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Synthesis of ferrocenyl quinones

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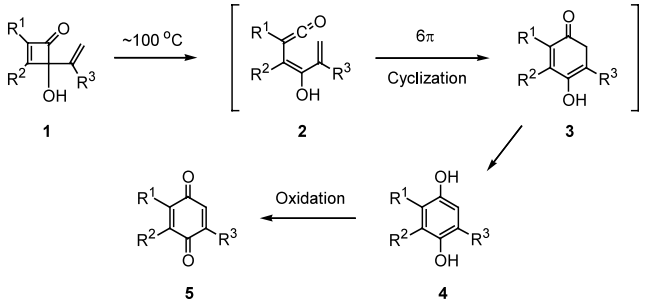
Abstract—A squarate-based synthesis of ferrocenyl quinones is described. Thermolysis of ferrocenyl-substituted cyclobutenones, prepared from ferrocenyl cyclobutenediones and alkenyllithiums, affords hydroquinones, which furnish, upon oxidation, ferrocenyl quinones. Ferrocenyl cyclobutenediones have been prepared from known cyclobutenediones by nucleophilic addition of ferrocenyllithium followed by hydrolysis, Pd/Cu-cocatalyzed cross-coupling with (tri-*n*-butylstannyl)ferrocene or Friedel–Crafts alkylation with ferrocene.

After the successful application of the pioneer 'cisplatin', i.e. *cis*-$[PtCl_2(NH_3)_2]$, as an antitumor agent,[1] interest in the use of transition metal complexes in medicine and other biological areas has grown rapidly.[2] Among these derivatives, ferrocenium salts,[3] $Cp_2Fe(III)X$ ($X = PF_6$, $FeCl_4$, $2,4,6\text{-}(NO_2)_3C_6H_2O$, $Cl_3CCO_2 \cdot 2Cl_3CCO_2H$), and ferrocifens,[4] (*Z*)-[(Et)(Fc)C=C(*p*-C_6H_4-R)(*p*-C_6H_4-O-CH_2-CH_2-NMe_2] (Fc = ferrocenyl, R = H, OH), have proved to be particularly active against a number of tumors. Moreover, ferrocifens are the first molecules shown to be active against both hormone-dependent and hormone-independent breast cancer cells.[4] It appears so far, however, that ferrocene derivatives act via mechanisms different from those of cisplatin and thus may lend themselves to treatment of a wider range of cancers.[4,5] Although, since its discovery, ferrocene and its derivatives have found large application in a number of areas, most notably in materials chemistry and asymmetric catalysis,[6] relatively few studies on the biological properties of molecules bearing the ferrocene moiety have been reported. Thus, in recent years, considerable interest has been devoted to the synthesis of new ferrocene derivatives since the properly functionalized ferrocene derivatives could be potential antitumor substances.[7]

Quinones have been studied for over a century and continue to demand attention by virtue of their presence in antitumor quinone natural products.[8] This, together with the finding that ferrocene derivatives are active against various animal and human tumors,[3,4] suggests that the incorporation of the essential structural features of quinones with a ferrocene moiety could provide compounds with enhanced antitumor activities. Surprisingly, ferrocenyl-substituted quinones are very scarce.[9] The development of a general synthetic entry to ferrocenyl quinones is therefore of considerable interest since it could be lead to a new source of biologically active compounds.

Recently, as shown in Scheme 1, cyclobutenones bearing an unsaturated substituent at the 4-position, such as **1**, have emerged as valuable reagents in organic synthesis since such cyclobutenones have been found to lead to a variety of quinones, such as **5**, after oxidation.[10] Since the starting cyclobutenones are now available with a variety of substitution patterns and the yields of the rearrangements are generally high, these ring expansions constitute one of the most versatile regiospecific routes to highly substituted quinones.[10] This methodology, however, has not been utilized for the synthesis of



Scheme 1.

Keywords: ferrocenes; ferrocenyl quinones; cyclobutenediones; cyclobutenones; cyclobutenols; hydroquinones; electrocyclization; oxidation.

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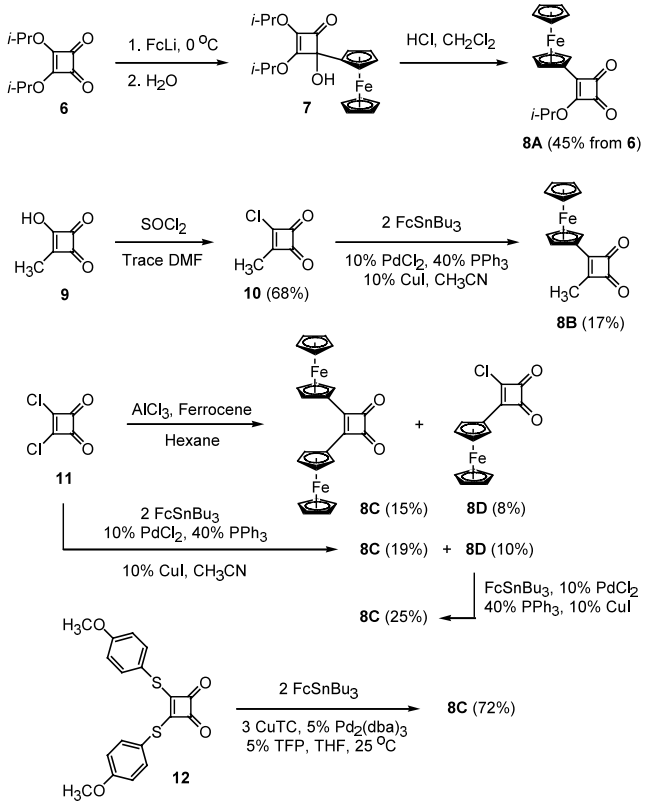
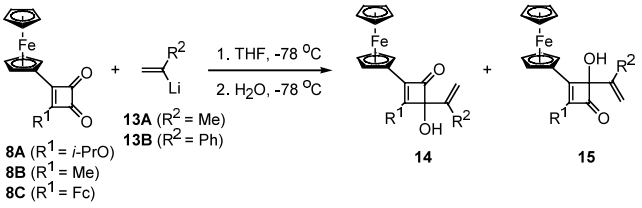
ferrocenyl quinones, presumably due to the scarce availability of starting ferrocenyl cyclobutenones. As part of our general involvement in ferrocene containing molecules, we have investigated the synthesis of ferrocenyl cyclobutenones and their rearrangements to quinones. We herein report the preliminary results of this study.

As depicted in Scheme 2, the synthesis of ferrocenyl-substituted cyclobutenediones was accomplished from known cyclobutenediones. Addition of ferrocenyllithium (FcLi)[11] to diisopropyl squarate (**6**)[12] led to formation of cyclobutenone **7**, which upon hydrolysis provided cyclobutenedione **8A**.[13] Treatment of cyclobutenedione **9**[12] with thionyl chloride afforded semisquaric chloride **10**,[14,15] which underwent Pd-catalyzed coupling with (tri-*n*-butylstannyl)ferrocene ($FcSnBu_3$)[16] to produce cyclobutenedione **8B**.[17] The synthesis of diferrocenyl cyclobutenedione **8C**[18] was accomplished from squaric dichloride (**11**)[14] by both Friedel–Crafts alkylation and Pd-catalyzed coupling, but both methods gave **8C** in low yields in addition to **8D**. Pd-catalyzed coupling of **8D** with $FcSnBu_3$ yielded **8C** in 25% yield. A high yielding protocol for **8C**, however, has recently been reported by Pena-Cabrera using Pd-catalyzed coupling of thioether **12** with $FcSnBu_3$ (Scheme 2).[19] We are still trying to improve the yields for both the Friedel–Crafts alkylation of **11** and the Pd-catalyzed couplings of **10** and **11**, especially by using the conditions of Diver[21] for the latter method. These results will be reported in due course.



Scheme 2.

Table 1. Synthesis of ferrocenyl cyclobutenones **14** and **15**[a]



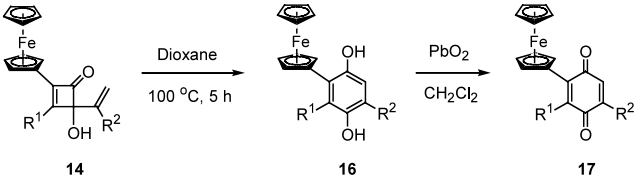
Entry[b]	R^1	R^2	Yield of **14** (%)	Yield of **15** (%)
A	*i*-PrO	Me	94	5
B	Me	Me	57	4
C	Fc	Me	65	0
D	*i*-PrO	Ph	40	0
E	Fc	Ph	47	0

[a] For a representative procedure, see Ref. 20.
[b] Entry letters define R^1 and R^2 for cyclobutenones **14** and **15**.

Having ferrocenyl cyclobutenediones **8** in hand, we next synthesized ferrocenyl cyclobutenones such as **14** and **15**, as shown in Table 1. The reaction of cyclobutenones **8A–C** with 2-lithiopropene (**13A**)[22] produced the expected cyclobutenones **14A–C** in moderate to good yields. A complication in these reactions was the formation of the regioisomers **15A** and **15B** in low yields (Table 1, entries **A** and **B**). However, the reaction between α-lithiostyrene (**13B**) and cyclobutenones **8A**,**C** produced the expected cyclobutenones **14D**,**E** without formation of any regioisomers. As will be discussed later, the indicated regiochemistry of cyclobutenones **14B** and **15B** was assigned indirectly by comparison of the HMBC-NMR spectra of their quinone products **17B** and **19B**, respectively, since during the conversion into quinones the regiochemistry does not change.

Finally, the synthesis of ferrocenyl quinones was accomplished. The results are summarized in Tables 2 and 3. Initially, the reaction of cyclobutenone **14A** was

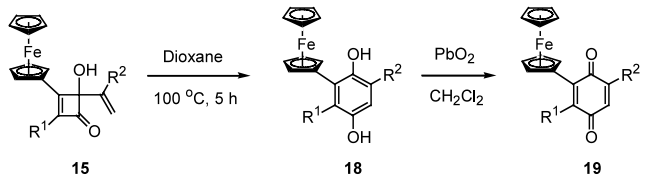
Table 2. Synthesis of ferrocenyl quinones **17**[a]



Entry[b]	R^1	R^2	Yield of **17** from **14** (%)[c]
A	*i*-PrO	Me	85
B	Me	Me	71
C	Fc	Me	56
D	*i*-PrO	Ph	61
E	Fc	Ph	75

[a] For a representative procedure, see Ref. 22. For spectral data of ferrocenyl quinones, see Ref. 23.
[b] Entry letters define R^1 and R^2 for compounds **14**, **16** and **17**.
[c] Hydroquinones **16** were not isolated and were directly oxidized to quinones **17**.

Table 3. Synthesis of ferrocenyl quinones **19**[a]



15 **18** **19**

Entry[b]	R^1	R^2	Yield of **19** from **15** (%)[c]
A	*i*-PrO	Me	77
B	Me	Me	70

[a] For spectral data of ferrocenyl quinones, see Ref. 24.
[b] Entry letters define R^1 and R^2 for compounds **15**, **18** and **19**.
[c] Hydroquinones **18** were not isolated and were directly oxidized to quinones **19**.

examined under a variety of conditions. The best results were obtained in dioxane at 100°C. Thermolysis of cyclobutenone **14A** produced hydroquinone **16A** and quinone **17A** in 72 and 17% yields, respectively. Clearly, quinone **17A** is the secondary product of the reaction and results from the oxidation of initially formed hydroquinone **16A**. We found that hydroquinone **16A** was not stable to air and was partially oxidized to quinone **17A**. Among the oxidants employed, PbO_2 proved to be the best since it did not further oxidize the ferrocene moiety into a ferrocenium ion or other side products, as has been shown before.[9b] The oxidation of **16A** with PbO_2 furnished quinone **17A** in 94% yield. In addition to hydroquinones, quinones in varying amounts often resulted from thermolysis reactions. Thus, we did not isolate the thermolysis products and directly oxidized the crude mixtures into quinones. As seen in Tables 2 and 3, cyclobutenones participated well in the benzannulation reactions, presumably via a similar mechanism to that depicted in Scheme 1, and yielded, upon oxidation, a variety of ferrocenyl quinones in moderate to good yields. Substituents on the cyclobutenones affected the outcome of the reactions to some extent. Cyclobutenones bearing electron-releasing substituents such as isopropoxy give quinones in relatively higher yields. The indicated regiochemistry of quinones **17B** and **19B** was assigned on the basis of comparison of their HMBC-NMR spectra. In **17B**, the hydrogens of both methyl groups (δ 2.12 and 2.05 ppm) give a three-bond coupling ($^3J_{CH}$) with the same carbonyl (δ 188.1 ppm). However, in **19B**, the hydrogens of each methyl group (δ 2.05 and 2.04 ppm) show similar interactions ($^3J_{CH}$) with the different carbonyl groups (δ 187.7 and 187.4 ppm, respectively). This also proves the indicated regiochemistry of cyclobutenones **14B** and **15B**.

In conclusion, we have demonstrated a concise and synthetically flexible cyclobutenedione-based approach to highly-substituted ferrocenyl quinones, which relies on the versatility of cyclobutenediones as scaffolds for the construction of a diverse range of molecular structures. Further study of ferrocenyl quinones is currently under investigation.

Acknowledgements

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13. Synthesis of **8A** from **6**. To a solution of ferrocene (2.00 g, 10.75 mmol) in THF (10 mL) at 0°C under argon was added via syringe *tert*-butyllithium (5.3 mL of a 1.7 M of C_6H_{12}–ether solution, 9.00 mmol) over a period of 15 min. The resulting mixture was stirred for 1.5 h at rt and then transferred via cannula to a solution of diisopropyl squarate (**6**) (1.43 g, 7.20 mmol) in THF (5.0 mL) at 0°C. After overnight stirring at rt, the reaction mixture was diluted with water (15 mL) and extracted with ether (3×150 mL). After the combined organic layers were removed on a rotary evaporator, the crude product **7** obtained was dissolved in CH_2Cl_2 (20 mL) and conc. HCl (8 drops, ca. 0.40 mL) was added. The resulting mixture was stirred at rt for approximately 30 min (the progress of the reaction was monitored by routine TLC for disappearance of **7**). On completion, the reaction mixture was diluted with saturated $NaHCO_3$ solution (20 mL). The layers were separated and the aqueous layer was extracted with CH_2Cl_2 (2×50 mL). The combined organic layers were dried over Na_2SO_4 and final purification was achieved by flash chromatography on silica gel using 9:1 hexane/ethyl acetate as eluent. The red fraction with $R_f=0.17$ in 9:1 hexane/ethyl acetate was collected and assigned as **8A** (red solid, 1.05 g, 45% from **6**).
    Spectral data for 8A: ^{1}H NMR ($CDCl_3$, 400.1 MHz): δ 5.52 (septet, 1H, $J=6.2$ Hz), 4.94 (s, 2H), 4.63 (s, 2H), 4.15 (s, 5H), 1.51 (d, 6H, $J=6.2$ Hz); ^{13}C NMR ($CDCl_3$, 100.6 MHz): δ 193 (C), 192.1 (C), 191.5 (C), 180.9 (C), 79.3 (CH), 73.2 (CH), 70.9 (CH), 69.2 (CH), 68 (C), 23.4 (CH_3); IR (CH_2Cl_2): 2984 (vw), 1786 (s), 1736 (vs), 1593 (vs), 1465 (s), 1385 (m), 1337 (m), 1092 (m), 1014 (w); MS (EI): 324 (M^+, 34), 279 (58), 277 (85), 226 (64), 201 (65), 175 (54), 157 (76), 125 (100), 117 (37), 99 (91); HRMS (EI): calcd for $C_{17}H_{16}{}^{56}FeO_3$ 324.0448, found 324.0439.
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17. **Spectral data for 8B**: ^{1}H NMR ($CDCl_3$, 400.1 MHz): δ 4.96 (s, 2H), 4.73 (s, 2H), 4.17 (s, 5H), 2.36 (s, 3H); ^{13}C NMR ($CDCl_3$, 100.6 MHz): δ 197.7 (C), 197.0 (C), 196.9 (C), 188.5 (C), 73.7 (CH), 70.5 (CH), 69.2 (CH), 67.8 (C), 11.8 (CH_3); IR (CH_2Cl_2): 1781 (vs), 1756 (s), 1590 (vs), 1454 (w), 1381 (w), 1312 (m), 1259 (m), 1201 (w), 1100 (w), 1044 (m), 908 (m); MS (EI): 280 (M^+, 48), 277 (23), 262 (22), 224 (100), 183 (11), 119 (10), 104 (14), 69 (21). HRMS (EI): calcd for $C_{15}H_{12}{}^{56}FeO_2$ 280.0186, found: 280.0177.
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20. **Representative procedure for synthesis of ferrocenyl cyclobutenones**. Synthesis of **14A** and **15A** (Table 1, entry **A**). To a solution of 2-bromo-1-propene (0.12 mL, 1.33 mmol) in THF (10 mL) at −78°C under argon was added via syringe, *tert*-butyllithium (1.5 mL of a 1.7 M of C_6H_{12}–ether solution, 2.55 mmol) over a period of 15 min. After stirring at −78°C for 30 min, the resulting mixture (2-lithiopropene) was transferred via cannula to a solution of **8A** (360.0 mg, 1.11 mmol) in THF (15 mL) at −78°C. The reaction mixture was stirred at −78°C for 3 h and then quenched with water (10 mL) at −78°C. The mixture was allowed to warm to rt and diluted with ether (50 mL). The layers were separated and the aqueous layer was extracted with ether (2×50 mL). The combined organic layers were dried over Na_2SO_4 and the solvents were removed on a rotary evaporator. Final purification was achieved by flash chromatography on silica gel using 9:1 hexane/ethyl acetate followed by 4:1 hexane/ethyl acetate as eluent. Two fractions were isolated. First fraction ($R_f=0.22$ in 9:1 hexane/ethyl acetate) was assigned as **15A** (20.3 mg, 5.0%). Second fraction ($R_f=0.16$ in 9:1 hexane/ethyl acetate) was identified as **14A** (382.0 mg, 94%).
    Spectral data for 14A: ^{1}H NMR ($CDCl_3$, 400.1 MHz): δ 5.31 (s, 1H), 5.10 (s, 1H), 4.85 (septet, 1H, $J=1.1$ Hz), 4.58 (s, 1H), 4.55 (s, 1H), 4.16 (t, 2H, $J=1.8$ Hz), 4.08 (s, 5H), 3.44 (s, 1H), 1.80 (s, 3H), 1.40 (d, 3H, $J=6.2$ Hz), 1.33 (d, 3H, $J=6.2$ Hz); ^{13}C NMR ($CDCl_3$, 100.6 MHz): δ 187.8 (C), 177.9 (C), 141.3 (C), 126.6 (C), 114.5 (CH_2), 95.9 (C), 78.4 (CH), 70.9 (C), 69.6 (CH), 69.1 (CH), 68.0 (CH), 67.8 (CH), 23.4 (CH_3), 23.3 (CH_3), 20.2 (CH_3); IR (CH_2Cl_2): 3564 (vw), 3364 (br), 1753 (s), 1631 (vs), 1471 (s), 1384 (s), 1330 (m), 1095 (s); MS (EI): 366 (M^+, 100), 324 (53), 258 (42), 257 (83), 229 (22); HRMS (EI): calcd for $C_{20}H_{22}{}^{56}FeO_3$ 366.0918, found 366.0926.
    Spectral data for 15A: ^{1}H NMR ($CDCl_3$, 400.1 MHz): δ 5.30 (s, 1H), 5.07 (s, 1H), 4.98 (septet, 1H, $J=6.0$ Hz), 4.69 (s, 1H), 4.54 (s, 1H), 4.42 (s, 1H), 4.38 (s, 1H), 4.14 (s, 5H), 2.49 (s, 1H), 1.70 (s, 3H), 1.33 (d, 3H, $J=6.0$ Hz), 1.28 (d, 3H, $J=6.0$ Hz); ^{13}C NMR ($CDCl_3$, 100.6 MHz): δ 187.5 (C), 156.2 (C), 150.0 (C), 143.3 (C), 114.0 (CH_2), 90.9 (C), 74.3 (CH), 71.8 (CH), 71.4 (CH), 71.3 (C), 70.6 (CH), 69.4 (CH), 68.7 (CH), 23.4 (CH_3), 20.3 (CH_3); IR (CH_2Cl_2): 3574 (br), 2980 (w), 1749 (vs), 1620 (s), 1463 (m), 1380 (m), 1328 (m), 1260 (m), 1104 (m); MS (EI): 366 (M^+, 100), 338 (42), 324 (44), 296 (73), 257 (65), 250 (80), 229 (49), 121 (24); HRMS (EI): calcd for $C_{20}H_{22}{}^{56}FeO_3$ 366.0918, found: 366.0901.
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22. **Representative procedure for synthesis of ferrocenyl hydroquinones and quinones**. Synthesis of **16A** and **17A** (Table 2, entry **A**). A solution of **14A** (275.0 mg, 0.75 mmol) in dioxane (15 mL) was heated to reflux under Ar for a period of 5 h. The mixture was allowed to cool to rt and the solvent was removed on a rotary evaporator. Final purification was achieved by flash chromatography on silica gel using 19:1 hexane/ethyl acetate as the eluent.

Two fractions were isolated. First fraction (R_f = 0.56 in 9:1 hexane/ethyl acetate) was assigned as **17A** (green solid, 46.5 mg, 17%). The second fraction (R_f = 0.44 in 9:1 hexane/ethyl acetate) was identified as **16A** (bright yellow crystals, 198.0 mg, 72%).

Note that, if hydroquinones were not isolated, the crude reaction mixture obtained above before column chromatography was immediately oxidized to the corresponding quinones according to the following procedure.

Oxidation of **16A** to **17A** (Table 2, entry **A**). A solution of **16A** (80.0 mg, 0.22 mmol) and PbO_2 (525.8 mg, 2.20 mmol) in CH_2Cl_2 (5 mL) was stirred at rt for 30 min. After filtration, the solvent was removed on a rotary evaporator. Final purification was achieved by flash chromatography on silica gel using 9:1 hexane/ethyl acetate as eluent. The fraction with R_f = 0.56 in 9:1 hexane/ethyl acetate was collected to give **17A** (74.8 mg, 94%).

Spectral data for 16A: ^{1}H NMR ($CDCl_3$, 400.1 MHz): δ 7.13 (s, 1H), 6.51 (s, 1H), 5.40 (s, 1H), 4.66 (s, 2H), 4.52 (s, 2H), 4.32 (s, 5H), 3.67 (septet, 1H, J = 6.1 Hz), 2.24 (s, 3H), 1.11 (d, 6H, J = 6.1 Hz); ^{13}C NMR ($CDCl_3$, 100.6 MHz): δ 147.2 (C), 142.1 (C), 142.0 (C), 124.1 (C), 113.1 (C), 112.7 (CH), 75.5 (CH), 69.9 (note that ferrocene carbons overlap each other and appear as broad singlet), 22.5 (CH_3), 16.1 (CH_3); IR (CH_2Cl_2): 3523 (br), 3374 (br), 2977 (m), 2928 (m), 2870 (vw), 1461 (vs), 1331 (m), 1203 (vs), 1104 (m), 1050 (s); MS (EI): 366 (M^+, 100), 323 (40), 257 (95), 229 (18); HRMS (EI): calcd for $C_{20}H_{22}{}^{56}FeO_3$ 366.0918, found 366.0901.

23. **Spectral data for 17A**: ^{1}H NMR ($CDCl_3$, 400.1 MHz): δ 6.52 (s, 1H), 5.14 (s, 2H), 4.73 (septet, 1H, J = 6.1 Hz), 4.51 (s, 2H), 4.14 (s, 5H), 2.08 (s, 3H), 1.27 (s, 3H, J = 6.1 Hz), 1.27 (s, 3H); ^{13}C NMR ($CDCl_3$, 100.6 MHz): δ 187.7 (C), 183.9 (C), 152.7 (C), 143.9 (C), 134.4 (CH), 134.0 (C), 76.3 (CH), 74.6 (C), 72.8 (CH), 70.7 (CH), 70.4 (CH), 23.1 (CH_3), 15.6 (CH_3); IR (CH_2Cl_2): 2981 (w), 1650 (vs), 1571 (w), 1380 (w), 1357 (w), 1188 (w), 1099 (m), 1064 (w); MS (EI): 364 (M^+, 69), 322 (100), 294 (92), 257 (44), 229 (31), 121 (13); HRMS (EI): calcd for $C_{20}H_{20}{}^{56}FeO_3$ 364.0761, found 364.0750.

Spectral data for 17B: ^{1}H NMR ($CDCl_3$, 400.1 MHz): δ 6.54 (d, 1H, J = 1.1 Hz), 4.67 (s, 2H), 4.49 (s, 2H), 4.13 (s, 5H), 2.12 (s, 3H), 2.05 (d, 3H, J = 1.1 Hz); ^{13}C NMR ($CDCl_3$, 100.6 MHz): δ 188.1 (C), 187.0 (C), 145.4 (C), 143.6 (C), 139.3 (C), 134.2 (CH), 77.6 (C), 72.9 (CH), 70.5 (CH), 70.4 (CH), 16.2 (CH_3), 15.5 (CH_3); IR (CH_2Cl_2): 3098 (w), 2961 (w), 2924 (w), 1650 (vs), 1636 (vs), 1580 (s), 1413 (m), 1270 (s), 1058 (m); MS (EI): 320 (M^+, 100), 256 (85), 181 (5), 69 (9); HRMS (EI): calcd for $C_{18}H_{16}{}^{56}FeO_2$ 320.0499, found 320.0490.

Spectral data for 17C: ^{1}H NMR ($CDCl_3$, 400.1 MHz): δ 6.54 (s, 1H), 4.32 (s, 8H), 4.01 (s, 5H), 3.99 (s, 5H), 2.10 (s, 3H); ^{13}C NMR ($CDCl_3$, 100.6 MHz): δ 186.2 (C), 185.7 (C), 145.4 (C), 141.8 (C), 141.5 (C), 133.6 (CH), 79.5 (C), 79.1 (C), 72.6 (CH), 70.1 (CH), 70.0 (CH), 69.6 (CH), 69.5 (CH), 16.0 (CH_3); IR (CH_2Cl_2): 3098 (w), 2926 (w), 1650 (vs), 1542 (w), 1457 (s), 1306 (m), 1270 (w), 1216 (w), 1002 (w); MS (EI): 490 (M^+, 100), 422 (46), 360 (10), 304 (14), 245 (8), 186 (8); HRMS (EI): calcd for $C_{27}H_{22}{}^{56}Fe_2O_2$ 490.0318, found 490.0326.

Spectral data for 17D: ^{1}H NMR ($CDCl_3$, 400.1 MHz): δ 8.25 (m, 2H), 7.45 (m, 3H), 7.37 (s, 1H), 6.00 (septet, 1H, J = 6.0 Hz), 5.38 (s, 2H), 4.55 (s, 2H), 4.11 (s, 5H), 1.47 (d, 6H, J = 6.0 Hz); ^{13}C NMR ($CDCl_3$, 100.6 MHz): δ 188.3 (C), 187.6 (C), 161.6 (C), 140.4 (C), 137.7 (CH), 133.7 (C), 133.4 (CH), 131.7 (CH), 128.9 (CH), 128.6 (C), 77.6 (C), 75.4 (CH), 71.9 (CH), 70.7 (CH), 70.5 (CH), 23.9 (CH_3); IR (CH_2Cl_2): 3069 (w), 2361 (vw), 1712 (w), 1667 (vs), 1625 (s), 1580 (m), 1451 (m), 1382 (m), 1358 (w), 1333 (w), 1094 (m); MS (EI): 426 (M^+, 37), 384 (100), 385 (25), 319 (11); HRMS (EI): calcd for $C_{25}H_{22}{}^{56}FeO_3$ 426.0918, found 426.0921.

Spectral data for 17E: ^{1}H NMR ($CDCl_3$, 400.1 MHz): δ 7.55 (m, 2H), 7.47 (m, 3H), 6.80 (s, 1H), 4.43 (s, 2H), 4.38 (s, 2H), 4.36 (s, 4H), 4.06 (s, 10H); ^{13}C NMR ($CDCl_3$, 100.6 MHz): δ 185.9 (C), 185.6 (C), 146.2 (C), 143.0 (C), 141.5 (C), 133.9 (CH), 133.4 (CH), 130.2 (CH), 129.6 (CH), 128.9 (CH), 73.5 (CH), 73.4 (CH), 71.2 (C), 71.0 (C), 70.9 (CH), 70.8 (CH), 70.7 (CH), 70.6 (CH) (note that some ferrocene carbons overlap on each other); IR (CH_2Cl_2): 3099 (vw), 2928 (vw), 1650 (vs), 1457 (m), 1310 (m), 1150 (m), 1043 (m); MS (EI): 552 (M^+, 100), 484 (23), 422 (9), 366 (21), 186 (6); HRMS (EI): calcd for $C_{32}H_{24}{}^{56}Fe_2O_2$ 552.0475, found 552.0498.

24. **Spectral data for 19A**: ^{1}H NMR ($CDCl_3$, 400.1 MHz): δ 6.41 (s, 1H), 5.01 (s, 2H), 4.72 (septet, 1H, J = 6.2 Hz), 4.40 (s, 2H), 4.03 (s, 5H), 2.00 (s, 3H), 1.18 (d, 6H, J = 6.2 Hz); ^{13}C NMR ($CDCl_3$, 100.6 MHz): δ 187.9 (C), 183.8 (C), 152.6 (C), 146.5 (C), 133.9 (C), 132.0 (CH), 76.4 (CH), 74.9 (C), 72.7 (CH), 70.5 (CH), 70.4 (CH), 23.1 (CH_3), 16.7 (CH_3); IR (CH_2Cl_2): 2979 (w), 1651 (vs), 1572 (w), 1380 (w), 1096 (m), 909 (s); MS (EI): 364 (M^+, 91), 322 (99), 294 (100), 257 (72), 229 (12), 69 (17); HRMS (EI): calcd for $C_{20}H_{20}{}^{56}FeO_3$ 364.0761, found 364.0748.

Spectral data for 19B: ^{1}H NMR ($CDCl_3$, 400.1 MHz): δ 6.56 (s, 1H), 4.67 (s, 2H), 4.49 (s, 2H), 4.13 (s, 5H), 2.05 (s, 3H), 2.04 (s, 3H); ^{13}C NMR ($CDCl_3$, 100.6 MHz):): δ 187.7 (C), 187.4 (C), 146.2 (C), 143.8 (C), 139.2 (C), 133.4 (CH), 77.6 (C), 72.9 (CH), 70.6 (CH), 70.4 (CH), 16.6 (CH_3), 15.1 (CH_3); IR (CH_2Cl_2): 2364 (w), 1650 (vs), 1632 (vs), 1583 (s), 1443 (m), 1372 (m), 1305 (s), 1051 (m); MS (EI): 320 (M^+, 100), 294 (10), 256 (67), 121 (8); HRMS (EI): calcd for $C_{18}H_{16}{}^{56}FeO_2$ 320.0499, found 320.0495.