

Cite this: *Chem. Sci.*, 2019, 10, 7554 All publication charges for this article have been paid for by the Royal Society of Chemistry

Received 13th June 2019

Accepted 18th June 2019

DOI: 10.1039/c9sc02905b

rsc.li/chemical-science

# $\alpha$ -Silicon effect assisted Curtin–Hammett allylation using allylcopper reagents derived from 1,3-dienylsilanes†

Shang Gao and Ming Chen \*

Cu-catalyzed stereoselective synthesis of (*E*)- $\delta$ -silyl-*anti*-homoallylic alcohols from 1,3-dienylsilane was developed. Mechanistic studies revealed that the borocupration of dienylsilane proceeded through a 1,2-addition pathway to give an allylcopper intermediate with Cu distal to the silyl group. However, the subsequent aldehyde allylation proceeded *via* Curtin–Hammett control to give (*E*)- $\delta$ -silyl-*anti*-homoallylic alcohols with high diastereoselectivities. This method was applied to the synthesis of the C<sub>1–9</sub> fragment of a polyketide natural product, mycinolide IV.

## Introduction

Stereoselective transformation of carbon–carbon multiple bonds catalyzed by transition-metal complexes is a powerful approach to generate molecular complexity from structurally simple  $\pi$ -bonds.<sup>1</sup> In particular, reactions employing 1,3-conjugated dienes are attractive because of multiple potential reaction pathways that can be involved in these processes. By proper selection of the catalyst/ligand combination, distinct products can be generated with high selectivities from these reactions.<sup>2</sup> Such processes are valuable because they can often form several chemical bonds, generate several stereocenters, and provide highly useful intermediates for chemical synthesis. Over the past several decades, significant advances in stereoselective transformation of 1,3-conjugated dienes,<sup>3–7</sup> enynes and allenes as well have been achieved,<sup>8</sup> and many highly innovative strategies have been developed.

Recently, transition-metal catalyzed reactions of 1,3-conjugated dienes with carbonyl compounds have emerged as an important method to synthesize alcohol products.<sup>9–11</sup> Synthetically valuable homoallylic alcohols in particular<sup>12</sup> can be produced from 1,3-conjugated dienes with high stereoselectivities.<sup>10</sup> The Krische group demonstrated that allyl-Ru intermediates, which can be catalytically generated from 1,3-butadiene, reacted with aldehydes to furnish homoallylic alcohols with high enantiopurities.<sup>10</sup> Ni-catalyzed borylative 1,3-diene-aldehyde coupling, developed by the Morken group, proceeds through a different mechanism to produce homoallylic alcohols with high diastereoselectivities.<sup>11</sup> By contrast, Cu-catalyzed reactions using 1,3-conjugated dienes and

carbonyl compounds received much less attention.<sup>13</sup> Liao and co-workers reported a three-component coupling of 1,3-butadiene, B<sub>2</sub>pin<sub>2</sub> and imines to generate *syn*-homoallylic amines.<sup>13a</sup> The Yu group recently showed a Cu-catalyzed reductive hydroxymethylation of 1,3-dienes with CO<sub>2</sub> and silane.<sup>13b</sup> And Cu-catalyzed enantioselective reductive coupling of ketones with 2-azadienes and dienes was disclosed by Malcolmson and Buchwald.<sup>13c,d</sup>

While 1,3-butadiene and aryl-substituted 1,3-butadiene were employed in these studies, we were intrigued whether 1,3-dienylsilanes can be used to produce silyl substituted homoallylic alcohols. With our continuing interest in carbonyl allylation chemistry,<sup>14</sup> we herein report a Cu-catalyzed stereoselective synthesis of (*E*)- $\delta$ -silyl-*anti*-homoallylic alcohols from B<sub>2</sub>pin<sub>2</sub>, aldehydes and 1,3-dienylsilanes. A notable feature of this method is that the homoallylic alcohol products obtained from the reactions contain a stereochemically defined 1,3-diol unit, and an *E*-vinyl silane group that is amenable to a variety of subsequent transformations. Mechanistic studies revealed that the reaction proceeded through 1,2-borocupration of the terminal alkene unit to generate an allylcopper intermediate, with Cu residing distal to the silyl group. Subsequent aldehyde allylation occurred under Curtin–Hammett control to give homoallylic alcohol products with high selectivities.

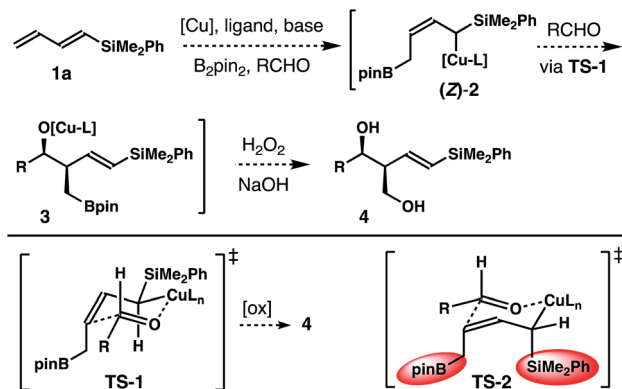
## Results and discussion

Inspired by recent studies on Cu–B addition to carbon–carbon multiple bonds<sup>15</sup> and allylcopper chemistry,<sup>16–18</sup> we envisioned a Cu-catalyzed reaction of dienylsilane, B<sub>2</sub>pin<sub>2</sub> and an aldehyde to synthesize  $\delta$ -silyl-homoallylic alcohols. As shown in Scheme 1, we anticipated that *in situ* generated, monodentate ligand-bound Cu–Bpin species would undergo 1,4-borocupration of dienylsilane **1a** to form an allylcopper intermediate (*Z*)-**2** first. It is conceivable that the kinetic product (*Z*)-**2** could undergo

Department of Chemistry and Biochemistry, Auburn University, Auburn, AL 36849, USA. E-mail: mzc0102@auburn.edu

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c9sc02905b



Scheme 1 Proposed approach to *(E)*-*syn*- $\delta$ -silyl homoallylic alcohols.

reversible 1,3-metalloshifts to give an *(E)*-isomer that is thermodynamically more stable. However, we surmised that such 1,3-metalloshifts might be slow owing to the electronic stabilization provided by the neighbouring  $-SiMe_2Ph$  group (silicon  $\alpha$ -anion effect).<sup>19</sup> Subsequent nucleophilic addition of the allyl-Cu intermediate (*Z*)-**2** to aldehyde substrates<sup>17,18</sup> should proceed through the well-established Zimmerman–Traxler transition state<sup>20</sup> ( $TS-1$ , Scheme 1) to produce *(E)*- $\delta$ -silyl-*syn*-homoallylic alcohol products **4** upon oxidative workup. The competing transition state for the allyl addition step,  $TS-2$ , which would lead to the formation of a *(Z)*-olefin isomer, suffers from a severe  $A^{1,3}$  allylic strain (shown in red in  $TS-2$ )<sup>21</sup> and therefore is disfavoured. Consequently, the formation of *syn*-homoallylic alcohols **4** was anticipated from this reaction sequence.

To implement the proposed strategy, we initiated our studies to identify suitable conditions for the stereoselective reaction of dienylsilane **1a**,  $B_2pin_2$  and benzaldehyde (Table 1). The initial experiments were conducted in the presence of 10 mol% CuCl and a ligand, 1.0 equiv. of dienylsilane **1a**, 1.0 equiv. of a base, 1.1 equiv. of  $B_2pin_2$  and 1.2 equiv. of benzaldehyde in THF at ambient temperature. Surprisingly, when a monodentate NHC ligand IPr·HCl was utilized with NaOt-Bu as the base, the reaction did not produce any detectable amount of the product (entry 1, Table 1). The reaction with IMes·HCl as the ligand and NaOt-Bu as the base, however, generated a 6 : 1 mixture of **5a** and **4a** in 21% yield (entry 2). In contrast to the anticipated *syn* relative configuration, the major product **5a** is an *anti*-isomer as determined by coupling constant analysis of the corresponding acetone derivative (please see the ESI† for details). The reaction with SiCy·HCl as the ligand precursor gave inferior results (entry 3). Next, reactions with a bidentate phosphor ligand were conducted. The reaction with dppbz as the ligand produced a 3 : 1 mixture of **5a** and **4a** in 32% yield (entry 4). The diastereoselectivity was improved to 10 : 1 when Xantphos was utilized (entry 5). A brief evaluation of the base such as LiOt-Bu or KOt-Bu showed either a lower yield or selectivity (entries 6 and 7). While modification of the base was not fruitful, the yield of reaction was improved to 77% at the expense of diastereoselectivity with toluene as the solvent (entry 8). The reaction did not occur in the absence of any base or ligand (entries 9 and 10). Gratifyingly, we discovered that when  $Cu(OMe)_2$  was

Table 1 Evaluation of the reaction conditions<sup>a</sup>

Entry	Ligand	Base	<i>Anti</i> : <i>syn</i> <sup>b</sup>	Yield ( <b>4a</b> + <b>5a</b> ) <sup>c</sup> (%)
1	IPr·HCl	NaOt-Bu	N.D.	N.R.
2	IMes·HCl	NaOt-Bu	6 : 1	21
3	SiCy·HCl	NaOt-Bu	2 : 1	19
4	dppbz	NaOt-Bu	3 : 1	32
5	Xantphos	NaOt-Bu	10 : 1	40
6	Xantphos	LiOt-Bu	10 : 1	26
7	Xantphos	KOt-Bu	7 : 1	61
8 <sup>d</sup>	Xantphos	NaOt-Bu	6 : 1	77
9	No ligand	NaOt-Bu	N.D.	N.R.
10	Xantphos	No base	N.D.	N.R.
11 <sup>e</sup>	Xantphos	No base	14 : 1	87
12 <sup>e</sup>	No ligand	No base	N.D.	N.R.

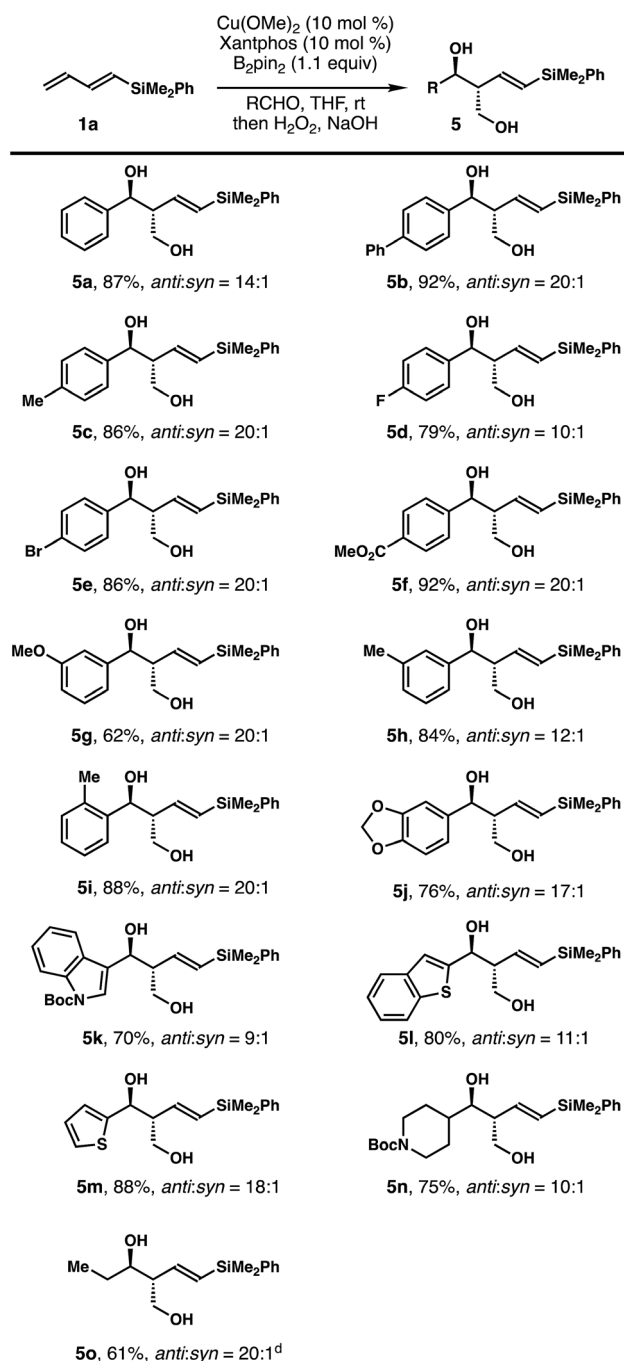
<sup>a</sup> Reaction conditions: dienylsilane **1a** (0.1 mmol, 1 equiv.), CuCl (10 mol%), ligand (10 mol%), base (0.1 mmol, 1 equiv.),  $B_2pin_2$  (0.11 mmol, 1.1 equiv.), benzaldehyde (0.12 mmol, 1.2 equiv.), and THF (0.3 mL); rt, 12 h. <sup>b</sup> The *anti*/*syn* and *E*/*Z* ratios were determined by  $^1H$  NMR analysis of the crude reaction products. <sup>c</sup> Yields of isolated products are listed. <sup>d</sup> The reaction was conducted in toluene. <sup>e</sup>  $Cu(OMe)_2$  (10 mol%) was used as the catalyst.

employed as the catalyst *in lieu* of CuCl, the reaction provided a 14 : 1 mixture of **5a** and **4a** in 87% yield without the addition of any base (entry 11).<sup>22</sup> Again, the presence of the xantphos ligand is crucial; the reaction in the absence of xantphos failed to provide any product with  $Cu(OMe)_2$  as the catalyst, which suggests that the ligand-bound Cu-complex is the active catalyst for this reaction (entry 12).

The scope of the aldehyde that participated in the reactions with dienylsilane **1a** is summarized in Table 2. In general, the reaction worked well with a variety of aldehydes. For example, aromatic aldehydes with substitution at the *para*-position regardless of the electronic properties reacted to give products **5a–f** in 79–92% yields with 10–20 : 1 *anti*/*syn* ratios. Reactions with aromatic aldehydes substituted at the *meta*- or *ortho*-position proceeded to provide alcohols **5g–j** in 62–88% yields with 12–20 : 1 diastereoselectivities. Reactions with heteroaromatic aldehydes proceeded smoothly to deliver diols **5k–m** in 70–88% yields with 9–18 : 1 diastereoselectivities. Finally, aliphatic aldehydes participated in the reaction as well to give products **5n–o** in 61–75% yields with 10–20 : 1 *anti*/*syn* ratios. The olefin geometry of alcohols **5** was assigned as *E* based on  $^1H$  NMR analysis of the coupling constant of olefinic protons.

To probe whether the size of the silyl group of 1,3-diene has any impact on the stereochemical outcomes of the reaction, dienylsilanes **1b–d** substituted with a different sized silyl group were synthesized, and reactions with these dienylsilanes under

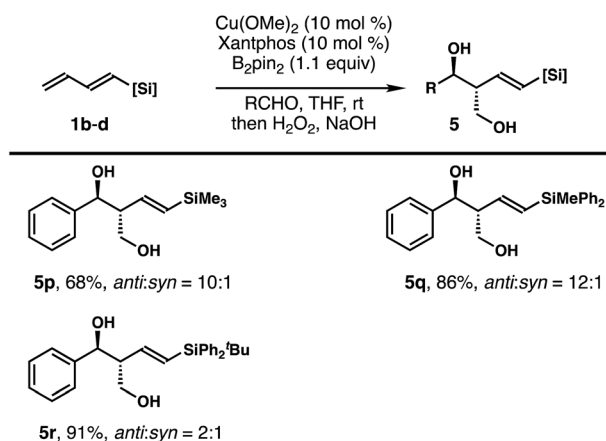


Table 2 Scope of aldehyde for reactions with dienylsilane **1a**<sup>a,b,c</sup>

<sup>a</sup> Reaction conditions: diene **1a** (0.1 mmol, 1 equiv.), Cu(OMe)<sub>2</sub> (10 mol%), Xantphos (10 mol%), B<sub>2</sub>pin<sub>2</sub> (0.11 mmol, 1.1 equiv.), aldehyde (0.12 mmol, 1.2 equiv.), and THF (0.3 mL); rt, 12–48 h.

<sup>b</sup> Diastereoselectivities were determined by <sup>1</sup>H NMR analysis of the crude reaction products. <sup>c</sup> Yields of isolated products are listed.

<sup>d</sup> Reactions were conducted at 0 °C.

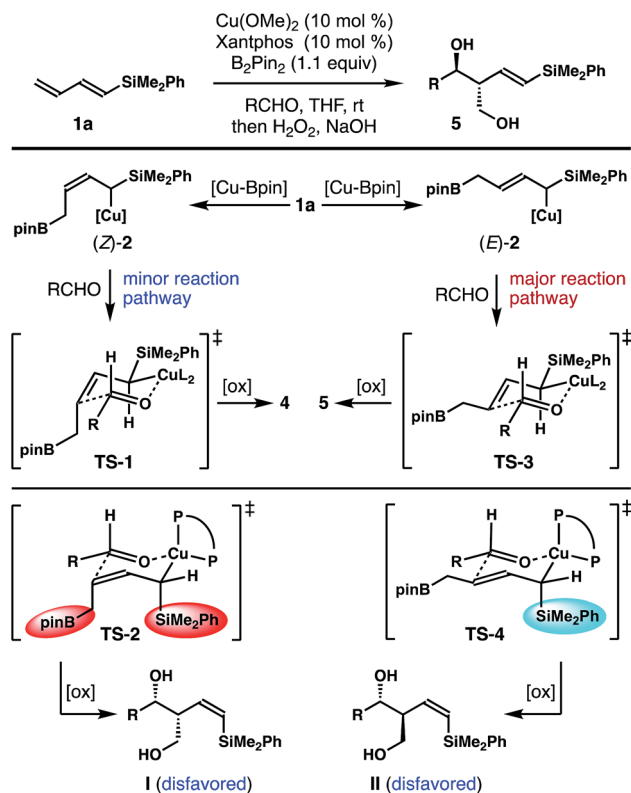
Table 3 Reactions with dienylsilanes **1b–d**

*anti/syn* selectivity. Diphenylmethylsilyl substituted 1,3-diene **1c** also reacted to generate product **5q** in 86% yield with 12 : 1 *anti/syn* selectivity. The reaction of benzaldehyde with a much more sterically demanding –SiPh<sub>2</sub><sup>t</sup>Bu substituted 1,3-diene **1d** under standard conditions provided diol **5r** as a 2 : 1 mixture of *anti* and *syn* isomers in 91% combined yield, with the *anti* adduct as the major product. In all cases, the formation of any isomer with *Z*-olefin geometry was not observed. Overall, the results indicate that the size of the silyl group of 1,3-diene does affect the *anti/syn* selectivity of the reaction, particularly in the case of the bulky SiPh<sub>2</sub><sup>t</sup>Bu group substituted 1,3-diene **1d**.

It has been well-established that the addition of allyl copper species to aldehyde proceeded by way of a 6-membered, chair-like transition state.<sup>16,20</sup> Therefore, the *anti* relative stereochemistry of homoallylic alcohols **5** suggests that the dominant reaction pathway of aldehyde addition is through the allylcopper intermediate (*E*)-**2** (Scheme 2). The reaction of aldehyde with isomer (*Z*)-**2** is only a minor pathway. As shown in Scheme 2, the minor reaction pathway involves the addition of (*Z*)-**2** to an aldehyde *via* **TS-1** to give the *syn*-isomer **4** because the competing transition state **TS-2** suffers from a severe A<sup>1,3</sup> allylic strain (shown in red in **TS-2**).<sup>21</sup> Therefore, the formation of the (*Z*)-homoallylic alcohol product **I** was disfavoured, and only the *syn*-adduct **4** was formed in this minor reaction pathway. On the other hand, the addition of (*E*)-**2** to the aldehyde proceeded through a transition state **TS-3** to deliver alcohol **5** as the product in the major reaction pathway. It is worth noting that, although the competing transition state **TS-4** lacks A<sup>1,3</sup> allylic strains, the reaction of (*E*)-**2** with an aldehyde did not proceed through **TS-4** with pseudo axial placement of the –SiMe<sub>2</sub>Ph group in the transition state (shown in light blue in **TS-4**) to provide product **II** with *Z*-olefin geometry (alcohol **II** was not detected from the reaction). Instead, –SiMe<sub>2</sub>Ph was oriented in the pseudo equatorial position in **TS-3** to give product **5** with *E*-olefin geometry. Based on the studies of stereoelectronic effects in allylboration chemistry conducted by Hoffmann,<sup>23</sup> σ–π\* delocalization between the σ-orbital of the C–Si single bond and the π\*-orbital of the olefin unit in **TS-3** is presumably responsible for the observed *E*-alkene stereoselectivity in product **5**. In

the developed conditions were conducted. As shown in Table 3, the reaction of less sterically demanding trimethylsilyl substituted 1,3-diene **1b** with benzaldehyde under standard conditions afforded the diol product **5p** in 68% yield with 10 : 1





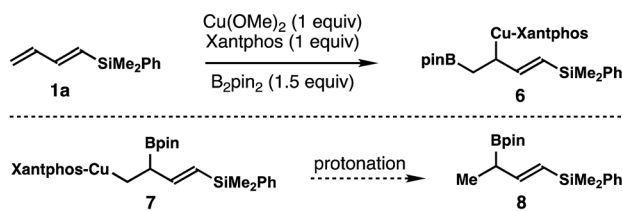
Scheme 2 Transition state analysis.

addition to the stereoelectronic effect, the large  $-\text{SiMe}_2\text{Ph}$  group occupying a pseudo equatorial position in the transition state **TS-3** could also make **TS-3** more favourable than **TS-4**.

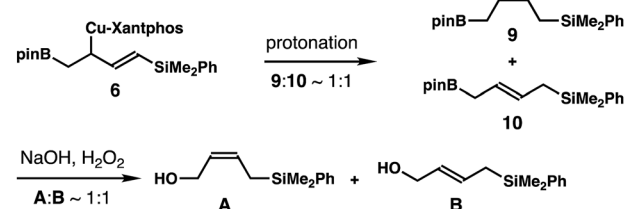
Although the data indicate that the dominant reaction pathway of aldehyde addition is through the allylcopper intermediate (*E*)-**2** (Scheme 2), it is not clear whether allylcopper (*E*)-**2** was generated as the major product from the addition of Xantphos-ligated Cu-Bpin species to diensilane **1a**. To gain mechanistic insight into this process, stoichiometric reaction studies with diensilane **1a** were conducted. As shown in the top panel of Scheme 3, 1 equiv. of  $\text{Cu}(\text{OMe})_2$ , Xantphos (1 equiv.), diensilane **1a** (1 equiv.), and  $\text{B}_2\text{Pin}_2$  (1.5 equiv.) were stirred at ambient temperature, and the reaction progress was monitored by  $^1\text{H}$ -NMR spectroscopy until diensilane **1a** was completely consumed. Surprisingly, we only observed one set of two olefinic proton signals (dd,  $J = 18.7$  Hz and d,  $J = 18.7$  Hz), which corresponds to a characteristic vinylsilane group with a methine group adjacent to one vinyl proton. Proton signals corresponding to either (*E*)-**2** or (*Z*)-**2** were not detected. The data indicate that the allylcopper species generated from the initial Cu-Bpin addition to diene **1a** should be a 1,2-borocupration adduct, **6** or **7** (Scheme 3a).

To determine which 1,2-addition product, **6** or **7**, was generated from the reaction, protonation of the intermediate obtained from stoichiometric borocupration of diene **1a** was performed. As shown in Scheme 3a, protonation of the intermediate formed *via* the stoichiometric reaction did not produce any detectable amount of the boronate intermediate **8**, which

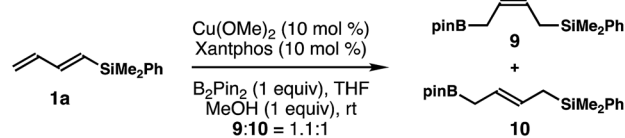
## a. stoichiometric reaction studies:



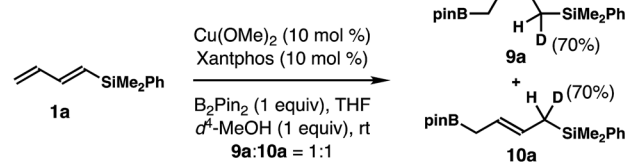
## b. protoboration under stoichiometric reaction conditions:



## c. protoboration under catalytic conditions:



## d. deuterium labeling studies:



Scheme 3 Mechanistic studies.

would be the product from protonation of intermediate **7**. Instead, a 1 : 1 mixture of (*Z*)- and (*E*)-allylboronates **9** and **10** was generated through a  $\text{S}_{\text{E}}2'$  pathway from allylcopper species **6** (Scheme 3b). A direct  $\text{S}_{\text{E}}2$  protonation product from **6** was not observed. Oxidation studies further corroborated the identity of **9** and **10** as a 1 : 1 mixture of (*Z*)- and (*E*)-allylic alcohols, **A** and **B**, was formed upon oxidation (Scheme 3b). Protoboration studies of diensilane **1a** under the developed catalytic conditions were also conducted. As shown in Scheme 3c, the reaction of diensilane **1a** with 1 equiv. of  $\text{B}_2\text{Pin}_2$  and 1 equiv. of MeOH in the presence of 10 mol%  $\text{Cu}(\text{OMe})_2$  and 10 mol% Xantphos ligand provided a 1.1 : 1 mixture of (*Z*)- and (*E*)-allylboronates **9** and **10**. Again, the formation of allylboronate **8** was not detected. Finally, deuterium-labeling studies of diensilane **1a** were conducted with  $d^4$ -MeOH under the developed catalytic conditions. As shown in Scheme 3d, the reaction of **1a** in the presence of 1 equiv. of  $d^4$ -MeOH provided a 1 : 1 inseparable mixture of (*Z*)- and (*E*)-allylboronates **9a** and **10a** with 70% deuterium incorporation at the positions  $\alpha$  to the  $-\text{SiMe}_2\text{Ph}$  group. These data further support the  $\text{S}_{\text{E}}2'$  protonation pathway of allylcopper intermediate **6** to give allylboronates **9** and **10**.

These data clearly demonstrate that the most stable allylcopper intermediate generated from the initial borocupration is the 1,2-adduct **6** with copper residing distal to the  $-\text{SiMe}_2\text{Ph}$

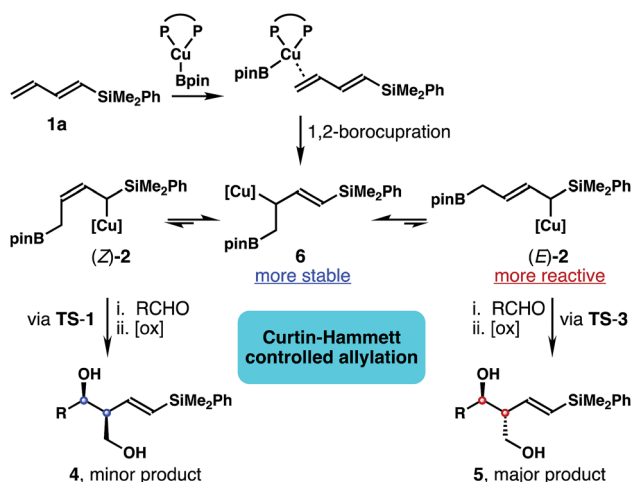




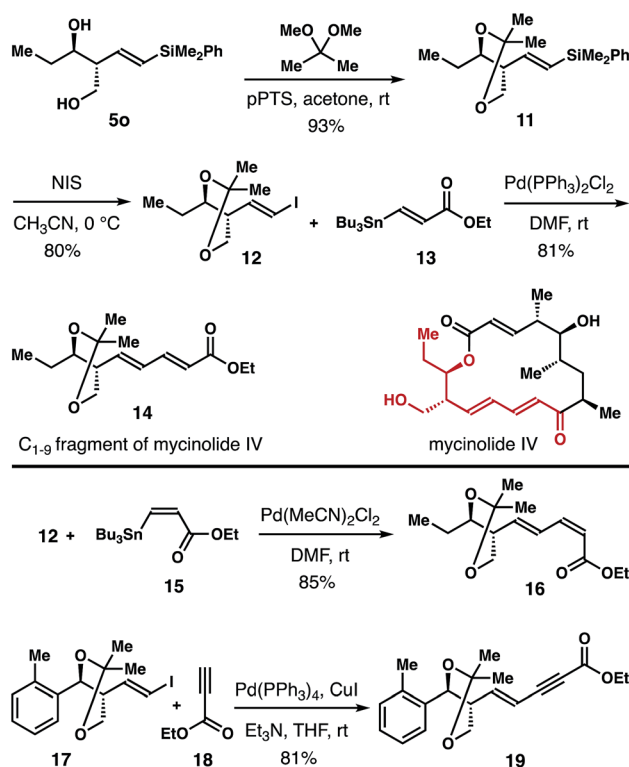
group, not the speculated allylcopper (*E*)-2 or (*Z*)-2 as shown in Scheme 2. Presumably the steric interaction between the Cu-Xantphos group and the  $-\text{SiMe}_2\text{Ph}$  group (as in either (*E*)-2 or (*Z*)-2 shown in Scheme 2) is too severe to overcome by the stereoelectronic stabilization from the  $-\text{SiMe}_2\text{Ph}$  group. By contrast, the results in Tables 1 and 2 indicate that the major reactive intermediate in the reactions is allylcopper (*E*)-2, and we were not able to detect any allylation product derived from allylcopper **6**.<sup>25</sup> Therefore, we conclude that (1) the activation energy for the addition of allylcopper species (*E*)-2 to aldehyde is much lower than that of allylcopper species **6**; (2) a fast equilibrium exists among allylcopper intermediates (*E*)-2, (*Z*)-2 and **6** through facile 1,3-metallo shifts; (3) the rate of equilibration among (*E*)-2, (*Z*)-2 and **6** is much faster than that of allylation with aldehydes.

Based on the data obtained from these studies, we propose the following reaction pathway. As illustrated in Scheme 4, the *in situ* generated Xantphos-Cu-Bpin species coordinates to the terminal alkene unit of dienyisilane **1a** to form a Cu-olefin complex. Subsequent borylcupration<sup>24</sup> of diene **1a** occurred in a 1,2-addition pathway to give intermediate **6** as the most stable allylcopper species. Although **6** was generated as the predominant allylcopper species from the initial 1,2-borylcupration, the addition to the aldehyde did not occur *via* allylcopper **6**. Instead, intermediate **6** equilibrates with (*E*)-2 and (*Z*)-2 *via* rapid and reversible 1,3-metallo shifts,<sup>25</sup> and subsequent nucleophilic addition to the aldehyde proceeded *via* the more reactive allylcopper (*E*)-2.<sup>26</sup> Therefore, intermediate **6** is funnelled to allylcopper (*E*)-2 under Curtin-Hammett control<sup>27</sup> to generate the *anti*-adduct **5** from the allylation. Presumably the stereoelectronic benefit from the  $\sigma-\pi^*$  delocalization of the  $\alpha$ -silyl group makes **TS-3** the lowest energy transition state for the allylation.

The homoallylic alcohol product **5** obtained from the reaction is highly valuable because it contains a stereochemically defined 1,3-diol unit, and a vinyl silane group that is amenable to a variety of subsequent transformations.<sup>28</sup> Synthetic applications of this method are shown in Scheme 5.



Scheme 4 Proposed reaction pathway.



Scheme 5 Synthesis of the C<sub>1-9</sub> fragment of mycinolide IV and derivatization of reaction products.

Diol **5o** was converted into acetonide **11** in 93% yield. Then acetonide **11** was transformed into vinyl iodide **12** in 80% yield with NIS as the iodination reagent. Pd-catalyzed Stille-coupling of vinyl iodide **12** with (*E*)-vinyl stannane **13**<sup>29</sup> gave product **14** in 81% yield, which corresponds to the C<sub>1-9</sub> fragment of the polyketide natural product mycinolide IV. In addition, Pd-catalyzed cross-coupling of **12** and (*Z*)-vinyl stannane **15**<sup>30</sup> delivered diene **16** in 85% yield. Sonogashira coupling of **17** with ethyl propiolate (**18**) furnished enyne **19** in 81% yield.<sup>31</sup>

## Conclusions

In summary, we developed Cu-catalyzed diastereoselective synthesis of (*E*)- $\delta$ -silyl-*anti*-homoallylic alcohols from 1,3-dienylsilanes.<sup>32</sup> Mechanistic studies revealed that the borylcupration proceeded through a 1,2-addition pathway to give the allylcopper intermediate **6** as the most stable allylcopper species. However, the allylcopper intermediate **6** was funnelled to more reactive allylcopper species (*E*)-2 *via* reversible 1,3-metallo shifts under Curtin-Hammett control in the subsequent aldehyde allylation step to give (*E*)- $\delta$ -silyl-*anti*-homoallylic alcohols with high diastereoselectivity. The  $\alpha$ -silicon effect is proposed to be the underlying driving force for the observed selectivity. This method was applied to the synthesis of the C<sub>1-9</sub> fragment of a polyketide natural product mycinolide IV. Other synthetic applications of this method will be reported in due course.



## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

Financial support provided by Auburn University is gratefully acknowledged. We thank AllylChem for generously gifting B<sub>2</sub>pin<sub>2</sub>.

## Notes and references

- For selected recent reviews: (a) H. C. Kolb, M. S. VanNieuwenhze and K. B. Sharpless, *Chem. Rev.*, 1994, **94**, 2483; (b) F. Agbossou, J.-F. Carpentier and A. Mortreux, *Chem. Rev.*, 1995, **95**, 2485; (c) I. Beletskaya and C. Moberg, *Chem. Rev.*, 1999, **99**, 3435; (d) E. M. McGarrigle and D. G. Gilheany, *Chem. Rev.*, 2005, **105**, 1563; (e) T. E. Müller, K. C. Hultsch, M. Yus, F. Foubelo and M. Tada, *Chem. Rev.*, 2008, **108**, 3795; (f) O. A. Wong and Y. Shi, *Chem. Rev.*, 2008, **108**, 3958; (g) F. Hebrard and P. Kalck, *Chem. Rev.*, 2009, **109**, 4272; (h) M. C. Willis, *Chem. Rev.*, 2010, **110**, 725; (i) R. I. McDonald, G. Liu and S. S. Stahl, *Chem. Rev.*, 2011, **111**, 2981; (j) Y. Zhu, Q. Wang, R. G. Cornwall and Y. Shi, *Chem. Rev.*, 2014, **114**, 8199.
- M. Holmes, L. A. Schwartz and M. J. Krische, *Chem. Rev.*, 2018, **118**, 6026.
- (a) M. Sugimoto, H. Nakamura, T. Matsuda and Y. Ito, *J. Am. Chem. Soc.*, 1998, **120**, 4248; (b) M. Shirakura and M. Sugimoto, *J. Am. Chem. Soc.*, 2008, **130**, 5410; (c) M. Shirakura and M. Sugimoto, *Angew. Chem., Int. Ed.*, 2010, **49**, 3827.
- (a) H. E. Burks, L. T. Kliman and J. P. Morken, *J. Am. Chem. Soc.*, 2009, **131**, 9134; (b) R. J. Ely and J. P. Morken, *J. Am. Chem. Soc.*, 2010, **132**, 2534; (c) C. H. Schuster, B. Li and J. P. Morken, *Angew. Chem., Int. Ed.*, 2011, **50**, 7906; (d) Z. Yu, R. J. Ely and J. P. Morken, *Angew. Chem., Int. Ed.*, 2014, **53**, 9632.
- (a) X.-H. Yang and V. M. Dong, *J. Am. Chem. Soc.*, 2017, **139**, 1774; (b) X.-H. Yang, A. Lu and V. M. Dong, *J. Am. Chem. Soc.*, 2017, **139**, 14049; (c) X.-H. Yang, R. Davison and V. M. Dong, *J. Am. Chem. Soc.*, 2018, **140**, 10443; (d) S.-Z. Nie, R. T. Davison and V. M. Dong, *J. Am. Chem. Soc.*, 2018, **140**, 16450.
- (a) M. S. McCamant, L. Liao and M. S. Sigman, *J. Am. Chem. Soc.*, 2013, **135**, 4167; (b) V. Saini, M. O'Dair and M. S. Sigman, *J. Am. Chem. Soc.*, 2015, **137**, 608.
- (a) Y. Yang, S.-F. Zhu, H.-F. Duan, C.-Y. Zhou, L.-X. Wang and Q.-L. Zhou, *J. Am. Chem. Soc.*, 2007, **129**, 2248; (b) J. Y. Wu, B. Moreau and T. Ritter, *J. Am. Chem. Soc.*, 2009, **131**, 12915; (c) Y. Xiong and G. Zhang, *J. Am. Chem. Soc.*, 2018, **140**, 2735; (d) K. B. Smith and M. K. Brown, *J. Am. Chem. Soc.*, 2017, **139**, 7721; (e) S. R. Sardini and M. K. Brown, *J. Am. Chem. Soc.*, 2017, **139**, 9823.
- For selected recent examples on transition metal-catalyzed carbonyl additions involving 1,3-enynes: (a) L. M. Geary, S. K. Woo, J. C. Leung and M. J. Krische, *Angew. Chem., Int. Ed.*, 2012, **51**, 2972; (b) F. Meng, F. Haefner and A. H. Hoveyda, *J. Am. Chem. Soc.*, 2014, **136**, 11304; (c) Y. Yang, I. B. Perry, G. Lu, P. Liu and S. L. Buchwald, *Science*, 2016, **353**, 144; (d) K. D. Nguyen, D. Herkommer and M. J. Krische, *J. Am. Chem. Soc.*, 2016, **138**, 5238; (e) X.-C. Gan, Q. Zhang, X.-S. Jia and L. Yin, *Org. Lett.*, 2018, **20**, 1070; (f) X.-C. Gan and L. Yin, *Org. Lett.*, 2019, **21**, 931; For selected recent examples on transition metal-catalyzed carbonyl additions involving allenes: (g) J. Rae, K. Yeung, J. J. W. McDouall and D. J. Procter, *Angew. Chem., Int. Ed.*, 2016, **55**, 1102; (h) K. Yeung, R. E. Ruscoe, J. Rae, A. P. Pulis and D. J. Procter, *Angew. Chem., Int. Ed.*, 2016, **55**, 11912; (i) T. Fujihara, A. Sawada, T. Yamaguchi, Y. Tani, J. Terao and Y. Tsuji, *Angew. Chem., Int. Ed.*, 2017, **56**, 1539; (j) A. Boreux, K. Indukuri, F. Gagosz and O. Riant, *ACS Catal.*, 2017, **7**, 8200; (k) A. Sawada, T. Fujihara and Y. Tsuji, *Adv. Synth. Catal.*, 2018, **360**, 2621; (l) R. Y. Liu, Y. Zhou, Y. Yang and S. L. Buchwald, *J. Am. Chem. Soc.*, 2019, **141**, 2251.
- (a) M. Kimura, A. Ezoe, K. Shibata and Y. Tamaru, *J. Am. Chem. Soc.*, 1998, **120**, 4033; (b) M. Kimura, H. Fujimatsu, A. Ezoe, K. Shibata, M. Shimizu, S. Matsumoto and Y. Tamaru, *Angew. Chem., Int. Ed.*, 1999, **38**, 397; (c) M. Kimura, S. Matsuo, K. Shibata and Y. Tamaru, *Angew. Chem., Int. Ed.*, 1999, **38**, 3386; (d) Y. Sato, M. Takimoto and M. Mori, *J. Am. Chem. Soc.*, 2000, **122**, 1624; (e) Y. Sato, N. Saito and M. Mori, *J. Am. Chem. Soc.*, 2000, **122**, 2371; (f) S. Ogoshi, K.-i. Tonomori, M.-a. Oka and H. Kurosawa, *J. Am. Chem. Soc.*, 2006, **128**, 7077; (g) M. Kimura, A. Ezoe, M. Mori, K. Iwata and Y. Tamaru, *J. Am. Chem. Soc.*, 2006, **128**, 8559.
- (a) J. R. Zbieg, E. Yamaguchi, E. L. McInturff and M. J. Krische, *Science*, 2012, **336**, 324; (b) E. L. McInturff, E. Yamaguchi and M. J. Krische, *J. Am. Chem. Soc.*, 2012, **134**, 20628; (c) K. D. Nguyen, D. Herkommer and M. J. Krische, *J. Am. Chem. Soc.*, 2016, **138**, 14210.
- (a) H. Y. Cho and J. P. Morken, *J. Am. Chem. Soc.*, 2008, **130**, 16140; (b) H. Y. Cho and J. P. Morken, *J. Am. Chem. Soc.*, 2010, **132**, 7576; (c) L. T. Kliman, S. N. Mlynarski, G. E. Ferris and J. P. Morken, *Angew. Chem., Int. Ed.*, 2012, **51**, 521; (d) G. E. Ferris, K. Hong, I. A. Roundtree and J. P. Morken, *J. Am. Chem. Soc.*, 2013, **135**, 2501.
- J. Feng, Z. A. Kasun and M. J. Krische, *J. Am. Chem. Soc.*, 2016, **138**, 5467.
- (a) L. Jiang, P. Cao, M. Wang, B. Chen, B. Wang and J. Liao, *Angew. Chem., Int. Ed.*, 2016, **55**, 13854; (b) Y.-Y. Gui, N. Hu, X.-W. Chen, L.-L. Liao, T. Ju, J.-H. Ye, Z. Zhang, J. Li and D.-G. Yu, *J. Am. Chem. Soc.*, 2017, **139**, 17011; (c) K. Li, X. Shao, L. Tseng and S. J. Malcolmson, *J. Am. Chem. Soc.*, 2018, **140**, 598; (d) C. Li, R. Y. Liu, L. T. Jesikiewicz, Y. Yang, P. Liu and S. L. Buchwald, *J. Am. Chem. Soc.*, 2019, **141**, 5062.
- (a) M. Wang, S. Khan, E. Miliordos and M. Chen, *Org. Lett.*, 2018, **20**, 3810; (b) S. Gao and M. Chen, *Org. Lett.*, 2018, **20**, 6174; (c) M. Wang, S. Khan, E. Miliordos and M. Chen, *Adv. Synth. Catal.*, 2018, **360**, 4634; (d) S. Gao, M. Wang



- and M. Chen, *Org. Lett.*, 2018, **20**, 7921; (e) S. Gao, J. Chen and M. Chen, *Chem. Sci.*, 2019, **10**, 3637; (f) M. Wang, S. Gao and M. Chen, *Org. Lett.*, 2019, **21**, 2151.
- 15 For selected reviews: (a) J. Yun, *Asian J. Org. Chem.*, 2013, **2**, 1016; (b) R. Barbeyron, E. Benedetti, J. Cossy, J.-J. Vasseur, S. Arseniyadis and M. Smietana, *Tetrahedron*, 2014, **70**, 8431; (c) Y. Shimizu and M. Kanai, *Tetrahedron Lett.*, 2014, **55**, 3727; (d) K. Semba, T. Fujihara, J. Terao and Y. Tsuji, *Tetrahedron*, 2015, **71**, 2183; (e) E. C. Neeve, S. J. Geier, I. A. I. Mkhaliid, S. A. Westcott and T. B. Marder, *Chem. Rev.*, 2016, **116**, 9091; (f) H. Yoshida, *ACS Catal.*, 2016, **6**, 1799.
- 16 M. Shibasaki and M. Kanai, *Chem. Rev.*, 2008, **108**, 2853.
- 17 (a) S. Yamasaki, K. Fujii, R. Wada, M. Kanai and M. Shibasaki, *J. Am. Chem. Soc.*, 2002, **124**, 6536; (b) R. Wada, K. Oisaki, M. Kanai and M. Shibasaki, *J. Am. Chem. Soc.*, 2004, **126**, 8910; (c) R. Wada, T. Shibuguchi, S. Makino, K. Oisaki, M. Kanai and M. Shibasaki, *J. Am. Chem. Soc.*, 2006, **128**, 7687; (d) M. Kanai, R. Wada, T. Shibuguchi and M. Shibasaki, *Pure Appl. Chem.*, 2008, **80**, 1055; (e) S.-L. Shi, L.-X. Xu, K. Oisaki, M. Kanai and M. Shibasaki, *J. Am. Chem. Soc.*, 2010, **132**, 6638.
- 18 For selected recent examples of Cu-catalyzed asymmetric carbonyl addition reactions: (a) R. Yazaki, N. Kumagai and M. Shibasaki, *J. Am. Chem. Soc.*, 2009, **131**, 3195; (b) R. Yazaki, N. Kumagai and M. Shibasaki, *J. Am. Chem. Soc.*, 2010, **132**, 5522; (c) D. R. Fandrick, K. R. Fandrick, J. T. Reeves, Z. Tan, W. Tang, A. G. Capacci, S. Rodriguez, J. J. Song, H. Lee, N. K. Yee and C. H. Senanayake, *J. Am. Chem. Soc.*, 2010, **132**, 7600; (d) K. R. Fandrick, D. R. Fandrick, J. T. Reeves, J. Gao, S. Ma, W. Li, H. Lee, N. Grinberg, B. Lu and C. H. Senanayake, *J. Am. Chem. Soc.*, 2011, **133**, 10332; (e) X.-F. Wei, X.-W. Xie, Y. Shimizu and M. Kanai, *J. Am. Chem. Soc.*, 2017, **139**, 4647.
- 19 (a) A. R. Bassindale and P. G. Taylor, in *The chemistry of organic silicon compounds*, ed. S. Patai and Z. Rappoport, Wiley, New York, 1989; p. 893; (b) T. H. Chan and D. Wang, *Chem. Rev.*, 1995, **95**, 1279; (c) G. A. Gornowicz and R. West, *J. Am. Chem. Soc.*, 1968, **90**, 4478; (d) C. H. DePuy, V. M. Bierbaum, L. A. Flippin, J. J. Grabowski, G. K. King, R. J. Schmitt and S. A. Sullivan, *J. Am. Chem. Soc.*, 1980, **102**, 5012; (e) P. V. R. Schleyer, T. Clark, A. J. Kos, G. W. Spitznagel, C. Rohde, D. Arad, K. N. Houk and N. G. Rondan, *J. Am. Chem. Soc.*, 1984, **106**, 6467; (f) D. M. Wetzel and J. I. Brauman, *J. Am. Chem. Soc.*, 1988, **110**, 8333; (g) E. A. Brinkman, S. Berger and J. I. Brauman, *J. Am. Chem. Soc.*, 1994, **116**, 8304.
- 20 (a) H. E. Zimmerman and M. D. Traxler, *J. Am. Chem. Soc.*, 1957, **79**, 1920; (b) Although boat-like transition states cannot be ruled out, chair-like transition states are proposed in all prior studies on allyl-copper addition to carbonyl compounds.
- 21 (a) R. W. Hoffmann, *Chem. Rev.*, 1989, **89**, 1841. For recent examples: (b) M. Althaus, A. Mahmood, J. R. Suárez, S. P. Thomas and V. K. Aggarwal, *J. Am. Chem. Soc.*, 2010, **132**, 4025; (c) M. Chen and W. R. Roush, *Org. Lett.*, 2010, **12**, 2706; (d) J.-L. Han, M. Chen and W. R. Roush, *Org. Lett.*, 2012, **14**, 3028; (e) B. Potter, A. A. Szymaniak, E. K. Edelstein and J. P. Morken, *J. Am. Chem. Soc.*, 2014, **136**, 17918.
- 22 The effect of methoxide vs. *tert*-butoxide on the diastereoselectivity of the reaction is not clear at the moment. It is a subject for future studies.
- 23 R. W. Hoffmann and J. J. Wolff, *Chem. Ber.*, 1991, **124**, 563.
- 24 (a) Y. Sasaki, C. Zhong, M. Sawamura and H. Ito, *J. Am. Chem. Soc.*, 2010, **132**, 1226; (b) K. Semba, M. Shinomiya, T. Fujihara, J. Terao and Y. Tsuji, *Chem.-Eur. J.*, 2013, **19**, 7125.
- 25 Addition of allylcopper **6** generated from the stoichiometric reaction to benzaldehyde produced a 1 : 3 mixture of **5a** and **4a**. These data are consistent with the fast equilibrium among **6**, (*E*)-**2** and (*Z*)-**2** via reversible 1,3-metalloshifts. Although **6** was generated as the only observed allylcopper intermediate from the stoichiometric reaction, any allylation product derived from **6** was not detected. These data also indicate that the activation energy for the addition of allylcopper **6** to an aldehyde is much higher than those of (*E*)-**2** and (*Z*)-**2**.
- 26 (*E*)-Allylation reagents are generally more reactive than (*Z*)-isomers toward aldehyde addition. For recent references, see: (a) T. Miura, J. Nakahashi and M. Murakami, *Angew. Chem., Int. Ed.*, 2017, **56**, 6989; (b) T. Miura, J. Nakahashi, W. Zhou, Y. Shiratori, S. G. Stewart and M. Murakami, *J. Am. Chem. Soc.*, 2017, **139**, 10903.
- 27 (a) J. I. Seeman, *Chem. Rev.*, 1983, **83**, 83; For selected examples: (b) J. Halpern, *Science*, 1982, **217**, 401; (c) C. R. Landis and J. Halpern, *J. Am. Chem. Soc.*, 1987, **109**, 1746; (d) M. Chen and W. R. Roush, *Tetrahedron*, 2013, **69**, 5468.
- 28 The vinyl silane unit in homoallylic alcohols **5** can be used directly for a variety of subsequent transformations. For selected references, see: (a) T. A. Blumenkopf and L. E. Overman, *Chem. Rev.*, 1986, **86**, 857; (b) I. Fleming, A. Barbero and D. Walter, *Chem. Rev.*, 1997, **97**, 2063; (c) S. E. Denmark and J. H.-C. Liu, *Angew. Chem., Int. Ed.*, 2010, **49**, 2978; (d) D. A. Evans and Y. Aye, *J. Am. Chem. Soc.*, 2006, **128**, 11034; (e) E. A. Ilardi, C. E. Stivala and A. Zakarian, *Org. Lett.*, 2008, **10**, 1727; (f) K. Aikawa, Y. Hioki and K. Mikami, *J. Am. Chem. Soc.*, 2009, **131**, 13922.
- 29 J. K. Stille and B. L. Groh, *J. Am. Chem. Soc.*, 1987, **109**, 813.
- 30 (a) M. S. Ermolenko, *Tetrahedron Lett.*, 1996, **37**, 6711; (b) L. C. Dias and C. d. C. S. Gonsalves, *Adv. Synth. Catal.*, 2008, **350**, 1017.
- 31 (a) R. Chinchilla and C. Nájera, *Chem. Soc. Rev.*, 2011, **40**, 5084; (b) E.-i. Negishi, M. Qian, F. Zeng, L. Anastasia and D. Babinski, *Org. Lett.*, 2003, **5**, 1597; (c) J. S. Yadav and V. Rajender, *Eur. J. Org. Chem.*, 2010, 2148.
- 32 1,3-Dienylsilanes with other substitution patterns did not proceed or proceeded with low conversions under the developed conditions.

