

Répondre éventuellement sur la présente feuille d'énoncé en indiquant son N° étudiant.
Documents et calculatrices interdits – Portables et assimilés doivent être éteints.

En relation avec la publication ci-jointe, répondez aux questions suivantes :

Exercice I

La réactivité du palladium est très riche pour ce qui concerne le couple Pd(0)/Pd(II). Différentes espèces du palladium à haute valence (Pd(IV) et Pd(III)) ont été récemment découvertes.

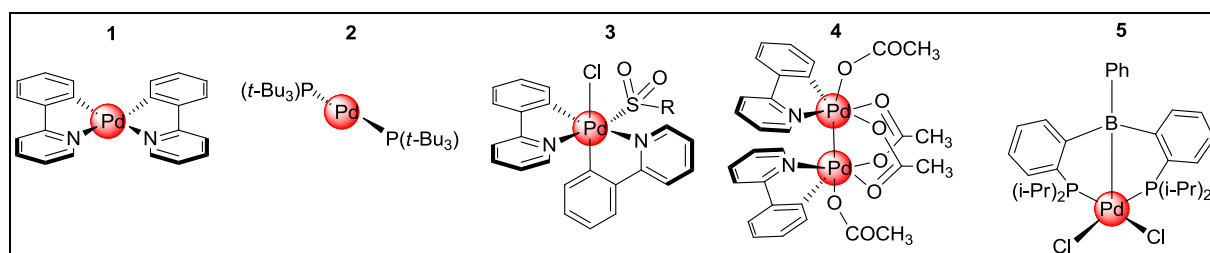



Schéma 1.

1.1 – Donner le degré d'oxydation formel et le nombre d'électrons sur la couche de valence des complexes métalliques **1**, **2**, **3**, **4** et **5** ci-dessus Schéma 1, en indiquant les ligands de type L, X ou Z coordonné à chaque centre métallique.

- **1** :
- **2** :
- **3** :
- **4** :
- **5** :

1.2 – Donner des conditions plausibles de réaction de couplages C–S pallado-catalysés entre un thiophénol et un chlorure d'aryle, et un thiophénol et un chlorure d'hétéroaryle (*écrire les deux équations équilibrées et indiquer les conditions que vous choisiriez et leur brève justification*)

-
-

	Master 2 Chimie Moléculaire-Dijon Contrôle de Chimie Organométallique et Catalyse (partie II)	N° Etudiant :	19 janvier 2015 Durée : 1h00 <i>Cours de J.-C. Hierso</i>
---	--	--------------------------------	---

Répondre éventuellement sur la présente feuille d'énoncé en indiquant son N° étudiant.
Documents et calculatrices interdits – Portables et assimilés doivent être éteints.

1.3 – D'après la publication de Zhao et Dong, les complexes du type **3** (**Schéma 1**) peuvent conduire à différentes réaction d'élimination réductrice.
Donner le type de liaison X–Y formées et la *formule développées des produits obtenus correspondants*. Quel est le facteur dominant la sélectivité de cette élimination réductrice ?

-

-

1.4 – Afin d'orienter la sélectivité vers une réaction spécifique d'élimination réductrice les auteurs choisissent d'ajouter un réactif. Quel est-il ? Quel est son rôle fondamental ? Donner la formule développée, le degré d'oxydation et le nombre d'électrons de valence du complexe de palladium issu des réactions du « *Scheme 2* » de l'article.

-

-

-

1.5 - Que diriez-vous des performances catalytiques du système présenté ? (*Justifier votre réponse quantitativement*)

-

1.6 – Sur la base des résultats précédents proposez d'autres réactifs que les chlorures de sulfonyle, susceptibles eux de conduire à l'élimination réductrice pour former une liaison C–O, C–F ou C–N :

-

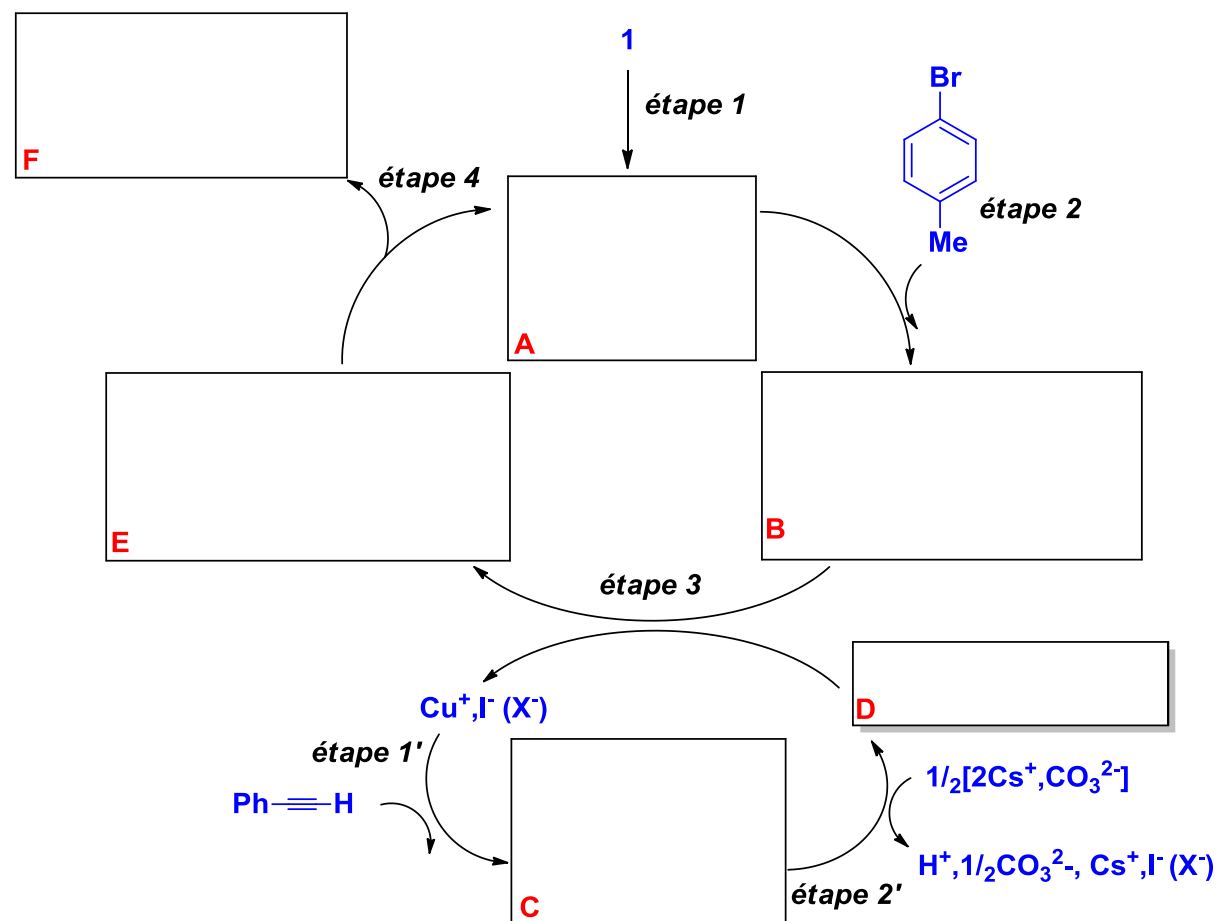
-

-

Répondre éventuellement sur la présente feuille d'énoncé en indiquant son N° étudiant.
 Documents et calculatrices interdits – Portables et assimilés doivent être éteints.

Exercice II

Le cycle catalytique classique proposé au palladium et au cuivre pour la réaction de Sonogashira est décrit ci-après.



2.1 – Indiquer une formule développée **plausible** de **A**, en détaillant la sphère de coordination du palladium, le ligand phosphoré et le degré d'oxydation du complexe.

2.2 – Dans le schéma ci-avant, représenter les complexes métalliques **B** à **E**, et leur degré d'oxydation, sans détailler le ligand (*écrire L_nPd*). Indiquer aussi **F**.

2.3 – Indiquer le **nom** des étapes élémentaires opérées sur les métaux dans le cycle proposé :

étape 1 :

étape 2 :

étape 3 :

étape 4 :

étape 1' :

étape 2' :

Barème indicatif – Question 1 : 14 points, Question 2 : 6 points.

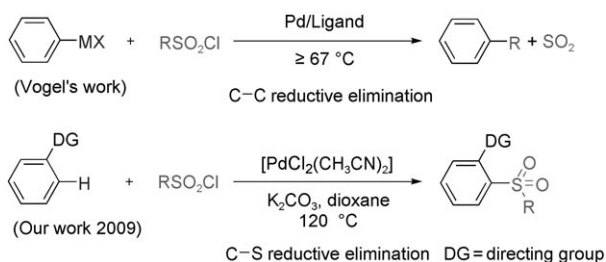
C–S Bond Formation

Carbon–Sulfur Reductive Elimination from Palladium(IV) Sulfinate Complexes**

Xiaodan Zhao and Vy M. Dong*

Palladium complexes are among the most versatile catalysts that are capable of constructing a variety of bonds.^[1,2] Consequently, fundamental studies on palladium complexes have a great impact on the design and understanding of practical catalytic processes. Studies on reductive elimination to form C–X bonds (X = CF₃, C, O, Cl, F) from Pd^{IV} complexes have recently been achieved.^[3–5] Despite the importance of sulfur-containing products,^[6] related mechanistic studies on C–S bond-forming reactions are rare.^[7] Herein we report the synthesis, characterization, and study of novel palladium(IV) sulfinate complexes. We describe the first direct observation of C–S bond-forming reductive elimination from Pd^{IV} complexes.^[1c]

Sulfonyl chlorides are convenient and versatile reagents for both palladium-catalyzed cross-coupling reactions and palladium-catalyzed C–H bond oxidation.^[8–10] Dubbaka and Vogel have reported cross-coupling reactions involving sulfonyl chlorides that occur by C–C reductive elimination with loss of SO₂.^[9] In contrast, we have observed C–H bond oxidations that presumably occur by C–S reductive elimination to produce sulfones.^[10] While Vogel's cross-coupling



reaction occurs via Pd⁰/Pd^{II} species, chelation-assisted C–H bond oxidation reactions are thought to occur via high-valent Pd species.^[11,12] However, direct evidence for C–S reductive elimination from high-valent Pd species has been elusive.^[13]

[*] Dr. X. Zhao, Prof. V. M. Dong
Department of Chemistry
University of Toronto
80 St. George Street
E-mail: vdong@chem.utoronto.ca

[**] We thank the University of Toronto, Canada Foundation for Innovation, Ontario Research Fund, and NSERC for funding. V.M.D. is grateful for an Alfred P. Sloan Fellowship. We acknowledge Prof. Melanie Sanford, Prof. Tobias Ritter, and Wiley O for suggestions, Elena Dimitrijević for help with synthesis and isolation of complex **3a**, and Dr. Alan Lough for X-ray crystallography.

Supporting information for this article is available on the WWW under <http://dx.doi.org/10.1002/anie.201005489>.

Inspired by this challenge, we aimed to 1) explore sulfonyl chlorides as oxidants for Pd^{II} and 2) study reductive elimination from palladium(IV) sulfinate complexes. Based on the previous reports,^[4,5] we chose [Pd(phpy)₂] (**1**, phpy = 2-phenylpyridyl) as the model complex for our initial investigations. Rigid and electron-rich C,N ligands are known to stabilize Pd^{IV} centers and promote the formation of carbon–carbon and carbon–heteroatom bonds.^[4,5] Indeed, treatment of complex **1** with 4-methylbenzenesulfonyl chloride (**2a**) in dichloromethane at room temperature for 20 minutes resulted in the desired palladium(IV) sulfinate complex **3a**, which was isolated as a yellow solid (66% yield; Table 1,

Table 1: Oxidation of [Pd(phpy)₂] to palladium(IV) sulfinate complexes using different sulfonyl chlorides.^[a]

Entry	2	R	3	Yield [%]
1	2a	4-MeC ₆ H ₄	3a	66
2	2b	4-MeOC ₆ H ₄	3b	53
3	2c	4-FC ₆ H ₄	3c	52
4	2d	Bn	3d	< 24
5	2e	CF ₃	3e	97

[a] Oxidation was performed in dichloromethane at room temperature. Complex **3b** was characterized by X-ray crystallography. Bn = benzyl.

entry 1). The molecular structure of complex **3a** was established by X-ray crystallography (Figure 1). The Pd–S bond (2.317 Å) is shorter than the Pd–Cl bond (2.421 Å). Complex **3a** is stable in the solid state and in a solution of dichloromethane for at least 5 days. However, **3a** will slowly decompose in a solution of dimethylsulfoxide (DMSO; 30% conversion in 5 days). Canty et al. have proposed the intermediacy of a palladium(IV) thiophenolate species,^[13]

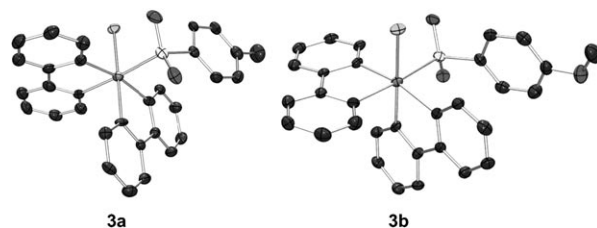


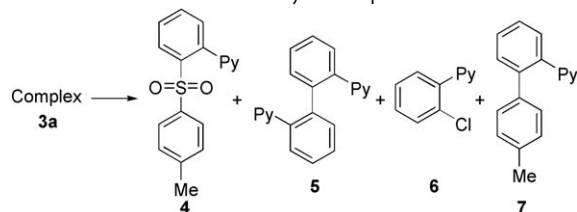
Figure 1. X-ray crystal structures of complexes **3a** and **3b**.

and characterized an unstable tris(pyrazolyl)borate analogue by ^1H NMR spectroscopy at -40°C .^[13b] To our knowledge, we have isolated and fully characterized the first Pd^{IV} complexes containing a $\text{Pd}-\text{SO}_2\text{R}$ bond.^[1,14,15]

We discovered that both aryl and alkyl sulfonyl chlorides oxidize complex **1** to generate palladium(IV) sulfinate complexes **3** (Table 1). Both electron-donating (methoxy) and electron-withdrawing (fluoro) substituents on the aryl sulfonyl chloride are tolerated (Table 1, entries 2 and 3). Oxidation of **1** with benzylsulfonyl chloride (**2d**) results in the corresponding palladium(IV) alkylsulfinate complex **3d**, albeit in low yield (Table 1, entry 4).^[16] In contrast, the use of trifluoromethanesulfonyl chloride (**2e**) provides complex **3e** in 97% yield in less than one minute at room temperature (Table 1, entry 5).

Next, we studied the transformation of complex **3a** at elevated temperatures in various solvents. We anticipated that decomposition of complex **3a** could result in various products including sulfone **4**, ligand dimer **5**, chloride **6**, and/or biphenyl **7**. These products result from C–S, C–C, C–Cl, and/or desulfinitative C–C bond formation, respectively. Heating complex **3a** results in the formation of all four products (Table 2). These results represent the first examples of

Table 2: Reductive elimination study of complex **3a**.^[a]



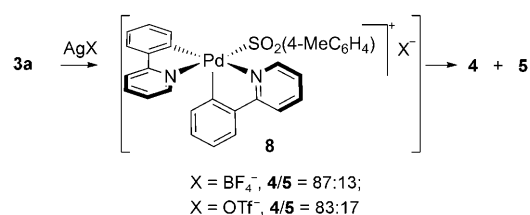
Entry	Solvent	4 [%]	5 [%]	6 [%]	7 [%]
1	DCE	52	19	8	1
2 ^[b]	DCE	71	14	9	1
3	AcOH	58	7	2	0
4	pyridine	64	17	10	<1
5	DMSO	58	30	5	<1

[a] Reductive elimination reactions were carried out at 120°C for 6 h. Yields were determined by gas chromatography based on an average of 2–3 runs, using dodecane as an internal standard. [b] 18 h.

C– SO_2R bond formation and C–C bond formation (with loss of SO_2) from a Pd^{IV} species. Our observations reveal that the formation of the C– SO_2R bond is favored over the formation of either C–C or C–Cl bonds. In 1,2-dichloroethane (DCE), sulfone **4** was observed as the major product (52%, 6 h; 71%, 18 h; Table 2, entries 1 and 2). In both acidic solvent (AcOH) and basic media (pyridine) we observed a preference for C–S bond formation, while desulfinitative C–C bond formation was suppressed (Table 2, entries 3 and 4). Complex **3a** underwent reductive elimination efficiently in DMSO to yield **4** as the major product (58%; Table 2, entry 5). Complexes **3b** and **3c** undergo reductive elimination to give comparable results to **3a**, while complex **3e** decomposes to give dimerization of the ligand.^[17]

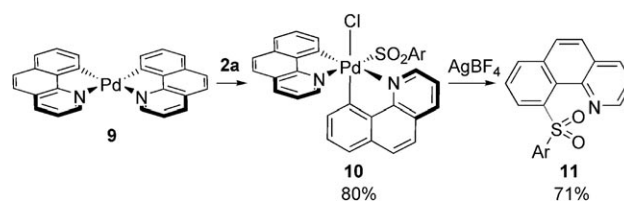
Elsevier and Sanford have shown that the addition of Ag salts (such as AgBF_4 and AgOTf) aids reductive elimination

by generating more reactive cationic intermediates.^[3b,4c] This salt metathesis results in a vacant coordination site on the Pd center. In accordance with these studies, **3a** was completely transformed into **4** and **5** when treated with AgBF_4 and AgOTf , respectively, at 120°C for 6 hours (Scheme 1). Product **6** was formed in trace amounts, but there was no



Scheme 1. Reductive elimination of **3a** upon addition of Ag salts. Tf = trifluoromethanesulfonyl.

product **7**. In each case, **4** was formed in more than 80% yield. This result suggests that the formation of the C– SO_2 bond may occur from a Pd^{IV} species via a five-coordinate cationic Pd^{IV} intermediate. Next, we examined the oxidation of complex **9** bearing a benzoquinoline ligand with 3 equivalents of **2a** at room temperature (Scheme 2). Complex **10** was



Scheme 2. Formation and reductive elimination of benzoquinoline-ligated palladium(IV) sulfinate complex **10**. Ar = 4- MeC_6H_4 .

produced in 80% yield. Sulfone **11** was obtained in 71% yield when complex **10** was treated with 1 equivalent of AgBF_4 . Crossover products were observed in less than 5% yield (based on gas chromatographic analysis) when complex **10** and **3b** were heated together. These results further support reductive elimination directly from Pd^{IV} as the major mechanistic pathway.

While these studies were inspired by our original sulfonylation reaction,^[10] they are not direct mechanistic studies of the catalytic process. Indeed, the use of complex **3a** as a catalyst for the ligand-assisted sulfonylation of C–H bonds results in less than two turnovers. Further kinetic and mechanistic studies are necessary to establish relevance to catalysis, but these results support the feasibility of palladium-catalyzed sulfonylation and desulfinitative C–C cross-coupling reactions through a $\text{Pd}^{\text{II}}/\text{Pd}^{\text{IV}}$ catalytic cycle.

To conclude, sulfonyl chlorides can oxidize Pd^{II} to Pd^{IV} to generate stable palladium(IV) sulfinate complexes. These novel complexes undergo reductive elimination to give products with C–S, C–C, and C–Cl bonds. This fundamental contribution to organopalladium(IV) chemistry will aid future studies on carbon–sulfur bond formation and bond activation.

Experimental Section

Complex **3a**: A 5 mL vial was charged with Pd^{II} complex **1** (8.3 mg, 0.02 mmol), 4-methylbenzenesulfonyl chloride (4.56 mg, 0.024 mmol), and dichloromethane (0.5 mL). The resulting solution was stirred at room temperature for 20 min. The solvent was removed under reduced pressure to afford a yellow residue. The resulting residue was washed with Et₂O (1 mL×3) and dissolved in a mixture of chloroform and hexanes (0.3 mL, CHCl₃/hexanes = 5:1, v/v). After 15 h, a yellow solid precipitated from the solution. The resulting mixture was filtered through a Celite plug in a Pasteur pipette. The solid was collected on the top of the Celite plug and washed with a mixture of chloroform and hexanes (0.2 mL×2, CHCl₃/hexanes = 1:1, v/v). The original vial and Celite were then washed with dichloromethane. The dichloromethane eluent was collected, concentrated, and dried in vacuo to afford a yellow solid. This reaction was conducted five times. The yellow solid **3a** was obtained in an average yield of 66% (8.0 mg). A single crystal suitable for X-ray diffraction was grown by diffusion of diethyl ether into a solution of **3a** in *N,N*-dimethylformamide.

Received: September 1, 2010

Published online: November 29, 2010

Keywords: organometallic reactions · palladium · reductive elimination · sulfonyl chlorides · sulfur

- [1] For reviews on Pd^{II}/Pd^{IV} catalysis, see: a) K. Muñoz, *Angew. Chem.* **2009**, *121*, 9576; *Angew. Chem. Int. Ed.* **2009**, *48*, 9412; b) A. J. Canty, *Dalton Trans.* **2009**, 10409; c) P. Sehnal, R. J. K. Taylor, I. J. S. Fairlamb, *Chem. Rev.* **2010**, *110*, 824; d) L.-M. Xu, B.-J. Li, Z. Yang, Z.-J. Shi, *Chem. Soc. Rev.* **2010**, *39*, 712; e) T. M. Lyons, M. S. Sanford, *Chem. Rev.* **2010**, *110*, 1147.
- [2] For selected reviews on Pd⁰/Pd^{II} catalysis, see: a) E. M. Beccalli, G. Broggini, M. Martinelli, S. Sottocornola, *Chem. Rev.* **2007**, *107*, 5318; b) D. S. Surry, S. L. Buchwald, *Angew. Chem.* **2008**, *120*, 6438; *Angew. Chem. Int. Ed.* **2008**, *47*, 6338; c) A. Brennfürer, H. Neumann, M. Beller, *Angew. Chem.* **2009**, *121*, 4176; *Angew. Chem. Int. Ed.* **2009**, *48*, 4114; d) X. Chen, K. M. Engle, D. H. Wang, J.-Q. Yu, *Angew. Chem.* **2009**, *121*, 5196; *Angew. Chem. Int. Ed.* **2009**, *48*, 5094.
- [3] a) P. K. Byers, A. J. Canty, A. H. Skelton, A. H. White, *J. Chem. Soc. Chem. Commun.* **1986**, 1722; b) R. van Asselt, E. Rijnberg, C. J. Elsevier, *Organometallics* **1994**, *13*, 706; c) A. J. Canty, H. Jin, A. S. Roberts, B. W. Skelton, A. H. White, *Organometallics* **1996**, *15*, 5713; d) Y. Yamamoto, T. Ohno, K. Itoh, *Angew. Chem.* **2002**, *114*, 3814; *Angew. Chem. Int. Ed.* **2002**, *41*, 3662; e) R. van Belzen, C. J. Elsevier, A. Dedieu, N. Veldman, A. L. Spek, *Organometallics* **2003**, *22*, 722; f) Y. Yamamoto, S. Kuwabara, S. Matsuo, T. Ohno, H. Nishiyama, K. Itoh, *Organometallics* **2004**, *23*, 389; g) J. Vicente, A. Arcas, F. Juliá-Hernández, D. Bautistab, *Chem. Commun.* **2010**, *46*, 7253.
- [4] a) A. R. Dick, J. W. Kampf, M. S. Sanford, *J. Am. Chem. Soc.* **2005**, *127*, 12790; b) S. R. Whitfield, M. S. Sanford, *J. Am. Chem. Soc.* **2007**, *129*, 15142; c) J. M. Racowski, A. R. Dick, M. S. Sanford, *J. Am. Chem. Soc.* **2009**, *131*, 10974; d) N. D. Ball, M. S. Sanford, *J. Am. Chem. Soc.* **2009**, *131*, 3796; e) P. L. Arnold, M. S. Sanford, S. M. Pearson, *J. Am. Chem. Soc.* **2009**, *131*, 13912; f) N. D. Ball, J. W. Kampf, M. S. Sanford, *J. Am. Chem. Soc.* **2010**, *132*, 2878.
- [5] a) T. Furuya, H. M. Kaiser, T. Ritter, *Angew. Chem.* **2008**, *120*, 6082; *Angew. Chem. Int. Ed.* **2008**, *47*, 5993; b) T. Furuya, T. Ritter, *J. Am. Chem. Soc.* **2008**, *130*, 10060; c) T. Furuya, D. Benitez, E. Tkatchouk, A. E. Strom, P. Tang, W. A. Goddard III, T. Ritter, *J. Am. Chem. Soc.* **2010**, *132*, 3793.
- [6] For general reviews, see: a) *Comprehensive Organic Chemistry*, Vol. 3 (Ed.: D. N. Jones), Pergamon, Oxford, **1979**, pp. 33–103; b) *The Chemistry of Sulfoxides and Sulfoxides* (Eds.: S. Patai, Z. Rappoport, C. J. M. Stirling), Wiley, New York, **1988**; c) R. M. Moriarty, R. Naithani, B. Surve, *Mini-Rev. Med. Chem.* **2007**, *7*, 827.
- [7] a) G. Mann, D. Baranano, J. F. Hartwig, A. L. Rheingold, I. A. Guzei, *J. Am. Chem. Soc.* **1998**, *120*, 9205; b) J. F. Hartwig, *Inorg. Chem.* **2007**, *46*, 1936.
- [8] a) S. S. Labadie, *J. Org. Chem.* **1989**, *54*, 2496; b) B. P. Bandgar, S. V. Bettigeri, J. Phopase, *Org. Lett.* **2004**, *6*, 2105.
- [9] a) S. R. Dubbaka, P. Vogel, *J. Am. Chem. Soc.* **2003**, *125*, 15292; b) S. R. Dubbaka, P. Vogel, *Angew. Chem.* **2005**, *117*, 7848; *Angew. Chem. Int. Ed.* **2005**, *44*, 7674; c) S. R. Dubbaka, P. Vogel, *Tetrahedron Lett.* **2006**, *47*, 3345.
- [10] X. Zhao, E. Dimitrijević, V. M. Dong, *J. Am. Chem. Soc.* **2009**, *131*, 3466.
- [11] a) L. V. Desai, K. J. Stowers, M. S. Sanford, *J. Am. Chem. Soc.* **2008**, *130*, 13285; b) N. R. Deprez, M. S. Sanford, *J. Am. Chem. Soc.* **2009**, *131*, 11234.
- [12] a) D. C. Powers, T. Ritter, *Nat. Chem.* **2009**, *1*, 302; b) D. C. Powers, M. A. L. Geibel, J. E. M. N. Klein, T. Ritter, *J. Am. Chem. Soc.* **2009**, *131*, 17050.
- [13] a) A. J. Canty, H. Jin, B. W. Skelton, A. H. White, *Inorg. Chem.* **1998**, *37*, 3975; b) A. J. Canty, H. Jin, *J. Organomet. Chem.* **1998**, *565*, 135.
- [14] a) J. P. Collman, W. R. Roper, *J. Am. Chem. Soc.* **1966**, *88*, 180; b) C. D. Cook, G. S. Jauhal, *Can. J. Chem.* **1967**, *45*, 301.
- [15] A Pd^{II} complex with a Pd–SO₂ bond has been reported, see: T. Kashiwabara, M. Tanaka, *Tetrahedron Lett.* **2006**, *46*, 7125.
- [16] Complex **3d** is not stable and will undergo decomposition at room temperature.
- [17] **3b** undergoes reductive elimination to produce 51% sulfone, 21% ligand dimer, 5% chloride, and no biaryl products. **3c** gives 51% sulfone, 7% ligand dimer, 17% chloride, and 1.5% of the biphenyl arising from desulfurative cross-coupling.