1/2.7/1) **23a/23b/23c**	94%[b,d] Int/E/Z (1/3.7/2.6)

[a]Yields refer to spectroscopically pure products.

[b]Yields and isomeric ratios are averaged over three runs.

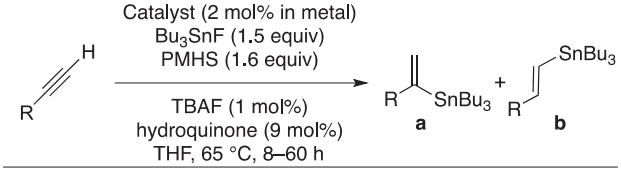
[c]Trace amounts of *Z*-isomer was observed.

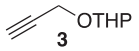
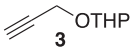
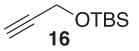
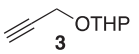
[d]Yields and isomeric ratio are calculated from ^{1}H-NMR of crude samples using hexamethyldisiloxane as an internal standard.

[e]Yields and isomeric ratios are averaged over two runs.

[f]Yield and isomeric ratio are based on a single run.

Table 5
Rh and Ru catalyzed hydrostannation of terminal alkynes



Entry	Alkyne	Catalyst[a]	Yields	
			Bu_3SnF/PMHS (Conditions I)	Bu_3SnH (Conditions J)
1	 **3**	I	trace	59%[b] Int/E (1.3/1)[b] **19a/19b**
2	 **3**	II	17%[b] Int/E (1/3.3)[b] **19a/19b**	75%[b] Int/E (1/1)[b]
3	 **16**	II	55%[b] Int/E (1/2.5)[b] **32a/32b/32c**	58%[b] Int/E (1/1)[b]
4	 **3**	III	complex mixture	20%[c] Int/E/Z (2.5/1.6/1)[c] **19a/19b/19c**

[a]Catalysts: $[RhCl(COD)]_2$ (**I**), $RhCl(CO)(PPh_3)_2$ (**II**), $RuCl_2(PPh_3)_4$ (**III**)

[b]Yields refer to spectroscopically pure products. Yields and isomeric ratios are averaged over two runs.

[c]Yields and isomeric ratios are based on a single run

3. Conclusion

We have demonstrated that the use of Bu_3SnF/PMHS serves as an effective in situ source of Bu_3SnH for transition metal-catalyzed hydrostannations. Our conditions allow the use of variety of alkynes to undergo transition metal-catalyzed hydrostannations. The use of $MoBI_3$ is useful for the formation of the proximal stannane isomer for a wide array of alkynes, as was demonstrated by Kazmaier. However, the ability of $MoBI_3$ to form proximal stannane isomers is compromised by increased steric bulk and/or conjugation.

4. Experimental section

4.1. General

Reactions were carried out in oven-dried pressure tubes or round-bottom flasks under nitrogen atmosphere unless otherwise noted. All commercial reagents were used without purification. Alkynes **1**, **2**, **3**, **5**, **6**, **7**, **9**, **10**, **11**, and **15** were purchased from Aldrich and GFS Chemicals and used as received. Alkynes **4**, **8**, **12**, **13**, **14**, and **16** were synthesized. $Mo(CO)_3(CN^tBu)_3$ ($MoBI_3$) was synthesized using known protocols.[17] Stannanes **24a**, **24b**, **28a**, **28b**, **29a**, **29b**, **30a**, and **30b** are novel and full spectroscopic characterization is provided. All other stannanes are known and their spectroscopic data were consistent with those previously reported. Although **25a** and **25b** have been reported in the literature,[21] details of their spectroscopic characterization have not and thus are reported herein. All solvents were reagent grades. THF was freshly distilled from sodium/benzophenone under nitrogen. Except as otherwise indicated, all reactions were magnetically stirred and monitored by thin layer chromatography. Column chromatography was performed with silica gel 60 Å (particle size 230–400 mesh ASTM). Yields refer to spectroscopically pure compounds unless otherwise stated.

*4.1.1. Preparation of 3-(prop-2-yn-1-yloxy)prop-1-ene (**4**) (Table 1).* The alcohol **1** (0.64 mL, 11 mmol) was added dropwise to a 50 mL round-bottom flask containing a cooled solution of sodium hydride (0.6 g, 25 mmol) in 20 mL of 10:1 ether/DMF solvent. This was stirred under inert atmosphere for 1 h, followed by dropwise addition of a solution of allyl bromide in ether (0.82 mL, 9.5 mmol in 5 mL ether). The resulting solution was kept at 0 °C for 5 h, before being quenched by 50 mL of brine. The layers were separated and the organic layer was then washed with 50 mL water and dried over $MgSO_4$. The resulting solution was then concentrated to alkyne **4** (402 mg, 38%). Spectroscopic data were consistent with literature reports.[18]

*4.1.2. Preparation of (4-methylpent-1-yn-3-yloxy)(tert-butyl)dimethylsilane (**8**) (Table 1).* To a dry 50 mL round-bottom flask was added methylene chloride (10 mL), TBSCl (0.829 g, 5.5 mmol), 4-methyl-1-pentyne-3-ol (**9**) (0.55 mL, 5 mmol), and triethylamine (0.84 mL, 6 mmol). The reaction mixture was stirred for 20 h until judged complete by TLC analysis. The resulting solution was rinsed with water (20 mL), 5% $HCl_{(aq)}$ (10 mL), water (10 mL), and 10% $NaHCO_{3(aq)}$ (10 mL) sequentially. The organic layer was then dried over $MgSO_4$ and concentrated to afford alkyne **8** as yellow oil (829 mg, 78% yield).

Data for **8**: IR (neat) 2978 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.03 (s, 3H), 0.03 (s, 3H), 0.85 (s, 9H), 0.94 (d, J=6.7 Hz, 3H), 0.96 (d, J=6.**7** Hz, 3H), 1.83 (m, 1H), 2.38 (m, 1H), 4.10 (dd, J=5.6, 2.1 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ −5.2, −4.6, 17.7, 17.9, 18.2, 25.8, 35.2, 68.1, 72.5, 84.5; HRMS (EI) m/z 155.0895 $[M-Bu]^+$; calcd for $C_8H_{15}OSi^+$ 155.0887.[19]

*4.1.3. Preparation of tert-butyldimethyl(prop-2-yn-1-yloxy)silane (**16**) (Table 3).* TBSCl (3.81 g, 25.3 mmol) was added to a 0 °C solution of propargyl alcohol (**1**) (1.29 g, 23 mmol), imidazole (1.88 g, 27.6 mmol), and DMAP (0.28 g, 2.3 mmol) in CH_2Cl_2 (125 mL). The reaction was stirred overnight at 0 °C and then poured into a saturated solution of NH_4Cl. The layers were separated. The organic phase was washed with saturated NH_4Cl (3×50 mL) and dried over

$MgSO_4$. Column chromatography [silica gel; hexane] afforded the desired alkyne (2.3 g, 59%). Spectroscopic data were consistent with literature reports.[20]

4.1.4. Representative procedure for $MoBI_3$-catalyzed hydrostannations with Bu_3SnF, catalytic TBAF, and PMHS (Table 1, conditions A). To a pressure tube were added THF (7 mL), alkyne (1 mmol), hydroquinone (10 mg, 9 mol %), Bu_3SnF (464 mg, 1.5 mmol), PMHS (0.1 mL, 1.6 mmol), $Mo(CO)_3(CN^tBu)_3$ ($MoBI_3$) (8.6 mg, 2 mol %), and TBAF (2 drops of a 1 M solution in THF, 1 mol %). The reaction was then heated in an oil bath at 60–65 °C until judged complete by TLC analysis. At that time, the reaction was concentrated; the crude product was analyzed by ^1H NMR to calculate isomeric ratios and then purified by column chromatography.

4.1.5. Representative procedure for $MoBI_3$-catalyzed hydrostannations of terminal alkynes with Bu_3SnH (Table 1, conditions B). The corresponding alkyne (1 mmol) was dissolved in THF (1 mL). Hydroquinone (10 mg, 9 mol %), and $Mo(CO)_3(CN^tBu)_3$ ($MoBI_3$) (4.3 mg, 1 mol %) were added. The mixture was warmed to 55–60 °C before Bu_3SnH (0.8 mL, 3 mmol) was added. The solution was stirred at this temperature for 12 h. After evaporation of the solvent, the crude product was analyzed by ^1H NMR to calculate isomeric ratios and then purified by column chromatography.

*4.1.5.1. Preparation of **17a**/**17b** (Table 1, entry 1).* Applying conditions A to propargyl alcohol (**1**) (56 mg, 1 mmol) for 3.5 h afforded **17a** and **17b** (5:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 90/10 hexane/EtOAc, 1% TEA] to afford a separable mixture of the isomers **17a** and **17b** as clear oils (312 mg, 90%). Spectroscopic data were consistent with literature reports.[21]

*4.1.5.2. Preparation of **18a**/**18b** (Table 1, entry 2).* Applying conditions A to alkyne **2** (98 mg, 1 mmol) for 4 h afforded **18a** and **18b** (17:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 98/2 hexane/EtOAc, 1% TEA] to afford a mixture of the isomers **18a** and **18b** as clear oils (233 mg, 60%). Spectroscopic data were consistent with literature reports.[10]

*4.1.5.3. Preparation of **19a**/**19b** (Table 1, entry 3).* Applying conditions A to alkyne **3** (140 mg, 1 mmol) for 4 h afforded **19a** and **19b** (19:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 98/2 hexane/EtOAc, 1% TEA] to afford a partially separable mixture of the isomers **19a** and **19b** as clear oils (366 mg, 85%). Spectroscopic data were consistent with literature reports.[10]

*4.1.5.4. Preparation of **20a**/**20b** (Table 1, entry 4).* Applying conditions A to alkyne **4** (96 mg, 1 mmol) for 4 h afforded **20a** and **20b** (10:1). By analysis of the crude reaction by ^1H NMR with hexamethyldisiloxane as an internal standard the yield was determined to be 40%. Spectroscopic data were consistent with literature reports.[10]

*4.1.5.5. Preparation of **21a**/**21b**/**21c** (Table 1, entry 5).* Applying conditions A to alkyne **5** (98 mg, 1 mmol) for 5 h afforded **21a**, **21b**, and **21c** (1:1:5). By analysis of the crude reaction by ^1H NMR with hexamethyldisiloxane as an internal standard the yield was determined to be 75%.

Applying conditions B to alkyne **5** (98 mg, 1 mmol) afforded, after 12 h, **21a**, **21b**, and **21c** (10:1:1.5). By analysis of the crude reaction by ^1H NMR with hexamethyldisiloxane as an internal standard the yield was determined to be 98%. Spectroscopic data were consistent with literature reports.[10,22]

*4.1.5.6. Preparation of **22a**/**22b** (Table 1, entry 6).* Applying conditions A to alkyne **6** (82 mg, 1 mmol) afforded, after 3 h, **22a** and **22b** (1:2.5). By analysis of the crude reaction by ^1H NMR with hexamethyldisiloxane as an internal standard the yield was determined to be 54%.

Applying conditions B to alkyne **6** (82 mg, 1 mmol) afforded, after 12 h, **22a** and **22b** (1:2.1). By analysis of the crude reaction by ^1H NMR with hexamethyldisiloxane as an internal standard the yield was determined to be 96%.[1,23]

*4.1.5.7. Preparation of **23a**/**23b**/**23c** (Table 1, entry 7).* Applying conditions A to alkyne **7** (102 mg, 1 mmol) afforded, after 3 h, **23a**, **23b**, and **23c** (1:5:2). By analysis of the crude reaction by ^1H NMR with hexamethyldisiloxane as an internal standard the yield was determined to be 99%.[21,24]

Applying conditions B to alkyne **7** (102 mg, 1 mmol) afforded, after 12 h, **23a**, **23b**, and **23c** (1:3.5:2). By analysis of the crude reaction by ^1H NMR with hexamethyldisiloxane as an internal standard the yield was determined to be 96%.

*4.1.5.8. Preparation of **24a**/**24b** (Table 1, entry 8).* Applying conditions A to alkyne **8** (212 mg, 1 mmol) for 3 h afforded **24a** and **24b** (2.9:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; hexane, 1% TEA] to afford **24a** and **24b** as oils (267 mg, 53%).

Applying conditions B to alkyne **8** (212 mg, 1 mmol) for 12 h afforded **24a** and **24b** (1.2:1). The crude reaction was concentrated and subjected to column chromatography [silica gel; hexane, 1% TEA] to afford **24a** and **24b** as (287 mg, 57%).

Note: **24a** fractions always had hexabutyldistannane impurity. Yield of **24a** was calculated from ^1H NMR of the fraction containing **24a** using hexamethyldisiloxane as an internal standard.

Data for **24a**: IR (neat) 2964 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 0.00 (s, 6H), 0.81–0.93 (m, 30H), 1.22–1.37 (m, 6H), 1.39–1.55 (m, 7H), 3.73 (d, J=6.9 Hz, 1H), 5.16 (m, 1H), 5.69 (m, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ −4.7, −3.8, 10.3, 13.7, 18.3, 19.8, 26.1, 27.5, 29.1, 33.9, 85.8, 124.8, 158.4; HRMS (EI) m/z 447.2109 $[M-Bu]^+$; calcd for $C_{20}H_{43}OSiSn^+$ 447.2100. Data for **24b**: IR (neat) 2939 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 0.00 (d, J=8.9 Hz, 6H), 0.79–0.92 (m, 30H), 1.21–1.35 (m, 6H), 1.41–1.54 (m, 6H), 1.54–1.68 (m, 1H), 3.73 (t, J=5.7 Hz, 1H), 5.78–6.08 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ −4.9, −4.2, 9.5, 13.7, 18.0, 18.5, 25.9, 27.3, 29.2, 34.4, 81.9, 127.7, 150.5; HRMS (EI) m/z 447.2099 $[M-Bu]^+$; calcd for $C_{20}H_{43}OSiSn^+$ 447.2100.

*4.1.5.9. Preparation of **25a**/**25b** (Table 1, entry 9).* Applying conditions A to alkyne **9** (98 mg, 1 mmol) for 5 h afforded **25a** and **25b** (3.7:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 95/5 hexane/EtOAc, 1% TEA] to afford a separable mixture of the isomers **25a** and **25b** as clear oils (155 mg, 40%).

Applying conditions B to alkyne **9** (98 mg, 1 mmol) for 12 h afforded **25a** and **25b** (4:1). The crude reaction was concentrated and subjected to column chromatography [silica gel; 95/5 hexane/EtOAc, 1% TEA] to afford a separable mixture of the isomers **25a** and **25b** as clear oils (327 mg, 84%). Spectroscopic data were consistent with literature reports.[21]

Data for **25a**: IR (neat) 3483 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 0.82–0.94 (m, 21H), 1.24–1.36 (m, 6H), 1.40–1.64 (m, 7H), 3.71–3.91 (m, 1H), 5.13–5.35 (m, 1H), 5.52–5.98 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 10.2, 13.7, 17.5,19.8, 27.4, 29.1, 33.2, 85.0, 124.8, 158.4; HRMS (EI) m/z 333.1237 $[M-Bu]^+$; calcd for $C_{14}H_{29}OSn^+$ 333.1235.

Data for **25b**: IR (neat) 3356 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 0.76–0.98 (m, 21H), 1.21–1.36 (m, 6H), 1.41–1.55 (m, 6H), 1.65–1.79 (m, 1H), 3.77–3.86 (m, 1H), 5.89–6.20 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 9.5, 13.7, 17.7, 18.2, 27.2, 29.1, 33.5, 80.5, 128.7,

149.4; HRMS (EI) *m/z* 333.1245 $[M-Bu]^+$; calcd for $C_{14}H_{29}OSn^+$ 333.1235.

*4.1.5.10. Preparation of **26a/26b** (Table 1, entry 10).* Applying conditions A to alkyne **10** (84 mg, 1 mmol) for 3 h afforded **26a** and **26b** (6:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 95/5 hexane/EtOAc, 1% TEA] to afford a separable mixture of the isomers **26a** and **26b** as clear oils (286 mg, 76%).

Applying conditions B to alkyne **10** (84 mg, 1 mmol) for 12 h afforded **26a** and **26b** (2.3:1). The crude reaction was concentrated and subjected to column chromatography [silica gel; 95/5 hexane/EtOAc, 1% TEA] to afford a separable mixture of the isomers **26a** and **26b** as clear oils (293 mg, 78%). Spectroscopic data was consistent with literature reports.[8]

*4.1.5.11. Preparation of **27a/27b** (Table 1, entry 11).* Applying conditions A to alkyne **11** (146 mg, 1 mmol) for 3 h afforded **27a** and **27b** (3.6:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 95/5 hexane/EtOAc, 1% TEA] to afford a separable mixture of the isomers **27a** and **27b** as clear oils (415 mg, 95%).

Applying conditions B to alkyne **11** (146 mg, 1 mmol) for 12 h afforded **27a** and **27b** (2.8:1). The crude reaction was concentrated and subjected to column chromatography [silica gel; 95/5 hexane/EtOAc, 1% TEA] to afford a separable mixture of the isomers **27a** and **27b** as clear oils (431 mg, 99%). Spectroscopic data were consistent with literature reports.[1,2]

*4.1.5.12. Preparation of **28a/28b** (Table 2, entry 1).* TBSCl (50.5 g, 335 mmol) was added in small portions to a 0 °C solution of 5-hexyn-1-ol (34.0 mL, 305 mmol) in CH_2Cl_2 (500 mL) containing TEA (51.0 mL, 366 mmol) and DMAP (3.7 g, 30.5 mmol). The solution was stirred for 20 min and then allowed to warm to room temperature while stirring. The reaction mixture was poured into a saturated $NH_4Cl_{(aq)}$ solution and the layers were separated. The organic phase was washed with $NH_4Cl_{(aq)}$ and the combined aqueous layers were extracted with ether. The combined organics were dried over $MgSO_4$, filtered, and concentrated. The crude product was subjected to column chromatography [silica gel; 90/10 hexane/EtOAc] to afford 64.3 g (100%) of *tert*-butyl(hex-5-ynyloxy) dimethylsilane. Spectroscopic data were consistent with literature reports.[25]

A solution of *n*-BuLi (100 mL, 1.6 M in THF, 160 mmol) was added to a −78 °C THF (400 mL) solution of *tert*-butyl(hex-5-yn-1-yloxy) dimethylsilane (28.32 g, 133.3 mmol) under N_2. The resulting mixture was stirred for 30 min. Ethyl chloroformate (15.3 mL, 160 mmol) was added. After stirring for 1 h at −78 °C, the reaction was quenched with saturated $NH_4Cl_{(aq)}$ and extracted with EtOAc. The combined organic layers were dried over $MgSO_4$, filtered, and concentrated to afford the crude product. Purification by column chromatography [silica gel; hexanes/EtOAc 90/10] resulted in 46.3 g (61% yield) of the ester **12**. Spectroscopic data were consistent with literature reports.[25]

Data for **12**: IR (neat) 2238, 1717, 1076, 839 cm^{-1}, ^1H NMR (300 MHz, $CDCl_3$) δ −0.01 (s, 6H), 0.85 (s, 9H), 1.26 (t, *J*=7.1 Hz, 3H), 1.60 (m, 4H), 2.33 (t, *J*=6.8 Hz, 2H), 3.59 (t, *J*=5.7 Hz, 2H), 4.17 (q, *J*=7.2 Hz, 2H). ^{13}C NMR (75 MHz, $CDCl_3$) δ −5.4, 14.0, 18.3, 18.4, 24.1, 25.9, 31.7, 61.7, 62.3, 73.2, 89.1, 153.8.

Applying conditions C, alkyne **12** (500 mg, 1.76 mmol), hydroquinone (18 mg, 9 mol %), and $MoBI_3$ (15.1 mg, 2 mol %) were dissolved in THF (1.76 mL) in a pressure tube. Bu_3SnF (817 mg, 2.64 mmol) was added to the solution followed by PMHS (0.16 mL, 2.64 mmol). The tube was sealed and the solution was heated to 55 °C. The reaction was complete in 1 h and then concentrated to afford **28a** and **28b** (3.3:1), which were then purified by column chromatography [silica gel; hexanes/EtOAc 90/10] to afford a partially separable mixture of the stannanes **28a** and **28b** (894 mg, 88%).

Applying conditions D, alkyne **12** (285 mg, 1 mmol), hydroquinone (10 mg, 9 mol %), and $MoBI_3$ (8.6 mg, 2 mol %) were dissolved in THF (1 mL) in a pressure tube. The Bu_3SnH (0.8 mL, 3 mmol) was added to the solution dropwise. The tube was sealed and the solution was heated to 55 °C to afford **28a** and **28b** (3.7:1). When complete as judged by TLC, the reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 90/10 hexane/EtOAc, 1% TEA] to afford a partially separable mixture of the isomers **28a** and **28b** as clear oils (436 mg, 76%).

Data for **28a**: IR (neat) 2956, 1700 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 0.02 (s, 6H), 0.81–0.94 (m, 21H), 1.22–1.35 (m, 10H), 1.42–1.55 (m, 12H), 2.41 (q, *J*=6.0 Hz, 2H), 3.58 (t, *J*=6.0 Hz, 2H), 4.11 (q, *J*=7.1 Hz, 2H), 6.00 (tt, *J*=30.2, 7.1 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ −5.3, 10.2, 13.7, 14.4, 18.3, 25.5, 25.9, 27.3, 28.9, 31.7, 32.4, 59.9, 63.0, 135.8, 153.3, 171.2; HRMS (EI) *m/z* 577.3092 $[M+H]^+$; calcd for $C_{27}H_{57}O_3SiSn^+$ 577.3093.

Data for **28b**: IR (neat) 2962, 1716 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 0.01 (s, 6H), 0.81–0.98 (m, 21H), 1.20–1.35 (m, 12H), 1.38–1.60 (m, 10H), 2.85 (t, *J*=7.7 Hz, 2H), 3.59 (t, *J*=6.3 Hz, 2H), 4.12 (q, *J*=7.1 Hz, 2H), 5.90 (s, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ −5.3, 9.9, 13.7, 14.3, 18.3, 26.0, 27.5, 29.0, 30.6, 33.0, 35.1, 59.6, 63.1, 127.7, 164.2, 173.9; HRMS (ESI) *m/z* 577.3228 $[M+H]^+$; calcd for $C_{27}H_{57}O_3SiSn^+$ 577.3093.

*4.1.5.13. Preparation of **29a/29b** (Table 2, entry 2).* Silyl ether **12** (0.15 g, 0.53 mmol) was stirred in MeOH (1 mL) overnight with Amberlyst-15 (0.15 g). The reaction mixture was filtered through Celite, concentrated, and subjected to column chromatography [silica gel; hexanes/EtOAc 80/20] to afford 65 mg (72%) of the alcohol **13**.

Data for **13**: IR (neat) 3405, 1701 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 1.26 (m, 3H), 1.65 (m, 5H), 2.35 (m, 2H), 3.63 (m, 2H), 4.17 (q, *J*=7.1 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.0, 18.4, 23.8, 31.6, 61.8, 62.0, 73.4, 88.9, 153.8.

Applying conditions C, alkyne **13** (2.00 g, 11.75 mmol), hydroquinone (118 mg, 9 mol %), and $MoBI_3$ (100 mg, 2 mol %) were dissolved in THF (11.75 mL) in a pressure tube. Bu_3SnF (5.44 g, 17.6 mmol) was added to the solution followed by PMHS (1.05 mL, 17.6 mmol). The tube was sealed and the solution was heated to 55 °C. The reaction was complete in 1 h and concentrated. The crude product **29a** and **29b** (3.4:1) was purified by column chromatography [silica gel; hexanes/EtOAc 80/20] to afford the stannanes **29a** and **29b** (3.50 g, 64%).

Applying conditions D, the alkyne **13** (170 mg, 1 mmol), hydroquinone (10 mg, 9 mol %), and $MoBI_3$ (8.6 mg, 2 mol %) were dissolved in THF (1 mL) in a pressure tube. The Bu_3SnH (0.8 mL, 3 mmol) was added to the solution dropwise. The tube was sealed and the solution was heated to 55 °C. When the reaction was judged complete by TLC it was concentrated. The crude product **29a** and **29b** (4.3:1) was purified by column chromatography [silica gel; hexanes/EtOAc 80/20] to afford the stannanes **29a** and **29b** (423 mg, 92%).

Data for **29a**: IR (neat) 3418, 2962, 1714 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 0.78–1.02 (m, 15H), 1.20–1.34 (m, 9H), 1.38–1.62 (m, 10H), 2.42 (q, *J*=7.1 Hz, 2H), 3.54 (t, *J*=6.6 Hz, 2H), 4.12 (q, *J*=7.1 Hz, 2H), 5.96 (tt, *J*=30.8, 7.1 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 10.2, 13.7, 14.4, 25.3, 27.2, 28.9, 31.6, 32.1, 60.0, 62.5, 136.0, 153.1, 171.2; HRMS (ESI) *m/z* 463.2231 $[M+H]^+$; calcd for $C_{21}H_{43}O_3Sn^+$ 463.2229.

Data for **29b**: IR (neat) 3455, 2956, 1714 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 0.81–1.06 (m, 15H), 1.21–1.36 (m, 9H), 1.40–1.53 (m, 8H), 1.54–1.65 (m, 2H), 1.91 (br s, 1H), 2.83 (t, *J*=7.7 Hz, 2H), 3.67 (q, *J*=6.6 Hz, 2H), 4.12 (q, *J*=7.1 Hz, 2H), 5.91 (t, *J*=32.5 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 9.8, 13.6, 14.3, 25.3, 27.3, 28.9, 32.1, 34.4, 59.7, 62.0, 127.7, 164.2, 174.3; HRMS (ESI) *m/z* 463.2233 $[M+H]^+$; calcd for $C_{21}H_{43}O_3Sn^+$ 463.2229.

*4.1.5.14. Preparation of **30a**/**30b** (Table 2, entry 3).* To a −78 °C solution of 5-hexyn-1-ol (7.43 mL, 66.7 mmol) in dry THF (200 mL) was added *n*-BuLi in hexanes (100 mL, 60 mmol). After 1 h, TMSCl (42.3 mL, 333.3 mmol) was added and stirred for 30 min and then at room temperature for 12 h. 10% HCl (55 mL) was added and stirred for 1 h, after neutralization with saturated $NaHCO_{3(aq)}$ the mixture was extracted with ethyl acetate. The solution was washed with water, dried, filtered, and concentrated. The residue was passed through a short plug of silica with 3/1 hexanes/ethyl acetate and concentrated. To a 0 °C solution of this TMS-5-hexyn-1-ol in dry CH_2Cl_2 (300 mL) was added DMSO (15.14 mL, 213.3 mmol), triethylamine (29.73 mL, 213.3 mL), and $SO_3 \cdot$ pyr (31.8 g, 200 mmol). After stirring at room temperature for 2.5 h the reaction was quenched with $NH_4Cl_{(aq)}$ and the mixture was extracted with CH_2Cl_2, washed with water, dried, filtered, and concentrated. The crude was purified by column chromatography [silica gel; 90/10 hexane/EtOAc] to afford 6-trimethylsilylhex-5-ynal (8.93 g, 71%). Spectroscopic data were consistent with literature reports.[26]

Data for 6-trimenthylsilylhex-5-ynal: ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.11 (s, 9H), 1.81 (quint, J=7.1 Hz, 2H), 2.27 (t, J=6.9 Hz, 2H), 2.55 (t, J=6.0 Hz, 2H), 9.78 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ −0.3, 18.8, 20.6, 42.3, 85.4, 105.5, 201.4.

A flask was charged with Zn dust (5.44 g, 83.2 mmol), PPh_3 (21.82 g, 83.2 mmol), CBr_4 (27.58 g, 83.2 mmol), and CH_2Cl_2 (300 mL). The resulting suspension was stirred at room temperature overnight. To this solution was added a solution of the 6-(trimethylsilyl)hex-5-ynal (6.88 g, 40.9 mmol) in CH_2Cl_2 (100 mL). After stirring it at room temperature for 8 h, the mixture was diluted with hexanes (1 L) and filtered to remove the insoluble material. The filtrate was concentrated and purified by column chromatography [silica gel; hexanes/EtOAc 95/5] to remove any residual aldehyde and to afford the impure dibromide intermediate that was taken forward without further purification.

The impure dibromide (9.91 g) was dissolved in THF (110 mL). After cooling to −78 °C, a solution of *n*-BuLi (44 mL, 70.3 mmol, 1.6 M in THF) was added to it. The reaction was stirred at −78 °C for 1 h then room temperature for 1 h. After the addition of ethyl chloroformate (7.9 mL, 82.6 mmol) the reaction was stirred overnight at room temperature. The reaction was quenched with saturated $NH_4Cl_{(aq)}$ solution and extracted with diethyl ether (3×150 mL). The combined organics were washed with brine and dried over Na_2SO_4. After filtration and concentration, the crude product was subjected to column chromatography [silica gel; hexanes/EtOAc 98/2] to afford 6.44 g (89%) of the ester **14**.

Data for **14**: IR (neat) 1711 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.10 (s, 9H), 1.26 (t, J=7.1 Hz, 3H), 1.74 (q, J=7.1 Hz, 2H), 2.31 (t, J=7.1 Hz, 2H), 2.42 (t, J=7.1 Hz, 2H), 4.17 (q, J=7.1 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 0.0, 14.0, 17.6, 19.0, 26.5, 61.8, 73.5, 85.6, 88.1, 105.3, 153.6.

Applying conditions C, ester **14** (140 mg, 0.5 mmol), hydroquinone (4.6 mg, 8 mol %), and $MoBI_3$ (4.3 mg, 2 mol %) were dissolved in THF (1.5 mL) in a pressure tube. Bu_3SnF (211 mg, 0.65 mmol) was added to the solution followed by PMHS (0.04 mL, 0.65 mmol). The tube was sealed and the solution was heated to 55 °C. The reaction was complete in 8 h and concentrated. Crude products **30a** and **30b** (2.8:1) were purified by column chromatography [silica gel; hexanes/EtOAc 95/5] to afford 229 mg (87%) of the stannanes.

Applying conditions D, ester **14** (236 mg, 1 mmol), hydroquinone (10 mg, 9 mol %), and $MoBI_3$ (86 mg, 2 mol %) were dissolved in THF (3 mL) in a pressure tube. Bu_3SnH (0.35 mL, 1.3 mmol) was added to the solution dropwise. The tube was sealed and the solution was heated to 55 °C. After the reaction was judged complete by TLC, it was concentrated. Crude products **30a** and **30b** (2:1) were subjected to column chromatography [silica gel; hexanes/EtOAc 90/10] to afford 352 mg (67% yield) of inseparable mixture of the stannanes. Individual ^{1}H and ^{13}C NMR data were extracted from spectra obtained on the mixture.

Data for **30a**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.11 (s, 9H), 0.81–0.99 (m, 15H), 1.20–1.36 (m, 11H), 1.39–1.52 (m, 6H), 2.20 (m, 2H), 2.46 (m, 2H), 4.11 (q, J=7.1 Hz, 2H), 5.97 (t, J=7.1 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 0.1, 10.3, 13.7, 14.4, 19.5, 27.2, 28.4, 28.9, 31.3, 60.0, 84.6, 107.0, 136.9, 151.6, 171.1.

Data for **30b**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.11 (s, 9H), 0.81–0.99 (m, 15H), 1.20–1.36 (m, 11H), 1.39–1.52 (m, 6H), 2.20 (m, 2H), 2.90 (m, 2H), 4.11 (q, J=7.1 Hz, 2H), 5.91 (s, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 0.1, 9.9, 13.6, 14.3, 20.0, 27.3, 28.4, 29.0, 34.6, 59.6, 84.5, 120.1, 128.4, 164.0, 172.7.

IR and MS analyses were performed on the mixture of **30a** and **30b**. IR (neat) 2176, 1717, 844 cm^{-1}. MS (EI) m/z 471.2 $[M-Bu]^+$; calcd for $C_{21}H_{39}O_2SiSn^+$ 471.2.

4.1.6. Representative procedure for Ni-catalyzed hydrostannations with Bu_3SnF, catalytic TBAF, and PMHS (conditions E). To a sealed tube were added THF (7 mL), alkyne (1 mmol), hydroquinone (10 mg, 9 mol %), Bu_3SnF (464 mg, 1.5 mmol), PMHS (0.09 mL, 1.5 mmol), $NiCl_2(PPh_3)_2$ (13 mg, 2 mol %), and TBAF (2 drops of a 1 M solution in THF, 1 mol %). The mixture was then heated in an oil bath at 65 °C until complete by TLC analysis (~4–5 h). Once complete, the reaction mixture was concentrated; the crude was passed through a short plug of silica to remove the catalyst and analyzed by ^{1}H NMR. Unless otherwise stated, the products were purified by column chromatography.

4.1.7. Representative procedure for Ni-catalyzed hydrostannations with Bu_3SnH (conditions F). The corresponding alkyne (1 mmol) was dissolved in THF (1 mL). Hydroquinone (10 mg, 9 mol %), and $NiCl_2(PPh_3)_2$ (13 mg, 2 mol %), and Bu_3SnH (0.4 mL, 1.5 mmol) were added. The reaction was stirred at 65 °C for a further 4–5 h until judged complete by TLC analysis. After evaporation of the solvent, the crude product was analyzed by ^{1}H NMR. Unless otherwise stated, the products were purified by column chromatography.

*4.1.7.1. Preparation of **17a**/**17b** (Table 3, entry 1).* Applying conditions E to propargyl alcohol (**1**) (56 mg, 1 mmol) for 4 h afforded **17a** and **17b** (2.4:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 90/10 hexane/EtOAc, 1% TEA] to afford a separable mixture of the isomers **17a** and **17b** as clear oils (232 mg, 67%).

Applying conditions F to propargyl alcohol (**1**) (56 mg, 1 mmol) for 4 h afforded **17a** and **17b** (4.1:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 90/10 hexane/EtOAc, 1% TEA] to afford a separable mixture of the isomers **17a** and **17b** as clear oils (208 mg, 60%). Spectroscopic data were consistent with literature reports.[21]

*4.1.7.2. Preparation of **19a**/**19b** (Table 3, entry 2).* Applying conditions E to alkyne **3** (140 mg, 1 mmol) for 4 h afforded **19a** and **19b** (1.6:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 98/2 hexane/EtOAc, 1% TEA] to afford a partially separable mixture of the isomers **19a** and **19b** as clear oils (282 mg, 65%).

Applying conditions F to alkyne **3** (140 mg, 1 mmol) for 4 h afforded **19a** and **19b** (7:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 98/2 hexane/EtOAc, 1% TEA] to afford a partially separable mixture of the isomers **19a** and **19b** as clear oils (210 mg, 49%). Spectroscopic data were consistent with literature reports.[10]

*4.1.7.3. Preparation of **31a**/**31b** (Table 3, entry 3).* Applying conditions E to alkyne **15** (132 mg, 1 mmol) for 5 h afforded **31a** and

31b (1.8:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 95/5 hexane/EtOAc, 1% TEA] to afford a separable mixture of the isomers **31a** and **31b** as clear oils (368 mg, 87%).

Applying conditions F to alkyne **15** (132 mg, 1 mmol) for 5 h afforded **31a** and **31b** (1.3:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 95/5 hexane/EtOAc, 1% TEA] to afford a separable mixture of the isomers **31a** and **31b** as clear oils (294 mg, 69%). Spectroscopic data were consistent with literature reports.[21]

*4.1.7.4. Preparation of **27a**/**27b** (Table 3, entry 4).* Applying conditions E to alkyne **11** (146 mg, 1 mmol) for 5 h afforded **27a** and **27b** (1:1.8). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 95/5 hexane/EtOAc, 1% TEA] to afford a separable mixture of the isomers **27a** and **27b** as clear oils (311 mg, 71%).

Applying conditions F to alkyne **11** (146 mg, 1 mmol) for 5 h afforded **27a** and **27b** (1:3.4). The crude reaction was concentrated and subjected to column chromatography [silica gel; 95/5 hexane/EtOAc, 1% TEA] to afford a separable mixture of the isomers **27a** and **27b** as clear oils (202 mg, 46%). Spectroscopic data were consistent with literature reports.[1,2]

*4.1.7.5. Preparation of **32a**/**32b** (Table 3, entry 5).* Applying conditions E to alkyne **16** (170 mg, 1 mmol) for 4 h afforded **32a** and **32b** (2.5:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; hexane, no TEA] to afford a separable mixture of the isomers **32a** and **32b** along with trace amounts of *Z*-isomer as clear oils (138 mg, 30%).

Applying conditions F to alkyne **16** (170 mg, 1 mmol) for 4 h afforded **32a** and **32b** (4:1). The crude reaction was concentrated and subjected to column chromatography [silica gel; hexane, no TEA] to afford a separable mixture of the isomers **32a** and **32b** along with trace amounts of *Z*-isomer as clear oils (240 mg, 52%). Spectroscopic data were consistent with literature reports.[21]

*4.1.7.6. Preparation of **22a**/**22b** (Table 3, entry 6).* Applying conditions E to alkyne **6** (82 mg, 1 mmol) afforded, after 4 h, **22a** and **22b** (1:22). The reaction was cooled to room temperature and subjected to column chromatography [silica gel; hexane, 1% TEA] to afford **22a** (trace) and **22b** as a clear oil (310 mg, 83%).

Applying conditions F to alkyne **6** (82 mg, 1 mmol) (for the ease of handling a sealed tube was used) afforded, after 4 h **22a** and **22b** (1:4.3). By analysis of the crude reaction by ^{1}H NMR with hexamethyldisiloxane as an internal standard the yield was determined to be quantitative.

Data for **22b**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.82–0.92 (m, 15H), 0.98 (s, 9H), 1.21–1.38 (m, 6H), 1.41–1.56 (m, 6H), 5.75 (d, J=19.3 Hz, 1H), 5.95 (d, J=19.3 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 9.4, 13.7, 27.2, 29.1, 29.2, 35.9, 119.7, 160.0. Spectroscopic data were consistent with literature reports.[1,23,27]

*4.1.7.7. Preparation of **23a**/**23b**/**23c** (Table 3, entry 7).* Applying conditions F to alkyne **7** (102 mg, 1 mmol) afforded, after 4 h, **23a**, **23b**, and **23c** (5:4.2:1). By analysis of the crude reaction by ^{1}H NMR with hexamethyldisiloxane as an internal standard the yield was determined to be 78%.[21,24]

4.1.8. Representative procedure for Co-catalyzed hydrostannations with Bu_3SnF, catalytic TBAF, and PMHS (conditions G). To a sealed tube were added THF (7 mL), alkyne (1 mmol), hydroquinone (10 mg, 9 mol %), Bu_3SnF (464 mg, 1.5 mmol), PMHS (0.10 mL, 1.6 mmol), $CoCl_2(PPh_3)_2$ (26 mg, 4 mol %), and TBAF (2 drops of a 1 M solution in THF). The mixture was then heated in an oil bath at 65 °C until judged complete by TLC analysis. At that time, the reaction mixture was concentrated; the crude was passed through a short plug of silica to remove the catalyst and analyzed by ^{1}H NMR. Unless otherwise stated, the products were purified by column chromatography.

4.1.9. Representative procedure for Co-catalyzed hydrostannations with Bu_3SnH (conditions H). The corresponding alkyne (1 mmol) was dissolved in THF (7 mL). Hydroquinone (10 mg, 9 mol %), and $CoCl_2(PPh_3)_2$ (26 mg, 4 mol %) and 1.5 mmol of Bu_3SnH was added slowly. The solution was stirred at 65 °C for further 12 h. After evaporation of the solvent the crude product was analyzed by ^{1}H NMR. Unless otherwise stated, the products were purified by column chromatography.

*4.1.9.1. Preparation of **19a**/**19b** (Table 4, entry 1).* Applying conditions G to alkyne **3** (140 mg, 1 mmol) for 1 d afforded **19a** and **19b** (1.4:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 98/2 hexane/EtOAc, 1% TEA] to afford a partially separable mixture of the isomers **19a** and **19b** as clear oils (237 mg, 55%).

Applying conditions H to alkyne **3** (140 mg, 1 mmol) for 12 h afforded **19a** and **19b** (1.3:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 98/2 hexane/EtOAc, 1% TEA] to afford a partially separable mixture of the isomers **19a** and **19b** as clear oils (361 mg, 84%). Spectroscopic data were consistent with literature reports.[10]

*4.1.9.2. Preparation of **22a**/**22b** (Table 4, entry 2).* Applying conditions G to alkyne **6** (82 mg, 1 mmol) afforded, after 1 d, **22a** and **22b** (1:99). By analysis of the crude reaction by ^{1}H NMR with hexamethyldisiloxane as an internal standard the yield was determined to be 90%.

Applying conditions H to alkyne **6** (82 mg, 1 mmol) afforded, after 12 h, **22a** and **22b** (1:5.3) and trace amounts of *Z*-stannane. By analysis of the crude reaction by ^{1}H NMR with hexamethyldisiloxane as an internal standard the yield was determined to be quantitative.[1,23]

*4.1.9.3. Preparation of **23a**/**23b** (Table 4, entry 3).* Applying conditions G to alkyne **7** (102 mg, 1 mmol) afforded, after 1 d, **23a**, **23b** and **23c** (1.5:4:1). By analysis of the crude reaction by ^{1}H NMR with hexamethyldisiloxane as an internal standard the yield was determined to be 99%.

Applying conditions H to alkyne **7** (102 mg, 1 mmol) afforded, after 12 h, **23a**, **23b** and **23c** (1:4:2.5). By analysis of the crude reaction by ^{1}H NMR with hexamethyldisiloxane as an internal standard the yield was determined to be 94%.[21,24]

4.1.10. Representative procedure for rhodium and ruthenium-catalyzed hydrostannations with Bu_3SnF, catalytic TBAF, and PMHS (conditions I). To a pressure tube were added THF (7 mL), alkyne (1 mmol), hydroquinone (10 mg, 9 mol %), Bu_3SnF (464 mg, 1.5 mmol), PMHS (0.1 mL, 1.6 mmol), catalyst (2 mol % in the metal), and TBAF (2 drops of a 1 M solution in THF). The mixture was then heated in an oil bath at 65 °C until judged complete by TLC analysis. Once complete, the reaction mixture was concentrated; the crude was passed through a short plug of silica to remove the catalyst, analyzed by ^{1}H NMR and purified by column chromatography.

4.1.11. Representative procedure for rhodium and ruthenium-catalyzed hydrostannations with Bu_3SnH (conditions J). The corresponding alkyne (1 mmol) was dissolved in THF (7 mL). Hydroquinone (10 mg, 9 mol %) and catalyst (2 mol % in the metal) were added. The mixture was warmed to 65 °C before Bu_3SnH (0.4 mL, 1.5 mmol) was added. The solution was stirred at this temperature until complete by TLC analysis. After evaporation of the solvent, the

crude product was analyzed by ^{1}H NMR and then purified by column chromatography.

*4.1.11.1. Preparation of **19a**/**19b** (Table 5, entry 1).* Applying conditions I to alkyne **3** (140 mg, 1 mmol) with $[RhCl(COD)]_2$ (5 mg, 1 mol %) for 60 h produced trace amounts of desired stannanes. The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 98/2 hexane/EtOAc, 1% TEA] to afford trace amounts of **19a** and **19b** as clear oils (<5%).

Applying conditions J to alkyne **3** (140 mg, 1 mmol) with $[RhCl(COD)]_2$ (5 mg, 1 mol %) for 16 h afforded **19a** and **19b** (1.4:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 98/2 hexane/EtOAc, 1% TEA] to afford a partially separable mixture of the isomers **19a** and **19b** as clear oils (239 mg, 55%).[10]

*4.1.11.2. Preparation of **19a**/**19b** (Table 5, entry 2).* Applying conditions I to alkyne **3** (140 mg, 1 mmol) with $RhCl(CO)(PPh_3)_2$ (14 mg, 2 mol %) for 8 h afforded **19a** and **19b** (1:3.3). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 98/2 hexane/EtOAc, 1% TEA] to afford a partially separable mixture of the isomers **19a** and **19b** as clear oils (79 mg, 18%).

Applying conditions J to alkyne **3** (140 mg, 1 mmol) with $RhCl(CO)(PPh_3)_2$ (14 mg, 2 mol %) for 12 h afforded **19a** and **19b** (1:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 98/2 hexane/EtOAc, 1% TEA] to afford a partially separable mixture of the isomers **19a** and **19b** as clear oils (319 mg, 74%).[10]

*4.1.11.3. Preparation of **32a**/**32b** (Table 5, entry 3).* Applying conditions I to alkyne **16** (170 mg, 1 mmol) with $Rh(CO)(PPh_3)_2$ (14 mg, 2 mol %) for 8 h afforded **32a** and 32**b** (1:2.5). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; hexane, no TEA] to afford a partially separable mixture of the isomers **32a** and **32b** as clear oils (269 mg, 58%).

Applying conditions J to alkyne **16** (170 mg, 1 mmol) with $Rh(CO)(PPh_3)_2$ (14 mg, 2 mol %) for 12 h afforded **32a** and 32**b** (1:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; hexane, no TEA] to afford a separable mixture of the isomers **32a** and **32b** as clear oils (258 mg, 56%).[21]

*4.1.11.4. Preparation of **19a**/**19b**/**19c** (Table 5, entry 4).* Applying conditions I to alkyne **3** (140 mg, 1 mmol) with $RuCl_2(PPh_3)_4$ (19 mg, 2 mol %) for 8 h failed to produce **19a** and **19b** and a complex mixture resulted.

Applying conditions J to alkyne **3** (140 mg, 1 mmol) with $RuCl_2(PPh_3)_4$ (19 mg, 2 mol %) for 18 h afforded **19a**, **19b** and **19c** (2.5:1.6:1). The reaction was cooled to room temperature, concentrated, and subjected to column chromatography [silica gel; 98/2 hexane/EtOAc, 1% TEA] to afford a mixture of the isomers **19a**, **19b**, and **19c** as clear oils (86 mg, 20%).[10]

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Supplementary data

A supplementary data file (^{1}H and ^{13}C NMR) of alkynes **8**, **12**–**14**, and stannanes **18a**/**b**, **24a**/**b**, **25a**/**b**, **28a**/**b**, **29a**/**b**, **30a**/**b** is available. Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.tet.2013.02.064.

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