Pergamon

Tetrahedron 57 (2001) 5097–5107

TETRAHEDRON

Ring expansion in the coupling of Fischer-carbene complexes with 1-alkynyl-1-hydroxy cyclic compounds

Metin Zora, James W. Herndon,* Yuhui Li and Jason Rossi

Department of Chemistry and Biochemistry, University of Maryland, College Park, MD 20742-2021, USA

Dedicated to Professor Barry M. Trost on the occasion of his 60th birthday

Received 2 February 2001; revised 21 February 2001; accepted 22 February 2001

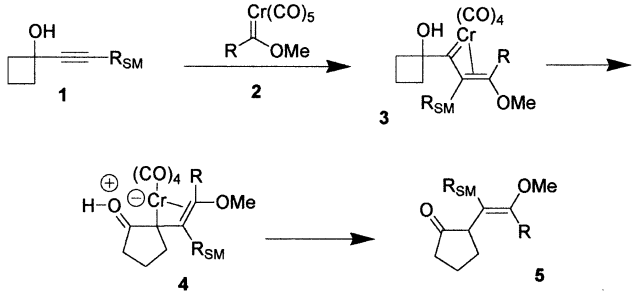
Abstract—The coupling of a variety of transition metal–carbene complexes with alkynols has been studied. In many cases, the intermediate vinylcarbene complexes formed in this reaction undergo a ring expansion to afford cyclic ketone derivatives. This scope and limit of this process is explored. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

Ring expansion reactions offer an important tool for the construction of cyclic molecules.[1] A key structural feature required for many of the synthetically useful ring expansion processes is an electrophilic center exocyclic to carbon-1 of a cyclic alcohol. A subsequent 1,2-shift of one of the carbon atoms in the ring leads to a ring-expanded ketone derivative. Examples of this type of reaction include pinacol-type rearrangements,[2] generation and rearrangement of exocyclic carbenes,[3] and metal-catalyzed rearrangements of 1-alkenyl[4] and 1-alkynyl[5] cyclic alcohols.

The focus of these studies involves a similar ring expansion process induced by carbene complexes exocyclic to carbon-1 of a cyclic alcohol (e.g. **3** of Scheme 1),[6] which are easily generated through coupling of alkynols (e.g. **1**) with Fischer-carbene complexes. Numerous reaction pathways are common for free carbenes and transition metal–carbene complexes;[7] however, among synthetically important examples, only cyclopropanation[8] and conversion to alkenes (β C–H insertion) are well documented.[9] Other β-insertion processes (1,2-shifts), including alkyl shifts[10] and silicon shifts,[11] have limited precedent for transition metal–carbene complexes, but have been proposed as important mechanistic events in various reaction processes.

In an earlier communication, we reported that the coupling of 4-alkynyl-4-hydroxy-2-cyclobuten-1-ones with Fischer-carbene complexes leads to 2-cyclopentene-1,3-diones.[6] In

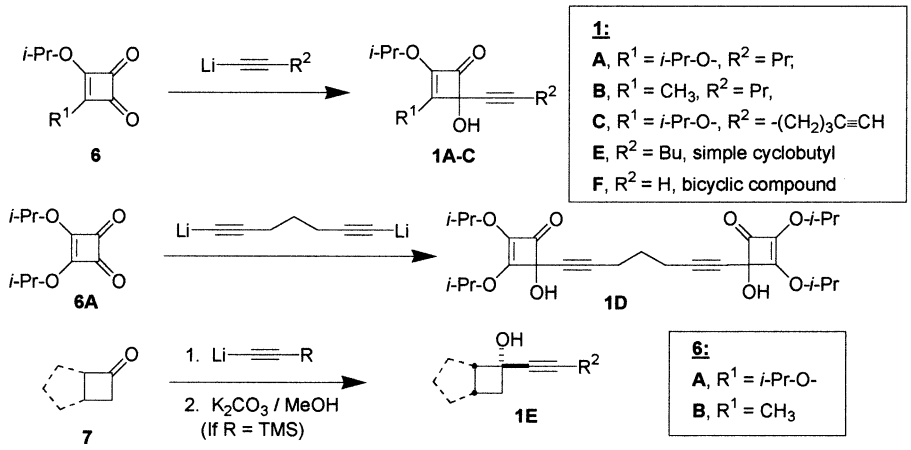


Scheme 1.

Keywords: ring expansion; carbene complexes; alkynols.

* Corresponding author. Address: Department of Chemistry and Biochemistry, New Mexico State University, MSC 3C, Las Cruces, NM 88003, USA. Tel.: +1-505-646-2505; fax: +1-505-646-2649; e-mail: jherndon@nmsu.edu

PII: S0040-4020(01)00359-3



Scheme 2.

this manuscript, we give a full and detailed account of the scope and limit of this process, and discuss further extension of these processes to less strained ring systems.

2. Results

2.1. Synthesis of alkynols

The alkynols used in this study were all prepared from the coupling of known or commercially available cyclic ketones with anions derived from terminal alkynes and *n*-butyllithium. Ketones **6A** and **B** were prepared from squaric acid using well-documented procedures (Scheme 2).[12]

2.2. Coupling of squarate-derived alkynols 1A–D with chromium–carbene complexes

The coupling of a variety of alkynols derived from squaric acid (**1A**–**D**) with chromium–carbene complexes leads to cyclopentenediones (**5**, **8**) as the exclusive reaction pathway (Table 1). The initial products of the coupling reaction are the enol ether derivatives (**5**), which in many cases are hydrolyzed to the corresponding triketone (**8**) by treatment with acid. Only the relatively unreactive aminocarbene complex **2B** (entry B) afforded a poor yield of ring expansion product (Scheme 3).

Even when carbene complexes **2C**,**D** were employed, a well-known alternative reaction pathway, the Dötz benzannulation reaction (resulting in phenols **10** or **11**),[13] was not observed. Similarly, a competing cyclopentannulation process,[14] resulting in cyclopentenone **12**, was not observed in the coupling of cyclopropylcarbene complex **2E** and alkynylcyclobutenol **1A**. A competing two-alkyne annulation process,[15] resulting in phenol **13**, was not observed in the coupling of diyne **1C** with methylcarbene complex **2A**. A double ring-expansion product, **8H**, was the exclusive product from the coupling of methylcarbene complex **1A** and diyne **1D**. As noted in recent papers, β-lactones (e.g. **14**, entry A) might also arise from coupling of propargyl alcohols with Fischer-carbene complexes;[16] however, these compounds were not observed.

2.3. Coupling of other alkynols with chromium–carbene complexes

A variety of other alkynols were tested in their reaction with chromium–carbene complex **2C** (Scheme 4). Ring expansion products were not observed for simple alkynylcyclobutanol **1E** or cyclopentanol derivatives **16** and **17**. In the coupling of simple alkynol derivatives **1E** and **16** with phenylcarbene complex **2C**, the only identifiable products are consistent with the cyclobutenone structures (e.g. **15**, IR: 1759 cm^{-1}).[17]

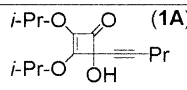
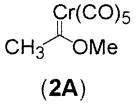
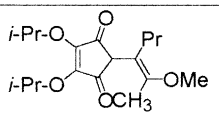
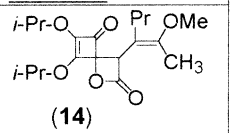
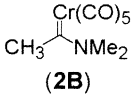
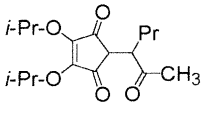
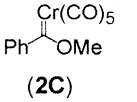
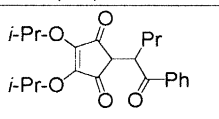
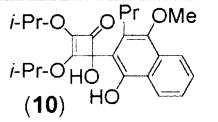
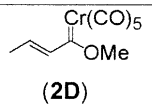
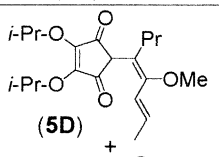
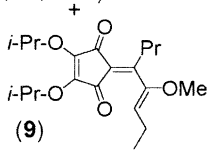
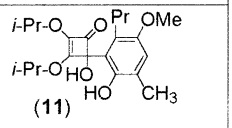
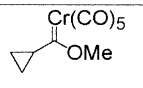
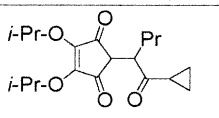
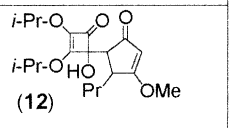
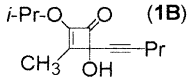
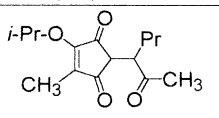
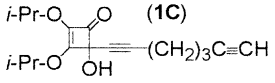
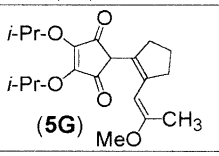
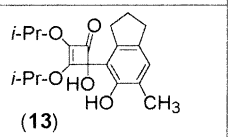
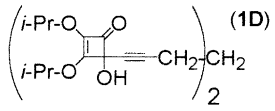
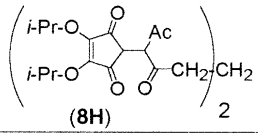
2.4. Coupling of alkynylcyclobutanols with molybdenum–carbene complexes

Treatment of alkynylcyclobutanol **1E** (Scheme 5) with molybdenum–carbene complex **18**[18] led to a complex mixture of ring-expanded products as evidenced by the appearance of peaks at 1740 and 1705 cm^{-1} in the crude NMR spectrum. A product consistent with alkylidenecyclopentanone structure **19** could be isolated from the reaction in low yield. Coupling of alkynylcyclobutanol **1F** with carbene complex **21** led to a far cleaner reaction mixture, affording cyclopentanone derivatives **21** and **8J**. These reaction mixtures were not subjected to hydrolysis prior to final purification, as were many of the examples in Table 1; however, the corresponding enol ether derivatives (**22**, **5I**,**J**) were never observed.

3. Discussion

Coupling of alkynylcyclobutenols derived from squaric acid led to cyclopentenedione products in good yields in all cases as the exclusive product of the reaction (Table 1). The mechanism depicted in Scheme 6, illustrated for the coupling of cyclobutenol **1A** with phenylcarbene complex **2C**, has been suggested to account for the formation of the observed products. Alkyne insertion affords vinylcarbene complex **3C**, which undergoes a rapid 1,2-acyl shift to afford the zwitterion **4C**, which undergoes internal proton transfer and reductive elimination to afford the observed product **5C**. The migration step is completely regioselective

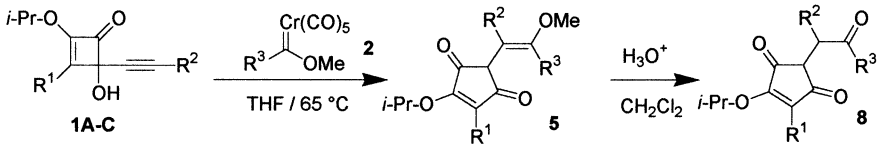
Table 1. Coupling of alkynylcyclobutenols **1A–D** with chromium–carbene complexes

Entry	Alkynol	Carbene Complex	Product(s)	Yield	E/Z	Alternate Products
A	 (**1A**)	 (**2A**)	 (**5A**)	72%	7:1	 (**14**)
B[a]	(**1A**)	 (**2B**)	 (**8A**)	20%		
C[a]	(**1A**)	 (**2C**)	 (**8C**)	72%		 (**10**)
D	(**1A**)	 (**2D**)	 (**5D**) +  (**9**)	39% 21%	7.8:1 2.5:1[b]	 (**11**)
E[a]	(**1A**)	 (**2E**)	 (**8E**)	66%		 (**12**)
F[a]	 (**1B**)	(**2A**)	 (**8F**)	58%	2.2:1[c]	
G[d]	 (**1C**)	(**2A**)	 (**5G**)	50%	4:1	 (**13**)
H[a]	 (**1D**)	(**2A**)	 (**8H**)	60%	1:1[c]	

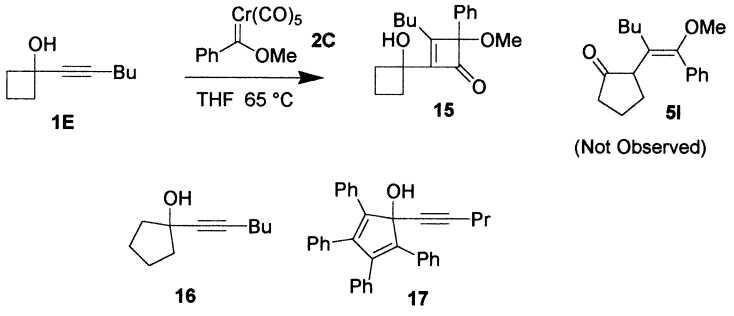
[a] In this case the crude enol ether was hydrolyzed to the ketone prior to final isolation.
[b] The identity of the major isomer could not be determined.
[c] Diastereomeric ratio.
[d] Attempted hydrolysis was unsuccesful.

resulting from migration of the acyl group and not the vinyl group.[19] Cyclobutenedione **25**, the expected product from this alternative reaction pathway, was not observed in the reaction mixture.

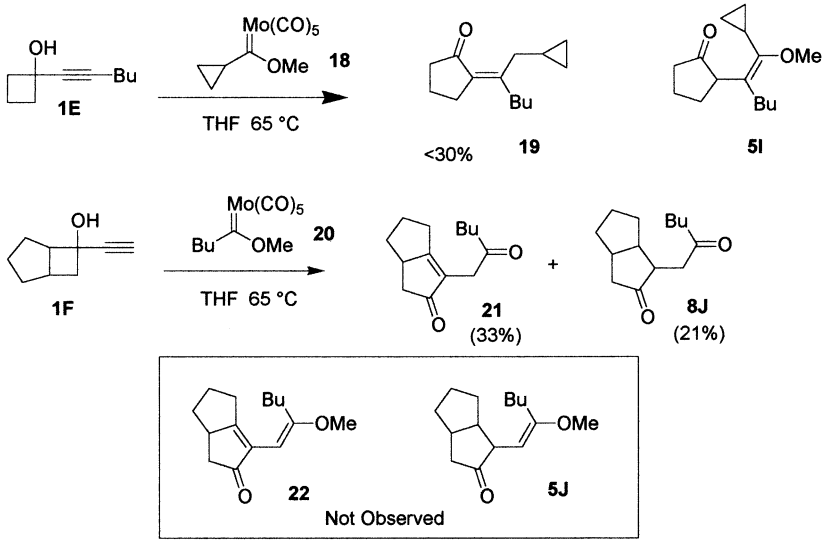
The examples in entries C–E are competitive processes in that a well-established reaction pathway has been demonstrated for the coupling of simple alkynes with these carbene complexes (**2C–E**).[13,14] Similarly an alternative reaction process has been demonstrated for the coupling of 1,6-diynes (e.g. **1C**, entry G of Table 1) with carbene complexes.[15] In the reaction depicted in Scheme 6, a hypothetical alternative product is the naphthalene derivative **10**, formed as a result of the Dötz benzannulation reaction (Scheme 7). In this coupling, the vinylcarbene complex intermediate formed as a result of alkyne insertion, **3C**, undergoes the ring expansion process in preference to the CO-insertion step (generating vinylketene complex **26**)



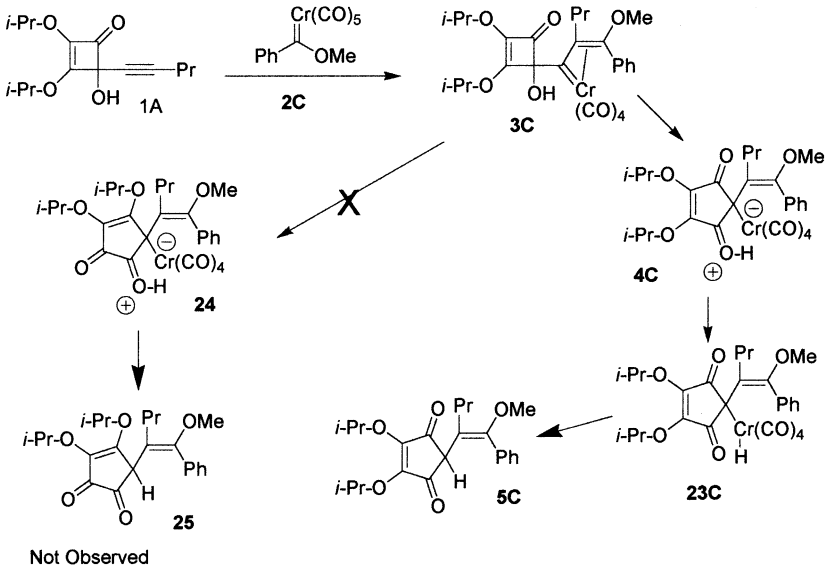
Scheme 3.



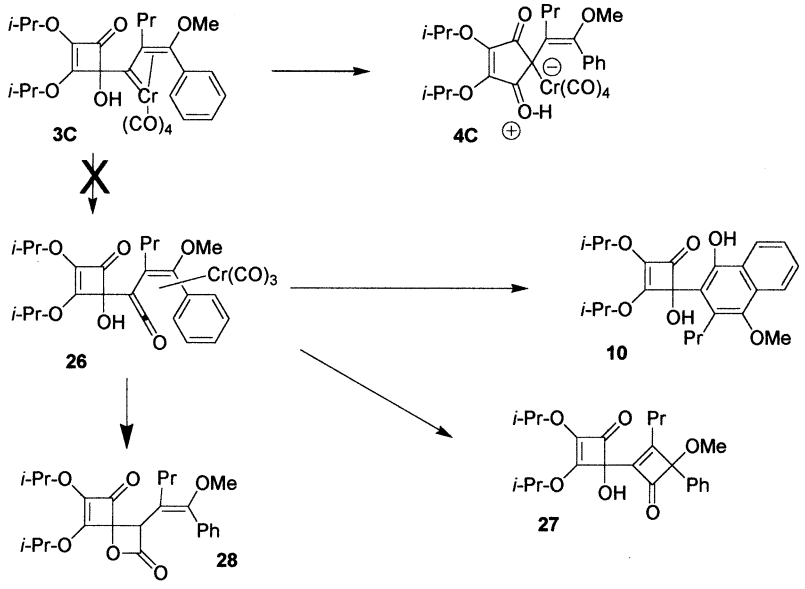
Scheme 4.



Scheme 5.



Scheme 6.

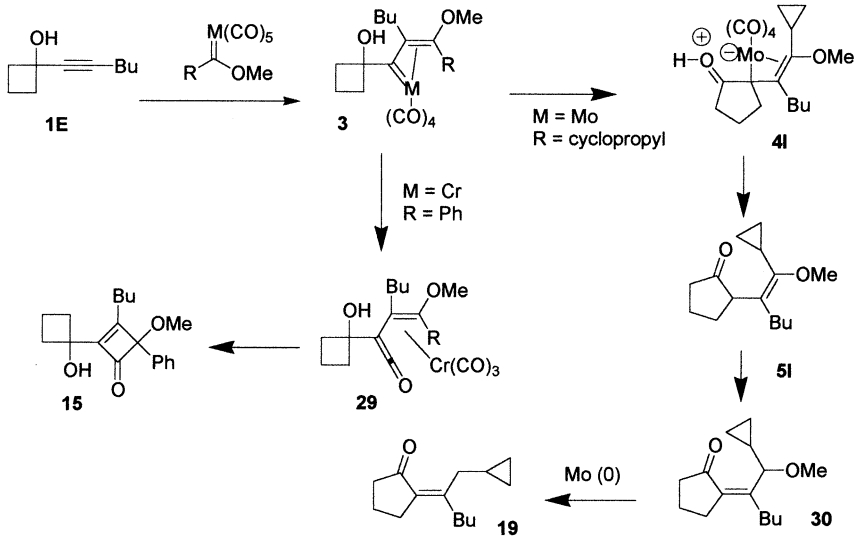


Scheme 7.

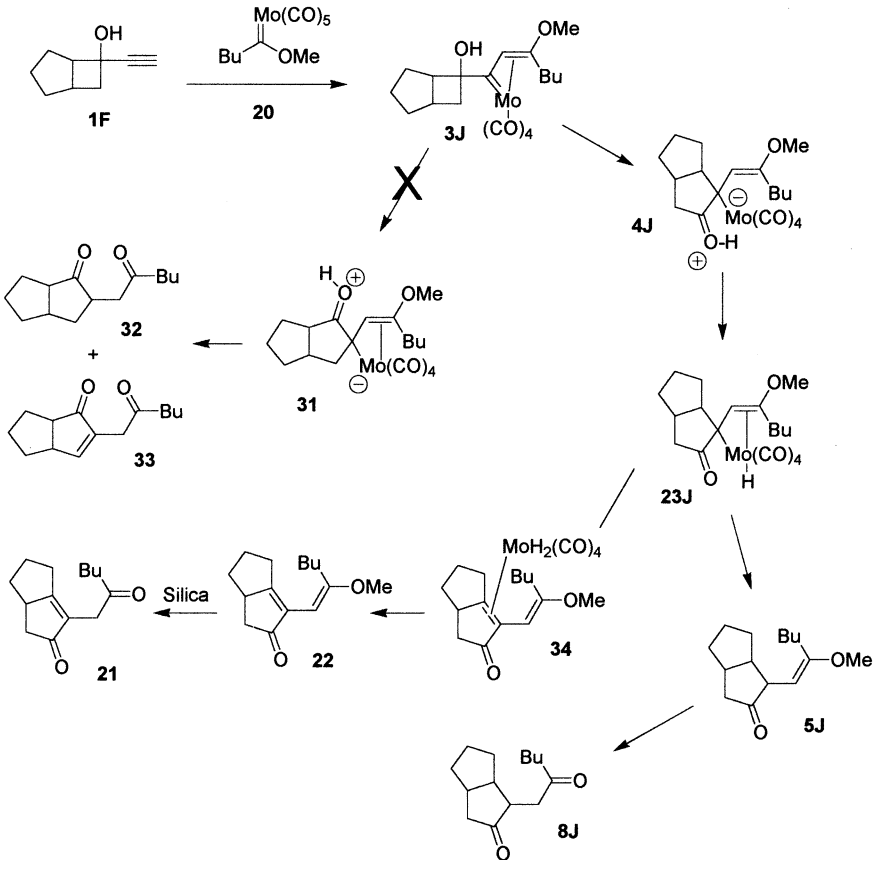
required for the Dötz reaction.[20] Vinylketene complex **26** is also required for the generation of cyclobutenones (e.g. **27**) and β-lactones (e.g. **28**), which have also been reported from the coupling of alkynes and α,β-unsaturated carbene complexes. Similarly, more favorable benzannulation processes involving stable alkenylcarbene complexes (entry D) and alkenylcarbene complexes generated in situ via the two-alkyne benzannulation processes (entry G) are not competitive with the ring expansion process. In these two entries, the competitive event is also CO-insertion vs. ring expansion after the alkyne insertion step. The cyclopentannulation product **12** (entry E) was not observed from the coupling of cyclopropylcarbene complex **2E** with alkynol **1A**; however, this process is anticipated to be less competitive than the Dötz reaction.[21]

The coupling of chromium–carbene complexes with alkynols in less-strained ring systems did not lead to ring-expanded products (Schemes 5 and 8). In the coupling of phenylcarbene complex **2C** with cyclobutanol derivative **1E**, the only observed product was the cyclobutenone derivative **15**. Either ring strain or the enhanced migratory aptitude of an acyl group is apparently a very important factor in the ring expansion process. Only the more reactive molybdenum–carbene complexes[18] (**18** and **20**) led to ring expansion products.

As noted in Schemes 5, 8 and 9, the anticipated enol ether derivatives (**5I** and **J**) were not obtained from the coupling of alkynols with molybdenum–carbene complexes. In all of these couplings, a highly complex reaction mixture was obtained from which only a few select compounds could be isolated in nearly pure form. Formation of **19** presumably arises through isomerization of **5I** to conjugated isomer **30**, which is then deoxygenated by low-valent molybdenum to afford **19** (Scheme 8).[22] A possible mechanism to account



Scheme 8.



Scheme 9.

for the formation of compounds **21** and **8J** is depicted in Scheme 9. Migration of the more substituted carbon[2] of the four-membered ring of vinylcarbene intermediate **3J** leads to zwitterion **4J**; migration of the other carbon leads to intermediate **31**. Diketone **8J** is presumably derived from inadvertent hydrolysis of the enol ether in anticipated product **5J**.[23] The analogous products from intermediate **31**, isomeric cyclopentanones **32** and **33**, were not observed. A possible mechanism to account for the formation of major product **21** is β-hydride elimination from intermediate **23J**,[24] followed by elimination of hydrogen and enol ether hydrolysis.

4. Summary and conclusions

In summary, the coupling of a variety of strained ring-substituted propargyl alcohols has been examined. Alkynols derived from cyclobutenediones couple with carbene complexes to provide ring-expanded products in a clean and high-yielding process. Other less strained analogues of these compounds undergo the ring expansion reaction with considerably greater difficulty. Only molybdenum–carbene complexes lead to ring expanded products when simple alkynylcyclobutanols are employed. Unfortunately, in these systems, the reaction mixtures are very complex and provide a variety of compounds derived from secondary processes occurring after the key ring expansion event.

5. Experimental

5.1. General considerations

Nuclear Magnetic Resonance (^{1}H and ^{13}C) spectra were recorded on a Bruker AF200 (200 MHz) or Bruker AF400 (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), m (multiplet). Infrared spectra were recorded on a Nicolet 5DXC FT-IR 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). Only diagnostic bands occurring outside the region 2800–3100 cm^{-1} are reported. Mass spectra (MS) were obtained on a VG 7070E spectrometer using electron impact (EI) or chemical ionization (CI) or on a Hewlett–Packard GC-Mass Spec 5970B with Mass Selection Detector; *m/e* values are reported, followed by the relative intensity in parentheses. Flash column chromatography was performed using thick-walled glass columns and 'flash grade' silica (Bodmann 230–400 mesh). Routine thin layer chromatography (TLC) was performed by using precoated 250 μm silica gel plates purchased from Whatman. Preparative thin layer chromatography (prep TLC) was performed by using precoated 1000 μm silica gel plates purchased

from Whatman. The relative proportion of solvents in mixed chromatography solvents refers to the volume : volume ratio. All 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, dichloromethane from calcium hydride prior to use. All reactions were performed in an inert atmosphere created by a slight positive pressure (ca. 0.1 psi) of nitrogen. Carbene complexes were prepared according to literature procedures.

5.2. General procedure 1—synthesis of alkynylcyclobutenol derivatives 1A–F

To a solution of alkyne (6 mmol) in THF (20 mL) at −78°C under nitrogen was added via syringe *n*-butyllithium (5.5 mmol) over a period of 15 min. The resulting solution was stirred at −78°C for 30 min, and transferred via cannula to a solution of cyclobutenedione (5 mmol) in THF (30 mL) at −78°C. The reaction mixture was stirred for 2 h, and then quenched by water (20 mL) at −78°C. The mixture was diluted with diethyl ether (40 mL), and the layers were separated. The aqueous layer was extracted with dichloromethane (2×25 mL). The combined organic layers were dried over sodium sulfate, 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 the eluent.

5.2.1. Alkynylcyclobutenol 1A. General procedure 1 was followed using 1-pentyne (0.600 mL, 6.00 mmol), *n*-butyllithium (2.75 mL of a 2.0 M pentane solution, 5.50 mmol) and diisopropyl squarate (**6A**) (0.990 g, 5.00 mmol). After chromatographic purification, a single fraction was isolated and assigned as compound **1A** (1.131 g, 85%).

^{1}H NMR ($CDCl_3$): δ 4.93 (septet, 1H, J=6.2 Hz), 4.76 (septet, 1H, J=6.2 Hz), 3.80 (s, 1H), 2.14 (t, 2H, J=7.2 Hz), 1.45 (sextet, 2H, J=7.2 Hz), 1.36 (d, 3H, J=6.2 Hz), 1.35 (d, 3H, J=6.2 Hz), 1.21 (d, 3H, J=6.2 Hz), 1.20 (d, 3H, J=6.2 Hz), 0.88 (t, 3H, J=7.2 Hz); ^{13}C NMR ($CDCl_3$): δ 181.4, 165.1, 133.4, 89.4, 78.4, 77.5, 75.0, 73.7, 22.5, 2.3, 21.6, 20.7, 13.3; IR ($CDCl_3$): 3581 (m), 3365 (m), 2248 (m), 2235 (m), 1776 (s), 1623 (vs) cm^{-1}; Mass Spec (EI): 266 (M, 25), 224 (21), 207 (6), 196 (7), 182 (100), 167 (20), 154 (43); HRMS: calcd for $C_{15}H_{22}O_4$ 266.1518, found 266.1529.

5.2.2. Alkynylcyclobutenol 1B. General procedure 1 was followed using 1-pentyne (0.600 mL, 6.00 mmol), *n*-butyllithium (2.75 mL of a 2.0 M pentane solution, 5.50 mmol) and 3-isopropoxy-4-methyl-3-cyclobutene-1,2-dione (**6B**)[12] (0.770 g, 5.00 mmol). After chromatographic purification, a single fraction was isolated and assigned as compound **1B** (0.977 g, 88%).

^{1}H NMR ($CDCl_3$): δ 5.04 (septet, 1H, J=6.2 Hz), 3.95 (s, 1H), 2.19 (t, 2H, J=7.3 Hz), 1.60 (s, 3H), 1.49 (sextet, 2H, J=7.3 Hz), 1.43 (d, 3H, J=6.2 Hz), 1.41 (d, 3H, J=6.2 Hz), 0.92 (t, 3H, J=7.3 Hz); ^{13}C NMR ($CDCl_3$): δ 188.0, 180.5, 124.0, 90.8, 83.1, 77.9, 74.9, 22.8, 22.6, 21.7, 20.8, 13.4, 6.3; IR ($CDCl_3$): 3588 (m), 3337 (m), 2248 (m), 2235 (m), 1767 (s), 1622 (vs) cm^{-1}; Mass Spec (EI): 222 (M, 19), 180 (100), 165 (35), 125 (29); HRMS: calcd for $C_{13}H_{18}O_3$ 222.1256, found 222.1257.

5.2.3. Alkynylcyclobutenol 1C. General procedure 1 was followed using 1,6-heptadiyne (0.507 g, 6.00 mmol), *n*-butyllithium (2.75 mL of a 2.0 M pentane solution, 5.50 mmol) and diisopropyl squarate (**6A**) (0.990 g, 5.00 mmol). After chromatographic purification, a single fraction was isolated and assigned as compound **1C** (1.077 g, 74%).

^{1}H NMR ($CDCl_3$): δ 4.90 (septet, 1H, J=6.2 Hz), 4.72 (septet, 1H, J=6.2 Hz), 4.23 (s, 1H), 2.28 (t, 2H, J=7.0 Hz), 2.18 (td, 2H, J=7.0, 2.6 Hz), 1.86 (t, 1H, J=2.6 Hz), 1.62 (quintet, 2H, J=7.0 Hz), 1.33 (d, 3H, J=6.2 Hz), 1.32 (d, 3H, J=6.2 Hz), 1.18 (d, 3H, J=6.2 Hz), 1.17 (d, 3H, J=6.2 Hz); ^{13}C NMR ($CDCl_3$): δ 181.5, 165.1, 133.2, 88.1, 83.2, 78.2, 77.7, 77.5, 73.7, 68.8, 27.0, 22.4, 22.3, 17.7, 17.3; IR ($CDCl_3$): 3581 (m), 3308 (s), 2248 (m), 2235 (m), 1776 (s), 1622 (vs) cm^{-1}; Mass Spec (CI): 291 (M+1, 24), 273 (10), 231 (17), 207 (22), 206 (100); HRMS: calcd for $C_{17}H_{23}O_4$ 291.1596, found 291.1585.

5.2.4. Alkynylcyclobutenol 1D. General procedure 1 was followed using 1,6-heptadiyne (0.254 g, 2.75 mmol), *n*-butyllithium (2.75 mL of a 2.0 M pentane solution, 5.50 mmol) and diisopropyl squarate (**6A**) (0.990 g, 5.00 mmol). After chromatographic purification, a single fraction was isolated and assigned as compound **1D** (inseparable mixture of diastereomers, 0.855 g, 70%).

^{1}H NMR ($CDCl_3$): δ 5.18 (s, 1H), 4.97 and 4.93 (two septets, total of 2H, J=6.2 Hz), 4.79 and 4.77 (two septets, total of 2H, J=6.2 Hz), 3.85 (s, 1H), 2.34 and 2.32 (two triplets, total of 4H, J=6.6 Hz), 1.68 (quintet, 2H, J=6.6 Hz), 1.39 and 1.38 (two doublets, total of 12H, J=6.2 Hz) 1.24 and 1.23 (two doublets, total of 12H, J=6.2 Hz); ^{13}C NMR ($CDCl_3$): δ 182.4, 181.1, 165.3, 164.7, 133.7, 133.2, 88.5, 78.6, 78.1, 77.9, 75.8, 74.0, 26.7, 26.0, 22.6, 22.5, 18.7, 18.2; IR ($CDCl_3$): 3581 (m), 3326 (m), 2280 (w), 2249 (m), 2235 (m), 1777 (s), 1622 (vs) cm^{-1}; Mass Spec (EI): 488 (M, 4), 404 (8), 362 (22), 320 (100), 302 (38), 274 (46); HRMS: calcd for $C_{27}H_{36}O_8$ 488.2410, found 488.2456.

5.2.5. Alkynylcyclobutanol 1E. General procedure 1 was followed using 1-hexyne (1.000 mL, 9.60 mmol), *n*-butyllithium (4.8 mL of a 2.0 M pentane solution, 9.6 mmol) and cyclobutanone (0.721 g, 10.00 mmol). Pentane was used as the extraction solvent. Excessive product loss occurred during rotary evaporation and chromatographic purification processes. The solvent was removed by careful distillation at room temperature using a Vigreux column until the solvent had been removed (1.255 g, 73%). Attempts to further purify the product led to significant material loss.

^{1}H NMR ($CDCl_3$): δ 2.45–2.15 (m, 4H) overlapping with 2.38 (brs, 1H, exchanges with D_2O) and 2.19 (t, 2H, J=6.9 Hz), 1.82–1.65 (m, 2H), 1.45–1.25 (m, 4H), 0.87 (t, 3H, J=6.9 Hz); ^{13}C NMR ($CDCl_3$): δ 83.9, 68.0, 38.7, 30.7, 21.9, 18.3, 13.5, 12.8 (one C is missing; however, in related compounds this C appears very close to the

3-line pattern for $CDCl_3$); IR (neat): 3596 (m), 2248 (m) cm^{-1}.

5.2.6. Alkynylcyclobutanol 1F. General procedure 1 was followed using trimethylsilylacetylene (1.410 mL, 10.00 mmol), *n*-butyllithium (4.80 mL of a 2.0 M pentane solution, 9.60 mmol) and bicyclo[3.2.0]heptan-6-one (**7**) (1.058 g, 9.60 mmol).[25] The crude reaction mixture from general procedure 1 was dissolved in methanol (40 mL) and potassium carbonate (2.76 g, 20 mmol) was added. The mixture was stirred at 0°C for 2 h and the resultant desilylated alkyne was poured into 1% aqueous hydrochloric acid (20 mL). The layers were separated, and the aqueous layer was extracted with *n*-pentane (3×10 mL). The combined organic extracts were washed with saturated sodium bicarbonate (10 mL) and dried over sodium sulfate. The solvent was removed by careful distillation at room temperature using a Vigreux column until the vast majority of solvent had been removed (0.656 g, 50%, about 5% pentane). Attempts to further purify the product led to significant material loss.

^{1}H NMR ($CDCl_3$): δ 2.96 (m, 1H), 2.62 (m, 2H), 2.54 (s, 1H), 2.00 (dt, 1H, J=13.6, 5.4 Hz), 1.88 (brs, 1H), 1.82–1.68 (m, 3H), 1.52–1.38 (m, 3H); IR (neat): 3550 (m), 3296 (m), 2105 (m) cm^{-1}.

5.3. General procedure 2—coupling of carbene complexes with alkynols

A solution of alkynol (1.00 mmol) and carbene complex (1.20 mmol) in THF (10 mL) was heated at reflux under nitrogen for a 4 h period. The mixture was cooled to room temperature, and the solvent was removed on a rotary evaporator. The residue was dissolved in 9:1 hexane/ethyl acetate (50 mL), and the solution was filtered through Celite. Solvent was removed on a rotary evaporator to provide the crude enol ether. If isolation of the enol ether is desired, final purification is achieved by Flash Chromatography on silica gel using 9:1 hexane/ethyl acetate followed by 9:1 hexane/ethyl acetate as the eluent. Alternatively, if the ketone is desired the crude product is subjected to hydrolysis according to general procedure 3 (below).

5.4. General procedure 3—enol ether hydrolysis procedure

A mixture of alkene stereoisomers (0.50 mmol) was dissolved in dichloromethane (25 mL) and concentrated aqueous hydrochloric acid (5 drops, ca 0.25 mL) was added. The reaction mixture was stirred at room temperature until all the starting material had been consumed as diagnosed by TLC analysis. Water (10 mL) was added, and the mixture was extracted with dichloromethane. After drying the combined organic layers over sodium sulfate, the solvent was removed on a rotary evaporator. Final purification was achieved by Flash Chromatography on silica gel using 19:1 hexane/ethyl acetate followed by 9:1 hexane/ethyl acetate as the eluent.

5.4.1. Reaction of methylcarbene complex 2A with alkynylcyclobutenol 1A; Table 1, entry A. General procedure 2 was followed using alkynol **1A** (0.266 g, 1.00 mmol) and carbene complex **2A**[26] (0.300 g, 1.20 mmol). After chromatographic purification, two fractions were isolated. The product in the first fraction was assigned as the minor alkene isomer (*Z*) of **5A** (0.029 g, 9%). The product in the second fraction was identified as the major alkene isomer (*E*) of **5A** (0.205 g, 63%).

Minor (*Z*) isomer: ^{1}H NMR ($CDCl_3$): δ 5.34 (septet, 2H, J=6.1 Hz), 3.36 (s, 1H), 3.27 (s, 3H), 1.91 (t, 2H, J=7.5 Hz), 1.75 (s, 3H), 1.29 (sextet, 2H, J=7.5 Hz), 1.27 (d, 6H, J=6.1 Hz), 1.26 (d, 6H, J=6.1 Hz), 0.83 (t, 3H, J=7.5 Hz); ^{13}C NMR ($CDCl_3$): δ 195.6, 150.2, 149.5, 111.9, 73.9, 55.2, 53.2, 33.9, 2.9, 21.7, 13.7, 12.7; IR (CH_2Cl_2): 1686 (s), 1618 (m) cm^{-1}; Mass Spec (EI): 324 (M, 94), 282 (100), 253 (22), 240 (52), 211 (82); HRMS: calcd for $C_{18}H_{28}O_5$ 324.1937, found 324.1942.

Major (*E*) isomer: ^{1}H NMR ($CDCl_3$): δ 5.38 (septet, 2H, J=6.1 Hz), 3.52 (s, 1H), 3.47 (s, 3H), 1.83 (t, 2H, J=7.5 Hz), 1.82 (s, 3H), 1.28 (d, 6H, J=6.1 Hz), 1.27 (d, 6H, J=6.1 Hz), 1.11 (sextet, 2H, J=7.5 Hz), 0.73 (t, 3H, J=7.5 Hz); ^{13}C NMR ($CDCl_3$): δ 194.7, 152.7, 150.9, 111.4, 74.3, 55.8, 53.5, 29.3, 22.8, 22.6, 14.2, 13.4; IR (CH_2Cl_2): 1687 (s), 1612 (m) cm^{-1}; Mass Spec (EI): 324 (M, 100), 282 (72), 253 (16), 240 (29), 211 (61); HRMS: calcd for $C_{18}H_{28}O_5$ 324.1937, found 324.1937.

5.4.2. Triketone 8A. General procedure 3 was followed using both stereoisomers of cyclopentenedione **5A** (0.162 g, 0.50 mmol) and concentrated aqueous hydrochloric acid (5 drops, ~0.25 mL). After chromatographic purification, a single fraction was isolated and assigned as triketone **8A** (0.147 g, 95%).

^{1}H NMR ($CDCl_3$): δ 5.39 (septet, 1H, J=6.1 Hz), 5.28 (septet, 1H, J=6.1 Hz), 3.07 (m, 1H), 2.83 (d, 1H, J=4.1 Hz), 2.08 (s, 3H), 1.80 (m, 1H), 1.72 (m, 1H), 1.41 (m, 1H), 1.32 (m, 1H), 1.30 (d, 3H, J=6.1 Hz), 1.29 (d, 3H, J=6.1 Hz), 1.26 (d, 6H, J=6.1 Hz), 0.89 (t, 3H, J=7.3 Hz); ^{13}C NMR ($CDCl_3$): δ 208.8, 194.5, 194.3, 150.7, 150.7, 74.3, 74.1, 51.2, 48.4, 30.4, 28.5, 22.9, 22.8, 21.1, 13.8; IR ($CDCl_3$): 1709 (m), 1686 (s), 1616 (m) cm^{-1}; Mass Spec (EI): 310 (M, 7), 268 (13), 226 (33), 184 (60), 183 (100); HRMS: calcd for $C_{17}H_{26}O_5$ 310.1780, found 310.1759.

5.4.3. Reaction of aminocarbene complex 2B with alkynylcyclobutenol 1A; Table 1, entry B. General procedure 2 was followed using alkynol **1A** (0.266 g, 1.00 mmol) and carbene complex **2B**[27] (0.316 g, 1.20 mmol). The crude reaction mixture was then hydrolyzed according to general procedure 3. After chromatographic purification, a single fraction was isolated and assigned as triketone **8A** (0.063 g, 20%).

5.4.4. Reaction of phenylcarbene complex 2c with alkynylcyclobutenol 1A; Table 1, entry C. General procedure 2 was followed using alkynol **1A** (0.266 g, 1.00 mmol) and carbene complex **2C**[26] (0.375 g, 1.20 mmol). The crude reaction mixture was then hydrolyzed according to general procedure 3. After chromatographic purification, a single fraction was isolated and assigned as triketone **8C** (0.268 g, 72%).

^{1}H NMR ($CDCl_3$): δ 7.80 (d, 2H, J=7.5 Hz), 7.47 (t, 1H, J=7.5 Hz), 7.36 (t, H, J=7.5 Hz), 5.45 (septet, 1H, J=6.2 Hz), 5.23 (septet, 1H, J=6.2 Hz), 4.00 (m, 1H), 2.94 (d, 1H, J=4.1 Hz), 1.89 (m, 1H), 1.77 (m, 1H), 1.43 (m, 1H), 1.35 (m, 1H) 1.34 (d, 3H, J=6.2 Hz), 1.31 (d, 3H, J=6.2 Hz), 1.20 (d, 3H, J=6.2 Hz), 1.18 (d, 3H, J=6.2 Hz), 0.86 (t, 3H, J=7.3 Hz); ^{13}C NMR ($CDCl_3$): δ 200.9, 194.4, 194.1, 151.3, 150.1, 136.1, 133.1, 128.6, 128.4, 74.4, 74.0, 48.5, 46.0, 31.5, 22.9, 22.7, 21.0, 13.8; IR ($CDCl_3$): 1686 (vs), 1614 (s) cm^{-1}; Mass Spec (EI): 372 (M, 30), 330 (32), 289 (12), 288 (53), 183 (100); HRMS: calcd for $C_{22}H_{28}O_5$ 372.1937, found 372.1937.

5.4.5. Reaction of propenylcarbene complex 2D with alkynylcyclobutenol 1A; Table 1, entry D. General procedure 2 was followed using alkynol **1A** (0.266 g, 1.00 mmol) and carbene complex **2D**[28] (0.332 g, 1.20 mmol). After chromatographic purification, two fractions were isolated. The product in the first fraction was assigned as alkene-isomerized compound **9** (0.074 g, 21%, 2.5:1 mixture of *E* and *Z* isomers). The product in the second fraction was identified as the unisomerized alkene **5D** (0.137 g, 39%, 2.8:1 mixture of *E* and *Z* isomers).

5.4.6. Unisomerized diene 5D. ^{1}H NMR ($CDCl_3$): major isomer: δ 3.78 (s, 1H), 3.51 (s, 3H), 1.95 (t, 2H, J=7.3 Hz), 0.79 (t, 3H, J=7.3 Hz); minor isomer: δ 3.68 (s, 1H, 3.38 (s, 3H), 1.99 (t, 2H, J=7.3 Hz), 0.86 (t, 3H, J=7.3 Hz); the following peaks are overlapping in both isomers: δ 6.08–5.80 (m, 2H), 5.43 (septet, 2H, J=6.2 Hz), 1.80–1.75 (m, 3H), 1.32 (d, 12H, J=6.2 Hz); ^{13}C NMR ($CDCl_3$): δ 194.7, 194.3, 155.4, 153.0, 150.9, 150.2, 130.4, 128.5, 122.3, 121.5, 117.7, 116.1, 74.4, 74.1, 59.3, 58.9, 53.4, 53.0, 32.7, 30.0, 22.9, 22.7, 22.1, 18.2, 14.3, 13.9; IR (CCl_4): 1690 (s), 1613 (s) cm^{-1}; Mass Spec (EI): 350 (M, 100), 335 (11), 308 (29), 293 (21), 279 (21), 265 (30), 251 (42), 237 (67); HRMS: calcd for $C_{20}H_{30}O_5$ 350.2093, found 350.2109.

5.4.7. Isomerized diene 9. ^{1}H NMR ($CDCl_3$): major isomer: δ 5.43 (septet, 2H, J=6.1 Hz), 4.76 (t, 1H, J=7.4 Hz), 3.43 (s, 3H), 2.75 (t, 2H, J=7.5 Hz), 2.19 (m, 2H), 1.33 (d, 6H, J=6.1 Hz), 1.32 (d, 6H, J=6.1 Hz), 0.97 (t, 3H, J=7.5 Hz); minor isomer: δ 5.47 (septet, 1H, J=6.1 Hz), 5.39 (septet, 1H, J=6.1 Hz), 4.61 (t, 1H, J=7.6 Hz), 3.58 (s, 3H), 2.80 (m, 2H), 1.80 (m, 2H), 1.29 (d, 6H, J=6.1 Hz), 0.93 (t, 3H, J=7.5 Hz), 0.90 (t, 3H, J=7.5 Hz); the following peaks are overlapping in both isomers: δ 1.47 (sextet, 2H, J=7.5 Hz), 1.33 (d, 6H, J=6.1 Hz); ^{13}C NMR ($CDCl_3$): δ 187.4, 187.2, 185.1, 185.6, 154.8, 151.4, 151.3, 150.5, 149.3, 149.2, 149.1, 148.7, 125.2, 119.2, 102.3, 74.4, 74.3, 57.7, 55.1, 34.1, 32.4, 22.9, 22.2, 21.5, 20.6, 18.5, 15.0, 14.3, 14.1, 13.8; IR (CCl_4): 1680 (s), 1633 (s), 1606 (s) cm^{-1}; Mass Spec (EI): 350 (M, 45), 308 (85), 293 (15), 279 (22), 266 (82), 265 (62), 251 (58), 237 (100); HRMS: calcd for $C_{20}H_{30}O_5$ 350.2093, found 350.2103.

5.4.8. Reaction of cyclopropylcarbene complex 2E with alkynylcyclobutenol 1A; Table 1, entry E. General procedure 2 was followed using alkynol **1A** (0.266 g, 1.00 mmol) and carbene complex **2E**[14] (0.332 g, 1.20 mmol). The crude reaction mixture was then hydrolyzed according to general procedure 3. After chromatographic purification, a single fraction was isolated and assigned as triketone **8E** (0.222 g, 66%).

^{1}H NMR ($CDCl_3$): δ 5.43 (septet, 1H, J=6.1 Hz), 5.31 (septet, 1H, J=6.1 Hz), 3.30 (m, 1H), 2.86 (d, 1H, J=4.0 Hz), 1.89 (m, 1H), 1.89 (m, 3H), 1.47 (m, 1H), 1.39 (m, 1H) 1.33 (d, 3H, J=6.1 Hz), 1.32 (d, 3H, J=6.1 Hz), 1.28 (d, 3H, J=6.1 Hz), 1.27 (d, 3H, J=6.1 Hz), 0.95 (t, 3H, J=7.3 Hz), 0.93 (m, 2H), 0.84 (m, 2H); ^{13}C NMR ($CDCl_3$): δ 210.1, 194.4, 194.1, 151.0, 150.0, 74.3, 74.0, 51.4, 48.6, 30.6, 22.9, 22.7, 21.1, 19.6, 13.8, 11.2; IR (CCl_4): 1691 (vs), 1619 (s) cm^{-1}; Mass Spec (EI): 336 (M, 15), 294 (19), 252 (61), 225 (11), 209 (14), 184 (27), 183 (100); HRMS: calcd for $C_{19}H_{28}O_5$ 336.1937, found 336.1924.

5.4.9. Reaction of methylcarbene complex 2A with alkynylcyclobutenol 1B; Table 1, entry F. General procedure 2 was followed using alkynol **1B** (0.222 g, 1.00 mmol) and carbene complex **2A** (0.300 g, 1.20 mmol). The crude reaction mixture was then hydrolyzed according to general procedure 3. After chromatographic purification, a single fraction was isolated and assigned as triketone **8F** (0.155 g, 58%, inseparable 2.2:1 mixture of diastereomers).

^{1}H NMR ($CDCl_3$): major isomer: δ 5.56 (septet, 2H, J=6.1 Hz), 3.21 (ddd, 1H, J=9.5, 5.5, 4.0 Hz), 2.75 (d, 1H, J=4.0 Hz), 2.09 (s, 3H), 1.81 (s, 3H), 1.33 (d, 3H, J=6.1 Hz), 1.31 (d, 3H, J=6.1 Hz), 0.94 (t, 3H, J=7.5 Hz); minor isomer: δ 5.43 (septet, 1H, J=6.1 Hz), 3.04 (ddd, 1H, J=8.8, 6.2, 4.1 Hz), 2.87 (d, 1H, J=4.1 Hz), 2.11 (s, 3H), 1.87 (s, 3H), 1.29 (d, 6H, J=6.1 Hz), 0.90 (t, 3H, J=7.5 Hz); the following peaks are overlapping in both isomers: δ 1.90–1.62 (m, 2H), 1.55–1.25 (m, 2H); ^{13}C NMR ($CDCl_3$): δ 209.1, 208.6, 199.0, 198.5, 197.6, 197.2, 165.9, 164.8, 136.9, 135.5, 74.3, 74.1, 51.8, 51.3, 49.3, 48.9, 30.5, 30.1, 28.4, 28.2, 23.2, 23.1, 21.1, 21.0, 13.8, 7.0, 6.8; IR (CCl_4): 1713 (s), 1688 (s), 1623 (s) cm^{-1}; Mass Spec (EI): 266 (M, 21), 224 (24), 182 (100), 181 (51), 168 (23), 153 (75); HRMS: calcd for $C_{15}H_{22}O_4$ 266.1518, found 266.1516.

5.4.10. Reaction of methylcarbene complex 2A with dialkynylcyclobutenol 1C; Table 1, entry G. General procedure 2 was followed using alkynol **1C** (0.291 g, 1.00 mmol) and carbene complex **2A** (0.300 g, 1.20 mmol). After chromatographic purification, two fractions were isolated. The product in the first fraction was assigned as the major alkene isomer (*E*) of **5G** (0.140 g, 40%). The product in the second fraction was identified as the minor alkene isomer (*Z*) of **5G** (0.035 g, 10%).

Major (*E*) alkene isomer: ^{1}H NMR ($CDCl_3$): δ 5.41 (septet, 2H, J=6.1 Hz), 5.11 (s, 1H), 3.81 (s, 1H), 3.52 (s, 3H), 2.52 (t, 2H, J=7.2 Hz), 2.11 (t, 2H, J=7.2 Hz), 1.88 (s, 3H), 1.81 (quintet, 2H, J=7.2 Hz), 1.32 (d, 6H, J=6.1 Hz), 1.30 (d, 6H, J=6.1 Hz), 0.83; ^{13}C NMR ($CDCl_3$): δ 194.2, 156.6, 151.0, 140.2, 127.6, 93.9, 74.4, 54.5, 51.7, 37.1, 32.2, 22.9, 22.1, 18.2; IR (CH_2Cl_2): 1686 (s), 1613 (s) cm^{-1}; Mass Spec (EI): 348 (M, 2), 292 (12), 250 (24), 208 (32), 207 (42), 192 (38), 74 (100); HRMS: calcd for $C_{20}H_{28}O_5$ 348.1937, found 348.1923.

Minor (*Z*) alkene isomer: ^{1}H NMR ($CDCl_3$): δ 5.42 (septet,

2H, J=6.1 Hz), 5.17 (s, 1H), 3.84 (s, 1H), 3.54 (s, 3H), 2.72 (t, 2H, J=7.2 Hz), 2.05 (t, 2H, J=7.2 Hz), 1.89 (s, 3H), 1.75 (quintet, 2H, J=7.2 Hz), 1.32 (d, 6H, J=6.1 Hz), 1.31 (d, 6H, J=6.1 Hz), 0.83; IR (CH_2Cl_2): 1683 (s), 1609 (s) cm^{-1}; Mass Spec (EI): 348 (M, 1), 292 (13), 250 (29), 223 (19), 208 (41), 207 (57), 192 (56), 89(100); HRMS: calcd for $C_{20}H_{28}O_5$ 348.1937, found 348.1917.

5.4.11. Reaction of methylcarbene complex 2A with dialkynyldicyclobutenol 1D; Table 1, entry H. General procedure 2 was followed using alkynol **1D** (0.244 g, 0.50 mmol) and carbene complex **2A** (0.300 g, 1.20 mmol). The crude reaction mixture was then hydrolyzed according to general procedure 3. After chromatographic purification, a single fraction was isolated and assigned as hexaketone **8H** (0.173 g, 60%, inseparable 1:1 mixture of diastereomers).

^{1}H NMR ($CDCl_3$): δ 5.41 and 5.40 (two septets, total of 2H, J=6.1 Hz), 5.32 (septet, 2H, J=6.1 Hz), 3.08 (m, 2H), 2.90 and 2.89 (two doublets, total of 2H, J=3.0 Hz), 2.13 and 2.12 (two singlets, total of 6H), 1.95–1.75 (m, 4H), 1.50 (m, 2H), 1.41 (m, 1H), 1.33 and 1.32 (two doublets, total of 12H, J=6.1 Hz), 1.29 (d, 12H, J=6.1 Hz), 1.26 (d, 6H, J=6.1 Hz), 0.89 (t, 3H, J=7.3 Hz); ^{13}C NMR ($CDCl_3$): δ 208.3, 208.2, 194.3, 194.1, 193.9, 150.7, 150.2, 150.1, 74.4, 74.2, 74.1, 51.0, 50.9, 48.6, 48.1, 28.5, 28.5, 28.0, 26.0, 25.9, 22.9, 22.8; IR ($CDCl_3$): 1710 (s), 1684 (s), 1615 (s) cm^{-1}; Mass Spec (EI): 534 (18), 492 (19), 450 (28), 449 (16), 421 (14), 408 (28), 407 (28), 347 (100); HRMS: calcd for $C_{31}H_{44}O_{10}$ 576.2934, found 576.2932.

5.4.12. Reaction of cyclopropylcarbene–molybdenum complex 18 with alkynylcyclobutanol 1E. General procedure 2 was followed using alkynol **1E** (0.120 g, 1.00 mmol) and carbene complex **18**[29] (0.324 g, 1.00 mmol). After chromatographic purification using 19:1 hexane/ethyl acetate as eluent, the major component was isolated and determined to be alkylidenecyclopentenone **19** (0.072 g, 35% yield) of about 90% purity. Further purification by TLC using 19:1 hexane/ethyl acetate and cutting only the center of the major band afforded a pure sample of **19**.

^{1}H NMR ($CDCl_3$): δ 2.65 (d, 2H, J=6.3 Hz), 2.61 (t, 2H, J=7.6 Hz), 2.29 (t, H, J=7.6 Hz), 2.20 (t, 2H, J=6.6 Hz), 1.84 (quintet, 2H, J=7.6 Hz), 1.39 (m, 2H), 1.36 (sextet, 2H, J=7.2 Hz), 0.92 (t, 3H, J=7.2 Hz), 0.79 (m, 1H), 0.39 (m, 2H), 0.15 (m, 2H); Irradiate at δ 2.63: δ 1.84 (t), 0.79 (pattern altered); Irradiate at δ 2.29: δ 1.84 (t); Irradiate at δ 2.20: δ 1.39 (pattern altered); Irradiate at δ 1.84: δ 2.61 (s), 2.29 (s); Irradiate at δ 1.38: δ 2.20 (brs), 0.92 (brs); Irradiate at δ 0.79: δ 2.65 (s), 0.39 (pattern altered), 0.15 (pattern altered); ^{13}C NMR ($CDCl_3$): δ 207.9, 155.6, 130.6, 40.7, 35.5, 34.5, 29.5, 29.2, 23.1, 19.5, 13.9, 10.3, 4.4; IR ($CDCl_3$): 1706 (s), 1621 (s) cm^{-1}; Mass Spec (EI): 206 (M, 10), 177 (71), 149 (100), 135 (16); HRMS: calcd for $C_{14}H_{22}O$ 206.1670, found 206.1668.

5.4.13. Reaction of butylcarbene–molybdenum complex 20 with alkynylcyclobutanol 1F. General procedure 2 was followed using crude alkynol **1F** (0.170 g, 1.25 mmol) and carbene complex **20**[30] (0.340 g, 1.00 mmol). After chromatographic purification using 19:1 hexane/ethyl acetate as eluent, the major fraction was isolated and determined to be a mixture of alkylidenecyclopentenones **20** and **8J**. Further purification by TLC using 19:1 hexane/ethyl acetate afforded two bands, identified as diketones **21** (0.073 g, 33%) and **8J** (0.047 g, 21%).

21: ^{1}H NMR ($CDCl_3$): δ 3.37 (d, 1H, J=15.1 Hz), 3.11 (d, 1H, J=15.1 Hz), 2.82 (dddd, 1H, J=10.8, 7.2, 6.0, 3.3 Hz), 2.61 (dd, 1H, J=16.4, 6.0 Hz), 2.55 (m, 1H), 2.43 (t, 2H, J=7.2 Hz), 2.40 m, 1H), 2.14 (m, 1H), 2.05 (dd, 1H, J=16.4, 3.3 Hz), 2.00 (m, 2H), 1.52 (quintet, 2H, J=7.2 Hz), 1.38 (sextet, 2H, J=7.2 Hz), 1.09 (qd, 1H, J=10.8, 7.2 Hz), 0.88 (t, 3H, J=7.2 Hz); Irradiate at δ 2.82: δ 2.61 (d, J=16.4 Hz), 2.05 (d, J=16.4 Hz), 2.00 (pattern altered), 1.09 (td, J=10.8, 7.2 Hz); ^{13}C NMR ($CDCl_3$): δ 209.4, 206.9, 187.6, 129.4, 45.0, 42.4, 41.4, 37.6, 31.2, 25.8, 25.6, 25.5, 22.3, 13.8; IR ($CDCl_3$): 1707 (vs), 1664 (s) cm^{-1}; Mass Spec (EI): 220 (26), 178 (8), 137 (34), 136 (100), 129 (10), 108 (16); HRMS: calcd for $C_{14}H_{20}O_2$ 220.1463, found 220.1479.

8J: ^{1}H NMR ($CDCl_3$): δ 2.79 (dd, 1H, J=16.8, 4.2 Hz), 2.63–2.52 (m, 3H), 2.40 (t, 2H, J=7.2 Hz), 2.35–2.10 (m, 2H), 1.95–1.57 (m, 5H), 1.53 (quintet, 2H, J=7.2 Hz), 1.45 (m, 2H), 1.40 (sextet, 2H, J=7.2 Hz), 0.88 (t, 3H, J=7.2 Hz); ^{13}C NMR ($CDCl_3$): δ 220.8, 209.1, 49.8, 46.2, 43.9, 42.7, 42.6, 37.8, 33.6, 32.4, 25.9, 25.6, 22.3, 13.8; IR ($CDCl_3$): 1737, 1714 cm^{-1}; Mass Spec (EI): 222 (M, 6), 180 (38), 165 (32), 137 (52), 123 (100); HRMS: calcd for $C_{14}H_{22}O_2$ 222.1620, found 222.1612.

Acknowledgements

We thank the Petroleum Research Fund, administered by the American Chemical Society, and the National Science Foundation REU program at the University of Maryland for financial support of this research.

References

1. Hesse, M. *Ring Enlargements in Organic Chemistry*; VCH Verlagagesellschaft: Weinheim, Germany, 1991.
2. Coveney, D. J. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Pattenden, G., Eds.; Pergamon: Oxford, 1991; Vol. 3, pp. 777–801.
3. Ohno, M.; Noda, M.; Yamamoto, Y.; Eguchi, S. *J. Org. Chem.* **1999**, *64*, 707–712.
4. (a) Nemoto, H.; Yoshida, M.; Fukumoto, K. *J. Org. Chem.* **1997**, *62*, 6450–6451. (b) Ismail, M. A.-H.; Nemoto, H.; Ihara, M. *J. Chem. Soc., Perkin Trans. 1* **2000**, 2629–2635.
5. Liebeskind, L. S.; Bombrun, A. *J. Org. Chem.* **1994**, *59*, 1149–1159.
6. For a preliminary account of this work, see: Zora, M.; Herndon, J. W. *J. Org. Chem.* **1994**, *59*, 699–701.
7. Recent general reviews: (a) Herndon, J. W. Applications of carbene complexes directed toward organic synthesis. *Coord. Chem. Rev.* **2000**, 206–207, 237–262. (b) Dorwald, F. Z. *Metal Carbenes in Organic Synthesis*; Wiley–VCH: Weinheim, 1999. (c) Hegedus, L. S. In *Transition Metals in*

the Synthesis of Complex Organic Molecules, 2nd ed., University Science Books: Sausalito, CA, 1999; pp. 143–186.
8. For the most recent paper focusing on this process, see: Barluenga, J.; Lopez, S.; Trabanco, A. A.; Fernandez-Acebes, A.; Florez, J. *J. Am. Chem. Soc.* **2000**, *122*, 8145–8154.
9. (a) Söderberg, B. C.; Liu, J.; Ball, T. W.; Turbeville, M. J. *J. Org. Chem.* **1997**, *62*, 5945–5952. (b) Harvey, D. F.; Neil, D. A. *Tetrahedron* **1993**, *49*, 2145–2150. (c) Barluenga, J.; Ballesteros, A.; Santamaría, J.; Bernardo de la Rúa, R.; Rubio, E.; Tomás, M. *J. Am. Chem. Soc.* **2000**, *112*, 12874–12875. (d) Wulff, W. D.; Bauta, W. E.; Kaesler, R. W.; Lankford, P. J.; Miller, R. A.; Murray, C. K.; Yang, D. C. *J. Am. Chem. Soc.* **1990**, *112*, 3642–3659. (e) Fischer, E. O.; Plabst, D. *Chem. Ber.* **1974**, *107*, 3326–3321. (f) Macomber, D. W. *Organometallics* **1984**, *3*, 1589–1591.
10. We are not aware of an example of this process for heteroatom-stabilized Fischer-carbene complexes other than the examples in this manuscript and Ref. 6. Nonheteroatom-stabilized complexes undergo this process: Bly, R. S.; Bly, R. K.; Hossain, M. M.; Lebioda, L.; Raja, M. *J. Am. Chem. Soc.* **1988**, *110*, 7723–7730.
11. (a) Macomber, D. W.; Madhukar, P.; Rogers, R. D. *Organometallics* **1991**, *10*, 2121–2126. (b) Herndon, J. W.; Zhu, Y. *Tetrahedron Lett.* **1998**, *39*, 7443–7446.
12. Liebeskind, L. S.; Fengl, R. W.; Wirtz, K. R.; Shawe, T. T. *J. Org. Chem.* **1988**, *53*, 2482–2488.
13. For a recent review of this process, see: Dotz, K. H.; Tomuschat, P. *Chem. Soc. Rev.* **1999**, *28*, 187–198.
14. Tumer, S. U.; Herndon, J. W.; McMullen, L. A. *J. Am. Chem. Soc.* **1992**, *114*, 8394–8404.
15. Wulff, W. D.; Kaesler, R. W.; Peterson, G. A.; Tang, P.-C. *J. Am. Chem. Soc.* **1985**, *107*, 1060–1062.
16. (a) Caldwell, J. J.; Harrity, J. P. A.; Heron, N. M.; Kerr, W. J.; McKendry, S.; Middlemiss, D. *Tetrahedron Lett.* **1999**, *40*, 3481–3484. (b) Caldwell, J. J.; Kerr, W. J.; McKendry, S. *Tetrahedron Lett.* **1999**, *40*, 3485–3486. (c) Ishibashi, T.; Ochifuji, N.; Mori, M. *Tetrahedron Lett.* **1996**, *37*, 6165–6168.
17. Cyclobutenones are often the major products in the coupling of carbene complexes with highly hindered alkynes. For a recent example, see: Davies, M. W.; Johnson, C. N.; Harrity, J. P. A. *Chem. Commun.* **1999**, 2107–2108.
18. Harvey, D. F.; Brown, M. F. *Tetrahedron Lett.* **1990**, *31*, 2529–2532.
19. Le Drian, C.; Vogel, P. *Helv. Chim. Acta* **1987**, *70*, 1703–1720.
20. For detailed experimentally based mechanistic discussions of the Dötz reaction: (a) Bos, M. E.; Wulff, W. D.; Miller, R. A.; Chamberlin, S.; Brandvold, T. A. *J. Am. Chem. Soc.* **1991**, *113*, 9293–9319. (b) Waters, M. L.; Bos, M. E.; Wulff, W. D. *J. Am. Chem. Soc.* **1999**, *121*, 6403–6413.
21. Herndon, J. W.; Hayford, A. *Organometallics* **1995**, *14*, 1556–1558.
22. For deoxygenation by molybdenum carbonyls, see: (a) Alper, H.; Des Roches, D.; Durst, T.; Legault, R. *J. Org. Chem.* **1976**, *41*, 3611–3613. Very similar deoxygenations have been observed in reaction processes involving chromium–carbene complexes: (b) Zora, M.; Herndon, J. W. *Organometallics* **1993**, *11*, 249–250.
23. We note a similar nondeliberate enol ether hydrolysis in the direct formation of furanones from the coupling of molybdenum–carbene complexes and alkynes: Herndon, J. W.; Zora, M. *Synlett* **1993**, 363–365.
24. Oxidation through net dehydrogenation by zero-valent metal carbonyls has precedent: Barborak, J. C.; Watson, S. L.; McPhail, A. T.; Miller, R. W. *J. Organomet. Chem.* **1980**, *185*, C29–C33.
25. Wasserman, H. H.; Hearn, M. J.; Haveaux, B.; Thyes, M. *J. Org. Chem.* **1976**, *41*, 153–155.
26. Fischer, E. O.; Maasböl, A. *Chem. Ber.* **1967**, *100*, 2445–2456.
27. Fischer, E. O.; Connor, J. A. *J. Chem. Soc., Chem. Commun.* **1967**, *100*, 1024–1025.
28. Wulff, W. D.; Bauta, W. E.; Kaesler, R. W.; Lankford, P. J.; Miller, T. A.; Murray, C. K.; Yang, D. C. *J. Am. Chem. Soc.* **1990**, *112*, 3642–3659.
29. Herndon, J. W.; Zora, M.; Patel, P. P.; Chatterjee, G.; Matasi, J. J.; Tumer, S. U. *Tetrahedron* **1993**, *53*, 5507–5530.
30. Harvey, D. F.; Brown, M. F. *Tetrahedron Lett.* **1990**, *31*, 2529–2532.