Available online at www.sciencedirect.com
ScienceDirect
Tetrahedron 63 (2007) 6306–6316
Tetrahedron

Missing cyclization pathways and new rearrangements unveiled in the gold(I) and platinum(II)-catalyzed cyclization of 1,6-enynes

Catalina Ferrer, Mihai Raducan, Cristina Nevado, Christelle K. Claverie and Antonio M. Echavarren*

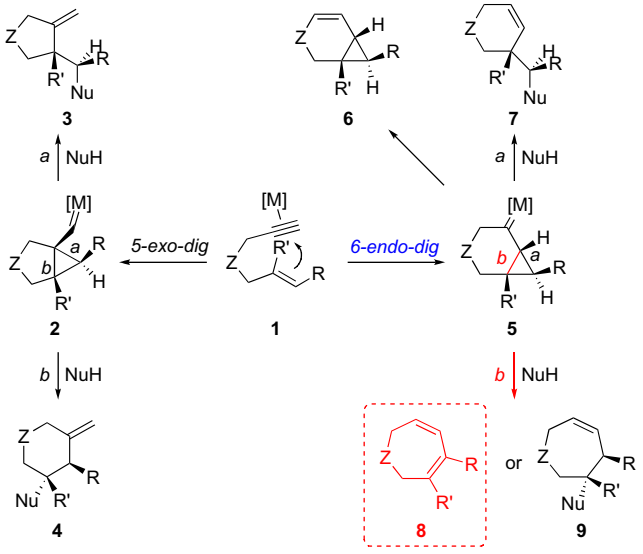
Institute of Chemical Research of Catalonia (ICIQ), Av. Països Catalans 16, 43007 Tarragona, Spain

Received 22 January 2007; revised 25 February 2007; accepted 27 February 2007
Available online 2 March 2007

Abstract—Cyclopropyl metal carbenes formed in the 6-*endo-dig* cyclization may evolve to form seven-membered ring intermediates. This has been achieved for the first time by using highly electrophilic platinum(II) and gold(I) complexes. Gold(I) also triggers a remarkable rearrangement of certain enynes leading to complex cyclic systems. A new cationic platinacycle is described, which catalyzes skeletal rearrangements and other reactions of enynes at room temperature.

1. Introduction

The mechanistic scheme of metal-catalyzed reactions between alkynes and alkenes[1–5] has been demonstrated in the context of 1,6-enyne cyclization.[6–8] Thus, work on Pt(II)-,[6,8] Pd(II)-,[7] and Au(I)-catalyzed[9,10] alkoxy- and hydroxycyclizations has identified two general manifolds upon monocoordination of the metal fragment to the alkyne in **1**: a 5-*exo-dig* cyclization via *anti*-cyclopropyl metal carbenes **2** to give products **3** or **4**,[9] and the relatively less common 6-*endo-dig* cyclization via **5** (Scheme 1). Recently, the addition of electron-rich aromatic compounds as carbon nucleophiles to 1,6-enynes has been achieved using cationic gold(I) catalysts.[11,12] In addition to the nucleophilic attack at intermediates **2** to give products **3** or **4**, certain carbon nucleophiles also react at the carbene carbon[12] in a process that is similar to the intermolecular cyclopropanation with alkenes catalyzed by gold(I).[13] Elimination of a proton to form dienes, a process that is different from the Alder-ene isomerization reaction, has also been reported.[10c,14] The endocyclic pathway proceeds by a shift of the metal in **1** to C-2 of the alkyne to form intermediates **5**, which can evolve to give cyclopropanes **6**, addition products **7**,[8] or the corresponding *endo* skeletal rearrangement derivatives.[9] However, the formation of seven-membered ring compounds **8** or **9** by cleavage of bond *b* from **5** has not yet been observed.[15]



Scheme 1.

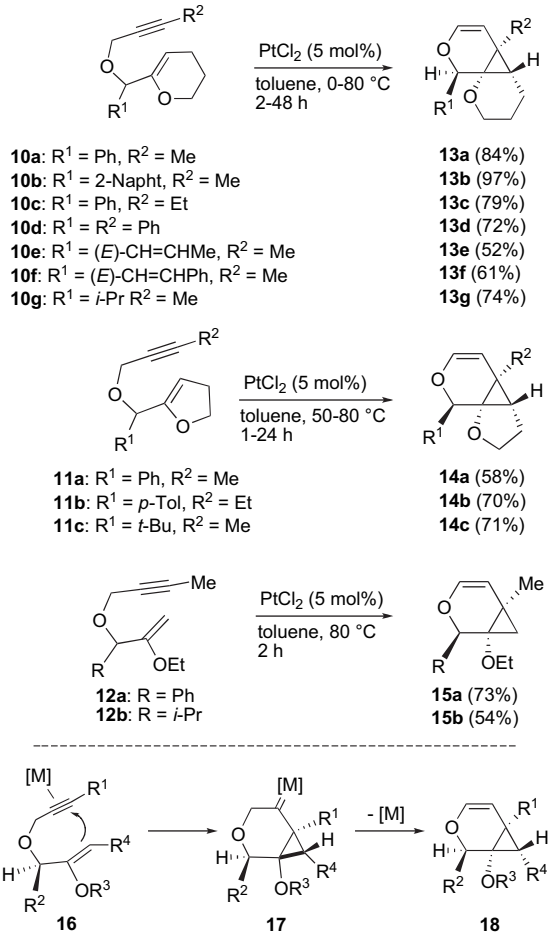
We have tried to obtain seven-membered ring compounds **8** or **9** by using enol ethers as substrates (R′=alkoxy group) to facilitate cleavage of bond *b* in intermediates **5**.[16] However, this strategy was not successful using $PtCl_2$ as catalyst.[15] We reasoned that by using more electrophilic catalysts, cleavage of bond *b* might be possible. Herein we report the realization of this concept by using more electrophilic platinum(II) and gold(I) catalysts, which allows the formation of compounds of type **8** by a formal 7-*endo-dig* cyclization. Gold(I) may also trigger a remarkable domino process leading to complex cyclic systems via seven-membered ring intermediates.

Keywords: Gold; Platinum; Enynes; Cyclizations; Rearrangements.
* Corresponding author. Tel.: +34 977920218; fax: +34 977920225; e-mail: aechavarren@iciq.es

0040–4020/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2007.02.122

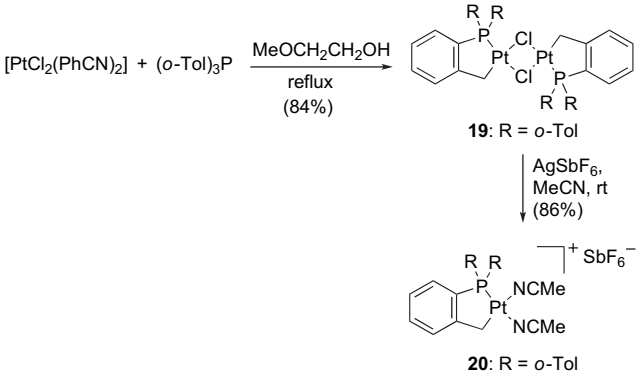
2. Results and discussion

Enynes **10–12** are readily available substrates assembled in a modular way in two steps by the addition of α-lithiated enol ethers to aldehydes, followed by propargylation of the resulting secondary alcohols. Cyclization of **10–12** was cleanly carried out with 5 mol % $PtCl_2$ in toluene (Scheme 2).[15] No skeletal rearrangement was observed under these conditions.[2,3,17] The reactions of **10–12** proceeded with total regiocontrol by 6-*endo*-*dig* cyclization, as a result of the terminal substitution at the alkyne and the electronegative character of the tether.[16] In addition, these reactions are highly stereoselective. Thus, only in the case of **15a** a C-2 epimer was detected. The cyclization presumably proceeds via complex **16**, by the formation of two carbon–carbon bonds from the face of the alkene opposite to the R^2 substituent. The intermediate carbene **17** then evolves by a hydrogen elimination to give enol ether **18**.



Scheme 2. Cyclization of enynes **10–12** catalyzed by $PtCl_2$.

Almost identical results were obtained when $PtCl_4$ was used as the catalyst,[17] which suggest that Pt(IV) is reduced to Pt(II) under the reactions conditions. In search for a more active platinum catalyst, we have previously found that a combination of $PtCl_2$ and bulky phosphine $(o\text{-Tol})_3P$ provided a catalytic system that outperformed $PtCl_2$.[10b] Although the exact nature of the active catalyst is not known, we reasoned that under the reaction conditions known dimeric Pt(II) complex **19** could be formed.[18] Indeed, complex **19** is readily prepared from $[PtCl_2(PhCN)_2]$ and $(o\text{-Tol})_3P$ as an insoluble solid by the procedure of Fornies et al. Cleavage of the chloride bridges of dimeric **19** with $AgSbF_6$ in acetonitrile provided new complex **20** in good yield as a white solid (Scheme 3). Complex **20** displays a ^{31}P resonance at δ 19.8 ($CDCl_3$) coupled to ^{195}Pt ($^1J_{PtP}$=4600 Hz). This cationic platinum complex is soluble in CH_2Cl_2 and partially soluble in toluene at room temperature.



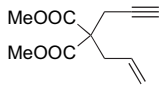
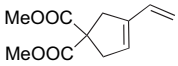
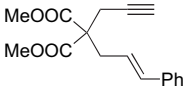
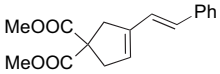
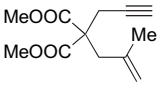
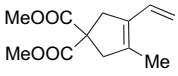
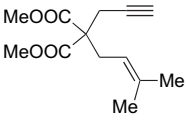
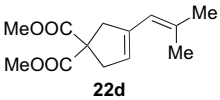
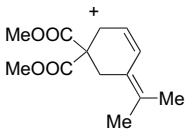
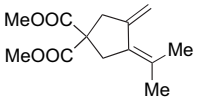
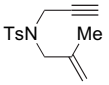
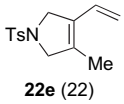
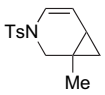
Scheme 3.

Complex **20** catalyzes the skeletal rearrangement of simple 1,6-enynes (Table 1). Thus, **21a–e** reacted with **20** (5 mol %) in CH_2Cl_2 at room temperature to afford dienes **22a–e**.[3,4] In the case of enyne **21d** (entry 4), *endo*-rearrangement product **23**[10a,c] and **24** were also obtained. We have also obtained **24** in the gold(I)-catalyzed reaction of **21d** performed in DMSO and have demonstrated that this diene results by the elimination of a proton from an intermediate of type **2**.[10c,14] Reaction of tosylamide **21e** with catalyst **20** affords 3-azabicyclo[4.1.0]hept-4-ene **25** as the major product (entry 5), a result that is similar to that has been found before in the reaction of **21e** with Au(I) catalysts.[10c] In this case, however, no endocyclic rearrangement was observed with the Pt(II) catalyst. Remarkably, whereas in the absence of donor ligands $PtCl_2$ catalyzes the Alder-ene cycloisomerization of 1,6-enynes,[6] this type of process was not observed with platinum complex **20**, which suggest that only one of the acetonitrile ligands is substituted by the incoming enyne. A preliminary kinetic study on the cyclization of **21c** catalyzed by **20** (entry 3) revealed first order dependence on the substrate with an enthalpy of activation $\Delta H^{\ddagger}$=12 kcal mol^{-1} and an entropy of activation $\Delta S^{\ddagger}$=−2.6 cal mol^{-1} K^{-1}.[10f]

In addition to new Pt(II) complex **20**, we assayed the cyclizations of substrates **10** and **11** with other Au(I) catalysts (Fig. 1). Complex **26**[10d,19] proved to be the best Au(I) catalyst, whereas **27**[13] led to poorer results, probably due to its higher electrophilicity, which led to decomposition of the acid-sensitive enol ethers used as substrates.

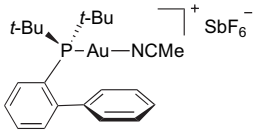
Enynes **10a–c** are cyclized with catalysts **20** and **26** to give tricyclic compounds **13a–c** (Table 2, entries 1–5). Best yields are obtained with Au(I) catalyst **26** (entries 2, 4, and 5). Reaction of enynes **10d** with catalyst **26** provided 3,4,7,9-tetrahydro-2*H*-pyrano[2,3-*c*]oxepine **28a**, in addition to the expected cyclopropane derivative **13d** (entry 7). Catalyst **27** led to oxepine **28a**, albeit in low yield (entry 8). Interestingly, whereas reaction of dienyne **10f** with $PtCl_2$

Table 1. Skeletal rearrangement of 1,6-enynes catalyzed by Pt(II) complex **20**

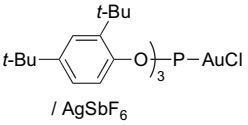
Entry	Enyne	Time (min)	Product(s) (yield, %)
1	 **21a**	120	 **22a** (63)
2	 **21b**	120	 **22b** (55)
3	 **21c**	15	 **22c** (87)
4	 **21d**	15	 **22d** +  **23** +  **24** 81(**22d**/**23**/**24** = 1:0.2:0.9)
5	 **21e**	20	 **22e** (22) +  **25** (78)

Reactions carried out with 5 mol % catalyst in CH_2Cl_2 at room temperature.

proceeded selectively between the acetylene and the more electron-rich enol ether to give **13f** (Scheme 2), reaction of **10f** with catalyst **26** afforded a mixture of regioisomeric cyclopropane **29** (25%) and tetracyclic acetal **30** (45%) (entry 9). The structure of this unexpected product of rearrangement was secured by X-ray diffraction (Fig. 2).[20] An interesting difference in the reactivity of Pt(II) and Au(I) catalysts was found in the reaction of substrate **10h**. Thus,



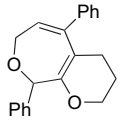
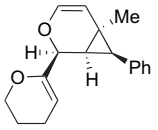
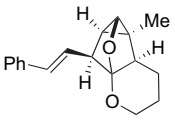
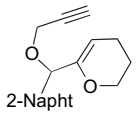
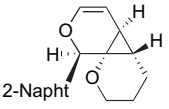
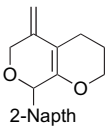
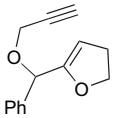
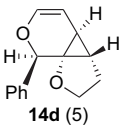
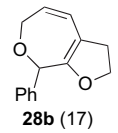
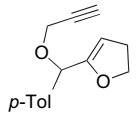
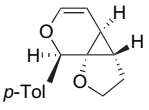
26



27

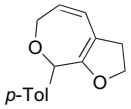
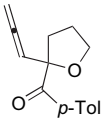
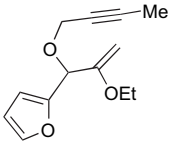
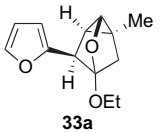
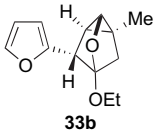
Figure 1. Gold(I) complexes with bulky ligands.

Table 2. Cyclizations of enynes **10**–**12** with catalysts **20**, **26**, or **27**

Entry	Enyne	Catalyst	Solvent	Time (h)	Product (yield, %)
1	**10a**	**20**	Toluene	2	**13a** (41)
2	**10a**	**26**	CH_2Cl_2	0.2	**13a** (75)
3	**10b**	**20**	CH_2Cl_2	0.7	**13b** (77)
4	**10b**	**26**	CH_2Cl_2	0.5	**13b** (78)
5	**10c**	**26**	CH_2Cl_2	0.5	**13c** (80)
6	**10d**	**20**	CH_2Cl_2	1	**13d** (38)
7	**10d**	**26**	CH_2Cl_2	0.3	**13d** (45) +  **28a** (14)
8	**10d**	**27**	CH_2Cl_2	5	**28a** (12)
9	**10f**	**26**	CH_2Cl_2	0.2	 **29** (25) +  **30** (45)
10	 **10h**	**20**	Toluene	0.2	 **13h** (29)
11	**10h**	**26**	CH_2Cl_2	0.1	 **31** (66)
12	**10h**	**27**	CH_2Cl_2	0.2	**31** (50)
13	 **11d**	**20**	Toluene	0.2	 **14d** (5) +  **28b** (17)
14	**11d**	**26**	CH_2Cl_2	0.1	**28b** (20)
15	**11d**	**27**	CH_2Cl_2	0.1	**28b** (10)
16	 **11e**	**20**	Toluene	0.2	 **14e** (5)

(*continued*)

Table 2. (*continued*)

Entry	Enyne	Catalyst	Solvent	Time (h)	Product (yield, %)
17	**11e**	**26**	CH_2Cl_2	0.1	 **28c** (20)
18	**11e**	AuCl	CH_2Cl_2	16	 **32** (60)
19	 **12c**	**26**	CH_2Cl_2	0.2	 **33a** +  **33b** (60, 3:1 **33a/33b**)

Reactions carried out with 5 mol % catalyst at room temperature.

whereas its reaction with catalyst **20** led to **13h** in low yield, Au(I) catalysts **26** and **27** gave bicyclic **31** (entries 10–12). Seven-membered ring derivatives **28b**,**c** were also obtained in the reactions of **11d** and **11e** (entries 13–15 and 17). Oxepine derivatives **28a–c** are labile and suffer extensive decomposition upon storage even at low temperatures (<0 °C). A totally different reactivity was found in the reaction of substrate **11e** with AuCl as catalyst (entry 18). In this case, allene **32** was obtained in 60% yield. Reaction of 2-furyl derivative **12c** with **26** as catalyst led to cyclic acetals **33a**,**b**, as a 3:1 mixture of epimers (entry 19) with a cage structure similar to that of **30**.

Allene **32** is formed by gold-catalyzed isomerization of **11e** to **34**, followed by Claisen rearrangement that is also probably catalyzed by gold (Scheme 4). Interestingly, related allene **35** had been obtained before in the reaction of **10a** with $AuCl_3$ as catalyst,[21] which points to the formation of the same gold catalyst in reactions with AuCl and $AuCl_3$.[22]

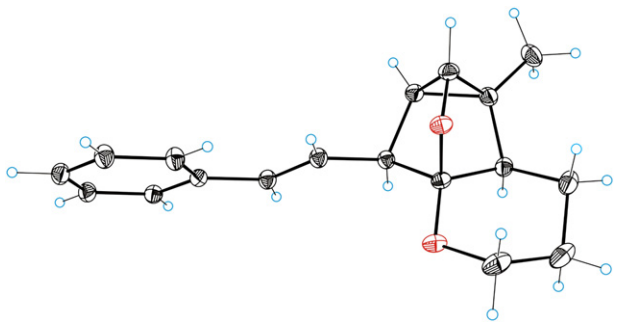
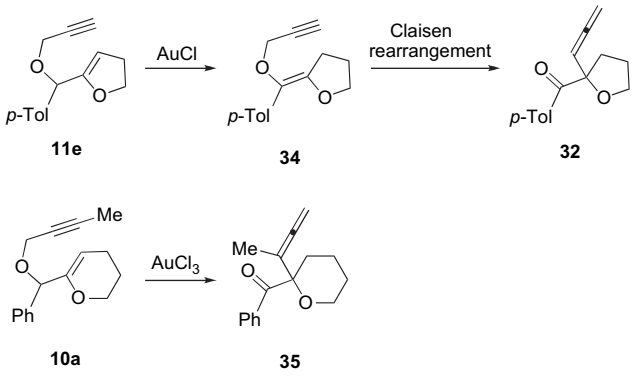
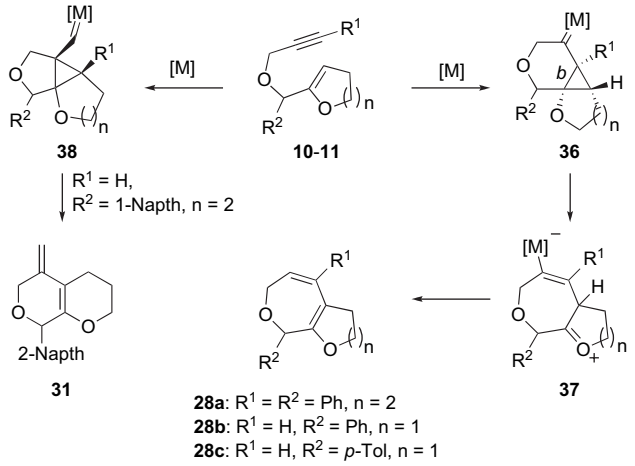


Figure 2. ORTEP diagram of **30**. Ellipsoids are shown at the 50% level.[20]



Scheme 4. Mechanism for the formation of allene **32**.

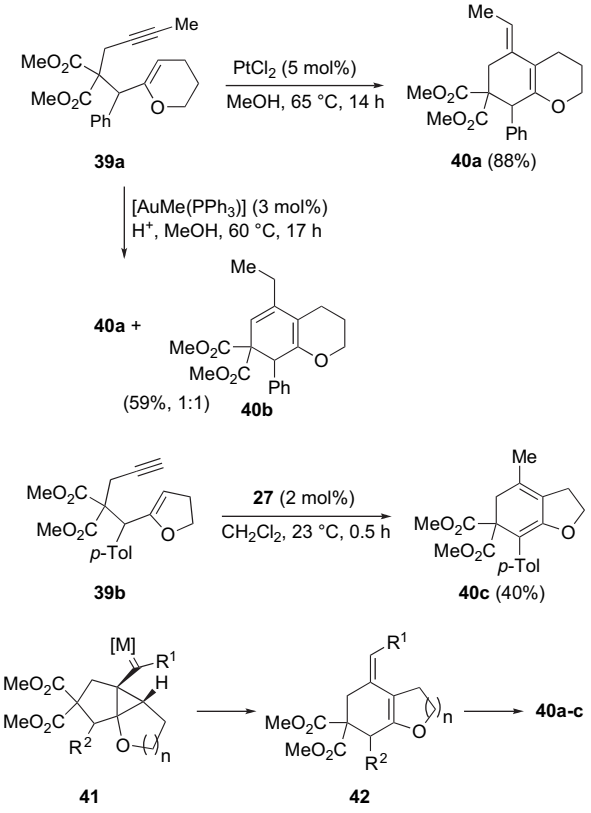
Oxepines **28a–c** are formed by an initial 6-*endo-dig* cyclization to give intermediates of type **36**, which suffer cleavage at bond *b* (see Scheme 1) leading to **37** (Scheme 5). Intermediates **37** undergo proton loss and a final protodemetalation to afford **28a–c**. The formation of **31** from **10h** (Table 2, entry 11) can be explained by an initial 5-*exo-dig* cyclization via an intermediate of type **38**.



Scheme 5.

We also observed the formation of compounds related to **31** in the reaction of malonates **39a**,**b** with Pt(II) or Au(I) catalysts (Scheme 6). Thus, reaction of **39a** with $PtCl_2$ in MeOH provided **40a** in 88% yield. Reaction of **39a** with a cationic Au(I) catalyst generated in situ by reaction of [AuMe(PPh_3)] with phosphotungstic acid[10a,c] led to a 1:1 mixture of **40a** and **40b** in 59% yield. On the other hand, treatment of **39b** with catalyst **27** in CH_2Cl_2 led to **40c** in 40% yield. These reactions probably take place through intermediates of type **41**, which open initially to give **42**. Gold- or proton-catalyzed isomerization of the exocyclic olefin of **42** then gives products **40a–c**.

Formation of rearranged compounds **30** and **33** probably also proceeds via seven-membered ring intermediates. For simplicity the proposed mechanism is shown for the formation of acetal **30** (Scheme 7). Accordingly, 6-*endo-dig* cyclization of **43** should give gold(I) carbene **44**, whose opening would afford oxonium cation **45**. In this case, instead of the loss of a proton, a ring contraction from **45** could lead to

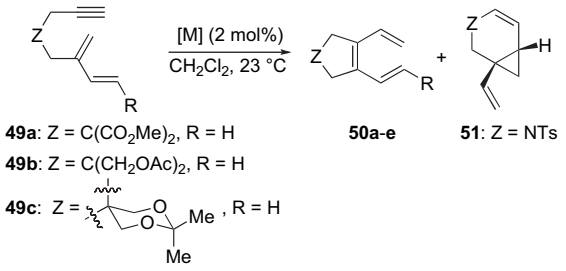


Scheme 6.

carbocation **46**, which would react with the alkenyl-gold to give **47**. The cyclopropane ring could be formed as shown to give **48**, from which a protodemetalation would then afford **30**. A similar series of transformations could also explain the formation of acetals **33**.

We also examined the cyclization of dienynes **49a–e** in which the vinyl group might also favor opening of the endocyclic intermediates to form seven-membered rings. However, in these cases the preferred reaction pathway for **49a–d** was the exocyclic skeletal rearrangement leading to divinylcyclopentenes **50a–c**. This type of compounds is of interest as configurationally locked *Z*-hexatrienes.[23] The best results were obtained using catalyst **26**, which led to

Table 3



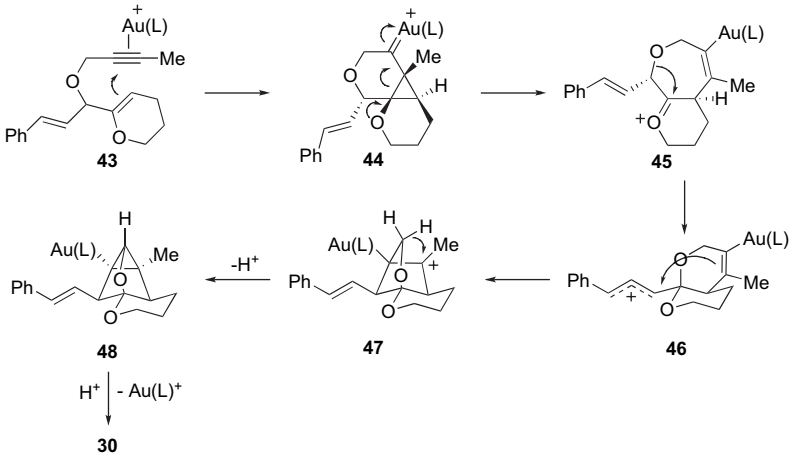
Entry	Dienyne	[M]	Product(s) (yield, %)
1	**49a**	**20**	**50a** (51)
2	**49a**	**26**	**50a** (67)
3	**49a**	[AuCl(PPh$_3$)]/AgSbF$_6$	**50a** (34)
4	**49a**	[AuCl(IMes)]/AgSbF$_6$	**50a** (25)
5	**49b**	**26**	**50b** (68)
6	**49c**	**26**	**50c** (60)
7	**49d**	**26**	**50d** (18)
8	**49e**	**26**	**50e** (33)+**51** (44)
9	**49e**	AuCl	**51** (67)

Reactions carried out with 2 mol % catalyst in CH_2Cl_2 for 5–20 min.

higher yields and cleaner reactions than [AuCl(PPh$_3$)]/AgSbF$_6$ or [AuCl(IMes)]/AgSbF$_6$[10d,24] (IMes=*N*,*N*-bismesitylimidazolylidene) (Table 3, entries 2–4). Divinylcyclopentene **50d** was obtained in low yield from **49d** (entry 7). On the other hand, tosylamide derivative **49e** reacted with **26** or AuCl as catalysts by an endocyclic pathway, leading to **51** as the major product (entries 8 and 9).

3. Conclusion

In summary, as predicted by the mechanistic scheme originally proposed for the Pt(II)-catalyzed nucleophilic additions to 1,6-enynes,[6b] the cyclopropyl metal carbene formed in the 6-*endo-dig* cyclization may evolve to form seven-membered ring intermediates. This has been realized by using more electrophilic platinum(II) and gold(I) complexes. Gold(I) also triggers a remarkable rearrangement leading to complex cyclic systems bearing up to six stereogenic centers in a single step from an achiral starting material. Cleavage of bond *b* in cyclopropyl metal carbene



Scheme 7.

formed in the 5-*exo-dig* cyclization has also been observed in the formation of **31** (Table 3, entry 11) and **40a–c** (Scheme 3).

Cationic complex **20** is the first platinacycle able to catalyze cyclizations of enynes. It is noteworthy that this Pt(II) complex bearing two acetonitrile ligands behaves similarly to cationic Au(I) complexes leading to the selective activation of the alkyne function of enynes.

4. Experimental

4.1. General

Alcohols precursors of compounds **10a–d**,[25] **12a**,[26] enyne **10a**, **22b**,[10c,27] **22c**,[28] **22d**,[10c,28] **23**,[27] **24**,[10c,29] **22e**,[10c,30] and **25**[10c,31] have been described. Experimental details for the preparation of compounds **13a–g**, **14a–c**, **15a**,**b** have been reported.[15]

4.1.1. 2-(1-(But-2-ynyloxy)-2-ethoxyallyl)furan (12c). Yield: 47% (800 mg, 3.29 mmol). Yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.38 (dd, J=1.8, 0.6 Hz, 1H), 6.37 (d, J=3.2 Hz, 1H), 6.33 (dd, J=3.2, 1.8 Hz, 1H), 5.02 (s, 1H), 4.39 (d, J=2.3 Hz, 1H), 4.18 (d, J=2.3 Hz, 1H), 4.17–4.15 (m, 2H), 3.38–3.76 (m, 2H), 1.85 (t, J=2.3 Hz, 3H), 1.28 (t, J=7.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 158.5 (C), 152.3 (C), 142.4 (CH), 110.2 (CH), 108.7 (CH), 84.0 (CH_2), 82.9 (C), 74.7 (C), 73.9 (CH), 63.3 (CH_2), 56.5 (CH_2), 14.3 (CH_3), 3.7 (CH_3). ESI-HRMS calcd for $C_{13}H_{16}O_3Na$ [M^++Na]: 243.0997, found: 243.0985.

4.1.2. Synthesis of [Pt{*o*-$CH_2C_6H_4P$(*o*-tolyl)$_2$-*C*,*P*}-(CH_3CN)$_2$][SbF_6] (20). (a) [$PtCl_2$(PhCN)$_2$] was prepared by a modification of a known procedure.[32] $PtCl_2$ (0.508 g, 1.901 mmol) in benzonitrile (30 mL) was heated at 180 °C. After 15 min, the mixture was cooled to room temperature. The solvent was partially evaporated to ca. 1/3 of the original volume (9 mbar, 55 °C). Hexane (20 mL) was added and the precipitate was filtered and washed with hexane (3×10 mL) to yield [Pt(PhCN)$_2$$Cl_2$] (cis and trans mixture) as a yellow powder (0.808 g, 90%). (b) [Pt{$CH_2C_6H_4P$(*o*-tolyl)$_2$-*C*,*P*}(μ-Cl)]$_2$,[18] a mixture of [$PtCl_2$(PhCN)$_2$] (cis+trans, 0.490 g, 1.04 mmol) and tri-*o*-tolylphosphine (0.325 mg, 1.04 mmol) in 2-methoxyethanol (6 mL), was refluxed for 30 min. The initial suspension was dissolved to give a clear pale yellow solution and then a white crystalline solid was deposited. After cooling, the solid was filtered off, washed with methanol and Et_2O to yield **19** as a pale yellow insoluble solid (0.468 g, 84%). (c) [Pt{*o*-$CH_2C_6H_4P$(*o*-tolyl)$_2$-*C*,*P*}(μ-Cl)]$_2$ (0.468 g, 0.44 mmol) and $AgSbF_6$ (0.307 g, 0.876 mmol) were stirred in acetonitrile (10 mL) in the absence of light for 23 h. The mixture was filtered and evaporated. The residue was dissolved in CH_2Cl_2 then filtered through silica and evaporated to yield a colorless oil that solidified on addition of a few drops of Et_2O. Complex **20** was obtained as a white solid (0.615 g, 86%). ^{1}H NMR (500 MHz, $CDCl_3$, 50 °C): δ 7.45 (tt, J=7.3, 1.6 Hz, 2H), 7.39–7.30 (m, 4H), 7.20 (t, J=7.2 Hz, 2 H), 7.08 (td, J=7.2, 2.7 Hz, 1H), 6.93 (dd, J=10.4, 7.7 Hz, 1H), 3.42 (br s, 2H, Pt satellites, J=100 Hz), 2.58 (br s, 6H), 2.46 (d, J=1.0 Hz, 3H), 2.09 (s, 3H); ^{13}C {^{1}H} NMR (125 MHz, $CDCl_3$, 50 °C): δ 156.9 (d, $J_{P,C}$=26 Hz, C), 142.0 (d, $J_{P,C}$=9 Hz, C), 133.3 (s, C), 133.2 (d, $J_{P,C}$=10 Hz, CH), 132.8 (s, C), 132.4 (d, $J_{P,C}$=10 Hz, CH), 132.3 (s, CH), 131.9 (br s, CH), 131.3 (d, $J_{P,C}$=5 Hz, CH), 128.3 (d, $J_{P,C}$= 17 Hz, CH), 126.4 (d, $J_{P,C}$=14 Hz, CH), 126.3 (d, $J_{P,C}$= 13 Hz, CH), 119.7 (s, CN), 119.6 (s, CN), 22.7 (d, $J_{P,C}$=8 Hz, CH_3), 12.2 (s, CH_2, Pt satellites, J=702 Hz), 2.9 (d, $J_{P,C}$=1 Hz, CH_3), 2.4 (s, CH_3); ^{31}P {^{1}H} NMR (162 MHz, $CDCl_3$): δ 19.8 (s, Pt satellites, J=4600 Hz).

4.2. General procedure for the cyclization of substrates 10–12 (Scheme 2, Table 2)

A mixture of enol ether (0.5 mmol, 1 equiv) and the stated catalyst ($PtCl_2$, **20**, **26**, or **27**) (0.05 equiv) was dissolved in toluene or CH_2Cl_2 (2.5 mL). The solution was stirred under conditions stated in Scheme 2 and Tables 2 and 3 and then filtered through a short path of Celite. The solvent was removed under reduced pressure and the residue was purified by silica gel chromatography (100:1 hexane/EtOAc containing 5% Et_3N) to yield the corresponding product. For **40b** a procedure detailed before was used.[10a,c]

4.2.1. Dimethyl 3-vinylcyclopent-3-ene-1,1-dicarboxylate (22a). Colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.51–6.44 (m, 1H), 5.58 (br s, 1H), 5.12–5.08 (m, 2H), 3.75 (s, 6H), 3.14 (br s, 2H), 3.11 (br s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPTQ): δ 172.4 (C), 139.9 (C), 132.3 (CH), 126.8 (CH), 115.0 (CH_2), 58.6 (C), 52.8 (CH_3), 40.8 (CH_2), 39.2 (CH_2). ESI-HRMS calcd for $C_{11}H_{14}O_4Na$ [M^++Na]: 233.0790, found: 233.0788.

4.2.2. 5,9-Diphenyl-3,4,7,9-tetrahydro-2*H*-pyrano[2,3-*c*]oxepine (28a). Colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.41–7.39 (m, 2H), 7.34–7.29 (m, 5H), 7.24–7.20 (m, 3H), 6.15 (t, J=6.8 Hz, 1H), 5.26 (s, 1H), 4.26 (dd, J=11.2, 6.8 Hz, 1H), 4.14 (overlapped dd, J=11.2, 6.8 Hz, 1H), 4.13–4.08 (overlapped m, 1H), 4.03–3.98 (m, 1H), 2.15–2.08 (m, 1H), 2.02–1.94 (m, 1H), 1.89–1.82 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 156.3 (C), 149.1 (C), 139.6 (C), 139.2 (C), 128.3 (CH, 2C), 127.9 (CH, 2C), 127.7 (CH, 2C), 127.6 (CH), 127.5 (CH, 2C), 127.2 (CH), 124.7 (CH), 111.3, 77.8 (CH), 66.7 (CH_2), 62.4 (CH_2), 23.4 (CH_2), 22.2 (CH_2). ESI-HRMS calcd for $C_{21}H_{20}O_2Na$ [M^++Na]: 327.1361, found: 327.1364.

4.2.3. 8-Phenyl-2,3,6,8-tetrahydrofuro[2,3-*c*]oxepine (28b). Colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.39–7.30 (m, 5H), 6.04 (d, J=10.5 Hz, 1H), 5.81 (dt, J=10.5, 5.1 Hz, 1H), 5.51 (br s, 1H), 4.39–4.30 (m, 2H), 4.18 (dd, J=15.3, 5.1 Hz, 1H), 4.08 (dd, J=15.4, 5.3 Hz, 1H), 2.94–2.83 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$, DEPT): δ 157.9 (C), 139.2 (C), 128.5 (CH, 2C), 128.4 (CH), 128.4 (CH, 2C), 127.1 (CH), 124.7 (CH), 109.7 (C), 80.3 (CH), 69.8 (CH_2), 64.9 (CH_2), 33.9 (CH_2). ESI-HRMS calcd for $C_{14}H_{14}O_2Na$ [M^++Na]: 237.0891, found: 237.0897.

4.2.4. 8-*p*-Tolyl-2,3,6,8-tetrahydrofuro[2,3-*c*]oxepine (28c). Colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.25 (d, J=8.1 Hz, 2H), 7.16 (d, J=7.9 Hz, 2H), 6.03 (d, J=10.5 Hz, 1H), 5.79 (dt, J=10.5, 5.2 Hz, 1H), 5.47 (s, 1H), 4.38–4.30 (m, 2H), 4.18 (dd, J=15.3, 5.1 Hz, 1H), 4.06 (dd, J=15.4, 5.4 Hz, 1H), 2.93–2.82 (m, 2H), 2.33 (s,

3H); ^{13}C NMR (125 MHz, $CDCl_3$, DEPT): δ 158.1 (C), 138.2 (C), 136.3 (C), 129.2 (CH, 2C), 128.4 (CH, 2C), 127.1 (CH), 124.7 (CH), 109.6, 80.0 (CH), 69.8 (CH_2), 64.8 (CH_2), 33.9 (CH_2), 21.2 (CH_3). ESI-HRMS calcd for $C_{15}H_{16}O_2Na$ [M^++Na]: 251.1048, found: 251.1044.

4.2.5. 2-(3,4-Dihydro-2*H*-pyran-6-yl)-6-methyl-7-phenyl-3-oxabicyclo[4.1.0]hept-4-ene (29). Colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.31–7.27 (m, 2H), 7.21–7.17 (m, 3H), 6.27 (d, J=5.9 Hz, 1H), 5.18 (d, J=5.9 Hz, 1H), 4.97 (t, J=3.9 Hz, 1H), 4.17 (br s, 1H), 4.07 (dd, J=5.9, 4.4 Hz, 2H), 2.47 (d, J=5.7 Hz, 1H), 2.06–2.02 (m, 2H), 1.89 (dd, J=5.7, 1.6 Hz, 1H), 1.87–1.81 (m, 2H), 0.91 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 153.0 (C), 140.8 (CH), 138.2 (C), 129.0 (CH, 2C), 128.1 (CH, 2C), 126.0 (CH), 111.5 (CH), 97.9 (CH), 70.6 (CH), 66.5 (CH_2), 35.0 (CH), 32.0 (CH), 22.4 (CH_2), 20.0 (CH_2), 19.9 (C), 17.9 (CH_3). ESI-HRMS calcd for $C_{18}H_{20}O_2Na$ [M^++Na]: 291.1361, found: 291.1356.

Acetal **30**: white solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.38–7.36 (m, 2H), 7.28–7.24 (m, 2H), 7.19–7.14 (m, 1H), 6.51 (d, J=15.9 Hz, 1H), 6.16 (dd, J=15.9, 8.5 Hz, 1H), 3.91–3.82 (m, 2H), 3.71 (d, J=4.2 Hz, 1H), 2.60 (d, J=8.3 Hz, 1H), 1.72–1.69 (m, 1H), 1.61–1.57 (m, 2H), 1.45–1.42 (m, 2H), 1.21 (dd, J=4.3, 1.0 Hz, 1H), 1.17 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 137.4 (C), 132.2 (CH), 128.3 (CH, 2C), 127.0 (CH), 126.3 (CH, 2C), 126.2 (CH), 103.6 (C), 65.2 (CH_2), 56.4 (CH), 48.5 (CH), 43.3 (CH), 24.7 (CH), 24.1 (C), 23.7 (CH_2), 20.8 (CH_2), 11.6 (CH_3). ESI-HRMS calcd for $C_{18}H_{20}O_2Na$ [M^++Na]: 291.1361, found: 291.1358.

4.2.6. 5-Methylene-8-(naphthalen-2-yl)-2,3,4,5,6,8-hexahydropyrano[3,4-*b*]pyran (31). Colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.85–7.81 (m, 4H), 7.52 (dd, J=8.5, 1.5 Hz, 1H), 7.48–7.46 (m, 2H), 5.28 (s, 1H), 4.74 (s, 1H), 4.63 (s, 1H), 4.32 (d, J=13.3 Hz, 1H), 4.24 (d, J=13.3 Hz, 1H), 4.06–3.97 (m, 2H), 2.36 (dt, J=16.5, 6.5 Hz, 1H), 2.26 (dtd, J=16.4, 6.6, 2.2 Hz, 1H), 2.02–1.96 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$, DEPT): δ 151.4 (C), 140.6 (C), 135.9 (C), 133.4 (C), 133.1 (C), 128.2 (CH), 128.2 (CH), 127.8 (CH), 127.7 (CH), 126.2 (CH), 126.1 (CH), 126.0 (CH), 106.9 (C), 101.0 (CH_2), 76.6 (CH), 66.9 (CH_2), 66.7 (CH_2), 22.3 (CH_2), 19.2 (CH_2). ESI-HRMS calcd for $C_{19}H_{18}O_2Na$ [M^++Na]: 301.1204, found: 301.1216.

Acetals **33a**,**b**: yellow oil, 3:1 isomer mixture. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.37–7.36 (m, 1H, minor), 7.34 (dd, J=1.7, 0.8 Hz, 1H, major), 6.33 (overlapped dd, J=3.2, 1.8 Hz, 1H, minor), 6.32 (overlapped dd, J=3.2, 1.8 Hz, 1H, major), 6.19 (d, J=3.1 Hz, 1H, major), 6.13–6.12 (m, 1H, minor), 3.95–3.87 (m, 1H, minor), 3.84 (d, J=4.2 Hz, 1H, major), 3.81–3.77 (overlapped m, 1H, minor), 3.78 (overlapped d, J=4.9 Hz, 1H, minor), 3.63 (q, J=7.1 Hz, 2H, major), 3.14 (s, 1H, major), 3.06 (s, 1H, minor), 1.74 (d, J=10.1 Hz, 1H, major), 1.70 (d, J=10.1 Hz, 1H, minor), 1.65 (d, J=10.1 Hz, 1H, major), 1.40 (d, J=10.2 Hz, 1H, minor), 1.38 (overlapped d, J=3.2 Hz, 1H, minor), 1.36 (overlapped d, J=4.4 Hz, 1H, major), 1.30 (s, 3H, minor), 1.26 (s, 3H, major), 1.24 (t, J=7.1 Hz, 3H, minor), 1.15 (t, J=7.1 Hz, 3H, major); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 153.3 (C, minor), 152.4 (C, major), 141.8 (CH, minor), 141.3 (CH, major), 110.7 (CH, major), 110.1 (CH, minor), 107.2 (minor), 106.9 (CH, minor), 106.8 (CH, major), 106.5 (major) (C), 62.3 (CH_2, major), 62.2 (CH_2, minor), 57.6 (CH, minor), 57.4 (CH, major), 44.3 (CH, major), 43.6 (CH, minor), 38.2 (CH_2, major), 35.6 (CH_2, minor), 23.9 (CH, major), 23.3 (CH, minor), 21.0 (minor) (C), 20.6 (major) (C), 15.6 (CH_3, major), 15.5 (CH_3, minor), 14.2 (CH_3, major), 14.0 (CH_3, minor). ESI-HRMS calcd for $C_{13}H_{16}O_3Na$ [M^++Na]: 243.0997, found: 243.1005.

4.2.7. (2-(Propa-1,2-dienyl)tetrahydrofuran-2-yl)(*p*-tolyl)methanone (32). Colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.05 (d, J=8.3 Hz, 2H), 7.21 (d, J=7.9 Hz, 2H), 5.49 (t, J=6.6 Hz, 1H), 4.90 (dd, J=11.3, 6.6 Hz, 1H), 4.84 (dd, J=11.3, 6.3 Hz, 1H), 4.02 (dt, J=14.3, 7.6 Hz, 1H), 3.87 (dt, J=14.3, 7.6 Hz, 1H), 2.70–2.62 (m, 1H), 2.39 (s, 3H), 2.14–2.07 (m, 1H), 2.01–1.95 (m, 1H), 1.90–1.84 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 207.2 (C), 198.8 (C), 143.5 (C), 132.1 (C), 130.5 (CH, 2C), 128.7 (CH, 2C), 95.0 (CH), 89.3 (C), 78.7 (CH_2), 68.9 (CH_2), 34.7 (CH_2), 25.0 (CH_2), 21.6 (CH_3). ESI-HRMS calcd for $C_{15}H_{16}O_2Na$ [M^++Na]: 251.1048, found: 251.1038.

4.3. Procedure for the preparation of 39a and 39b

4.3.1. (5,6-Dihydro-4*H*-pyran-2-yl)(phenyl)methyl acetate. A mixture of (5,6-dihydro-4*H*-pyran-2-yl)(phenyl)-methanol (1.00 g, 5.20 mmol), DMAP (32 mg, 0.30 mmol), and DIPEA (1.1 mL, 6.30 mmol) was dissolved in CH_2Cl_2 (5 mL) and cooled at 0 °C. Then, Ac_2O (0.6 mL, 6.30 mmol) was added and the mixture was stirred at 23 °C for 4 h. The reaction mixture was diluted with CH_2Cl_2, washed with H_2O, and dried over $MgSO_4$. After evaporation of the solvent, the residue was chromatographed (10:1 hexane/EtOAc with 5% Et_3N) to give the title compound as a colorless oil. Yield: 88% (1.10 g, 5.90 mmol). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.41–7.29 (m, 5H), 6.14 (s, 1H), 4.85 (t, J=3.8 Hz, 1H), 3.98 (td, J=5.7, 1.4 Hz, 2H), 2.14 (s, 3H), 2.06–2.03 (m, 2H), 1.84–1.76 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 170.6, 152.3, 138.5, 128.9, 128.7, 127.8, 100.4, 75.9, 67.2, 22.7, 21.9, 20.7. EI-HRMS calcd for $C_{14}H_{16}O_3$: 232.1099, found: 232.1101.

4.3.2. Dimethyl 2-[(5,6-dihydro-4*H*-pyran-2-yl)(phenyl)-methyl]malonate. A mixture of the above acetate (89 mg, 0.40 mmol), triphenylphosphine (10 mg, 0.04 mmol), and $Pd(PPh_3)_4$ (31 mg, 0.03 mmol) was refluxed in THF (1 mL) for 2 h. In a separate flask, dimethyl malonate (0.2 mL, 1.60 mmol) was slowly added to a suspension of NaH (60% in mineral oil, 6.3 mg, 1.60 mmol) in THF (3 mL) and stirred for 20 min. The resulting solution was added in one portion to the former and the combined mixture refluxed for 72 h. The reaction mixture was diluted with Et_2O and water, the aqueous phase was extracted with ether (3×10 mL), and the ether extracts were dried over $MgSO_4$. The solvent was evaporated and the residue was purified by chromatography (30:1 hexane/EtOAc with 5% Et_3N) yielding the corresponding product as a pale yellow oil. Yield: 18% (21 mg, 0.07 mmol). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.38–7.23 (m, 5H), 4.73 (t, J=3.6 Hz, 1H), 4.17 (d, J=11.7 Hz, 1H), 4.04 (d, J=11.7 Hz, 1H), 4.05–3.89 (m, 2H), 3.80 (s, 3H), 3.50 (s, 3H), 2.04–1.97 (m, 2H), 1.79–1.72 (m, 2H); ^{13}C NMR

(75 MHz, $CDCl_3$): δ 169.0, 168.8, 153.4, 140.1, 128.9, 128.7, 127.7, 98.6, 67.1, 55.8, 53.2, 53.0, 51.2, 22.8, 20.9. EI-HRMS calcd for $C_{17}H_{20}O_5$: 304.1311, found: 304.1322.

4.3.3. Dimethyl 2-(4,5-dihydrofuran-2-yl)(*p*-tolyl-methyl)-malonate. Yield: 43% (570 mg, 1.74 mmol). White solid. ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.20 (d, J=8.1 Hz, 2H), 7.10 (d, J=8.1 Hz, 2H), 4.74 (t, J=2.5 Hz, 1H), 4.33–4.22 (m, 3H), 4.03 (d, J=11.3 Hz, 1H), 3.78 (s, 3H), 3.49 (s, 3H), 2.60–2.54 (m, 2H), 2.31 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$, DEPT): δ 168.2 (C), 167.7 (C), 157.4 (C), 137.0 (C), 135.2 (C), 129.1 (CH, 2C), 128.1 (CH, 2C), 95.9 (CH), 70.3 (CH_2), 55.8 (CH), 52.7 (CH_3), 52.4 (CH_3), 44.5 (CH), 29.9 (CH_2), 21.1 (CH_3). ESI-HRMS calcd for $C_{17}H_{20}O_5Na$ [M^++Na]: 327.1208, found: 327.1198.

4.3.4. Dimethyl 2-(but-2-ynyl)-2-[(5,6-dihydro-4*H*-pyran-2-yl)(phenyl)methyl]malonate (39a). To a suspension of NaH (60% in mineral oil, 3 mg, 0.07 mmol) in DMF (0.5 mL) at 0 °C a solution of dimethyl 2-[(5,6-dihydro-4*H*-pyran-2-yl)(phenyl)methyl]malonate (21 mg, 0.07 mmol) in DMF (1 mL) was added. The mixture was stirred for 5 min and 1-bromo-2-propyne (9 μL, 0.07 mmol) was then added. The reaction mixture was stirred for 3 h at room temperature and then quenched with an ice-water mixture and extracted with Et_2O. The organic layer was washed with water (3×1 mL), dried over $MgSO_4$, and concentrated in vacuo. The residue was purified by chromatography (50:1 hexane/EtOAc with 2% Et_3N) to give **39a** as a yellow oil. Yield: 80% (20 mg, 0.06 mmol). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.50–7.45 (m, 2H), 7.33–7.25 (m, 3H), 4.75 (t, J=3.6 Hz, 1H), 4.26 (s, 1H), 4.03–3.92 (m, 2H), 3.76 (s, 3H), 3.72 (s, 3H), 2.80 (dq, J=16.6, 2.4 Hz, 1H), 2.72 (dq, J=16.6, 2.4 Hz, 1H), 2.09–1.97 (m, 2H), 1.80–1.77 (m, 2H), 1.75 (t, J=2.4 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 171.1 (C), 171.1 (C), 153.0 (C), 139.0 (C), 131.0 (CH), 128.2 (CH), 127.6 (CH), 100.8 (CH), 79.0 (C), 75.1 (CH), 66.8 (CH_2), 61.0 (C), 54.9 (CH or CH_3), 53.0 (CH or CH_3), 52.8 (CH or CH_3), 26.3 (CH_2), 22.6 (CH_2), 21.1 (CH_2), 4.2 (CH_3). FAB-HRMS calcd for $C_{21}H_{24}O_5$: 356.1624, found: 356.1613.

4.3.5. Dimethyl 2-(4,5-dihydrofuran-2-yl)(*p*-tolylmethyl)-2-(prop-2-ynyl)malonate (39b). Yield: 98% (560 mg, 1.53 mmol). Colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.25 (d, J=7.9 Hz, 2H), 7.08 (d, J=7.9 Hz, 2H), 4.76 (br s, 1H), 4.43 (s, 1H), 4.33–4.24 (m, 2H), 3.75 (s, 3H), 3.70 (s, 3H), 2.79 (dd, J=16.8, 2.5 Hz, 1H), 2.66 (dd, J=16.8, 2.8 Hz, 1H), 2.56–2.52 (m, 2H), 2.31 (s, 3H), 1.99 (t, J=2.8 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$, DEPT): δ 170.0 (C), 169.7 (C), 156.3 (C), 137.2 (C), 133.6 (C), 130.0 (CH, 2C), 128.7 (CH, 2C), 98.8 (CH), 79.8 (C), 71.0 (CH), 70.3 (CH_2), 60.2 (C), 52.6 (CH_3), 52.5 (CH_3), 48.5 (CH), 29.9 (CH_2), 25.0 (CH_2), 21.1 (CH_3). ESI-HRMS calcd for $C_{20}H_{22}O_5Na$ [M^++Na]: 365.1365, found: 365.1359.

4.3.6. (5*E*)-Dimethyl 5-ethylidene-3,4,5,6-tetrahydro-8-phenyl-2*H*-chromene-7,7(8*H*)-dicarboxylate (40a). Colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.32–7.28 (m, 5H), 5.43 (qd, J=6.9, 2.0 Hz, 1H), 4.34 (s, 1H), 4.10–4.03 (m, 1H), 3.82–3.74 (m, 1H), 3.76 (s, 3H), 3.56 (s, 3H), 3.16 (dd, J=16.2, 1.6 Hz, 1H), 2.66 (dquint, J=16.2, 2.0 Hz, 1H), 2.32–2.15 (m, 2H), 1.99–1.82 (m, 2H), 1.77 (dd, J=6.9, 1.6 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$, DEPT): δ 170.7 (C), 169.5 (C), 149.6 (C), 137.8 (C), 131.3 (C), 129.0 (CH), 128.3 (CH), 127.5 (CH), 114.8 (CH), 108.5 (C), 66.2 (CH_2), 58.5 (C), 52.7 (CH_3), 52.2 (CH_3), 48.1 (CH), 25.9 (CH_2), 22.4 (CH_2), 20.2 (CH_2), 13.6 (CH_3). EI-HRMS calcd for $C_{21}H_{24}O_5$: 356.1624, found: 356.1610.

4.3.7. Dimethyl 5-ethyl-3,4-dihydro-8-phenyl-2*H*-chromene-7,7(8*H*)-dicarboxylate (40b). Colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.32–7.20 (m, 5H), 5.36 (dd, J=2.4, 1.0 Hz, 1H), 4.09 (d, J=2.4 Hz, 1H), 3.80–3.61 (m, 2H, overlapped), 3.78 (s, 3H), 3.75 (s, 3H), 2.35 (q, J=7.5 Hz, 2H), 1.68–1.37 (m, 4H), 1.26 (t, J=7.5 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 170.3, 169.5, 151.8, 136.4, 127.9, 127.2, 97.7, 95.2, 61.6, 56.0, 52.9, 52.1, 50.9, 32.9, 27.2, 24.6, 11.3.

4.3.8. Dimethyl 4-methyl-7-*p*-tolyl-2,3-dihydrobenzofuran-6,6(5*H*)-dicarboxylate (40c). Colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34 (d, J=8.2 Hz, 2H), 7.07 (d, J=7.9 Hz, 2H), 4.26 (t, J=7.4 Hz, 2H), 3.60 (s, 6H), 3.00 (s, 2H), 2.66 (br s, 2H), 2.29 (s, 3H), 1.85 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 172.6 (2C), 152.9 (C), 135.6 (C), 133.4 (C), 128.8 (CH, 2C), 128.5 (CH, 2C), 127.6 (C), 126.5 (C), 100.2 (C), 70.5 (CH_2), 61.5 (C), 52.6 (CH_3, 2C), 39.2 (CH_2), 26.6 (CH_2), 21.2 (CH_3), 19.6 (CH_3). ESI-HRMS calcd for $C_{20}H_{22}O_5Na$ [M^++Na]: 365.1365, found: 365.1356.

4.4. Synthesis of dienynes 49a–e dienynes (Table 3)

4.4.1. Dimethyl 2-(2-methylenebut-3-enyl)-2-(prop-2-ynyl)propanedioate (49a). (a) To a solution of dimethyl 2-(2-bromo-2-propenyl)malonate (1.25 g, 5.0 mmol) in toluene (10 mL) was added [$Pd(PPh_3)_4$] (289 mg, 0.25 mmol). The solution was stirred at room temperature for 15 min and tributylvinyltin (1.75 mL, 6 mmol) was added. The mixture was heated to reflux for 2 h. After extractive workup (EtOAc/saturated aqueous solution of KF) and chromatography (9:1 hexane/EtOAc), dimethyl 2-(2-methylene-3-butenyl)malonate was obtained as a colorless oil. Yield: 75% (731 mg, 3.75 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.35 (dd, J=11.0, 17.7 Hz, 1H), 5.26 (d, J=17.7 Hz, 1H), 5.12 (d, J=11 Hz, 1H), 5.08 (s, 1H), 5.04 (s, 1H), 3.74 (s, 6H), 3.66 (dt, J=7.5, 1.5 Hz, 1H), 2.86 (d, J=7.5 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 169.4 (C), 142.3 (C), 137.7 (CH), 117.9 (CH_2), 113.9 (CH_2), 52.5 (CH_3), 50.6 (CH), 30.5 (CH_2). ESI-HRMS calcd for $C_{10}H_{14}O_4Na$ [M^++Na]: 221.0790, found: 221.0789. (b) To a cold suspension of NaH (60% in mineral oil, 165.5 mg, 4.14 mmol) in dry DMF (5 mL) was added via cannula a solution of the above diene (820 mg, 4.14 mmol) in dry DMF (5 mL). The reaction mixture was stirred at this temperature for 30 min before adding propargyl bromide (80% wt in toluene, 461 μL, 4.14 mmol). The cooling bath was removed and the reaction mixture was stirred for 12 h at room temperature. After extractive workup (Et_2O/10% aqueous HCl) and chromatography (9:1 hexane/EtOAc), enyne **49a** was obtained as a colorless oil, which solidifies on standing at <0 °C. Yield: 83% (815 mg, 3.44 mmol). The spectroscopic data were in agreement with those reported.[33]

4.4.2. 2-(2-Methylenebut-3-enyl)-2-(prop-2-ynyl)propane-1,3-diyl diethanoate (49b). (a) To a solution of diester

49a (815 mg, 3.45 mmol) in Et_2O (20 mL) at 0 °C was added $LiAlH_4$ portionwise (131 mg, 3.45 mmol). The reaction mixture was stirred at this temperature for 1 h before being quenched with a saturated solution of sodium potassium tartrate. After extractive workup (EtOAc/water) and chromatography (7:3 hexane/EtOAc), 2-(2-methylene-3-butenyl)-2-(2-propynyl)-1,3-propanediol was obtained as a colorless oil. Yield: 47% (295 mg, 1.62 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.43 (dd, J=10.8, 17.5 Hz, 1H), 5.40 (d, J=17.5 Hz, 1H), 5.24 (s, 1H), 5.15 (s, 1H), 5.08 (d, J=10.8 Hz, 1H), 4.62 (s, 4H), 2.57 (br s, 2H), 2.34 (s, 2H), 2.30 (d, J=2.7 Hz, 2H), 2.07 (t, J=2.7 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 142.3 (C), 140.2 (CH), 119.8 (CH_2), 114.0 (CH_2), 85.0 (C), 71.3 (CH), 67.4 (CH_2), 42.8 (C), 32.2 (CH_2), 21.9 (CH_2). ESI-HRMS calcd for $C_{11}H_{16}O_2Na$ [M^++Na]: 203.1048, found: 203.1053. (b) To a solution of the above diol (151.5 mg, 0.84 mmol), diisopropylethylamine (351 μL, 2.02 mmol), and acetic anhydride (275 μL, 2.02 mmol) in CH_2Cl_2 (1.5 mL) was added DMAP (5.1 mg, 0.04 mmol). After 30 min, the mixture was diluted with CH_2Cl_2. After extractive workup and chromatography (85:15 hexane/EtOAc), diacetate **49b** was obtained as a colorless oil. Yield: 57% (126.8 mg, 0.48 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.38 (dd, J=10.8, 17.5 Hz, 1H), 5.34 (d, J=17.5 Hz, 1H), 5.26 (s, 1H), 5.08 (s, 1H), 5.065 (d, J=10.8 Hz, 1H), 4.00 (s, 4H), 2.44 (s, 2H), 2.31 (s, 2H), 2.07 (br s, 7H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 170.6 (C), 141.0 (C), 139.6 (CH), 120.1 (CH_2), 113.9 (CH_2), 79.8 (C), 71.8 (CH), 65.4 (CH_2), 40.3 (C), 31.9 (CH_2), 22.5 (CH_2), 20.8 (CH_3). ESI-HRMS calcd for $C_{15}H_{20}O_4Na$ [M^++Na]: 287.1259, found: 287.1251.

4.4.3. 2,2-Dimethyl-5-(2-methylene-3-butenyl)-5-(2-propynyl)-1,3-dioxane (49c). To a solution of 2-(2-methylene-3-butenyl)-2-(2-propynyl)-1,3-propanediol (143.5 mg, 0.77 mmol) in dimethoxypropane (3 mL) at 0 °C was added *p*-TSA (15 mg, 0.077 mmol). After 30 min the reaction mixture was quenched with Et_3N (200 μL) and the solvent was evaporated. After extractive workup (Et_2O/10% aqueous NaOH) and chromatography (basic alumina, 19:1 hexane/EtOAc), acetonide **49c** was obtained as a colorless oil. Yield: 58% (101 mg, 0.45 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.24 (dd, J=11.0, 17.5 Hz, 1H), 5.40 (d, J=17.5 Hz, 1H), 5.06 (s, 1H), 5.01 (s, 1H), 4.93 (d, J=11.0 Hz, 1H), 3.60 (s, 4H), 2.35 (s, 2H), 2.29 (s, 2H), 1.76 (t, J=2.6 Hz, 1H), 1.35 (s, 3H), 1.32 (s, 3H); ^{13}C NMR (100 MHz, C_6D_6, DEPT): δ 142.9 (C), 140.8 (CH), 120.5 (CH_2), 115.0 (CH_2), 98.6 (C), 82.0 (C), 72.4 (CH), 67.4 (CH_2), 36.4 (C), 33.9 (CH_2), 25.8 (CH_3), 23.8 (CH_2), 23.4 (CH_3). ESI-HRMS calcd for $C_{14}H_{20}O_2Na$ [M^++Na]: 243.1361, found: 243.1351.

4.4.4. Dimethyl 2-[(*E*)-2-methylene-3-heptenyl]-2-(2-propynyl)malonate (49d). (a) To a stirred solution of dimethyl 2-(2-bromo-2-propenyl)malonate (500 mg, 1 mmol) in THF (30 mL) were added under N_2, $Pd(dba)_2$ (99.6 mg, 0.05 mmol), tri-*o*-tolyl phosphine (60 mg, 0.1 mmol), penten-1-boronic acid (340 mg, 1.5 mmol) and CsF (912 mg, 4.5 mmol). The reaction mixture was heated up to reflux overnight. After extractive workup (EtOAc, water) and chromatography (90:10 hexane/EtOAc), dimethyl 2-[(*E*)-2-methylene-3-heptenyl]malonate was obtained as a colorless oil. Yield: 64% (308.1 mg, 0.64 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.02 (d, J=15.9 Hz, 1H), 5.72 (td, J=6.9, 15.9 Hz, 1H), 4.93 (s, 1H), 4.88 (s, 1H), 3.73 (s, 3H), 3.67 (s, 3H), 3.65 (t, J=7.6 Hz, 1H), 2.83 (d, J=7.6 Hz, 2H), 2.07 (q, J=7.0 Hz, 2H), 1.42 (sextuplet, J=7.3 Hz, 2H), 0.90 (t, J=7.3 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 170.0 (C), 140.9 (C), 131.8 (CH), 131.1 (CH), 117.2 (CH_2), 79.5 (C), 52.5 (CH_3), 71.7 (CH), 52.6 (CH), 35.0 (CH_2), 33.4 (CH_2), 22.8 (CH_2), 22.4 (CH_2), 13.8 (CH_3). (b) To a cold suspension of NaH (60% in mineral oil, 25.3 mg, 0.633 mmol) in dry DMF (2 mL) was added via cannula a solution of the above diene (152.2 mg, 0.633 mmol) in dry DMF (1 mL). The reaction mixture was stirred at this temperature for 30 min before adding propargyl bromide (80% wt in toluene, 70.5 mL, 0.633 mmol). The cooling bath was removed and the reaction mixture was stirred overnight at room temperature. After extractive workup (10% HCl, Et_2O) and chromatography (85:15 hexane/EtOAc), dienyne **49d** was obtained as a colorless oil. Yield: 81% (142.8 mg, 0.51 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.98 (d, J=15.9 Hz, 1H), 5.83 (td, J=6.8, 15.9 Hz, 1H), 5.08 (s, 1H), 4.93 (s, 1H), 3.72 (s, 6H), 3.00 (s, 2H), 2.84 (d, J=2.6 Hz, 2H), 2.07–2.02 (m, 3H), 1.40 (sextuplet, J=7.4 Hz, 2H), 0.90 (t, J=7.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 170.7 (C), 141.2 (C), 132.2 (CH), 131.4 (CH), 117.6 (CH_2), 79.9 (C), 72.0 (CH), 57.6 (C), 53.0 (CH_3), 35.3 (CH_2), 33.7 (CH_2), 23.1 (CH_2), 22.8 (CH_2), 14.1 (CH_3). CI-HRMS calcd for $C_{16}H_{23}O_4$ [M^++H]: 279.1596, found: 279.1596.

4.4.5. 4-Methyl-*N*-(2-methylene-3-butenyl)-*N*-(2-propynyl)benzenesulfonamide (49e). (a) To a suspension of NaH (60% in mineral oil, 294.8 mg, 7.37 mmol) in DMF (20 mL) was added portionwise TsNHBoc[34] (2.0 g, 7.37 mmol) at 0 °C. The reaction mixture was stirred for 1 h at this temperature before adding 2,3-dibromopropene (80%, 820 μL, 7.37 mmol) and the mixture was left to warm up overnight. After extractive workup (Et_2O/water) the solvent was evaporated to give a thick orange oil, which solidifies on standing. The product was recrystallized from hexane to give *N*-(2-bromo-2-propenyl)-*N*-[(2,2-dimethylpropanoyl)oxy]-4-methylbenzenesulfonamide as a white beige solid. Yield: 56% (1.61 g, 4.13 mmol). Mp 96–97.5 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.84 (d, J=8.4 Hz, 2H), 7.32 (d, J=8.4 Hz, 2H), 5.88–5.87 (m, 1H), 5.66–5.64 (m, 1H), 4.68 (appt t, J=1.5 Hz, 2H), 2.46 (s, 3H), 1.39 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 150.3 (C), 144.5 (C), 136.6 (C), 129.2 (CH), 128.4 (CH), 127.9 (C), 117.9 (CH_2), 84.9 (C), 53.1 (CH_2), 27.8 (CH_3), 21.6 (CH_3). ESI-HRMS calcd for $C_{15}H_{20}O4SBrNa$ [M^++Na]: 412.0194, found: 412.0201. (b) To a solution of the above vinyl bromide (780.6 mg, 2.0 mmol) in toluene (6 mL) was added $[Pd(PPh_3)_4]$ (115.6 mg, 0.1 mmol) followed by tributylvinyltin (700 μL, 2.4 mmol). The mixture was heated to reflux for 2 h. The crude mixture was directly chromatographed (9:1 hexane/EtOAc) to give *N*-[(2,2-dimethylpropanoyl)oxy]-4-methyl-*N*-(2-methylene)-3-butenyl)benzenesulfonamide was obtained as an oil. Yield: 62% (418 mg, 1.24 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.84 (d, J=8.4 Hz, 2H), 7.30 (d, J=8.1 Hz, 2H), 6.44 (dd, J=11.2, 17.9 Hz, 1H), 5.26 (d, J=17.9 Hz, 1H), 5.19 (s, 1H), 5.135 (s, 1H), 5.09 (s, 1H), 4.65 (s, 2H), 2.44 (s, 3H), 1.36 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 150.8 (C), 144.3 (C), 141.0 (C), 137.0 (C), 136.7 (CH), 129.1 (CH), 128.3 (CH), 115.2

(CH_2), 113.9 (CH_2), 84.3 (C), 47.5 (CH_2), 27.8 (CH_3), 21.6 (CH_3). ESI-HRMS calcd for $C_{17}H_{23}NO_4SNa$ [M^++Na]: 360.1245, found: 360.1252. (c) To a solution of Boc protected amine (395 mg, 1.17 mmol) in CH_2Cl_2 (2 mL) at 0 °C was added TFA (350 μL) dropwise. The reaction mixture was stirred at room temperature for 2 h. After extractive workup (CH_2Cl_2/saturated aqueous $NaHCO_3$) and chromatography (90:5:5 to 85:10:5 hexane/EtOAc/Et_3N), 4-methyl-*N*-(2-methylene-3-butenyl)benzenesulfonamide was obtained as a white solid. Yield: 76% (211 mg, 0.89 mmol). The spectroscopic data were in agreement with those reported.[35] (d) To a slurry of NaH (60% in mineral oil, 33 mg, 0.83 mmol) in DMF (1.0 mL) at 0 °C was added dropwise a solution of the above amine (196 mg, 0.83 mmol) in DMF (1.0 mL). The solution was stirred for 30 min at this temperature before adding propargyl bromide (80% wt in toluene, 92.0 μL, 0.82 mmol) and the solution was left to reach room temperature and stirred for 12 h. After extractive workup (Et_2O/water) and chromatography (90:8:2 hexane/EtOAc/Et_3N), enyne **49e** was obtained as a white solid. Yield: 84% (191 mg, 0.70 mmol). The spectroscopic data were in agreement with those reported.[36]

4.4.6. Dimethyl 3,4-divinyl-3-cyclopentene-1,1-dicarboxylate (50a). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.75 (dd, J=10.3, 17.7 Hz, 2H), 5.182 (d, J=10.3 Hz, 2H), 5.178 (d, J=17.7 Hz, 2H), 3.74 (s, 6H), 3.26 (s, 4H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 172.3 (C), 135.2 (C), 129.1 (CH), 115.9 (CH_2), 56.7 (C), 52.9 (CH_3), 40.9 (CH_2). ESI-HRMS calcd for $C_{13}H_{16}O_4Na$ [M^++Na]: 259.0946, found: 259.0934.

4.4.7. 1-[(Acetyloxy)methyl]-3,4-divinyl-3-cyclopenten-1-yl methyl acetate (50b). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.80 (dd, J=10.8, 17.2 Hz, 2H), 5.15–5.11 (m, 4H), 4.04 (s, 4H), 2.51 (4H), 2.07 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 171.1 (C), 136.1 (C), 129.7 (CH), 115.5 (CH_2), 67.2 (CH_2), 42.5 (C), 39.2 (CH_2), 20.8 (CH_3). EI-HRMS calcd for $C_{13}H_{16}O_4$: 236.1049, found: 236.1055.

4.4.8. 8,8-Dimethyl-2,3-divinyl-7,9-dioxaspiro[4,5]dec-2-ene (50c). ^{1}H NMR (400 MHz, C_6D_6): δ 6.74 (dd, J=10.7, 17.2 Hz, 2H), 5.09–5.02 (m, 4H), 3.41 (s, 4H), 2.35 (4H), 1.40 (s, 6H); ^{13}C NMR (100 MHz, C_6D_6, DEPT): δ 137.0 (C), 130.5 (CH), 115.1 (CH_2), 97.8 (C), 69.3 (CH_2), 40.7 (CH_2), 38.4 (C), 24.2 (CH_3). ESI-HRMS calcd for $C_{14}H_{21}O_2$: 221.1542, found: 221.1535.

4.4.9. Dimethyl 3-[(*E*)-1-pentenyl]-4-vinyl-3-cyclopentene-1,1-dicarboxylate (50d). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.76 (dd, J=11.4, 17.1 Hz, 1H), 6.46 (d, J=15.8 Hz, 1H), 5.69 (dt, J=7.1, 15.8 Hz, 1H), 5.133 (d, J=11.4 Hz, 1H), 5.125 (d, J=17.1 Hz, 1H), 3.750 (s, 3H), 3.748 (s, 3H), 3.24 (s, 4H), 2.13 (q, J=7.3 Hz, 2H), 1.43 (sextuplet, J=7.3 Hz, 2H), 0.92 (t apparent dd, J=7.6 and 7.3 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 172.5 (C), 135.2 (C), 133.7 (CH), 132.6 (C), 129.4 (CH), 122.1 (CH), 114.8 (CH_2), 56.8 (C), 52.9 (CH_3), 41.6 (CH_2), 40.8 (CH_2), 35.4 (CH_2), 22.5 (CH_2), 13.7 (CH_3). CI-HRMS: calcd for $C_{16}H_{23}O_4$ [M^++H]: 279.1596, found: 279.1602.

4.4.10. 1-[(4-Methylphenyl)sulfonyl]-3,4-divinyl-2,5-dihydro-1*H*-pyrrole (50e). White solid. Mp 122–125 °C (dec). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.75 (d, J=8.2 Hz, 2H), 7.33 (d, J=8.2 Hz, 2H), 6.6 (dd, J=10.9, 17.6 Hz, 2H), 5.23 (d, J=11.0 Hz, 2H), 5.08 (d, J=17.6 Hz, 2H), 4.30 (s, 4H), 2.42 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 143.6 (C), 133.9 (C), 132.5 (C), 129.8 (CH), 127.5 (CH), 126.9 (CH), 117.2 (CH_2), 55.0 (CH_2), 21.5 (CH_3). ESI-HRMS calcd for $C_{15}H_{17}NO_2NaS$ [M^++Na]: 298.0878; found: 298.0880.

4.4.11. (1*R,6*S**)-3-[(4-Methylphenyl)sulfonyl]-1-vinyl-3-azabicyclo[4.1.0]hept-4-ene (51).** White solid. Mp 55–55.5 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.66 (d, J=8.2 Hz, 2H), 7.32 (d, J=8.2 Hz, 2H), 6.35 (d, J=7.7 Hz, 1H), 5.48 (dd, J=10.3, 17.7 Hz, 1H), 5.42 (dd, J=5.8, 7.7 Hz, 1H), 4.97 (d, J=10.3 Hz, 1H), 4.93 (d, J=17.7 Hz, 1H), 3.97 (d, J=11.1 Hz, 1H), 2.99 (d, J=11.1 Hz, 1H), 2.42 (s, 3H), 1.21–1.16 (m, 1H), 0.95–0.92 (m, 1H), 0.81 (t, J=4.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$, DEPT): δ 143.8 (C), 140.3 (CH), 134.9 (C), 129.8 (CH), 127.0 (CH), 121.3 (CH), 112.0 (CH_2), 111.8 (CH), 43.1 (CH_2), 32.2 (C), 21.5 (CH), 19.6 (CH_2), 17.2 (CH). ESI-HRMS calcd for $C_{15}H_{17}NO_2NaS$ [M^++Na]: 298.0878, found: 298.0891.

Acknowledgements

We are grateful to the MEC (project CTQ2004-02869, Consolider Ingenio 2010, Grant CSD2006-0003, and PFU predoctoral fellowship to M.R.), the AGAUR (project 2005 SGR 00993, predoctoral and postdoctoral fellowships to C.F. and C.K.C., respectively), the Comunidad de Madrid (predoctoral fellowship to C.N.), and the ICIQ Foundation for financial support. We also thank E. Escudero-Adán and Dr. J. Benet-Buchholz (X-ray diffraction unit, ICIQ) for the structure of **30**.

References and notes

1. Lloyd-Jones, G. C. *Org. Biomol. Chem.* **2003**, 215–236.
2. Diver, S. T.; Giessert, A. J. *Chem. Rev.* **2004**, *104*, 1317–1382.
3. Echavarren, A. M.; Nevado, C. *Chem. Soc. Rev.* **2004**, *33*, 431–436.
4. Jiménez-Núñez, E.; Echavarren, A. M. *Chem. Commun.* **2007**, 333–346.
5. (a) Zhang, L.; Sunm, J.; Kozmin, S. A. *Adv. Synth. Catal.* **2006**, *348*, 2271–2296; (b) Hashmi, A. S. K.; Hutchings, G. J. *Angew. Chem., Int. Ed.* **2006**, *45*, 7896–7936.
6. (a) Méndez, M.; Muñoz, M. P.; Echavarren, A. M. *J. Am. Chem. Soc.* **2000**, *122*, 11549–11550; (b) Méndez, M.; Muñoz, M. P.; Nevado, C.; Cárdenas, D. J.; Echavarren, A. M. *J. Am. Chem. Soc.* **2001**, *123*, 10511–10520.
7. Nevado, C.; Charruault, L.; Michelet, V.; Nieto-Oberhuber, C.; Muñoz, M. P.; Méndez, M.; Rager, M. N.; Genêt, J.-P.; Echavarren, A. M. *Eur. J. Org. Chem.* **2003**, 706–713.
8. Nevado, C.; Cárdenas, D. J.; Echavarren, A. M. *Chem.—Eur. J.* **2003**, *9*, 2627–2635.
9. Nieto-Oberhuber, C.; López, S.; Jiménez-Núñez, E.; Echavarren, A. M. *Chem.—Eur. J.* **2006**, *11*, 5916–5923.
10. (a) Nieto-Oberhuber, C.; Muñoz, M. P.; Buñuel, E.; Nevado, C.; Cárdenas, D. J.; Echavarren, A. M. *Angew. Chem., Int. Ed.* **2004**, *43*, 2402–2406; (b) Muñoz, M. P.; Adrio, J.;

Carretero, J. C.; Echavarren, A. M. *Organometallics* **2005**, *24*, 1293–1300; (c) Nieto-Oberhuber, C.; Muñoz, M. P.; López, S.; Jiménez-Núñez, E.; Nevado, C.; Herrero-Gómez, E.; Raducan, M.; Echavarren, A. M. *Chem.—Eur. J.* **2006**, *11*, 1677–1693; (d) Nieto-Oberhuber, C.; López, S.; Muñoz, M. P.; Jiménez-Núñez, E.; Buñuel, E.; Cárdenas, D. J.; Echavarren, A. M. *Chem.—Eur. J.* **2006**, *11*, 1694–1702; (e) Nieto-Oberhuber, C.; López, S.; Echavarren, A. M. *J. Am. Chem. Soc.* **2005**, *127*, 6178–6179; (f) Nieto-Oberhuber, C.; López, S.; Muñoz, M. P.; Cárdenas, D. J.; Buñuel, E.; Nevado, C.; Echavarren, A. M. *Angew. Chem., Int. Ed.* **2005**, *44*, 6146.

11. Toullec, P. Y.; Genin, E.; Leseurre, L.; Genêt, J.-P.; Michelet, V. *Angew. Chem., Int. Ed.* **2006**, *45*, 7427–7430.
12. Amijs, C. H. M.; Ferrer, C.; Echavarren, A. M. *Chem. Commun.* **2007**, 698–700.
13. López, S.; Herrero-Gómez, E.; Pérez-Galán, P.; Nieto-Oberhuber, C.; Echavarren, A. M. *Angew. Chem., Int. Ed.* **2006**, *45*, 6029–6032.
14. Lee, S. I.; Kim, S. M.; Kim, S. Y.; Chung, Y. K. *Synlett* **2006**, 2256–2260.
15. Nevado, C.; Ferrer, C.; Echavarren, A. M. *Org. Lett.* **2004**, *6*, 3191–3194.
16. Pt(II) and Au(III)-catalyzed methoxycyclization of enol ethers with alkynes: See Ref. 8.
17. Skeletal rearrangement of enynes catalyzed by $PtCl_4$: (a) Oh, C. H.; Bang, S. Y.; Rhim, C. Y. *Bull. Korean Chem. Soc.* **2003**, *24*, 887–888; See also: (b) Blum, J.; Beer-Kraft, H.; Badrieh, Y. *J. Org. Chem.* **1995**, *60*, 5567–5569; (c) Fürstner, A.; Szillat, H.; Gabor, B.; Mynott, R. *J. Am. Chem. Soc.* **1998**, *120*, 8305–8314; (d) Fürstner, A.; Szillat, H.; Stelzer, F. *J. Am. Chem. Soc.* **2000**, *122*, 6785–6786.
18. Fornies, J.; Martin, A.; Navarro, R.; Sicilia, V.; Villarroya, P. *Organometallics* **1996**, *15*, 1826–1833.
19. Herrero-Gómez, E.; Nieto-Oberhuber, C.; López, S.; Benet-Buchholz, J.; Echavarren, A. M. *Angew. Chem., Int. Ed.* **2006**, *45*, 5455–5459.
20. Crystallographic data (excluding structure factors) for **30** has been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC 633407. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: +44 (0)1223 336033 or e-mail: deposit@ccdc.cam.ac.uk).
21. Nevado, C.; Echavarren, A. M. *Tetrahedron* **2004**, *60*, 9735–9744.
22. For a recent discussion on the nature of the actual catalyst in reactions performed with AuCl, see: Lemière, G.; Gandon, V.; Agenet, N.; Goddard, J.-P.; de Kozak, A.; Aubert, C.; Fensterbank, L.; Malacria, M. *Angew. Chem., Int. Ed.* **2006**, *45*, 7596–7599.
23. ten Wolde, A.; Dekkers, H. P. J. M.; Jacobs, H. J. C. *Tetrahedron* **1993**, *27*, 6045–6052.
24. de Fremont, P.; Scott, N. M.; Stevens, E. D.; Nolan, S. P. *Organometallics* **2005**, *24*, 2411–2418.
25. Lebouc, A.; Delaunay, J.; Riobe, O. *Synthesis* **1979**, 610–613.
26. Bao, R.; Valverde, S.; Herradon, B. *Synlett* **1992**, 217–219.
27. Faller, J. W.; Fontaine, P. P. *J. Organomet. Chem.* **2006**, *691*, 1912–1918.
28. Hoye, T. R.; Suriano, J. A. *Organometallics* **1992**, *11*, 2044–2050.
29. Trost, B. M.; Lee, D. C.; Rise, F. *Tetrahedron Lett.* **1989**, *30*, 651–654.
30. Kang, S. K.; Ko, B. S.; Lee, D. M. *Tetrahedron Lett.* **2002**, *43*, 6693–6696.
31. Fürstner, A.; Stelzer, F.; Szillat, H. *J. Am. Chem. Soc.* **2001**, *123*, 11863–11869.
32. Uchiyama, T.; Toshiyasu, Y.; Nakamura, Y.; Miwa, T.; Kawaguchi, S. *Bull. Chem. Soc. Jpn.* **1981**, *54*, 181–185.
33. Bailey, M. D.; Halmos, T.; Adamson, D.; Bordeleau, J.; Grand-Maître, C. *Tetrahedron: Asymmetry* **1999**, *10*, 3285–3295.
34. Neustadt, R. *Tetrahedron Lett.* **1994**, *35*, 379–380.
35. Feldman, K. S.; Mareska, D. A. *J. Org. Chem.* **1999**, *64*, 5650–5660.
36. Bertolini, T. M.; Nguyen, Q. H.; Harvey, D. F. *J. Org. Chem.* **2002**, *67*, 8675–8678.