Allene formation by gold catalyzed cross-coupling of masked carbenes and vinylidenes

Vincent Lavallo, Guido D. Frey, Shazia Kousar, Bruno Donnadieu, and Guy Bertrand*

University of California Riverside–Centre National de la Recherche Scientifique Joint Research Chemistry Laboratory (Unité Mixte Internationale 2957), Department of Chemistry, University of California, Riverside, CA 92521-0403

Edited by Jack Halpern, University of Chicago, Chicago, IL, and approved July 11, 2007 (received for review June 21, 2007)

Addition of a sterically demanding cyclic (alkyl)(amino)carbene (CAAC) to AuCl(SMe₂) followed by treatment with [Et₃Si(Tol)]⁺[B(C₆F₅)₄][−] in toluene affords the isolable [(CAAC)Au(η²-toluene)]⁺[B(C₆F₅)₄][−] complex. This cationic Au(I) complex efficiently mediates the catalytic coupling of enamines and terminal alkynes to yield allenes and not propargyl amines as observed with other catalysts. Mono-, di-, and tri-substituted enamines can be used, as well as aryl-, alkyl-, and trimethylsilyl-substituted terminal alkynes. The reaction tolerates sterically hindered substrates and is diastereoselective. This general catalytic protocol directly couples two unsaturated carbon centers to form the three-carbon allenic core. The reaction most probably proceeds through an unprecedented “carbene/vinylidene cross-coupling.”

catalysis | enamines | alkynes | transition metal

Carbon-carbon bond-forming reactions are at the heart of synthetic organic chemistry; they allow for constructing simple feedstock chemicals as well as complex pharmaceuticals. Among them are reactions that directly couple two different sp²-hybridized carbon centers to form an olefin (1–13). Conceptually, the simplest process would be the dimerization and cross-coupling of two free carbenes (Fig. 1, Eq. 1), but because of the very high reactivity of these species, this route is not selective and is plagued by carbene insertion, cyclopropanation, and other side reactions (14). In marked contrast, when “masked” carbene reagents are used, this synthetic approach is highly effective stoichiometrically and catalytically as exemplified by the Wittig (1), McMurry (2) (Fig. 1, Eqs. 2 and 3), and the olefin metathesis reaction (3, 4) (Fig. 1, Eq. 4), respectively. Most of the stoichiometric processes can be extended to the preparation of allenes (15–17) by analogous “carbene/vinylidene cross-coupling” processes (Fig. 1, Eq. 5). However, there are only two known catalytic methods that couple two fragments to directly form the three-carbon allene core, namely allene cross-metathesis (18) (Fig. 1, Eq. 6), and the Crabbé homologation (19, 20) (Fig. 1, Eq. 7). For the former, a single paper reports that one of the terminal carbon units of a preformed allene can be exchanged to yield a new symmetrically substituted 1,2-diene, although extensive polymerization side reactions occur. The latter, reported in 1979, is a CuBr-mediated three-component reaction among a terminal alkyne, formaldehyde, and diisopropylamine. The most important drawback of this process is that ketones and aldehydes cannot be used in place of formaldehyde, and thus only terminal allenes can be produced.

In the last decade, allenes have evolved from exotic molecules into extremely useful synthons in natural-product construction (15, 16). Considering the lack of efficient and versatile catalytic processes to assemble directly the skeletal carbons of the allene π-system from two different fragments, a general coupling protocol is highly desirable. Here, we report the synthesis of an isolable cationic Au(I)η²-toluene complex featuring a cyclic (alkyl)(amino)carbene (CAAC) ligand (21–24). We demonstrate its ability to mediate the efficient catalytic coupling of alkynes and enamines to yield a wide range of nonterminal, unsymmetrically substituted, allenes. It is proposed that this

Fig. 1. Stoichiometric and catalytic cross-coupling reactions of unsaturated carbon fragments.

cross-coupling reaction proceeds through a unique reaction pathway involving Au(carbene)(vinylidene) intermediates.

Results and Discussion

In the last few years there have been amazing developments in gold catalysis (25–28). Once thought to be a noble metal with little synthetic utility, gold has recently demonstrated its unique and exciting catalytic properties. The most common systems involve LAuCl complexes (L = monodentate ligand), which, through *in situ* salt metathesis reactions, generate the active species often postulated to be LAu⁺. Because CAACs have been shown to stabilize cationic species (22), where other ligands were ineffective, they seemed particularly well suited for the preparation of robust LAu⁺ catalysts.

Addition of the novel spirocyclic adamantyl-substituted CAAC (1) with (Me₂S)AuCl afforded the prerequisite

Author contributions: V.L. designed research; G.D.F. and S.K. performed research; B.D. contributed new reagents/analytic tools; and G.B. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Abbreviation: CAAC, cyclic (alkyl)(amino)carbene.

Data deposition: The atomic coordinates have been deposited in the Cambridge Structural Database, Cambridge Crystallographic Data Centre, Cambridge CB2 1EZ, United Kingdom (CSD reference nos. 651272–651275).

*To whom correspondence should be addressed. E-mail: gbertran@mail.ucr.edu.

This article contains supporting information online at www.pnas.org/cgi/content/full/0705809104/DC1.

© 2007 by The National Academy of Sciences of the USA

Fig. 2. Synthesis of gold catalyst 3.

(CAAC)AuCl (**2**) in excellent yield (Fig. 2). Reacting a toluene suspension of complex **2** with the silylium-like salt $[(\text{ToI})\text{SiEt}_3]^+ [\text{B}(\text{C}_6\text{F}_5)_4]^-$ (**29**), which is a potent halophile (**30**), and subsequent removal of all volatiles under high vacuum affords a solid yellow foam. Analysis of a CDCl_3 solution of the residue by ^1H NMR shows signals in a 1:1 ratio resembling those of carbene **1** and toluene, thus suggesting the formation of cation **3**. Its structure was determined unambiguously by a single-crystal x-ray diffraction study (Fig. 3). In the solid state, the toluene molecule is η^2 -coordinated to the gold center with little perturbation of the aromatic ring, implying weak coordination. Interestingly, complex **3** appeared to be indefinitely stable in solution and in the solid state. Recently, similar complexes bearing very bulky phosphine ligands have been isolated (**31**).

The catalytic activity of **3** was tested toward the gold-catalyzed coupling reaction of enamines **4** with alkynes **5**, which is known to yield the corresponding propargyl amines **6** (**32–34**). Thus, a C_6D_6 solution of enamine **4a** and alkyne **5a** were loaded into a J-Young NMR tube containing 5 mol% of complex **3**, and the reaction was monitored by ^1H NMR spectroscopy. At room temperature no catalytic reaction was observable, even after 24 h. However, upon heating the sample at 90°C , the intensity of the signals for **4a** and **5a** diminished, and two new resonances, which did not correspond to the expected propargyl amine **6a**, appeared in the olefinic region. The ^{13}C NMR spectrum of the crude reaction mixture showed three resonances at 203.7, 102.4, and 95.7 ppm, characteristic of an allene π -system; moreover, traces of imine **8a** were detected (imine **8a** is partly degraded under the reaction conditions, whereas imine **8b** is stable) (Fig. 4). After purification by column chromatography, the allene **7a**

Fig. 3. Ball and stick depiction of catalyst **3** with 50% displacement ellipsoids. Anions and hydrogen atoms have been omitted. Selected bond lengths [pm]: Au—C 201.0(2), Au—Cl 234.1(3), Au—C2 232.0(3), C1—C2 142.5(5), C2—C3 141.1(4), C3—C4 137.5(4), C4—C5 144.3(5), C5—C6 136.8(5), C6—C1 141.7(4).

Fig. 4. Fate of the catalytic cross-coupling of enamine **4a** and alkyne **5a** depending on the nature of the catalyst.

was unambiguously identified by comparison of its spectroscopic data with those reported in the literature (**35**). Note that *in situ* generation of the catalyst **3**, prepared by mixing (CAAC)AuCl (**2**) with one equivalent of $\text{KB}(\text{C}_6\text{F}_5)_4$, affords similar catalytic results. Importantly, when AuCl (**A**), AuCl/(ToI)SiEt₃⁺B(C₆F₅)₄[−] (**B**), (PPh₃)AuCl/KB(C₆F₅)₄ (**C**), and even the neutral complex (CAAC)AuCl **2** are used as catalysts, the propargyl amine **6a** was the major product (>95%), with traces of allene **7a** (<2%) detected only in the cases of **2** and (PPh₃)AuCl/KB(C₆F₅)₄ **C**. From these results, it is clear that for the gold center to catalyze allene formation efficiently, it must be coordinated by the CAAC ligand and also rendered cationic by Cl abstraction.

To test the scope of this catalytic reaction, a set of four different enamines **4** and five terminal alkynes **5** were considered (Table 1). With one exception (entry 15), the corresponding allenes **7** were obtained in moderate to excellent yields. Interestingly, mono-, di-, and tri-substituted enamines can be used, as well as aryl-, alkyl-, and trimethylsilyl-substituted alkynes. The reaction tolerates sterically hindered substrates. Notably, ac-

Table 1. Catalytic cross-coupling of enamines **4** and alkynes **5** leading to allenes **7**

Entry	R	R ¹	R ²	R ³	R ⁴	Yields, %
1	<i>i</i> -Pr	H	H	Ph	Ph	70
2	<i>i</i> -Pr	H	H	Ph	<i>t</i> -Bu	80
3	<i>i</i> -Pr	H	H	Ph	<i>n</i> -Bu	71
4	<i>i</i> -Pr	H	H	Ph	<i>c</i> -Hex	70
5	<i>i</i> -Pr	H	H	Ph	Me ₃ Si	40
6	<i>i</i> -Pr	H	Me	Me	Ph	67
7	<i>i</i> -Pr	H	Me	Me	<i>t</i> -Bu	99
8	<i>i</i> -Pr	H	Me	Me	<i>n</i> -Bu	87
9	<i>i</i> -Pr	H	Me	Me	<i>c</i> -Hex	99
10	<i>i</i> -Pr	H	Me	Me	Me ₃ Si	65
11	Pyr	Ph	Me	Me	Ph	71
12	Pyr	Ph	Me	Me	<i>t</i> -Bu	70
13	Pyr	Ph	Me	Me	<i>n</i> -Bu	83
14	Pyr	Ph	Me	Me	<i>c</i> -Hex	86
15	pyr	Ph	Me	Me	Me ₃ Si	0
16	<i>i</i> -Pr	H	Me	Ph	Ph	71
17	<i>i</i> -Pr	H	Me	Ph	<i>t</i> -Bu	80
18	<i>i</i> -Pr	H	Me	Ph	<i>n</i> -Bu	92
19	<i>i</i> -Pr	H	Me	Ph	<i>c</i> -Hex	99
20	<i>i</i> -Pr	H	Me	Ph	Me ₃ Si	55

Catalyst **3** (5 mol%), enamine **4** (0.45 mmol), alkyne **5** (0.49 mmol), C_6D_6 (1 ml), 90°C , 16 h. NMR yields are based on enamines and determined by ^1H NMR using benzylmethyl ether as an internal standard. For entries 11–15, the enamine is derived from pyrrolidine (Pyr). Only one distereomer was obtained for entries 16–20.

Fig. 5. Stoichiometric addition of alkyne **5a** to complex **3** and subsequent reaction of the resulting complex **9a** with enamine **4a**, which affords acetylide complex **10a** and salt **11a**.

cording to multinuclear NMR spectroscopy, all of the allenes obtained by coupling the enamine, which bears $R^2 = \text{Me}$ and $R^3 = \text{Ph}$, were obtained as a single diastereomer (entries 16–20). The only serious limitation that was found is the absence of reaction when an internal alkyne was used, preventing the synthesis of tetrasubstituted allenes (see above).

Mechanistic Investigation. During our catalytic experiments, we noticed that if a C₆D₆ solution of phenyl acetylene **5a** was added to the gold catalyst **3**, in the absence of enamines **4**, a deep green-colored solution formed rapidly. Upon subsequent addition of enamines **4**, the solution immediately turned pale yellow. These observations suggested that two sequential reactions occurred at ambient temperature before active catalysis. To identify the intermediates involved in this two-step process, both the green and yellow solutions were concentrated to dryness, and the residues were characterized by NMR spectroscopy. The ¹H NMR spectrum in CD₂Cl₂ of the green residue **9a** shows the absence of toluene and resonances resembling those of the CAAC ligand, as well as those of a single molecule of phenyl acetylene (Fig. 5). To determine the coordination mode of the alkyne and exclude the CH activation of the terminal CH bond, which has been postulated by Wei and Li for related systems (32), we performed a ¹H-¹³C-coupled heteronuclear single quantum correlation NMR experiment. In the ¹H part of the spectrum, a singlet resonance at 4.5 ppm, integrating for one H, correlated with two ¹³C signals at 71 ppm ($^1J = 262 \text{ Hz}$) and 95 ppm ($^2J = 45 \text{ Hz}$), indicating that the terminal CH bond of the acetylene was intact. Therefore, the alkyne is most likely η^2 -coordinated to the cationic gold center. $\text{LAu}(\eta^2\text{-alkyne})^+\text{X}^-$ complexes such as **9a** have been proposed as reactive intermediates in numerous catalytic cycles, but only a single isolable example has been reported (36). The yellow solution, resulting from subsequent addition of enamine **4a** to a solution of **9a**, was identified by ¹³C and ¹H NMR spectroscopy as a 1:1 mixture of the neutral complex **10a** (37) and salt **11a** (Fig. 5); an independent preparation of **10a** and **11a** confirmed their identity. Importantly (see below), **11a** exists in solution as a mixture of ammonium salt and aldiminium tautomers (4:1 ratio).

Complex **10a** or salt **11a** alone does not mediate the coupling reaction; however, when a 1/1 mixture of independently prepared **10a** and **11a** (5 mol%) was added to a 1/1.1 solution of enamine **4a** and alkyne **5a**, the corresponding allene **7a** was produced with the same efficiency as when complex **3** was used.

η^2 -Alkyne and acetylide complexes related to **9a** and **10a**, as well as salts such as **11a**, have been proposed as intermediates in the catalytic preparation of propargyl amines **6** from enamines and alkynes (38). Therefore, it seemed possible that **6** were the precursors of the observed allenes **7**, as postulated for the Crabbé homologation (19, 20, 39). Palladium has also been shown to fragment preformed propargylamines to yield allenes. Under our standard coupling conditions, addition of a catalytic amount of **3** to a solution of **6a** did not yield allene **7a**. This experiment also rules out the possibility of a metal-mediated

retroiminoene fragmentation (40) from an *in situ*-generated η^2 -propargyl amine gold complex, which can also be represented as an η^1 -coordinated vinyl cation. Propargyl amine **6a** also remained intact after adding a 5 mol% amount of a **10a/11a** 1/1 mixture. However, in this case, 5% of allene **7a** (equivalent to the amount of coordinated acetylide and ammonium salt added) were obtained, demonstrating that complex **10a** and salt **11a** are the coupling partners. Lastly, when the coupling reaction of **4a** and **5a** was performed with a catalytic amount of **3** (or a 1/1 mixture of **10a/11a**) in the presence of a 10-fold excess of **6a**, the coupling proceeded smoothly without any consumption of **6a**. These experiments unambiguously demonstrate that in contrast to the Crabbé homologation, the coupling reactions mediated by catalyst **3** do not involve propargyl amine intermediates.

Because of the concomitant formation of imines **8**, it is clear that C3 and C4 originate from the enamines **4**, and consequently C1 and C2 come from the alkynes **5**. To ascertain the exact origin of H_a and H_b in the resulting allene **7a**, enamine **4b** was reacted with deuterated phenyl acetylene, in the presence of catalyst **3** (Fig. 6); 75% deuterium incorporation was observed for H_a, leading us to conclude that H_a and H_b come from the alkynes **5** and the α -position of the nitrogen moiety of enamines **4**, respectively. Note, that in this case imine **8b** has been isolated (as mentioned above, imine **8a** is partly degraded under the reaction conditions, whereas imine **8b** is stable), and its spectroscopic data compared with those reported in the literature (41).

Taking the above data as a whole, the catalytic cycle depicted in Fig. 7 can be postulated. Complex **3** undergoes ligand substitution of the coordinated arene by alkynes **5** to yield the isolated Au(I) η^2 -alkyne adducts **9**. Subsequent proton abstraction of H_a from the activated terminal alkynes with enamines **4** affords a mixture of the neutral Au(I) acetylide complexes **10** and ammonium salts **11** (represented as their iminium tautomers). Oxidative addition (42) of **11** to **10** produces the transient cationic Au(III) alkyl complexes **12**, which can also be regarded as allenyl-like cations. Hydride transfer of H_b from the α -position of the amine moiety to the positively charged carbon results in the formation of imines **8** and Au(carbene)(vinylidene) intermediates **13**. As recently reviewed by Gorin and Toste (25)

Fig. 6. Origin of the various fragments of the resulting allene **7a**.

Fig. 7. Proposed catalytic cycle for the cross-coupling of enamines **4** with alkynes **5** leading to allenes **7**.

and Fürstner and Davies (27), the representation of the carbene ligand of **13** as a gold-stabilized carbocation is perfectly valid and in this case helps to avoid the uncommon Au(V) oxidation state. Reductive coupling of the carbene and vinylidene produces allenes **7** and regenerates the catalyst **3**.

Concluding Remarks. The cross-coupling reaction of enamines with terminal alkynes, mediated by the cationic gold(I) complex **3**, which bears a CAAC ligand, is a general catalytic protocol that directly couples two unsaturated carbon centers and forms the three-carbon allenic core. The reaction most probably proceeds through an unprecedented carbene/vinylidene cross-coupling. The diastereoselectivity observed is encouraging, and consequently an enantioselective version of this catalytic reaction, using the appropriate optically pure CAAC ligand should be possible.

Materials and Methods

For more details on the procedures used, see supporting information (SI) *Materials and Methods*.

CAAC 1. Diethyl ether (15 ml) was added at -78°C to a Schlenk tube containing the conjugate acid of CAAC **1** with HCl_2 as counteranion (900 mg, 2.0 mmol) and potassium bis(trimethylsilyl)amide (800 mg, 4.0 mmol). The reaction mixture was stirred for 5 min and then removed from the cold bath as stirring was continued until the solution reached room temperature. The solvent was removed under vacuum, and the residue was extracted with *n*-hexane (3×10 ml). After removing the solvent under vacuum, CAAC **1** was isolated as white microcrystalline solid (710 mg, 94% yield). Crystals suitable for a single crystal x-ray diffraction study were obtained from an *n*-hexane solution at -20°C . ^1H NMR (300 MHz, C_6D_6) δ 7.23 (t, $J = 7.0$ Hz, 1H),

7.15 (d, $J = 7.2$ Hz, 2H), 3.56 (m, 2H), 3.08 (sept, $^3J = 6.8$ Hz, 2H), 2.21–1.62 (m, 14H), 1.23 (d, $^3J = 6.8$ Hz, 6H), 1.12 (d, $^3J = 6.8$ Hz, 6H), 1.11 (s, 6H); ^{13}C NMR (75 MHz, C_6D_6) δ 322.7, 146.3, 138.9, 128.4, 124.1, 81.2, 69.2, 48.7, 39.7, 38.8, 35.6, 35.3, 30.0, 29.8, 29.7, 28.6, 26.4, 22.3.

AuCl(CAAC) Complex 2. A THF solution (6 ml) of free carbene **1** (640 mg, 1.69 mmol) was added to a THF solution (5 ml) of $\text{AuCl}(\text{SMe}_2)$ (475 mg, 1.61 mmol). The reaction mixture was stirred for 12 h at room temperature. The solvent was removed under vacuum, and the residue was washed with *n*-hexane (10 ml). The residue was extracted with methylene chloride (10 ml), and the solvent was removed under vacuum, affording complex **2** as a white solid (850 mg, 86% yield). Crystals suitable for an x-ray diffraction study were obtained by slow evaporation of a CH_2Cl_2 solution. m.p. 194 – 195°C (dec); ^1H NMR (300 MHz, CDCl_3) δ 7.37 (t, $J = 7.7$ Hz, 1H), 7.20 (d, $J = 7.7$ Hz, 2H), 4.00 (m, 2H), 2.71 (sept, $^3J = 6.7$ Hz, 2H), 2.32–1.78 (m, 14H), 1.39 (d, $^3J = 6.7$ Hz, 6H), 1.31 (s, 6H), 1.26 (d, $^3J = 6.7$ Hz, 6H); ^{13}C NMR (75 MHz, C_6D_6) δ 239.9, 144.8, 135.2, 129.7, 125.0, 76.9, 63.7, 48.5, 39.0, 37.0, 35.2, 34.6, 29.2, 29.1, 27.6, 27.1, 26.9, 23.1; fast atom bombardment MS calculated for $\text{C}_{27}\text{H}_{39}\text{NAu} [\text{M}]^+$: m/z 574; found 574.

[Au(CAAC)(Toluene)] $^+$ [B(C $_6$ F $_5$) $_4$] $^-$ Catalyst 3. Toluene (5 ml) was added at room temperature to a Schlenk tube containing complex **2** (1.48 g, 2.43 mmol) and $[(\text{Tol})\text{SiEt}_3]^+ [\text{B}(\text{C}_6\text{F}_5)_4]^-$ (2.15 g, 2.43 mmol). After stirring the biphasic mixture for 30 min., *n*-hexane (50 ml) was added. The upper layer was removed by cannula, and the oily residue was dried under high vacuum to afford complex **3** as a solid white foam (3.04 g, 93% yield). Crystals suitable for an x-ray diffraction study were obtained by layering a fluorobenzene solution of **3** with *n*-hexane. m.p. 156 – 157°C (dec); ^1H NMR (300 MHz, CDCl_3) δ 7.52 (t, $J = 7.8$ Hz, 1H), 7.31 (d, $J = 7.8$ Hz, 2H), 7.23–7.19 (m, 4H), 7.02 (m, 1H), 3.05 (m, 2H), 2.57 (sept, $^3J = 6.7$ Hz, 2H), 2.33 (s, 3H, CH_3), 2.34–1.34 (m, 14H), 1.38 (s, 6H), 1.29 (d, $^3J = 6.7$ Hz, 6H), 1.25 (d, $^3J = 6.7$ Hz, 6H); ^{13}C NMR (75 MHz, CDCl_3) δ 237.0, 148.4 (m, $^1J = 245$ Hz), 145.7, 144.7, 138.3 (m, $^1J = 241$ Hz), 136.5 (m, $^1J = 241$ Hz), 135.9, 130.9, 127.2, 125.7, 123.8, 117.1, 79.1, 63.7, 48.4, 38.6, 36.9, 35.2, 34.1, 29.5, 29.2, 27.6, 26.9, 26.7, 23.2.

General Catalytic Procedure for the Preparation of Allenes 7. A C_6D_6 solution (1 ml) of enamines **4** (0.446 mmol) and alkynes **5** (0.490 mmol) was added to a J-Young NMR tube containing catalyst **3** (30 mg, 0.023 mmol) and benzylmethyl ether as internal standard (5 mg, 0.041 mmol). The tube was sealed and heated at 90°C for 16 h, and the yields of the resulting allenes were calculated by ^1H NMR spectroscopy.

This work was supported by National Institutes of Health Grant R01 GM 68825 (to G.B.) and RHODIA, Inc. (G.B.). G.D.F. and S.K. were supported by fellowships from the Alexander von Humboldt Foundation and the Higher Education Commission of Pakistan, respectively.

1. Takeda T, ed (2004) *Modern Carbonyl Olefination* (Wiley, Weinheim, Germany).
2. Fürstner A, Bogdanovic B (1996) *Angew Chem Int Ed Engl* 35:2442–2469.
3. Grubbs RH, ed (2003) *Handbook of Metathesis* (Wiley, Weinheim, Germany).
4. Schrock RR, Czekelius C (2007) *Adv Synth Cat* 349:55–77.
5. Li JJ, Corey EJ, eds (2007) *Name Reactions of Functional Group Transformations* (Wiley, New York).
6. Herreras CI, Yao X, Li Z, Li C (2007) *Chem Rev* 107:2546–2562.
7. Fagnoni M, Dondi D, Ravelli D, Albini A (2007) *Chem Rev* 107:2725–2756.
8. Yin L, Liebscher J (2007) *Chem Rev* 107:133–173.
9. Alberico D, Scott ME, Lautens M (2007) *Chem Rev* 107:174–238.
10. Takanori S (2006) *Adv Synth Cat* 348:2328–2336.
11. Chopade PR, Louie J (2006) *Adv Synth Cat* 348:2307–2327.
12. Kuehn FE, Scherbaum A, Herrmann WA (2004) *J Organomet Chem* 689:4149–4164.
13. Trost BM, Frederiksen MU, Rudd MT (2005) *Angew Chem Int Ed* 44:6630–6666.
14. Moss RA, Platz MS, Jones M, Jr, eds (2004) *Reactive Intermediate Chemistry* (Wiley, New York), pp 273–461.
15. Brummond KM, DeForrest J (2007) *Synthesis* 795–818.
16. Krause N, Hashmi ASK, eds (2004) *Modern Allene Chemistry* (Wiley, Weinheim, Germany).
17. Aksnes G, Froyen P (1968) *Acta Chem Scand* 22:2347–2352.
18. Ahmed M, Arnauld T, Barret AGM, Braddock DC (2000) *Org Lett* 2:551–553.
19. Crabbé P, André D, Fillion H (1979) *Tetrahedron Lett* 20:893–896.
20. Searles S, Li Y, Nassim B, Lopes MTR, Tran PT, Crabbé P (1984) *J Chem Soc Perkin Trans* 1:747–751.
21. Lavallo V, Canac Y, Präsang C, Donnadieu B, Bertrand G (2005) *Angew Chem Int Ed* 44:5705–5709.

22. Lavallo V, Canac Y, DeHope A, Donnadiou B, Bertrand G (2005) *Angew Chem Int Ed* 44:7236–7239.
23. Frey GD, Lavallo V, Donnadiou B, Schoeller WW, Bertrand G (2007) *Science* 316:439–441.
24. Anderson DR, Lavallo V, O’Leary DJ, Bertrand G, Grubbs RH (2007) *Angew Chem Int Ed* 10.1002/anie.200702085.
25. Gorin DJ, Toste FD (2007) *Nature* 446:395–403.
26. Jiménez-Núñez E, Echavarren AM (2007) *Chem Commun* 333–346.
27. Fürstner A, Davies PW (2007) *Angew Chem Int Ed* 46:3410–3449.
28. Hashmi ASK, Hutchings GJ (2006) *Angew Chem Int Ed* 45:7896–7936.
29. Lambert JB, Zhang S, Stern CL, Huffman JC (1993) *Science* 260:1917–1918.
30. Douvris C, Stoyanov ES, Tham FS, Reed CA (2007) *Chem Commun* 1145–1147.
31. Herrero-Gómez E, Nieto-Oberhuber C, López S, Benet-Buchholz J (2006) *Angew Chem Int Ed* 45:5455–5459.
32. Wei C, Li C (2003) *J Am Chem Soc* 125:9584–9585.
33. Kantam ML, Prakash BV, Reedy CRV, Sreedhar B (2005) *Synlett* 15:2329–2332.
34. Lo VKY, Liu Y, Wong MK, Che CM (2006) *Org Lett* 8:1529–1532.
35. Jayanth TT, Jegannmohan M, Cheng MJ, ChuSY, Cheng CH (2006) *J Am Chem Soc* 128:2232–2233.
36. Akana JA, Bhattacharyya KX, Müller P, Sadighi JP (2007) *J Am Chem Soc* 129:7736–7737.
37. Wang HMJ, Chen CYL, Lin IJB (1999) *Organometallics* 18:1216–1223.
38. Koradin C, Gommermann N, Polborn K, Knochel P (2003) *Chem Eur J* 9:2797–2811.
39. Nakamura H, Onagi S, Kamakura T (2005) *J Org Chem* 70:2357–2360.
40. Ipatktschi J, Mohsseni-Ala J, Dülmer A, Loschen C, Frenking G (2005) *Organometallics* 24:977–989.
41. Nicolaou KC, Mathiason CJN, Montagnon T (2004) *J Am Chem Soc* 126:5192–5201.
42. Raubenheimer HG, Olivier PJ, Lindeque L, Desmet M, Hrusak J, Kruger GJ (1997) *J Organomet Chem* 544:91–100.