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Coupling of cyclopropylcarbene–chromium complex with ferrocenyl alkynes: synthesis of 5-ferrocenyl-5-hydroxy-2-cyclopentenones and 4-ferrocenyl-4-cyclopentene-1,3-diones

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Abstract—The coupling of ferrocenyl alkynes with cyclopropylcarbene–chromium complex leads to ferrocenyl-substituted 2-cyclopentenones with or without a hydroxy substituent, namely 4-cyclopentene-1,3-diones, 2-cyclobutenones, and α,β-unsaturated aldehydes in varying amounts. The reaction initially produces a cyclopentadienone intermediate, then to the double bond of which, bearing a ferrocenyl group, addition of water occurs to afford hydroxy-substituted 2-cyclopentenones. In all the products, the hydroxy group ends up α to the ferrocenyl moiety. In contrast, where no addition of water occurs, the alkenic bond is reduced to give 2-cyclopentenones. A secondary reaction product, namely 4-cyclopentene-1,3-dione, is formed by hydrolysis of the cyclopentadienone intermediates.
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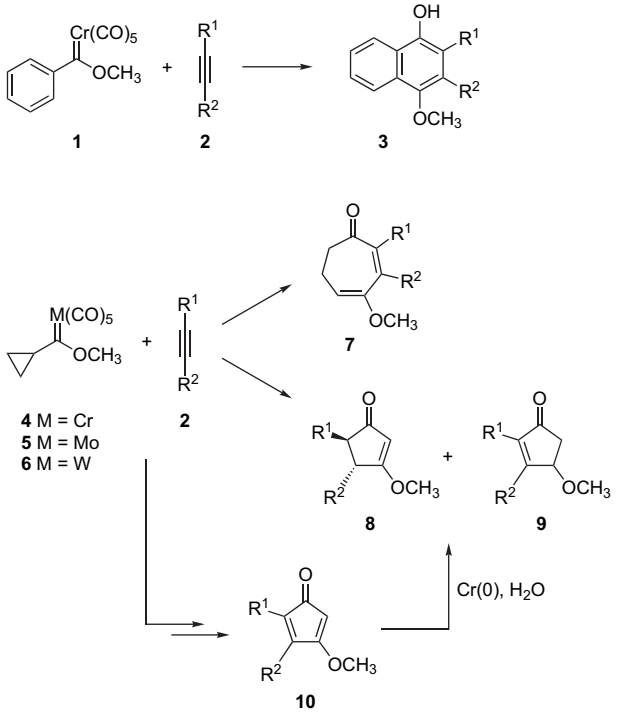
1. Introduction

Fischer type metal carbene complexes have emerged as valuable reagents for organic synthesis in recent years.[1] One of the most intensely studied reactions of metal carbene complexes is the coupling of α,β-unsaturated Fischer carbene complexes, such as **1**, with alkynes **2**, known as the Dötz reaction (Scheme 1).[2,3] The first product ever isolated from this type of reaction has been a phenol derivative, such as **3**, which is normally the predominant product of the reaction. Under appropriate conditions, cyclobutenones, cyclopentenones, furans, cyclohexadienones, indenes, and vinylketenes have also resulted from these reactions.[2,3] An ever-continuing aspect of these studies has been the use of a structurally diverse set of Fischer carbene complexes to afford a diverse array of organic compounds. Interestingly, as shown by Herndon and co-workers,[4] the analogous reaction, which employs cyclopropyl-substituted carbene–chromium complex **4** and alkynes **2**, did not produce the expected cycloheptadienones **7**, rather it gave exclusively the cyclopentenone derivatives **8** and **9** (Scheme 1). The scope, limitations, and mechanism of this five-membered ring-forming reaction were studied in detail.[4] It was shown that the reaction initially produces



Scheme 1.

Keywords: Fischer metal carbene; Chromium–carbene complex; Ferrocene; Ferrocenyl alkynes; Carbocyclic five-membered rings; Cyclopentenones; Cyclopentenediones; Cyclobutenones; α,β-Unsaturated aldehydes; Coupling.
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a cyclopentadienone derivative, such as **10**, which is then reduced to cyclopentenones **8** and **9** by the low-valent chromium by-products and water. Notably, the conversion of complex **4** and alkynes **2** to cyclopentenones allows the construction of highly functionalized five-membered ring systems from readily available reagents. The analogous molybdenum and tungsten carbene complexes **5** and **6**, however, produced the seven-membered ring derivatives **7** upon reaction with alkynes.[5]

Cyclopentenones are present in a variety of biologically important molecules such as jasmonoids and prostaglandins (PGs).[6,7] For some time, PGs have attracted considerable attention since they play an important role in the human body, controlling a wide variety of physiological responses.[8] More recently, studies on the biological activities of the so-called 'cyclopentenone PGs' have shown that these compounds have the potential to become very important in a therapeutic context. Some cyclopentenone PGs, such as Δ^7-PG-A_1 and its methyl derivative, display significant anti-tumor activity as well.[9] It should be noted that the α,β-unsaturated carbonyl functionality is essential for many of the biological actions of such compounds, as confirmed in model studies, where 2-cyclopentenone has exhibited significant biological activity, while related compounds, cyclopentanone and cyclopentene, were found to be unreactive.[10] Furthermore, due to the versatility of α,β-unsaturated carbonyl functionality, cyclopentenones are very useful building blocks for the synthesis of other biologically active compounds, such as cyclopentanoid antibiotics.[7] Although numerous methods are known for the synthesis of cyclopentenones and related pharmacophores,[7,11] new variants continue to appear stimulated by the broad spectrum of biological activity of these type of compounds.

Recent studies have shown that the integration of a ferrocenyl group into such structures may enhance their biological activities or generate new medicinal properties.[12,13] Surprisingly, cyclopentenones bearing a ferrocenyl moiety are rare.[14] The development of a general synthetic entry to ferrocenyl-substituted cyclopentenones is therefore of interest since it could lead to a new source of biologically active compounds. We anticipated that the reaction between ferrocenyl alkynes and cyclopropylcarbene–chromium complex **2** would produce 2-ferrocenyl-2-cyclopentenone derivatives. This methodology, however, has not been utilized for the synthesis of ferrocenyl-substituted cyclopentenones, presumably due to the scarce availability of starting ferrocenyl alkynes. As part of our general involvement in ferrocene[15,16] and metal carbene chemistry,[17] as well as small and medium-size ring systems,[18] we have investigated the reaction between ferrocenyl alkynes and the cyclopropylcarbene–chromium complex **4**, which affords ferrocenyl-substituted cyclopentenones.[19] We herein report the results of this study.

2. Results and discussion

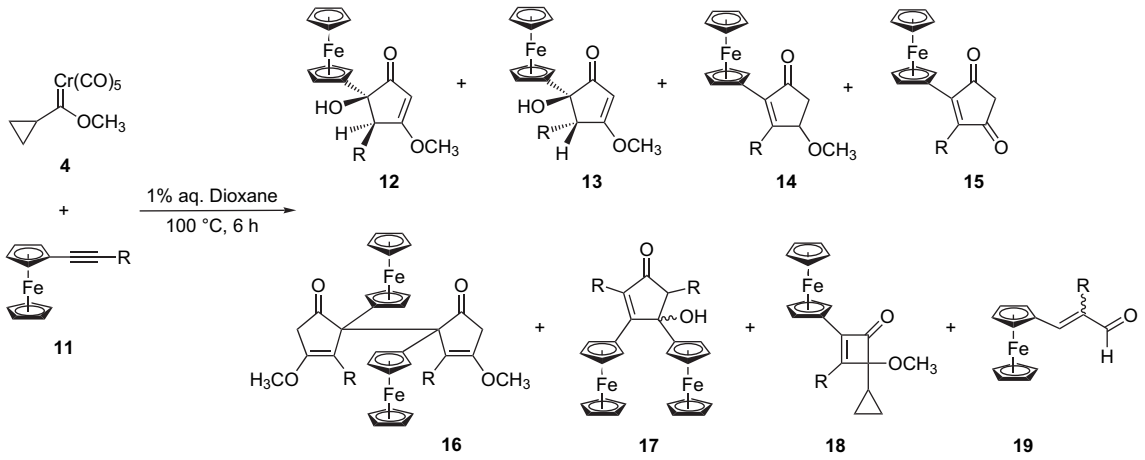
The synthesis of ferrocenyl alkynes was accomplished from ethynylferrocene (**11a**)[20] according to known or modified literature procedures. Treatment of ethynylferrocene (**11a**) with *n*-butyllithium produced in situ lithioethynylferrocene that was further reacted with methyl iodide, benzyl bromide or trimethylsilyl chloride to yield propynylferrocene (**11b**), (3-phenylpropynyl)ferrocene (**11c**), and (trimethylsilylethynyl)ferrocene (**11d**), respectively.[21] On the other hand, the reaction of ethynylferrocene (**11a**) and iodobenzene in the presence of copper iodide, triphenylphosphine, and potassium carbonate in refluxing DMF produced (phenylethynyl)ferrocene (**11e**).[22] Diferrocenylethyne (**11f**) was synthesized by the metathesis of propynylferrocene (**11b**) in the presence of molybdenum hexacarbonyl and 2-fluorophenol in refluxing chlorobenzene.[23] Cyclopropylcarbene–chromium complex **4** was prepared from cyclopropyl bromide and chromium hexacarbonyl according to a standard procedure.[4d]

Subsequently, we investigated the reactions of ferrocenyl alkynes **11** with carbene complex **4**. The results of this study are summarized in Table 1. The reactions were carried out under optimal conditions, in which a 1:1.5 mole ratio of carbene complex **4** and alkyne **11**, respectively, was added to a refluxing 1% aq dioxane solution over a period of 2 h, and then the resulting reaction mixture was further refluxed for 6 h. As indicated in Table 1, the coupling of a variety of ferrocenyl alkynes **11** with carbene complex **4** led to varying amounts of 2-cyclopentenones with or without a hydroxy substituent, giving 4-cyclopentene-1,3-diones, 2-cyclobutenones, and/or α,β-unsaturated aldehydes.

The most interesting aspect in these reactions was the formation of 5-hydroxy-2-cyclopentenone derivatives **12** and/or **13** (Table 1). To the best of our knowledge, such hydroxy-substituted cyclopentenones have not been observed previously from similar reactions. The structure of compound **12b** was unambiguously determined by X-ray crystal analysis, as shown in Figure 1.[24] Although two molecules are present in the asymmetric unit of **12b**, only one molecule is shown in Figure 1 for clarity. In the solid state, the five-membered ring is very close to planarity and ferrocenyl group is almost in an eclipsed conformation. As concluded from X-ray structure, in the major diastereomers **12a–f**, ferrocenyl and the R groups are trans while they are cis in the minor diastereomer **13b**. For a particular case, cyclopentenone **12** could be expected to be more stable than its diastereomer **13** on the basis of steric considerations. From these reactions, cyclopentenones **14**, which do not contain a hydroxy group, were also isolated (Table 1).

The proposed mechanism for the formation of cyclopentenones **12–14** is outlined in Scheme 2. The loss of a cis carbon monoxide ligand from complex **4** and coordination of alkyne **11** produces alkyne–carbene complex **20**, which undergoes a [2+2] cycloaddition reaction to afford metallacyclobutene **21**. Electrocyclic ring opening then occurs to yield internally coordinated vinyl carbene complex **22**. The involvement of metallacyclobutenes in these processes has recently been questioned by Hofmann, and found to be unfavorable on the basis of theoretical calculations.[25] Thus complex **22** could be directly formed from **20** via alkyne insertion without formation of metallacyclobutene **21**. It should be noted that the mechanism up to vinyl carbene complex **22** is identical to that proposed for the Dötz reaction.[3] Afterward, cyclopropane ring of **22** opens by a 1,5-alkyl shift to give metallacycloheptadiene **23**. CO insertion affords metallacyclooctadienone **24**, which then converts to complex **26** with and/or without formation of complex **25**. The fragmentation

Table 1. Reaction of cyclopropylcarbene–chromium complex **4** with ferrocenyl alkynes **11**



Entry[a]	Starting alkyne	R	Products (isolated yield, %)
A	**11a**	H	**12a** (45)+**17a** (6)
B	**11b**	CH_3	**12b** (36)+**13b** (16)+**14b** (17)+**15b** (17)+**16b** (4)+**19b**[b] (6)
C	**11c**	CH_2–Ph	**12c** (16)+**15c** (57)
D	**11d**	$Si(CH_3)_3$	**12a** (26)
E	**11e**	Ph	**12e** (31)+**14e** (5)+**15e** (55)
F	**11f**	Fc (ferrocenyl)	**12f** (18)+**14f** (9)+**15f** (32)+**18f** (7)

[a] Entry letters define R group for compounds **11**–**19**.
[b] Configuration of double bond was not determined.

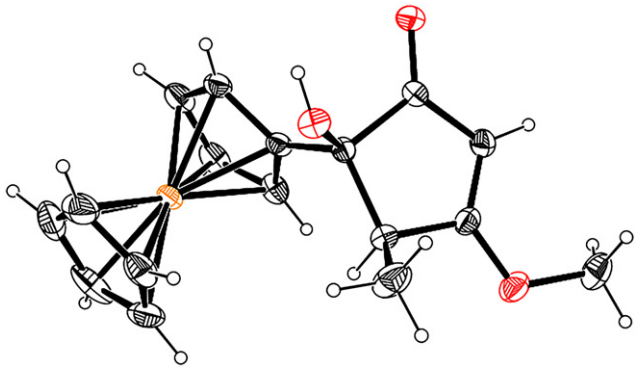
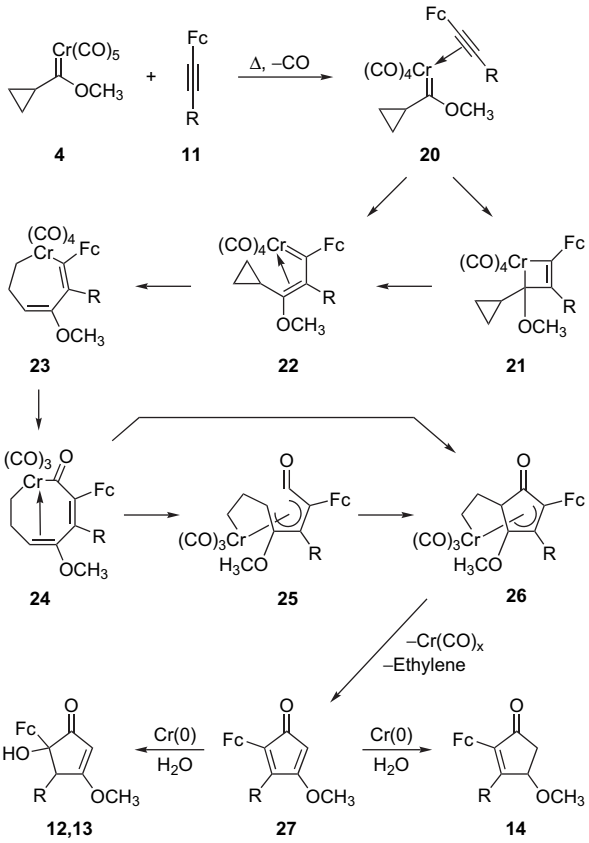


Figure 1. ORTEP diagram of (4*R*(*S*),5*R*(*S*))-5-ferrocenyl-5-hydroxy-3-methoxy-4-methyl-2-cyclopentenone (**12b**): ellipsoids are drawn at 20% probability.

of complex **26** with ethylene loss yields cyclopentadienone **27**. It should be noted that the formation of cyclopentadienone intermediates in these processes was already verified by the Herndon group using similar reactions.[4b]

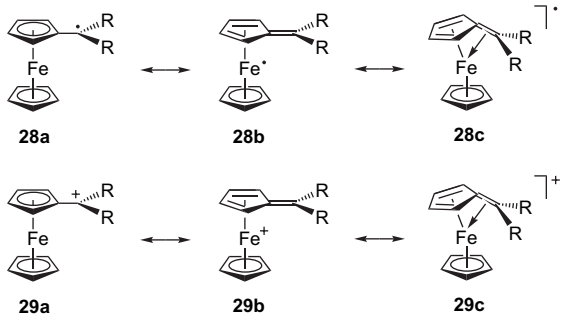
Eventually, in **27**, water addition occurs to the double bond adjacent to ferrocenyl group, which provides 5-hydroxy-2-cyclopentenones **12** and/or **13** (Scheme 2), in contrast to earlier studies.[4] Although, the mechanism of this addition is unclear at present, it might be a transition metal catalyzed or mediated process in our reaction conditions, which may proceed through a radical or ionic mechanism. It is interesting to note that the hydroxy substituent in cyclopentenones **12** and **13** ends up α to the ferrocenyl group. This might be attributed to the developing radical or positive charge at that carbon during the course of the reaction, which is well stabilized, although it is also α to the carbonyl, since the ferrocenyl group is very effective at stabilizing an α radical[26] or



Scheme 2.

carbocation,[27] especially the latter. In general, as depicted in Scheme 3, the radical and carbocation stabilizing ability of the ferrocenyl group can be explained by a delocalization

mechanism involving the Fe atom and a major contribution from an η^4-form, as represented by structures **28b** and **29b**, respectively.[26,27] More recently, regarding the ferrocenyl-stabilized carbocations, the combination of physical methods and calculations has affirmed a fulvenoid structure, such as **29c**, in which, depending upon the steric and electronic nature of the substituents R, the exocyclic double bond leans toward the metal to maximize the metal–ligand interaction, which increases the stability of the complex.[27c] Similarly, in the light of these studies, a fulvenoid type structure, such as **28c**, can be proposed for the ferrocenyl-stabilized radicals.



Scheme 3.

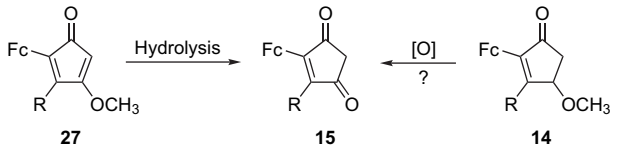
It is tempting to simply argue that the exceptional radical or carbocation stabilizing aptitude of the ferrocenyl group in the α position could facilitate the water addition to cyclopentadienone **27** to afford cyclopentenones **12** and/or **13**. This is also indirectly supported by the previous studies of Herndon that the reaction of carbene complex **4** with phenylacetylene, 1-phenylpropyne or diphenylacetylene did not produce any hydroxy-substituted cyclopentenones, rather it gave exclusively cyclopentenones **8** and/or **9**, where R^1=Ph, R^2=H, Me or Ph (Scheme 1).[4] Therefore, the formation of 5-hydroxy-2-cyclopentenones **12** and/or **13** in these reactions is attributed to the ferrocenyl group since it is a much better radical and carbocation stabilizing group than the phenyl group.

To deduce whether the effect of the ferrocenyl group in these processes is internal or external, the reaction between carbene complex **4** and diphenylacetylene was carried out in the presence of ferrocene under the same conditions. However, this reaction afforded only cyclopentenones **8** and/or **9**, where R^1=R^2=Ph, no hydroxy-included cyclopentenones were formed. This is clearly indicative of the internal effect of the ferrocenyl group, which could relate to its radical and/or carbocation stabilizing ability as mentioned above.

In contrast, no water addition occurs in the formation of cyclopentenones **14**; instead, the other double bond of cyclopentadienone **27**, adjacent to methoxy group, is reduced by the combination of Cr(0) species and water (Scheme 2), as manifested in previous studies.[4] Notably, for this reduction, a hydrogen source is needed. As suggested,[4a] water and low oxidation state chromium may interact to form metal hydrides, which could furnish the source of hydrogen. Alternatively, Cr(0) may reduce H_2O to H_2, which could also supply the source of hydrogen. The detailed studies of Herndon have shown that water, not the hydrogen gas, provides the source of hydrogen for these reductions.[4a] It was also proposed that reduction mechanism involves a net two-electron transfer-double protonation process.[4e]

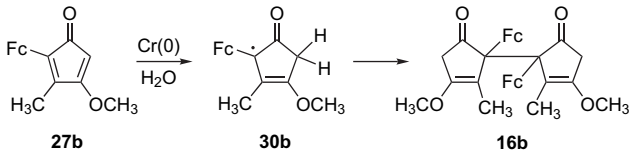
As can be seen in Scheme 2, the overall regiochemistry of the reaction is set in the metallacyclobutene forming step (**20**→**21**) or in the vinyl carbene forming step (**20**→**22**), where the larger group of alkyne (i.e., ferrocenyl group) ends up α to the chromium in order to minimize steric interactions. Following this substituent through the mechanism, it is predicted that the larger group will be α to the carbonyl in the final products **12**–**14**. The observed regiochemistry is consistent with those found in the similar reactions.[4,5]

In some reactions, ferrocenyl-substituted cyclopentenediones **15** were also observed (entries B, C, E, and F). Notably, in most cases, they were the major product of the reaction. In fact, cyclopentenediones **15** are the secondary products of the reaction, resulting from the hydrolysis of initially formed cyclopentadienones **27** (Scheme 4), which is presumably catalyzed by low-valent chromium and water. The hydrolysis of 3-alkoxy-2,4-cyclopentadienones to 4-cyclopentene-1,3-diones is a well-known process.[28] Alternatively, the oxidation of 4-methoxy-2-cyclopentenones **14** by metal species could also be expected to produce cyclopentenediones **15** to some extent, but these types of oxidations do not have ample precedent.



Scheme 4.

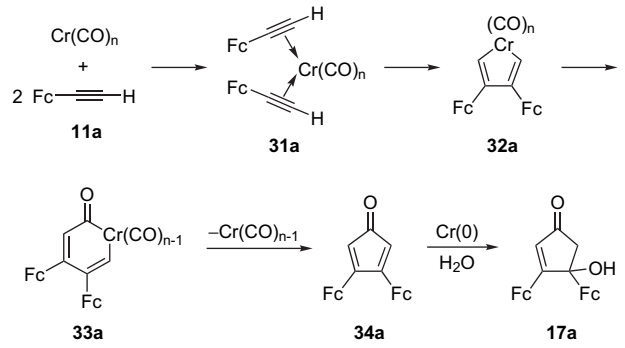
Surprisingly, from the reaction between carbene complex **4** and propynylferrocene (**11b**), a dimeric cyclopentenone derivative was also isolated and assigned as compound **16b** (entry B). The proposed mechanism for its formation is illustrated in Scheme 5. Under the reaction conditions, cyclopentadienone **27b** first produces radical **30b**, which is then dimerized to compound **16b**. This clearly provides an indirect evidence for the reduction of cyclopentadienones **27** through the radical type mechanism.



Scheme 5.

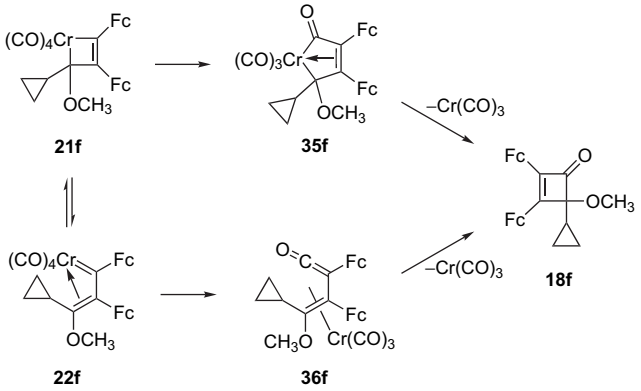
Interestingly, the reaction of carbene complex **4** with ethynylferrocene (**11a**) produced a side product, identified as 4-hydroxy-2-cyclopentenone **17a** (entry A), in addition to 5-hydroxy-2-cyclopentenone **12a**. The proposed mechanism for the formation of **17a** is outlined in Scheme 6. Coordination of two ethynylferrocene molecules (**11a**) to an in situ formed unsaturated $Cr(CO)_n$ species gives alkyne complex **31a**, which converts to metallacyclopentadiene **32a** through

a Reppe-type coupling.[29] CO insertion then affords metallacyclohexadienone **33a**, which generates cyclopentadienone **34a** upon reductive elimination. Finally, water addition to one of the double bonds yields hydroxy-substituted cyclopentenone **17a**. As expected, the hydroxy substituent ends up α to the ferrocenyl group for the reasons mentioned above. It should be noted that the coupling of terminal alkynes with metal carbenes often produce cyclopentadienones, similar to **34a**, and their reduction products as the side products.[4d]



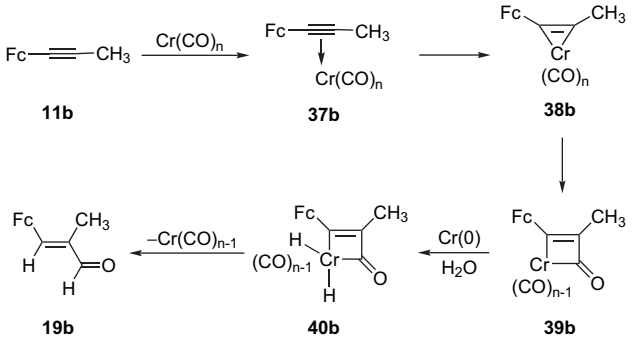
Scheme 6.

From the reaction with diferrocenylacetylene (**11f**) (entry F), a cyclobutenone derivative, **18f**, was also obtained. Cyclobutenones are frequently observed as the minor by-products in the coupling of alkynes with metal carbene complexes. Their formation is mechanistically important since they support the intermediacy of metallacyclobutenes, vinyl carbenes, and/or vinylketenes.[2b,4d] Cyclobutenone **18f** could arise via two possible pathways as depicted in Scheme 7. Metallacyclobutene **21f** first gives CO insertion to afford internally coordinated metallacyclopentenone **35f**, which produces cyclobutenone **18f** upon reductive elimination Alternatively, vinyl carbene complex **22f** experiences CO insertion and yields vinylketene complex **36f**, which furnishes cyclobutenone **18f** after electrocyclic ring closure followed by decomplexation. Note that metallacyclobutene **21f** and vinyl carbene complex **22f** are interconvertible and their formation has been shown in Scheme 2. It should be noted that cyclobutenone **18f** was also observed in the reaction between pentacarbonyl[(cyclopropyl)methoxymethylene]molybdenum complex and diferrocenylacetylene (**11f**), the formation of which presumably involves similar intermediates.[30]



Scheme 7.

Surprisingly, an α,β-unsaturated aldehyde derivative, **19b**,[31] was also formed in these reactions (entry B), most likely arising via a hydroformylation reaction,[31] as proposed in Scheme 8. Coordination of alkyne **11b** to an in situ formed unsaturated $Cr(CO)_n$ species produces alkyne complex **37b**, which converts to metallacyclopropene **38b**. CO insertion then provides metallacyclobutene **39b**. Oxidative addition of hydrogen into chromium yields hydrido complex **40b**, which, upon tandem reductive eliminations, affords aldehyde **19b**.[32] Importantly, for the oxidative addition step (**39b**→**40b**), hydrogen is needed. Presumably, as noted before, water could furnish the source of hydrogen upon interaction with Cr(0).



Scheme 8.

It should be noted that the reaction between (trimethylsilylethynyl)ferrocene (**11d**) and carbene complex **4** revealed a complex reaction mixture; only cyclopentenone **12a** could be isolated (entry D), in which desilylation occurred.

In general, as can be seen in Table 1, a variety of ferrocenyl alkynes **11** participated smoothly in the coupling with chromium complex **4**, producing 5-hydroxy-2-cyclopentenones **12** and/or 4-cyclopentene-1,3-diones **15** as the major products of these reactions. It is particularly noteworthy that α-hydroxy cyclic ketones, such as 5-hydroxy-2-cyclopentenone derivatives, occupy a central position in the synthesis of complex natural products, which stimulated an intense search for oxidants capable of effecting the direct α-hydroxylation of cyclic ketones.[33] Along this line, 4-cyclopentene-1,3-diones have also proven as useful precursors, particularly for the synthesis of 2-alkylidene/arylidene-4-cyclopentene-1,3-diones,[34] which show a high degree of anti-tumor activity.[15d,35]

3. Conclusions

In summary, we have shown that cyclopropylcarbene–chromium complex **4** can couple with ferrocenyl alkynes **11** to afford ferrocenyl-substituted 2-cyclopentenones, 4-cyclopentene-1,3-diones, 2-cyclobutenones, and/or α,β-unsaturated aldehydes in varying amounts. For the first time, 5-hydroxy-2-cyclopentenones resulted from these reactions. Formation of these new products was attributed to the radical or carbocation stabilizing ability of the ferrocenyl group, which has not been utilized before in such reactions. Interestingly, an α,β-unsaturated aldehyde derivative was also isolated from these reactions, which most likely happens via a hydroformylation reaction, a rare occurrence for metal

carbene complexes. In conclusion, we anticipate that these new insights will be of value in the continued development of the synthetic applications of Fischer carbene complexes in synthesis.

4. Experimental

4.1. General consideration

Nuclear magnetic resonance (^{1}H and ^{13}C) spectra were recorded on a Bruker Spectrospin Avance DPX400 Ultrashield (400 MHz) spectrometer. Chemical shifts are reported in parts per million (δ) downfield from an internal tetramethylsilane reference. Coupling constants (J values) are reported in hertz (Hz), and spin multiplicities are indicated by the following symbols: s (singlet), d (doublet), t (triplet), q (quartet), and m (multiplet). DEPT ^{13}C NMR information is given in parenthesis as C, CH, CH_2 and CH_3. Infrared spectra were recorded on a Perkin–Elmer 1600 FTIR or Bruker Vertex 70 FTIR spectrometer. Band positions are reported in reciprocal centimeters (cm^{-1}). Band intensities are reported relative to the most intense band and are listed as: br (broad), vs (very strong), s (strong), m (medium), w (weak), and vw (very weak). Mass spectra (MS) were obtained on a Finnigan MAT 95 spectrometer, using EI at 70 eV, or on a Bruker Daltonics spectrometer using MALDI-TOF, in which matrix was DCTP; m/z values are reported. High resolution mass spectra (HRMS) were obtained on a Finnigan MAT 95 spectrometer by preselected-ion peak matching at $R \approx 10{,}000$ to be within ± 3 ppm of the exact masses. Elemental analyses were carried out on a LECO CHNS-932 instrument. Flash chromatography was performed using thick-walled glass columns and 'flash grade' silica (Merck 230–400 mesh). Routine thin layer chromatography (TLC) was effected by using precoated 0.25 mm silica gel plates purchased from Merck. The relative proportion of solvents in mixed chromatography solvents refers to the volume:volume ratio. Ferrocenyl alkynes (**11a–f**)[3–6] and cyclopropylcarbene–chromium complex **4**[4d] were synthesized according to a well-known literature procedures. All other commercially available reagents and reactants were obtained in reagent grade and used without purification. All reaction solvents were distilled for purity. Diethyl ether, THF, and dioxane were distilled from sodium/benzophenone ketyl. The inert atmosphere was created by slight positive pressure (ca. 0.1 psi) of argon.

4.2. General procedure for the reaction of cyclopropylcarbene–chromium complex 4 with ferrocenyl alkynes 11 (Table 1)

To a three-neck round-bottom flask equipped with reflux condenser, stopper, and septum, under argon, was added 20 mL of 1% aqueous dioxane solution. The dioxane solution was heated to reflux. To this refluxing solution was added a solution of carbene complex **4** (0.5 mmol) and ferrocenyl alkyne **11** (0.75 mmol) in dioxane (10 mL) by syringe pump over a period of 2 h. After the addition was complete, the mixture was allowed to reflux for a period of 6 h. The mixture was then allowed to cool to room temperature, and the solvent was removed on a rotary evaporator. Ethyl acetate (50 mL) was added, and the solution was filtered through Celite. The solvent was removed in vacuo, and the residue purified by flash chromatography on silica gel (eluant: hexane/EtOAc from 19:1 to 1:1). The products given in Table 1 were isolated with the indicated yields.

4.2.1. Spectral data for products given in Table 1.

4.2.1.1. 5-Ferrocenyl-5-hydroxy-3-methoxy-2-cyclopentenone (12a). Yellow solid; mp 190.5–190.7 °C; 70.2 mg (45% yield from **4** and **11a**), 40.6 mg (26% yield from **4** and **11d**); ^{1}H NMR ($CDCl_3$): δ 5.29 (s, 1H), 4.28 (s, 1H), 4.19 (br s, 8H), 3.89 (s, 3H), 3.08 (d, 1H, J=17.4 Hz), 2.97 (d, 1H, J=17.4 Hz), 2.82 (s, 1H); IR (CH_2Cl_2): 3053 (s), 2982 (m), 2682 (vw), 2302 (w), 1692 (w), 1599 (w), 1402 (s), 1270 (vs), 896 (s), 733 (vs) cm^{-1}; MS (EI): 312 (M^+, 100), 294, 247, 229, 213, 185, 169, 145, 129, 121, 56; HRMS calcd for $C_{16}H_{16}FeO_3$: 312.0449. Found: 312.0452. Anal. Calcd for $C_{16}H_{16}FeO_3$: C, 61.57; H, 5.17. Found: C, 61.21; H, 5.42.

4.2.1.2. (4*R*(*S*),5*R*(*S*))-5-Ferrocenyl-5-hydroxy-3-methoxy-4-methyl-2-cyclopentenone (12b). Brownish yellow solid; mp 127.5–127.8 °C; 58.7 mg (36% yield); ^{1}H NMR ($CDCl_3$): δ 5.21 (s, 1H), 4.20 (s, 1H), 4.18 (s, 5H), 4.14 (br s, 3H), 3.87 (s, 3H), 3.13 (q, 1H, J=7.3 Hz), 2.76 (s, 1H), 1.27 (d, 3H, J=7.3 Hz); ^{13}C NMR ($CDCl_3$): δ 203.7 (C), 192.4 (C), 99.1 (CH), 92.7 (C), 77.2 (C), 68.9 (CH), 68.4 (CH), 68.3 (CH), 66.2 (CH), 65.9 (CH), 58.7 (CH_3), 48.0 (CH), 13.7 (CH_3); IR (CH_2Cl_2): 3056 (s), 2983 (w), 2298 (vw), 1691 (w), 1582 (s), 1418 (w), 1270 (vs), 892 (w), 744 (vs) cm^{-1}; MS (EI): 326 (M^+, 100), 308, 261, 243, 213, 186, 185, 149, 129, 84; HRMS calcd for $C_{17}H_{18}FeO_3$: 326.0605. Found: 326.0602.

4.2.1.3. (4*R*(*S*),5*R*(*S*))-4-Benzyl-5-ferrocenyl-5-hydroxy-3-methoxy-2-cyclopentenone (12c). Off yellow solid; mp 63.6–63.9 °C; 32.2 mg (16% yield); ^{1}H NMR ($CDCl_3$): δ 7.36–7.26 (m, 3H), 7.22–7.10 (m, 2H), 5.20 (s, 1H), 4.13 (s, 3H), 4.10 (s, 5H), 4.01 (s, 1H), 3.82 (s, 3H), 3.36 (dd, 1H, J=7.8, 4.4 Hz), 3.12 (dd, 1H, J=13.8, 7.8 Hz), 2.97 (dd, 1H, J=13.8, 4.4 Hz), 2.76 (s, 1H); IR (CH_2Cl_2): 3050 (s), 2977 (m), 2685 (vw), 2303 (w), 1699 (w), 1591 (m), 1420 (s), 1267 (vs), 898 (s), 746 (vs) cm^{-1}; MS (EI): 402 (M^+, 100), 384, 337, 319, 311, 246, 228, 213, 189, 170, 121, 91; HRMS calcd for $C_{23}H_{22}FeO_3$: 402.0918. Found: 402.0916.

4.2.1.4. (4*R*(*S*),5*R*(*S*))-5-Ferrocenyl-5-hydroxy-3-methoxy-4-phenyl-2-cyclopentenone (12e). Dark yellow solid; mp 183.3–183.6 °C; 60.2 mg (31% yield); ^{1}H NMR ($CDCl_3$): δ 7.11–6.99 (m, 3H), 6.71 (d, 2H, J=6.7 Hz), 5.55 (s, 1H), 4.30 (s, 1H), 4.24 (s, 5H), 3.96 (s, 1H), 3.83 (s, 3H), 3.76 (s, 1H), 3.73 (s, 1H), 3.50 (s, 1H), 3.12 (s, 1H); ^{13}C NMR ($CDCl_3$): δ 203.0 (C), 186.8 (C), 135.3 (C), 129.4 (CH), 127.6 (CH), 126.9 (CH), 102.8 (CH), 91.1 (C), 81.9 (C), 68.8 (CH), 68.4 (CH), 67.6 (CH), 67.3 (CH), 66.3 (CH), 58.9 (CH), 58.6 (CH_3); IR (CH_2Cl_2): 3056 (s), 2987 (m), 2681 (w), 2303 (w), 1704 (s), 1597 (vs), 1421 (m), 1354 (m), 1267 (vs), 1171 (m), 1020 (m), 902 (m), 825 (m), 748 (vs) cm^{-1}; MS (EI): 388 (M^+, 100), 372, 323, 305, 234, 213, 178, 175, 165, 121, 93; HRMS calcd for $C_{22}H_{20}FeO_3$: 388.0762. Found: 388.0761. Anal. Calcd for $C_{22}H_{20}FeO_3$: C, 67.82; H, 5.19. Found: C, 68.06; H, 5.43.

4.2.1.5. (4*R*(*S*),5*R*(*S*))-4,5-Diferrocenyl-5-hydroxy-3-methoxy-2-cyclopentenone (12f). Brownish yellow solid;

mp 199.5–199.7 °C; 44.7 mg (18% yield); ^{1}H NMR ($CDCl_3$): δ 5.37 (s, 1H), 4.30 (s, 1H), 4.25 (s, 7H), 4.20 (s, 7H), 4.14 (s, 1H), 3.99 (s, 1H), 3.98 (s, 3H), 3.88 (s, 1H), 2.74 (s, 1H), 2.13 (s, 1H); ^{13}C NMR ($CDCl_3$): δ 202.6 (C), 187.8 (C), 101.2 (CH), 93.4 (C), 84.5 (C), 78.9 (C), 69.5 (CH), 69.4 (CH), 69.2 (CH), 68.6 (CH), 68.5 (CH), 68.4 (CH), 68.0 (CH), 66.9 (CH), 66.7 (CH), 66.1 (CH), 58.6 (CH_3), 54.6 (CH); IR (CH_2Cl_2): 3055 (s), 2983 (m), 2682 (vw), 2301 (w), 1698 (w), 1596 (w), 1423 (m), 1270 (vs), 898 (m), 762 (vs) cm^{-1}; MS (EI): 496 (M^+, 100), 478, 358, 293, 283, 248, 213, 199, 129, 121; HRMS calcd for $C_{26}H_{24}Fe_2O_3$: 496.0424. Found: 496.0426.

4.2.1.6. (4*S*(*R*),5*R*(*S*))-5-Ferrocenyl-5-hydroxy-3-methoxy-4-methyl-2-cyclopentenone (13b). Off yellow solid; mp 81.5–81.8 °C; 26.1 mg (16% yield); ^{1}H NMR ($CDCl_3$): δ 5.30 (s, 1H), 4.33 (s, 5H), 4.30 (s, 1H), 4.18 (s, 1H), 4.16 (s, 1H), 3.81 (s, 3H), 3.75 (s, 1H), 3.06 (q, 1H, J=7.3 Hz), 2.98 (s, 1H), 0.74 (d, 3H, J=7.3 Hz); ^{13}C NMR ($CDCl_3$): δ 203.5 (C), 189.3 (C), 100.5 (CH), 80.4 (C), 77.2 (C), 69.6 (CH), 69.4 (CH), 67.9 (CH), 67.8 (CH), 66.4 (CH), 58.5 (CH_3), 46.8 (CH), 12.0 (CH_3); IR (CH_2Cl_2): 3052 (m), 2981 (w), 1700 (m), 1591 (s), 1463 (vw), 1354 (w), 1268 (vs), 1104 (vw), 896 (vw), 819 (vw), 746 (vs) cm^{-1}; MS (EI): 326 (M^+, 100), 308, 262, 261, 243, 213, 185, 131, 113, 78; HRMS calcd for $C_{17}H_{18}FeO_3$: 326.0605. Found: 326.0607.

4.2.1.7. 2-Ferrocenyl-4-methoxy-3-methyl-2-cyclopentenone (14b). Brown solid; mp 96.3–97.1 °C; 26.4 mg (17% yield); ^{1}H NMR ($CDCl_3$): δ 4.79 (s, 1H), 4.69 (s, 1H), 4.30 (s, 2H), 4.27 (dd, 1H, J=6.0, 2.1 Hz), 4.08 (s, 5H), 3.40 (s, 3H), 2.69 (dd, 1H, J=18.0, 6.0 Hz), 2.39 (dd, 1H, J=18.0, 2.1 Hz), 2.21 (s, 3H); ^{13}C NMR ($CDCl_3$): δ 202.9 (C), 164.3 (C), 139.0 (C), 79.9 (CH), 74.8 (C), 69.4 (CH), 68.9 (CH), 68.8 (CH), 68.6 (CH), 56.9 (CH_3), 41.1 (CH_2), 15.6 (CH_3); IR (CH_2Cl_2): 3053 (s), 2981 (m), 2683 (vw), 2300 (w), 1703 (w), 1414 (m), 1267 (vs), 1097 (vw), 896 (m), 755 (vs) cm^{-1}; MS (EI): 310 (M^+, 100), 279, 258, 227, 212, 186, 163, 129, 121, 91, 55; HRMS calcd for $C_{17}H_{18}FeO_2$: 310.0656. Found: 310.0659.

4.2.1.8. 2-Ferrocenyl-4-methoxy-3-phenyl-2-cyclopentenone (14e). Reddish orange solid; 9.3 mg (5% yield); ^{1}H NMR ($CDCl_3$): δ 7.45–7.35 (m, 5H), 4.89 (dd, 1H, J= 5.9, 1.5 Hz), 4.58 (s, 1H), 4.39 (s, 1H), 4.34 (s, 1H), 4.26 (s, 1H), 4.09 (s, 5H), 3.47 (s, 3H), 2.80 (dd, 1H, J=18.2, 5.9 Hz), 2.57 (dd, 1H, J=18.2, 1.5 Hz); IR (CH_2Cl_2): 3050 (s), 2982 (m), 2679 (vw), 2307 (w), 1701 (w), 1420 (m), 1273 (vs), 901 (m), 751 (vs); MS (EI): 372 (M^+, 100), 356, 342, 291, 277, 249, 191, 165, 149, 121; HRMS calcd for $C_{22}H_{20}FeO_2$: 372.0813. Found: 372.0816.

4.2.1.9. 2,3-Diferrocenyl-4-methoxy-2-cyclopentenone (14f). Reddish orange solid; mp 188.5–188.7 °C; 21.6 mg (9% yield); ^{1}H NMR ($CDCl_3$): δ 4.90 (s, 2H), 4.85 (d, 1H, J=5.5 Hz), 4.55 (s, 1H), 4.46 (s, 2H), 4.43 (s, 1H), 4.37 (s, 1H), 4.25 (s, 1H), 4.14 (s, 5H), 4.08 (s, 5H), 3.45 (s, 3H), 2.69 (dd, 1H, J=18.2, 5.5 Hz), 2.51 (d, 1H, J=18.2 Hz); IR (CH_2Cl_2): 3051 (s), 2983 (m), 2683 (vw), 2306 (w), 1702 (w), 1420 (m), 1270 (vs), 899 (m), 748 (vs) cm^{-1}; MS (EI): 480 (M^+, 100), 478, 415, 355, 328, 300, 263, 240, 235, 178, 121; HRMS calcd for $C_{26}H_{24}Fe_2O_2$: 480.0475. Found: 480.0474.

4.2.1.10. 4-Ferrocenyl-5-methyl-4-cyclopentene-1,3-dione (15b). Claret red solid; mp 130.1–130.7 °C; 25.0 mg (17% yield); ^{1}H NMR ($CDCl_3$): δ 5.03 (s, 2H), 4.57 (s, 2H), 4.12 (s, 5H), 2.93 (s, 2H), 2.11 (s, 3H); ^{13}C NMR ($CDCl_3$): δ 199.5 (C), 199.1 (C), 156.2 (C), 150.3 (C), 72.1 (C), 71.7 (CH), 70.5 (CH), 70.0 (CH), 41.8 (CH_2), 10.5 (CH_3); IR (KBr): 3131 (vw), 3096 (w), 2919 (w), 1732 (s), 1687 (vs), 1596 (vs), 1457 (s), 1332 (s), 1271 (vs), 1189 (s); MS (MALDI-TOF): 294 (M^+, 100), 292, 264, 242, 220, 219; HRMS calcd for $C_{16}H_{14}FeO_2$: 294.0343. Found: 294.0341.

4.2.1.11. 4-Benzyl-5-ferrocenyl-4-cyclopentene-1,3-dione (15c). Claret red solid; mp 153.4–153.8 °C; 105.5 mg (57% yield); ^{1}H NMR ($CDCl_3$): δ 7.33–7.27 (m, 2H), 7.25–7.10 (m, 3H), 4.98 (s, 2H), 4.56 (s, 2H), 4.03 (s, 5H), 3.97 (s, 2H), 3.02 (s, 2H); ^{13}C NMR ($CDCl_3$): δ 199.4 (C), 199.2 (C), 157.7 (C), 151.2 (C), 136.8 (C), 128.8 (CH), 128.2 (CH), 126.7 (CH), 72.2 (CH), 71.7 (C), 70.8 (CH), 70.2 (CH), 42.1 (CH_2), 29.9 (CH_2); IR (KBr): 3134 (vw), 3096 (w), 2958 (vw), 1736 (m), 1694 (vs), 1594 (s), 1496 (m), 1455 (m), 1349 (m), 1352 (s), 1267 (s); MS (MALDI-TOF): 370 (M^+, 100), 368, 316, 301, 251, 250, 235, 195; HRMS calcd for $C_{22}H_{18}FeO_2$: 370.0656. Found: 370.0659.

4.2.1.12. 4-Ferrocenyl-5-phenyl-4-cyclopentene-1,3-dione (15e). Purple solid; mp 171.2–171.4 °C; 98.0 mg (55% yield); ^{1}H NMR ($CDCl_3$): δ 7.45–7.33 (m, 3H), 7.31–7.22 (m, 2H), 4.66 (s, 2H), 4.48 (s, 2H), 4.08 (s, 5H), 3.11 (s, 2H); ^{13}C NMR ($CDCl_3$): δ 199.1 (C), 197.8 (C), 156.5 (C), 150.2 (C), 130.7 (C), 129.3 (CH), 128.9 (CH), 128.6 (CH), 72.1 (CH), 71.5 (C), 71.2 (CH), 70.5 (CH), 42.6 (CH_2); IR (KBr): 3139 (vw), 3094 (w), 3078 (w), 2956 (vw), 1731 (s), 1696 (vs), 1582 (s), 1489 (m), 1440 (m), 1382 (m), 1352 (s), 1257 (s), 1186 (m); MS (MALDI-TOF): 356 (M^+, 100), 354, 294, 250, 242; HRMS calcd for $C_{21}H_{16}FeO_2$: 356.0500. Found: 356.0503.

4.2.1.13. 4,5-Diferrocenyl-4-cyclopentene-1,3-dione (15f). Purple solid; 74.2 mg (32% yield); ^{1}H NMR ($CDCl_3$): δ 4.79 (s, 4H), 4.47 (s, 4H), 4.06 (s, 10H), 3.03 (s, 2H); ^{13}C NMR ($CDCl_3$): δ 197.6 (C), 152.2 (C), 73.5 (C), 71.1 (CH), 70.5 (CH), 70.3 (CH), 43.2 (CH_2); IR (CH_2Cl_2): 3050 (s), 2985 (m), 2301 (w), 1725 (m), 1690 (vs), 1574 (w), 1475 (m), 1417 (m), 1381 (w), 1311 (w), 1275 (vs), 1211 (w), 1156 (vw), 1108 (w), 902 (m), 825 (w), 748 (vs) cm^{-1}; MS (EI): 464 (M^+, 100), 399, 396, 341, 277, 232, 186, 165, 152, 121; HRMS calcd for $C_{25}H_{20}Fe_2O_2$: 464.0162. Found: 464.0159.

4.2.1.14. 1,1′-Diferrocenyl-4,4′-dimethoxy-5,5′-dimethylbicyclopentyl-3,3′-diene-2,2′-dione (16b). Dark yellow solid; mp 156.8–157.2 °C; 12.4 mg (4% yield); ^{1}H NMR ($CDCl_3$): δ 4.78 (s, 1H), 4.75 (s, 1H), 4.35 (s, 1H), 4.34 (s, 1H), 4.11 (s, 5H), 3.16 (s, 3H), 2.62 (d, 1H, J=18.9 Hz), 2.40 (d, 1H, J=18.9 Hz), 2.20 (s, 3H); ^{13}C NMR ($CDCl_3$): δ 202.0 (C), 163.9 (C), 142.2 (C), 87.6 (C), 74.1 (C), 69.8 (CH), 69.4 (CH), 69.3 (CH), 69.2 (CH), 68.4 (CH), 50.9 (CH_3), 40.8 (CH_2), 15.6 (CH_3); IR (CH_2Cl_2): 3054 (m), 2989 (vw), 2365 (vw), 1704 (w), 1423 (vw), 1273 (vs), 1105 (vw), 896 (vw), 749 (vs) cm^{-1}; MS (EI): 618 (M^+, 100), 556, 492, 310, 309, 294, 229, 199, 159, 121, 77; HRMS calcd for $C_{34}H_{34}Fe_2O_4$: 618.1156. Found: 618.1153.

4.2.1.15. 3,4-Diferrocenyl-4-hydroxy-2-cyclopentenone (17a). Dark red solid; mp 154.8–155.2 °C; 14.0 mg (6% yield); ^{1}H NMR ($CDCl_3$): δ 6.07 (s, 1H), 4.70 (s, 1H), 4.69 (s, 1H), 4.61 (s, 1H), 4.46 (s, 1H), 4.43 (s, 1H), 4.25 (s, 7H), 4.00 (s, 1H), 3.96 (s, 5H), 3.37 (d, 1H, J=17.7 Hz), 2.99 (d, 1H, J=17.7 Hz), 2.67 (s, 1H); IR (CH_2Cl_2): 3052 (s), 2981 (m), 2685 (vw), 2306 (w), 1686 (w), 1583 (w), 1426 (m), 1268 (vs), 899 (m), 741 (vs) cm^{-1}; MS (EI): 466 (M^+, 100), 450, 383, 328, 300, 233, 186, 178, 152, 121; HRMS calcd for $C_{25}H_{22}Fe_2O_2$: 466.0319. Found: 466.0320.

4.2.1.16. 4-Cyclopropyl-2,3-diferrocenyl-4-methoxy-2-cyclobutenone (18f). Dark purple solid; mp 160.5–160.8 °C; 17.7 mg (7% yield); ^{1}H NMR ($CDCl_3$): δ 5.02 (s, 1H), 4.92 (s, 1H), 4.89 (s, 1H), 4.64 (s, 1H), 4.62 (s, 1H), 4.40 (s, 1H), 4.39 (s, 1H), 4.30 (s, 5H), 4.18 (s, 5H), 4.06 (s, 1H), 3.28 (s, 3H), 1.44 (m, 1H), 0.85 (m, 1H), 0.71 (m, 1H), 0.63 (m, 1H), 0.39 (m, 1H); MS (EI): 506 (M^+, 100). The spectral data are in agreement with those reported previously for this compound.[30]

4.2.1.17. 3-Ferrocenyl-2-methylpropenal (19b). Reddish orange solid; mp 67.9–68.1 °C; 7.6 mg (6% yield); ^{1}H NMR ($CDCl_3$): δ 9.44 (s, 1H), 7.07 (s, 1H), 4.59 (t, 2H, J=1.8 Hz), 4.48 (t, 2H, J=1.8 Hz), 4.14 (s, 5H), 1.91 (s, 3H); ^{13}C NMR ($CDCl_3$): δ 194.5 (C), 151.4 (CH), 134.8 (C), 72.0 (C), 71.4 (CH), 71.1 (CH), 69.7 (CH), 10.6 (CH_3); IR (CH_2Cl_2): 3052 (s), 2976 (m), 2682 (vw), 2411 (vw), 2307 (w), 1669 (vs), 1616 (vs), 1420 (m), 1259 (vs), 896 (m), 751 (vs) cm^{-1}; MS (EI): 254 (M^+, 100), 242, 226, 213, 189, 185, 160, 134, 121, 81; HRMS calcd for $C_{14}H_{14}FeO$: 254.0394. Found: 254.0392.

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