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# 2-Ferrocenyl-2-thiazoline as a building block of novel phosphine-free ligands†

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New 1,2-disubstituted ferrocenes [**5(b–j)**, in which R = –SMe, –SPh, –SiPr, –$SiMe_3$, –SePh, –$SnBu_3$, –$B(OH)_2$, –Me, –I] with a thiazoline ring in the ferrocene backbone using as key intermediate a ferrocenyl Fischer carbene complex were synthesized. The capability of the 2-thiazoline moiety as an *ortho*-directed metalation group was demonstrated by subsequent quenching of lithium intermediate with several electrophiles, proving to be an excellent method for synthesizing bidentate ligands. The catalytic scope of the [*N*,*S*] ligand **5b** as the corresponding palladium complex **5b-PdCl$_2$** in a microwave-promoted Heck reaction was also tested. Results obtained showed better catalytic activity of **5b-PdCl$_2$** compared to other catalytic systems based on a [*N*,*S*] ferrocenyl ligand.

## Introduction

Since the discovery of ferrocene in 1951,[1] this organometallic compound continues to be the focus of tremendous attention and, in fact, it has various applications.[2] As a result, currently a large number of ferrocenyl derivatives are widely used as ligands in homogeneous transition metal catalysts.[3]

The most widespread method for preparing 1,2-disubstituted ferrocenes is based on a directed *ortho*-metalation (DoM) reaction and its subsequent quenching with an appropriate electrophile.[4] On the basis of Ugi's pioneering work,[5] several 1,2-disubstituted ferrocenes can be accessed by a variety of DoM reactions using a suitable directed metalation group (DMG).[6] As a consequence of the great utility of this strategy, Sammakia,[7] Richards[8] and Uemura[9] simultaneously introduced oxazolines derived from amino alcohols as one of the most successful ligand motifs in homogeneous catalysis.[10] Similarly, the imidazoline ring has also been used for the same purpose.[11] Unlike the widely applied oxazoline ligands, thiazolines have rarely been used in catalysis although some studies have demonstrated that replacing an oxazoline motif with a thiazoline ring markedly changes the reactivity of the resulting ligand when applied in catalysis.[12]

In general, the synthesis of thiazolines involves the preparation of a thioamide precursor. Although the synthesis of alkyl thioamides is well-known,[13] few syntheses of ferrocenyl analogues have been reported, which may be due to the difficulty in obtaining a thiocarbonyl moiety directly bonded to the ferrocene. Reported methods for the synthesis of ferrocenyl thioamides lack generality, involve several steps, and have very low overall yields.[14] Nevertheless, we have previously reported that a sulfurative demetalation reaction of Fischer carbene complexes using elemental sulphur/$NaBH_4$ could be a convenient method for producing ferrocenyl thioamides.[15]

Despite efforts in this area, the synthesis of ferrocenyl thiazolines is seldom reported. In this regard, only some 5-ferrocenyl-2-thiazolines (Scheme 1) have been designed,[16] but to date no information on their use in catalysis as DMG or ligands has been reported.

To the best of our knowledge, there is no precedent in the literature regarding the use of the 2-thiazoline moiety as a DMG in the preparation of 1,2-disubstituted ferrocenes. Considering that both oxazoline and imidazoline rings have been known to be good directing groups in *ortho* lithiation, we expect that the thiazoline ring will also promote selective lithiation of ferrocene. In this context, we report the synthesis of 2-ferrocenyl-2-thiazoline as an efficient and easily accessible DMG for the preparation of a new family of 1,2-disubstituted ferrocenes using a synthetic strategy based on sulfurative demetalation of a Fischer aminocarbene complex. The catalytic applications of one of these ligands were tested in the palladium-catalyzed Mizoroki–Heck reaction.

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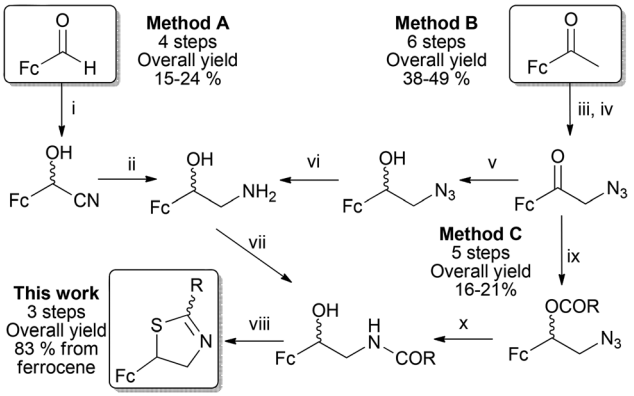
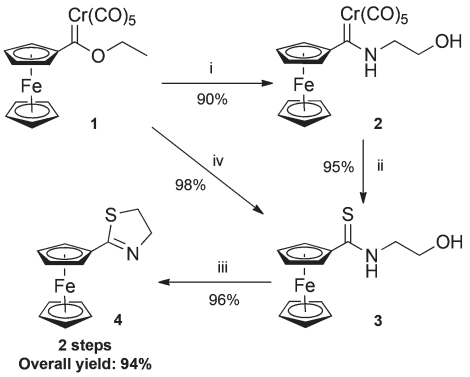



**Scheme 1** *Reagents and conditions*. (i) $Et_2AlCN$, THF, −78 °C; (ii) $LiAlH_4$, THF, reflux; (iii) LDA, $Me_3SiCl$, THF, −78 °C then NBS; (iv) (P)-$^+NR_3N_3^-$, $CH_2Cl_2$, rt; (v) $BH_3$·SMe, CBS oxazaborolidine, THF, 0 °C; (vi) $H_2$, Pd/C, EtOH, rt; (vii) RCOCl, $CH_2Cl_2$, $Et_3N$, rt; (viii) Lawesson reagent (2 equiv.), THF, reflux; (ix) *n*-BuLi, THF, −78 °C then RCOCl; (x) *n*-$Bu_3P$, THF, rt. Fc = ferrocenyl, CBS = Corey–Bakshi–Shibata catalyst, (P)-$^+NR_3N_3^-$ = polymeric quaternary ammonium azide.

## Results and discussion

Our retrosynthetic analysis of substituted 2-ferrocenyl-2-thiazolines **5** is described in Scheme 2. As detailed above, we expect that several functional groups might be introduced by a DoM/electrophile quench process using the 2-thiazoline ring as a DMG. We envisaged that the 2-thiazoline moiety could be constructed by an intramolecular cyclization of the corresponding *N*-(β-hydroxy) ferrocenylthioamide. We believe that the target thioamide **3** could be synthesized through a sulfurative demetalation reaction of a Fischer aminocarbene complex, which would in turn be derived from **1** *via* an aminolysis reaction with the appropriate β-amino alcohol. Finally, the Fischer ethoxycarbene complex required **1** to be synthesized in a straightforward manner using commercially available ferrocene.

At first, initial compound **1** was prepared from ferrocene, which was converted to a ferrocenyl-ethoxycarbene chromium complex in accordance with a protocol developed earlier by our group.[17] Thereafter, ethanolamine was added to easily obtain chromium ferrocenylaminocarbene complex **2**, which was isolated in high yields (95%) (Scheme 3).

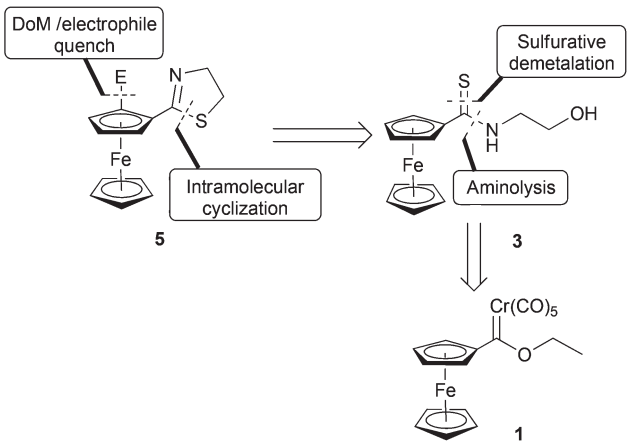



**Scheme 3** *Reagents and conditions.* (i) Ethanolamine, $Et_2O$, rt; (ii) $S_8/NaBH_4$, EtOH, rt; (iii) MsCl–$Et_3N$, $CH_2Cl_2$, 0 °C; (iv) Ethanolamine, EtOH, rt, then $S_8/NaBH_4$, EtOH, rt.

Complex **2** was subsequently transformed under mild conditions into ferrocenylthioamide **3** by a sulfurative demetalation reaction with $S_8/NaBH_4$.[15] Compound **3** was characterized by conventional spectroscopic techniques. The mass spectrum (EI) of **3** agrees with the molecular formula and confirms the loss of the metallic fragment [$Cr(CO_5)$]. The $^{13}C$ NMR spectrum exhibits a signal around $\delta$ = 198.4 ppm assigned to C═S.

The structural arrangement for **3** was fully established by a single-crystal X-ray diffraction analysis (Fig. 1).

The thiocarbonyl moiety is directly bonded to ferrocene; the sum of bond angles around C11 ($\Sigma$ = 360°) indicates that this group has a trigonal geometry. The bond distance C═S [S(1)–C(11) 1.677(2)] is quite similar to that of other reported thioamides, whereas the bond distance N(1)–C(11) 1.319(3) is slightly shorter.[18] The structure presents disorder of the unsubstituted Cp ring generating two orientations in 77 : 23 ratio. Only the major contributor is shown in Fig. 1.




**Scheme 2** Retrosynthetic approach for the synthesis of substituted 2-ferrocenyl-2-thiazolines.

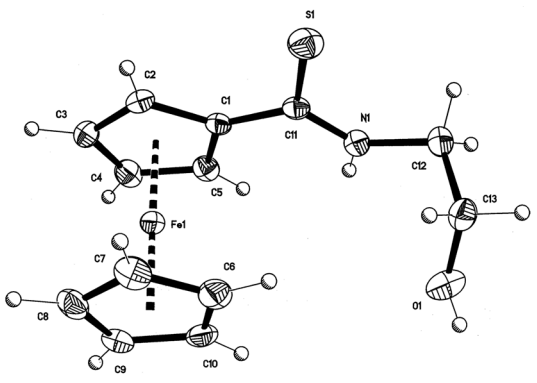


**Fig. 1** ORTEP representation of ferrocenyl thioamide **3**. Ellipsoids are shown at 30% probability level. Selected bond lengths [Å] and angles [°]: S(1)–C(11) 1.677 (2), N(1)–C(11) 1.319 (3), C(1)–C(11) 1.472 (3); N(1)–C(11)–S(1) 122.93(16), C(1)–C(11)–S(1) 120.87(15), N(1)–C(12)–C(13) 111.35(17).

Furthermore, the resulting ferrocenylthioamide **3** was converted to 2-ferrocenyl-2-thiazoline **4** using an intramolecular cyclization with *p*-TsOH or MsCl–$Et_3N$ in $CH_2Cl_2$ at room temperature. Acidic conditions for the cyclization step resulted in a moderate yield (76%), however, carrying out cyclization with 1.5 equiv. MsCl and 4 equiv. $Et_3N$ raises the yield to 96% in only 10 minutes, giving almost pure **4**. In an attempt to improve the yield of **4**, we used an aminolysis–sulfurative demetalation tandem reaction as the key sequence and as a consequence the yield of the intermediate thioamide **3** was increased. This slight modification enabled **4** to be prepared from the ferrocenyl ethoxycarbene chromium complex **1** with a 94% overall yield. The mass spectrum of **4** agrees with the molecular formula expected and confirms the cyclization of **3**. The $^1$H NMR spectrum shows two coupled triplet signals at 3.34 and 4.25 ppm assigned to the methylene groups of thiazoline, two broad singlet signals at 4.36 and 4.71 ppm that correspond to the hydrogens of monosubstituted Cp ring and finally a simple signal shifted at 4.2 ppm with integration of 5 hydrogens was assigned to the Cp ring. The $^{13}$C NMR spectrum exhibits two signals at 33.6 and 64.9 ppm for the methylene groups of thiazoline, and a signal at 168.8 ppm assigned to C=S. Characteristic signals for a monosubstituted ferrocene were also seen.

In order to confirm the structural arrangement of **4**, we conducted a coordination reaction between **4** and $Pd(CH_3CN)_2Cl_2$/$PPh_3$ obtaining the corresponding complex *cis*-**4-Pd($PPh_3Cl_2$)**, where the thiazoline moiety behaves as an *N*-monodentated ligand. Thus, suitable crystals were obtained and the structural arrangement for **4** was established by single-crystal X-ray diffraction analysis (Fig. 2).

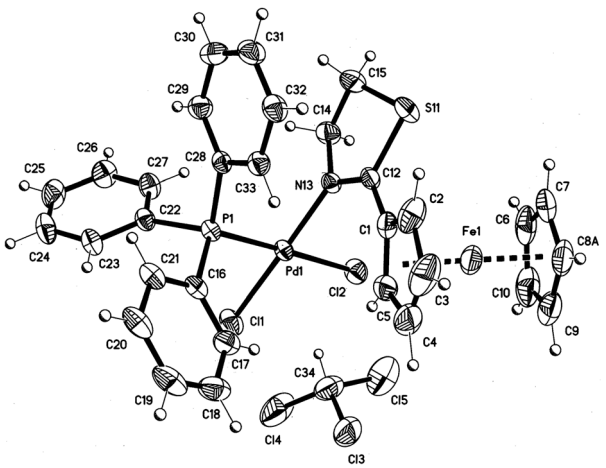



**Fig. 2** ORTEP representation of ferrocenyl thiazoline **4-Pd($PPh_3Cl_2$)**. Ellipsoids are shown at 30% probability level. Selected bond lengths [Å] and angles [°]: S(11)–C(12) 1.751 (2), S(11)–C(15) 1.803(4), C(12)–N(13) 1.276(3), N(13)–C(14) 1.474(3), C(14)–C(15) 1.519, C(1)–C(12) 1.449(4), Pd(1)–N(13) 2.020(2), Pd(1)–P(1) 2.244(1), Pd(1)–Cl(1) 2.287(1), 2.360(1); N(13)–Pd(1)–P(1) 93.72(6), N(13)–Pd(1)–Cl(1) 177.07(6), P(1)–Pd(1)–Cl(1) 87.00(3), N(13)–Pd(1)–Cl(2) 86.88(6), P(1)–Pd(1)–Cl(2) 178.60(3), Cl(1)–Pd(1)–Cl(2) 94.46(3), C(12)–S(11)–C(15) 89.98(13), N(12)–C(12)–C(1) 125.5(2), N(13)–C(12)–S(11) 115.82(19), C(1)–C(12)–S(11) 118.67(19), C(12)–N(13)–C(14) 113.5(2), C(12–N(13)–Pd(1) 128.87(17), N(13)–C(14)–C(15) 107.6(2), C(14)–C(15)–S(11) 104.9(2).

The coordination polyhedron around the palladium atom can be best described as being a distorted square-planar, in which the phosphine molecule and the nitrogen atom adopt a *cis* arrangement with P(1)–Pd(1)–N(13) angle of 93.72°. The thiazoline group is directly bonded to ferrocene at 2-position and adopts an envelope conformation with the carbon atom C(15) as a flap with a puckering amplitude of 0.300(3) Å out of the Cremer–Pople plane. Additionally, the structure presents disorder of the un-substituted Cp ring generating two orientations in 88 : 12 ratio. Only the major contributor is shown in Fig. 2.

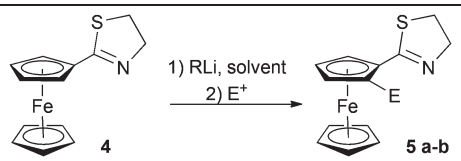
Moreover, 2-ferrocenyl-2-thiazoline **4** was investigated as a DMG in the selective DoM of ferrocene (Table 1).

To ascertain the most feasible temperature for the DoM reaction, we developed a deuterium incorporation analysis. Thus a solution of **4** in dry $Et_2O$ was cooled to −78 °C and *t*-BuLi was then added dropwise, the reaction mixture was warmed to several temperatures followed by consecutive quenching using an excess of $D_2O$. Finally, deuterium incorporation was determined by NMR, comparing the integrations of the substituted Cp ring protons. When the ferrocenyl thiazoline **4** was subjected to lithiation with this standard reaction protocol at −78 °C, **5a** was obtained in moderate yield and displayed incomplete deuterium incorporation. However, gradual warming of the reaction at room temperature produces better deuterium incorporation, leading to **5a** in 81% yield (entry 5).

In view of those results, we carried out the DoM reaction followed by the quenching of the lithium intermediate with $(MeS)_2$ at room temperature; however, **5b** was obtained in poor yields, which could either be because the lithium intermediate is not so stable at room temperature, or because the reaction with $(MeS)_2$ is slower.

We proceeded to conduct this reaction at 0 °C, and obtained very good yields of **5b** (Table 1; entry 6). As part of our attempts to improve the yield, other reaction conditions

**Table 1** DoM reaction under various screening conditions[a]




| Entry | Solvent | RLi | $E^+$ | Temperature | Yield[b] (%) |
|---|---|---|---|---|---|
| 1 | $Et_2O$ | *t*-BuLi | $D_2O$ | −78 °C | 65 |
| 2 | $Et_2O$ | *t*-BuLi | $D_2O$ | −78 °C to −50 °C | 68 |
| 3 | $Et_2O$ | *t*-BuLi | $D_2O$ | −78 to −30 °C | 71 |
| 4 | $Et_2O$ | *t*-BuLi | $D_2O$ | −78 to 0 °C | 74 |
| 5 | $Et_2O$ | *t*-BuLi | $D_2O$ | −78 °C to rt | 81 |
| 6 | $Et_2O$ | *t*-BuLi | $(SMe)_2$ | −78 °C to rt | 87 |
| 7 | THF | *t*-BuLi | $(SMe)_2$ | −78 °C to rt | 70 |
| 8 | $Et_2O$ | *n*-BuLi | $(SMe)_2$ | −78 °C to rt | 74 |
| 9 | $Et_2O$ | *s*-BuLi | $(SMe)_2$ | −78 °C to rt[c] | 51(8) |
| 10 | THF | *t*-BuLi | $(SMe)_2$ | −78 °C | 62(15) |

[a] Reaction conditions: 1 equiv. of **4**, 1.2 equiv. of RLi, 1.5 equiv. of electrophile. [b] Yield of the isolated product after $SiO_2$ column chromatography. Values in brackets denote recovered starting materials. [c] Addition of $(SMe)_2$ at 0 °C.

were investigated (entries 7–10). Changing the solvent from $Et_2O$ to THF causes a decrease of the desired compound (entry 7). When we changed the *t*-BuLi to *n*-BuLi in $Et_2O$, **5b** was obtained in 74% yield (entry 8), while the use of *s*-BuLi leads to the poorest outcomes (entry 9). Optimized conditions involved adding 1.2 equiv. of *t*-BuLi to an ethereal solution of **4** at −78 °C and warming the reaction mixture to room temperature, followed by the addition of the electrophile at 0 °C.

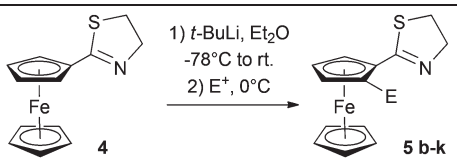
Compound **5b** was characterized by means of conventional spectroscopic techniques, which confirms the incorporation of the electrophile in an adjacent position to the thiazoline group, providing a new 1,2-disubstituted ferrocene. Mass spectrum of **5b** thus agrees with the expected molecular formula. The $^1$H NMR spectrum shows a broad singlet at 2.35 ppm assigned to $CH_3S$, two multiple signals at 3.33 and 4.35 ppm assigned to the methylene groups of thiazoline, three multiple signals at 4.46, 4.77 and 4.78 ppm that correspond to the disubstituted Cp ring and finally a simple signal shifted at 4.22 ppm with integration of 5 hydrogens was assigned to the Cp ring. The $^{13}$C NMR spectrum exhibits a signal shifted at 19.7 ppm for the SMe, two signals at 33.5 and 64.5 ppm for methylene groups of the thiazoline, and a signal at 167.7 ppm assigned to C=(N)S. The characteristic signals for a 1,2-disubstituted ferrocene are also observed.

With these conditions at hand, we examined the scope of the reaction by using a range of different electrophilic substrates. Selected results for DoM-electrophilic quenching of thiazoline **4** are shown in Table 2.

In the case of **5c**, suitable crystals make it possible to fully establish the structural arrangement of this compound by single-crystal X-ray diffraction analysis (Fig. 3).

The structure indicates that the phenylsulfide moiety is directly bonded to the monosubstituted Cp ring at 2-position, confirming the behavior of the thiazoline ring as a DMG in the selective DoM of ferrocene. No significant differences were

**Table 2** Selective DoM of **4**[a]




**4** **5 b-k**

| Entry | Product | Electrophile | −E | % Yield[b] |
|---|---|---|---|---|
| 1 | **5b** | $(SMe)_2$ | –SMe | 87 |
| 2 | **5c** | $(SPh)_2$ | –SPh | 78 |
| 3 | **5d** | $(S\text{-}iPr)_2$ | –SiPr | 63 |
| 4 | **5e** | $Me_3SiCl$ | $–SiMe_3$ | 98 |
| 5 | **5f** | $(SePh)_2$ | –SePh | 79 |
| 6 | **5g** | $n\text{-}Bu_3SnCl$ | $–SnBu_3$ | 51 |
| 8 | **5h** | $B(O\text{-}iPr)_3$ | $–B(OH)_2$ | 72 |
| 9 | **5i** | $CH_3I$ | –Me | 86 |
| 10 | **5j** | $I_2$ | –I | 75 |

[a] Reaction condition: 1 equiv. of **4**, 1.2 equiv. of *t*-BuLi, $Et_2O$, −78 °C to rt, 1.5 equiv. of electrophile. [b] Yield of the isolated product after $SiO_2$ column chromatography.

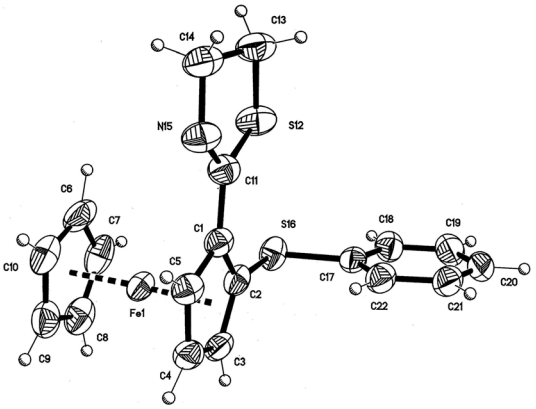



**Fig. 3** ORTEP representation of ferrocenyl thiazoline **5c**. Ellipsoids are shown at 30% probability level. Selected bond lengths [Å] and angles [°]: C(1)–C(11) 1.467(4), C(2)–S(16) 1.752(3), C(11)–N(15) 1.282(6), C(11)–S(12) 1.774(5), S(12)–C(13) 1.793(13), C(14)–N(15) 1.449(12), S(16)–C(17) 1.777(3); C(2)–C(1)–C(11) 130.1(3), C(1)–C(2)–S(16) 128.4, N(15)–C(11)–S(12) 116.1(7), C(1)–C(11)–S(12) 121.0(4), C(11)–S(12)–C(13) 90.4(5), C(14)–C(13)–S(12) 104.8(7), N(15)–C(14)–C(13) 107.9(8), C(11)–N(15)–C(14) 114.4(8), C(2)–S(16)–C(17) 102.7(1).

observed in bond and angle distances of the thiazoline moiety compared to those reported in the literature.[18a] The structure of **5c** presents disorder in the thiazoline ring generating two different envelope conformations (both with C13 as a flap) in 83 : 17 ratio. Only the major contribution is shown in Fig. 3.

By and large, the reaction is successful for a wide range of electrophiles and gives good yields of the resulting substituted ferrocenyl thiazolines, after flash chromatography on silica gel. This procedure provides access to a diversity of ferrocenyl thiazolines with several valuable functionalities for further use as bidentate ligands, or as versatile substrates for cross-coupling reactions. In that context, we decided to carry out a preliminary study in order to determine the capacity of coordination of **5b** to Pd(II).

Complex **5b-PdCl$_2$** was prepared by treating **5b** with $Pd(CH_3CN)_2Cl_2$, giving an air-stable orange complex with 93% yield. This complex was characterized by conventional spectroscopic techniques. The structural arrangement for **5b-PdCl$_2$** was unequivocally established by X-ray diffraction analysis (Fig. 4).

The most salient feature of the structure is the coordination mode of **5b** as an effective [*N*,*S*] bidentate ligand,[19] forming a six-membered chelated ring with a half-chair conformation (Cremer–Pople puckering parameters: $q_2$ = 0.643(2), $q_3$ = 0.360(2), $Q$ = 0.737(2) Å, $\theta$ = 60.7(2), $\phi$ = 22.4(2)°), where the methyl group adopts an axial orientation to prevent steric hindrance with the ferrocene moiety. The ligand bite angle (91.02°) and the Cl(1)–Pd(1)–Cl(2) angle (91.27°) are the origins of slight distortion from square-planar symmetry in the palladium atom. Data on the crystals and the refining of the compounds **3**, **4-Pd(PPh$_3$Cl$_2$)**, **5c**, and **5b-PdCl$_2$** are summarized in Table 6.

To study the catalytic properties of complex **5b-PdCl$_2$**, we performed a series of experiments using as a model reaction: the cross-coupling between 4-iodotoluene and methyl acrylate under microwave irradiation and conventional heating.

To determine the optimal conditions, a series of experiments were performed changing parameters such as temperature, solvent, base and catalyst loading. We found that 0.05 mol% of **5b-PdCl$_2$** provides the best result, with optimum yields of the coupled product (Table 3, entry 3). Reactions were also carried out in DMF, NMP or DMA as solvents using different bases (*e.g.* $Et_3N$, NaOAc, $K_2CO_3$, $K_3PO_4$).

Among the solvents tested, DMF gave the best results in the presence of $Et_3N$ as a base, whereas under the same conditions the other bases gave low yields.

The effectiveness of the microwave irradiation and conventional heating for Heck reaction has been compared. We performed the Heck reaction under thermal conditions using a DMF reflux. In this case a slightly lower yield than that obtained with the microwave method was found (entry 10). Although both methods are efficient, for the Heck coupling, the microwave-assisted reactions were faster in comparison to conventional thermal conditions. These results showed that in this reaction, the microwave irradiation is a more efficient heating method.

Optimized conditions for this cross-coupling involves the use of $Et_3N$ as a base, and 0.05 mol% of **5b-PdCl$_2$** in DMF heating at 160 °C under microwave irradiation.

As a further step, we also compared these findings with known related phosphine free [*N*,*S*] bidentate complexes **7a–c** and new oxazoline analogous complex **10** in order to make evident the role of the thiazoline moiety in the efficiency and the activity of these complexes.

Firstly, precursor ligands **6a–c** were synthesized in excellent yields using a modified method taken from the literature,[20] starting from *N*,*N*-dimethylaminomethyl ferrocene and the corresponding alkyl disulphide, as is shown in Scheme 4.

Compounds were characterized by using various spectroscopic techniques and the structure of compound **6b** was further confirmed by single crystal X-ray diffraction analysis

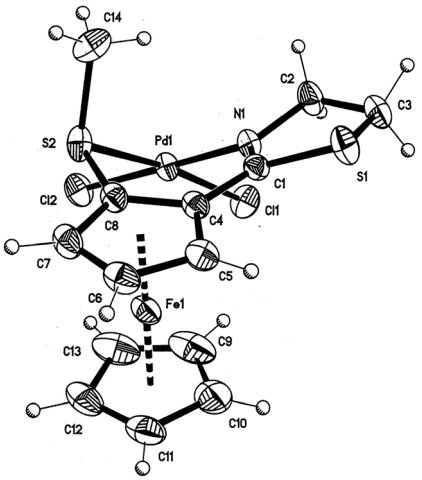
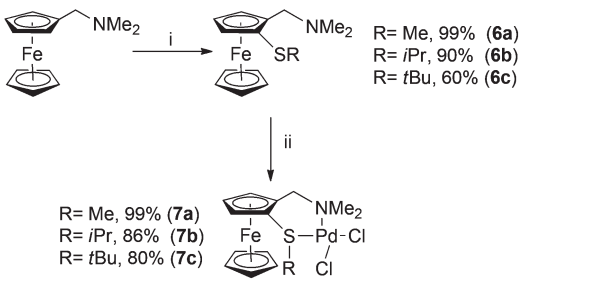
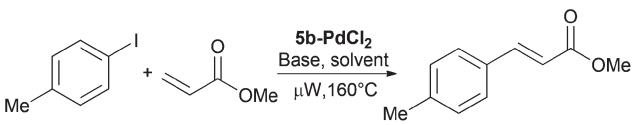



**Fig. 4** ORTEP representation of ferrocenyl thiazoline **5b-PdCl$_2$**. Ellipsoids are shown at 30% probability level. Selected bond lengths [Å] and angles [°]: Pd(1)–N(1) 2030(2), Pd(1)–S(2) 2.2765(8), Pd(1)–Cl(2) 2.2956(8), Pd(1)–Cl(1) 2.3250(8), S(1)–C(1) 1.742(3), S(1)–C(3) 1.820(3), S(2)–C(8) 1.756(3), S(2)–C(14) 1.807(4), N(1)–C(1) 1.284(3), N(1)–C(2) 1.477(3), C(1)–C(4) 1.453(4); N(1)–Pd(1)–S(2) 91.02(7), N(1)–Pd(1)–Cl(2) 178.35(6), S(2)–Pd(1)–Cl(2) 87.35(3), N(1)–Pd(1)–Cl(1) 90.31(7), S(2)–Pd(1)–Cl(1) 173.02(3), Cl(2)–Pd(1)–Cl(1) 91.27(3).




**Scheme 4** *Reagents and conditions.* (i) *t*-BuLi, $Et_2O$, –78 °C then $(SR)_2$, 0 °C; (ii) $Pd(CH_3CN)_2Cl_2$, $CH_2Cl_2$, rt.

**Table 3** Mizoroki–Heck cross-coupling of 4-iodotoluene with methyl acrylate under microwave irradiation[a]




| Entry | Base | Solvent | % Mol [Pd] | Time[b] (min) | % Yield[c] | TON | TOF |
|---|---|---|---|---|---|---|---|
| 1 | $Et_3N$ | DMF | 1% | 5 | 94 | 94 | 1128 |
| 2 | $Et_3N$ | DMF | 0.1% | 5 | 87 | 870 | 10 440 |
| 3 | $Et_3N$ | DMF | 0.05% | 8 | 96 | 1920 | 14 400 |
| 4 | $Et_3N$ | DMF | 0.01% | 15 | 47 | 4700 | 18 800 |
| 5 | $Et_3N$ | NMP | 0.05% | 8 | 90 | 1800 | 13 500 |
| 6 | $Et_3N$ | DMA | 0.05% | 8 | 90 | 1800 | 13 500 |
| 7 | NaOAc | DMF | 0.05% | 8 | 40 | 800 | 6000 |
| 8 | $K_2CO_3$ | DMF | 0.05% | 8 | 37 | 740 | 5550 |
| 9 | $K_3PO_4$ | DMF | 0.05% | 8 | 20 | 400 | 3000 |
| 10 | $Et_3N$ | DMF | 0.05% | 150[d] | 89 | 1780 | 712 |

[a] Reaction conditions: 1.0 mmol of aryl iodide, 1.2 mmol of acrylate, 1.5 mmol of base, 5 mL of solvent at 160 °C. [b] Time reaction based on total consumption of aryl iodide determined by TLC. [c] Isolated yield after $SiO_2$ column chromatography. [d] Conventional thermal conditions.

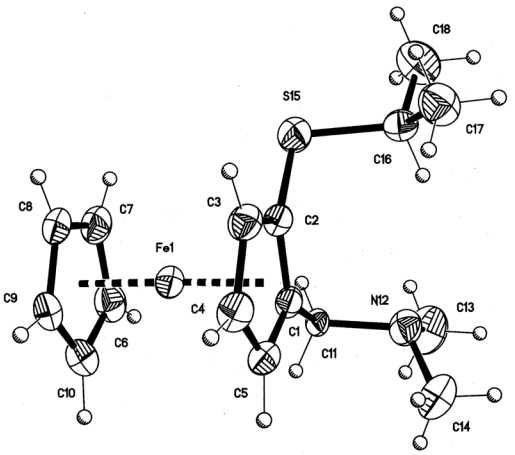
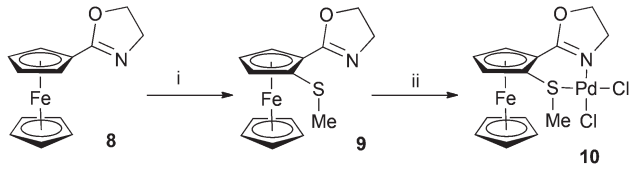



**Fig. 5** ORTEP representation of **6b**. Ellipsoids are shown at 30% probability level. Selected bond lengths [Å] and angles [°]:C(1)–C(11) 1.577(4), C(11)–N(12) 1.532(4), C(2)–S(15) 1.750(3), S(15)–C(16) 1.794(4), C(2)–C(1)–C(11) 124.9(3), C(1)–C(2)–S(15) 125.7(2), C(1)–C(11)–N(15) 106.8(2), C(2)–S(15)–C(16) 101.7(2).

(Fig. 5). The structure indicates that the isopropylsulfide moiety is directly bonded to the monosubstituted Cp ring at 2-position. The dimethylamino group shows slight differences in both angle and distances to those reported in the literature.[21] In particular, the bond angle between N(12)–C(11)–C(1), 106.8(2)° is smaller to that measured in other ferrocenyl compounds [(112.5°)[22] and (115.8°)[23]]. The structure presents disorder of the unsubstituted Cp ring generating two orientations in 74 : 26 ratio. Only the major contributor is shown in Fig. 5.

Treatment of **6a–c** with one equivalent of $Pd(CH_3CN)_2Cl_2$ in $CH_2Cl_2$ at room temperature gives the corresponding **7a–c** complexes as air-stable brown solids. These complexes were fully characterized using conventional spectroscopic techniques and all data are in agreement with those previously reported in the literature.[20]

Similarly, the palladium complex **10** was synthetized from the oxazoline **9**, which was prepared analogously to the method above described for the synthesis of functionalized




**Scheme 5** *Reagents and conditions.* (i) *n*-BuLi, $EtO_2$, −78 °C, then $(SMe)_2$, 0 °C. (ii) $Pd(CH_3CN)_2Cl_2$, $CH_2Cl_2$, rt.

thiazolines by a directed metalation reaction, using ferrocenyloxazoline **8** as a DMG and the corresponding alkyl disulfide as an electrophile (Scheme 5). The desired oxazoline **8** was constructed using the conditions developed by Richards.[8b]

Once complexes **7a–c** and **10** are synthesized, their potential as catalyst precursors in the Mizoroki–Heck reaction was also evaluated with coupling between methyl acrylate and 4-iodotoluene under the same conditions as **5b-PdCl$_2$** (Table 4).

We found that the catalytic performance was highly influenced by the type of nitrogen donor group: thiazoline, oxazoline or amino group as well as thioether substituents on the dimethylaminomethyl ferrocene moiety.

Comparison of the results revealed that **5b-PdCl$_2$** was the best catalytic precursor for the reaction giving the coupled product in 89% yield (entry 1) while complexes **7a–c** and **10** gave lower yields when the reactions were performed under thermal conditions.

Regarding the effect of thioether substituents on complex **7a–c**, we found that these groups affected both the efficiency and the activity of the coupling (Table 4, entries 2–4). We found that the presence of methyl thioether substituent as a donor group in complex **7a** has a negative effect on efficiency, since the reaction is 12 times slower compared with complex **5b-PdCl$_2$**. Nevertheless, couplings using complexes **7b** and **7c** were completed faster than the reaction with **5b-PdCl$_2$**; but in these cases, the activity was less and the coupled products were obtained in lower yields. In the same way, complex **10** with an oxazoline moiety provides a good efficiency (entry 5) but unfortunately the activity decreases compared with **5b-PdCl$_2$**.

**Table 4** Mizoroki–Heck cross-coupling of 4-iodotoluene with methyl acrylate under conventional heating and microwave irradiation[a]


| Entry | Complex | Type of heating | Time[b] (min) | % Yield[c] | TON | TOF |
|---|---|---|---|---|---|---|
| 1 | **5b-PdCl$_2$** | Conventional | 150 | 89 | 1780 | 712 |
| 2 | **7a** | Conventional | 1800 | 76 | 1520 | 51 |
| 3 | **7b** | Conventional | 130 | 84 | 1680 | 775 |
| 4 | **7c** | Conventional | 100 | 63 | 1260 | 759 |
| 5 | **10** | Conventional | 120 | 73 | 1460 | 730 |
| 6 | **5b-PdCl$_2$** | Microwave | 8 | 96 | 1900 | 16 286 |
| 7 | **7b** | Microwave | 20 | 93 | 1860 | 5580 |
| 8 | **10** | Microwave | 11 | 95 | 1900 | 10 364 |

[a] Reaction conditions: 1.0 mmol of aryl iodide, 1.2 mmol of acrylate, 1.5 mmol of base, 5 mL of DMF, 0.05% mol [Pd]. [b] Time reaction based on total consumption of aryl iodide determined by TLC. [c] Isolated yield after $SiO_2$ column chromatography.

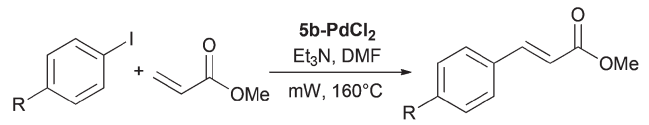
To further study the potential of these complexes, we performed the Pd-catalyzed Heck reaction under microwave irradiation (Table 4, entries 6–8). In contrast to the results obtained using conventional heating, microwave irradiation proved to be suitable for this coupling since the three complexes showed excellent catalytic activity. However, the complex with a thiazoline fragment was three times more efficient than **7b** and also better than complex **10**. To sum up, we can affirm that introducing a 2-thiazoline moiety into the thioether ferrocene ligand is convenient for the Heck reaction.

Encouraged by these excellent results, we evaluated the scope of this reaction by studying the effect of the substituent on the reactivity of the aromatic iodide employing this complex (Table 5).

Cross-couplings of a wide range of activated and deactivated aryl iodides with methyl acrylate were carried out. In every case, the substrate was cleanly converted into the desired methyl cinnamate with isolated yields, after CC ranging from 71 to 99%.

The results show that the yields and time of the coupling reaction depend on the nature of the substituent in aryl iodide. As shown in Table 5, the aryl iodides with electron-withdrawing substituents reacted completely in less than 5 minutes under microwave irradiation with the **5b-PdCl$_2$** complex, except the aryl iodide *p*-substituted with a nitro group which reacts completely after 7 min (entry 9), while for the aryl iodides with electron-donor substituents, longer reaction times were needed but excellent yields were achieved.

**Table 5** Scope of Mizoroki–Heck reaction of aryl iodides with methyl acrylate under microwave irradiation[a]




| Entry | R | Time[b] (min) | Yield[c] (%) |
|---|---|---|---|
| 1 | –$CH_3$ | 8 | 96 |
| 2 | –OMe | 7 | 92 |
| 3 | –$NH_2$ | 6 | 99 |
| 4 | –H | 5 | 84 |
| 5[d] | –COOMe | 5 | 71 |
| 6[d] | –$COCH_3$ | 3 | 87 |
| 7[d] | –Br | 3 | 89 |
| 8[d] | –$CF_3$ | 4 | 79 |
| 9[d] | –$NO_2$ | 7 | 84 |

[a] Reaction conditions: 1.0 mmol of aryl iodide, 1.2 mmol of acrylate, 1.5 mmol of base, 5 mL of solvent at 160 °C. [b] Time reaction based on total consumption of aryl iodide determined by TLC. [c] Isolated yield after $SiO_2$ column chromatography. [d] The formation of side-products was observed.[24]

**Table 6** Crystal data and structure refinement for **3**, **4-Pd(PPh$_3$Cl$_2$)**, **5c**, **5b-PdCl$_2$** and **6b**

| | **3** | **4-Pd(PPh$_3$Cl$_2$)** | **5c** | **5b-PdCl$_2$** | **6b** |
|---|---|---|---|---|---|
| Empirical formula | $C_{13}H_{15}FeNOS$ | $C_{31}H_{28}Cl_2FeNPPdS$ | $C_{19}H_{17}FeNS_2$ | $C_{14}H_{15}Cl_2FeNPdS_2$ | $C_{16}H_{23}FeNS$ |
| Formula weight (g mol$^{-1}$) | 289.17 | 710.74 | 379.31 | 494.56 | 317.26 |
| Crystal size (mm) | 0.48 × 0.19 × 0.10 | 0.42 × 0.26 × 0.10 | 0.31 × 0.29 × 0.22 | 0.21 × 0.13 × 0.13 | 0.314 × 0.292 × 0.222 |
| Color | Red | Red | Red | Red | Orange |
| Crystal system | Monoclinic | Monoclinic | Monoclinic | Monoclinic | Monoclinic |
| Space group | *C*2/*c* | $P2_1/n$ | $P2_1/n$ | $P2_1/c$ | $P2_1/c$ |
| *a* (Å) | 17.861(2) | 12.137(1) | 7.364(1) | 9.590(1) | 16.558(5) |
| *b* (Å) | 7.376(1) | 14.818(1) | 9.245(2) | 13.685(1) | 8.011(2) |
| *c* (Å) | 18.937(2) | 19.733(2) | 25.189(5) | 16.626(1) | 12.175(4) |
| *α* (°) | 90 | 90 | 90 | 90 | 90 |
| *β* (°) | 92.073(2) | 105.843(1) | 91.759(3) | 104.265(1) | 96.932(4) |
| *γ* (°) | 90 | 90 | 90 | 90 | 90 |
| *V* (Å$^3$) | 2493.0(4) | 3414.0(5) | 1714.1(6) | 2114.6(3) | 1603.2(8) |
| *Z* | 8 | 4 | 4 | 4 | 4 |
| $D_{calc}$ (g cm$^3$) | 1.541 | 1.615 | 1.470 | 1.928 | 1.314 |
| Number of collected reflections | 8240 | 36 660 | 9131 | 22 995 | 16 388 |
| Number of independent reflections ($R_{int}$) | 2258, $R_{int}$ = 0.0293 | 6244, $R_{int}$ = 0.0236 | 3120, $R_{int}$ = 0.0268 | 3889, $R_{int}$ = 0.0274 | 2925, $R_{int}$ = 0.0905 |
| Maximum and minimum transmission | 0.7452 and 0.6188 | 0.8630 and 0.6109 | 0.8257 and 0.5671 | 0.7833 and 0.5137 | 0.8171 and 0.7133 |
| Data/restraints/parameters | 2258/205/206 | 6244/230/453 | 3120/78/245 | 3889/48/255 | 2925/236/222 |
| Final *R* indices [$I > 2\sigma(I)$] | $R$ = 0.0294, w$R_2$ = 0.0685 | $R$ = 0.0281, w$R_2$ = 0.0698 | $R$ = 0.0432, w$R_2$ = 0.1009 | $R$ = 0.0270, w$R_2$ = 0.0629 | R = 0.0475, w$R_2$ = 0.1284 |
| *R* indices (all data) | $R$ = 0.0345, w$R_2$ = 0.0707 | $R$ = 0.0329, w$R_2$ = 0.0727 | $R$ = 0.0621, w$R_2$ = 0.1105 | $R$ = 0.0310, w$R_2$ = 0.0650 | $R$ = 0.0534, w$R_2$ = 0.1326 |
| GoF($F^2$) | 1.058 | 1.035 | 1.021 | 1.073 | 1.059 |
| Absorption correction method | Semi-empirical from equivalents | Semi-empirical from equivalents | Semi-empirical from equivalents | Semi-empirical from equivalents | Semi-empirical from equivalents |

Thus, we have demonstrated that **5b-PdCl$_2$** based on a thiazoline ring was highly active and efficient as a catalyst precursor in the Mizoroki–Heck reaction.

## Conclusions

We have established an appropriate method for the synthesis of 2-ferrocenyl-2-thiazolines, *via* a three-step procedure. We have shown that this versatile strategy could generate a wide range of thiazolines substituted by only changing the β-amino alcohol used in the aminolysis reaction. Furthermore, we have identified the 2-thiazoline moiety as an efficient DoM for the selective deprotonation of ferrocene, and we have established the first DoM-electrophilic quenching process for producing several 1,2-disubstituted ferrocene derivatives with a 2-thiazoline moiety.

The final results show that the palladium complex **5b-PdCl$_2$** might be a convenient and highly efficient catalytic system for the Heck coupling reaction of methyl acrylate and aryl iodides compared with other palladium complexes based on [*N*,*S*] ferrocenyl ligands. The asymmetric version of these compounds and their possible applications in asymmetric catalysis are now being pursued in our laboratory.

## Experimental

### General considerations

All operations were carried out under an inert atmosphere of nitrogen or argon gas using standard Schlenk techniques. Anhydrous THF was obtained by distillation under an inert atmosphere over sodium benzophenone. Column chromatography was performed using 70–230 mesh silica gel. All reagents and solvents were obtained from commercial suppliers and used without further purification. All compounds were characterized by IR spectra, recorded on a Perkin-Elmer 283B or 1420 spectrophotometer, by means of film and KBr techniques, and all data are expressed in wave numbers (cm$^{-1}$). Melting points were obtained on a Melt-Temp II apparatus and are uncorrected. NMR spectra were measured with a JEOL Eclipse +300 using $CDCl_3$ as a solvent. Chemical shifts are in ppm ($\delta$), relative to TMS. The MS-FAB and MS-EI spectra were obtained on a JEOL SX 102A, the values of the signals are expressed in mass/charge units (*m*/*z*), followed by the relative intensity with reference to a 100% base peak. Elemental analyses for carbon, hydrogen, nitrogen and sulfur atoms were performed on a Perkin-Elmer 2400 elemental analyzer using cystine as a standard.

Microwave irradiation experiments were performed using a Monowave 300 single-mode microwave reactor. The reaction temperature is monitored by an internal fiber-optic (FO) temperature probe (ruby thermometer) protected by a borosilicate immersion well inserted directly into the reaction mixture. Reaction times refer to the hold time at the desired set temperature and not to the total irradiation time. Pressure sensing is achieved by a hydraulic sensor integrated in the swiveling cover of the instrument. The reusable 10 mL Pyrex vial is sealed with PEEK snap caps and standard PTFE coated silicone septa. Reaction cooling is performed using compressed air automatically after the heating period has elapsed.

### Structure determination by X-ray crystallography

Suitable X-ray quality crystals of **3**, **4-Pd(PPh$_3$Cl$_2$)**, **5c**, **5-PdCl$_2$** and **6b** were grown by slow evaporation of *n*-hexane–benzene mixture at −5 °C and chloroform at room temperature, respectively. The crystals of each compound were mounted on a glass fiber at room temperature, and then placed on a Bruker Smart Apex CCD diffractometer, equipped with Mo Kα radiation; decay was negligible in both cases. Details of crystallographic data collected on compounds **3**, **4**-Pd(PPh$_3$Cl$_2$), **5c** and **5-PdCl$_2$** are provided in Table 6. Systematic absences and intensity statistics were used in space group determination. The structure was solved using direct methods.[25] Anisotropic structure refinements were achieved using full matrix, least-squares technique on all non-hydrogen atoms. All hydrogen atoms were placed in idealized positions, based on hybridization, with isotropic thermal parameters fixed at 1.2 times the value of the attached atom. Structure solutions and refinements were performed using SHELXTL V6.10.[26]

### Synthesis of Fischer ethoxy ferrocenyl carbene complex (1), Fischer hydroxyl ethyl amine ferrocenyl carbene complex (2) and *N*-(2-hydroxyethyl) ferrocenyl thioamide (3)

The preparation of compounds **1**, **2** and **3** was carried out using the methodology previously described elsewhere.[15,17]

### Synthesis of 2-ferrocenyl-2-thiazoline (4)

To an ice-cooled solution of thioamide **3** (1 g, 3.5 mmol) in 15 mL of dichloromethane were successively added methanesulfonyl chloride (0.35 mL, 4.5 mmol) and triethylamine (1.95 mL, 14 mmol). The reaction mixture was stirred for 10 min at 0 °C, and then the reaction was quenched by adding 30 mL of water. The organic phase was washed with the same amount of water and then dried over anhydrous $Na_2SO_4$. The solvent was evaporated under vacuum and the crude product was purified by flash chromatography using silica-gel and hexane–ethyl acetate 9 : 1 as an eluent to give 0.89 g of an orange solid (96% yield). Mp: 100–102 °C. $^1$H NMR ($CDCl_3$, ppm): $\delta$ 3.31 (t, 2H, $J$ = 8.1 Hz, –$CH_2$S–), 4.16 (s, 5H, Cp), 4.20 (t, 2H, $J$ = 8.1 Hz, –$CH_2$N–), 4.34 (br s, 2H, subst Cp), 4.68 (br s, 1H, subst Cp). $^{13}$C NMR ($CDCl_3$, ppm): $\delta$ 33.6 (–$CH_2$S–), 64.8 (–$CH_2$N═), 69.3 (CH, subst Cp), 70.0 (Cp), 70.4 (CH, subst Cp), 77.3 ($C_{ipso}$, Fc), 168.8 (C═S). $IR_{vmax}$ (KBr, cm$^{-1}$): 1608, 1453, 1251. MS-IE+ *m*/*z* (rel. intensity %): 271 [M$^+$] (100), 211 (38). HRMS (FAB+): calculated for $C_{13}H_{13}FeNS$: 271.0118. Found: 271.0111. Elemental analysis (%): calcd for $C_{13}H_{13}FeNS$: C 57.58, H 4.83, N 5.17, S 11.83; found: C 57.92, H 4.73, N 5.55, S 19.39.

### Synthesis of 2-ferrocenyl-2-thiazoline palladium complex 4-Pd($PPh_3Cl_2$)

A solution of ligand **4** (0.1 g, 0.37 mmol) in methanol (5 mL) was added, at room temperature, to a fresh solution of $Li_2PdCl_4$ [65 mg (0.37 mmol), $PdCl_2$ and 16 mg (0.37 mmol) of LiCl in methanol (5 mL)]. A brown precipitate was formed when the reaction mixture was stirred overnight at room temperature. After this time, a solution of $PPh_3$ (97 mg, 0.37 mmol) in 3 mL of dichloromethane was added and the mixture was stirred for 5 min. The resulting clear solution was filtered through celite, and then was washed with water and brine. The organic phase was dried with anhydrous sodium sulfate and the solvent was evaporated under vacuum, obtaining the corresponding palladium complex as a brown solid in 87% yield. Mp: 196–198 °C. MS-FAB+ *m*/*z* (rel. intensity %): 710 [$M^+$] (5). HRMS (FAB+): calculated for $C_{31}H_{28}Cl_2FeNPPdS$: 708.9441. Found: 708.9445.

### Deuterium incorporation analysis

A solution of 2-ferrocenyl-2-thiazoline **4** (100 mg, 0.37 mmol) in anhydrous diethyl ether under nitrogen atmosphere was cooled to −78 °C (dry ice/acetone bath), then *t*-butyl lithium in pentane 1.7 M (0.22 mL, 0.45 mmol) was added dropwise. On completing the *t*-butyl lithium addition, the deuterium incorporation was determined by quenching the reaction mixture with excess $D_2O$, after warming to several different temperatures. The aqueous mixtures were extracted with dichloromethane, and the organic layers were dried with $Na_2SO_4$. Recovered yields of the deuterated product were determined by $^1H$ NMR comparing the integrations of the substituted Cp ring protons.

### General procedure for the DoM-electrophile quenching of 2-ferrocenyl-2-thiazoline (4)

A solution of **4** (150 mg, 0.55 mmol) in 3 mL of anhydrous diethyl ether under nitrogen atmosphere was cooled to −78 °C (dry ice/acetone bath), then *t*-butyl lithium in pentane 1.7 M (0.33 mL, 0.68 mmol) was added dropwise. The mixture was gradually warmed to room temperature (approximately 1.5 hours). After reaching this temperature, the mixture was stirred for an additional 5 min. The reaction mixture was then cooled at 0 °C and quenched by adding an electrophile (1.5 equiv.). The solution was further stirred overnight at room temperature, before quenching with a saturated solution of $NaHCO_3$. After standard work-up, the crude product was purified by flash chromatography on silica-gel.

**1-(2-Thiazolin-2-yl)-2-(methylthio)-ferrocene (5b).** The compound was purified by flash chromatography using hexane–EtOAc 9 : 1 as an eluent affording an orange solid in 87% yield (152 mg, 0.48 mmol). Mp: 64–65 °C. $^1H$ NMR ($CDCl_3$, ppm): $\delta$ 2.35 (br s, 3H, $-CH_3$), 3.33 (br s, 2H, $-CH_2S-$), 4.22 (br s, 5H, Cp), 4.35 (br s, 2H, $-CH_2N-$), 4.78 (m, 1H, subst Cp), 4.46 (m, 1H, subst Cp), 4.77 (m, 1H, subst Cp). $^{13}C$ NMR ($CDCl_3$, ppm): $\delta$ 19.7 ($-CH_3$), 33.5 ($-CH_2S-$), 64.5 ($-CH_2N=$), 69.1 (CH, subst Cp), 71.4 (CH, subst Cp), 71.0 (Cp), 72.7 (CH, subst Cp), 78.3 ($C_{ipso}$, Fc), 85.1 ($C_{ipso}$, Fc), 167.7 (C=S). $IR_{vmax}$ (KBr, $cm^{-1}$): 1616, 1434, 1243, 994. MS-IE+ *m*/*z* (rel. intensity %): 317 [$M^+$] (100), 302 [$M^+ - CH_3$], (58), 242 [Fc-N=C=S]$^+$ (67). HRMS (FAB+): calculated for $C_{14}H_{15}FeNS_2$: 316.9995. Found: 316.9998. Elemental analysis (%): calcd for $C_{14}H_{15}FeNS_2$: C 53.00, H 4.77, N 4.42, S 20.21; found: C 53.12, H 4.42, N 4.95, S 19.06.

**1-(2-Thiazolin-2-yl)-2-(phenylthio)-ferrocene (5c).** The compound was purified by flash chromatography using hexane–EtOAc 9 : 1 as an eluent affording an orange solid in 78% yield (163 mg, 0.43 mmol). Mp: 112–113 °C. $^1H$ NMR ($CDCl_3$, ppm): $\delta$ 3.18–3.37 (m, 2H, $-CH_2S-$), 4.15 (t, 2H, $J$ = 8.4 Hz, $-CH_2N-$), 4.27 (s, 5H, Cp), 4.48 (s, 1H, sust Cp), 4.52 (s, 1H, subst Cp), 5.01 (s, 1H, subst Cp), 7.06–7.19 (m, 5H, $H_{arom}$). $^{13}C$ NMR ($CDCl_3$, ppm): $\delta$ 33.9 ($-CH_2S-$), 63.8 ($-CH_2N=$), 71.1 (CH, subst Cp), 71.5 (CH, subst Cp), 71.8 (Cp), 77.8 ($C_{ipso}$, Fc), 78.0 (CH, subst Cp), 80.6. ($C_{ipso}$, Fc), 125.5 ($CH_{arom}$), 126.8 ($CH_{arom}$), 128.9 ($CH_{arom}$), 139.8 ($C_{ipso}$, Ph), 167.5 (C=S). $IR_{vmax}$ (KBr, $cm^{-1}$): 1590, 1474, 1433, 1246, 997. MS-IE+ *m*/*z* (rel. intensity %): 379 [$M^+$] (100), 371 [$M^+$ − SPh] (78). HRMS (FAB+): Calculated for $C_{19}H_{17}FeNS_2$: 379.0152. Found: 379.0149. Elemental analysis (%): calcd for $C_{19}H_{17}FeNS_2$: C 60.16, H 4.52, N 3.69, S 16.91; found: C 60.52, H 4.43, N 4.07, S 16.38.

**1-(2-Thiazolin-2-yl)-2-(isopropylthio)-ferrocene (5d).** The compound was purified by flash chromatography using hexane–EtOAc 9 : 1 as an eluent affording an orange solid in 63% yield (120 mg, 0.35 mmol). Mp: 50–52 °C. $^1H$ NMR ($CDCl_3$, ppm): $\delta$ 1.14 (dd, $J$ = 15, 6.6 Hz, 6H, $-CH(CH_3)_2$), 2.92–3.01 (m, 1H, $-CH(CH_3)_2$), 3.27 (t, 2H, $-CH_2S-$), 4.14–4.18 (m, 7H, $-CH_2N-$, Cp), 4.37 (s, 1H, subst Cp), 4.46 (s, 1H, subst Cp), 4.87 (s, 1H, subst Cp). $^{13}C$ NMR ($CDCl_3$, ppm): $\delta$ 22.8 ($-CH(CH_3)_2$), 23.2 ($-CH(CH_3)_2$), 33.8 ($-CH_2S-$), 40.6 ($-CH(CH_3)_2$), 63.7 ($-CH_2N=$), 70.2 (CH, subst Cp), 71.0 (CH, subst Cp), 71.6 (Cp), 78.2 (CH, subst Cp), 79.4 ($C_{ipso}$, Fc), 80.8 ($C_{ipso}$, Fc), 167.9 (C=S). $IR_{vmax}$ (KBr, $cm^{-1}$): 3098, 1587, 1454, 1242, 998. MS-IE+ *m*/*z* (rel. intensity %): 345 [$M^+$] (100), 302 [$M^+ - CH(CH_3)_2$], (78), 242 [Fc-N=C=S]$^+$ (59). HRMS (FAB+): Calculated for $C_{16}H_{19}FeNS_2$: 345.0308. Found: 345.0311. Elemental analysis (%): calcd for $C_{16}H_{19}FeNS_2$: C 55.65, H 5.55, N 4.06, S 18.57; found: C 56.28, H 5.14, N 4.41, S 15.68.

**1-(2-Thiazolin-2-yl)-2-(trimethylsilyl)-ferrocene (5e).** The compound was purified by flash chromatography using hexane as an eluent affording an orange solid in 98% yield (185 mg, 0.54 mmol). Mp: 71–73 °C. $^1H$ NMR ($CDCl_3$, ppm): $\delta$ 0.26 (s, 9H, $-Si(CH_3)_3$), 3.17–3.37 (m, 2H, $-CH_2S-$), 3.93–4.04 (m, 1H, –CHHN–), 4.18 (s, 5H, Cp), 4.26 (s, 1H, subst Cp), 4.32–4.39 (m, 1H, –CHHN–). 4.43 (s, 1H, subst Cp), 4.74 (s, 1H, subst Cp). $^{13}C$ NMR ($CDCl_3$, ppm): $\delta$ 0.6 ($-Si(CH_3)_3$), 33.9 ($-CH_2S-$), 65.1 ($-CH_2N=$), 70.1 (Cp), 71.8 (CH, subst Cp), 72.3 (CH, subst Cp), 74.9 (CH, subst Cp), 76.9 ($C_{ipso}$, Fc), 83.3 ($C_{ipso}$, Fc), 167.9 (C=S). $IR_{vmax}$ (KBr, $cm^{-1}$): 3089, 1611, 1241, 822. MS-IE+ *m*/*z* (rel. intensity %): 343 [$M^+$] (68), 328 (100). HRMS (FAB+): Calculated for $C_{16}H_{21}FeNSiS$: 343.0513. Found: 343.0515. Elemental analysis (%): calcd for $C_{16}H_{21}FeNSiS$: C 55.97, H 6.16, N 4.08, S 9.34; found: C 56.83, H 6.16, N 4.46, S 8.92.

**1-(2-Thiazolin-2-yl)-2-(phenylseleno)-ferrocene (5f).** The compound was purified by flash chromatography using hexane–EtOAc 8 : 2 as an eluent affording a yellow solid in 79% yield (185 mg, 0.43 mmol). Mp: 98–99 °C. $^1$H NMR ($CDCl_3$, ppm): $\delta$ 4.05–4.07 (m, 1H, subst Cp), 4.15 (s, 5H, Cp), 4.18 (s, 2H, –$CH_2$N–), 4.32 (t, 1H, subst Cp), 4.46 (m, 1H, –$CH_2$S–), 4.72–4.74 (s, 1H, subst Cp), 4.85 (s, 1H, –$CH_2$S–), 7.33–742 (m, 3H, $H_{arom}$), 7.70–7.72 (m, 2H, $H_{arom}$). $^{13}$C NMR ($CDCl_3$, ppm): $\delta$ 33.9. (–$CH_2$S–), 64.3 (–$CH_2$N═), 70.8 (CH, subst Cp), 71.6 (Cp), 75.2 (CH, subst Cp) 76.6 (CH, subst Cp), 79.3 ($C_{ipso}$, Fc), 126.9 ($CH_{arom}$), 129.1 ($CH_{arom}$), 131.9 ($CH_{arom}$), 132.9 ($C_{ipso}$, Ph), 167.9 (C═S). $IR_{vmax}$ (KBr, $cm^{-1}$): 1590, 1472, 1432, 1244, 998. MS-IE+ *m*/*z* (rel. intensity %): 427 [$M^+$] (100), 347 (25), 287 (45). HRMS (FAB+): Calculated for $C_{19}H_{17}FeNSeS$: 426.9596. Found: 426.9600.

**1-(2-Thiazolin-2-yl)-2-(tri-*n*-butylstannyl)-ferrocene (5g).** The compound was purified by flash chromatography using hexane–EtOAc 9 : 1 as an eluent affording an orange solid in 51% yield (157 mg, 0.28 mmol). Mp: 36–37 °C. $^1$H NMR ($CDCl_3$, ppm): $\delta$ 0.9–1.00 (m, 15H, –$SnBu_3$), 1.26–1.38 (m, 6H, –$SnBu_3$), 1.48–1.58 (m, 6H, –$SnBu_3$), 3.20–3.38 (m, 2H, –$CH_2$S–), 3.90–4.00 (m, 1H, –$CH_2$N═), 4.11 (s, 5H, Cp), 4.21–4.45 (m, 2H, subst Cp and –$CH_2$N═), 4.46 (s, 1H, subst Cp), 4.68 (s, 1H, subst Cp). $^{13}$C NMR ($CDCl_3$, ppm): $\delta$ 11.6, 13.9, 27.6 and 29.4 (–$SnBu_3$), 33.8 (–$CH_2$S–), 64.5 (–$CH_2$N═), 69.7 (Cp), 71.6 (CH, subst Cp), 72.4 (CH, subst Cp), 72.9 (CH, subst Cp), 77.1 ($C_{ipso}$, Fc), 82.6 ($C_{ipso}$, Fc), 168.5 (C═S). $IR_{vmax}$ (KBr, $cm^{-1}$): 1609, 1459, 1106, 1000. MS-IE+ *m*/*z* (rel. intensity %): 504 [$M^+$ – *n*Bu] (100), 390 (40). HRMS (FAB+): Calculated for $C_{21}H_{30}FeNSSn$: 504.0470. Found: 504.0475. Elemental analysis (%): calcd for $C_{21}H_{30}FeNSSn$: C 53.60, H 7.02, N 2.50, S 5.72; found: C 54.28, H 7.12, N 2.83, S 5.77.

**1-(2-Thiazolin-2-yl)-2-(methyl)-ferrocene (5h).** The compound was purified by flash chromatography using hexane–EtOAc 9 : 1 as an eluent affording an orange solid in 86% yield (135 mg, 0.47 mmol). Mp: 98–99 °C. $^1$H NMR ($CDCl_3$, ppm): $\delta$ 2.27 (s, 3H, –$CH_3$), 3.24–3.33 (m, 2H, –$CH_2$S–), 4.12–4.33 (m, 9H, Cp, 2 subst Cp and –$CH_2$N═), 4.54 (s, 1H, –$CH_2$N–), 4.55 (s, 1H, subst Cp). $^{13}$C NMR ($CDCl_3$, ppm): $\delta$ 15.1 (–$CH_3$), 33.2 (–$CH_2$S–), 65.2 (–$CH_2$N═), 67.9 (CH, subst Cp), 70.6 (CH, subst Cp), 70.8 (Cp), 72.7 (CH, subst Cp), 76.1 ($C_{ipso}$, Fc), 84.7 ($C_{ipso}$, Fc), 168.7 (C═S). $IR_{vmax}$ (KBr, $cm^{-1}$): 1609, 997. MS-IE+ *m*/*z* (rel. intensity %): 285 [$M^+$] (100), 225 (20). HRMS (FAB+): Calculated for $C_{14}H_{15}FeNS$: 285.0750. Found: 285.0271. Elemental analysis (%): calcd for $C_{14}H_{15}FeNS$: C 58.96, H 5.30, N 4.91, S 11.24; found: C 58.28, H 5.59, N 4.51, S 9.34.

**1-(2-Thiazolin-2-yl)-2-(iodo)-ferrocene (5j).** The compound was purified by flash chromatography using hexane–EtOAc 9 : 1 as an eluent affording brown oil in 75% yield (159 mg, 0.40 mmol). $^1$H NMR ($CDCl_3$, ppm): $\delta$ 3.28–3.43 (m, 2H, –$CH_2$S–), 4.23–4.40 (m, 8H, Cp, subst Cp and –$CH_2$N═), 4.65 (s, 1H, subst Cp), 4.71 (s, 1H, subst Cp). $^{13}$C NMR ($CDCl_3$, ppm): $\delta$ 33.9 (–$CH_2$S–), 64.9 (–$CH_2$N═), 70.3 (CH, subst Cp), 71.0 (CH, subst Cp), 73.0 (Cp), 77.3 ($C_{ipso}$, Fc), 78.5 (CH, subst Cp), 78.6 ($C_{ipso}$, Fc), 166.8 (C═S). $IR_{vmax}$ (KBr, $cm^{-1}$): 1616, 1434, 1243, 994. MS-IE+ *m*/*z* (rel. intensity %): 397 [M+] (100), 269 (47), 242 [Fc-N═C═S]$^+$ (64). HRMS (FAB+): Calculated for $C_{13}H_{12}IFeNS$: 396.9085. Found: 396.9085. Elemental analysis (%): calcd for $C_{13}H_{12}IFeNS$: C 39.32, H 3.05, N 3.53, S 8.08; found: C 39.72, H 2.95, N 3.88, S 7.2.

### Synthesis of [1-(2-thiazolin-2-yl)-2-(methylthio)-ferrocene palladium(II) dichloride] (5b-$PdCl_2$)

To a solution of **5b** (0.1 g, 0.36 mmol) in dichloromethane (10 mL) was added [$Pd(CH_3CN)_2Cl_2$] (0.09 g, 0.36 mmol), then the mixture was stirred for 30 min at room temperature. The solvent was removed under vacuum, leaving a brown residue which was dissolved in the minimum amount of dichloromethane. The resulting solution was filtered through celite, and then the slow addition of hexane gave an orange solid complex, which was filtered, washed with hexane, and dried under vacuum to give 0.16 g of complex (93% yield). Mp: 178–179 °C (dec). $^1$H NMR ($CDCl_3$, ppm): $\delta$ 2.36 (m, 3H, $CH_3$S–), 3.52–3.60 (m, 2H, –$CH_2$S–), 4.07–4.20 (m, 1H, –$CH_2$N–), 4.85 (s, 5H, Cp), 4.89–4.92 (m, 1H, –$CH_2$N–), 5.04–5.05 (m, 1H, subst Cp), 5.23 (s, 1H, subst Cp), 5.31–5.41 (m, 1H, subst Cp). $IR_{vmax}$ (KBr, $cm^{-1}$): 1571, 1412, 1246, 1113. MS-FAB+ *m*/*z* (rel. intensity %): 495 [$M^+$] (3), 460 [$M^+$ – Cl] (5). Elemental analysis (%): calcd for $C_{14}H_{15}Cl_2FeNPdS_2$: C 34.00, H 3.06, N 2.83, S 12.97; found: C 34.7, H 3.41, N 2.82, S 11.03.

### General procedure for the synthesis of 1-[(dimethylamino)-methyl]-2-(alkylthio)ferrocenes 6a–c

A solution of (dimethylamino)methylferrocene (0.5 mL, 2.52 mmol) in 5 mL of anhydrous diethyl ether under nitrogen atmosphere was cooled to −78 °C, then *t*-butyl lithium in pentane 1.7 M (1.76 mL, 3 mmol) was added dropwise. The mixture was gradually warmed to room temperature. After reaching this temperature, the reaction was cooled at −10 °C and the corresponding alkyl disulphide (2 equiv.) was added to the reaction mixture. The solution was further stirred overnight at room temperature, before quenching with a saturated solution of $NaHCO_3$. After standard work-up, the crude product was purified by flash chromatography on silica-gel to give the desired compounds **6a–c**.

**1-[(Dimethylamino)methy1]-2-(methylthio)ferrocene (6a).** The compound was purified by flash chromatography using hexane–dichloromethane as an eluent affording a yellow solid in 99% yield (721 mg, 2.49 mmol). Mp: 76–77 °C. $^1$H NMR ($CDCl_3$, ppm): $\delta$: 2.20 (s, 6H, –$N(CH_3)_2$), 2.26 (s, 3H, –$SCH_3$), 3.24 (d, 1H, –$CH_2$N, *J* = 12.3 Hz), 3.59 (d, 1H, –$CH_2$N, *J* = 12.3 Hz), 4.10 (s, 5H, Cp), 4.20 (m, 1H, subst Cp), 4.30 (m, 2H, subst Cp). $^{13}$C NMR ($CDCl_3$, ppm $\delta$: 20.2 (–$SCH_3$), 45.1 (–$N(CH_3)_2$), 57.1 (–$CH_2$N), 67.5 (CH, subst Cp), 69.9 (Cp), 70.5 (CH, subst Cp), 71.7 (CH, subst Cp), 83.78 ($C_{ipso}$, Fc), 86.2 ($C_{ipso}$, Fc). $IR_{vmax}$ (KBr, $cm^{-1}$): 3078, 2854, 2771, 1421. MS-IE+ *m*/*z* (rel. intensity %): 289 [$M^+$] (21), 245 [M – $N(CH_3)_2$]$^+$ (9).

**1-[(Dimethylamino)methy1]-2-(isopropylthio)ferrocene (6b).** The compound was purified by flash chromatography using hexane–dichloromethane as an eluent affording a yellow solid in 90% yield (719 mg, 2.27 mmol). Mp: 82–83 °C. $^1$H NMR ($CDCl_3$, ppm): $\delta$: 1.20 (dd, *J* = 14.1, 6.6 Hz, 6H, –$(CH_3)_2$), 2.19

(s, 6H, –N($CH_3$)$_2$), 3.02 (m, 1H, –SCH–), 3.17 (d, $J$ = 12.9 Hz, 1H, –$CH_2$N), 3.60 (d, $J$ = 12.9 Hz, 1H, –$CH_2$N), 4.09 (s, 5H, Cp), 4.17 (m, 1H, subst Cp), 4.33 (m, 2H, subst Cp). $^{13}$C NMR ($CDCl_3$, ppm $\delta$: 22.9 (–CH$CH_3$–), 23.7 (–C$HCH_3$–), 39.6 (–SCH–), 45.4 (–N($CH_3$)$_2$), 57.4 (–$CH_2$N), 67.8 (CH, subst Cp), 70.1 (CH, subst Cp), 70.9 (Cp), 75.2 (CH, subst Cp), 78.9 ($C_{ipso}$, Fc), 88.1 ($C_{ipso}$, Fc). $IR_{vmax}$ (KBr, $cm^{-1}$): 2758, 1737, 1369, 627. MS-IE+ $m/z$ (rel. intensity %): 317 [$M^+$] (100), 273 [$M$ – N($CH_3$)$_2$]$^+$ (39).

**1-[(Dimethylamino)methy1]-2-(tertbutylthio)ferrocene (6c).** The compound was purified by flash chromatography using hexane–dichloromethane as an eluent affording a yellow solid in 60% yield (500 mg, 1.51 mmol). Mp: 82–83 °C. $^1$H NMR ($CDCl_3$, ppm): $\delta$ 1.24 (s, 9H, –S($CH_3$)$_3$), 2.23 (s, 6H, –N($CH_3$)$_2$), 3.18 (d, $J$ = 13.2 Hz, 1H, –$CH_2$N), 3.53 (d, $J$ = 13.2 Hz, 1H, –$CH_2$N), 4.08 (s, 5H, Cp), 4.20 (t, $J$ = 5.1 Hz, 1H, subst Cp), 4.36 (t, $J$ = 3.9 Hz, 1H, subst Cp), 4.42 (t, $J$ = 3.9 Hz, 1H, subst Cp). $^{13}$C NMR ($CDCl_3$, ppm) $\delta$: 22.9 (–N$CH_3$–), 23.7 (–N$CH_3$–), 39.6 (–$C$($CH_3$)$_3$), 45.4 (–N($CH_3$)$_2$), 57.4 (CH, subst Cp), 67.8 (CH, subst Cp), 70.1 (CH, subst Cp), 70.9 (Cp), 75.2 (CH, subst Cp), 78.9 ($C_{ipso}$, Fc), 88.1 ($C_{ipso}$, Fc). $IR_{vmax}$ (KBr, $cm^{-1}$): 2758, 1737, 1369, 627. MS-IE+ $m/z$ (rel. intensity %): 331 [$M^+$] (53), 273 (100).

### General procedure for the synthesis of [1-[(dimethylamino)-methy1]-2-(alkylthio)ferrocene] palladium(II) dichloride 7a–c

To a solution of **6** (0.62 mmol) in dichloromethane (10 mL) was added [Pd($CH_3CN$)$_2$$Cl_2$] (0.16 g, 0.62 mmol), then the mixture was stirred for 1 hour at room temperature. The resulting solution was filtered through celite, and the crude product was purified by flash chromatography on silica-gel to give the desired complexes as brown solids. These complexes were characterized using conventional spectroscopic techniques and all data are in agreement with those previously reported in the literature.[20]

**[1-[(Dimethylamino)methy1]-2-methylthio)ferrocene]-palladium(II) dichloride (7a).** The compound was purified by flash chromatography affording a brown solid in 99% yield (283 mg, 0.61 mmol). Mp: 176 °C. $^1$H NMR ($CDCl_3$, ppm): $\delta$ 2.18 (s, 3H, –S$CH_3$), 2.33 (s, 3H, –N$CH_3$–), 3.09 (s, 3H, –N$CH_3$–), 2.82 (d, 1H, –$CH_2$N, $J$ = 13 Hz), 3.97 (d, 1H, –$CH_2$N, $J$ = 13 Hz), 4.32 (s, 5H, Cp), 4.42 (t, 1H, subst Cp, $J$ = 5 Hz), 4.48 (s, 1H, subst Cp), 4.61 (s, 1H, subst Cp). $^{13}$C NMR ($CDCl_3$, ppm: $\delta$ 29.5 (–S$CH_3$), 31.0 (–N($CH_3$)$_2$), 48.7 (CH, subst Cp), 63.8 (–$CH_2$N), 68.5 (CH, subst Cp), 71.4 (Cp), 74.4 ($C_{ipso}$, Fc), 79.20 ($C_{ipso}$, Fc). $IR_{vmax}$ (KBr, $cm^{-1}$): 3021, 1741, 1443, 1370, 689. MS-IE+ $m/z$ (rel. intensity %): 465 [$M^+$] (1), 419 [$M$ – S$CH_3$]$^+$ (3).

**[1-[(Dimethylamino)methy1]-2-isopropylthio)ferrocene]-palladium(II) dichloride (7b).** The compound was purified by flash chromatography affording a brown solid in 86% yield (261 mg, 0.53 mmol). Mp: 174 °C. $^1$H NMR ($CDCl_3$, ppm) $\delta$: 1.67 (d, 3H, –CH$CH_3$–, $J$ = 7 Hz), 1.73 (d, 3H, –CH$CH_3$–, $J$ = 7 Hz), 2.51 (s, 3H, –N$CH_3$–), 3.07 (s, 3H, –N$CH_3$–), 2.82 (d, 1H, –$CH_2$N, $J$ = 13.5 Hz), 3.56 (d, 1H, –$CH_2$N, $J$ = 13.5 Hz), 3.75 (m, 1H, –SCH–), 4.39 (s, 5H, Cp), 4.45 (s, 1H, subst Cp), 4.68 (s, 2H, subst Cp). $^{13}$C NMR ($CDCl_3$, ppm) $\delta$: 23.2 (–CH$CH_3$–), 23.5 (–C$HCH_3$–), 31.0 (–N($CH_3$)$_2$), 50.6 (–SCH–), 63.3 (–$CH_2$N), 71.8 (Cp), 70.6 (CH, subst Cp), 72.1 (CH, subst Cp), 74.5 (CH, subst Cp), 84.0 ($C_{ipso}$, Fc), 84.9 ($C_{ipso}$, Fc). $IR_{vmax}$ (KBr, $cm^{-1}$): 2860, 1148, 728. MS-IE+ $m/z$ (rel. intensity %): 493 [$M^+$] (2), 317 [$M^+$ – $PdCl_2$]$^+$ (7).

**[1-[(Dimethylamino)methy1]-2-tertbutylthio)ferrocene]-palladium(II) dichloride (7c).** The compound was purified by flash chromatography affording a brown solid in 80% yield (249 mg, 0.49 mmol). Mp: 176 °C. $^1$H NMR ($CDCl_3$, ppm): $\delta$ 1.48 (s, 9H, –($CH_3$)$_3$), 2.66 (d, 1H, –$CH_2$N, $J$ = 14.1 Hz), 3.05 (s, 3H, –N$CH_3$–), 3.22 (s, 3H, –N$CH_3$–), 3.32 (d, 1H, –$CH_2$N, $J$ = 14.1 Hz), 4.53 (t, 1H, subst Cp, $J$ = 5.1 Hz), 4.64 (s, 5H, Cp), 4.84 (s, 1H, subst Cp), 5.33 (t, 1H, subst Cp, $J$ = 5.1 Hz). $^{13}$C NMR ($CDCl_3$, ppm) $\delta$: 89.1 ($C_{ipso}$, Fc), 78.3 ($C_{ipso}$, Fc), 75.0 (CH, subst Cp), 73.8 (CH, subst Cp), 69.7 (CH, subst Cp), 72.7 (Cp), 61.6 (–$CH_2$N), 55.0 (–$C$($CH_3$)$_3$), 51.9 (–N$CH_3$–), 52.7 (–N$CH_3$–), 30.9 (–($CH_3$)$_3$). $IR_{vmax}$ (KBr, $cm^{-1}$): 3083, 2918, 1454, 1369, 731. MS-IE+ $m/z$ (rel. intensity %): 437 [$M^+$ – 2Cl] $^+$ (3).

### Synthesis of 2-ferrocenyloxazoline (8)

The preparation of compound **8** was carried out using the methodology previously described elsewhere.[8b]

### Synthesis of 1-(2-oxazolin-2-yl)-2-(methylthio)-ferrocene (9)

A stirred solution of ferrocenyloxazoline **8** (100 mg, 0.39 mmol) and TMEDA in $Et_2O$ (0.07 mL, 0.47 mmol) under nitrogen was cooled to −78 °C and then $n$-BuLi (0.2 mL, 0.5 mmol) was added dropwise. After stirring at −78 °C for 2 h, the mixture was transferred to an ice bath and the stirring was maintained for a further 5 min. To the resultant solution was added $(SMe)_2$ (0.07 mL, 0.78 mmol) and the reaction mixture was allowed to warm to room temperature and stirred overnight. After this time, the reaction was quenched with a saturated solution of $NaHCO_3$ and diluted with $EtO_2$. The combined organic layer was dried with anhydrous $Na_2SO_4$, filtered and evaporated. The crude product was purified by column chromatography to give **9** as a yellow solid (89 mg, 76%). Mp: 111–112 °C. $^1$H NMR ($CDCl_3$, ppm): $\delta$ 2.40 (s, 3H, –$CH_3$), 3.95–4.03 (m, 2H, –$CH_2$N–), 4.21 (s, 5H, Cp), 4.29 (s, 1H, subst Cp), 4.30–4.39 (m, 2H, –$CH_2$O–). 4.42 (br s, 1H, subst Cp), 4.75 (s, 1H, subst Cp). $^{13}$C NMR ($CDCl_3$, ppm): $\delta$ 18.4 (–$CH_3$), 55.2 (–$CH_2$N═), 67.0 (–$CH_2$O–), 68.5 (CH, subst Cp), 70.3 (CH, subst Cp), 70.7 (CH, subst Cp), 71.0 (Cp), 86.6 ($C_{ipso}$, Fc), 166.2 (C═S). $IR_{vmax}$ (KBr, $cm^{-1}$): 1651, 1258, 1185, 1103. MS-IE+ $m/z$ (rel. intensity %): 301 [$M^+$] (100), 286 [$M^+$ – $CH_3$] (58).

### Synthesis of [1-(2-oxazolin-2-yl)-2-(methylthio)-ferrocene palladium(II) dichloride] (10)

To a solution of **9** (50 mg, 0.16 mmol) in dichloromethane (5 mL) was added [Pd($CH_3CN$)$_2$$Cl_2$] (66 mg, 0.16 mmol), then the mixture was stirred for 30 min at room temperature. The resulting solution was filtered through celite and the solvent was removed under vacuum, leading to an orange colored residue. This residue was dissolved in a small amount of $CH_2Cl_2$ and precipitated with a large excess of hexane. After filtration, the solid was washed with small portions of hexane,

and dried under vacuum to give 64 mg of complex **10** as an orange solid (81% yield). Mp: 198 °C (dec). $IR_{v\ max}$ (KBr, $cm^{-1}$): 1619, 1248, 1180, 839. MS-FAB+ *m*/*z* (rel. intensity %): 479 [$M^+$] (2), 443 [$M^+$ − Cl], (7). Elemental analysis (%): calcd for $C_{14}H_{15}Cl_2FeNOPdS$: C 35.14, H 2.96, N 2.93, S 6.70; found: C 35.77, H 2.96, N 2.94, S 5.68.

### General procedure for Mizoroki–Heck coupling reactions under conventional thermal heating

In a 10 mL round-bottomed flask, 4-iodotoluene (880 mg, 4 mmol), methyl acrylate (0.44 mL, 4.8 mmol) and $Et_3N$ (0.84 mL, 6 mmol) were placed in 5 mL of DMF, then the palladium complex (0.05% mol) was added. The reaction mixture was refluxed for the time stated in Table 4 at 140 °C. The reaction mixture was poured into water (20 mL) and extracted with hexane (2 × 20 mL). The combined organic layers were dried over anhydrous sodium sulfate. The crude product was finally purified by flash column chromatography on silica-gel. *Note*: the entire flasks used in each coupling reaction were meticulously cleaned with aqua regia to avoid the presence of unseen palladium catalyst.

### General procedure for Mizoroki–Heck coupling reactions under microwave irradiation

A 10 mL microwave-transparent process vial was filled with aryl iodide (4 mmol), methyl acrylate (0.44 mL, 4.8 mmol), base (6 mmol), 5 mL of solvent and the palladium complex. The vial was sealed with PEEK snap caps and standard PTFE coated silicone septa. The reaction mixture was then exposed to microwave heating for the time stated in Table 5 at 160 °C. The reaction vial was thereafter cooled to room temperature and the mixture was diluted with 30 mL of water and extracted with 3 × 20 mL of ether or hexane. The combined organic layers were dried over anhydrous sodium sulfate. The crude product was finally purified by flash column chromatography on silica-gel to give the isolated products in yields stated in Table 5. *Note*: The entire vials used in each coupling reaction were meticulously cleaned with *aqua regia* to avoid the presence of unseen palladium catalysts.

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