

Pd(quinox)-catalyzed allylic relay Suzuki reactions of secondary homostyrenyl tosylates *via* alkene-assisted oxidative addition†Cite this: *Chem. Sci.*, 2014, 5, 2336

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## Introduction

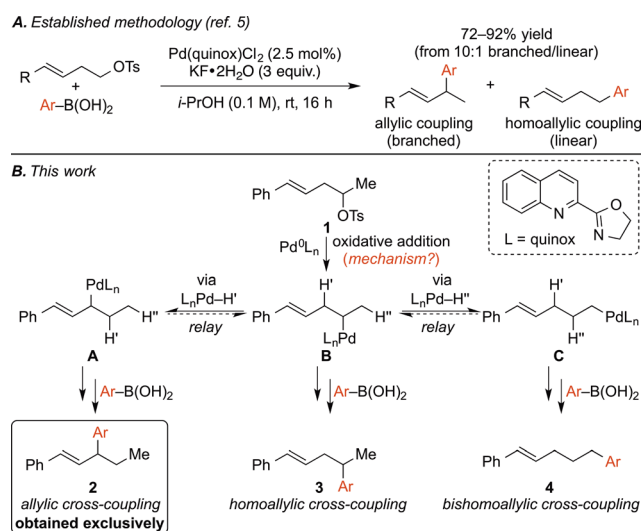
The Pd-catalyzed Suzuki cross-coupling is among the most widely-used transition metal-catalyzed carbon-carbon bond-forming reactions because of the ease with which a vast array of coupling partners can be combined from commercially-available reactants under mild conditions.<sup>1</sup> Despite the diversity of coupling partners commonly employed in these reactions, including many  $sp^2$  and  $sp^3$  nucleophiles and electrophiles, secondary  $sp^3$  electrophiles remain difficult to utilize.<sup>2,3</sup> This is chiefly a result of the  $S_N2$ -type oxidative addition of secondary halides and pseudohalides to Pd(0), which is severely limited through presumed steric interactions.<sup>4</sup>

We recently reported an unusual example of such an oxidative addition in the context of exploring the reaction depicted in Scheme 1A.<sup>5</sup> In this report, primary homoallylic tosylates were found to undergo oxidative addition followed by the relay of Pd to the allylic position *via* a proposed sequential  $\beta$ -hydride elimination and migratory insertion.<sup>6</sup> The resultant stabilized Pd-allyl intermediate then undergoes cross-coupling to an aryl boronic acid to afford difficult-to-access secondary allylic Suzuki products<sup>3</sup> with generally good selectivity (>10 : 1) over the less-hindered linear homoallylic cross-coupling product. Through two mechanistic experiments employing secondary homostyrenyl tosylates, oxidative addition was found to proceed through a stereoinvertive,  $S_N2$ -type mechanism – a rare example of a Pd-catalyzed oxidative addition of an unactivated secondary electrophile.<sup>7</sup> Herein, we present an improved procedure for Pd-

catalyzed allylic relay Suzuki cross-coupling reactions of secondary alkyl tosylates, featuring a sterically-hindered oxidative addition and precise control of  $\beta$ -hydride elimination, are reported. The identification of a linear free energy relationship between the relative rates of substrate consumption and the electronic nature of the substrate alkene suggests that the oxidative addition requires direct alkene involvement. A study of the effect of alkyl chain length on the reaction outcome supports a chelation-controlled oxidative addition.

catalyzed relay Suzuki reactions of this challenging electrophile class (1, Scheme 1B), as well as preliminary mechanistic evidence as to why such secondary electrophiles are capable of undergoing oxidative addition.

Since mixtures of allylic (relay) and homoallylic (non-relay) cross-coupling products were routinely observed in reactions of primary homostyrenyl tosylates (Scheme 1A),<sup>5</sup> secondary homostyrenyl tosylates such as 1 were anticipated to afford mixtures of three cross-coupling products (Scheme 1B). Mechanistically, these products could result from divergent reaction following oxidative addition. Specifically, from Pd-alkyl B, transmetalation of a boronic acid and subsequent reductive



Scheme 1 (A) Previous relay Suzuki cross-coupling of primary homostyrenyl tosylates. (B) Mechanistic rationale to account for three potential products resulting from the reaction of a secondary homostyrenyl tosylate under Pd(quinox) catalysis.

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elimination could give homoallylic cross-coupling product **3**; alternatively,  $\beta$ -hydride elimination/migratory insertion could transpose the Pd atom to either the stabilized allylic position, **A**, or to the terminal alkyl position, **C**, which, after transmetallation and reductive elimination, could afford the allylic cross-coupling product **2** or the bishomoallylic cross-coupling product **4**, respectively. Using Pd(quinox) as catalyst, we now report that relay Suzuki reactions of secondary homostyrenyl tosylates afford the allylic cross-coupling product, **2**, exclusively, thus showcasing the control of  $\beta$ -hydride elimination in addition to the surprising oxidative addition of a secondary electrophile.

## Results and discussion

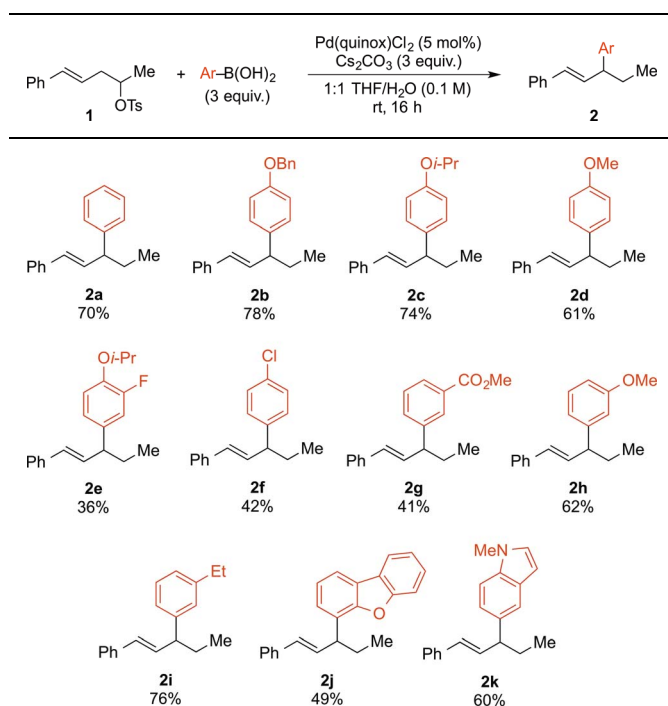
Our previous relay Suzuki cross-coupling conditions, which employed  $\text{KF}\cdot 2\text{H}_2\text{O}$  as base in isopropanol (Scheme 1A), necessitated the use of 10–15 mol% of Pd(quinox) $\text{Cl}_2$  to achieve sufficient conversion of secondary homostyrenyl tosylates for mechanistic studies.<sup>5</sup> In an effort to decrease the precatalyst load for secondary tosylates, we identified  $\text{Cs}_2\text{CO}_3$  and THF– $\text{H}_2\text{O}$  to be a suitable base–solvent combination, allowing the reaction to be carried out at ambient temperature with just 5 mol% load of Pd(quinox) $\text{Cl}_2$ .<sup>8</sup> Under these conditions, the scope of boronic acid coupling partners in the relay Suzuki cross-coupling of **1** was probed using three equivalents of boronic acid (Table 1). Unsubstituted (**2a**) and 4-alkoxy-substituted phenylboronic acids (**2b–2d**) were found to afford good yields of the corresponding desired products. On the other hand, the presence of electron-deficient substituents on the arylboronic

acid results in noticeably attenuated yields. For example, 3-fluoro-4-isopropoxyphenylboronic acid gives **2e** in just 36% yield, 4-chlorophenylboronic acid couples to give 42% yield of **2f**, and 3-carbomethoxyphenylboronic acid affords 41% yield of the corresponding relay product **2g** (although the methyl ester may be sensitive to the hydrolytic reaction conditions). Interestingly, 3-methoxyphenylboronic acid, which also possesses a relatively electron-deficient boron-bearing carbon atom, is coupled in good yield (**2h**). Electron-rich 3-ethylphenylboronic acid also affords a good yield of the corresponding relay product **2i**. Polycyclic heteroaromatic boronic acids were also investigated for their propensity to undergo relay cross-coupling. To this end, *ortho*-substituted 2-dibenzofuranyl boronic acid gave **2j** in reasonable yield, and indole-incorporated relay product **2k** was accessed in 60% yield.

An important observation based on crude NMR analyses of each of these reactions is that the yield is generally comparable to substrate conversion. That is to say, substrate **1** is not fully consumed in these reactions, even upon doubling the amount of reactants, reagents, and catalyst.<sup>8,9</sup> The conversion is not improved substantially by the addition of a second batch of catalyst after 16 h, which suggests that boronic acid decomposition, rather than catalyst decomposition, prevents substrate conversion under these conditions.<sup>10</sup> This may also explain the lower yields observed in relay cross-couplings of electron-deficient boronic acids as shown in Table 1.<sup>11</sup>

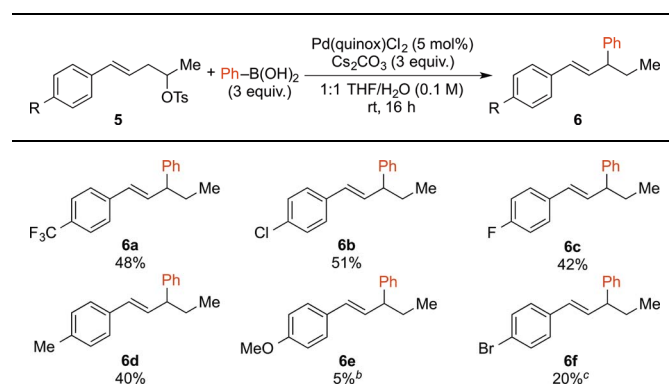
Turning our attention towards substrate scope, we next evaluated a series of electronically-disparate alkene substrates through the preparation of *para*-substituted secondary homostyrenyl tosylates (**5a–5f**, Table 2). Isolated yields were fair for trifluoromethyl-, chloro-, fluoro-, and methyl-containing products (**6a–6d**), while the 4-methoxy-substituted variant resisted reaction almost entirely, resulting in less than 5% yield of product **6e** by NMR analysis. Finally, substrate **5f**, containing an aryl bromide functional group, afforded 20% yield of **6f**. In this reaction, both **1** and **2a** were observed as byproducts, thus illustrating that aryl bromides are prone to oxidative addition to Pd(0) under these conditions, while aryl chlorides are not (*cf.*, **6b**).

Table 1 Scope of aryl boronic acids in the relay Suzuki reaction<sup>a</sup>



<sup>a</sup> Isolated yields are reported.

Table 2 Scope of substrates containing *para*-substituents<sup>a</sup>

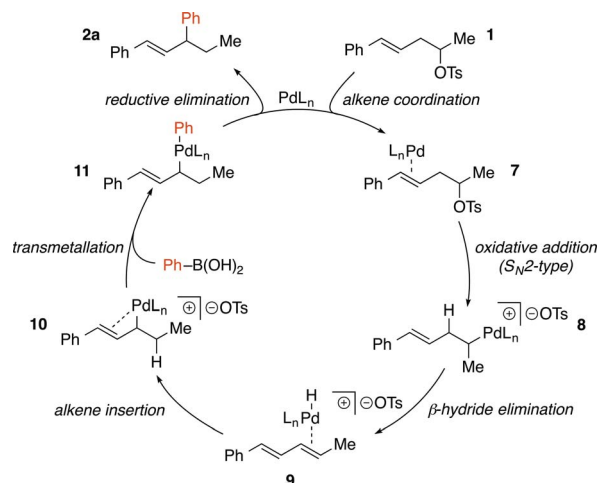


<sup>a</sup> Isolated yields are reported. <sup>b</sup> Yield determined by <sup>1</sup>H NMR spectroscopy using  $\text{CH}_2\text{Br}_2$  as an *ex situ* internal standard. <sup>c</sup> In addition, **1** and **2a** were isolated in 10% and 23% yield, respectively.

Based on the observed sensitivity of the reaction to the electronics of the alkene, we became intrigued by the possibility that the styrenyl portion of the substrate may facilitate the oxidative addition of the hindered tosylate.<sup>12</sup> To probe this hypothesis, a relative rate experiment was designed to compare the rate of conversion of homostyrenyl tosylates **5a–5e** to that of **1**.<sup>13</sup> This revealed that the relative rates correlate to the Hammett  $\sigma$  values<sup>14</sup> of the arene substituent (Scheme 2). The positive  $\rho$  value observed implies a buildup of negative charge in the transition state of the conversion-influencing step, which suggests an inverse-electron-demand ligand substitution of the alkene onto Pd(0) that would be enabled by a more electron-deficient alkene.<sup>15,16</sup> This evidence supports the hypothesis that the substrate alkene is required for the oxidative addition step in relay Suzuki cross-coupling reactions.<sup>17</sup>

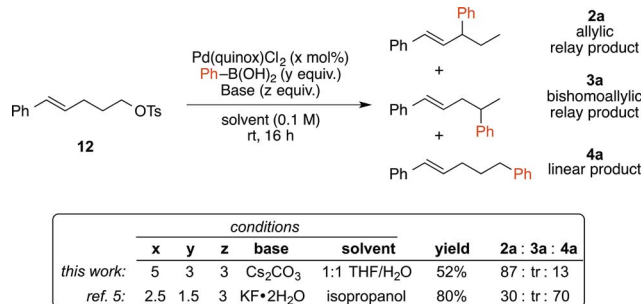
A proposed mechanism for the relay Suzuki cross-coupling reaction of secondary homostyrenyl tosylates is summarized in Scheme 3. Initially, the alkene of **1** coordinates Pd(0) (**7**) and brings Pd into proximity to the tosylate for the S<sub>N</sub>2-type oxidative addition, leading to destabilized Pd-alkyl **8**. Then,  $\beta$ -hydride elimination may generate the diene-Pd-H intermediate **9**, which undergoes migratory insertion to afford the stabilized allyl-Pd intermediate **10**.<sup>18</sup> Boronic acid transmetalation and reductive elimination may then give rise to the cross-coupling product **2a**.

Based on this newfound insight regarding the alkene-dependent oxidative addition, we sought to investigate the influence that the number of carbon atoms separating the alkene from the tosylate might have on oxidative addition. This was accomplished by first subjecting bishomostyrenyl tosylate **12** to the optimized conditions (Scheme 4). This resulted in reasonable substrate conversion, and all three of the possible cross-coupling products (**2a**, **3a**, and **4a**) were observed despite having only observed the allylic relay product (**2**) in the aforementioned reactions of homostyrenyl tosylates **1** and **5a–5f**. Interestingly, under our previously-reported reaction conditions,

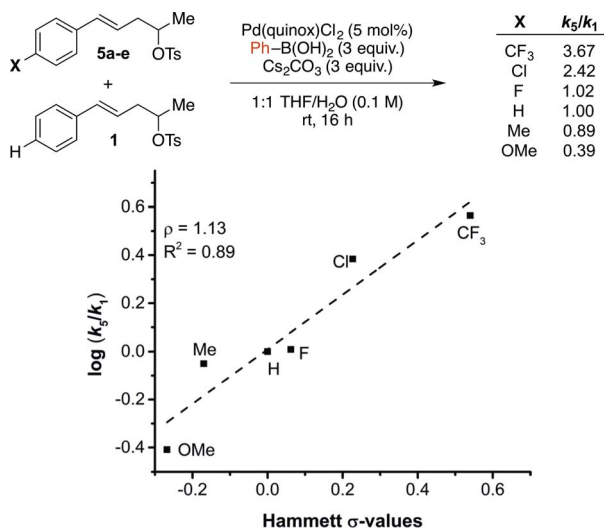


Scheme 3 Proposed mechanism for the relay Suzuki cross-coupling of a secondary homostyrenyl tosylate to phenylboronic acid.

the major reaction product is not the allylic relay product **2a**, but rather the linear arylation product **4a**.<sup>5</sup> This selectivity reversal signifies the sensitivity of relay Suzuki cross-couplings to reaction conditions.

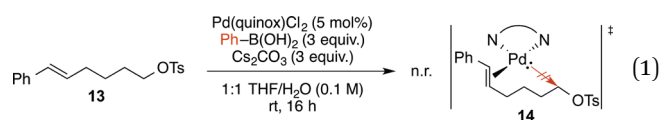


Scheme 4 Investigation of the relay cross-coupling of bishomostyrenyl tosylate.



Scheme 2 Hammett correlation to the relative rates of consumption of *para*-substituted and -unsubstituted secondary homostyrenyl tosylates.

Incorporating an additional carbon between the alkene and tosylate, as in substrate **13**, resulted in no reaction (eqn (1)). This implies that the olefin and tosylate are not able to bind to the metal simultaneously in order for oxidative addition to be achieved. This could be due to excessive strain in the oxidative addition transition state (**14**) arising from the increased length of the aliphatic chain, which may reasonably be expected to prohibit a requisite chelation.



## Conclusions

We have developed an allyl-selective relay Suzuki cross-coupling reaction of secondary homostyrenyl tosylates at ambient

temperature. Linear free energy relationship analysis is consistent with a mechanism whereby the substrate alkene coordinates Pd prior to oxidative addition. Systematic evaluation of the distance between the alkene and the electrophile reveals that the alkene must be within three carbon atoms of the oxidant. Thus, homostyrenyl and bishomostyrenyl substituents may now be considered directing groups for oxidative additions of unactivated alkyl electrophiles to Pd(0). New cross-coupling reactions exploiting alkene-assisted oxidative addition of traditionally inert alkyl electrophiles are currently being explored.

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