Molecular diversity through gold catalysis with alkynes

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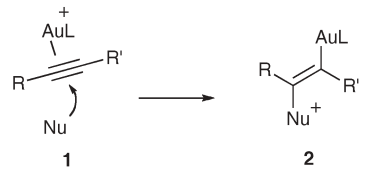
Received (in Cambridge, UK) 21st August 2006, Accepted 3rd October 2006
First published as an Advance Article on the web 9th November 2006
DOI: 10.1039/b612008c

In this *feature article* we cover most recent efforts in gold-catalysed transformations, highlighting the wide molecular diversity that can be achieved, in particular with regard to the formation of C–C bonds. Mechanistic interpretations of some cyclisations are based on our own work on the skeletal rearrangement of 1,6-enynes.

Introduction

In the past few years, gold has emerged as a powerful homogeneous catalyst for the electrophilic activation of alkynes towards a variety of nucleophiles, *via* π-complexes **1**, to give alkenyl–gold complexes of type **2** as intermediates (Scheme 1).[1–5] This electrophilic activation of alkynes has been clearly demonstrated in the context of enyne cyclisation,[6–9] for which gold(I) complexes surpass the reactivity shown by Pt(II) and other electrophilic metal salts and complexes.[10,11] Earlier work on Pt(II)- and Pd(II)-catalysed alkoxy and hydroxycyclisations of enynes has identified two distinct reaction pathways for the activation of enynes (Scheme 2).[12–17] If the metal coordinates exclusively with the alkyne such as in **3**, cyclopropyl metal carbenes **4** are initially formed,[18] which can react with alcohols or water to give products of alkoxy- or hydroxycyclisation. In the absence of nucleophiles, skeletal rearrangement takes place to form dienes **5** and/or **6**.[6–9,12,13] Alternatively, coordination of MX_n to the alkyne and the alkene (such as in **7**) forms **8**, which usually evolves by β-hydrogen elimination to give Alder-ene type products **9**.[6–9] Enynes substituted at the alkyne usually cyclise by *endo* pathways *via* **10** to give cyclopropanes **11**[9,19] or products of endocyclic skeletal rearrangement.[18] Gold complexes are unique in their high reactivity as carbon Lewis acids, as, unlike other transition metal complexes, they bind exclusively to the alkyne function and therefore the oxidative cyclometalation to form **8** does not take place.



1 **2**

Scheme 1

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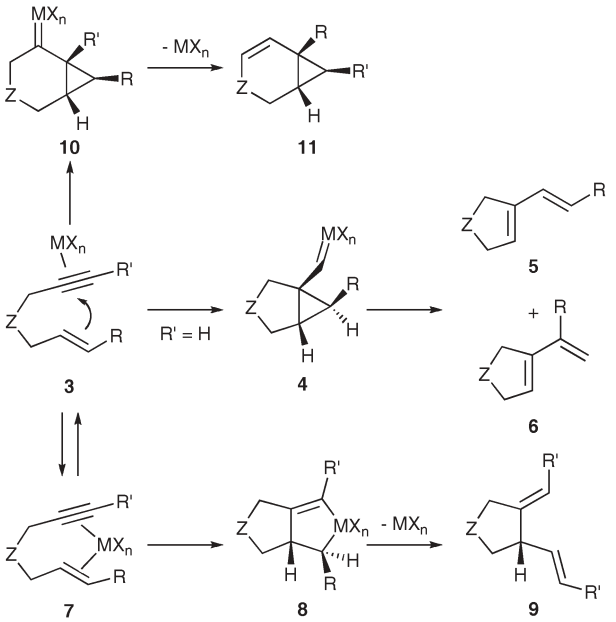


Scheme 2

Simple AuCl or $AuCl_3$ are sufficiently alkynophilic to catalyse reactions of alkynes with a variety of nucleophiles. However, higher turnovers are usually obtained by using $[AuCl(PPh_3)]$,[20] or related phosphine complexes, with an equivalent of silver salt, to generate the corresponding cationic complex *in situ*. More conveniently, preformed complex **12**[21,22] allows reactions of substituted alkynes to be performed in the absence of silver salts. Gold(I) complexes with bulky phosphines **13a–b**, in combination with Ag(I) salts, or cationic complexes **14a–b** are particularly effective catalysts for the reaction of enynes and arylalkynes (Fig. 1).[18,22,23] Good results have also been obtained with Au(I) complexes with bis(trifluoromethanesulfonyl)amide ligands.[24] Gold complexes with N-heterocyclic ligands, such as **15**,[23,25] are also good pre-catalysts in some instances. Recently, we have found that complex **16**, bearing a bulky phosphite, leads to a very electrophilic cationic complex *in situ* after being mixed with $AgSbF_6$.[26]

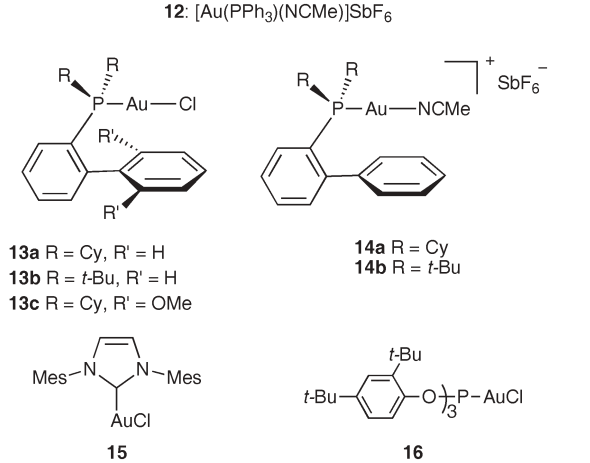


Fig. 1

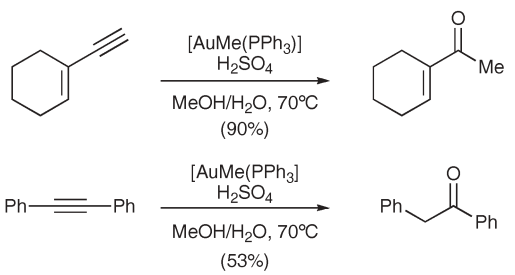
It is the purpose of this *feature article* to cover recent efforts in gold-catalysed transformations, highlighting the increase in molecular diversity and complexity that can be achieved, in particular in the formation of more than one C–C bond. First, the conceptually more simple reactions of heteronucleophiles with alkynes will be reviewed briefly. Mechanisms will be discussed in detail only in the context of some complex transformations of 1,5- and 1,6-enynes. In these cases, the mechanistic interpretations that will be presented are based on our own mechanistic work on the skeletal rearrangement of 1,6-enynes.

1. Reactions of alkynes with heteronucleophiles

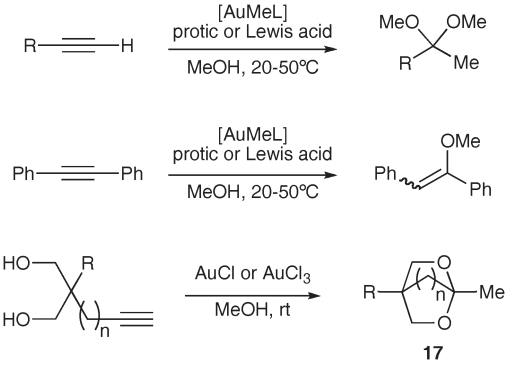
1.1. Oxygen nucleophiles

The first examples of hydration of alkynes catalysed by gold salts were reported in 1976 by Thomas *et al.*[27] Later, Utimoto and Fukuda found that the reaction could be carried out with lower amounts of catalyst.[28,29] Tanaka and co-workers reported a general hydration of alkynes using cationic Au(I) complexes generated *in situ* by protonolysis of $[AuMe(PPh_3)]$ (Scheme 3).[30] Markovnikov-type addition is observed in all the cases. Other complexes of Au(I) and Au(III) have proved to be effective in this reaction.[31–33] The somewhat related gold-catalysed addition of HCl to alkynes is an industrial process for the generation of vinyl chloride.[34]

The nucleophilic addition of alcohols to alkynes was reported by Utimoto and Fukuda[28] with $NaAuCl_4$ and later by Teles *et al.* with cationic gold complexes.[20] The enol ethers formed can be hydrolysed to form carbonyl compounds or trapped as ketals (Scheme 4). An intramolecular version of this reaction was recently reported by the group of Genêt to give



Scheme 3



Scheme 4

bicyclic ketals of type **17** (Scheme 4).[35–37] Recently, based on this concept, a new glycosidation reaction was developed using propargyl glysosides as glycosyl donors with $AuCl_3$ as catalyst in acetonitrile.[38]

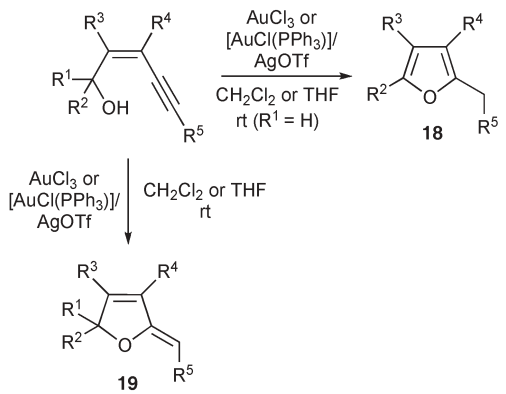
Hashmi *et al.* reported the gold-catalysed formation of furans **18** by intramolecular addition of alcohols to alkynes[39] and more recently Liu *et al.* applied this reaction to the synthesis of dihydrofurans **19** (Scheme 5).[40] Carbonyl compounds and epoxides also act as nucleophiles in the addition to alkynes to give furans.[39,41,42]

A related transformation was reported by the group of Floreancig for the synthesis of **20** (Scheme 6).[43] This transformation involves an elimination of a leaving group at the β position, followed by a conjugate addition.

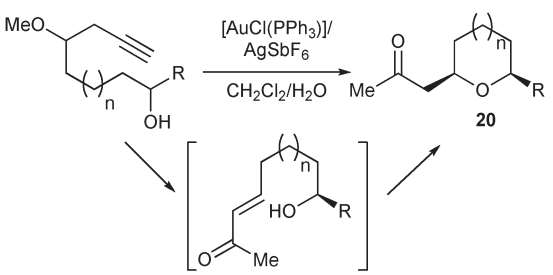
Carboxylic acids,[44] carbonates,[45–47] carbamates,[48] and related nucleophiles[49] also add to alkynes (Scheme 7). Similarly, the intramolecular addition of amides to alkynes leads to oxazoles **22** by isomerisation of the initially-formed 5-methylene-4,5-dihydrooxazoles **21**.[50] An interesting reaction was reported by Asao *et al.*, in which nitro groups add to alkynes intramolecularly with $AuBr_3$ as catalyst.[51]

The group of Barluenga reported the formation of enol ethers **23**, which are protonated *in situ* to form oxonium intermediates **24** that undergo a Prins reaction to afford eight-membered ring carbocycles **25** (Scheme 8).[52]

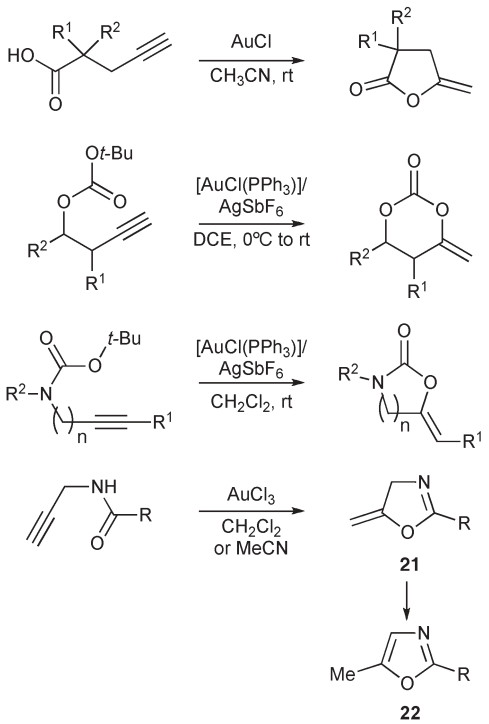
An interesting class of reactions is initiated by the intramolecular attack of a carbonyl group on an alkyne to form a pyrylium **26**, which can react further with alkynes to form naphthalenes **27** by a [4 + 2] cycloaddition followed by a cycloreversion (Scheme 9).[53] This chemistry has been studied extensively by the groups of Asao,[54–57] Dyker,[58,59] Oh,[60] and others[61] and has been recently reviewed.[62] A notable



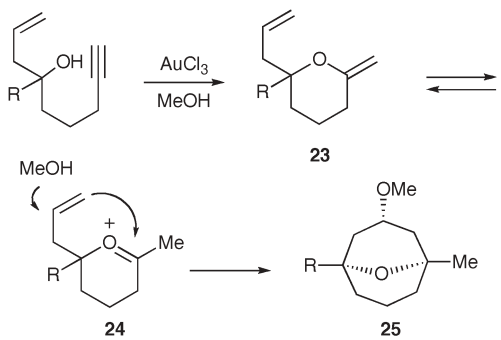
Scheme 5



Scheme 6



Scheme 7



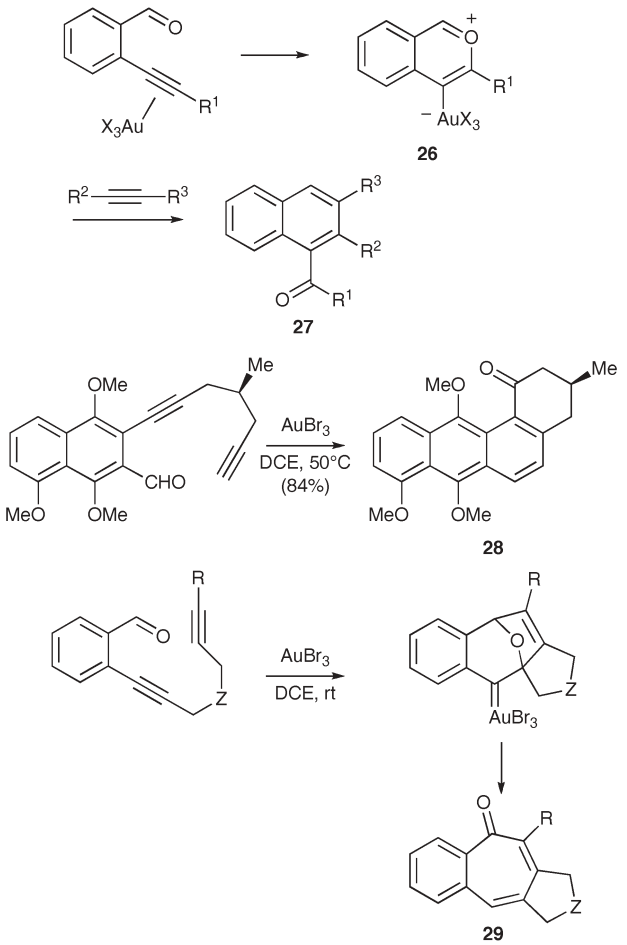
Scheme 8

application of this chemistry is the synthesis of tetracyclic compound **28**, which was transformed in one or two steps into the angucyclinone antibiotics (+)-rubiginone B_2 and (+)-ochromycinone.[63] The intermediate pyrylium gold species can also undergo [3 + 2] cycloaddition to form tricyclic compounds of type **29**.[60] Formation of intermediate azomethine ylides by reaction of imines with alkynes catalysed by gold has been reported by the group of Iwasawa.[64]

Arylalkynes bearing benzylic ethers at the *ortho* position also cyclise with cationic Au(I) catalysts to give indenyl ethers **30** (Scheme 10).[65]

1.2. Nitrogen nucleophiles

The hydroamination of terminal alkynes with $NaAuCl_4$ was developed in 1987.[66] In 1991, Utimoto and Fukuda described the preparation of tetrahydropyridines from 5-alkynylamines with Au(III) catalysts.[67] This idea was further extended by Müller to give the corresponding iminium compounds.[68,69]



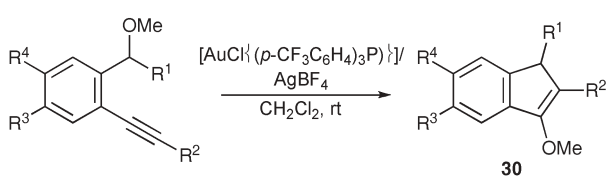
Scheme 9

Later, Arcadi *et al.* showed that β-keto-imines react with alkynes intramolecularly to give pyrroles.[70] The intermolecular amination with anilines was later developed by Hayashi *et al.*[71] using a cationic Au(I) catalyst to form imines (Scheme 11). More recently, Arcadi *et al.* developed an intramolecular version for the cyclisation of **31** to form indoles **32**.[72,73]

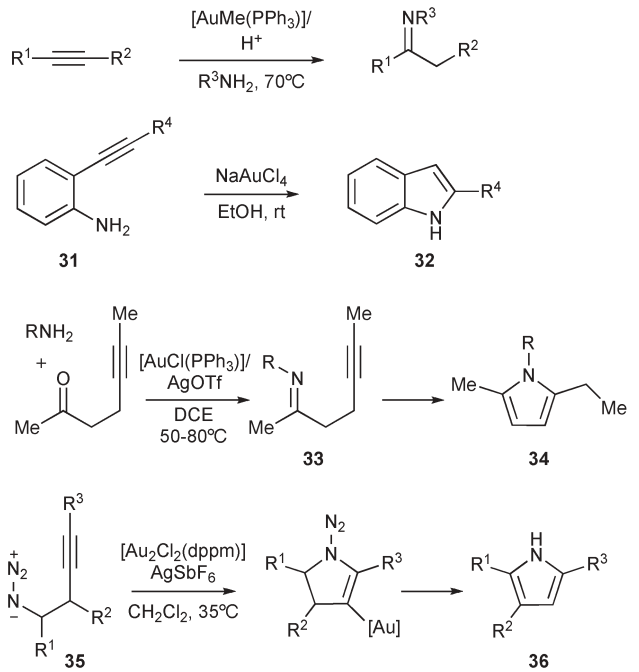
Imines **33** react with alkynes to give pyrroles **34**.[74] A related transformation of azides **35** has been reported by the group of Toste, to afford pyrroles **36** by an acetylenic Schmidt reaction (Scheme 11).[75] The intramolecular hydroamination of trichloroacetimidates derived from propargyl and homopropargyl alcohols also proceeds with cationic Au(I) as catalysts.[76]

1.3. Sulfur nucleophiles

The addition of sulfur nucleophiles to alkynes is relatively rare. However, recently, Yamamoto *et al.* described the attack of



Scheme 10



Scheme 11

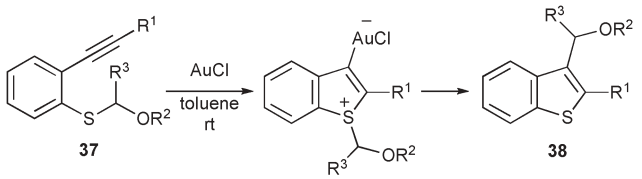
the sulfur atom of substrates **37** to afford benzothiophenes **38** (Scheme 12).[77] This transformation is based on a similar synthesis of benzofurans using Pt(II) as catalyst, developed independently by the groups of Yamamoto[78] and Fürstner.[79]

2. Carbon nucleophiles

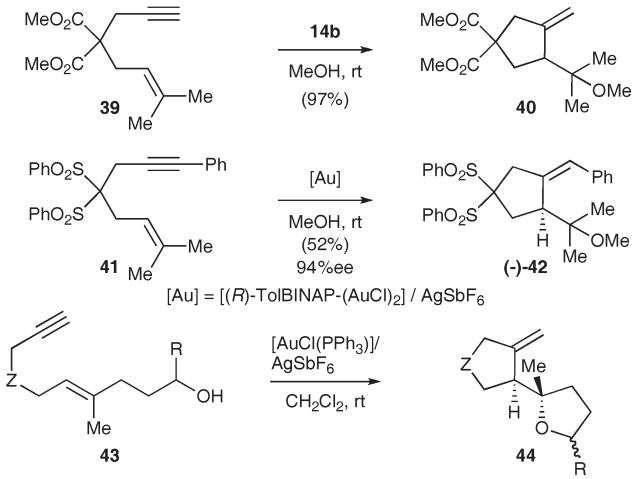
2.1. Reactions with alkenes

Alkenes act as nucleophiles with alkynes in the presence of gold catalysts.[10,22] Thus, by using conditions developed by Tanaka and co-workers for the hydration of alkynes,[30] reaction of enynes with [AuMe(PPh_3)] and a protic acid in MeOH led to the formation of products of methoxycyclisation.[10] Similar results were obtained from [AuCl(PPh_3)] and $AgSbF_6$ or from preformed cationic gold complexes (Scheme 13). Thus, for example, enyne **39** was readily converted into **40**.[21,24] and, by using a chiral Au(I) complex, the methoxycyclisation of **41** afforded **(−)-42** with 94% ee, although lower ees were obtained with other enynes.[16] Intramolecular attack of the hydroxyl function of **43** afforded tetrahydrofuranyl derivatives **44** in good yields.[21] Related intramolecular hydroxycyclisations, as well as related sulfonamido cyclisations, have also been observed from 1,5-enynes.[80]

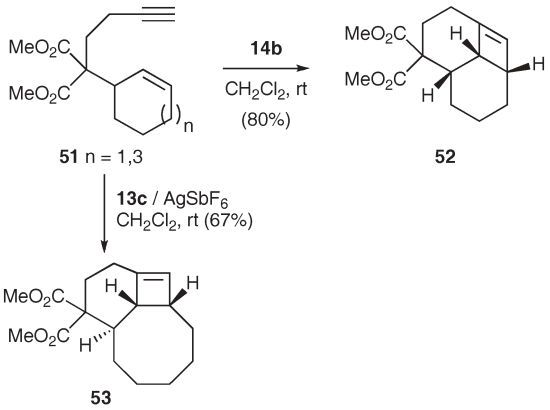
In the absence of nucleophiles, 1,6-enynes give products of skeletal rearrangement **5** and **6** (Scheme 2) with cationic Au(I)



Scheme 12



Scheme 13



Scheme 15

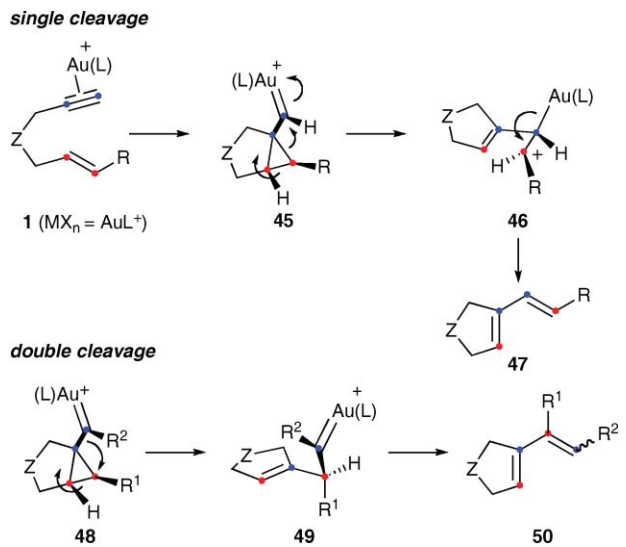
catalysts.[10,21,81] Formation of products **47** (Scheme 14) of single cleavage in metal-catalysed reactions of enynes had been proposed to proceed by conrotatory ring opening of intermediate cyclobutenes, although recent experimental and theoretical calculations do not support that proposal.[82] Thus, the initial cyclopropyl gold carbene **45**, formed in the 5-*exo*-*dig* cyclisation, evolves to form cation **46**, which then undergoes metal-elimination to give diene **47** (single cleavage). For the double cleavage rearrangement, intermediate **48** can suffer a dyotropic rearrangement[83–85] to give **49**, which then eliminates an α-hydrogen to give diene **50** (double cleavage). Intermediate **46** can also suffer a 1,2-shift of the alkenyl group to give an intermediate of type **49**.[82] *Endo*-cyclisations to give products of type **10** and **11** also take place with certain enynes,[21] as well as in the reaction of 1-alkynyl-2-ethenylarenes with Au(I), which leads to the formation of substituted naphthalenes along with indenes, as secondary products.[86]

Cyclobutenes such as **52** and **53** are obtained in the cyclisations of 1,7-enynes **51** with Au(I) catalysts, presumably as a result of a *syn*-attack of the alkene on the alkyne–Au(I) complex (Scheme 15).[82]

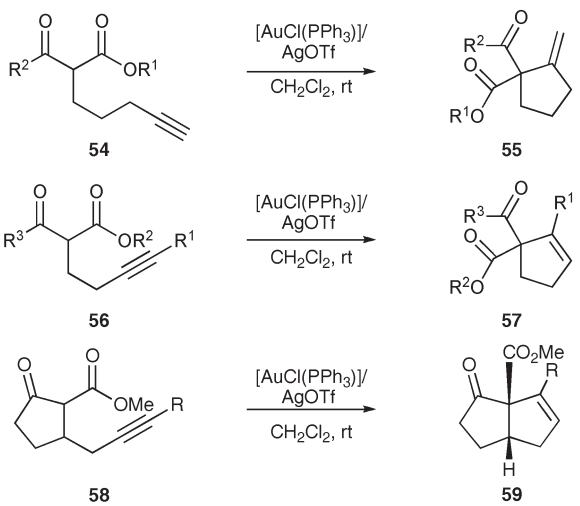
Toste *et al*. described the addition of enols of β-ketoesters to alkynes catalysed by gold(I).[87,88] Thus, reaction of substrates like **54** proceeds in an *exo* fashion to give **55**, whereas **56** and **58** react by endocyclic processes to give **57** and **59**, respectively (Scheme 16). An enantioselective version of this reaction was developed using chiral palladium complexes.[89] The analogous reaction of silyl enol ethers with alkynes has been applied for the synthesis of the pyridine alkaloid lycopladine A.[90]

Toste *et al*. also reported the cyclisation of 1,5-enynes **60** to give bicyclo[3.1.0]hexanes **61** under mild conditions (Scheme 17).[91] Interestingly, in a similar reaction, Gagosz found that enyne **62** gave the expected bicyclo[3.1.0]hexane **63**, accompanied by **64**, a product of skeletal rearrangement.[92]

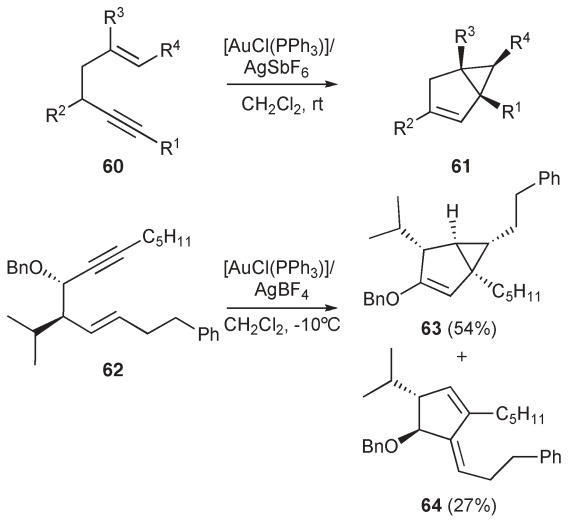
The formation of products **61**, **63**, and **64** can be rationalised as shown in Scheme 18. Thus, upon complexation of Au(I) to the alkyne in **65**, an endocyclisation occurs to form cyclopropyl gold carbene **66**,[14] which can be trapped by a nucleophile to form **67**.[91] α-Hydrogen elimination and protodemetalation of **66** can afford bicyclic products **68**.[91,92] Alternatively, **66** may suffer a skeletal rearrangement that can be rationalised as



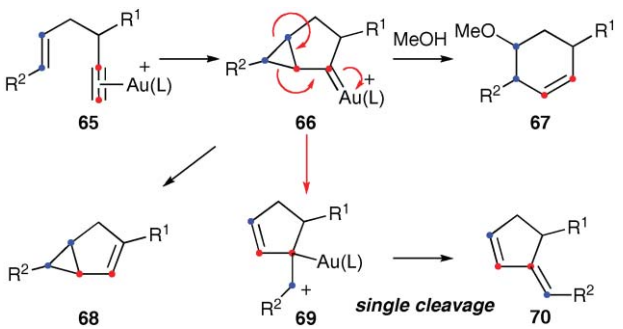
Scheme 14



Scheme 16



Scheme 17

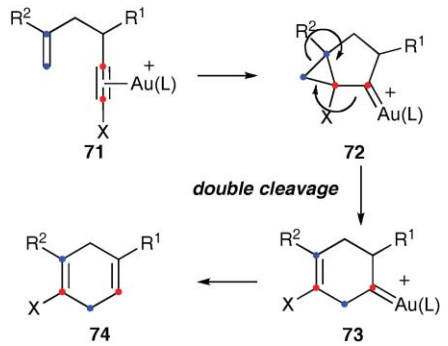


Scheme 18

proceeding *via* **69** and **70** in a reaction similar to that shown before for **45** (Scheme 14).

Kozmin *et al*. found that siloxy 1,5-enynes react with Au(I) catalysts to give cyclohexadienes,[93,94] which is probably another example of a double skeletal rearrangement (Scheme 19). Thus, complex **71** (X = OTIPS) could give carbene **72**, which then undergoes ring expansion by a process reminiscent of that found for **48** (Scheme 14). A similar transformation has been found with other 1,5-enynes.[92,94]

Propargyl vinyl ethers **75** undergo Claisen rearrangement with Au(I) catalysts to give allenes **76**, which were isolated as

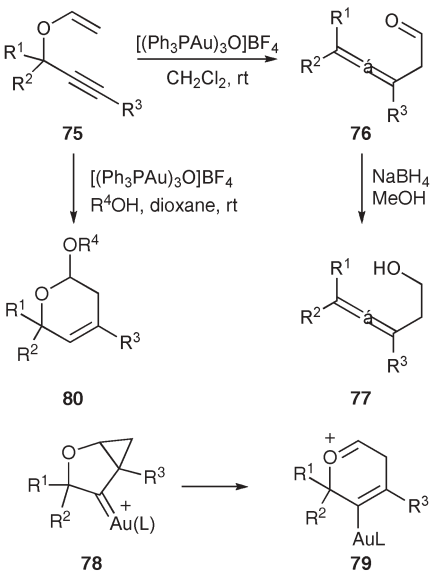


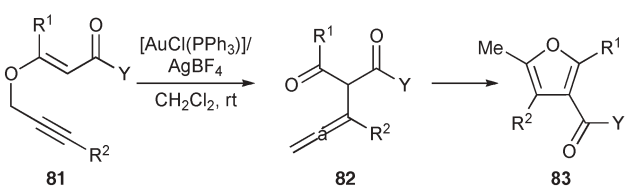
Scheme 19

the corresponding alcohols **77** (Scheme 20).[95] This result can be interpreted as a ring expansion of the initial cyclopropyl gold carbene **78**, to form an oxonium cation **79**, followed by a C–O fragmentation to afford the allenes. Indeed, by performing the reaction in the presence of water or alcohols, dihydropyrans **80** were obtained in good yields.[96] A related transformation has been reported by Kirsch *et al*. in which compounds **81** are converted into allenes **82**, which cyclise to afford furans **83**.[97] A variation of this procedure has been developed for the synthesis of pyrroles by performing the first rearrangement with an Ag(I) catalyst. The intermediate 1,3-dicarbonyl compound was then condensed with primary amines, which was followed by a final Au(I)-catalysed cyclisation.[98]

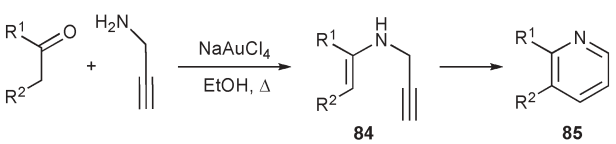
Recently, the groups of Lee and Toste reported that allyl silyl alkynes react with Au(I) catalysts in the presence of alcohols to give alkenylsilanes[99,100] by a process that might involve the fragmentation of a cyclopropyl gold carbene.

The first examples of cyclisation of 1,5-enynes with gold were disclosed by the group of Arcadi in the context of a new synthesis of pyridines (Scheme 21).[101] Thus, cyclisation of propargyl enanimes **84**, catalysed by sodium tetrachloroaurate, gives substituted pyridines **85** in a general way. The enamines





Scheme 20



Scheme 21

were formed *in situ* from propargylamine and the corresponding ketone.

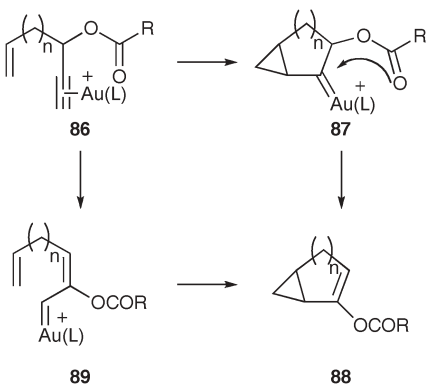
Reactions of enynes bearing carboxylate groups at the propargylic position proceed somewhat differently (Scheme 22). Two mechanistically distinct possibilities probably exist with different metal complexes, depending on the order of attack of the acyl and the alkene on the alkyne in complexes of type **86**. As illustrated in Scheme 22 for Au(I), if the alkene reacts first, the usual cyclopropyl metal carbene **87** would be formed, which could then suffer an intramolecular attack of the acyl to the carbene, followed by an elimination (formal 1,2-migration of the acyl) to form **88** after metal loss. Alternatively, the acyl group might undergo first the 1,2-migration, to form carbene **89**, which would then form **88** by intramolecular cyclopropanation.

The first pathway (**86** to **87**) is most likely followed when n = 2, as shown by Fürstner and Hannen in a key Pt(II)-catalysed cyclisation for the synthesis of (−)-α-cubebene and (−)-cubebol.[102] (−)-Cubebol was also synthesised by Fehr and Galindo using a similar cyclisation catalysed by Pt(II), Au(I), or Cu(I).[103] A cyclisation of this type, catalysed by $AuCl_3$, was used for the synthesis of 2-sesquicarene (**90**) and related compounds (Scheme 23).[102,104] The key step in the synthesis of **90** is the cyclisation of propargyl acetate **91** to **92**, which proceeds with remarkable stereoselectivity.

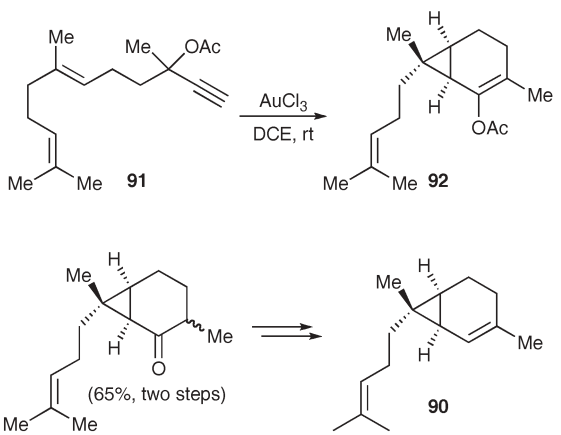
Toste *et al*. have shown that 1,4-enynes **93**, substituted at the propargylic position with a carboxylate, undergo the so-called Rautenstrauch rearrangement to afford cyclopentenones **94** in a general way (Scheme 24).[105] This reaction has been shown to proceed by 1,2-acyl migration to give a carbene of type **89** (n = 0), followed by an electrocyclisation.[106] The transformation proceeds enantioselectively by a remarkable center to helix chirality transfer, which indicates that the cyclisation is faster than rates of helix interconversion and carboxylate rotation.[106] Interestingly, the intermolecular reaction of propargyl carboxylates with alkenes leads instead to allyl cyclopropanes **95** by formation of an alkenyl gold carbene by 1,2-acyl migration followed by intermolecular cyclopropanation.[107]

A synthesis of cyclopentenones somewhat related to that reported by Toste *et al*. was found by Zhang and Wang from substrates **96**, which involves a 1,3-migration of the acetate followed by a Nazarov-type cyclisation (Scheme 25).[108] Simple propargylic esters **98** also undergo a 1,3-acyl migration catalysed by Au(III),[109] leading finally to 1,3-dicarbonyl compounds.[110] Other 1,3-acyl migrations of propargylic carboxylates catalysed by gold led to intermediate allenes that can afford heterocyclic compounds by intramolecular attack of the appropriate nucleophiles.[111] The intermediate allenes formed by 1,3-acyl migrations can also react intramolecularly with alkynes to form naphthalenes, although this reaction was found to be more efficiently catalysed by Ag(I).[112]

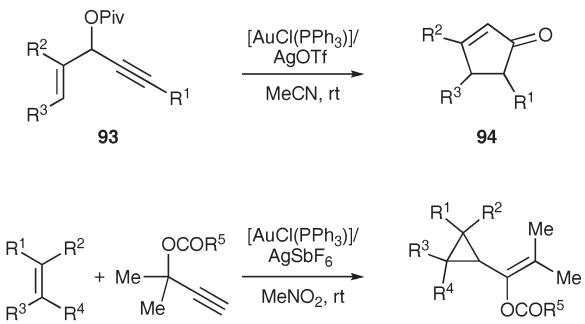
The Meyer–Schuster rearrangement (isomerisation of propargylic alcohols to α,β-unsaturated carbonyl compounds) has been recently described using $AuCl_3$ as the catalyst in the presence of EtOH.[113]



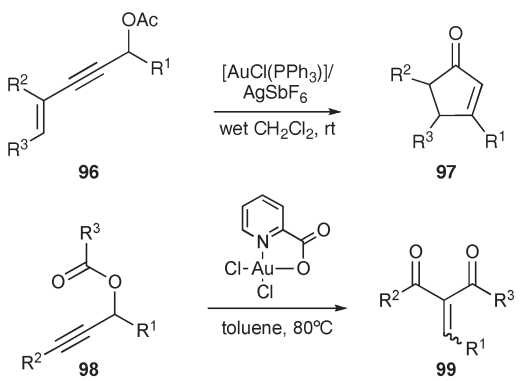
Scheme 22



Scheme 23



Scheme 24



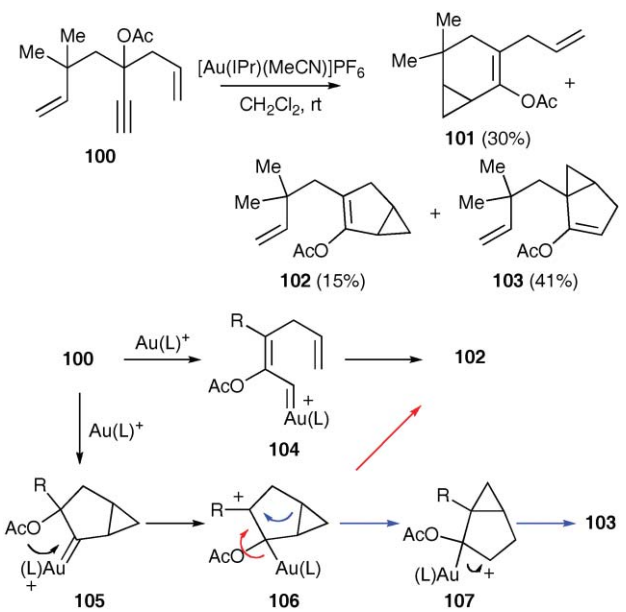
Scheme 25

An interesting cyclisation of propargylic acetate **100** has been shown to afford **101–103** using a Au(I) complex with an N-heterocyclic carbene as ligand (Scheme 26).[114] Product **101** is that expected from a 1,6-enyne (see Scheme 23). On the other hand, formation of products **102** and **103** by cyclisation of the 1,5-enyne suggests that the two alternative mechanisms outlined in Scheme 22 might take place in this case. Thus, a 1,2-acetate migration from **100** would give carbene **104**, which could cyclopropanate the terminal alkene to give **102**. Alternatively, reaction of the alkene with the alkyne might give **105**, which after 1,2-acyl migration would give **106**, which could be in equilibrium with **107**. Metal loss in **106** would give cyclopropane **103**. An elimination of Au(I) from **106** could also afford **102**.

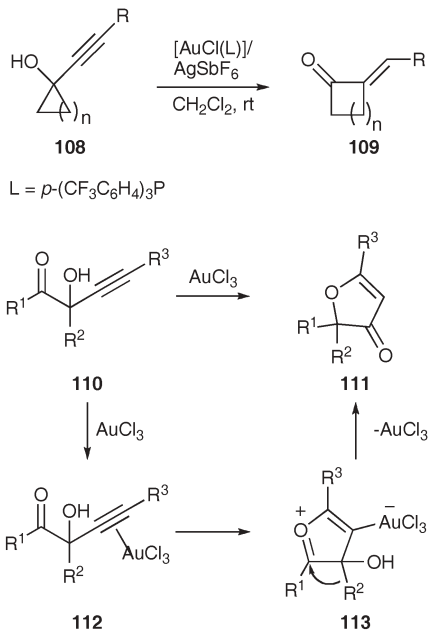
The group of Toste have found that ring expansion of cyclopropanols and cyclobutanols **108** leads to a straightforward synthesis of cyclobutanones and cyclopentanones **109** with Au(I) catalysts (Scheme 27).[115] In contrast, an interesting ring contraction, which occurs upon treatment of hydroxyketones **110**, to give 3(2*H*)-furanones **111**, with $AuCl_3$ at 23–38 °C in CH_2Cl_2 or with $PtCl_2$ in toluene at 80 °C, has been reported by the group of Kirsch (Scheme 27).[116] The reaction proceeds through intermediates **112** and **113**, where the 1,2-migration of R^2 takes place. When R^1 and R^2 are part of a ring, this rearrangement leads to a ring contraction.

2.2. More complex transformations of substituted enynes

Substitution at the alkyne of 1,6-enynes with different functional groups may lead to different reactions. Thus, dienynes **114** react with cationic Au(I) catalysts formed from complexes **13a–c**, leading to products of formal [4 + 2] cycloaddition **115** (Scheme 28).[23] Similarly, enynes **116**, substituted at the alkyne with an aryl group, led to products **117** resulting from a formal intramolecular [4 + 2] cycloaddition occurring at an unusually low temperature.[23] On the other hand, substrates **116** with $R^1 = R^2 = H$ or $R^1 = Me$, $R^2 = H$ gave cyclobutenes with Au(I)[23] or Pt(II) catalysts.[117]



Scheme 26

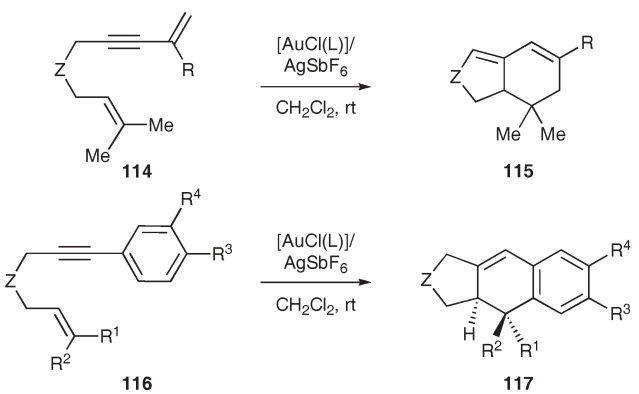


Scheme 27

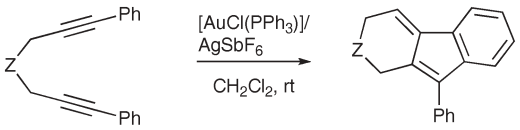
The groups of Shibata[118] and Liu[119] have examined the intramolecular reaction between two arylalkynes, which, according to the most recent work,[119] leads to [3 + 2] cycloaddition products (Scheme 29).

By using Au(I) catalysts, dienynes **118** undergo totally stereoselective cyclisations to yield tetracyclic compounds **119**, *via* intermediates **120**, (Scheme 30) under milder conditions[10,11] than those required with other metal catalysts.[120–123] Similarly, the intermolecular reaction between enynes **121** and alkenes proceeds with Au(I) catalysts formed *in situ* from complex **15**.[26] Interestingly, by using this catalyst or the more electrophilic **16**, gold(I) carbene **49** (see Scheme 14) has also been trapped intermolecularly by alkenes.[26]

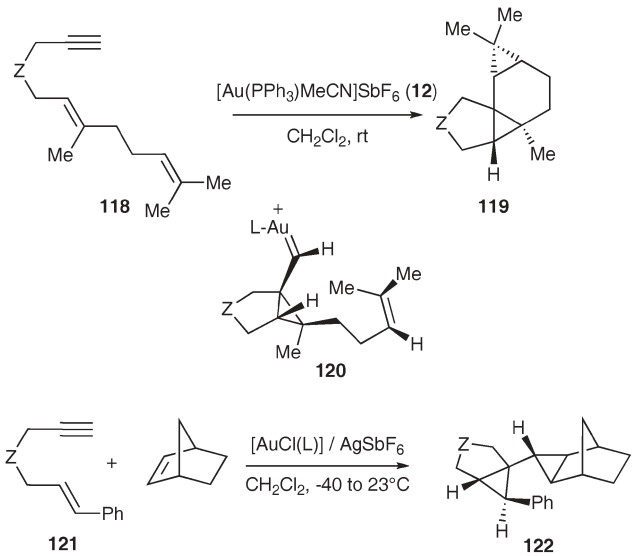
Cyclisations of enynes **123**, bearing carbonyl groups, with Au(I) catalysts provides tricyclic compounds **124**, along with ketones **125**as minor products (Scheme 31).[124] The best yields of **124** (58–84%) were obtained using AuCl as the catalyst. In these cyclisations, the carbonyl group acts as an internal



Scheme 28

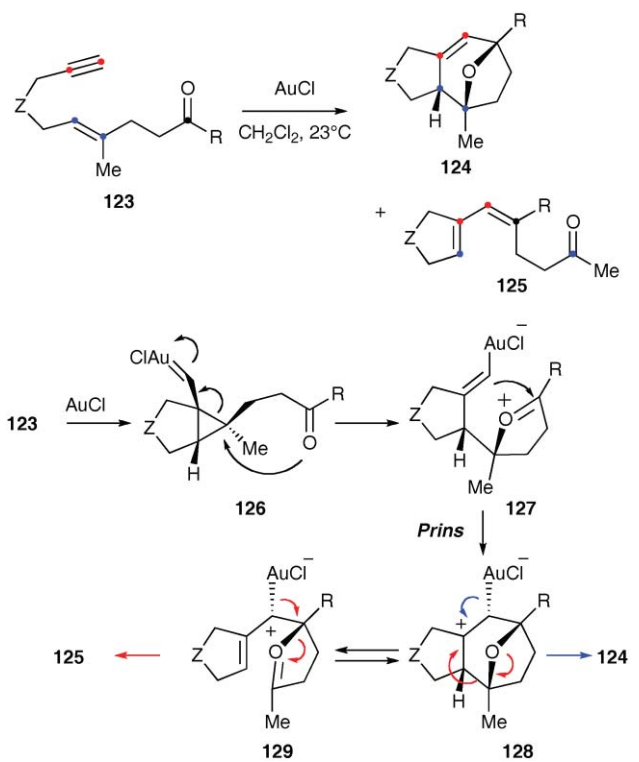


Scheme 29



Scheme 30

nucleophile, as shown in **126**, to form an oxonium intermediate **127**, which undergoes an intramolecular Prins reaction to give **128**. Elimination of the metal fragment forms tricycles **124**.



Scheme 31

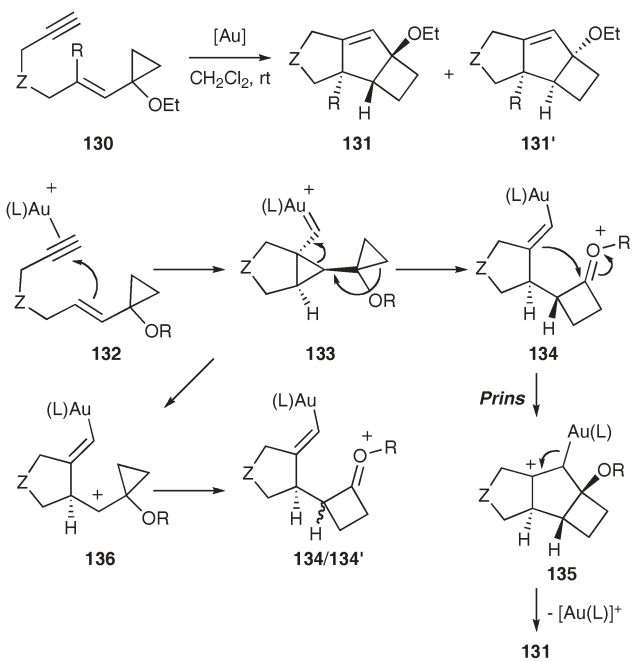
Alternatively, an elimination with fragmentation of the seven-membered ring *via* **129** leads to carbonyl compounds **125**.

A Prins cyclisation is also involved in the reaction of cyclopropylenynes **130** with AuCl or cationic Au(I) complexes, to give tricyclic derivatives **131/131′** with a octahydrocyclobuta[*a*]pentalene skeleton (Scheme 32).[124] Formation of stereoisomers **131′** was unexpected and suggests that two different pathways are competing in this process. Accordingly, **132** forms cyclopropyl metal carbene **133**, which undergoes ring expansion to form **134**. The alkenyl–gold **134** could undergo a Prins reaction with the oxonium to form **135**, which upon demetalation forms tricycles **131**. The concerted pathway (**133** to **134**) is favoured for AuCl as catalyst, whereas cationic Au(I) complexes apparently favour a non-concerted reaction *via* cyclopropyl-stabilised cation **136**, which undergoes a non-stereospecific ring expansion to give mixtures of **134/134′**. Cyclobutanones were also formed as minor side products in the reactions of **130**.[124]

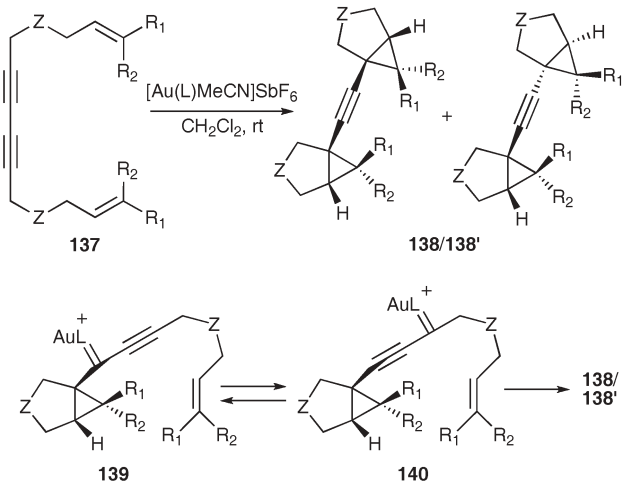
Additional evidence for the involvement of metal carbenes in these reactions was obtained in the reaction of dimeric substrates **137** with cationic Au(I) catalyst **14b** to give **138/138′** (Scheme 33).[124] These reactions can be explained by isomerisation of the initially formed cyclopropyl gold carbene **139** to form **140** by a [1,3] metallotropic shift, followed by intramolecular trapping of the gold carbene by the alkene. Other examples of [1,3] metallotropic shifts in gold chemistry have been observed recently.[125,126]

2.3. Arenes and heteroarenes as nucleophiles

In general, two pathways are followed in the reactions of alkynes with arenes catalysed by transition metals. Reaction of $[M(CO)_6]$ (M = Cr, Mo, W) and certain Ru(II) complexes with terminal alkynes, or with alkynes substituted with migrating groups (SiR_3, SR, I) may proceed *via* vinylidene metal



Scheme 32



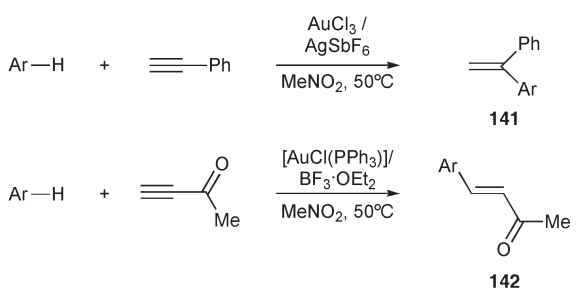
Scheme 33

complexes. On the other hand, electrophilic metal salts or complexes favor coordination to the alkyne, triggering an electrophilic substitution reaction with the arene. Gold complexes promote reactions according to this second pathway. This subject was reviewed in 2005.[127]

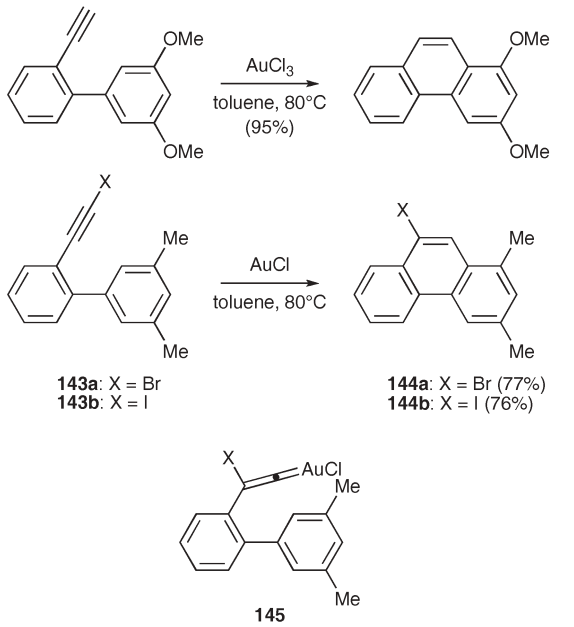
The groups of Reetz[128] and He[129,130] explored independently the gold-catalysed hydroarylation of alkynes (or alkenylation of arenes) (Scheme 34). The reaction leads to 1,1-disubstituted alkenes **141** with electron-rich alkynes; alkynes with electron-withdrawing groups lead to 1,2-disubstituted derivatives **142**.[131] We have reported the cyclisation of arylalkynes with Pt(II) or Au(I) catalysts.[10,132] Computational work[132] indicates that two pathways compete, a Friedel–Crafts alkenylation and a reaction proceeding through metal cyclopropyl carbenes, which show very similar activation energies.

The group of Fürstner applied this chemistry to the synthesis of phenanthrenes by cyclisation of *ortho*-alkynylated biphenyl derivatives with Au(III) and other metal catalysts (Scheme 35).[133–135] Interestingly, haloalkynes **143a–b** react with AuCl to give phenanthrenes **144a–b** in which the halide has suffered a 1,2-shift, which indicates that in these cases the cyclisation proceeds *via* gold vinylidene species **145**.[135]

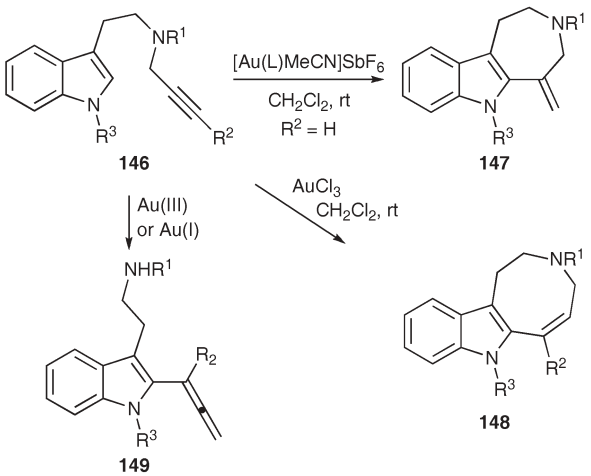
The reaction of substituted indoles **146** with alkynes, catalysed by Au(I) or Au(III), leads to seven- (**147**) and eight-membered rings (**148**), respectively (Scheme 36).[136] Allenes **149** were also obtained in some cases, when the reactions were carried out for longer reaction times.



Scheme 34



Scheme 35

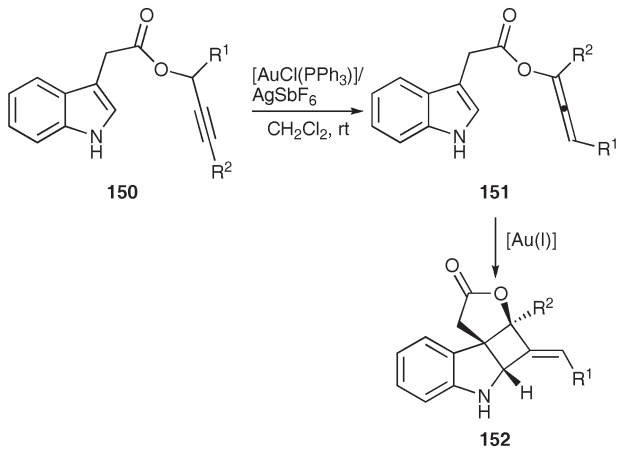


Scheme 36

A different transformation involving the indole nucleus was found by Zhang (Scheme 37).[137] Thus, the 1,3-acyl migration of propargylic carboxylates **150** catalysed by Au(I) was coupled with a subsequent reaction of the resulting allenes **151** with indoles to give tetracyclic compounds **152**. An allene of type **151** was isolated when the reaction was performed with $AuCl_3$ as catalyst.

The acyl migration from substrates **153** was also applied by the group of Nolan for the synthesis of indenes **154** (Scheme 38).[138] Isomeric indenes **155** were also obtained as minor products. Formation of **154** was shown actually to proceed *via* allenes **156**, which could be prepared by Ag(I)-catalysed 1,3-acetate migration from **153**. Somewhat related cyclisations to form indenes had been reported previously, using Ru(II)[139] or Pt(II)[140] catalysts, although in these reactions the acetate undergoes a 1,2-migration.

In contrast to the usual Friedel–Crafts-like cyclisations of arenes with alkynes, Hashmi *et al*. found that reaction of

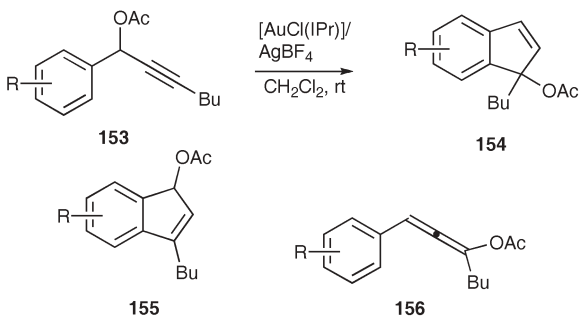


Scheme 37

alkynyl furans **157** affords phenols **158** in good to excellent yields, using $AuCl_3$ as catalyst (Scheme 39).[141–147] Au(I),[148] heterogeneous gold,[149] and Pt(II)[150,151] catalysts were also shown to be effective in this reaction. A synthesis of sesquiterpene jungianol (**159**), together with its *cis* isomer, was achieved by using the Au(III)-catalysed phenol synthesis.[144] Recently, an application for the synthesis of phenols bearing bulky groups at the *ortho* position has been described.[152]

According to experimental and theoretical studies on gold- and platinum-catalysed reactions,[142,145,150,151] the phenol synthesis proceeds by nucleophilic attack of the furan on the (η^2-alkyne)–Au complex **160** to form carbene **161**, similar to the intermediates formed in reactions of enynes with Au(I) or other metal complexes (Scheme 40). After cleavage of a C–C and C–O bond of the tricyclic intermediate, a new carbene **162** is formed, which cyclises to form **163**. Elimination of the metal forms oxepine **164**, which is in equilibrium with the arene oxide **165**, whose opening leads to the formation of phenols **166** and **167**. Oxepines **164** and arene oxides **165** have been observed in the reaction catalysed by an Au(III) complex.[146]

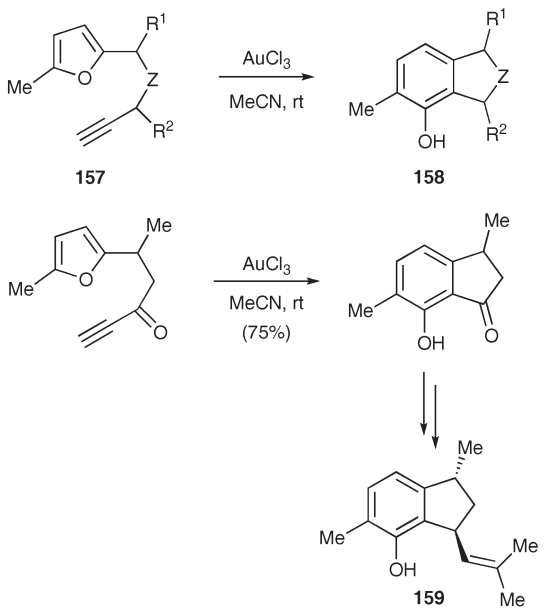
An example of intermolecular reaction of a furan with phenylacetylene has been reported to proceed in moderate yield with Au(I) catalysts.[153] In addition, the gold-catalysed Michael addition of furans to ethynyl vinyl ketones gives substrates that undergo *in situ* cyclisation leading to hydroxyindanones in a domino process.[154]



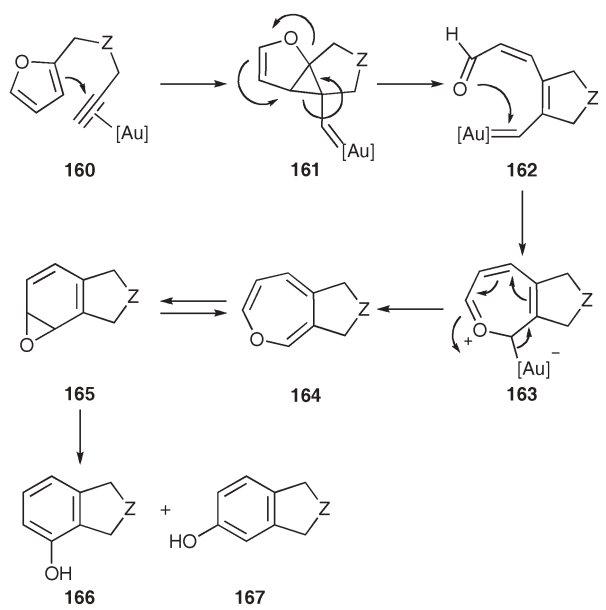
Scheme 38

Conclusions

Gold complexes are, in most cases, the most effective catalysts for the reactions of alkynes with hetero- and carbo-nucleophiles. In particular, cationic gold(I) complexes bearing bulky phosphines or phosphites as ligands usually surpass the most active platinum complexes reported thus far. However, the higher Lewis acidity of gold complexes can, on occasion, be detrimental in terms of selectivity and because of their low tolerance to certain functional groups. In these instances, less Lewis-acidic Pt(II) complexes could be the catalyst of choice.[79,117,155]



Scheme 39



Scheme 40

The gold-catalysed activation of alkynes is dominated by four major themes: (i) nucleophilic additions of heteronucleophiles; (ii) formation of cyclopropyl gold carbenes in the reaction with alkenes; (iii) 1,2- or 1,3-acyl migrations in propargylic substrates; and (iv) Friedel–Crafts-type reactions with arenes and heteroarenes. The reactions of furans with alkynes leading to phenols actually belong to type (ii) as these transformations are initiated by the formation of cyclopropyl gold carbenes as intermediates.

Despite the rapid development of new synthetic applications based on alkyne–gold chemistry, many aspects still require further clarification. Thus, relatively little is known about the factors that control the *exo*/*endo* selectivity in the activation of alkynes. In addition, the area of chiral gold catalysis[16] in the context of alkyne chemistry is still an underdeveloped field.

Acknowledgements

We thank the MEC (project CTQ2004-02869, FPU predoctoral fellowship to E. J.-N., and Consolider Ingenio 2010, Grant CSD2006-0003), the AGAUR (2005 SGR 00993), and the ICIQ Foundation for financial support. We are indebted to our past and present co-workers for their contributions to different aspects of gold chemistry included in this feature article.

References

1 A. S. K. Hashmi, *Gold Bull. (London, U. K.)*, 2003, **36**, 3–9.
2 A. S. K. Hashmi, *Gold Bull. (London, U. K.)*, 2004, **37**, 51–65.
3 A. Hoffmann-Röder and N. Krause, *Org. Biomol. Chem.*, 2005, **3**, 387–391.
4 S. Ma, S. Yu and Z. Gu, *Angew. Chem., Int. Ed.*, 2005, **44**, 200–203.
5 A. S. K. Hashmi, *Angew. Chem., Int. Ed.*, 2005, **44**, 6990–6993.
6 G. C. Lloyd-Jones, *Org. Biomol. Chem.*, 2003, **1**, 215–236.
7 C. Aubert, O. Buisine and M. Malacria, *Chem. Rev.*, 2002, **102**, 813–834.
8 S. T. Diver and A. J. Giessert, *Chem. Rev.*, 2004, **104**, 1317–1382.
9 A. M. Echavarren and C. Nevado, *Chem. Soc. Rev.*, 2004, **33**, 431–436.
10 C. Nieto-Oberhuber, M. P. Muñoz, E. Buñuel, C. Nevado, D. J. Cárdenas and A. M. Echavarren, *Angew. Chem., Int. Ed.*, 2004, **43**, 2402–2406.
11 C. Nieto-Oberhuber, M. P. Muñoz, S. López, E. Jiménez-Núñez, C. Nevado, E. Herrero-Gómez, M. Raducan and A. M. Echavarren, *Chem.–Eur. J.*, 2006, **11**, 1677–1693.
12 M. Méndez, M. P. Muñoz and A. M. Echavarren, *J. Am. Chem. Soc.*, 2000, **122**, 11549–11550.
13 M. Méndez, M. P. Muñoz, C. Nevado, D. J. Cárdenas and A. M. Echavarren, *J. Am. Chem. Soc.*, 2001, **123**, 10511–10520.
14 C. Nevado, D. J. Cárdenas and A. M. Echavarren, *Chem.–Eur. J.*, 2003, **9**, 2627–2635.
15 C. Nevado, C. Ferrer and A. M. Echavarren, *Org. Lett.*, 2004, **6**, 3191–3194.
16 M. P. Muñoz, J. Adrio, J. C. Carretero and A. M. Echavarren, *Organometallics*, 2005, **24**, 1293–1300.
17 C. Nevado, L. Charruault, V. Michelet, C. Nieto-Oberhuber, M. P. Muñoz, M. Méndez, M. N. Rager, J.-P. Genêt and A. M. Echavarren, *Eur. J. Org. Chem.*, 2003, 706–713.
18 C. Nieto-Oberhuber, S. López, E. Jiménez-Núñez and A. M. Echavarren, *Chem.–Eur. J.*, 2006, **12**, 5916–5923.
19 T. Shibata, Y. Kobayashi, S. Maekawa, N. Toshida and K. Takagi, *Tetrahedron*, 2005, **61**, 9018–9024.
20 J. H. Teles, S. Brode and M. Chabanas, *Angew. Chem., Int. Ed.*, 1998, **37**, 1415–1418.
21 C. Nieto-Oberhuber, S. López, M. P. Muñoz, E. Jiménez-Núñez, E. Buñuel, D. J. Cárdenas and A. M. Echavarren, *Chem.–Eur. J.*, 2006, **11**, 1694–1702.
22 E. Herrero-Gómez, C. Nieto-Oberhuber, S. López, J. Benet-Buchholz and A. M. Echavarren, *Angew. Chem., Int. Ed.*, 2006, **45**, 5455–5459.
23 C. Nieto-Oberhuber, S. López and A. M. Echavarren, *J. Am. Chem. Soc.*, 2005, **127**, 6178–6179.
24 N. Mézailles, L. Ricard and F. Gagosz, *Org. Lett.*, 2005, **7**, 4133–4136.
25 P. de Frémont, N. M. Scott, E. D. Stevens and S. P. Nolan, *Organometallics*, 2005, **24**, 2411–2418.
26 S. López, E. Herrero-Gómez, P. Pérez-Galán, C. Nieto-Oberhuber and A. M. Echavarren, *Angew. Chem., Int. Ed.*, 2006, **45**, 6029–6032.
27 R. O. C. Norman, W. J. E. Parr and C. B. Thomas, *J. Chem. Soc., Perkin Trans. 1*, 1976, 1983–1987.
28 Y. Fukuda and K. Utimoto, *J. Org. Chem.*, 1991, **56**, 3729–3731.
29 Y. Fukuda and K. Utimoto, *Bull. Chem. Soc. Jpn.*, 1991, **64**, 2013–2015.
30 E. Mizushima, K. Sato, T. Hayashi and M. Tanaka, *Angew. Chem., Int. Ed.*, 2002, **41**, 4563–4565.
31 R. Casado, M. Contel, M. Laguna, P. Romero and S. Sanz, *J. Am. Chem. Soc.*, 2003, **125**, 11925–11935.
32 P. Roembke, H. Schmidbaur, S. Cronje and H. Raubenheimer, *J. Mol. Catal. A: Chem.*, 2004, **212**, 35–42.
33 P. Wessig and J. Teubner, *Synlett*, 2006, 1543–1546.
34 B. Nkosi, N. J. Coville and G. J. Hutchings, *J. Chem. Soc., Chem. Commun.*, 1988, 71–72.
35 S. Antoniotti, E. Genin, V. Michelet and J.-P. Genêt, *J. Am. Chem. Soc.*, 2005, **127**, 9976–9977.
36 V. Belting and N. Krause, *Org. Lett.*, 2006, **8**, 4489–4492.
37 B. Liu and J. K. De Brabander, *Org. Lett.*, 2006, **8**, 4907–4910.
38 S. Hotha and S. Kashyap, *J. Am. Chem. Soc.*, 2006, **128**, 9620–9621.
39 A. S. K. Hashmi, L. Schwarz, J. H. Choi and T. M. Frost, *Angew. Chem., Int. Ed.*, 2000, **39**, 2285–2288.
40 Y. Liu, F. Song, Z. Song, M. Liu and B. Yan, *Org. Lett.*, 2005, **7**, 5409–5412.
41 A. S. K. Hashmi and P. Sinha, *Adv. Synth. Catal.*, 2004, **346**, 432–438.
42 T. Yao, X. Zhang and R. C. Larock, *J. Am. Chem. Soc.*, 2004, **126**, 11164–11165.
43 H. Hoon and P. E. Floreancig, *Org. Lett.*, 2006, **8**, 1949–1951.
44 E. Genin, P. Y. Toullec, S. Antoniotti, C. Branour, J.-P. Genêt and V. Michelet, *J. Am. Chem. Soc.*, 2006, **128**, 3112–3113.
45 S. Shin, *Bull. Korean Chem. Soc.*, 2005, **26**, 1925–1926.
46 J.-E. Kang and S. Shin, *Synlett*, 2006, 717–720.
47 A. Buzas and F. Gagosz, *Org. Lett.*, 2006, **8**, 515–518.
48 R. Robles-Machín, J. Adrio and J. C. Carretero, *J. Org. Chem.*, 2006, **71**, 5023–5026.
49 Y. Liu, M. Liu, S. Guo, H. Tu, Y. Zhou and H. Gao, *Org. Lett.*, 2006, **8**, 3445–3448.
50 A. S. K. Hashmi, J. P. Weyrauch, W. Frey and J. W. Bats, *Org. Lett.*, 2004, **6**, 4391–4394.
51 N. Asao, K. Sato and Y. Yamamoto, *Tetrahedron Lett.*, 2003, **44**, 5675–5677.
52 J. Barluenga, A. Diéguez, A. Fernández, F. Rodríguez and F. J. Fañanás, *Angew. Chem., Int. Ed.*, 2006, **45**, 2091–2093.
53 B. F. Straub, *Chem. Commun.*, 2004, 1726–1728.
54 N. Asao, T. Nogami, S. Lee and Y. Yamamoto, *J. Am. Chem. Soc.*, 2006, **128**, 10921–10925.
55 N. Asao, K. Sato, Menggenbateer and Y. Yamamoto, *J. Org. Chem.*, 2005, **70**, 3682–3685.
56 N. Asao, H. Aikawa and Y. Yamamoto, *J. Am. Chem. Soc.*, 2004, **126**, 7458–7459.
57 N. Asao, T. Kasahara and Y. Yamamoto, *Angew. Chem., Int. Ed.*, 2003, **42**, 3504–3506.
58 G. Dyker, D. Hildebrandt, J. Liu and K. Merz, *Angew. Chem., Int. Ed.*, 2003, **42**, 4399–4402.
59 D. Hildebrandt and G. Dyker, *J. Org. Chem.*, 2006, **71**, 6728–6733.
60 N. Kim, Y. Kim, W. Park, D. Sung, A. K. Gupta and C. H. Oh, *Org. Lett.*, 2005, **7**, 5289–5291.
61 X. Yao and C.-J. Li, *Org. Lett.*, 2006, **8**, 1953–1955.

62 N. Asao, *Synlett*, 2006, 1645–1656.
63 K. Sato, N. Asao and Y. Yamamoto, *J. Org. Chem.*, 2005, **70**, 8977–8981.
64 H. Kusama, Y. Miyashita, J. Takaya and N. Iwasawa, *Org. Lett.*, 2006, **8**, 289–292.
65 P. Dubé and F. D. Toste, *J. Am. Chem. Soc.*, 2006, **128**, 12062–12063.
66 Y. Fukuda, K. Utimoto and H. Nozaki, *Heterocycles*, 1987, **25**, 297–300.
67 Y. Fukuda and K. Utimoto, *Synthesis*, 1991, 975–978.
68 T. E. Müller, *Tetrahedron Lett.*, 1998, **39**, 5961–5962.
69 T. E. Müller, M. Grosche, E. Herdtweck, A.-K. Pleier, E. Walter and Y.-K. Yan, *Organometallics*, 2000, **19**, 170–183.
70 A. Arcadi, S. Di Giuseppe, F. Marinelli and E. Rossi, *Adv. Synth. Catal.*, 2001, **343**, 443–446.
71 E. Mizushima, T. Hayashi and M. Tanaka, *Org. Lett.*, 2003, **5**, 3349–3352.
72 A. Arcadi, G. Bianchi and F. Marinelli, *Synthesis*, 2004, 610–618.
73 M. Alfonsi, A. Arcadi, M. Aschi, G. Bianchi and F. Marinelli, *J. Org. Chem.*, 2005, **70**, 2265–2273.
74 T. J. Harrison, J. A. Kozak, M. Corbella-Pané and G. R. Dake, *J. Org. Chem.*, 2006, **71**, 4525–4529.
75 D. J. Gorin, N. R. Davis and F. D. Toste, *J. Am. Chem. Soc.*, 2005, **127**, 11260–11261.
76 J.-E. Kang, H.-B. Kim, J.-W. Lee and S. Shin, *Org. Lett.*, 2006, **8**, 3537–3540.
77 I. Nakamura, T. Sato and Y. Yamamoto, *Angew. Chem., Int. Ed.*, 2006, **45**, 4473–4475.
78 I. Nakamura, Y. Mizushima and Y. Yamamoto, *J. Am. Chem. Soc.*, 2005, **127**, 15022–15023.
79 A. Fürstner and P. W. Davies, *J. Am. Chem. Soc.*, 2005, **127**, 15024–15025.
80 L. Zhang and S. A. Kozmin, *J. Am. Chem. Soc.*, 2005, **127**, 6962–6963.
81 M.-Y. Lin, A. Das and R.-S. Liu, *J. Am. Chem. Soc.*, 2006, **128**, 9340–9341.
82 C. Nieto-Oberhuber, S. López, M. P. Muñoz, D. J. Cárdenas, E. Buñuel, C. Nevado and A. M. Echavarren, *Angew. Chem., Int. Ed.*, 2005, **44**, 6146–6148.
83 M. T. Reetz, *Angew. Chem., Int. Ed. Engl.*, 1972, **11**, 129–130.
84 M. T. Reetz, *Angew. Chem., Int. Ed. Engl.*, 1972, **11**, 130–131.
85 D. H. Nouri and D. J. Tantillo, *J. Org. Chem.*, 2006, **71**, 3686–3695.
86 T. Shibata, Y. Uneno and K. Kanda, *Synlett*, 2006, 411–414.
87 J. J. Kennedy-Smith, S. T. Staben and F. D. Toste, *J. Am. Chem. Soc.*, 2004, **126**, 4526–4527.
88 S. T. Staben, J. J. Kennedy-Smith and F. D. Toste, *Angew. Chem., Int. Ed.*, 2004, **43**, 5350–5352.
89 B. K. Corkey and F. D. Toste, *J. Am. Chem. Soc.*, 2005, **127**, 17168–17169.
90 S. T. Staben, J. J. Kennedy-Smith, D. Huang, B. K. Corkey, R. L. LaLonde and F. D. Toste, *Angew. Chem., Int. Ed.*, 2006, **45**, 5991–5994.
91 M. R. Luzung, J. P. Markham and F. D. Toste, *J. Am. Chem. Soc.*, 2004, **126**, 10858–10859.
92 F. Gagosz, *Org. Lett.*, 2005, **7**, 4129–4132.
93 L. Zhang and S. Kozmin, *J. Am. Chem. Soc.*, 2004, **126**, 11806–11807.
94 J. Sun, M. P. Conley, L. Zhang and S. A. Kozmin, *J. Am. Chem. Soc.*, 2006, **128**, 9705–9710.
95 B. D. Sherry and F. D. Toste, *J. Am. Chem. Soc.*, 2004, **126**, 15978–15979.
96 B. D. Sherry, L. Maus, B. N. Laforteza and F. D. Toste, *J. Am. Chem. Soc.*, 2006, **128**, 8132–8133.
97 M. H. Suhre, M. Reif and S. F. Kirsch, *Org. Lett.*, 2005, **7**, 3925–3927.
98 J. T. Binder and S. F. Kirsch, *Org. Lett.*, 2006, **8**, 2151–2153.
99 S. Park and D. Lee, *J. Am. Chem. Soc.*, 2006, **128**, 10664–10665.
100 Y. Horino, M. R. Luzung and F. D. Toste, *J. Am. Chem. Soc.*, 2006, **128**, 11364–11365.
101 G. Abbiati, A. Arcadi, G. Bianchi, S. Di Giuseppe, F. Marinelli and E. Rossi, *J. Org. Chem.*, 2003, **68**, 6959–6966.
102 A. Fürstner and P. Hannen, *Chem.–Eur. J.*, 2006, **11**, 3006–3019.
103 C. Fehr and J. Galindo, *Angew. Chem., Int. Ed.*, 2006, **45**, 2901–2904.
104 A. Fürstner and P. Hannen, *Chem. Commun.*, 2004, 2546–2547.
105 X. Shi, D. J. Gorin and F. D. Toste, *J. Am. Chem. Soc.*, 2005, **127**, 5802–5809.
106 O. Nieto Faza, C. Silva López, R. Álvarez and A. R. de Lera, *J. Am. Chem. Soc.*, 2006, **128**, 2434–2437.
107 M. J. Johansson, D. J. Gorin, S. T. Staben and F. D. Toste, *J. Am. Chem. Soc.*, 2005, **127**, 18002–18003.
108 L. Zhang and S. Wang, *J. Am. Chem. Soc.*, 2006, **128**, 1442–1443.
109 S. Wang and L. Zhang, *Org. Lett.*, 2006, **8**, 4585–4587.
110 S. Wang and L. Zhang, *J. Am. Chem. Soc.*, 2006, **128**, 8414–8415.
111 A. Buzas, F. Istrate and F. Gagosz, *Org. Lett.*, 2006, **8**, 1957–1959.
112 J. Zhao, C. O. Hughes and F. D. Toste, *J. Am. Chem. Soc.*, 2006, **128**, 7436–7437.
113 D. A. Engel and G. B. Dudley, *Org. Lett.*, 2006, **8**, 4027–4029.
114 N. Marion, P. de Frémont, G. Lemière, E. D. Stevens, L. Fensterbank, M. Malacria and S. P. Nolan, *Chem. Commun.*, 2006, 2048–2050.
115 J. P. Markham, S. T. Staben and F. D. Toste, *J. Am. Chem. Soc.*, 2005, **127**, 9708–9709.
116 S. F. Kirsch, J. T. Binder, C. Liébert and H. Menz, *Angew. Chem., Int. Ed.*, 2006, **45**, 5878–5880.
117 A. Fürstner, P. W. Davies and T. Gress, *J. Am. Chem. Soc.*, 2005, **127**, 8244–8245.
118 T. Shibata, R. Fujiwara and D. Takano, *Synlett*, 2005, 2062–2066.
119 J.-J. Lian, P.-C. Chen, Y.-P. Lin, H.-C. Ting and R.-S. Liu, *J. Am. Chem. Soc.*, 2006, **128**, 11372–11373.
120 N. Chatani, K. Kataoka, S. Murai, N. Furukawa and Y. Seki, *J. Am. Chem. Soc.*, 1998, **120**, 9104–9105.
121 E. Mainetti, V. Mouriès, L. Fensterbank, M. Malacria and J. Marco-Contelles, *Angew. Chem., Int. Ed.*, 2002, **41**, 2132–2135.
122 Y. Harrak, C. Blaszykowski, M. Bernard, K. Cariou, E. Mainetti, V. Mouriès, A.-L. Dhimane, L. Fensterbank and M. Malacria, *J. Am. Chem. Soc.*, 2004, **126**, 8656–8657.
123 B. P. Peppers and S. T. Diver, *J. Am. Chem. Soc.*, 2004, **126**, 9524–9525.
124 E. Jiménez-Núñez, C. K. Claverie, C. Nieto-Oberhuber and A. M. Echavarren, *Angew. Chem., Int. Ed.*, 2006, **45**, 5452–5455.
125 E. J. Cho, M. Kim and D. Lee, *Eur. J. Org. Chem.*, 2006, 3074–3078.
126 K. Ohe, M. Fujita, H. Matsumoto, Y. Tai and K. Miki, *J. Am. Chem. Soc.*, 2006, **128**, 9270–9271.
127 C. Nevado and A. M. Echavarren, *Synthesis*, 2005, 167–182.
128 M. T. Reetz and K. Sommer, *Eur. J. Org. Chem.*, 2003, 3485–3496.
129 Z. Shi and C. He, *J. Org. Chem.*, 2004, **69**, 3669–3671.
130 Z. Li, Z. Shi and C. He, *J. Organomet. Chem.*, 2005, **690**, 5049–5054.
131 A. S. K. Hashmi and M. C. Blanco, *Eur. J. Org. Chem.*, 2006, 4340–4342.
132 C. Nevado and A. M. Echavarren, *Chem.–Eur. J.*, 2005, **11**, 3155–3164.
133 A. Fürstner and V. Mamane, *J. Org. Chem.*, 2002, **67**, 6264–6267.
134 A. Fürstner and V. Mamane, *Chem. Commun.*, 2003, 2112–2113.
135 V. Mamane, P. Hannen and A. Fürstner, *Chem.–Eur. J.*, 2004, **10**, 4556–4575.
136 C. Ferrer and A. M. Echavarren, *Angew. Chem., Int. Ed.*, 2006, **45**, 1105–1109.
137 L. Zhang, *J. Am. Chem. Soc.*, 2005, **127**, 16804–16805.
138 N. Marion, S. Díez-González, P. de Frémont, A. R. Noble and S. P. Nolan, *Angew. Chem., Int. Ed.*, 2006, **45**, 3647–3650.
139 K. Miki, K. Ohe and S. Uemura, *J. Org. Chem.*, 2003, **68**, 8505–8513.
140 B. A. Bhanu Prasad, F. K. Yoshimoto and R. Sarpong, *J. Am. Chem. Soc.*, 2005, **127**, 12468–12469.
141 A. S. K. Hashmi, T. M. Frost and J. W. Bats, *J. Am. Chem. Soc.*, 2000, **122**, 11553–11554.
142 A. S. K. Hashmi, T. M. Frost and J. W. Bats, *Org. Lett.*, 2001, **3**, 3769–3771.
143 A. S. K. Hashmi, T. M. Frost and J. W. Bats, *Catal. Today*, 2002, **72**, 19–27.
144 A. S. K. Hashmi, L. Ding, J. W. Bats, P. Fischer and W. Frey, *Chem.–Eur. J.*, 2003, **9**, 4339–4345.

145 A. S. K. Hashmi, J. P. Weyrauch, M. Rudolph and E. Kurpejovic, *Angew. Chem., Int. Ed.*, 2004, **43**, 6545–6547.
146 A. S. K. Hashmi, M. Rudolph, J. P. Weyrauch, M. Wölfle, W. Frey and J. W. Bats, *Angew. Chem., Int. Ed.*, 2005, **44**, 2798–2801.
147 A. S. K. Hashmi, J. P. Weyrauch, E. Kurpejovic, T. M. Frost, B. Miehlich, W. Frey and J. W. Bats, *Chem.–Eur. J.*, 2006, **12**, 5806–5814.
148 A. S. K. Hashmi, P. Haufe, C. Schmid, A. Rivas Nass and W. Frey, *Chem.–Eur. J.*, 2006, **12**, 5376–5382.
149 S. Carrettin, M. C. Blanco, A. Corma and A. S. K. Hashmi, *Adv. Synth. Catal.*, 2006, **348**, 1283–1288.
150 B. Martín-Matute, C. Nevado, D. J. Cárdenas and A. M. Echavarren, *Angew. Chem., Int. Ed.*, 2001, **40**, 4754–4757.
151 B. Martín-Matute, C. Nevado, D. J. Cárdenas and A. M. Echavarren, *J. Am. Chem. Soc.*, 2003, **125**, 5757–5766.
152 A. S. K. Hashmi, R. Satathé and W. Frey, *Chem.–Eur. J.*, 2006, **12**, 6991–6996.
153 A. S. K. Hashmi, M. C. Blanco, E. Kurpejovic, W. Frey and J. W. Bats, *Adv. Synth. Catal.*, 2006, **348**, 709–713.
154 A. S. K. Hashmi and L. Grundl, *Tetrahedron*, 2005, **61**, 6231–6236.
155 A. Fürstner and C. Aïssa, *J. Am. Chem. Soc.*, 2006, **128**, 6306–6307.

