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Reactivity of (1-methoxycarbonylpentadienyl)iron(1+) cations with hydride, methyl, and nitrogen nucleophiles

Yuzhi Ma, Young K. Yun, Julie Wondergem (nee Lukesh), Anobick Sar [1], Jayapal Reddy Gone, Sergey Lindeman, William A. Donaldson*

Department of Chemistry, Marquette University, P. O. Box 1881, Milwaukee, WI 53201-1881, USA

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ABSTRACT

The reaction of tricarbonyl and (dicarbonyl)triphenylphosphine (1-methoxycarbonyl-pentadientyl) iron(1+) cations **7** and **8** with methyl lithium, $NaBH_3CN$, or potassium phthalimide affords (pentenediyl) iron complexes **9a-c** and **11a-b**, while reaction with dimethylcuprate, gave (*E,Z*-diene)iron complexes **10** and **12**. Oxidatively induced-reductive elimination of **9a-c** gave vinylcyclopropanecarboxylates **17a-c**. The optically active vinylcyclopropane (+)-**17a**, prepared from (1*S*)-**7**, undergoes olefin cross-metathesis with excess (+)-**18** to yield (+)-**19**, a C9–C16 synthon for the antifungal agent ambruticin. Alternatively reaction of **7** with methanesulfonamide or trimethylsilylazide gave (*E,E*-diene)iron complexes **14d** and **e**. Huisgen [3 + 2] cyclization of the (azidodienyl)iron complex **14e** with alkynes afforded triazoles **25a-e**.

1. Introduction

Acyclic (pentadienyl)iron(1+) cations are versatile precursors for organic synthesis, due to the wide variety of structural motifs which may be produced upon nucleophilic addition (Scheme 1).[1] While NMR spectra for most cations **1** are indicative of the "U" or cisoid structure in solution, it is generally believed that the "S" or transoid form does exist in an equilibrium with the more stable "U" form (Scheme 1).[1] The spectroscopic detection of a transoid structure has only been reported for a single sterically biased case.[2] Nucleophilic attack on the "U" structure may proceed via attack at one of the pentadienyl termini to afford *cis*-diene complexes **2** (path A), or with weak nucleophiles such as water, amines and electron-rich aromatics, via the less-stable but more reactive "S" form to generate *trans*-diene complexes (path B). For certain combinations of nucleophiles and cations, attack occurs at an internal carbon of the dienyl ligand to afford (3-pentene-1,5-diyl)iron complexes **4** (path C). Stable complexes **4**, which possess an electron withdrawing substituent at the σ-bound (C1) carbon, may be decomposed under oxidative conditions to afford vinylcyclopropanes. Alternatively, unstable complexes **4** are known to afford 5-substituted-2-cyclohexenones **6** via cyclocarbonylation.

The reactivity of (1-methoxycarbonylpentadienyl)iron(1+) cations **7** and **8** with *carbon* nucleophiles is observed to proceed via all three pathways.[3–5] This reactivity has been utilized in the synthesis of methyl 5-hydroxyeicosatetraenoate (5-HETE),[3a] iron containing HETE analogs,[3c] and the C7–C24 segments of macrolactin A,[3b] (path A), and 2-(2'-carboxycyclopropyl)-glycines,[5c] bicyclopropanes,[5h] and dysibetaine CPa[5i] (path C). There are fewer examples of the reaction of (dienyl)iron cations.

2. Results and discussion[8]

The (1-methoxycarbonylpentadienyl)iron(1+) cations (±)-**7** and (±)-**8** were prepared by literature methods.[3a,5b] Cationic complex (±)-**8** was isolated as an amorphous solid. Recrystallization from acetone/diethyl ether gave yellow block crystals that were characterized by X-ray diffraction analysis (Fig. 1).[9] The structure of **8** revealed that the triphenylphosphine ligand occupies the basal site *anti* to the methoxycarbonyl substitutent on the pentadienyl ligand. This relative orientation of the PPh_3 ligand, in solution, was previously proposed on the basis of the upfield shifts of H-7 and H-8exo (numbering in Fig. 1) compared to those for **7**.[5b] As anticipated, the Fe–CO bond distances (Table 1) are shorter (1.784–1.812 Å) and the carbonyl C–O distances (1.133–1.142 Å) for **8** compared to those observed in the crystal structure of **7**

* Corresponding author.
E-mail address: william.donaldson@marquette.edu (W.A. Donaldson).
[1] Deceased May 2014.

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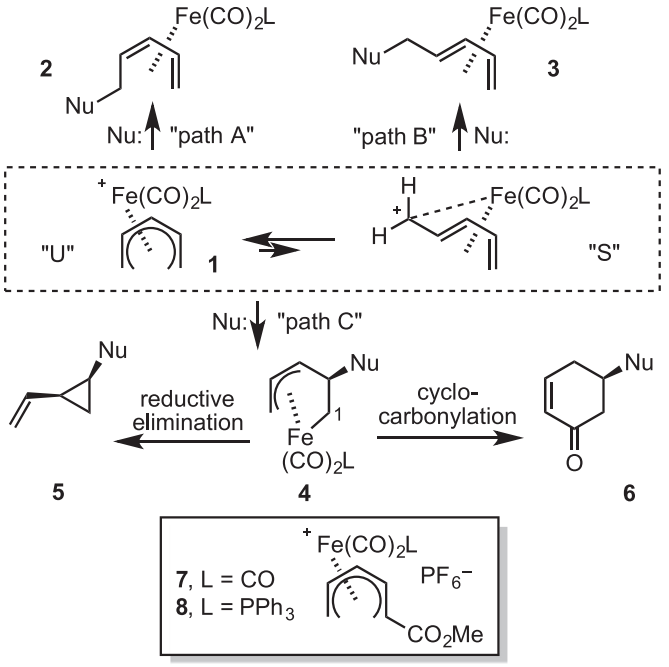


Scheme 1. **7** and **8** with non-carbon nucleophiles.[6] We herein report on the reactivity of these cations with hydride, methyl,[7] and nitrogen nucleophiles, and their subsequent reactions.

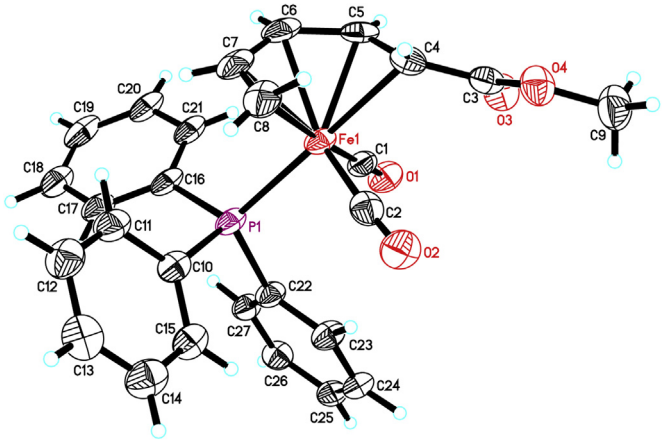


Fig. 1. ORTEP of **8** (PF_6^- counterion and solvent molecule omitted for clarity).

(Fe–CO = 1.835–1.837 Å; FeC–O = 1.121–1.137 Å).[3c] *In contrast*, the C4–C5, C5–C6 and C6–C7 distances within the pentadienyl ligand and the iron-to-pentadienyl distances Fe–C4, Fe–C5 and.

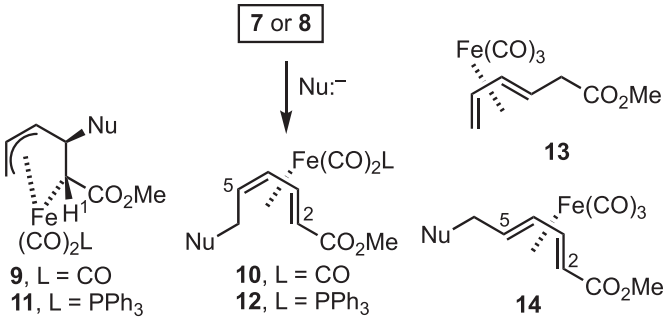
Fe–C6 for **7** and **8** are relatively similar, while the C-7-C8, Fe–C7 and Fe–C8 distances (1.395 Å, 2.102 Å and 2.165 Å) are slightly shorter for **8**, compared to those for **7** (1.419 Å, 2.141 Å and 2.207 Å).

We have previously reported[7] that addition of a solution of methyllithium in ether to a solution of **7** in dichloromethane gave predominantly the pentendiyl complex **9a** along with variable amounts of the known[10] complex **13**, while reaction of **7** with Me_2CuLi (formed from MeLi/CuBr) gave primarily the *E,Z*-diene complexes **10a** (Scheme 2, Table 2). The reactions of **7** with Me_3Al or MeTi(*i*-PrO)$_3$ were less selective and gave mixtures of **9a** and **10a**. Reaction of **8** with MeLi or with Me_2CuLi gave predominantly pentenediyl complex **11a** or diene complex **12a**. The reaction of **7** with $NaBH_3CN$ gave a separable mixture of pentenediyl complex **9b** and *E,Z*-diene complex **10b**. Use of LiAlH(*t*-BuO)$_3$ instead of $NaBH_3CN$ gave lower yields of **9b**. In a similar fashion, reaction of **8** with $NaBH_3CN$ gave predominantly pentenediyl complex **11b**. Finally, reaction of **7** with KNPhth, $MeSO_2NH_2$ or $TMSN_3$ gave pentendiyl complex **9c** or *E,E*-diene complexes **14d** or **14e**.

The structures of the products were assigned on the basis of their NMR spectral data. In particular for **9a-c** the presence of three

Table 1
Bond lengths (Å) for (pentadienyl)iron cations **7** and **8** (atom numbering corresponds to structure in Fig. 1).

Bond	**7** (ref. 3c)	**8** (this work)
Fe–C1	1.835(7)	1.812(5)
Fe–C2	1.837(6)	1.784(5)
C1–O1	1.137(8)	1.133(6)
C2–O2	1.121(7)	1.142(6)
Fe–C4	2.168(7)	2.177(5)
Fe–C5	2.114(7)	2.101(5)
Fe–C6	2.129(7)	2.128(5)
Fe–C7	2.141(6)	2.102(5)
Fe–C8	2.207(7)	2.165(5)
C4–C5	1.402(9)	1.404(7)
C5–C6	1.418(9)	1.408(8)
C6–C7	1.417(9)	1.417(8)
C7–C8	1.419(10)	1.395(8)



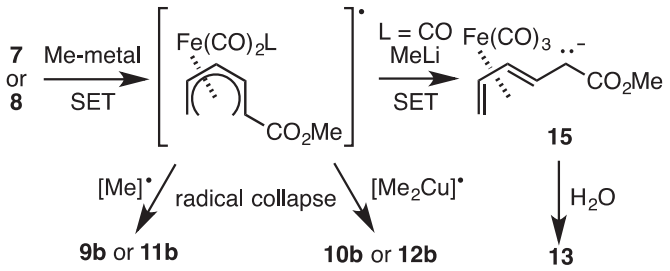
a, Nu = Me; **b**, Nu = H; **c**, Nu = NPhth; **d**, Nu = $NHSO_2Me$; **e**, Nu = N_3

Scheme 2. Nucleophilic addition to (1-methoxypentadienyl)iron cations.

Table 2
Nucleophilic addition to (1-methoxycarbonylpenta-dienyl)iron cations.

	Reagents	Nu	Product(s)
7	MeLi[c]	Me	**9a** (46–71%) + **13** (0–25%)[a]
7	MeLi/CuBr–SMe_2[d]	Me	**10a** + **9a** (14:1, 58%)[a]
7	Me_3Al[e]	Me	**10a** + **9a** (3:1, 59%)[b]
7	MeLi/TiCl(*i*-PrO)$_3$[c]	Me	**10a** + **9a** (2:1, 37%)[b]
8	MeLi[c]	Me	**11a** (66%) + **12a** (2%)[b]
8	MeLi/CuBr–SMe_2[d]	Me	**12a** (56%)[b]
7	$NaBH_3CN$[f]	H	**9b** (78%) + **10b** (12%)[b]
7	LiI/LiAlH(*t*-BuO)$_3$[f]	H	**9b** (31%)[b]
8	$NaBH_3CN$[f]	H	**11b** (87%) + **12b** (5%)[b]
7	K^+ $^-$NPhth[g]	NPhth	**9c** (62%)[b]
7	H_2NSO_2Me[h]	NHMs	**14d** (98%)[b]
7	$TMSN_3$[h]	N_3	**14e** (56%)[b]

[a] Reported in preliminary communication (ref. 7).
[b] This work.
[c] CH_2Cl_2/−78 °C.
[d] THF–Et_2O (3:1)/−78 °C.
[e] CH_2Cl_2/−30 °C.
[f] THF/0 °C.
[g] CH_3NO_2/23 °C.
[h] CH_2Cl_2/23 °C.



Scheme 3. Mechanism for addition of methyl nucleophiles.

metal carbonyl signals in their ^{13}C NMR spectra (ca. δ 211-203 ppm) is characteristic of (pentenediyl)$Fe(CO)_3$ complexes, while the upfield signals in the ^{1}H NMR spectra of **9a-b** and **11a-b** (ca. δ 0.0–0.17 ppm) are consistent with the hydrogen attached to the pentenediyl carbon σ-bonded to iron (i.e. H^1 of structure in Scheme 2).[5b,c,i] For (*E,Z*-diene)$Fe(CO)_3$ complexes **10a-b** signals at ca. δ 92 and 85–87 ppm in their ^{13}C NMR and at ca. δ 6.0 and 5.3 ppm in their ^{1}H NMR spectra are characteristic of C3 and C4 and their attached hydrogens respectively.[3a,b] For the corresponding (*E,Z*-diene)$Fe(CO)_1PPh_3$ complex **12a**, the signals for H3 and H4 appear at δ 5.87 and 4.28 ppm; shifted upfield (compared to **10a-b**) due to the anisotropic effect of the triphenylphosphine ligand.[3b,5b] Finally, for (*E,E*-diene)$Fe(CO)_3$ complexes **14d-e** signals at ca. δ 86 and 85 ppm in their ^{13}C NMR and at ca. δ 5.85 and 5.35 ppm in their ^{1}H NMR spectra are characteristic of C3 and C4 and their attached hydrogens respectively.[4]

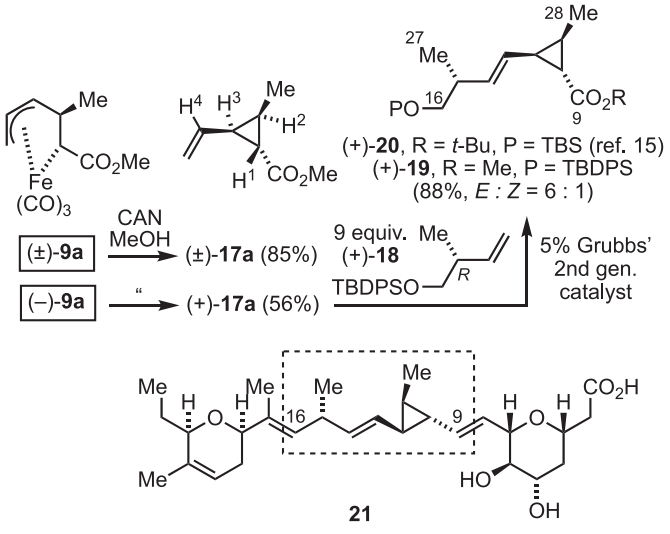
There appears to be little difference between the tricarbonyl-ligated and (dicarbonyl)triphenylphosphine-ligated cations (**7** and **8** respectively) in the regioselectivity for addition of methyl lithium or dimethylcuprate. The formation of the regioisomeric (pentenediyl) or (diene) products may be rationalized by initial single electron transfer from either methyl reagent to form a transient (pentadienyl)iron radical and a methyl-metal radical (Scheme 3). Single electron transfer reactions to (pentadienyl)iron cations have previously been reported by Kochi.[11] For methyllithium, collapse of the radical pair occurs via C–C bond formation at the internal dienyl carbon. Alternatively, for methylcuprate, collapse of the radical pair occurs at the less sterically hindered terminal carbon. If the radical pair escapes the solvent cage, then a second single electron transfer can occur to afford the pentadienyl anion **15**. Aqueous work-up of the reaction mixture gives the protonated product **13**.

While the regioselectivity observed for hydride or phthalimide anion addition to **7** (i.e. at C-2) mirrors that previously observed for stabilized carbon nucleophiles,[5b,c,12] it is different compared to that for addition of these nucleophiles to the (1-ethoxycarbonyl-2-methylpentadienyl)$Fe(CO)_3^+$ cation **16** (eqn. (1)).[13] In the latter case, addition is observed to proceed at the C-5 pentadienyl carbon. The difference in regioselectivity can be attributed to the steric hindrance of the C-2 methyl group in **16** which is not present in cations **7** and **8**.

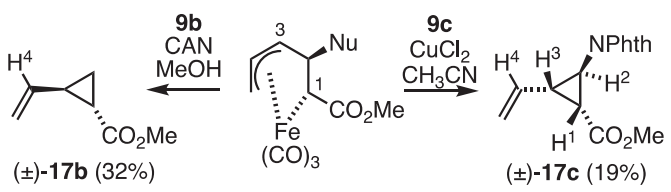
The oxidatively induced-reductive elimination of (pentenediyl) iron complexes (±)-**9a** with ammonium cerium nitrate [CAN] gave the vinylcyclopropane carboxylate (±)-**17a** (Scheme 4). The structure of **17a** was assigned based on its spectral data. In particular, signals at δ 2.14 (ddd), 1.73–1.60 (m) and 1.45 (dd) ppm are assigned to H-3, H-2 and H-1 of the cyclopropane respectively. Furthermore, the large coupling between H-2 and H-3 (9.4 Hz) indicates a *cis* relationship, while smaller couplings between H-1 and H-2, and between H-1 and H-3 (ca. 4.5 Hz each) indicate a *trans* relationship. In a similar fashion decomplexation of (−)-**9a** (prepared from (1*S*)-**7a**) gave (+)-**17a** (56%). Ru-catalyzed cross-metathesis of (+)-**17a** with (+)-**18**[14] (9 equiv.) catalyzed by Grubbs' 2nd generation catalyst gave (+)-**19** as a 6:1 mixture of *E*- and *Z*-stereoisomers. The NMR spectral data for (+)-**19** was similar to that reported for (+)-**20**, a C9–C16 intermediate in Hanessian's synthesis of ambruticin (**21**).[15]

Oxidative decomplexation of **9b** with CAN gave the vinylcyclopropane carboxylate **17b** (Scheme 5). The relatively modest isolated yield of **17b** may be due to the volatility of this low molecular weight ester. The structure of **17b** was confirmed by comparison of its ^{1}H NMR spectral data with the literature values.[16] While attempted decomplexation of **9c** with CAN or H_2O_2/HO^- gave a complex mixture of unidentified products, use of copper(II) chloride gave a low yield of **17c**. We have previously observed that vinylcyclopropane carboxylates bearing an electron rich substituent are prone to secondary oxidation with CAN,[5b] and this is the likely explanation for the low yields of **17c**. The relative configuration of **17c** was assigned based of its ^{1}H NMR spectral data. The signal for H-2 appears at δ 3.60 (dd) ppm; the smaller couplings (4.4 and 5.2 Hz) are indicative of *trans* relative stereochemistry with respect to H-1 and H-3. In addition, the signal for H-4 of **17c** appears at δ 5.95–5.82 ppm, downfield of the signals for H-4 of **17a** (δ 5.55 ppm) and **17b** (δ 5.44 ppm). This further downfield shift is attributed to the deshielding effect of the *cis*-ester substituent.

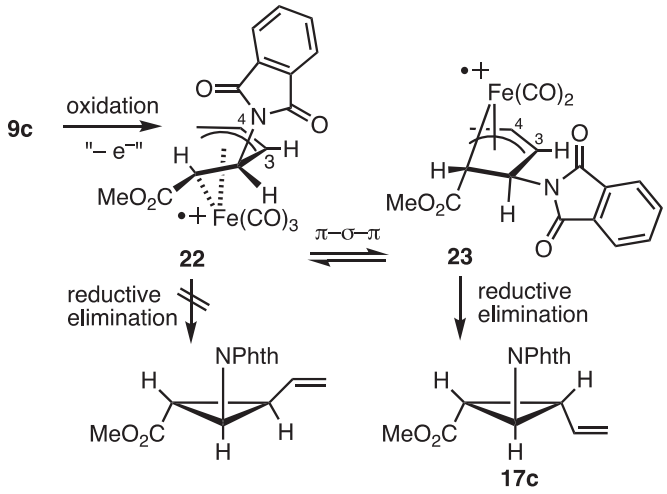
The vinylcyclopropane carboxylates **17a** and **b** are the result of an oxidatively induced-reductive elimination which is known to occur with retention of configuration. The product **17c** is the product from apparent inversion of configuration at C3 of **9c**. This is rationalized on the basis of a rapid π-to-σ-to-π rearrangement of the oxidized pentenediyl **22** to **23** prior to reductive elimination (Scheme 6).[5c] The steric repulsion inherent in the gauche relationship between C4 and the phthalimide substituent in **22** is relieved in **23**, where these two groups are anti. Reductive



Scheme 4. Oxidative decomplexation of **9a** and further transformation into a C9–C16 synthon for ambruticin.



Scheme 5. Oxidative decomplexation of **9b** and **9c**.



Scheme 6. Rationale for formation of **16c**.

elimination from **23** to afford **17c** occurs more rapidly than reductive elimination from **22**.

Copper-catalyzed azide acetylene coupling (Cu-ACC) reactions of ferrocenylmethyl azides has been reported,[17] including the "labelling" of estradiol with a redox active organometallic functionality.[17a-c] In addition, estradiol complexes of metal carbonyls have been previously prepared for Cr, Mo, W, Mn, Re, Ru, and Co as both tracers for the steroid in biological systems by FT IR, and as radiopharmaceuticals (Tc).[18] While there have been a number of (5-azido-1,3-cyclodiene)iron complexes reported,[19] to our knowledge there are no reports of Cu-ACC reactions from these azides. The reaction of dienyl azide **14e** with terminal alkynes **24a-e**, in the presence of copper(I) iodide, gave the (dienyl)triazoles **25a-e** in moderate isolated yield (eqn. (2)). The 1,4-substituent pattern about the triazole ring of **20a-e** was assigned on the basis of their NMR spectral data. In particular, a signal in their ^{13}C NMR spectra in the range δ 119.2–121.0 ppm was assigned to the C5′ carbon of the triazole ring.[20] These assignments are consistent with the formation of isomers of this type by Cu-catalyzed "click" reactions.[21] The preparation of estradiol complex **25e** represents another example of a metal carbonyl "labelled" steroid.

3. Conclusions

Addition of hydride, methyl lithium or phthalimide nucleophiles to (1-methoxycarbonylpentadienyl)iron(1+) cations **7** and **8** proceeds via bond formation at the internal C-2 carbon to afford (pentenediyl)iron complexes. Oxidative decomplexation of (pentenediyl)iron complexes **9a-c** affords vinylcyclopropanecarboxylates **17a-c**, and (+)-**17a** was utilized in a synthesis of the C9–C16 segment of ambruticin. Alternatively, reaction of **7** with weak nucleophiles proceeds via the transoid form of the cation to afford (*E*,*E*-diene)iron complexes **14d** and **e**. The azidodienyl complex **14e** expands the range of azides which undergo Huisgen [3 + 2] cycloadditions to generate organometallic functionalized triazoles.

4. Experimental

4.1. General data

All reactions involving moisture or air sensitive reagents were carried out under a nitrogen atmosphere in oven-dried glassware with anhydrous solvents. THF and ether were distilled from sodium/benzophenone. Purifications by chromatography were carried out using flash silica gel (32–63 μ). NMR spectra were recorded on either a Varian Mercury+ 300 MHz or a Varian UnityInova 400 MHz instrument. $CDCl_3$ was purchased from Cambridge Isotope Laboratories. ^1H and ^{13}C NMR spectra were calibrated to 7.27 ppm for residual $CHCl_3$ and the central peak at 77.23 ppm for $CDCl_3$. Coupling constants are reported in Hz. Elemental analyses were obtained from Midwest Microlabs, Ltd., Indianapolis, IN, and high-resolution mass spectra were obtained from the University of Nebraska Center for Mass Spectrometry and the COSMIC lab at Old Dominion University.

4.2. Tricarbonyl(1-methoxycarbonyl-2-methyl-3-pentene-1,5-diyl) iron (±)-*9a*

To a solution of (±)-**7** (1.640 g, 4.000 mmol) in CH_2Cl_2 (40 mL, 0.1 M soln) flame dried flask under N_2 cooled to −78 °C, was added dropwise a solution of methyllithium in ether (4.0 mL, 1.6 M, 6.4 mmol) over a period of 10 min. The reaction mixture was stirred at −78 °C for 1 h. It was then quenched with saturated aqueous NH_4Cl (100 mL) and the mixture was slowly warmed to room temperature. The layers were separated and the aqueous layer was extracted with CH_2Cl_2. The combined organic layers were dried ($MgSO_4$) and concentrated. The crude brown residue was purified by chromatography (SiO_2, hexanes–ethyl acetate = 40:1) to give (±)-**9a** as a yellow solid (0.7916 g, 71%). mp 63–64 °C; IR (KBr, cm^{-1}) 2068, 1976, 1689; δ_H (300 MHz, $CDCl_3$) 4.58–4.44 (2H, m, H-3 and H-4), 3.67 (3H, s, OMe), 3.59–3.52 (1H, m, H-5exo), 3.20–3.02 (1H, m, H-2), 2.50 (1H, dd, *J* 2.2, 11.0 Hz, H-5endo), 0.70 (3H, d, *J* 7.5 Hz, Me), 0.00 (1H, d, *J* 8.5, H-1); δ_C (75 MHz, $CDCl_3$) 211.0, 210.6, 203.9, 180.8, 97.3, 67.6, 54.2, 51.5, 34.2, 25.8, 14.6. Anal. calcd for $C_{11}H_{12}O_5Fe$: C, 47.17; H, 4.32. Found: C, 46.93; H, 4.26%.

4.3. (1*S*)-Tricarbonyl(1-methoxycarbonyl-2-methyl-3-pentene-1,5-diyl)iron (−)-*9a*

The reaction of (1*S*)-**7** (0.7490 g, 1.830 mmol) in CH_2Cl_2 at −78 °C with an ethereal solution of methyl lithium (2.013 mmol) was carried out in a fashion similar to the reaction of (±)-**7** with methyl lithium. Purification of the crude product by chromatography (SiO_2, hexanes–ethyl acetate = 40:1) to give (−)-**9a** as a yellow solid (0.2486 g, 49%). mp 66–67 °C; $[\alpha]_D^{23} = -545$ (c 0.252, $CHCl_3$). The ^1H and ^{13}C NMR spectra for this product were identical to that for the racemic compound.

4.4. Tricarbonyl(methyl 2*E*,4*Z*-heptadienoate)iron (±)-*10a*

To a solution of methyllithium (2.0 mL, 1.4 M in ether, 2.8 mmol) in THF (15 mL) and ether (5 mL) at −78 °C was added CuBr·Me_2S (200 mg, 0.972 mmol). The mixture was stirred for 45 min, and then solid (±)-**7** (200 mg, 0.487 mmol) was added in one portion. The mixture was stirred for an additional 2 h at −78 °C, then quenched with saturated aqueous NH_4Cl (20 mL) and the mixture was slowly warmed to room temperature. The resultant mixture was extracted several times with ether and the combined organic extracts were washed with brine, dried ($MgSO_4$) and concentrated. The residue was purified by column chromatography (SiO_2, hexanes–ethyl acetate = 3:1) to afford (±)-**10b** as a yellow oil (80 mg, 58%). δ_H (300 MHz, $CDCl_3$) 6.02 (1H, dd, *J* 5.1, 8.1 Hz, H-3), 5.26 (1H, dd, *J* 5.4, 7.8 Hz, H-4), 3.64 (3H, s, OMe), 2.73 (1H, dt, *J* 6.3, 7.6 Hz, H-5), 2.14 (1H, d, *J* 8.6 Hz, H-2), 1.54 (1H, m, H-6), 1.19 (1H, m, H-6′), 0.96 (3H, t, *J* 7.2 Hz, Me-7); δ_C (75 MHz, $CDCl_3$) 173.3, 92.5, 85.5, 63.9, 51.6, 45.7, 22.6, 17.4.

4.5. Reaction of (±)-7 with trimethylaluminum

A solution of trimethylaluminum (1.22 mL, 2.0 M in toluene, 2.44 mmol) was added to CH_2Cl_2 (6 mL), and water (6.8 equiv) was added. The mixture was cooled to −30 °C and solid (±)-**7** (100 mg, 0.243 mmol) was added in one portion. The mixture was stirred for 2 h, while warming to room temperature. The reaction mixture was quenched with water, extracted several times with ethyl acetate and the combined extracts were washed with water, dried ($MgSO_4$) and concentrated. The residue was purified by column chromatography (SiO_2, hexanes–ethyl acetate = 10:1) to afford a mixture of (±)-**10a** and (±)-**9a** (3:1 ratio by ^{1}H NMR, 40 mg, 59%).

4.6. Reaction of (±)-7 with methyl tris(isopropoxy)titanium

To a solution of TiCl(*i*-PrO)$_3$ (1.71 g, 6.57 mmol) in dry ether (20 mL) at −30 °C was added a solution of methyllithium (4.69 mL, 1.4 M in ether, 6.56 mmol) and the mixture was warmed to 0 °C over 1 h period. The mixture was transferred by cannula to a flame-dried round bottom flask and the solvent evaporated. The residue was taken up in dry CH_2Cl_2 (10 mL) and cooled to −78 °C. A solution of **7** (200 mg, 0.486 mmol) in dry CH_2Cl_2 (10 mL) was slowly added by syringe. The mixture was warmed to room temperature and stirred for 18 h. The mixture was quenched with methanol until effervescence ceased and then poured into ice water. The mixture was extracted several times with CH_2Cl_2 and the combined extracts washed with water, brine, dried ($MgSO_4$) and concentrated. The residue was purified by column chromatography (SiO_2, hexanes–ethyl acetate = 10:1) to afford a mixture of (±)-**10a** (±)-**9a** (2:1 ratio by ^{1}H NMR, 50 mg, 36%).

4.7. Dicarbonyl(1-methoxycarbonyl-2-methyl-3-pentene-1,5-diyl)(triphenylphosphine)iron (±)-11a

The reaction of (±)-**8** (0.640 g, 0.994 mmol) with methyllithium in CH_2Cl_2 was carried out in a similar fashion to the reaction of **7** with methyl lithium. Purification of the residue gave (±)-**12a** (9.1 mg, 2%) followed by (±)-**11a** (0.3362 g, 66%) both as yellow solids. **11a**: mp 194–195 °C; IR (KBr, cm^{-1}) 1983, 1933, 1680, 1433, 1152; δ_H (300 MHz, $CDCl_3$) 7.44–7.28 (15H, m, PPh_3), 4.31 (1H, t, *J* 6.6 Hz, H-3), 3.81–3.72 (1H, m, H-3), 3.74 (3H, s, OMe), 3.17 (1H, app q, *J* 7.7 Hz, H-2), 2.57–2.49 (1H, m, H-5exo), 2.35–2.25 (1H, m, H-5endo), 0.61 (3H, d, *J* 7.0 Hz, Me), 0.01 (1H, dd, *J* 3.5, 7.9 Hz, H-1); δ_C (75 MHz, $CDCl_3$) 218.1, 217.9, 182.4, 133.4 (d, $J_{C\text{-}P}$ 28.0 Hz), 132.9 (d, $J_{C\text{-}P}$ 9.7 Hz), 130.3, 128.6 (d, $J_{C\text{-}P}$ 9.1 Hz), 96.6, 66.1, 56.8, 51.3, 35.2, 25.6 (d, $J_{C\text{-}P}$ 6.3 Hz), 13.5 (d, $J_{C\text{-}P}$ 15.5 Hz). Anal. calcd for $C_{28}H_{27}O_4PFe\cdot 1/2H_2O$: C, 64.26; H, 5.39. Found: C, 64.29; H, 5.28%.

4.8. Dicarbonyl(methyl 2E,4Z-heptadienoate)(triphenyl-phosphine) iron (±)-12a

The reaction of (±)-**8** (314 mg, 0.487 mmol) with methyllithium-CuBr was carried out in a similar fashion to the reaction of **7** with Me_2CuLi. Purification of the residue by column chromatography (SiO_2, hexanes–ethyl acetate = 10:1) gave (±)-**12a** as a yellow solid (140 mg, 56%). δ_H (300 MHz, $CDCl_3$) 7.52–7.32 (15H, m, PPh_3), 5.87 (1H, dd, *J* 5.4, 7.6 Hz, H-3), 4.28 (1H, br m, H-4), 3.66 (3H, s, OMe), 1.95 (1H, br d, *J* 8.4 Hz, H-2), 1.75–1.45 (2H, m, CH_2), 1.05 (1H, m, H-5), 0.72 (3H, t, *J* 7.5 Hz, Me-7); δ_C (75 MHz, $CDCl_3$) δ 175.2, 134.3 ($J_{C\text{-}P}$ 40 Hz), 133.2 ($J_{C\text{-}P}$ 9.7 Hz), 130.0, 128.3 ($J_{C\text{-}P}$ 9.7 Hz), 89.2, 87.7, 65.3, 51.2, 40.1 (br), 31.5, 22.7 ($J_{C\text{-}P}$ 17 Hz), 17.5, 14.1.

4.9. Tricarbonyl(1-methoxycarbonyl-3-pentene-1,5-diyl)iron (±)-9b and Tricarbonyl(methyl 2E,4Z-hexadienoate)iron (±)-10b

To a solution/suspension of (±)-**7** (500 mg, 1.22 mmol) in THF (30 mL) at 0 °C was added portion wise, solid $NaBH_3CN$ (92 mg, 1.46 mmol). The mixture was stirred at 0 °C for 2 h. The reaction mixture was diluted with water and extracted several times with ether. The combined organic extracts were washed with brine, dried ($MgSO_4$) and concentrated. Analysis of the crude product by ^{1}H NMR spectroscopy indicated that this was a mixture of **9b** and **10b** (ca. 7:1). Purification of the residue by column chromatography (SiO_2, hexanes–ethyl acetate = 10:1) gave (±)-**10b** (38 mg, 12%), followed by (±)-**9b** (252 mg, 78%), both as yellow oils. **9b** solidified upon standing.

(±)-**9b**: mp 84–85 °C; IR (CH_2Cl_2, cm^{-1}) 2063, 1989, 1689; δ_H (300 MHz, $CDCl_3$) 4.57 (1H, td, *J* 7.3, 12.0 Hz, H-4), 4.35 (1H, m, H-3), 3.70–3.66 (4H, m and s, OMe and H-5exo), 3.04 (1H, td, *J* 7.5, 14.6 Hz, H-2), 2.57 (1H, dd, *J* 2.0, 12.0 Hz, H-5endo), 2.34 (1H, dddd, *J* 1.2, 3.2, 8.8, 14.6 Hz, H-2′), 0.15 (1H, dd, *J* 7.4, 8.7 Hz, H-1); δ_C (75 Hz, $CDCl_3$) 211.4, 210.9, 204.1, 181.7, 98.9, 59.3, 53.1, 51.4, 25.2, −0.9; Anal. Calcd for $C_{10}H_{10}O_5Fe$: C, 45.15; H, 3.79. Found: C, 44.74; H, 3.76.

(±)-**10b**: δ_H (300 MHz, $CDCl_3$) 6.04 (1H, ddd, *J* 1.2, 5.1, 8.4 Hz, H-3), 5.33 (1H, dd, *J* 5.1, 7.8 Hz, H-4), 3.67 (3H, s, OMe), 2.90 (1H, qd, *J* 7.2, 7.8 Hz, H-5), 2.22 (1H, d, *J* 8.1 Hz, H-2), 1.17 (3H, d, *J* 7.2 Hz, Me-6); δ_C (75 Hz, $CDCl_3$) δ 174.3 ($\underline{C}O_2Me$), 92.2 (C-3), 87.1 (C-4), 54.8 (OMe), 51.7, 46.0, 14.4 (Me-6).

4.10. Dicarbonyl(1-methoxycarbonyl-3-pentene-1,5-diyl)(triphenylphosphine)iron (±)-11b

The reaction of (±)-**8** (500 mg, 0.775 mmol) with $NaBH_3CN$ (58 mg, 0.92 mmol) in THF at 0 °C was carried out in a fashion similar to the reaction of **7** with $NaBH_3CN$. Purification of the residue by column chromatography (SiO_2, hexanes–ethyl acetate = 10:1) gave (±)-**12b** (20 mg, 5%) followed by (±)-**11b** as a yellow solid (339 mg, 87%). **11b**: δ_H (300 MHz, $CDCl_3$) 7.50–7.20 (15H, m, Ph_3P), 4.13 (1H, m, H-3), 3.83 (1H, m, H-4), 3.75 (3H, s, OMe), 3.08 (1H, td, *J* 7.2, 14.1 Hz, H-2), 2.66 (1H, m, H-5exo), 2.35 (2H, m, H-5endo and H-2′), 0.17 (1H, m, H-1); δ_C (75 MHz, $CDCl_3$) 183.1, 133.4, 132.8 (J_{PC} 9.8 Hz), 130.1, 128.4 (J_{PC} 8.5 Hz), 98.0 (J_{PC} 2.4 Hz), 57.0, 55.6, 51.0, 26.5, −1.7; Anal. Calcd for $C_{27}H_{25}O_4FeP$: C, 64.82; H, 5.04. Found: C, 64.65; H, 5.05.

4.11. Tricarbonyl(1-methoxycarbonyl-2-phthalimido-3-pentene-1,5-diyl)iron (±)-9c

To a solution of **7** (400 mg, 0.910 mmol) in CH_2Cl_2 (10 mL) and nitromethane (3 mL) was added solid potassium phthalimide (214 mg, 1.16 mmol). The mixture was stirred for 18 h, and then poured into water and the resulting mixture extracted several times with CH_2Cl_2. The combined extracts were washed with brine, dried (Na_2SO_4) and concentrated. The residue was purified by chromatography (SiO_2, hexanes–ethyl acetate = 4:1) to give **9c** as a yellow solid (242 mg, 65%). mp 150–151 °C; δ_H (300 MHz, $CDCl_3$) 7.65–7.82 (4H, m, Phth), 5.57 (1H, dd, *J* 7.3, 10.2 Hz, H-2), 4.83 (1H, ddd, *J* 7.2, 9.0, 12.3 Hz, H-4), 4.66 (1H, t, *J* 7.2 Hz, H-3), 3.68 (3H, s, OMe), 3.63 (1H, br d, *J* 7.8 Hz, H-5exo), 3.50 (1H, dd, *J* 2.1, 12.3 Hz, H-5endo), 1.53 (1H, d, *J* = 10.2 Hz, H-1); δ_C (75 MHz, $CDCl_3$) 210.4, 209.0, 203.6, 179.1, 167.8, 134.3, 131.2, 123.6, 123.4, 100.8, 64.4, 55.8, 51.7, 47.8, 17.6. Anal. calcd for $C_{18}H_{13}NO_7Fe$: C, 52.58; H, 3.19. Found: C, 52.78; H, 3.24%.

4.12. Tricarbonyl(methyl 6-methylsulfonamido-2E,4E-hexadienoate)iron (±)-**14d**

To a solution of methane sulfonamide (36 mg, 0.38 mmol) in CH_2Cl_2 (6 mL) was added solid **7** (100 mg, 0.228 mmol). The mixture was stirred for 4 h, evaporated to dryness, and the residue was dissolved in ethyl acetate and the organic solution was extracted with water. The organic layer was washed with brine, dried (Na_2SO_4) and concentrated. The residue was purified by chromatography (SiO_2, hexanes–ethyl acetate = 7:3) to give (±)-**14d** as a yellow oil (80 mg, 98%). δ_H (300 MHz, $CDCl_3$) 5.85 (1H, dd, *J* 5.1, 8.0 Hz, H-3), 5.40 (1H, dd, *J* 5.1, 8.1 Hz, H-4), 4.89–4.82 (1H, br m, NHSO$_2$Me), 3.67 (3H, s, OMe), 3.36–3.26 (2H, m, CH$_2$NHMs), 2.97 (3H, s, SO$_2$Me), 1.32–1.22 (1H, m, H-5), 1.11 (1H, d, *J* 8.2 Hz, H-2); δ_C (75 MHz, $CDCl_3$) 172.5, 86.5, 86.0, 58.6, 52.1, 46.9, 46.3, 41.2. HRMS (FAB): M + H^+, found 359.9837. $C_{11}H_{14}NO_7SFe$ requires 359.9840.

4.13. Tricarbonyl(methyl 6-azido-2E,4E-hexadienoate)iron (±)-**14e**

To a solution of **7** (205 mg, 0.500 mmol) in dry CH_2Cl_2 (15 mL) was added trimethylsilyl azide (86 mg, 0.75 mmol). The reaction was stirred overnight and then quenched with water. The mixture was extracted several times with CH_2Cl_2 and the combined extracts dried ($MgSO_4$) and concentrated. The residue was purified by chromatography (SiO_2, hexanes–ethyl acetate = 10:1) to give **14e** as a yellow oil (85 mg, 56%). δ_H (300 MHz, $CDCl_3$) 5.86 (1H, ddd, *J* 0.9, 5.1, 8.1 Hz, H-3), 5.35 (1H, dd, *J* 5.1, 8.1 Hz, H-4), 3.67 (3H, s, OMe), 3.50–3.35 (2H, m, CH$_2$N$_3$), 1.27 (1H, q, *J* 7.2 Hz, H-5), 1.12 (1H, dd, *J* 0.9, 8.4 Hz, H-2); δ_C (75 MHz, $CDCl_3$) 172.3, 86.1, 85.1, 56.3, 53.9, 52.0, 46.8.

4.14. (±)-Methyl (1S*,2S*,3R*)-2-ethenyl-3-methylcyclopropanecarboxylate (±)-**17a**

To a solution of **9a** (418.6 mg, 1.495 mmol) in anhydrous methanol (15 mL) was added solid ceric ammonium nitrate in portions of one equivalent every 10 min (4.084 g, 7.475 mmol total) until no more starting material was observed by tlc. After addition was complete, the reaction mixture was stirred for an additional 1 h and then partitioned between water and CH_2Cl_2, and the aqueous layer was extracted several times with CH_2Cl_2. The combined layers were dried ($MgSO_4$) and concentrated. The crude oil was subjected to kugelrohr distillation to give (±)-**16b** (177.1 mg, 85%) as a volatile colorless oil. IR (neat, cm^{-1}) 3085, 2954, 1728, 1635, 1442, 1409, 1309, 1173, 1069, 919; δ_H (300 MHz, $CDCl_3$) 5.55 (1H, ddd, *J* 17.0, 10.3, 8.7 Hz, CH=CH$_2$), 5.22 (1H, *J* 16.9, 1.6. 0.6 Hz, CH=CH$_E$H$_Z$), 5.11 (1H, *J* 10.3, 1.6, 0.6 Hz, CH=CH$_E$H$_Z$), 3.67 (3H, s, OCH_3), 2.14 (1H, ddd, *J* 9.6, 9.6, 4.7 Hz, H-3), 1.73–1.60 (1H, m, H-2), 1.45 (1H, dd, *J* 4.7, 4.7 Hz, H-1), 1.13 (3H, d, *J* 6.4 Hz, CH_3); δ_C (75 Hz, $CDCl_3$) 174.1, 134.2, 117.2, 52.0, 31.4, 28.8, 23.1, 12.8; HRMS (EI): [M − CH_3]$^+$ found 125.1335. $C_7H_9O_2$ requires 125.0602.

4.15. (+)-Methyl (1S,2S,3R)-2-ethenyl-3-methylcyclopropanecarboxylate (+)-**17a**

The decomplexation of (−)-**9a** (0.4200 g, 1.500 mmol) with CAN (4.282 g, 7.810 mmol) in methanol was carried out in a fashion similar to the decomplexation of (±)-**9a**. Purification of the crude oil by kugelrohr distillation gave (−)-**17a** as a volatile colorless oil (0.1177 g, 56%); $[\alpha]_D^{23}$ = +139 (c 0.294, $CHCl_3$). The ^1H and ^{13}C NMR spectra for this product were identical to that for the racemic compound.

4.16. (+)-Methyl (1S,2S,3R)-2-[(1E,3R)-4-[[(1,1-dimethylethyl)-diphenylsilyl]oxy]-3-methyl-1-butenyl]-3-methylcyclopropanecarboxylate (+)-**19a**

To a solution of (+)-**17a** (90.90 mg, 0.6492 mmol) and (+)-**18** (1.8919 g, 5.8391 mmol) in CH_2Cl_2 (7.0 mL) under N_2 was added Grubbs' 2nd generation catalyst (27.7 mg, 0.0326 mmol). The reaction mixture was heated at reflux for 30 h, and then cooled and concentrated under a stream of N_2. The residue was purified by column chromatography (SiO_2, hexanes–ethyl acetate = 40:1) to afford (+)-**19** (249 mg, 88%) as a pale oil. $[\alpha]_D^{23}$ = +50 (c 0.25, $CHCl_3$); IR (neat, cm^{-1}) 1728, 1427, 1313, 1173, 1112, 824, 702; δ_H (300 MHz, $CDCl_3$) 7.70–7.62 (4H, m, ArH), 7.46–7.30 (6H, m, ArH), 5.54 (1H, dd, *J* = 7.3, 15.5 Hz, H-14), 5.15 (1H, dd, *J* = 8.5, 15.8 Hz, H-13), 3.16 (3H, s, OMe), 3.51–3.46 (2H, m, CH_2OSi), 2.42–2.31 (1H, m, H-15), 2.06 (1H, ddd, *J* = 4.4, 9.0, 9.0 Hz, H-12), 1.72–1.57 (1H, m, H-11), 1.34 (1H, dd, *J* = 4.7, 4.7 Hz, H-10), 1.10 (3H, d, *J* = 6.4 Hz, Me-28), 1.05 (9H, s, *t*-Bu), 0.99 (3H, d, *J* = 6.7 Hz, Me-27) (atom designation corresponding to ambruticin numbering, assignments were aided by COSY NMR); δ_C (75 Hz, $CDCl_3$) 174.1, 136.2, 135.7, 133.9, 129.6, 127.7, 125.4, 68.8, 51.9, 39.8, 30.9, 28.8, 27.1, 22.9, 19.6, 12.9; HRMS (FAB) M + Li^+, found 443.2580. $C_{27}H_{36}O_3SiLi$ requires 443.2594.

4.17. Methyl trans-2-vinylcyclopropanecarboxylate (±)-**17b**

To a solution of **9b** (130 mg, 0.489 mmol) in anhydrous methanol (10 mL) at room temperature was added in one portion, solid ammonium cerium nitrate (2.68 g, 4.89 mmol). The reaction mixture was stirred for 3 h, poured into water and extracted several times with ethyl acetate. The combined extracts were washed with brine, dried ($MgSO_4$) and the solvent evaporated under reduced pressure. The residue was purified by chromatography (SiO_2, hexanes–ethyl acetate = 10:1) to give (±)-**17b** as a volatile oil (20 mg, 32%). δ_H (300 MHz, $CDCl_3$) 5.44 (1H, ddd, *J* 8.1, 10.2, 18.3 Hz, CH=CH$_2$), 5.21 (1H, dd, *J* 1.5, 18.3 Hz, CH=CH$_E$H$_Z$), 5.04 (1H, dd, *J* 1.5, 10.2 Hz, CH=CH$_E$H$_Z$), 3.72 (3H, s, OMe), 1.70 (1H, td, *J* 4.8, 8.7 Hz, H-1), 1.42 (1H, td, *J* 4.5, 8.7 Hz, H-2), 1.07–0.97 (2H, m, H-3 and H-3′); δ_C (75 MHz, $CDCl_3$) 171.0, 137.9, 114.8, 51.7, 25.5, 21.6, 15.5. The NMR spectral data for this compound is consistent with the literature values.[16]

4.18. Methyl 2-phthalimido-3-vinylcyclopropanecarboxylate (±)-**17c**

To a solution of **9c** (80 mg, 0.20 mmol) dissolved in anhydrous acetonitrile (10 mL) under nitrogen was added copper (II) chloride (79 mg, 0.59 mmol). The reaction mixture was heated at 50 °C for 1 h and then concentrated to remove acetonitrile. The residue was dissolved in CH_2Cl_2 and purified by column chromatography (SiO_2, hexanes–ethyl acetate = 10:1) to afford (±)-**17c** as a colorless oil (10 mg, 0.037 mmol, 19%). δ_H (300 MHz, $CDCl_3$) 7.85–7.70 (4H, m, Phth), 5.95–5.82 (1H, m, CH=CH$_2$), 5.43 (1H, ddd, *J* 0.6, 1.8, 17.2 Hz, CH=CH$_E$H$_Z$), 5.24 (1H, ddd, *J* 0.6, 1.5, 10.3 Hz, CH=CH$_E$H$_Z$), 3.75 (3H, s, OMe), 3.60 (1H, dd, *J* 4.4, 5.2 Hz, H-2), 2.77–2.61 (2H, m, H-1 and H-3); δ_C (100 MHz, $CDCl_3$) 210.0, 134.3, 131.7, 131.6, 123.4, 119.0, 52.1, 35.1, 29.8, 26.4. HRMS (ESI): M_2Na^+, found 565.1588. $(C_{15}H_{13}NO_4)_2Na^+$ requires 565.1581.

4.19. (Tricarbonyl)(methyl 6-phenyl-1H-1,2,3-triazole-2E,4E-hexadienoate)iron (±)-**25a**

To a solution of (±)-**14e** (20 mg, 0.065 mmol) in CH_3CN (10 mL) was added phenylacetylene (10 mg, 0.098 mmol) and copper (I) iodide (2 mg, 10 mol %). The mixture was heated to 70 °C under nitrogen. After 19 h, the temperature was raised to 100 °C and the

solution started to reflux. This temperature was maintained for another 5 h. After cooling, the mixture was quenched with H_2O, extracted several times with CH_2Cl_2, and the combined organic extracts was washed with brine, dried (Na_2SO_4) and concentrated. The residue was purified by column chromatography (SiO_2, hexanes–ethyl acetate gradient = 2:1 → pure ethyl acetate) to afford (±)-**25a** (16 mg, 0.039 mmol, 60%) as a yellow oil. δ_H (300 MHz, $CDCl_3$) 7.85–7.79 (3H, m, Ph and triazole-H), 7.46–7.32 (3H, m, Ph), 5.91 (1H, ddd, *J* 0.9, 5.2, 8.6 Hz, H-3), 5.57 (1H, ddd, *J* 0.9, 5.2, 8.6 Hz, H-4), 4.60 (1H, dd, *J* 5.9, 14.6 Hz, H-6), 4.48 (1H, dd, *J* 8.6, 14.5 Hz, H-6′), 3.67 (3H, s, OMe), 1.47–1.38 (1H, m, H-5), 1.15 (1H, dd, *J* 0.9, 8.2 Hz, H-2); δ_C (75 MHz, $CDCl_3$) 172.2, 148.3, 130.6, 129.1, 128.6, 126.0, 119.2, 86.3, 85.8, 55.3, 53.0, 52.0, 47.3. HRMS (ESI): M + Na^+, found 432.0250. $C_{18}H_{15}N_3O_5FeNa$ requires 432.0253.

4.20. (Tricarbonyl)(methyl 6-butyl-1H-1,2,3-triazole-2E,4E-hexadienoate)iron (±)-*25b*

The reaction of (±)-**14e** (20 mg, 0.065 mmol) with 1-hexyne (11 mg, 0.13 mmol) in the presence of copper (I) iodide (2 mg, 10 mol%) was carried out in a fashion similar to the preparation of **25a**. Purification of the residue by column chromatography (SiO_2, hexanes–ethyl acetate gradient = 2:1 → pure ethyl acetate) gave (±)-**25b** (12 mg, 0.031 mmol, 48%) as a yellow oil. δ_H (400 MHz, $CDCl_3$) 7.30 (1H, s, triazole-H), 5.89 (1H, dd, *J* 5.1, 8.3 Hz, H-3), 5.53 (1H, dd, *J* 5.1, 8.3 Hz, H-4), 4.52–4.38 (2H, m, H-6 and H-6′), 3.66 (3H, s, OMe), 2.72 (2H, t, *J* 7.8 Hz, $C\underline{H}_2(CH_2)_2CH_3$), 1.69–1.60 (4H, m), 1.44–1.33 (3H, m, H-5 and $C\underline{H}_2CH_3$), 1.12 (1H, d, *J* 8.3 Hz, H-2), 0.93 (3H, t, *J* 7.4 Hz, Me); δ_C (75 MHz, $CDCl_3$) 172.2, 149.1, 120.3, 86.2, 85.7, 56.0, 52.8, 52.1, 47.1, 31.8, 25.5, 22.4, 13.9. HRMS (ESI): M + Na^+, found 412.0565. $C_{16}H_{19}N_3O_5FeNa$ requires 412.0566.

4.21. (Tricarbonyl)[methyl 6-(4-ethynylphenyl)-1H-1,2,3-triazole-2E,4E-hexadienoate]iron (±)-*25c*

The reaction of (±)-**14e** (21 mg, 0.068 mmol) with 1,4-diethynylbenzene (9 mg, 0.071 mmol) in the presence of copper (I) iodide (2 mg, 10 mol%) was carried out in a fashion similar to that for **25a**. The residue was purified by column chromatography (SiO_2, hexanes–ethyl acetate gradient = 2:1 → pure ethyl acetate) to afford (±)-**25c** (12 mg, 0.028 mmol, 41%) as a yellow oil. δ_H (400 MHz, $CDCl_3$) 7.82–7.77 (3H, m, ArH and triazole-H), 7.57–7.53 (2H, m, ArH), 5.92 (1H, ddd, *J* 0.8, 5.0, 8.2 Hz, H-3), 5.57 (1H, dd, *J* 5.1, 8.2 Hz, H-4), 4.63–4.45 (2H, m, H-6 and H-6′), 3.67 (3H, s, OMe), 3.13 (1H, s, C≡C$\underline{H}$), 1.44–1.37 (1H, m, H-5), 1.15 (1H, dd, *J* 0.8, 8.2 Hz, H-2); δ_C (100 MHz, $CDCl_3$) 171.9, 147.4, 132.7, 130.7, 125.6, 122.0, 119.3, 86.0, 85.6, 83.4, 78.0, 55.0, 52.8, 51.9, 47.1. HRMS (ESI): M + Na^+, found 456.0252. $C_{20}H_{15}N_3O_5FeNa$ requires 456.0253].

4.22. (Tricarbonyl)methyl 6-[6-methoxy-2-naphthyl)-1H-1,2,3-triazole-2E,4E-hexadienoate)iron (±)-*25d*

The reaction of (±)-**14e** (20 mg, 0.065 mmol) with 2-ethynyl-6-methoxy-naphthalene (18 mg, 0.099 mmol) in the presence of copper (I) iodide (2 mg, 10 mol%) was carried out in a fashion similar to the preparation of **25a**. Purification of the residue by column chromatography (SiO_2, hexanes–ethyl acetate gradient = 2:1 → pure ethyl acetate) gave (±)-**25d** (16 mg, 0.033 mmol, 50%) as a yellow solid. mp 151–154 °C; δ_H (400 MHz, $CDCl_3$) 8.25 (1H, s, napthyl-H), 7.90–7.86 (2H, m, napthyl-H and triazole-H), 7.80–7.76 (2H, m, napthyl-H), 7.18–7.13 (2H, m, napthyl-H), 5.91 (1H, ddd, *J* 1.2, 5.2, 8.1 Hz, H-3), 5.58 (1H, ddd, *J* 0.8, 5.1, 8.3 Hz, H-4), 4.65–4.45 (2H, m, H-6 and H-6′), 3.93 (3H, s, OMe), 3.66 (3H, s, OMe), 1.48–1.41 (1H, m, H-5), 1.16 (1H, dd, *J* = 1.2, 8.0 Hz, H-2); δ_C (100 MHz, $CDCl_3$) 172.1, 158.0, 148.4, 134.5, 129.7, 129.0, 127.4, 125.6, 124.4, 119.4, 118.9, 105.8, 86.1, 85.6, 55.3, 52.8, 51.8, 47.0. HRMS (ESI): M + Na^+, found 512.0515. $C_{23}H_{19}N_3O_6FeNa$ requires 512.0515.

4.23. (Tricarbonyl)methyl 6-[4-(3,17-dihydroxyestra-1,3,5(10)-trien-17-yl)-1H-1,2,3-triazole-2E,4E-hexadienoate)iron *25e*

The reaction of (±)-**14e** (23 mg, 0.074 mmol) with 17α-ethynylestradiol (33 mg, 0.11 mmol) in the presence of copper (I) iodide (2 mg, 10 mol%) was carried out in a fashion similar to the preparation of **25a**. Purification of the residue by column chromatography (SiO_2, hexanes-ethyl acetate gradient = 2:1 → pure ethyl acetate) gave **25e** (16 mg, 0.027 mmol, 36%) as a yellow oil. This was determined to be a mixture of diastereomeric complexes by NMR spectroscopy. δ_H (300 MHz, $CDCl_3$) 7.49 and 7.47 (1H, 2 × s, triazole-H), 7.05 (1H, d, *J* 8.4 Hz, ArH), 6.63–6.52 (2H, m, ArH), 5.91 (1H, dd, *J* 8.2, 5.3 Hz, H-3), 5.55 (1H, dd, *J* 8.2, 5.3 Hz, H-4), 5.19 (1H, s, OH), 4.51 (2H, d, *J* 7.0 Hz, H-6 and H-6′), 3.67 (3H, s, OMe), 2.85–2.65 (3H, m), 2.50–2.35 (1H, m), 2.22–2.06 (2H, m), 2.03–1.82 (3H, m), 1.64–1.29 (8H, m), 1.14 (1H, d, *J* 8.2 Hz, H-2), 1.05 (3H, s, Me-18), 0.73 (1H, br t, *J* 7.0 Hz). δ_C (75 MHz, $CDCl_3$) 172.3, 154.3, 153.7, 138.5, 132.7, 126.7, 121.0, 115.5, 112.9, 86.2, 85.7, 82.8, 55.7, 53.0, 52.2, 48.6, 47.5, 47.3, 43.4, 39.7, 38.3, 33.1, 29.9, 27.5, 26.4, 23.6, 14.4. HRMS (ESI): M + Na^+, found 626.1558. $C_{30}H_{33}N_3O_7FeNa$ requires 626.1560].

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.tet.2017.06.026.

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