Chemical Science

EDGE ARTICLE

View Article Online
View Journal | View Issue

Cite this: *Chem. Sci.*, 2017, **8**, 7132

Synthesis of azasilacyclopentenes and silanols *via* Huisgen cycloaddition-initiated C–H bond insertion cascades†

Jiun-Le Shih, ‡ Santa Jansone-Popova, ‡ Christopher Huynh and Jeremy A. May *

Received 17th July 2017
Accepted 21st August 2017

DOI: 10.1039/c7sc03130k

rsc.li/chemical-science

An unusual transition metal-free cascade reaction of alkynyl carbonazidates was discovered to form azasilacyclopentenes. Mild thermolysis afforded the products *via* a series of cyclizations, rearrangements, and an α-silyl C–H bond insertion (rather than the more common Wolff rearrangement, 1,2-shift, or β-silyl C–H insertion) to form silacyclopropanes. A mechanistic proposal for the sequence was informed by control experiments and the characterization of reaction intermediates. The substrate scope and post-cascade transformations were also explored.

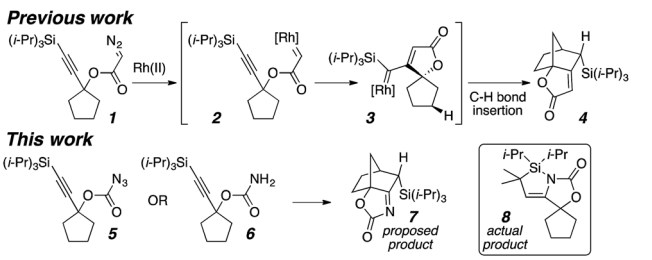
Introduction

Carbenes have been employed in cyclopropanations,[1] Büchner ring expansion,[2] ylide formation,[3] X–H bond insertion,[4] and especially C–H bond insertions,[5] which have provided a powerful tool for synthetic chemistry.[6] Cascade reactions using highly reactive carbenes allow the efficient synthesis of complex molecules.[7] Our research group recently reported the formation of bridged polycycles *via* carbene/alkyne cascade reactions terminated in C–H bond insertion (Scheme 1).[8] We were also interested in utilizing this cascade reaction to synthesize nitrogen-containing polycyclic compounds like **7**. Instead, a complex sequence with an unusual α-silyl C–H bond insertion formed azasilacyclopentene **8** from carbonazidate **5**.

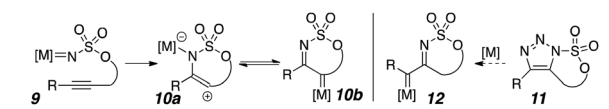
Nitrenes have been used for the aziridination of olefins,[9] the C–H amination of alkanes,[10] and the synthesis of bioactive molecules.[11] Pioneering work from Blakey showed nitrene/alkyne cascades proceeded through an endo-cyclization with the alkyne to the postulated vinyl cation/metalloenamine **10a**, which potentially could rearrange to the α-iminometallocarbene **10b** or react directly (Scheme 2).[12] Importantly, metallocarbene **12** could not be accessed *via* that approach, and α-diazoimines are difficult to synthesize. Carbene **12** could be directly produced from a transition metal catalyzed triazole ring opening.[13] The incorporation of C–H bond insertions in these cascade reactions is still rare.[14,15] An investigation to generate intermediate **12** and use that highly reactive species and its high potential for complex and interesting transformations has unveiled surprising and novel reactivity. Starting with carbonazidates like **5**, carbene **12** was accessed *via* a metal-free Huisgen cyclization and dediazatization. From this reactive intermediate, C–H bond insertion, bond fragmentations, and pseudopericyclic rearrangements have been identified, and mechanistic intermediates isolated. Reactivity patterns suggest the intermediacy of imino-conjugated triplet carbenes.

Results and discussion

The initial goal was to establish a nitrene/alkyne cascade reaction to synthesize nitrogen-containing polycycles like **7**.



Scheme 1 Carbene- and nitrene-based cascade reactions.



Scheme 2 Nitrene and triazole carbene formation.

Department of Chemistry, University of Houston, Fleming Building Room 112, 3585 Cullen Blvd, Houston, TX 77204-5003, USA. E-mail: jmay@uh.edu

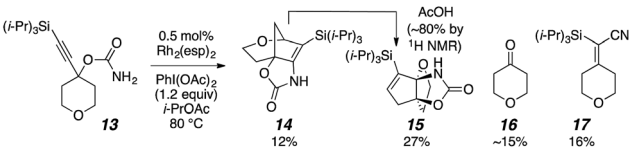
† Electronic supplementary information (ESI) available: Full experimental details and compound characterizations, including X-ray diffraction data, are provided. CCDC 1477662–1477666 and 1477728. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c7sc03130k

‡ Current affiliation: Chemical Science Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6119, UAS.

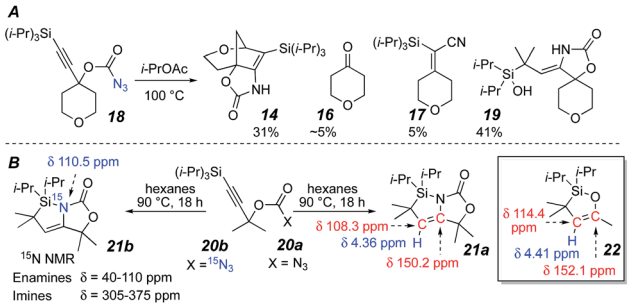
Treating carbamate **13** with $Rh_2(esp)_2$ and $PhI(OAc)_2$ resulted in the formation of multiple products: the predicted bridged tricycle **14**, propellane **15**,[16] tetrahydropyranone **16**, and silyl vinyl nitrile **17** (Scheme 3).[16] A control experiment revealed that acetic acid, produced during the carbamate oxidation, slowly promoted the rearrangement of **14** to propellane **15** *in situ*. This exploratory reaction demonstrated a proof-of-principle for a nitrene/alkyne cascade that results in C–H insertion to generate a C–C bond; however, controlling product selectivity was problematic. Consequently, other nitrene precursors were sought to achieve a more selective outcome.

Carbonazidate[17] **18** allowed an improved yield (31%) of tricycle **14** without a catalyst (Scheme 4A). Surprisingly, silanol **19** was also isolated, which was thought to be the result of silica gel-mediated hydrolysis of a labile product during purification since it was not observed in the NMR of the crude reaction material. Dimethyl carbonazidate **20a** was prepared to minimize overlapping NMR signals in order to identify the immediate product of the reaction. After ^1H and ^{13}C NMR analysis, its structure was determined to be azasilacyclopentene[18] **21a** (Scheme 4B). The NMR signals of **21a** (vinyl proton: 4.36 ppm; enamine carbons: 108.3 and 150.2 ppm) correlated well to those of oxasilacyclopentene **22**.[19] In addition, ^{15}N NMR analysis of ^{15}N-enriched azasilacyclopentene **21b** (110.5 ppm, no signals from 305 to 375 ppm)[20] suggested that the nitrogen was involved in an enamine motif, corroborating the ^1H and ^{13}C NMR data. Hydrolysis of **21a** to the silanol proved to be facile with a small amount of water.

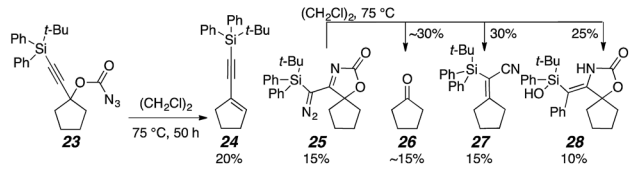
The products **19** and **21** appeared to be formed *via* C–H bond insertion at one of the isopropyl groups. In order to bias product formation toward the bridged tricycle by removing all α-silyl C–H bonds, *tert*-butyldiphenyl silylacetylene carbonazidate **23** was prepared (Scheme 5). The reaction produced five compounds, **24–28**. The α-diazo oxazolone **25** and the silanol **28** were crystallized and analyzed by X-ray diffraction to confirm the structures shown.[21] In a control experiment, diazoimine **25**



Scheme 3 Cascade reaction of a carbamate.



Scheme 4 Cascade reaction of carbonazidates.



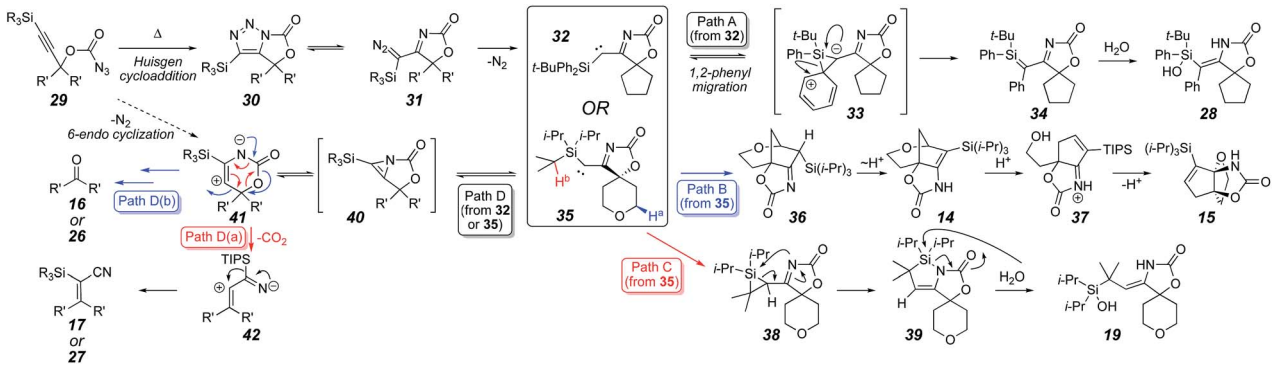
Scheme 5 Avoiding α-silyl C–H bond insertion.

was heated again to form **26–28**, indicating that it is a viable reaction intermediate and that the vinyl nitrile and ketone products are derived from it. Enyne **24**, however, was not observed, demonstrating that it likely formed by elimination from **23**.

These results have been incorporated in a proposed mechanism for the cascade reaction (Scheme 6). Identification of α-diazo imine **25** suggests that a Huisgen cycloaddition[22] generated triazole **30**, followed by ring opening to **31**.[13,23] The α-imino carbene **32** (for R_3Si = Ph_2t-BuSi) could be directly produced *via* dinitrogen extrusion. Silanol **28** would be produced from **32** by 1,2-phenyl migration (see **33** to **34**, Path A)[14b] and hydration. When R_3Si = i-Pr_3Si, loss of N_2 would form carbene **35**, which could proceed through either a transannular ring insertion into the ether-activated methylene (H^a, see Path B), or insertion into the isopropyl C–H bond (H^b, see Path C). The former leads to the bridged tricycles **36** and **14**, which can rearrange in the presence of acid to propellane **15** through an elimination/addition sequence.[8] The latter pathway would form silacyclopropane **38**. Silacyclopropanes are usually formed through silylene transfer,[24] but there are a few cases of formation *via* intramolecular C–H bond insertion, though these intermediates were unstable and were not isolated.[25] Likewise, intermediate **38** was not stable, but rearranged[26] to azasilacyclopentene **39**, which could be observed and characterized spectroscopically (*vide supra*). Exposure to water rapidly hydrolyzed the weak N–Si bond to give silanol **19**.

The isolation of ketone **26** and vinyl nitrile **27** suggested either a 6-endo reaction of a nitrene derived from **29** to form zwitterion **41**, or else **41** would be derived from carbenes **32** or **35** (Path D).[10–15] Since **26** and **27** were formed from heating diazoimine **25** (Scheme 5), it is likely that the latter route was operative. Therefore, a carbene electrocyclization of **32** (likely pseudopericyclic) would allow the highly strained azirine **40** to be transiently formed.[26] Either of the C–N bonds could fragment, with an internal fragmentation forming the ring expanded product **41**. A retro-hetero Diels–Alder reaction allows for decarboxylation (Path D(a)), and 1,2-silyl migration in zwitterion **42** would give the vinyl nitriles **17** or **27**. Alternatively, C–C bond fragmentation would provide ketones **16** or **26** (Path D(b)). These pathways account for all the observed products and intermediates.

Only a few examples of intramolecular C–H bond insertion to form silacyclopropanes have been reported, and in those cases these intermediates were also fleeting and inferred from downstream products rather than observed directly.[25] For simple silicon-substituted carbenes like **44**, the triplet state is significantly stabilized relative to the singlet state.[27,28] 1,2-



Scheme 6 Proposed mechanism.

Rearrangements to silenes are the most common outcomes for these compounds,[29] though cyclopropanations and C–H insertions have also been observed in suitable substrates (see **47** and **51**). Intramolecular cyclopropanations appear to be possible with silyl carbenes of either a triplet or singlet nature if pendant olefins are present (**47** and **49**, respectively). On the other hand, the presence of a carbonyl induces more singlet-like reactivity,[28,30] including Wolff rearrangements and X–H insertion reactions.[31] Intramolecular C–H bond insertions may also occur for these cases, but the preference for insertion is typically at the β- or γ-position relative to silicon (see **60**).[32] A single report exists for imine-adjacent silyl carbene formation, which is also derived from a triazole precursor (**61**). In this case, the sole product was a 1,2-silyl shift to give ketene imine **63**. Based on these precedents, products **36** (intramolecular C–H bond insertion) or **66** (1,2-shift: see **34**, Scheme 6) would have been expected to dominate this reaction, but instead outcomes derived from silacyclopropane formation (see Schemes 3 and 4A) dominated when C–H bond insertion was possible and the formation of **66** and derivatives thereof were not observed.

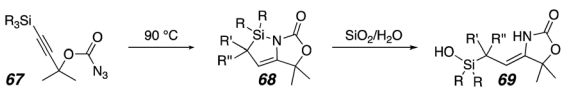
The unanticipated formation of the azasilacyclopentenes from the reaction cascade prompted further investigation. The acyclic carbonazidate **20a** was selected to bias the reaction for azasilacyclopentene formation by eliminating competitive C–H insertion in an appended ring (Table 1, entries 1–5). A lower yield of **21a** resulted from the use of a halogenated solvent, dichloroethane, but the use of hexanes resulted in fewer byproducts and a slightly higher yield (entry 3). However, the use of $Rh_2(esp)_2$ or Cp*RuCl(cod)[14] was deleterious (entries 4 and 5).

We were curious if C–H bond insertion would take place at different positions on larger silyl alkanes, or the α-position was preferred. However, all of the alkyl groups only generated the azasilacyclopentenes corresponding to insertion into the C–H bond alpha to silicon (entries 6–9).[19b] These results contradict literature examples of singlet or metal carbene insertion into alkylsilanes, which show insertion primarily at the methylene or methine beta to silicon,[33] presumably due to the "β-silicon effect". In the examples in Table 1, none of the available β, γ, or δ-C–H bonds reacted. High regioselectivity was shown even in the isobutyl substrate **69f**, where the electron-rich β-methine was untouched.

It appears that unlike the other acyl silyl carbenes in Scheme 7, the carbenes **32** and **35** are triplet carbenes and therefore exhibit diradical character.[35] The C–C bond formation would then proceed *via* hydrogen atom abstraction from the carbon attached to the silicon in **71** to generate an α-silyl radical[36] **72** (Scheme 8), which would be stabilized by back-bonding from silicon δ-orbitals.[37] Then, the silacyclopropane **73** would be formed from radical combination.

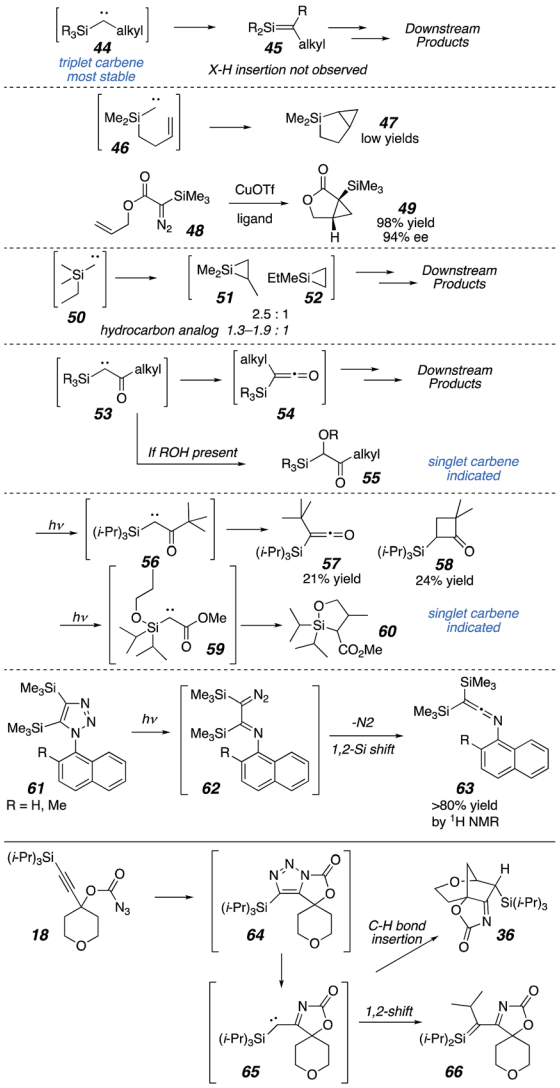
Next, a series of acyclic, cyclic, and heterocyclic carbonazidates was examined (Table 2). Varying the alkyl groups at R^1

Table 1 Variation of the silyl alkyl group[34]

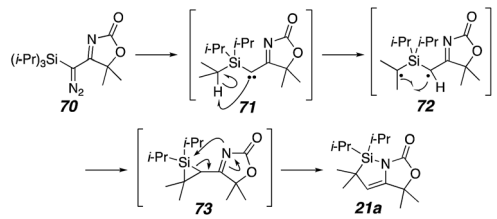


Entry	Carbonazidate	Solvent	Azasilacyclopentene	Yield[a]	Silanol	Yield[b] (2 steps)
1		*i*-PrOAc		48%		
2		$(CH_2Cl)_2$		25%		
3		Hexanes		52%		50%
4		Hexanes[c]		43%		
5	**20a**	Hexanes[d]	**21a**	19%	**69a**	
6	**67b**	Hexanes	**68b**	38%	**69b**	38%
7	**67c**	Hexanes	**68c**	42%	**69c**	42%
8	**67d**	Hexanes	**68d**	56%	**69d**	43%
9	**67e**	Hexanes	**68e**	56%	**69e**	44%
10	**67f**	Hexanes	**68f**	55%	**69f**	43%

[a] Yield based on ^{1}H NMR peak integration relative to methyl-4-nitrobenzoate. [b] Isolated yields (average of 2 trials). [c] 1 mol% $Rh_2(esp)_2$. [d] 2 mol% Cp*RuCl(cod).



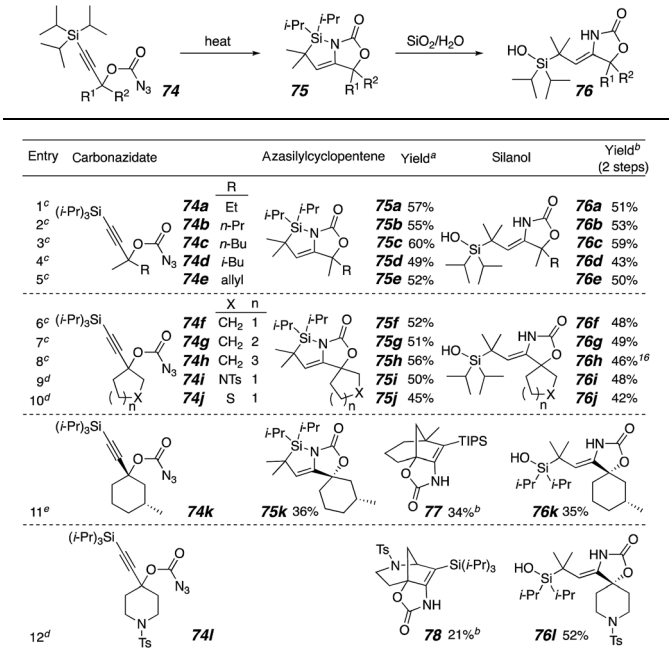
Scheme 7 Typical outcomes for silyl-substituted carbenes.



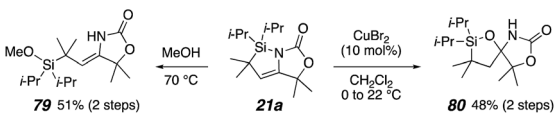
Scheme 8 Proposed triplet carbene/diradical pathway.

and R^2 of **74** does not significantly affect the formation of the azasilacyclopentene. Although an allyl group could potentially undergo cyclopropanation with an intermediate silyl carbene,[32a,38] only the azasilacyclopentene **75e** is seen (entry 5). Cyclic substrates generally provided spiro-oxazolones (entry 6–10). Bridged polycycles were not observed, even for pyrrolidine **74i** and thiolane **74j**, where the heteroatoms could activate α-C–H bonds for carbene insertion.[39] Two substrates with six-membered rings provided a different result, presumably due to greater conformational flexibility to react with the activated C–H bonds compared to the 5-membered rings (entries 11 and 12). For the 3-methyl cyclohexane **74k**, the reaction produced a 1 : 1 ratio of azasilacyclopentene **75k** and bridged tricycle **77**. For the tosyl piperidine **74l**, the major isolated product was the silanol **76l**, but some bridged bicycle was observed.[40]

Table 2 Propargylic variation in the substrates[34]



[a] Yield based on ^{1}H NMR peak integration relative to methyl-4-nitrobenzoate. [b] Isolated yields (average of 2 trials). [c] Hexanes, 90 °C. [d] Isopropyl acetate, 100 °C. [e] Hexanes, 100 °C.



Scheme 9 Reactions of azasilacyclopentene.

Preliminary tests were made for transformations of the azasilacyclopentene products. Methyl silyl ether **79** is obtained in good yield by ring opening of **21a** in methanol. Treatment of **21a** with $CuBr_2$ generated spiro-hemiaminal **80**.[16] Silanol **69a** also produced **80** with $CuBr_2$, suggesting that **21a** is first hydrolyzed by adventitious water before spirocycle formation (Scheme 9).

Conclusions

A novel approach for the synthesis of azasilacyclopentenes *via* a Huisgen cycloaddition-initiated cascade reaction terminating in an α-silyl C–H bond insertion has been discovered. Control experiments suggest a likely mechanism with triplet silylcarbene intermediates undergoing C–H bond insertion at the

carbon attached to silicon to form transient silacyclopropanes. Further reaction of the azasilacyclopentene showed the formation of interesting products. Ongoing efforts are seeking selective synthesis of bridged polycycles and vinyl nitriles from the same precursors.

Conflicts of interest

There are no conflicts of interest to declare.

Acknowledgements

The authors thank the Welch Foundation (grant E-1744) and the NSF (grant CHE-1352439) for funding. J.-L. S. is grateful to CBIP (UH) and the Studying Abroad Scholarship of Taiwan for fellowships. They are also grateful to Dr Ilja Popovs for discussion of the spectroscopic characterization of mechanistic intermediates.

Notes and references

1 (*a*) C. Qin, V. Boyarskikh, J. H. Hansen, K. I. Hardcastle, D. G. Musaev and H. M. L. Davies, *J. Am. Chem. Soc.*, 2011, **133**, 19198; (*b*) B. T. Parr and H. M. L. Davies, *Angew. Chem., Int. Ed.*, 2013, **52**, 10044; (*c*) S.-H. Hou, Y.-Q. Tu, L. Liu, F.-M. Zhang, S.-H. Wang and X.-M. Zhang, *Angew. Chem., Int. Ed.*, 2013, **52**, 11373; (*d*) H. Lu, W. I. Dzik, X. Xu, L. Wojtas, B. de Bruin and X. P. Zhang, *J. Am. Chem. Soc.*, 2011, **133**, 8518; (*e*) V. N. G. Lindsay, C. Nicolas and A. B. Charette, *J. Am. Chem. Soc.*, 2011, **133**, 8972; (*f*) A. DeAngelis, R. Panish and J. M. Fox, *Acc. Chem. Res.*, 2016, **49**, 115.

2 (*a*) P. Panne and J. M. Fox, *J. Am. Chem. Soc.*, 2007, **129**, 22; (*b*) A. L. Crombie, J. L. Kane, K. M. Shea and R. L. Danheiser, *J. Org. Chem.*, 2004, **69**, 8652.

3 (*a*) X. Xu, P. Y. Zavalij and M. P. Doyle, *Angew. Chem., Int. Ed.*, 2012, **51**, 9829; (*b*) J. Barluenga, G. Lonzi, L. Riesgo, L. A. López and M. Tomás, *J. Am. Chem. Soc.*, 2010, **132**, 13200; (*c*) X. Wang, X. Xu, P. Y. Zavalij and M. P. Doyle, *J. Am. Chem. Soc.*, 2011, **133**, 16402; (*d*) X. Xu, P. Y. Zavalij and M. P. Doyle, *J. Am. Chem. Soc.*, 2013, **135**, 12439; (*e*) C. Qin and H. M. L. Davies, *J. Am. Chem. Soc.*, 2013, **135**, 14516.

4 (*a*) Z. Qu, W. Shi and J. Wang, *J. Org. Chem.*, 2004, **69**, 217; (*b*) A. DeAngelis, O. Dmitrenko and J. M. Fox, *J. Am. Chem. Soc.*, 2012, **134**, 11035; (*c*) T. C. Maier and G. C. Fu, *J. Am. Chem. Soc.*, 2006, **128**, 4594; (*d*) S.-F. Zhu, B. Xu, G.-P. Wang and Q.-L. Zhou, *J. Am. Chem. Soc.*, 2012, **134**, 436; (*e*) B. Liu, S.-F. Zhu, W. Zhang, C. Chen and Q.-L. Zhou, *J. Am. Chem. Soc.*, 2007, **129**, 5834; (*f*) R. Sambasivan and Z. T. Ball, *J. Am. Chem. Soc.*, 2010, **132**, 9289.

5 (*a*) P. Herrmann and T. Bach, *Chem. Soc. Rev.*, 2011, **40**, 2022; (*b*) M. P. Doyle, R. Duffy, M. Ratnikov and L. Zhou, *Chem. Rev.*, 2010, **110**, 704; (*c*) J. H. Hansen, T. M. Gregg, S. R. Ovalles, Y. Lian, J. Autschbach and H. M. L. Davies, *J. Am. Chem. Soc.*, 2011, **133**, 5076; (*d*) H. Wang, G. Li, K. M. Engle, J.-Q. Yu and H. M. L. Davies, *J. Am. Chem. Soc.*, 2013, **135**, 6774; (*e*) H. M. L. Davies and D. Morton, *Chem. Soc. Rev.*, 2011, **40**, 1857; (*f*) Y. Lian and H. M. L. Davies, *J. Am. Chem. Soc.*, 2011, **133**, 11940.

6 (*a*) H. M. L. Davies and J. R. Denton, *Chem. Soc. Rev.*, 2009, **38**, 3061; (*b*) J. Yamaguchi, A. D. Yamaguchi and K. Itami, *Angew. Chem., Int. Ed.*, 2012, **51**, 8960; (*c*) P. Lu, Z. Gu and A. Zakarian, *J. Am. Chem. Soc.*, 2013, **135**, 14552; (*d*) P. Lu, A. Mailyan, Z. Gu, D. M. Guptill, H. Wang, H. M. L. Davies and A. Zakarian, *J. Am. Chem. Soc.*, 2014, **136**, 17738; (*e*) O. Daugulis, J. Roane and L. D. Tran, *Acc. Chem. Res.*, 2015, **48**, 1053.

7 (*a*) A. Padwa and M. D. Weingarten, *Chem. Rev.*, 1996, **96**, 223; (*b*) T. R. Hoye, *J. Am. Chem. Soc.*, 1991, **113**, 4343; (*c*) Z. Zheng and L. Zheng, *Org. Chem. Front.*, 2015, **2**, 1556; (*d*) A. Padwa, *Chem. Soc. Rev.*, 2009, **38**, 3072.

8 (*a*) S. Jansone-Popova and J. A. May, *J. Am. Chem. Soc.*, 2012, **134**, 17877; (*b*) S. Jansone-Popova, P. Q. Le and J. A. May, *Tetrahedron*, 2014, **70**, 4118; (*c*) P. Q. Le and J. A. May, *J. Am. Chem. Soc.*, 2015, **137**, 12219.

9 (*a*) J. W. Rigoli, C. D. Weatherly, J. M. Alderson, B. T. Vo and J. M. Schomaker, *J. Am. Chem. Soc.*, 2013, **135**, 17238; (*b*) A. A. Desai and W. D. Wulff, *J. Am. Chem. Soc.*, 2010, **132**, 13100; (*c*) M. R. Fructos, E. Álvarez, M. M. Díaz-Requejo and P. J. Pérez, *J. Am. Chem. Soc.*, 2010, **132**, 4600; (*d*) L. Maestre, W. M. C. Sameera, M. M. Díaz-Requejo, F. Maseras and P. J. A. Pérez, *J. Am. Chem. Soc.*, 2013, **135**, 1338; (*e*) K. Guthikonda and J. Du Bois, *J. Am. Chem. Soc.*, 2002, **124**, 13672.

10 (*a*) E. Milczek, N. Boudet and S. Blakey, *Angew. Chem., Int. Ed.*, 2008, **47**, 6825; (*b*) D. N. Zalatan and J. Du Bois, *J. Am. Chem. Soc.*, 2008, **130**, 9220; (*c*) Q. Nguyen, T. Nguyen and T. G. Driver, *J. Am. Chem. Soc.*, 2013, **135**, 620; (*d*) A. Nörder, S. A. Warren, E. Herdtweck, S. M. Huber and T. Bach, *J. Am. Chem. Soc.*, 2012, **134**, 13524; (*e*) D. N. Zalatan and J. Du Bois, *J. Am. Chem. Soc.*, 2009, **131**, 7558.

11 (*a*) G. Dequirez, V. Pons and P. Dauban, *Angew. Chem., Int. Ed.*, 2012, **51**, 7384; (*b*) A. Sloan Devlin and J. Du Bois, *Chem. Sci.*, 2013, **4**, 1059; (*c*) J. J. Fleming, M. D. McReynolds and J. Du Bois, *J. Am. Chem. Soc.*, 2007, **129**, 9964; (*d*) A. Hinman and J. Du Bois, *J. Am. Chem. Soc.*, 2003, **125**, 11510; (*e*) J. V. Mulcahy and J. Du Bois, *J. Am. Chem. Soc.*, 2008, **130**, 12630; (*f*) K. W. Quasdorf, A. D. Huters, M. W. Lodewyk, D. J. Tantillo and N. K. Garg, *J. Am. Chem. Soc.*, 2012, **134**, 1396.

12 (*a*) A. R. Thornton and S. B. Blakey, *J. Am. Chem. Soc.*, 2008, **130**, 5020; (*b*) A. R. Thornton, V. I. Martin and S. B. Blakey, *J. Am. Chem. Soc.*, 2009, **131**, 2434; (*c*) A. H. Stoll and S. B. Blakey, *J. Am. Chem. Soc.*, 2010, **132**, 2108; (*d*) A. H. Stoll and S. B. Blakey, *Chem. Sci.*, 2011, **2**, 112; (*e*) N. Mace, A. R. Thornton and S. B. Blakey, *Angew. Chem., Int. Ed.*, 2013, **52**, 5836; (*f*) A. Boyer, *J. Org. Chem.*, 2015, **80**, 4771.

13 (*a*) J. E. Spangler and H. M. L. Davies, *J. Am. Chem. Soc.*, 2013, **135**, 6802; (*b*) J. S. Alford, J. E. Spangler and H. M. L. Davies, *J. Am. Chem. Soc.*, 2013, **135**, 11712; (*c*) B. T. Parr, S. A. Green and H. M. L. Davies, *J. Am. Chem. Soc.*, 2013, **135**, 4716; (*d*)

T. Miura, Y. Funakoshi and M. Murakami, *J. Am. Chem. Soc.*, 2014, **136**, 2272; E. E. Schultz and R. Sarpong, *J. Am. Chem. Soc.*, 2013, **135**, 4696. (*e*) T. Miura, T. Tanaka, K. Hiraga, S. G. Stewart and M. Murakami, *J. Am. Chem. Soc.*, 2013, **135**, 13652; (*f*) T. Horneff, S. Chuprakov, N. Chernyak, V. Gevorgyan and V. V. Fokin, *J. Am. Chem. Soc.*, 2008, **130**, 14972; (*g*) J. S. Alford and H. M. L. Davies, *J. Am. Chem. Soc.*, 2014, **136**, 10266.

14 (*a*) S. Chuprakov, J. A. Malik, M. Zibinsky and V. V. Fokin, *J. Am. Chem. Soc.*, 2011, **133**, 10352; (*b*) B. C. Boren, S. Narayan, L. K. Rasmussen, L. Zhang, H. Zhao, Z. Lin, G. Jia and V. V. Fokin, *J. Am. Chem. Soc.*, 2008, **130**, 8923.

15 V. N. G. Lindsay, H. M. F. Viart and R. Sarpong, *J. Am. Chem. Soc.*, 2015, **137**, 8368.

16 Structure confirmed *via* single crystal X-ray diffraction.

17 (*a*) R. Singh, J. N. Kolev, P. A. Sutera and R. Fasan, *ACS Catal.*, 2015, **5**, 1685; (*b*) T. Heinisch and T. R. Ward, *Eur. J. Inorg. Chem.*, 2015, **2015**, 3406; (*c*) T. Bach, B. Schlummer and K. Harms, *Chem.–Eur. J.*, 2001, **7**, 2581; (*d*) D. P. Uccello, S. M. Miller, N. A. Dieterich, A. F. Stepan, S. Chung, K. A. Farley, B. Samas, J. Chen and J. I. Montgomery, *Tetrahedron Lett.*, 2011, **52**, 4247.

18 Z. Nevárez and K. A. Woerpel, *Org. Lett.*, 2007, **9**, 3773.

19 (*a*) S. A. Calad and K. A. Woerpel, *J. Am. Chem. Soc.*, 2005, **127**, 2046; (*b*) R. Bruckmann and G. Maas, *Chem. Ber.*, 1987, **120**, 635.

20 G. C. Kevy and R. L. Lichter, *Nitrogen-15 Nuclear Magnetic Resonance Spectroscopy*, J. Wiley, New York, NY, 1979.

21 Crystal structures have been deposited in the Cambridge Crystallographic Data Centre, reference numbers 1477662–1477666 and 1477728.†

22 (*a*) S. Bräse, C. Gil, K. Knepper and V. Zimmermann, *Angew. Chem., Int. Ed.*, 2005, **44**, 5188; (*b*) R. G. Brisbois, A. M. Bergan, A. J. Ellison, P. Y. Griffin, K. C. Hackbarth and S. R. Larson, *Tetrahedron Lett.*, 2013, **54**, 272.

23 G. Mitchell and C. W. Rees, *J. Chem. Soc., Perkin Trans. 1*, 1987, 413.

24 (*a*) A. K. Franz and K. A. Woerpel, *Acc. Chem. Res.*, 2000, **33**, 813; (*b*) T. G. Driver, A. K. Franz and K. A. Woerpel, *J. Am. Chem. Soc.*, 2002, **124**, 6524; (*c*) J. Ćiraković, T. G. Driver and K. A. Woerpel, *J. Am. Chem. Soc.*, 2002, **124**, 9370; (*d*) T. G. Driver and K. A. Woerpel, *J. Am. Chem. Soc.*, 2003, **125**, 10659.

25 (*a*) J. W. Connolly and G. J. Urry, *J. Org. Chem.*, 1964, **29**, 619; (*b*) J. W. Connolly, *J. Organomet. Chem.*, 1968, **11**, 429.

26 (*a*) R. Huisgen, *Angew. Chem., Int. Ed. Engl.*, 1980, **19**, 947; (*b*) H. Ji, L. Li, X. Xu, S. Ham, L. A. Hammad and D. M. Birney, *J. Am. Chem. Soc.*, 2009, **131**, 528.

27 G. Maas, *Silicon-Substituted Carbenes*, John Wiley & Sons, Ltd, Chichester, UK, 2nd edn, 2009, vol. I.

28 A. Nemirowski and P. R. Schreiner, *J. Org. Chem.*, 2007, **72**, 9533.

29 (*a*) W. Ando, T. Hagiwara and T. Migita, *J. Am. Chem. Soc.*, 1973, **95**, 7518; (*b*) W. Ando, A. Sekiguchi, J. Ogiwara and T. Migita, *J. Chem. Soc., Chem. Commun.*, 1975, 145.

30 K. Hirai, T. Itoh and H. Tomioka, *Chem. Rev.*, 2009, **109**, 3275.

31 (*a*) W. Ando, A. Sekiguchi, T. Hagiwara, T. Migita, V. Chowdhry, F. H. Westheimer, S. L. Kammula, M. Green and M. Jones, *J. Am. Chem. Soc.*, 1979, **101**, 6393; (*b*) R. Brückmann, K. Schneider and G. Maas, *Tetrahedron*, 1989, **45**, 5517; (*c*) M. J. Davies, C. J. Moody and R. J. Taylor, *J. Chem. Soc., Perkin Trans. 1*, 1991, 1; (*d*) M. Alt and G. Maas, *Tetrahedron*, 1994, **50**, 7435; (*e*) S. P. Marsden and W. K. Pang, *Tetrahedron Lett.*, 1998, **39**, 6077; (*f*) D. C. Braddock, D. M. Badine, T. Gottschalk, A. Matsuno and M. Rodriguez-Lens, *Synlett*, 2003, 345.

32 (*a*) U. Schöllkopf, D. Hoppe, N. Rieber and V. Jacobi, *Eur. J. Org. Chem.*, 1969, **730**, 1; (*b*) R. Brückmann, K. Schneider and G. Maas, *Tetrahedron*, 1989, **45**, 5517.

33 (*a*) D. Seyferth, S. S. Washburne and C. J. Attridge, *J. Am. Chem. Soc.*, 1970, **92**, 4405; (*b*) P. Wang and J. Adams, *J. Am. Chem. Soc.*, 1994, **116**, 3296; (*c*) Y. Hatanaka, M. Watanabe, S.-Y. Onozawa, M. Tanaka and H. Sakurai, *J. Org. Chem.*, 1998, **63**, 422.

34 Although azasilacyclopentenes can be observed in the NMR and GC/MS of the crude reaction mixture, they do not survive silica gel chromatography. Thus, NMR-based yields are reported for the azasilacyclopentenes and isolated yields are reported for the corresponding silanols.

35 (*a*) M. J. Ellis and M. F. G. Stevens, *J. Chem. Soc., Perkin Trans. 1*, 2001, 3174; (*b*) D. J. Hagan, D. Chan, C. H. Schwalbe and M. F. G. Stevens, *J. Chem. Soc., Perkin Trans. 1*, 1998, 915.

36 R. Walsh, *Acc. Chem. Res.*, 1981, **14**, 246.

37 (*a*) J. W. Wilt, O. Kolewe and J. F. Kraemer, *J. Am. Chem. Soc.*, 1969, **91**, 2624; (*b*) T. Manabe, S.-I. Yanagi, K. Ohe and S. Uemura, *Organometallics*, 1998, **17**, 2942; (*c*) Y. J. Lee, R. Linf and P. S. Mariano, *J. Org. Chem.*, 1996, **61**, 3304; (*d*) S. Bogen, L. Fensterbank and M. Malacria, *J. Org. Chem.*, 1999, **64**, 819; (*e*) P. Grieco, Y. Yokoyama and E. Williams, *J. Org. Chem.*, 1978, **43**, 1285; (*f*) M. Cocivera and E. Grunwald, *J. Am. Chem. Soc.*, 1965, **87**, 2071; (*g*) P. J. Krusic and J. K. Kochi, *J. Am. Chem. Soc.*, 1969, **91**, 6161.

38 (*a*) W. Ando, A. Sekiguchi, T. Hagiwara and T. Migita, *J. Chem. Soc., Chem. Commun.*, 1974, 372; (*b*) T. J. Barton, J. A. Kilgour, R. G. Gallucci, A. J. Rothschild, J. Slutsky, A. D. Wolf and M. Jones, *J. Am. Chem. Soc.*, 1975, **97**, 657; (*c*) G. Maas, B. Daucher, A. Maier and V. Gettwert, *Chem. Commun.*, 2004, **26**, 238; (*d*) S. Inoue, K. Nagatani, H. Tezuka, Y. Hoshino and M. Nakada, *Synlett*, 2017, **28**, 1065.

39 *i*-PrOAc was used for solubility.

40 The azasilylcyclopentene intermediate could not accurately be quantified.