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## Sonogashira coupling in natural product synthesis

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This review will focus on selected applications of Sonogashira coupling and subsequent transformations as key steps in the total synthesis of natural products. A brief introduction to the history and development of Sonogashira coupling will be presented. The organization of the synthetic applications is based on the structure of target molecules and the transformations followed by the Sonogashira coupling, which includes (1) preparation of natural products containing conjugated enynes or enediynes; (2) Sonogashira coupling followed by stereoselective reduction and (3) Sonogashira coupling followed by regioselective annulations.

### 1. Introduction

Significant advances have been made over the past four decades in palladium (Pd)-catalyzed cross-coupling reactions to form carbon–carbon (C–C) bonds.<sup>1</sup> As a result, Pd-catalyzed inter- and intramolecular reactions and cyclizations are widely used to synthesize natural products, therapeutic agents and organic materials.<sup>2</sup> These reactions dramatically improve the efficiency of organic syntheses, such as those involving the formation of sp-sp<sup>2</sup> bonds. These bonds occur in arylalkynes, conjugated enynes and enediynes, synthons that occur in

such natural products as phorbaside A (**1**),<sup>3</sup> pyrrhocanthin (**2**),<sup>4</sup> dynemicin A (**3**),<sup>5</sup> kedarcidin chromophore (**4**)<sup>6</sup> and calicheamicin  $\gamma_1$  (**5**)<sup>7</sup> (Fig. 1). The value of such natural products as medicinal chemistry targets and as inspiration for methodological advances makes sp-sp<sup>2</sup> bond formation particularly important in organic synthesis.

In 1975, Heck<sup>8</sup> and Cassar<sup>9</sup> independently reported the Pd-catalyzed arylation and alkenylation of alkynes in the presence of organic or inorganic bases at temperatures around 100 °C. Subsequently, Sonogashira and Hagihara demonstrated that adding a catalytic amount of copper(i) iodide dramatically improved the rate of this alkynylation, even allowing the cross-coupling to be performed at room temperature.<sup>10</sup> The core of the Sonogashira–Hagihara protocol, known as Sonogashira coupling, has become a generally accepted method; in this reaction, Pd and Cu co-catalyze the construction of sp-sp<sup>2</sup>

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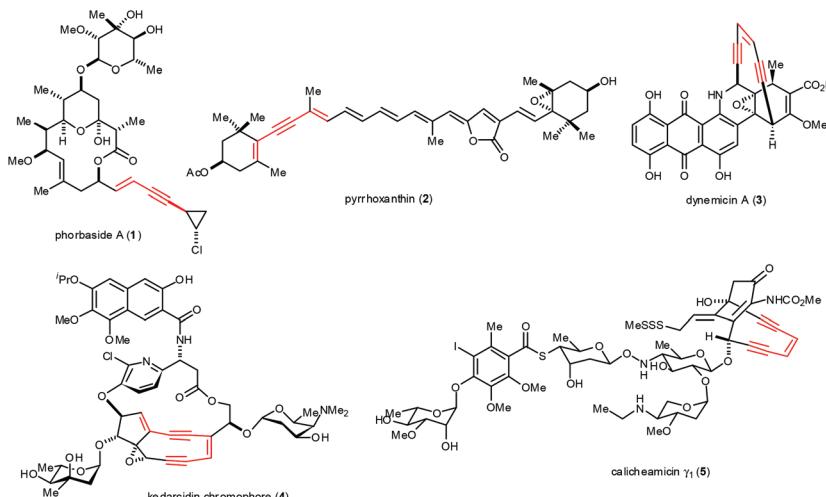
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Shuanhu Gao

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**Fig. 1** Selective natural products containing conjugated enynes.

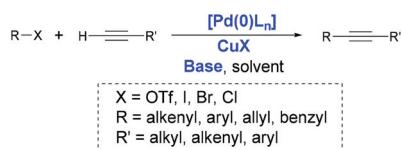
bonds involving terminal alkynes and aryl or alkanyl halides or triflates (Scheme 1). Since its discovery, Sonogashira coupling has been extensively studied in an effort to understand its mechanism as well as explore different catalysts, ligands, and additives.<sup>2</sup>

Despite these efforts, the mechanism of Pd/Cu-catalyzed cross-coupling remains unclear. It is assumed to proceed through the combination of Pd-catalyzed and Cu-catalyzed cycles (Scheme 2). In the Pd-catalyzed cycle, *in situ* reduction of Pd(II) complexes may give rise to a catalytically active species Pd(0)L<sub>n</sub>, which facilitates the fast oxidative addition of R-X. The rate of oxidative addition of R-X depends on the electronic properties of the R-X bond as well as on the reactivity of X (I ≥ OTf > Br > Cl). Normally, electron-withdrawing groups activate the R-X bond by decreasing its electron density. Next, in the Cu-catalyzed cycle, the copper acetyllide undergoes trans-

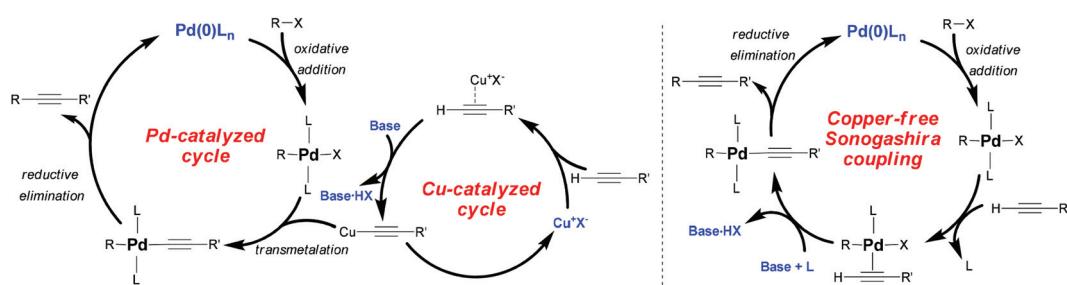
metalation. This step, which is the rate-determining reaction in the overall coupling, generates a RPd(-C≡CR')L<sub>2</sub> species, which then undergoes reductive elimination to yield the final coupled alkyne and regenerate the Pd(0)L<sub>n</sub> catalyst.

One problem with Pd/Cu-cocatalyzed Sonogashira coupling is that the alkyne can undergo homocoupling in the presence of oxygen *via* the Hay/Glaser reaction.<sup>11</sup> To avoid this side reaction, researchers have explored Cu-free Sonogashira coupling.<sup>2</sup> While the mechanism of this reaction is poorly understood, it is thought that reversible π-coordination and deprotonation, analogous to those in the Cu-catalyzed cycle of Pd/Cu-cocatalyzed coupling, generate an alkyne-Pd(II) complex [RPd(-C≡CR')L<sub>2</sub>].

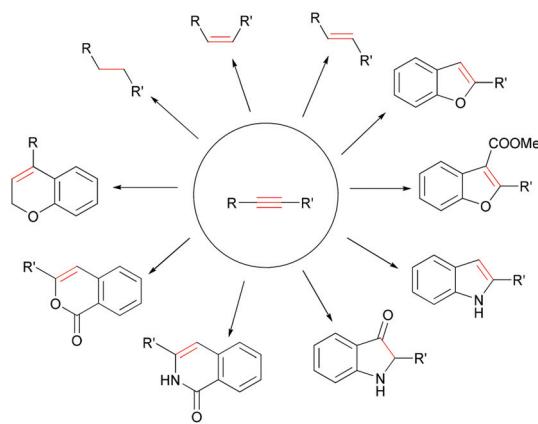
Sonogashira coupling efficiently produces arylalkynes and conjugated enynes that can participate in a broad variety of transformations. For example, reduction or regioselective annulation of Sonogashira products can generate diverse building blocks and heterocycles, such as alkyl, alkene, benzofuran, indole, oxyindole, isoquinolinone, isochromenone systems and related structures (Scheme 3). Comprehensive reviews of the Sonogashira reaction which covered the catalyst system, mechanism studies and applications have been published in recent years,<sup>2</sup> which indicated a trend of its rapid expansion and applications. In this review, we focus on



**Scheme 1** Sonogashira coupling.



**Scheme 2** The proposed mechanism of Sonogashira coupling.



**Scheme 3** Transformations of arylalkynes and conjugated enynes generated by Sonogashira coupling.

selected applications of Sonogashira coupling and subsequent transformations as key steps in the total synthesis of natural products.

## 2. Synthetic applications

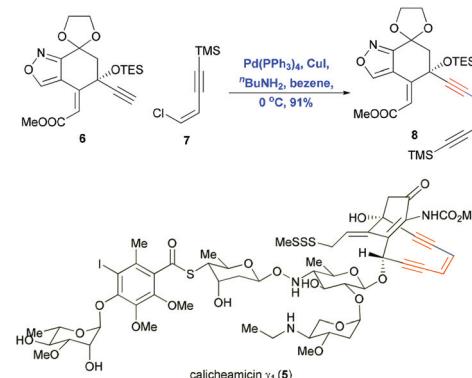
Efficiency is essential in organic synthesis, particularly natural product synthesis. Designing efficient reactions means satisfying several constraints, including the need for chemoselectivity,<sup>12</sup> atom economy,<sup>13</sup> step economy<sup>14</sup> and redox economy.<sup>15</sup> Achieving all these things is made more challenging by the fact that total synthesis of complex natural products nearly always requires several steps.<sup>16,17</sup> In many cases, these steps can be carried out by a straightforward linear procedure, but this sometimes leads to low yields because of relatively poor material balance and supply, which suppress its practicability.<sup>17</sup> In these and other cases, a convergent approach can prove much more efficient than a linear one because it couples the synthesis of individual fragments. Its advantages include: (1) convergent synthesis is usually simpler to execute than linear synthesis; (2) it involves better material balance and supply and (3) it gives higher overall yields.<sup>17</sup> On the other hand, convergent synthesis requires designing effective coupling steps involving efficient reactions that are tolerant of diverse functional groups. Sonogashira couplings enable convergent synthesis strategies, which are of value due to their advantages in efficiency over more linear synthesis strategies. Here we describe examples where the Sonogashira reaction serves as a key coupling step in the convergent synthesis of natural products.

### 2.1. Natural products containing conjugated enynes

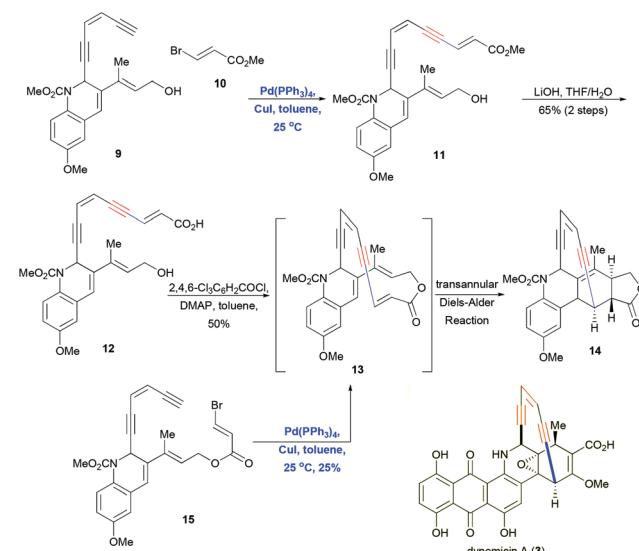
Natural products containing conjugated enynes or enediynes have attracted considerable attention from organic chemists and biologists because of their sensitive structural features and their potential as bioactive compounds and as starting compounds in chemical biology studies.<sup>3–7</sup> The total synthesis of these natural products is challenging mostly because of the

difficulty in efficiently constructing the sensitive motif containing the conjugated enynes and enediynes. Inter- or intramolecular Sonogashira reactions to construct the sp-sp<sup>2</sup> bond have proven useful for achieving this step. In pioneering work in 1992, Nicolaou and co-workers demonstrated the power of Sonogashira coupling in the total synthesis of calicheamicin  $\gamma_1$  (5).<sup>7</sup> The Pd/Cu-catalyzed coupling of alkyne 6 with vinyl chloride 7 gave the enediyne product 8 in 91% yield (Scheme 4). This reaction proceeded smoothly under mild conditions at low temperature, preserving the sensitive protecting groups as well as the Z conformation of the alkene.

Schreiber and co-workers performed Sonogashira coupling followed by a transannular Diels–Alder reaction to construct the core skeleton of dynemicin A (3),<sup>5</sup> a potent enediyne-containing antibiotic. Coupling enediyne 9 with vinyl bromide 10 in the presence of Pd(PPh<sub>3</sub>)<sub>4</sub> and CuI gave the polyunsaturated ester 11, which was transformed through alkaline hydrolysis into the corresponding carboxylic acid 12 (Scheme 5).



**Scheme 4** Construction of the enediyne motif using a Sonogashira coupling in the total synthesis of calicheamicin  $\gamma_1$  (5).

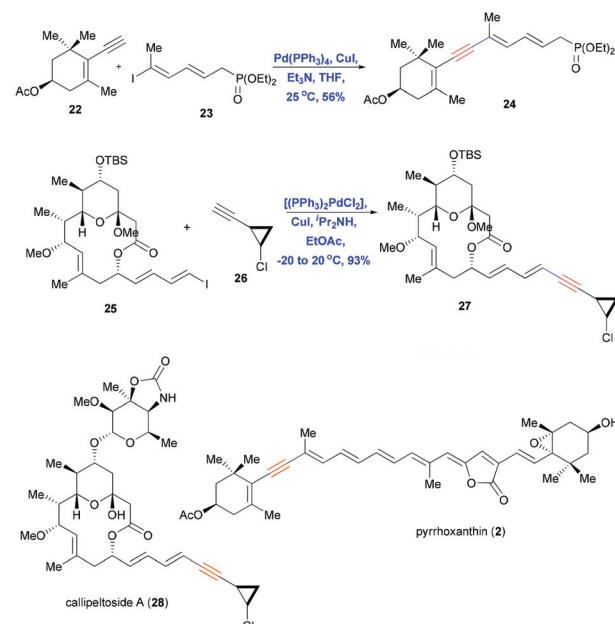


**Scheme 5** Sonogashira coupling followed by the transannular Diels–Alder reaction to construct the core skeleton of dynemicin A.

Subsequent Yamaguchi macrocyclization gave the pentacyclic product **14** in 50% yield. The proposed mechanism involves formation of the macrocyclic ring **13**, followed by a spontaneous transannular Diels–Alder reaction. Dramatically, Schreiber and co-workers showed that intramolecular Sonogashira coupling of **15** in the presence of  $\text{Pd}(\text{PPh}_3)_4$  and  $\text{CuI}$  yielded **14** directly in 25% yield. This impressive one-pot cascade reaction efficiently constructed three rings with a highly strained enediyne motif and four contiguous stereocenters.

Sonogashira coupling also proved useful for synthesizing the highly complex maduropeptin chromophore (**21**), which contains a bicyclo[7.3.0]enediyne and a 15-membered ansamacrolactam with atropisomerism. This compound exhibits potent antitumor and antibacterial activity through a mechanism that differs from that of other enediyne natural products. In 2007, Inoue and co-workers used a convergent approach including Sonogashira coupling to synthesize the aglycon of **21** (Scheme 6).<sup>18</sup> Coupling vinyl triflate **16** with the densely functionalized terminal alkyne **17** under mild  $\text{Pd}/\text{Cu}$ -cocatalytic conditions yielded the corresponding product **18** in quantitative yield, and this was converted to aldehyde **19** through deprotection and oxidation. Remarkably, scaling up this Sonogashira coupling (7.35 mmol) gave excellent yield in only 20 min, helping ensure sufficient substrate for the next step of the synthesis. Ring closure of the strained nine-membered diyne ring was achieved by acetylidyne-aldehyde condensation promoted by  $\text{LiN}(\text{SiMe}_2\text{Ph})_2$  and  $\text{CeCl}_3$ .

The Sonogashira reaction is also used as a key coupling step in the convergent syntheses of pyrrhocanthin (**2**)<sup>4</sup> and callipeltoside A (**28**),<sup>3</sup> both of which contain conjugated enynes (Scheme 7). Coupling a trisubstituted dienyl iodide **22** with terminal alkyne **23** in the presence of  $\text{Pd}(\text{PPh}_3)_4$  and  $\text{CuI}$  in



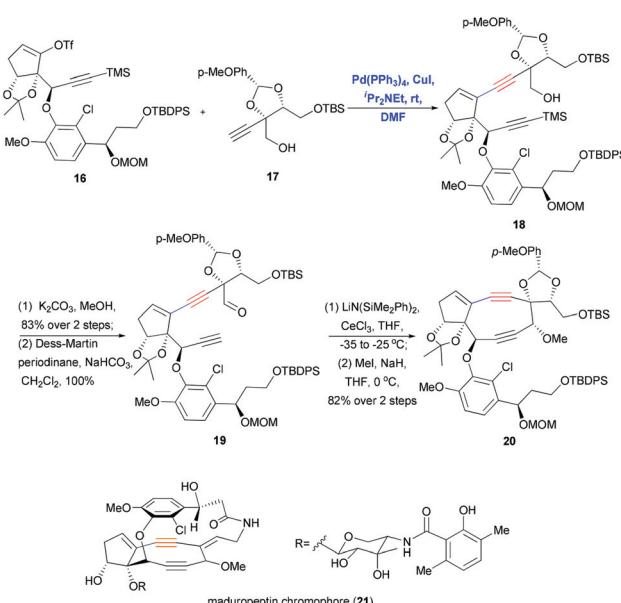
**Scheme 7** Sonogashira coupling in the total syntheses of pyrrhocanthin (**2**) and callipeltoside A (**28**).

$^{\text{n}}\text{BuNH}_2$  in benzene gave the desired product **24** in 56% yield. In contrast, reacting dienyl iodide **25** with terminal alkyne **26** under the same conditions failed to provide the desired product. Andrus *et al.* reported the same problem during the synthesis of stipiamide and related polyenes.<sup>19</sup> Those authors screened reaction conditions of the Sonogashira coupling and found  $\text{Pd}(\text{II})$  chloride  $[(\text{PPh}_3)_2\text{PdCl}_2]$  to be a much better catalyst than  $\text{Pd}(\text{PPh}_3)_4$ , especially for couplings involving the electron-deficient alkynyl amides. Using this improved catalyst together with  $\text{CuI}$  and  $^{\text{i}}\text{Pr}_2\text{NH}$  in ethyl acetate, they obtained the protected aglycon **27** in 93% yield with retention of double-bond geometry.

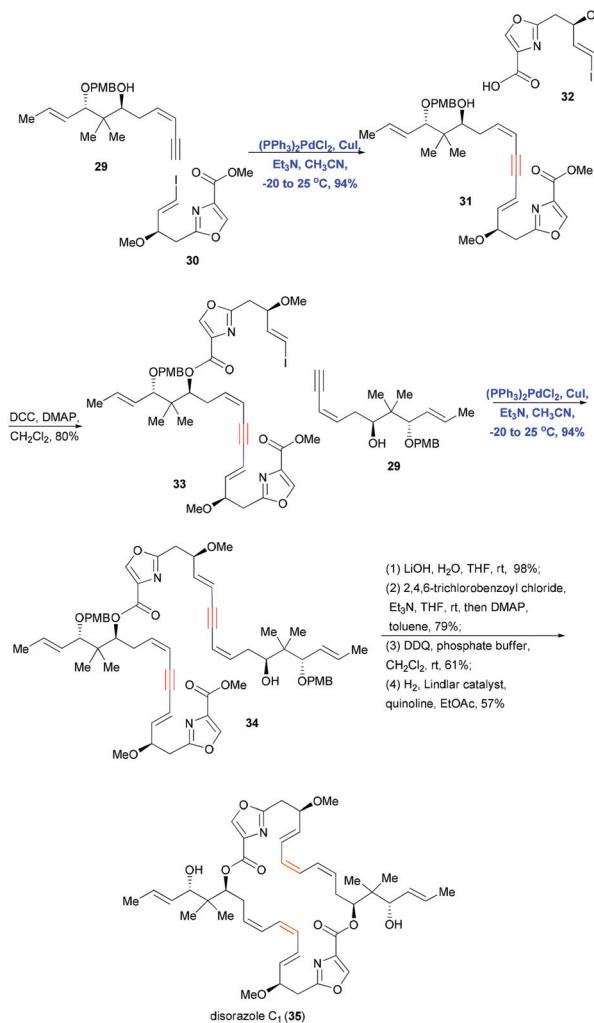
## 2.2. Sonogashira coupling followed by reduction

Since Sonogashira coupling provides a reliable and effective method of constructing inter- and intramolecular  $\text{sp}-\text{sp}^2$  C–C bonds, it can be combined with reduction reactions to convert the triple bonds of alkyne–alkene systems into  $\text{sp}^2-\text{sp}^2$ ,  $\text{sp}^2-\text{sp}^3$  and  $\text{sp}^3-\text{sp}^3$  bonds in a regio- and stereoselective fashion. In addition, reaction conditions can be adjusted to control the *E* or *Z* geometry of the alkene. This combination of Sonogashira coupling followed by stereoselective reduction has been used in many convergent syntheses of natural products, including polyketides, alkaloids and polycyclic xanthones.

In 2004, Wipf and co-workers used a convergent, stereoselective approach to achieve the total synthesis of disorazole C<sub>1</sub> (**35**),<sup>20</sup> which has significant cytotoxic and antitubulin activities at nanomolar concentrations. To generate **35**, which has a dimeric structure composed of a macrocyclic–heterocyclic ring with labile polyene systems (*E*, *Z*, *Z*), the authors assembled four fragments using double Sonogashira coupling, esterification and Yamaguchi macrocyclization (Scheme 8).



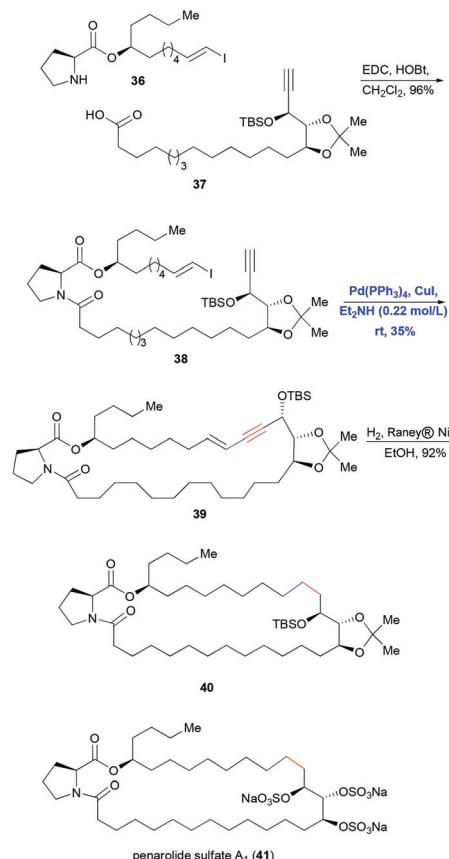
**Scheme 6** Sonogashira coupling of fragments to synthesize the aglycon of maduropeptin chromophore (**21**).



**Scheme 8** Convergent total synthesis of disorazole C<sub>1</sub> (35).

Coupling terminal alkyne 29 with vinyl iodide 30 in the presence of  $(PPh_3)_2PdCl_2$  and CuI gave the coupling product in 94% yield, which was then esterified with fragment 32 to achieve vinyl iodide 33. A second Sonogashira coupling under the same conditions was performed to introduce segment 29. A subsequent series of simple transformations, including saponification, Yamaguchi lactonization, deprotection and stereoselective reduction, completed the total synthesis of 35. Notably, this approach allowed the labile triene to remain protected until late in the synthesis, when the Lindlar catalyst was used to construct *Z* olefins stereoselectively.

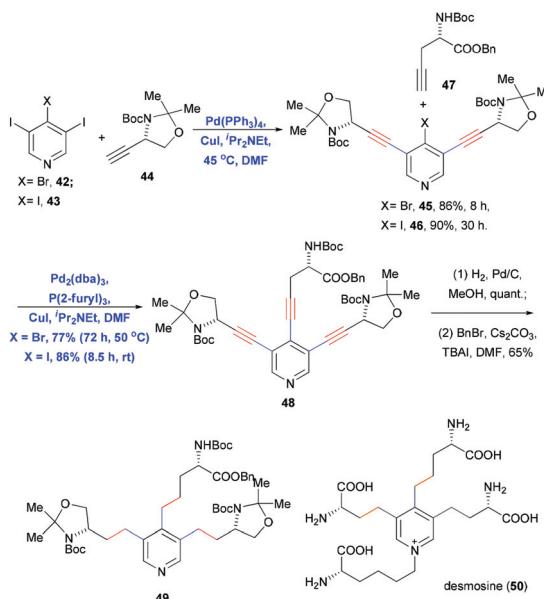
Intramolecular Sonogashira coupling has been reported less often in total syntheses, partly because it is effective only for constructing macrocycles with more than approximately 15 members as the conjugated enyne produces ring strain. One of the few examples of intramolecular Sonogashira coupling in total synthesis is the strategy reported by Mohapatra and co-workers in 2008 for making penarolide sulfate A<sub>1</sub> (41) (Scheme 9).<sup>21</sup> Fragments 36 and 37 were connected in high yield using EDC/HOBt-mediated coupling, and then an intramolecular Sonogashira reaction catalyzed by Pd( $PPh_3$ )<sub>4</sub>



**Scheme 9** Total synthesis of penarolide sulfate A<sub>1</sub> (41) using intramolecular Sonogashira coupling.

and CuI in Et<sub>2</sub>N solvent furnished the 30-membered macrocyclic ring. Finally the conjugated enyne was hydrogenated using RANEY® Ni in ethanol to generate the saturated ring system.

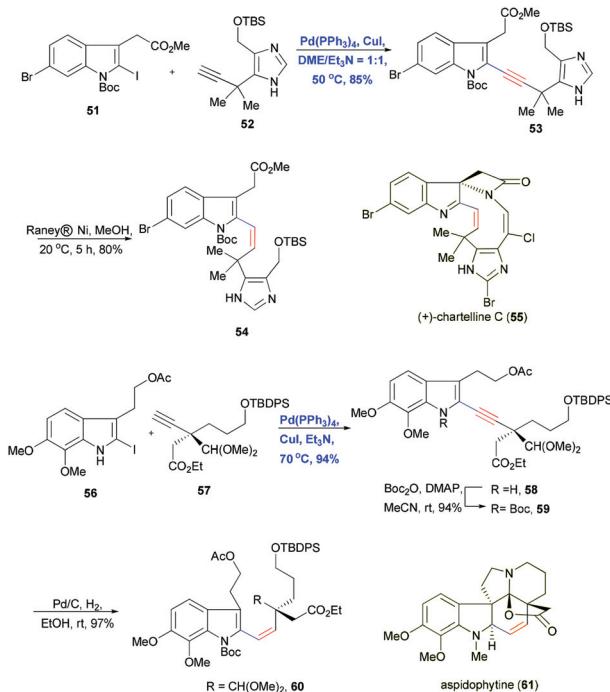
Selectivity of the Sonogashira coupling of terminal alkynes to different electrophilic groups is normally controlled by adjusting the reactivity of the C-X bond ( $I \geq OTf \geq Br > Cl$ ). If the steric effects of specific substrates are adjusted as well, the coupling can be carried out in a stepwise, regioselective fashion. One example is the total synthesis of desmosine (50) reported by Usuki and co-workers in 2012.<sup>22</sup> This compound contains four amino acid side chains of different lengths. In their approach, those authors performed the regioselective Sonogashira coupling of 42 or 43 with terminal alkyne 44 at the 3- and 5-positions in the presence of Pd( $PPh_3$ )<sub>4</sub> and CuI in DMF and  $iPr_2NEt$  (Scheme 10). Oxidative addition of I or Br at the C-4 position was avoided because of steric hindrance from the neighboring 3,5-diido groups. For the same reason, achieving the third Sonogashira coupling at the sterically hindered C-4 required a more reactive catalyst system. The authors created this catalyst by reacting Pd<sub>2</sub>(dba)<sub>3</sub> with the electron-rich phosphine ligand  $P(2-furyl)_3$  in the presence of CuI in DMF and  $iPr_2NEt$ . This catalyst facilitated the conversion of either 45 or 46 into the desired 3,4,5-trialkynyl pyridine 48 in good yield. Finally, Pd/C-catalyzed hydrogenation saturated the



Scheme 10 Total synthesis of desmosine (50).

trialkynyl motif, generating the corresponding alkyl side chain.

Regioselective Sonogashira coupling was also used by Baran and Shenvi in 2006 to combine the doubly halogenated indole 51 and imidazole-containing alkyne 52 in the total synthesis of chartelline C (55).<sup>23</sup> The active C–I bond facilitated the Pd/Cu-catalyzed cross-coupling and gave the desired indole-imidazole product 53 in 85% yield, leaving the C–Br bond intact (Scheme 11). These results indicate that Sonogashira coupling



Scheme 11 Total synthesis of chartelline C (55) and aspidophytine (61).

can tolerate imidazoles, which should be useful for synthesizing alkaloids. The alkyne motif was then selectively reduced with RANEY® nickel to olefin 54 with Z geometry and subsequently transformed by macrocyclization.

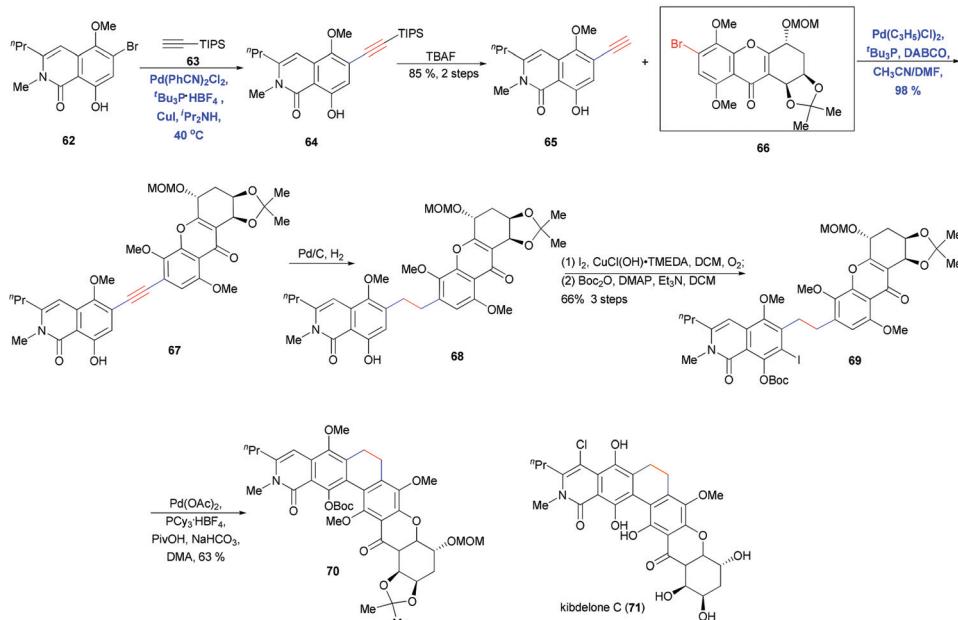
Another example of Sonogashira coupling followed by stereoselective reduction was reported by Tokuyama and Fukuyama and co-workers in 2003 with the convergent total synthesis of indole-type alkaloid aspidophytine (61).<sup>24</sup>  $Pd(PPh_3)_4$  and  $CuI$  in  $Et_3N$  solvent reliably cross-coupled 56 and terminal alkyne 57, which contains an all-carbon quaternary center, furnished the corresponding product in 94% yield (Scheme 11). The conjugated enyne allowed subsequent construction of the Z olefin in aspidophytine (61).

Silyl acetylene carrying either the TMS or TIPS group is a two-carbon alkyne building block that can act as a mono- or double cross-coupling component to elongate a carbon chain or couple fragments. This building block has been used by Ready and co-workers in the total synthesis of kibdelone C (71) (Scheme 12).<sup>25</sup> Cross-coupling of 62 and (triisopropyl)acetylene 63 followed by desilylation generated another terminal alkyne 65 in 85% yield. A second Sonogashira coupling of 65 with 66 gave the desired coupling product in nearly quantitative yield; this reaction was carried out in the absence of Cu and with slow addition of the alkyne in order to avoid oxidative dimerization. Subsequent hydrogenation, iodination and protection generated 69, which underwent ring closure *via* intramolecular C–H bond arylation.

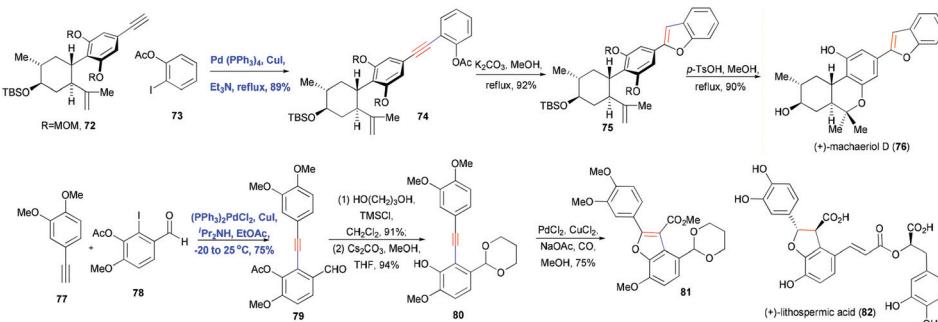
### 2.3. Sonogashira coupling followed by regioselective annulation

Heterocycles are ubiquitous in natural products, pharmaceuticals, dyes and organic materials. “*Of the more than 20 million chemical compounds currently registered, about one half contain heterocyclic systems.*”<sup>26</sup> As a result, the efficient construction of heterocycles is of great significance in organic synthesis. Sonogashira coupling to generate substituted alkynes followed by their regioselective hetero-annulation can be used to construct furan, benzofuran, indole, oxindole, isoquinolinone, isochromanone rings and related structures. An even greater diversity of hetero-annulation products can be achieved by adding a base to increase the nucleophilicity of hetero-nucleophiles or by using transition metal catalysts to activate the alkynes. Here we describe some examples of Sonogashira coupling in the total synthesis of natural products in which the alkyne is transformed into a heterocyclic ring.

In 2006, Pan, She and co-workers reported using Sonogashira coupling followed by regioselective hetero-annulation to construct a benzofuran ring as part of the asymmetric synthesis of (+)-machaeiol D (76).<sup>27</sup> Cross-coupling 72 with *ortho*-iodophenyl acetate 73 in the presence of Pd–Cu cocatalyst gave intermediate 74 in 89% yield (Scheme 13). Subsequent saponification and cyclization of phenolic acetate 74 afforded the desired benzofuran 75 in high yield. A similar example is the total synthesis of frondosin B reported by Danishefsky and co-workers,<sup>28</sup> who used a one-pot, Pd/Cu-cocatalyzed Sonogashira coupling and hetero-annulation sequence to combine a



Scheme 12 Total synthesis of kibdelone C (71).



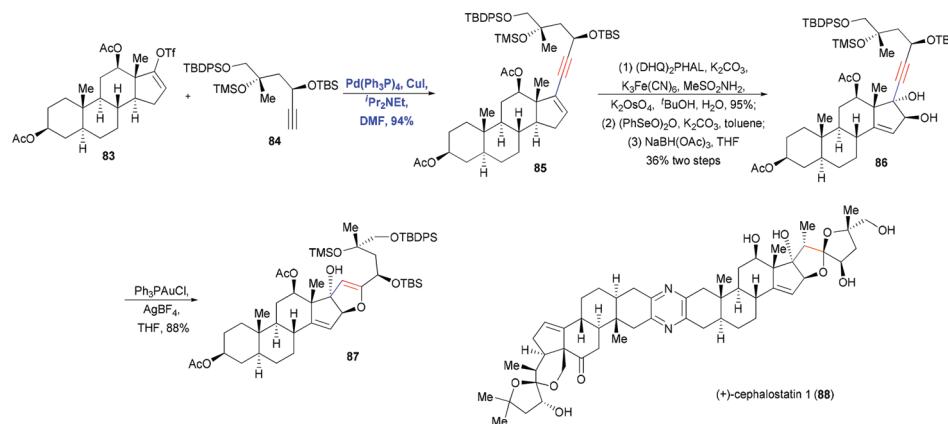
Scheme 13 Total synthesis of (+)-machaeriol D (76) and (+)-lithospermic acid (82).

terminal alkyne and *ortho*-iodophenol. Coster and co-workers used this approach in the formal total synthesis of lithospermic acid (82) (Scheme 13).<sup>29</sup> In this synthesis, Sonogashira coupling of fragments 77 and 78 generated 79 in good yield, during which the aldehyde group was protected as acetal. Deacetylation was carefully performed at low temperature to avoid direct annulation. Carbonylative annulation of *ortho*-hydroxydiarylalkyne 80 was catalyzed with  $\text{PdCl}_2$  and  $\text{CuCl}_2$  in the presence of CO, which not only installed the benzofuran but also introduced a carbomethoxy functionality.

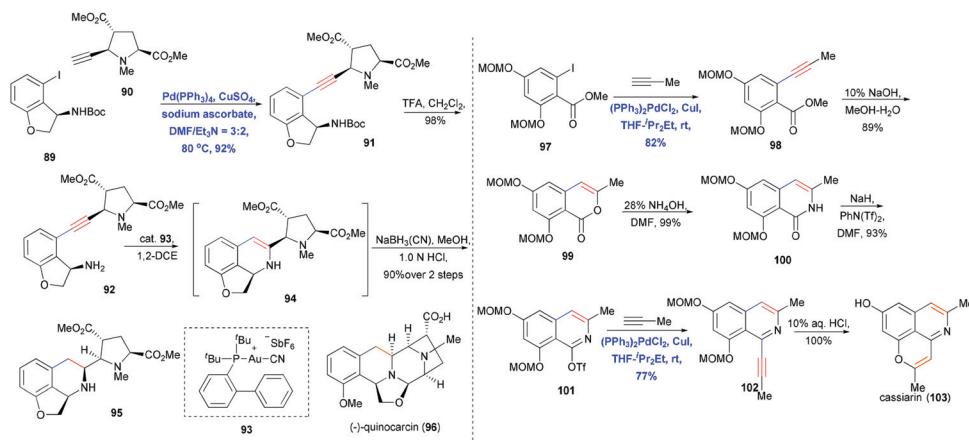
A particularly impressive example of Sonogashira coupling followed by hetero-annulation was reported by Shair and co-workers in the total synthesis of cephalostatin 1 (88).<sup>30</sup> In this approach, Pd-catalyzed Sonogashira coupling and Au-catalyzed hetero-annulation were used to construct the dihydrofuran ring (Scheme 14). Cross-coupling of vinyl triflate 83 and terminal alkyne 84 in the presence of  $\text{Pd}(\text{PPh}_3)_4$ ,  $\text{CuI}$  and  ${}^1\text{Pr}_2\text{NET}$  in DMF produced the enyne 85 in 94% yield. After a two-step

sequence in which Sharpless dihydroxylation and oxidation generated an  $\alpha$ -hydroxy cyclopentenone, which was then reduced in a stereocontrolled manner, the *trans*-diol 86 was obtained in 36% yield. Activation of the alkyne motif with Au(i) and subsequent nucleophilic attack by a hydroxyl group led to the formation of dihydrofuran 87 in 88% yield through 5-*endo*-dig cyclization. This dihydrofuran was then used to install the spiroketal moiety in the right fragment of the natural cephalostatin 1 (88).

Tetrahydroisoquinoline-type alkaloids are a large family of isoquinoline natural products that have attracted considerable attention from chemists and biologists for their fascinating structures and remarkable biological activities.<sup>31</sup> The isoquinoline core of these compounds has traditionally been constructed using Pictet-Spengler condensation<sup>32</sup> and asymmetric imine hydrogenation.<sup>33</sup> Fujii, Ohno and co-workers reported a convergent synthesis of quinocarcin (96) using Sonogashira coupling and Au(i)-catalyzed hydroamination (Scheme 15).<sup>34</sup>



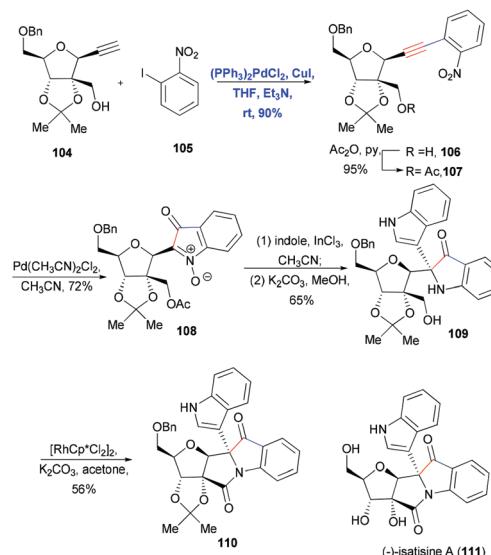
Scheme 14 Total synthesis of cephalostatin (88).



Scheme 15 Total synthesis of quinocarcin (96) and cassiarin A (103).

Cross coupling of **89** and **90** at 80 °C in the presence of  $Pd(PPh_3)_4$ ,  $CuSO_4$ , and sodium ascorbate in DMF and  $Et_3N$  gave the coupling product **91** in 92% yield. Using equimolar amounts of  $CuSO_4$  and sodium ascorbate effectively prevented the homocoupling side reaction. After extensively surveying reaction conditions and catalysts, the authors found **93** to be the most effective Au catalyst for hydroaminating the free amine-containing **92**. The desired 6-*endo*-dig annulation proceeded smoothly, giving **94** in high yield; this compound was then reduced with  $NaBH_3CN$  in a stereocontrolled fashion to form the tetrahydroisoquinoline core **95**.

An alternative way to generate the isoquinoline core *via* Sonogashira coupling was reported by Honda and co-workers, who prepared isoquinoline from isocoumarine to achieve the total synthesis of alkaloid cassiarin A (**103**) (Scheme 15).<sup>35</sup> The first Sonogashira coupling of iodide **97** and *in situ*-generated propyne was performed in the presence of Pd/Cu cocatalyst, yielding **98** in 82% yield. Hydrolysis followed by acidification generated the isocoumarine **99**, which was transformed into



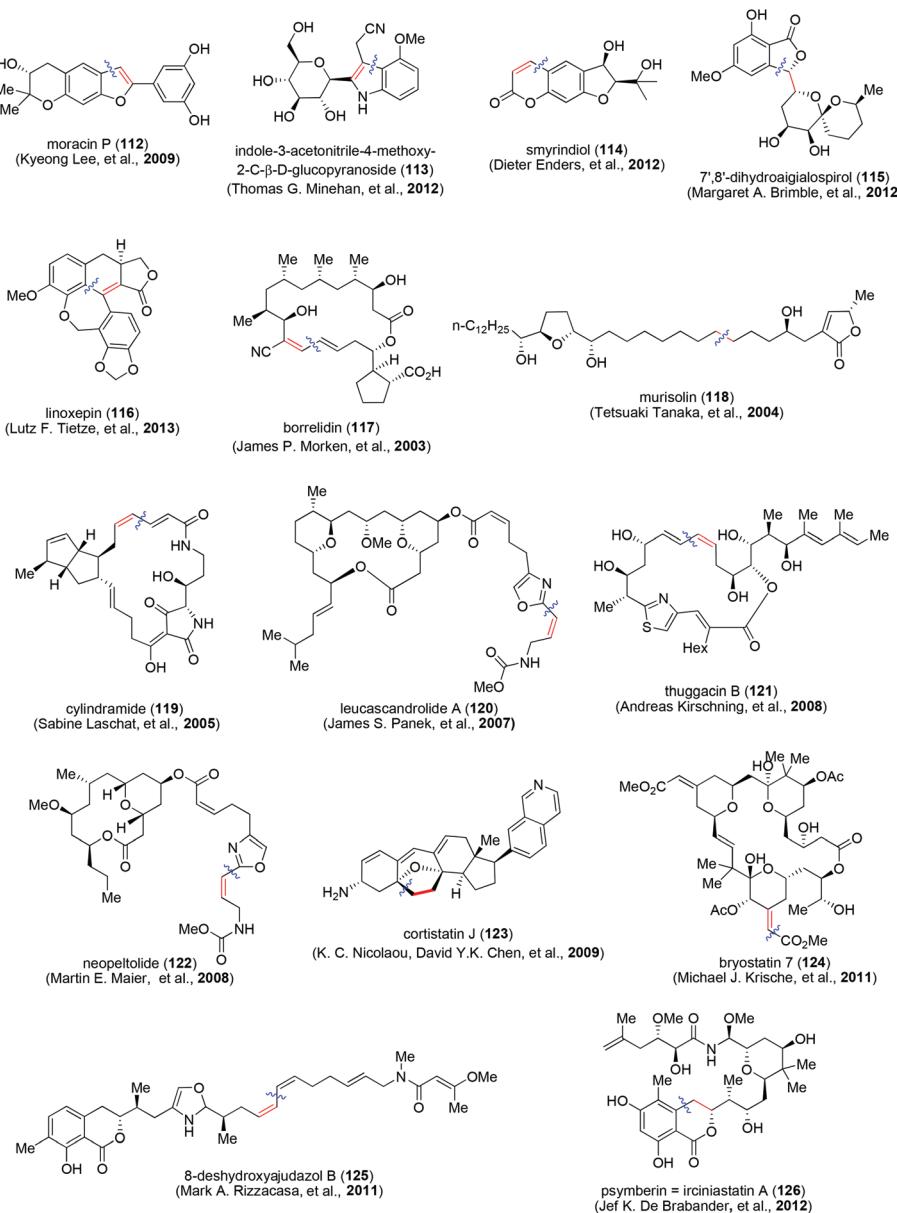
Scheme 16 Total synthesis of (-)-isatisine A (111).

isoquinolone **100** after treatment with ammonium hydroxide in DMF and cyclization of a ketoamide intermediate. Impressively, this isoquinolone was converted into its active triflate form **101**, which underwent a second Sonogashira coupling with propyne to furnish isoquinoline **102**. Finally deprotection using HCl promoted the 6-*endo*-dig annulation and provided cassiarin A (**103**) in quantitative yield.

In 2012, Ramana and co-workers reported the total synthesis of (−)-isatisine A (**111**)<sup>36</sup> using four consecutive metal-mediated transformations: Sonogashira coupling, Pd-catalyzed nitroalkyne cycloisomerization, InCl<sub>3</sub>-promoted indole addition and Rh-catalyzed oxidative N-heterocyclization (Scheme 16). The standard Sonogashira coupling furnished the nitroalkyne **106** in 90% yield, which underwent nitroalkyne cycloisomerization catalyzed by 5 mol% of Pd(CH<sub>3</sub>CN)<sub>2</sub>Cl<sub>2</sub>,

yielding isatogen **108** in 72% yield. Then the basic skeleton of **110** was efficiently constructed using another two metal-mediated transformations.

A selection of recent reports of total syntheses of natural products with intriguing structural features and involving Sonogashira coupling are shown in Fig. 2. They include moracin P (**112**, Kyeong Lee and co-workers, 2009),<sup>37</sup> indole-3-acetonitrile-4-methoxy-2-C-β-D-glucopyranoside (**113**, Thomas G. Minehan and co-workers, 2012);<sup>38</sup> smyrindiol (**114**, Dieter Enders and co-workers, 2012);<sup>39</sup> 7',8'-dihydroaigialospirol (**115**, Margaret A. Brimble and co-workers, 2012);<sup>40</sup> linoxepin (**116**, Lutz F. Tietze and co-workers, 2013);<sup>41</sup> borrelidin (**117**, James P. Morken and co-workers, 2003);<sup>42</sup> murisolin (**118**, Tetsuaki Tanaka and co-workers, 2004);<sup>43</sup> cylindramide (**119**, Sabine Laschat and co-workers, 2005);<sup>44</sup> leucascandrolide A (**120**,



**Fig. 2** Total synthesis of natural products involving Sonogashira coupling.

James S. Panek and co-workers, 2007);<sup>45</sup> thuggacin B (121, Andreas Kirschning and co-workers, 2008);<sup>46</sup> neopeltolide (122, Martin E. Maier, 2008);<sup>47</sup> cortistatin J (123, K. C. Nicolaou, David Y.K. Chen, and co-workers, 2009);<sup>48</sup> bryostatin 7 (124, Michael J. Krische and co-workers, 2011);<sup>49</sup> 8-deshydroxyajudazol B (125, Mark A. Rizzacasa and co-workers, 2011)<sup>50</sup> and psymberin = irciniastatin A (126, Jef K. De Brabander and co-workers, 2012).<sup>51</sup>

### 3. Conclusion

Palladium-catalyzed inter/intramolecular cross-coupling reactions have dramatically improved the efficiency of organic synthesis. As we demonstrate herein, Sonogashira coupling provides an effective methodology for the construction of C–C bonds ( $sp-sp^2$ ) which has been widely used in the synthesis of natural products. Rational design using Sonogashira coupling and transformations based on the Sonogashira products facilitates the fragment coupling and construction of heterocycles in convergent approaches. At present, the traditional reaction procedure using a Pd–Cu co-catalyzed system in the presence of an amine predominates in most cases. There is no doubt that more synthetic applications will be reported with the improvement and development of catalysts, ligands and reaction conditions.

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### References

- (a) *Metal-Catalyzed Cross-Coupling Reactions*, ed. A. de Meijere and F. Diederich, Wiley-VCH, Weinheim, 2nd edn, 2004; (b) *Handbook of Organopalladium Chemistry for Organic Synthesis*, ed. E. Negishi, Wiley Interscience, New York, 2002; (c) *Cross-Coupling Reactions: A Practical Guide*, ed. N. Miyaura, Springer, Berlin, 2002; (d) *Metal-Catalyzed Cross Coupling Reactions*, ed. P. J. Stang and F. Diederick, Wiley-VCH, Weinheim, 1998; For reviews of the Heck reaction, see: (e) A. de Meijere and F. E. Meyer, *Angew. Chem., Int. Ed. Engl.*, 1994, **33**, 2379–2411; (f) M. Shibasaki and E. M. Vogl, *J. Organomet. Chem.*, 1999, **576**, 1–15; (g) I. P. Belestskaya and A. V. Cheprakov, *Chem. Rev.*, 2000, **100**, 3009–3066; (h) M. Shibasaki, C. D. J. Boden and A. Kojima, *Tetrahedron*, 1997, **53**, 7371–7393; For reviews of the Stille reaction, see: (i) V. Farina, V. Krishnamurthy and W. J. Scott, *Org. React.*, 1997, **50**, 1–652; (j) J. K. Stille, *Angew. Chem., Int. Ed. Engl.*, 1986, **25**, 508–524; (k) P. Espinet and A. M. Echavarren, *Angew. Chem., Int. Ed.*, 2004, **43**, 4704–4734; For reviews of the Suzuki reaction, see: (l) A. Suzuki, *Acc. Chem. Res.*, 1982, **15**, 178–184; (m) N. Miyaura and A. Suzuki, *Chem. Rev.*, 1995, **95**, 2457–2483; For reviews of Negishi reactions, see: (n) E. Negishi and L. Anastasia, *Chem. Rev.*, 2003, **103**, 1979–2018; For reviews of the Tsuji-Trost reaction, see: (o) B. M. Trost, *Acc. Chem. Res.*, 1980, **13**, 385–393; (p) J. Tsuji, *Tetrahedron*, 1986, **42**, 4361–4401; For reviews of the palladium-catalyzed asymmetric alkylation reaction, see: (q) B. M. Trost and M. L. Crawley, *Chem. Rev.*, 2003, **103**, 2921–2943; (r) B. M. Trost, *J. Org. Chem.*, 2004, **69**, 5813–5837; For reviews of palladium-catalyzed cross-coupling reactions in total synthesis, see: (s) K. C. Nicolaou, P. G. Bulger and D. Sarlah, *Angew. Chem., Int. Ed.*, 2005, **42**, 4442–4489.
- (a) R. R. Tykwinski, *Angew. Chem., Int. Ed.*, 2003, **42**, 1566–1568; (b) R. Rossi, A. Carpita and F. Bellina, *Org. Prep. Proced. Int.*, 1995, **27**, 127–160; (c) K. Sonogashira, in *Comprehensive Organic Synthesis*, ed. B. M. Trost and I. Fleming, Pergamon, Oxford, 1991, vol. 3, p. 521; (d) R. Chinchilla and C. Nájera, *Chem. Rev.*, 2007, **107**, 874–922; (e) H. Doucet and J.-C. Hierro, *Angew. Chem., Int. Ed.*, 2007, **46**, 834–871; (f) R. Chinchilla and C. Nájera, *Chem. Soc. Rev.*, 2011, **40**, 5084–5121.
- (a) I. Paterson, R. D. M. Davies and R. Marquez, *Angew. Chem., Int. Ed.*, 2001, **40**, 603–607; (b) I. Paterson and T. Paquet, *Org. Lett.*, 2010, **12**, 2158–2161.
- B. Vaz, L. Otero, R. Álvarez and Á. R. de Lera, *Chem. – Eur. J.*, 2013, **19**, 13065–13074.
- (a) J. Taunton, J. L. Wood and S. L. Schreiber, *J. Am. Chem. Soc.*, 1993, **115**, 10378–10379; (b) J. L. Wood, J. A. Porco Jr., J. Taunton, A. Y. Lee, J. Clardy and S. L. Schreiber, *J. Am. Chem. Soc.*, 1992, **114**, 5898–5900; (c) H. Chikashita, J. A. Porco Jr., T. J. Stout, J. Clardy and S. L. Schreiber, *J. Org. Chem.*, 1991, **56**, 1692–1694; (d) J. A. Porco Jr., F. J. Schoenen, T. J. Stout, J. Clardy and S. L. Schreiber, *J. Am. Chem. Soc.*, 1990, **112**, 7410–7411.
- (a) A. G. Myers, P. C. Hogan, A. R. Hurd and S. D. Goldberg, *Angew. Chem., Int. Ed.*, 2002, **41**, 1062–1067; (b) Y. Koyama, M. J. Lear, F. Yoshimura, I. Ohashi, T. Mashimo and M. Hirama, *Org. Lett.*, 2005, **7**, 267–270, and references therein.
- K. C. Nicolaou, C. W. Hummel, E. N. Pitsinos, M. Nakada, A. L. Smith, K. Shibayama and H. Saimoto, *J. Am. Chem. Soc.*, 1992, **114**, 10082–10084.
- H. Dieck and F. Heck, *J. Organomet. Chem.*, 1975, **93**, 259–263.
- L. Cassar, *J. Organomet. Chem.*, 1975, **93**, 253–257.
- K. Sonogashira, Y. Tohda and N. Hagihara, *Tetrahedron Lett.*, 1975, **16**, 4467–4470.
- (a) G. Evano, N. Blanchard and M. Toumi, *Chem. Rev.*, 2008, **108**, 3054–3131; (b) P. Siemsen, R. C. Livingston and F. Diederich, *Angew. Chem., Int. Ed.*, 2000, **39**, 2632–2657.
- (a) B. M. Trost and T. N. Salzmann, *J. Am. Chem. Soc.*, 1973, **95**, 6840–6842; (b) B. M. Trost, *Science*, 1983, **219**, 245–250;

- (c) R. A. Shenvi, D. P. O'Malley and P. S. Baran, *Acc. Chem. Res.*, 2009, **42**, 530–541.
- 13 (a) B. M. Trost, *Science*, 1991, **254**, 1471–1477; (b) B. M. Trost, *Angew. Chem., Int. Ed. Engl.*, 1995, **34**, 259–281.
- 14 (a) P. A. Wender, M. P. Croatt and B. Witulski, *Tetrahedron*, 2006, **62**, 7505–7511; (b) P. A. Wender, V. A. Verma, T. J. Paxton and T. H. Pillow, *Acc. Chem. Res.*, 2008, **41**, 40–49; (c) P. A. Wender and B. L. Miller, *Nature*, 2009, **460**, 197–201.
- 15 (a) J. M. Richter, Y. Ishihara, T. Masuda, B. W. Whitefield, T. Llamas, A. Pohjakallio and P. S. Baran, *J. Am. Chem. Soc.*, 2008, **130**, 17938–17954; (b) N. Z. Burns, P. S. Baran and R. W. Hoffmann, *Angew. Chem., Int. Ed.*, 2009, **48**, 2854–2867.
- 16 (a) *Classics in Total Synthesis*, ed. K. C. Nicolaou and E. J. Sorensen, Wiley-VCH, Weinheim, 1996; (b) *Classics in Total Synthesis II*, ed. K. C. Nicolaou and S. A. Snyder, Wiley-VCH, Weinheim, 2003; (c) *Classics in Total Synthesis III*, ed. K. C. Nicolaou and J. S. Chen, Wiley-VCH, Weinheim, 2010.
- 17 *The Logic of Chemical Synthesis*, ed. E. J. Corey and X.-M. Cheng, Wiley-VCH, Weinheim, 1995.
- 18 K. Komano, S. Shimamura, M. Inoue and M. Hirama, *J. Am. Chem. Soc.*, 2007, **129**, 14184–14186.
- 19 M. B. Andrus, S. D. Lepore and T. M. Turner, *J. Am. Chem. Soc.*, 1997, **119**, 12159–12169.
- 20 P. Wipf and T. H. Graham, *J. Am. Chem. Soc.*, 2004, **126**, 15346–15347.
- 21 D. K. Mohapatra, D. Bhattachari, M. K. Gurjar, M. I. Khan and K. S. Shashidhara, *Eur. J. Org. Chem.*, 2008, 6213–6224.
- 22 T. Usuki, H. Yamada, T. Hayashi, H. Yanuma, Y. Koseki, N. Suzuki, Y. Masuyama and Y. Y. Linb, *Chem. Commun.*, 2012, **48**, 3233–3235.
- 23 P. S. Baran and R. A. Shenvi, *J. Am. Chem. Soc.*, 2006, **128**, 14028–14029.
- 24 T. Miyazaki, S. Yokoshima, S. Simizu, H. Osada, H. Tokuyama and T. Fukuyama, *Org. Lett.*, 2007, **9**, 4737–4740.
- 25 J. R. Butler, C. Wang, J. Bian and J. M. Ready, *J. Am. Chem. Soc.*, 2011, **133**, 9956–9959.
- 26 *The Chemistry of Heterocycles*, ed. T. Eicher and S. Hauptmann, Wiley-VCH, Weinheim, 2nd edn, 2003.
- 27 Q. Wang, Q. Huang, B. Chen, J. Lu, H. Wang, X. She and X. Pan, *Angew. Chem., Int. Ed.*, 2006, **45**, 3651–3653.
- 28 M. Inoue, M. W. Carson, A. J. Frontier and S. J. Danishefsky, *J. Am. Chem. Soc.*, 2001, **123**, 1878–1889.
- 29 J. Fischer, G. P. Savage and M. J. Coster, *Org. Lett.*, 2011, **13**, 3376–3379.
- 30 K. C. Fortner, D. Kato, Y. Tanaka and M. D. Shair, *J. Am. Chem. Soc.*, 2010, **132**, 275–280.
- 31 (a) D. Jack and R. Williams, *Chem. Rev.*, 2002, **102**, 1669–1730; (b) K. W. Bentley, *Nat. Prod. Rep.*, 2006, **23**, 444–463; (c) Q. Y. Zhang, G. Z. Tu, Y. Y. Zhao and T. M. Cheng, *Tetrahedron*, 2002, **58**, 6795–6798; (d) A. J. Aladesanmi, C. J. Kelly and J. D. Leary, *J. Nat. Prod.*, 1983, **46**, 127–131; (e) A. Zhang, J. L. Neumeyer and R. J. Baldessarini, *Chem. Rev.*, 2007, **107**, 274–302; (f) K. Ye, Y. Ke, N. Keshava, J. Shanks, J. A. Kapp, R. R. Tekmal, J. Petros and H. C. Joshi, *Proc. Natl. Acad. Sci. U. S. A.*, 1998, **95**, 1601–1606.
- 32 (a) M. Chrzanowska and M. D. Rozwadowska, *Chem. Rev.*, 2004, **104**, 3341–3370; (b) J. Stęcik, A. P. Antonchick, F. Wu and H. Waldmann, *Angew. Chem., Int. Ed.*, 2011, **50**, 8538–8564.
- 33 (a) Y. G. Zhou, *Acc. Chem. Res.*, 2007, **40**, 1357–1366; (b) D. S. Wang, Q. A. Chen, S. M. Lu and Y. G. Zhou, *Chem. Rev.*, 2012, **112**, 2557–2590.
- 34 (a) H. Chiba, S. Oishi, N. Fujii and H. Ohno, *Angew. Chem., Int. Ed.*, 2012, **51**, 9169–9172; (b) H. Chiba, Y. Sakai, A. Ohara, S. Oishi, N. Fujii and H. Ohno, *Chem. – Eur. J.*, 2013, **19**, 8875–8883.
- 35 M. Rudyanto, Y. Tomizawa, H. Morita and T. Honda, *Org. Lett.*, 2008, **10**, 1921–1922.
- 36 P. Patel and C. V. Ramana, *J. Org. Chem.*, 2012, **77**, 10509–10515.
- 37 N. Kaur, Y. Xia, Y. L. Jin, N. T. Dat, K. Gajulapati, Y. Choi, Y.-S. Hong, J. J. Lee and K. Lee, *Chem. Commun.*, 2009, 1879–1881.
- 38 A. Yepremyan and T. G. Minehan, *Org. Biomol. Chem.*, 2012, **10**, 5194–5196.
- 39 D. Enders, J. Fronert, T. Bisschops and F. Boeck, *Beilstein J. Org. Chem.*, 2012, **8**, 1112–1117.
- 40 T.-Y. Yuen and M. A. Brimble, *Org. Lett.*, 2012, **14**, 5154–5157.
- 41 L. F. Tietze, S.-C. Duefert, J. Clerc, M. Bischoff, C. Maaß and D. Stalke, *Angew. Chem., Int. Ed.*, 2013, **52**, 3191–3194.
- 42 M. O. Duffey, A. LeTiran and J. P. Morken, *J. Am. Chem. Soc.*, 2003, **125**, 1458–1459.
- 43 N. Maezaki, H. Tominaga, N. Kojima, M. Yanai, D. Urabe and T. Tanaka, *Chem. Commun.*, 2004, 406–407.
- 44 (a) N. Cramer, S. Laschat, A. Baro, H. Schwalbe and C. Richter, *Angew. Chem., Int. Ed.*, 2005, **44**, 820–822; (b) N. Cramer, M. Buchweitz, S. Laschat, W. Frey, A. Baro, D. Mathieu, C. Richter and H. Schwalbe, *Chem. – Eur. J.*, 2006, **12**, 2488–2503.
- 45 Q. B. Su, L. A. Dakin and J. S. Panek, *J. Org. Chem.*, 2007, **72**, 2–24.
- 46 M. Bock, R. Dehn and A. Kirschning, *Angew. Chem., Int. Ed.*, 2008, **47**, 9134–9137.
- 47 V. V. Vintonyak, B. Kunze, F. Sasse and M. E. Maier, *Chem. – Eur. J.*, 2008, **14**, 11132–11140.
- 48 K. C. Nicolaou, X. S. Peng, Y. P. Sun, D. Polet, B. Zou, C. S. Lim and D. Y. K. Chen, *J. Am. Chem. Soc.*, 2009, **131**, 10587–10597.
- 49 Y. Lu, S. K. Woo and M. J. Krische, *J. Am. Chem. Soc.*, 2011, **133**, 13876–13879.
- 50 S. Birkett, D. Ganame, B. C. Hawkins, S. Meiries, T. Quach and M. A. Rizzacasa, *Org. Lett.*, 2011, **13**, 1964–1967.
- 51 Y. Feng, X. Jiang and J. K. De Brabander, *J. Am. Chem. Soc.*, 2012, **134**, 17083–17093.