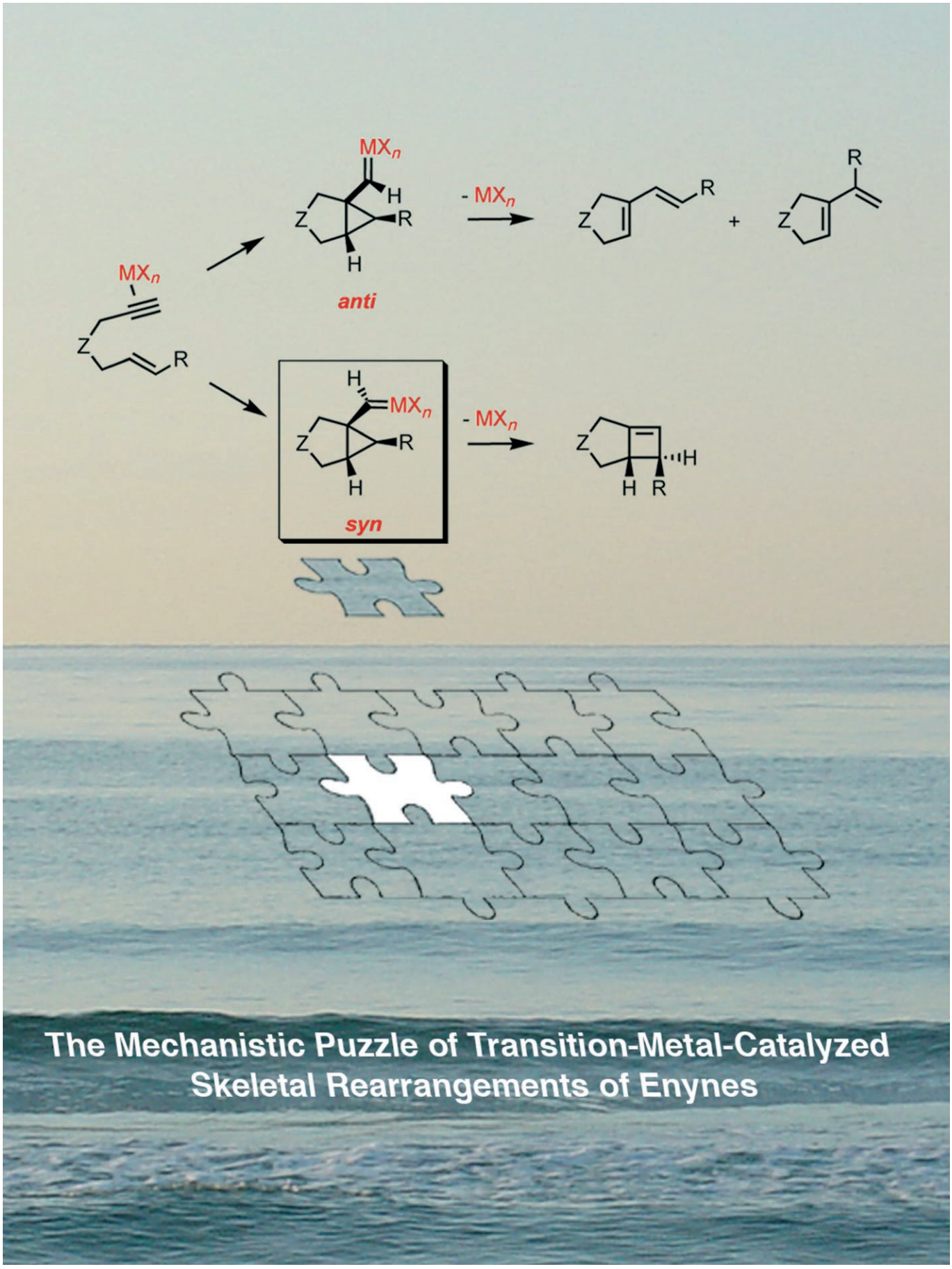


DOI: 10.1002/chem.200600174

The Mechanistic Puzzle of Transition-Metal-Catalyzed Skeletal Rearrangements of Enynes

Cristina Nieto-Oberhuber, Salomé López, Eloísa Jiménez-Núñez, and Antonio M. Echavarren*[a]

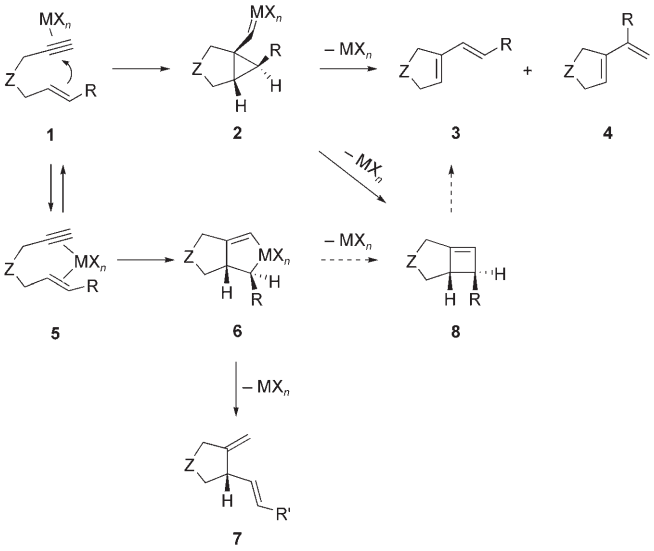
Abstract: Three pathways actually compete in metal-catalyzed cyclizations of enynes in which the metal selectively activates the alkyne: an endocyclic process and two *exo*-cyclizations, one proceeding by *anti* attack of the alkene and a second one resulting in a *syn* addition. Although cyclobutenes may be formed in transition-metal-catalyzed cyclization of some enynes, particularly, 1,7-enynes, these compounds are not necessarily the intermediates in the skeletal rearrangement. Cyclobutenes are formed by ring expansion of *syn*-cyclopropyl metal–carbenes formed in the *syn* pathway.

Keywords: alkynes · cyclization · density functional calculations · gold · rearrangement

Introduction

Reactions of enynes catalyzed by electrophilic late-transition-metal complexes have attracted much attention because of the great diversity of products that can be obtained from rather simple substrates under experimentally simple conditions. However, this very same diversity can be viewed as a drawback from the synthetic point of view as the outcome of a particular transformation may be difficult to predict. Therefore, determining the mechanisms of these transformations is of primary importance to gain predictive power for their application in the synthesis of complex structures.[1,2]

Earlier work on Pt^{II}-catalyzed alkoxy and hydroxycyclizations has identified two clearly distinct reaction pathways (Scheme 1).[2,3] If the metal coordinates exclusively with the alkyne as in **1**, cyclopropyl metal–carbenes **2** are initially formed that can react with alcohols or water to give products of alkoxy- or hydroxycyclization. In the absence of nucleophiles, skeletal rearrangement takes place to form dienes **3** and/or **4**.[1,4–9] Alternatively, coordination of MX_n to the alkyne and the alkene (as in **5**) is followed by oxidative cyclometalation to form **6**, which usually evolves by β-hydrogen elimination to give Alder–ene type products **7**.[1,2] Formation of products **3** could also result by conrotatory ring-opening of cyclobutenes **8**,[1,10,11] formed from **2** or by reductive elimination of **6**.

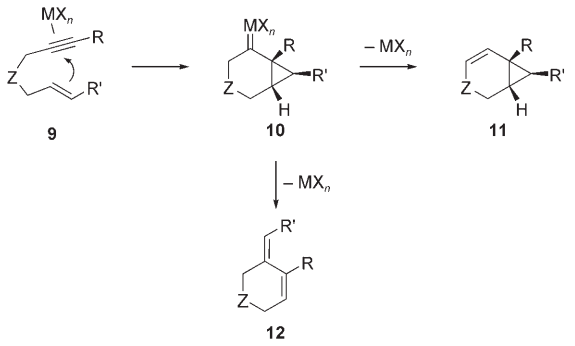


Scheme 1. e*xo*-Cyclizations of 1,6-enynes.

Enynes substituted at the alkyne usually cyclize by the *endo* pathway via **9** and **10** to give products such as **11**.[2d,5b,c,12,13] By using cationic gold(I) complexes $[Au(L)(S)]^+X^-$ as catalysts we uncovered the first examples of *6-endo-dig* skeletal rearrangements that lead to products of type **12**,[2,3,5b,c,14] a reaction of enynes that had not been

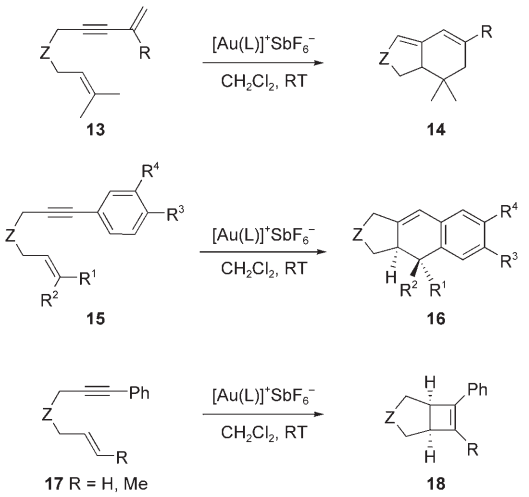
[a] C. Nieto-Oberhuber, Dr. S. López, E. Jiménez-Núñez, Prof. Dr. A. M. Echavarren
Institute of Chemical Research of Catalonia (ICIQ)
Av. Països Catalans 16, 43007 Tarragona (Spain)
Fax: (+34) 977-920-255
E-mail: aechavarren@iciq.es

reported before with other transition-metal catalysts (Scheme 2).



Scheme 2. *endo*-Cyclizations of 1,6-enynes.

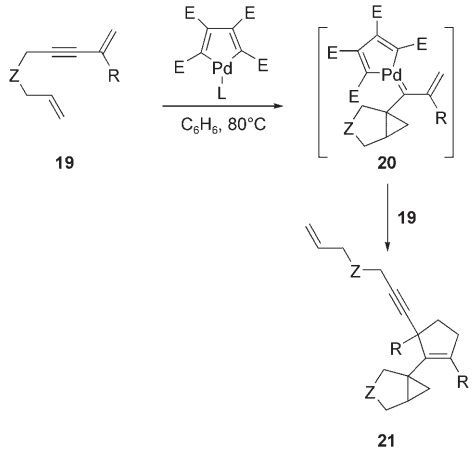
Substitution at the alkyne may lead to different reactions. Thus, dienynes **13** react with cationic Au^{I} catalysts leading to products of formal [4+2] cycloaddition **14** (Scheme 3).[15]



Scheme 3. Cyclizations of 1,6-enynes substituted at the alkyne with alkenyl or aryl groups.

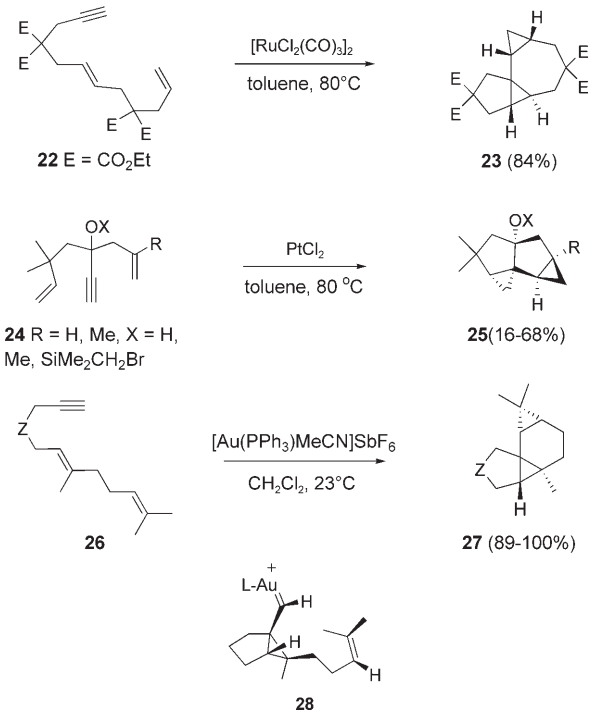
The analogous thermal intramolecular [4+2] cycloadditions (dehydro-Diels–Alder reactions) of dienynes, such as 2-methylnona-1,8-dien-3-yne, only take place temperatures as high as 600 °C.[16] Similarly, enynes **15** substituted at the alkyne with an aryl group led to products **16** resulting from a formal intramolecular [4+2] cycloaddition occurring at an unusual low temperature.[15] On the other hand, substrates **17** with R = H or Me gave cyclobutenes **18** with Au^{I} catalysts.[17,18]

We proposed the involvement of intermediates **2** and **10** in Pt^{II}- and Au^{I}-catalyzed cyclizations of enynes based on DFT calculations[2a,b,14] and on the isolation of cyclopropyl carbaldehyde in Pt^{II}[2b] or Pd^{II} hydroxycyclization[3a] of certain enynes. Cyclopropyl derivatives **21** had been actually obtained first by Trost et al. in the dimerization of dienynes **19** catalyzed by Pd^{II} complexes in a process that probably takes place by a [4+2] cycloaddition of intermediate **20** with the double bond of the conjugate enyne (Scheme 4).[19]



Scheme 4. Pd^{II}-catalyzed dimerization of dienynes **19** via intermediate **20**.

Strong evidence for the existence of intermediates **2** was obtained in the reaction of dienynes catalyzed by electrophilic metal complexes described by the groups of Murai[20] and Malacria[21] (Scheme 5). In the cyclization of **22**, the ruthenium–carbene intermediate is trapped intramolecularly by the terminal alkene to give tetracycle **23**, containing two cyclopropane units. Similarly, the $PtCl_2$-catalyzed reaction of substrates **24** forms tetracycles **25**.[22] By using Au^{I} catalysts, we have also found totally stereoselective cyclizations of di-



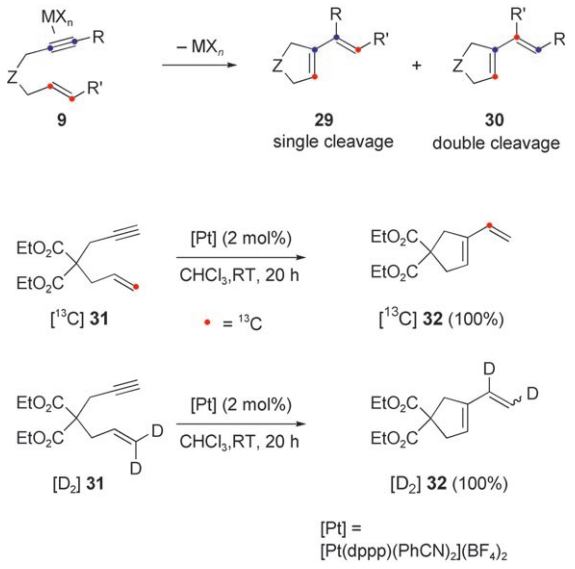
Scheme 5. Biscyclopropanations of dienynes.

enynes **26** to give **27** that proceed through intermediates **28** under remarkably mild conditions.[14a,23]

A pathway for the formation of skeletal rearrangement products **3** through the opening of cyclobutenes **8** is favored by most authors.[4–6,9,24] However, formation of dienes **4** requires a different mechanistic explanation. Herein we present a concise mechanistic framework that accounts for the experimental results and that indicates that once the alkyne is activated by coordination with an electrophilic transition metal, the alkene can react in two manners: in addition to the more common *anti* pathway, a *syn* attack of the alkene is also possible.

Two Different Types of Skeletal Rearrangements

Pioneer work by Trost by using Pd^{II} catalysts[4] established that two different types of skeletal rearrangement can compete in reactions of enynes **9** leading to 1,3-dienes **29** and **30** (Scheme 6). These rearrangements were later found to take

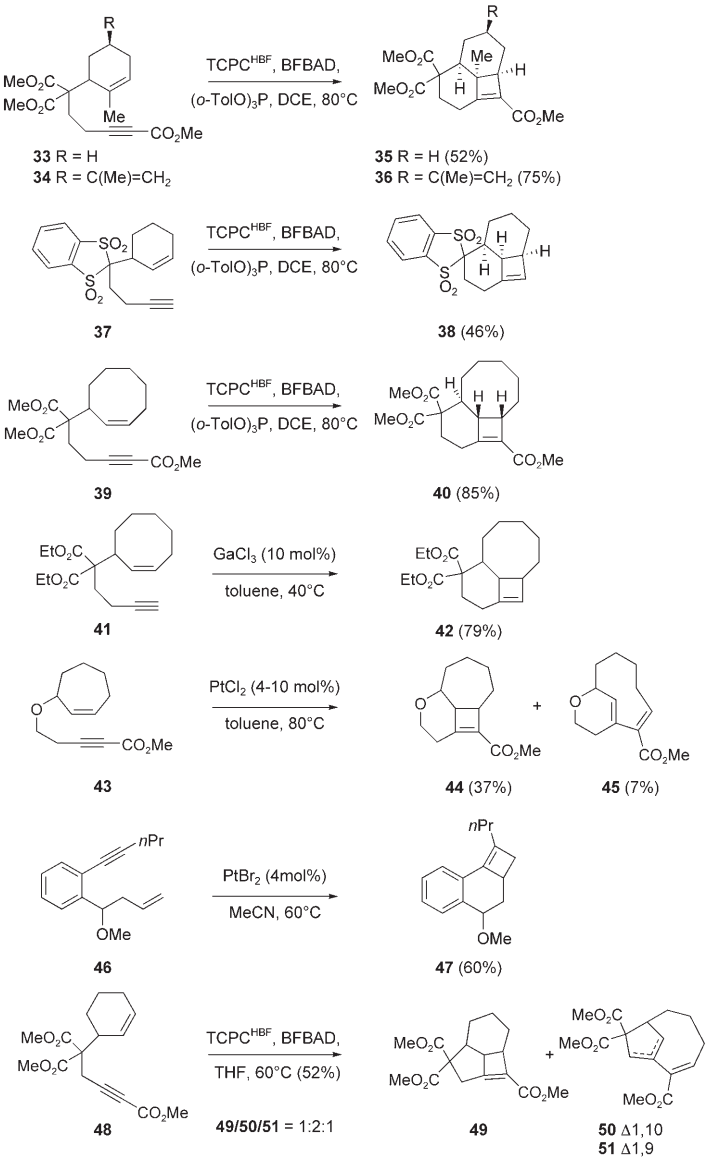


Scheme 6. Single- and double-cleavage rearrangement of 1,6-enyens.

place more efficiently with Pt^{II}, Ru^{II}, Ga^{III}, and other catalysts.[5–7,9] In products **29**, the terminal alkene carbon has migrated to the terminus of the alkyne (single cleavage rearrangement), whereas for the formation of products **30** both the alkene and the alkyne are cleaved (double-cleavage rearrangement). In general, single cleavage is favored for enynes unsubstituted at the alkyne (R = H), although malonate **31** (R = R′ = H) reacts exclusively by the double-cleavage pathway.[7] A similar result had been observed before with $PtCl_2$ as catalyst.[6b] Enynes substituted with alkyl or ester groups at the alkyne usually suffer double cleavage rearrangement.[4,6,7]

[2+2] Cycloaddition of Enynes

Although less common, 1,7-enynes can also undergo skeletal rearrangement reactions.[5–7] More interestingly, certain 1,7-enynes give products of formal [2+2] cycloaddition (Scheme 7). Thus, Trost found that 1,7-enynes **33** and **34** react with a Pd^{II} catalyst formed in situ to form tricyclic derivatives **35** and **36**, respectively.[4c] Similarly, disulfone **37** provided **38** with the same relative configuration as **35** and **36**.[4c] Enyne **39**, with a cyclooctene ring afforded **40** with a *cis-trans* tricyclic ring system.[4c] The group of Chatani and Murai reported a similar transformation of **41** to give **42** using $GaCl_3$ as the catalyst.[6d] By using $PtCl_2$, Fürstner et al. reported a single example of cyclobutene formation in the



Scheme 7. Formation of cyclobutenes by [2+2] cycloaddition of 1,7-enynes. TCPC^{HBF} = 2,3,4,5-tetrakis(heptafluorobutyl)palladacyclopentadiene; BFBAD = bis(heptafluorobutyl) acetylenedicarboxylate; DCE = 1,2-dichloroethane.

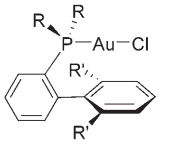
reaction of **43**. In this case, in addition to **44**, diene **45**, the product of skeletal rearrangement was also obtained.[5c] Formation of cyclobutenes and dienes in these reactions has been considered as an evidence for the involvement of the former as intermediates in the skeletal rearrangement. Recently, the group of Yamamoto reported the formation of **47** in the reaction of **46** with $PtBr_2$ as the catalyst.[11] In this example, cyclobutene **47** was shown to undergo conrotatory opening, although only after being heated in MeCN at 120 °C for 14 h.

The only example of a cyclobutene isolated in a cyclization of a 1,6-enyne was reported by Trost in the cyclization of substrate **48**[4b] (Scheme 7).[25] In this transformation, in addition to **49**, with a strained bicyclo [3.2.0]hept-5-ene system, skeletal rearrangement product **50** and an isomerized derivative **51** were also obtained.

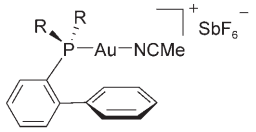
Au^I-Catalyzed Skeletal Rearrangements and [2+2] Cycloadditions

Au^I catalysts have been shown to be particularly active for the cyclization of 1,6-enynes.[14,15,23,27] These complexes also promote a variety of reactions of 1,5-enynes.[26] Alder-ene type products have not been observed in Au^I-catalyzed reactions, which is consistent with the selective coordination of cationic complexes $[Au(L)]^+$ to the alkyne.

We have found that Au^I species formed from complexes **52a–c** and $AgSbF_6$,[15] or cationic complexes **53a**,**b**[27] are



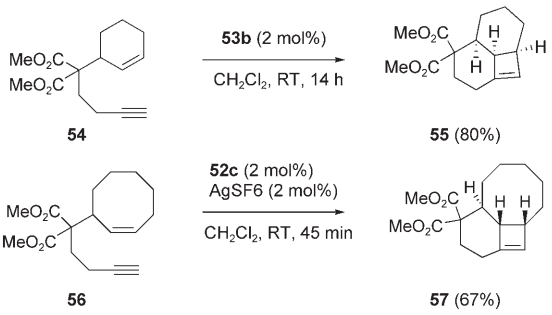
52a R = Cy, R' = H
52b R = *t*Bu, R' = H
52c R = Cy, R' = OMe



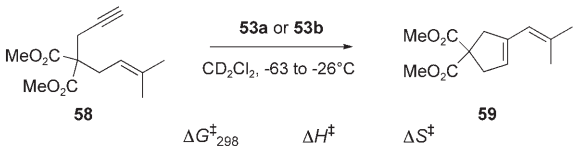
53a R = Cy
53b R = *t*Bu

particularly active catalysts for the cyclization of enynes.[14b,23] Thus, enyne **54** reacts with catalyst **53b** to give cleanly **55** at room temperature. Similarly, reaction of enyne **56** with a cationic Au^I catalyst generated from **52c** gave **57** (Scheme 8). Tricycles **55** and **57** did not undergo ring-opening at 120–150 °C to form 1,3-dienes. In addition, no opening was observed after being heated in the presence of $PtCl_2$.[11,27,28]

Single-cleavage rearrangement of enyne **58** to form quantitatively **59** could be carried at a temperature as low as −63 °C with catalyst **53a** (Scheme 9). Importantly, no intermediate was observed during clean formation of diene **59** from **58** by ^1H NMR spectroscopy in CD_2Cl_2. The rearrangement was found to be pseudo-first-order in **58**, which led to the determination the thermodynamic parameters shown in Scheme 9. These results indicate that the reaction proceeds with a low enthalpic barrier and the process is a entropically



Scheme 8. Formation of cyclobutenes by [2+2] cycloaddition of 1,7-enynes with Au^I catalysts.

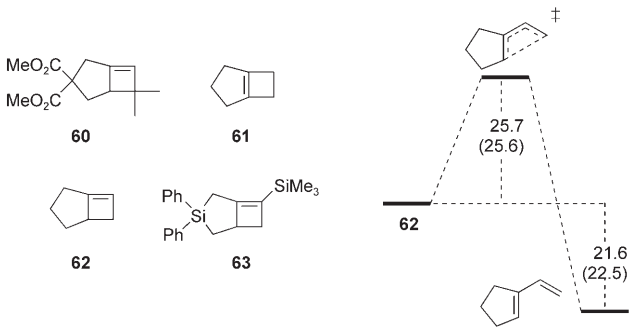


	$\Delta G^{\ddagger}_{298}$	$\Delta H^{\ddagger}$	$\Delta S^{\ddagger}$
53a	21.7 ± 1.1	3.7 ± 0.3	-60.6 ± 1.2
53b	21.2 ± 2.1	6.2 ± 0.5	-50.3 ± 2.0

Scheme 9. $\Delta G^{\ddagger}_{298}$ and $\Delta H^{\ddagger}$ in kcal mol^{-1}, $\Delta S^{\ddagger}$ in cal mol^{-1} K^{-1}.

controlled. The large and negative activation entropies suggest that an associative ligand substitution[29] is the rate-determining step of the process. Most probably this corresponds to the last step in the catalytic cycle, namely the substitution of diene **59** coordinated to Au^I by the incoming enyne **58**.

These results establish a very low activation energy for the hypothetical conrotatory opening of cyclobutene **60** (Scheme 10) formed as an intermediate, which should be a fast process at temperatures as low as −63 °C. However, this is not consistent with experimental data for the thermal opening of cyclobutenes.[30] Thus, for the ring-opening of bicycle **61** and its 6,7-dimethyl derivatives,[31] activation energies of 29.0–32.7 kcal mol^{-1} and low entropies of activation (1.4–2.2 cal mol^{-1}) have been determined. In addition, DFT calculations predict an E_a of 25.6 kcal mol^{-1} for the conrotatory opening of bicyclo[3.2.0]hept-5-ene (**62**) to form 1-vinyl-1-cyclopentene. It is interesting that **62** has been calcu-



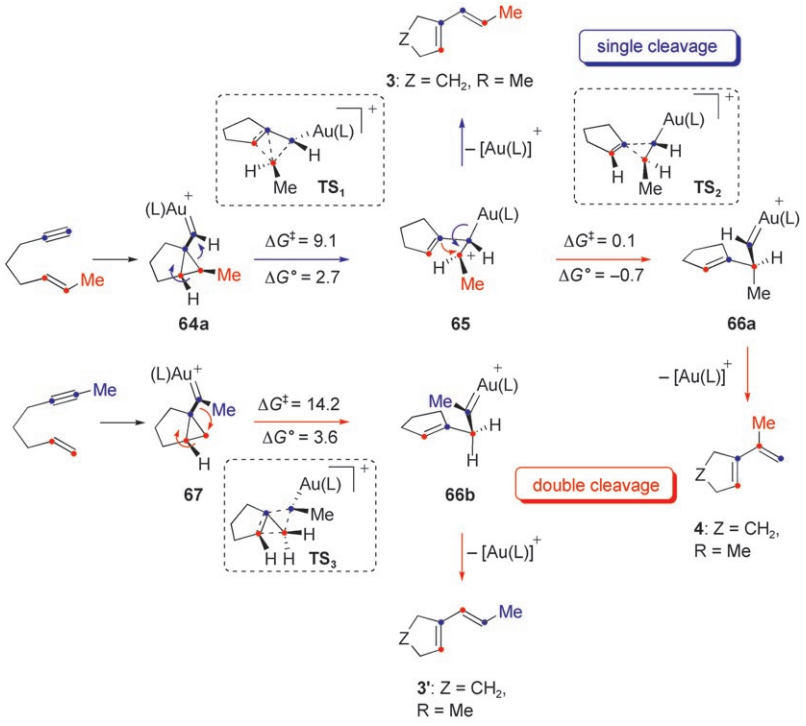
Scheme 10. Bicyclo[3.2.0]hept-5-ene (**62**) and related compounds and reaction coordinate for the conrotatory opening of **62**. ZPE-corrected energies are given in kcal mol^{-1}.[35] $\delta G^{\ddagger}$ and ΔG (298 K) in parentheses.

lated to be a less strained olefin (olefin strain = 16.7 kcal mol^{-1}) than **61** (olefin strain = 20.5 kcal mol^{-1}), which is an olefin stable up to 118 °C.[32] Additional evidence against the opening of a cyclobutene in the low-temperature skeletal rearrangement of 1,6-enynes is provided by the isolation of **49** from **48**[4b] in a reaction carried out at 60 °C (Scheme 7) and by the isolation of bicycle **63** as a stable compound.[33] Interestingly, bicyclo[3.2.0]hept-5-enes have been recently built by the thermal reaction of *gem*-disubstituted fuller-1,6-enynes.[34]

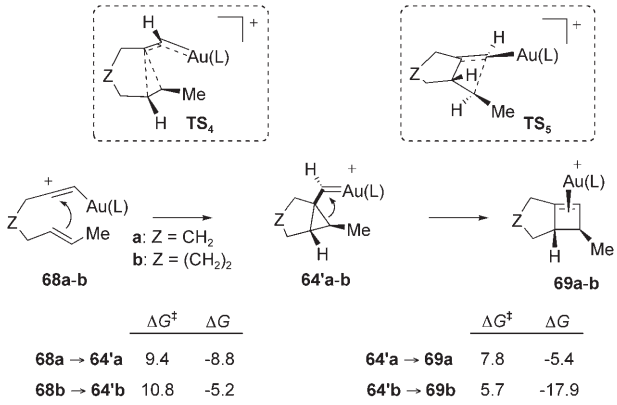
DFT calculations[35] support pathways for the skeletal rearrangement that do not involve the intermediacy of cyclobutenes. Thus, complex **64a** evolves via $\mathbf{TS_1}$ to form cation **65**, which would furnish dienes **3** by elimination of [Au(L)]$^+$ (Scheme 11).[27] Alternatively, a 1,2-alkenyl shift gives gold carbene **66a** via $\mathbf{TS_2}$ through an almost flat potential surface. Dienes **4** would result from **66a** by β-hydrogen elimination and demetalation. This β-hydrogen elimination probably involves a tautomerization of the carbene, followed by a proto-demetalation of the resulting alkenyl–metal complex.[5c] Intermediate **67** would be formed in the cyclization of 1-hepten-6-yne, a model for enynes substituted at the alkyne. In this case, the double cleavage rearrangement was found to give directly intermediate **66b**. This process is mechanistically quite remarkable as it involves a 1,2-shift of a metal–carbene with concomitant cleavage of the distal C–C bond of the cyclopropane and formation of a double bond.

The involvement of carbenes **66a** and **66b** as reactive intermediates nicely accounts for the deuterium labeling experiments (see reaction of [D$_2$]**31** to give [D$_2$]**32**,[7] Scheme 6) and the formation of mixtures of *E*/*Z* isomers in the double cleavage rearrangement of enynes bearing esters at the alkyne.[6a,b,c] On the other hand, single-cleavage skeletal rearrangements are stereospecific: the configuration at the alkene is retained in the final 1,3-diene product.[4–7,14]

Scheme 11 provides an explanation for the single- and double-cleavage rearrangements that does not involve the intermediacy of any cyclobutene. Indeed, a direct pathway for the formation of a cyclobutene from **64a** was not found. Similar results were obtained with the platinum analogue of **64a**. In contrast, *syn*-**64′a** forms **69a** via $\mathbf{TS_5}$ (Scheme 12). This ring expansion is more favorable for the formation of bicyclo[3.2.0]oct-6-enes from 1,7-enynes (**64′b** to **69b**) in accordance to experiments (see Scheme 7). Importantly, complexes *syn*-**64′a**,**b** are formed by a *syn*-type attack of the alkene to the (alkyne)gold moiety of **68a**,**b** via transition states such as $\mathbf{TS_4}$.



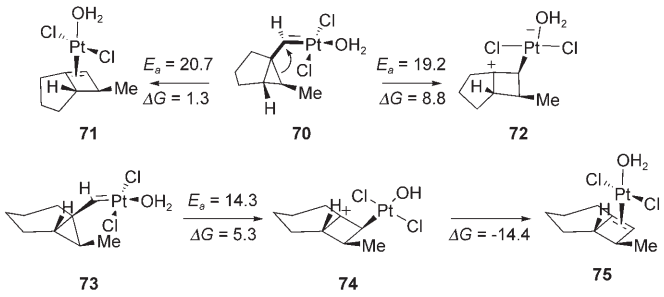
Scheme 11. L = PH$_3$. Δ*G* at 298 K (energies in kcal mol^{-1}).[35]



Scheme 12. L = PH$_3$. Δ*G* at 298 K (energies in kcal mol^{-1}).

The *anti* to *syn* isomerization from **64a** to **64′a** ($\Delta G^{\ddagger}$ = 3.1 kcal mol^{-1}) requires a rather high activation energy of 24.7 kcal mol^{-1}, which can be attributed to the loss of conjugation between the gold carbene and the cyclopropane. This isomerization process is rather unlikely under the reaction conditions, as the initially formed *anti*-**64a** would rather suffer a more facile rearrangement via **65** ($\Delta G^{\ddagger}$ = 9.1 kcal mol^{-1}, Scheme 11).

Related Pt^{II} carbene **70** gives cyclobutene **71** or cyclobutyl cation derivative **72**, in which the carbocationic center is stabilized by one of the chloride ligands (Scheme 13).[36] Again,

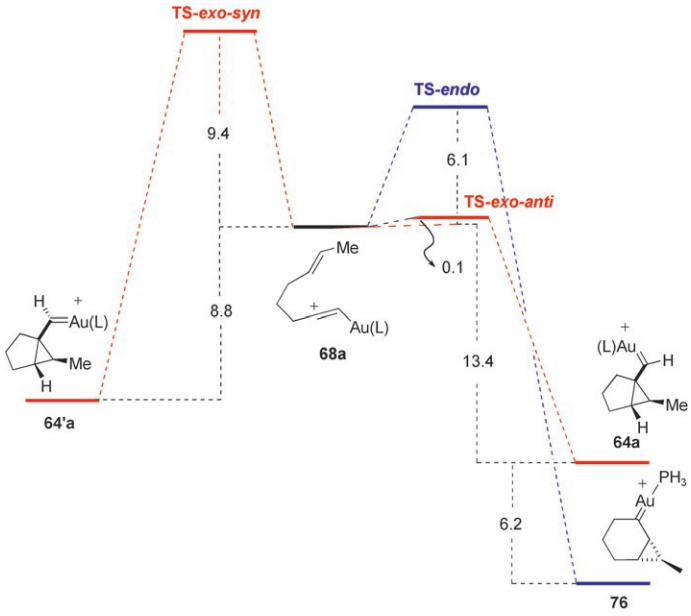


Scheme 13. L = PH_3. ΔG at 298 K (energies in kcal mol^{-1}).

the ring expansion is more facile for **73**, which would be formed from the corresponding 1,7-enynes. In this case, carbocation **74** is formed first, which then probably evolves to form more stable cyclobutene **75**.

General Pathways for the Cyclization of Enynes

Scheme 14 illustrates a more complete energy diagram that includes the three possible pathways for the intramolecular reaction of an alkene with an alkyne coordinated with a transition metal: an *endo* cyclization leading to **76** and two *exo* pathways giving **64a** or **64′a**. The relative energies of intermediates in this scheme should be taken only as an approximation of the real systems in which phosphines much bulkier than model PH_3 group are involved. In addition, substituents at the alkene, the alkyne, or the chain should alter significantly the relative heights of the transition states involved. As the calculated activation energies for the three processes are lower than 10–11 kcal mol^{-1}, probably the outcome of any particular reaction would depend on the relative rates of subsequent transformations of the three intermediates involved in equilibria, with the starting enyne coordinated to the transition metal.



Scheme 14. L = PH_3. ΔG at 298 K (energies in kcal mol^{-1}).

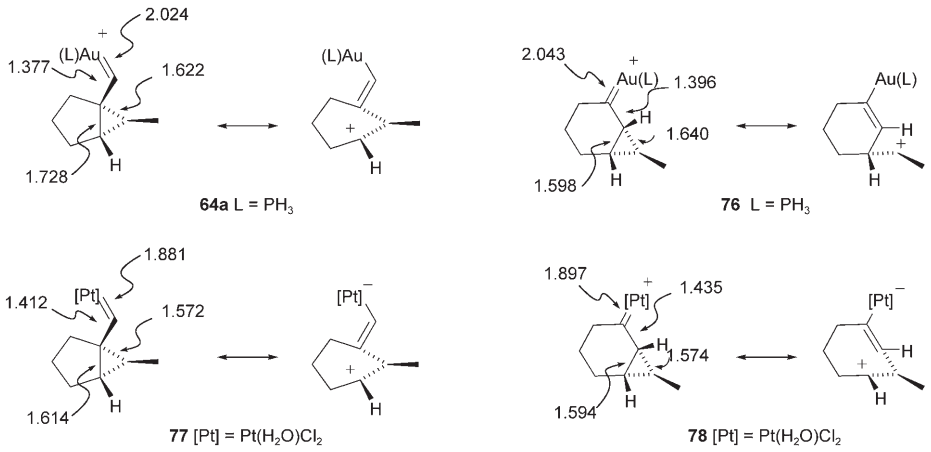
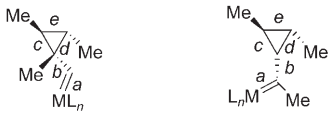


Figure 1. Cyclopropyl Au^{I} and Pt^{II} carbenes.

Structures of Cyclopropyl Metal–Carbenes

Finally, it is important to recall that, although intermediates involved in these processes may be drawn as cyclopropyl metal–carbenes, these species present highly distorted structures, particularly for the most electrophilic cationic Au^{I} complexes such as **64a** and **76** (Figure 1).[14,23] As shown for **64a**, and **76**–**78** the C–C bond connecting the carbene and the cyclopropane is rather short, consistent with a substantial double-bond character. This trend is also found in more simple models **79** and **80** for *exo* and *endo* cyclopropyl metal–carbenes (Table 1),[14a] which indicates that the elec-

Table 1. Calculated bond distances [Å] for cyclopropyl metal-carbenes.



ML_n	Complex	*a*	*b*	*c*	*d*	*e*
trans-Pd(H_2O)Cl_2	exo	1.879	1.419	1.619	1.563	1.470
trans-Pd(H_2O)Cl_2	*endo*	1.898	1.437	1.551	1.585	1.474
trans-Pt(H_2O)Cl_2	*exo*	1.891	1.401	1.655	1.558	1.467
trans-Pt(H_2O)Cl_2	*endo*	1.902	1.418	1.561	1.598	1.468
$AuCl_3$	*exo*	2.010	1.384	1.710	1.551	1.467
$AuCl_3$	*endo*	1.895	1.418	1.561	1.599	1.467
$[AuPH_3]^+$	*exo*	2.024	1.380	1.748	1.586	1.449
$[AuPH_3]^+$	*endo*	2.046	1.395	1.611	1.650	1.444

trophilicity of the metal centers increases in the order: Pd-$(H_2O)Cl_2 < Pt(H_2O)Cl_2 < AuCl_3 < Au(PH_3)^+$.

Acknowledgements

This work was supported by the MEC (project CTQ2004–02869, predoctoral fellowships to C.N.-O., E. J.-N., and a Torres Quevedo contract to S.L.), and the ICIQ Foundation. We thank Dr. D. J. Cárdenas, Dr. E. Buñuel, Dr. C. Nevado, and Dr. M. P. Muñoz for their contributions to different aspects of this work and Johnson Matthey PLC for a loan of metal salts.

[1] Reviews: a) G. C. Lloyd-Jones, *Org. Biomol. Chem.* **2003**, *1*, 215–236; b) C. Aubert, O. Buisine, M. Malacria, *Chem. Rev.* **2002**, *102*, 813–834; c) S. T. Diver, A. Giessert, *J. Chem. Rev.* **2004**, *104*, 1317–1382; d) A. M. Echavarren, M. Méndez, M. P. Muñoz, C. Nevado, B. Martín-Matute, C. Nieto-Oberhuber, D. J. Cárdenas, *Pure Appl. Chem.* **2004**, *76*, 453–463; e) A. M. Echavarren, C. Nevado, *Chem. Soc. Rev.* **2004**, *33*, 431–436; f) L. Añorbe, G. Domínguez, J. Pérez-Castells, *Chem. Eur. J.* **2004**, *10*, 4938–4943; g) C. Bruneau, *Angew. Chem.* **2005**, *117*, 2380–2386; *Angew. Chem. Int. Ed.* **2005**, *44*, 2328–2334; h) S. Ma, S. Yu, Z. Gu, *Angew. Chem.* **2006**, *118*, 206–209; *Angew. Chem. Int. Ed.* **2006**, *45*, 200–203.

[2] a) M. Méndez, M. P. Muñoz, A. M. Echavarren, *J. Am. Chem. Soc.* **2000**, *122*, 11549–11550; b) M. Méndez, M. P. Muñoz, C. Nevado, D. J. Cárdenas, A. M. Echavarren, *J. Am. Chem. Soc.* **2001**, *123*, 10511–10520; c) C. Nevado, D. J. Cárdenas, A. M. Echavarren, *Chem. Eur. J.* **2003**, *9*, 2627–2635; d) C. Nevado, C. Ferrer, A. M. Echavarren, *Org. Lett.* **2004**, *6*, 3191–3194; e) M. P. Muñoz, J. Adrio, J. C. Carretero, A. M. Echavarren, *Organometallics* **2005**, *24*, 1293–1300.

[3] a) C. Nevado, L. Charruault, V. Michelet, C. Nieto-Oberhuber, M. P. Muñoz, M. Méndez, M. N. Rager, J.-P. Genêt, ; A. M. Echavarren, *Eur. J. Org. Chem.* **2003**, 706–713; b) M. P. Muñoz, M. Méndez, C. Nevado, D. J. Cárdenas, A. M. Echavarren, *Synthesis* **2003**, 2898–2902.

[4] a) B. M. Trost, G. J. Tanoury, *J. Am. Chem. Soc.* **1988**, *110*, 1636–1638; b) B. M. Trost, M. K. Trost, *Tetrahedron Lett.* **1991**, *32*, 3647–3650; c) B. M. Trost, M. Yanai, K. Hoogsteed, *J. Am. Chem. Soc.* **1993**, *115*, 5294–5295.

[5] a) A. Fürstner, H. Szillat, B. Gabor, R. Mynott, *J. Am. Chem. Soc.* **1998**, *120*, 8305–8314; b) A. Fürstner, H. Szillat, F. Stelzer, *J. Am. Chem. Soc.* **2000**, *122*, 6785–6786; c) A. Fürstner, F. Stelzer, H. Szillat, *J. Am. Chem. Soc.* **2001**, *123*, 11863–11869.

[6] a) N. Chatani, T. Moromoto, T. Muto, S. Murai, *J. Am. Chem. Soc.* **1994**, *116*, 6049–6050; b) N. Chatani, N. Furukawa, H. Sakurai, S. Murai, *Organometallics* **1996**, *15*, 901–903; c) N. Chatani, H. Inoue, T. Morimoto, T. Muto, S. Murai, *J. Org. Chem.* **2001**, *66*, 4433–4436; d) N. Chatani, H. Inoue, T. Kotsuma, S. Murai, *J. Am. Chem. Soc.* **2002**, *124*, 10294–10295; e) Y. Miyanohana, H. Inoue, N. Chatani, *J. Org. Chem.* **2004**, *69*, 8541–8543.

[7] S. Oi, I. Tsukamoto, S. Miyano, Y. Inoue, *Organometallics* **2001**, *20*, 3704–3709.

[8] C. H. Ho, S. Y. Bang, C. Y. Rhim, *Bull. Korean Chem. Soc.* **2003**, *24*, 887–888.

[9] R. J. Madhushaw, C.-Y. Lo, C.-W. Hwang, M.-D. Su, H.-C. Shen, S. Pal, I. R. Shaikh, R.-S. Liu, *J. Am. Chem. Soc.* **2004**, *126*, 15560–15565.

[10] a) F. Marion, J. Coulomb, C. Courillon, L. Fensterbank, M. Malacria, *Org. Lett.* **2004**, *6*, 1509–1511.

[11] G. B. Bajracharya, I. Nakamura, Y. Yamamoto, *J. Org. Chem.* **2005**, *70*, 892–897.

[12] J. Blum, H. Berr-Kraft, Y. Badrieh, *J. Org. Chem.* **1995**, *60*, 5567–5569.

[13] T. Shibata, Y. Kobayashi, S. Maekawa, N. Toshida, K. Takagi, K. Takagi, *Tetrahedron* **2005**, *61*, 9018–9024.

[14] a) C. Nieto-Oberhuber, M. P. Muñoz, E. Buñuel, C. Nevado, D. J. Cárdenas, A. M. Echavarren, *Angew. Chem.* **2004**, *116*, 2456–2460; *Angew. Chem. Int. Ed.* **2004**, *43*, 2402–2406; b) C. Nieto-Oberhuber, M. P. Muñoz, S. López, E. Jiménez-Núñez, C. Nevado, E. Herrero-Gómez, M. Raducan, A. M. Echavarren, *Chem. Eur. J.* **2006**, *12*, 1677–1693.

[15] C. Nieto-Oberhuber, S. López, A. M. Echavarren, *J. Am. Chem. Soc.* **2005**, *127*, 6178–6179.

[16] R. C. Burrell, K. J. Daoust, A. Z. Bradley, K. J. DiRico, R. P. Johnson, *J. Am. Chem. Soc.* **1996**, *118*, 4218–4219.

[17] Related results using Pt^{II} catalysts: A. Fürstner, P. W. Davies, T. Gress, *J. Am. Chem. Soc.* **2005**, *127*, 8244–8245.

[18] Cyclobutenes related to **18** have been obtained by Trost by using palladacyclopentadienes as catalysts.[4a,b]

[19] a) B. M. Trost, A. S. K. Hashmi, *Angew. Chem.* **1993**, *105*, 1130–1132; *Angew. Chem. Int. Ed. Engl.* **1993**, *32*, 1085–1087; b) B. M. Trost, A. S. K. Hashmi, *J. Am. Chem. Soc.* **1994**, *116*, 2183–2184; c) B. M. Trost, A. S. K. Hashmi, R. G. Ball, *Adv. Synth. Catal.* **2001**, *343*, 490–494.

[20] N. Chatani, K. Kataoka, S. Murai, N. Furukawa, Y. Seki, *J. Am. Chem. Soc.* **1998**, *120*, 9104–9105.

[21] a) E. Mainetti, V. Mouriès, L. Fensterbank, M. Malacria, J. Marco-Contelles, *Angew. Chem.* **2002**, *114*, 2236–2239; *Angew. Chem. Int. Ed.* **2002**, *41*, 2132–2135; b) Y. Harrak, C. Blaszykowski, M. Bernard, K. Cariou, E. Mainetti, V. Mouriès, A.-L. Dhimane, L. Fensterbank, M. Malacria, *J. Am. Chem. Soc.* **2004**, *126*, 8656–8657.

[22] See also: B. P. Peppers, S. T. Divers, *J. Am. Chem. Soc.* **2004**, *126*, 9524–9525.

[23] C. Nieto-Oberhuber, S. López, M. P. Muñoz, E. Jiménez-Núñez, E. Buñuel, D. J. Cárdenas, A. M. Echavarren, *Chem. Eur. J.* **2006**, *12*, 1694–1702.

[24] E. Soriano, P. Ballesteros, J. Marco-Contelles, *Organometallics* **2005**, *24*, 3172–3181.

[25] Blom et al. proposed the involvement of a 3-oxabicyclo[3.2.0]hept-5-ene in a Pt^{IV}-catalyzed reaction.[12]

[26] a) V. Mamane, T. Gress, H. Krause, A. Fürstner, *J. Am. Chem. Soc.* **2004**, *126*, 8654–8655; b) M. R. Luzung, J. P. Markham, F. D. Toste, *J. Am. Chem. Soc.* **2004**, *126*, 10858–10859; c) L. Zhang, S. A. Kozmin, *J. Am. Chem. Soc.* **2004**, *126*, 11806–11807; d) A. Fürstner, P. Hannen, *Chem. Commun.* **2004**, 2546–2547; e) Reaction of 1,4-enynes: X. Shi, D. J. Gorin, F. D. Toste, *J. Am. Chem. Soc.* **2005**, *127*, 5802–5803.

[27] C. Nieto-Oberhuber, S. López, M. P. Muñoz, D. J. Cárdenas, E. Buñuel, C. Nevado, A. M. Echavarren, *Angew. Chem.* **2005**, *117*, 6302–6304; *Angew. Chem. Int. Ed.* **2005**, *44*, 6146–6148.

[28] Effect of metals on the opening of cyclobutenes: D. J. Tantillo, R. Hoffmann, *J. Am. Chem. Soc.* **2001**, *123*, 9855–9859.

[29] P. N. Dickson, A. Wehrli, G. Geier, *Inorg. Chem.* **1988**, *27*, 2921–2925.

[30] M. Murakami, M. Hasegawa, *Angew. Chem.* **2004**, *116*, 4982–4984; *Angew. Chem. Int. Ed.* **2004**, *43*, 4874–4876.

[31] P. S. Lee, S. Sakai, P. Hörstermann, W. R. Roth, E. A. Kallel, K. N. Houk, *J. Am. Chem. Soc.* **2003**, *125*, 5839–5848.

[32] W. F. Maier, P. v. R. Schleyer, *J. Am. Chem. Soc.* **1981**, *103*, 1891–1900.

[33] G. Oba, G. Moreira, G. Manuel, M. Koenig, *J. Organomet. Chem.* **2002**, *643–644*, 324–330.

[34] N. Martín, M. Altable, S. Filippone, A. Martín-Domenech, M. Güell, M. Solà, *Angew. Chem.* **2006**, *118*, 1467–1470; *Angew. Chem. Int. Ed.* **2006**, *45*, 1439–1442.

[35] Calculations at the B3LYP/6–31G(d) (C,H,P), LANL2DZ (Au) level.

[36] C. Nevado, E. Buñuel, D. J. Cárdenas, A. M. Echavarren, unpublished results.

Published online: June 6, 2006

