Heterofunctionalization catalysis with organometallic complexes of calcium, strontium and barium

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Despite the routine employment of Grignard reagents and Hauser bases as stoichiometric carbanion reagents in organic and inorganic synthesis, a defined reaction chemistry encompassing the heavier elements of Group II (M = Ca, Sr and Ba) has, until recently, remained unreported. This article provides details of the recent progress in heavier Group II catalysed small molecule transformations mediated by well-defined heteroleptic and homoleptic complexes of the form LMX or MX2; where L is a mono-anionic ligand and X is a reactive σ-bonded substituent. The intra- and intermolecular heterofunctionalization (hydroamination, hydrophosphination, hydrosilylation and hydrogenation) of alkenes, alkynes, dienes, carbodiimides, isocyanates and ketones is discussed.

Keywords: calcium; strontium; barium; heavier alkaline earth; heterofunctionalization; catalysis

1. Introduction

Over the past few decades, the understanding of the coordination chemistry of the elements of the heavy alkaline earth metals (M = Ca, Sr, Ba) has advanced dramatically, owing primarily to an interest in their application as chemical vapour deposition precursors (Hanusa 1990, 1993, 2000, 2002; Westerhausen 1998, 2001, 2006, 2008; Alexander & Ruhlandt-Senge 2002; Westerhausen et al. 2007). Reaction studies upon organometallic compounds of calcium, strontium and barium have, however, been largely overshadowed by those of the lighter congener, magnesium. Despite the routine employment of Grignard reagents and Hauser bases as stoichiometric carbanion reagents in organic and

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inorganic synthesis, a well-defined reaction chemistry encompassing the heavier elements of Group II has remained unreported. It is revealing that, although syntheses of ‘heavy Grignards’ (ArMX and RMX, X = halide) were documented contemporaneously with Grignard’s original reports of his eponymous reagents (Grignard 1900; Beckmann 1905; Gilman & Schulze 1926; Gilman et al. 1943), only in the last 3 years have arylcalcium halides been isolated and structurally characterized (Gartner et al. 2007b; Westerhausen 2008). Furthermore, the solid-state structures of the analogous strontium and barium complexes are, as yet, unknown (Langer et al. 2007).

With some recent remarkable exceptions (Green et al. 2007, 2008; Bonyhady et al. 2009; Krieb et al. 2009), the organometallic compounds of the heavy alkaline earths are overwhelmingly redox inactive species, which demonstrate a +2 oxidation state. The M$^{2+}$ cations achieve noble gas configurations, and compounds of the heavy metals possess a d$^0$ electron configuration. The ionic radii of the dications increase as the group is descended (Shannon 1976), whereas the Pauling electronegativity of the elements decreases as the group is descended. The combined result of these factors is that, while organometallic compounds of magnesium may show a degree of covalency in metal–ligand interactions, bonding in organometallic complexes of the heavier elements are dictated almost exclusively by ionic and non-directional interactions between the metal and auxiliary ligands. In this regard, parallels have often been drawn between the chemistry of the heavier alkaline earths and that of the trivalent organolanthanides. The latter compounds are also defined by highly ionic metal–ligand interactions and have begun a versatile reaction chemistry. Since the pioneering work of Marks (Hong & Marks 2004), it has been shown that trivalent organolanthanide compounds of the form $L_2MX^1$, where $L$ is a mono-anionic spectator ligand and $X^1$ is a mono-anionic $\sigma$-bonded substituent, demonstrate two fundamental types of reactivity: (i) $\sigma$-bond metathesis and (ii) insertion of unsaturated carbon–carbon or carbon–heteroatom bonds into Ln–X$^1$ $\sigma$-bonds (figure 1a,b).

By incorporating these two reaction steps into catalytic cycles, a vast number of lanthanide-mediated synthetic reactions have been developed, many of which have no direct parallels in conventional organic synthesis. Initial research in this area centred upon the application of sterically demanding pentamethylcyclopentadienyl ($L = \text{Cp}^*$) or $\text{ansa}$-bridged cyclopentadienyl [$L_2 = (\text{C}_5\text{Me}_4)_2\text{SiMe}_2$, (C$_5$Me$_4$)SiMe$_2$(N-t-Bu)] ligand sets to stabilize low-coordinate, highly reactive, organolanthanide intermediates. Work by Marks has demonstrated the application of compounds of the form $L_2MX^1$ [$X^1 = \text{H}$, $\text{CH(SiMe}_3)_2$, $\text{N(SiMe}_3)_2$] to the hydroamination, hydroposphination, hydrosilylation, hydrogenation and hydroboration of unsaturated carbon–carbon bonds (Togni & Grützmacher 2001; Molander & Romero 2002; Hong & Marks 2004).

Given the parallels between the bonding within heavier Group II and trivalent lanthanide compounds, it has been suggested that these complexes may be employed as homogeneous catalytic reagents using $\sigma$-bond metathesis and insertion reaction chemistries to construct catalytic cycles. Within the last 5 years, this hypothesis has been realized; herein, we present a review article on the emerging area of catalysis by organometallic complexes of the heavier alkaline earths.
Although striking progress has been made in the application of calcium, strontium and barium complexes for the polymerization of activated alkenes, such as styrene (Feil & Harder 2000, 2001, 2003; Weeber et al. 2000; Harder et al. 2001a,b; Harder & Feil 2002; Feil et al. 2003; Harder 2004; Piesik et al. 2007), the ring-opening polymerization of cyclic esters (Chisholm et al. 2003; Piao et al. 2003a,b; Westerhausen et al. 2003; Chisholm et al. 2004; Sarazin et al. 2006; Davidson et al. 2007), the dimerization of aldehydes (Crimmin et al. 2007b) and the trimerization of isocyanates (Orzechowski & Harder 2007), this review focuses on catalytic methods for carbon–heteroatom bond formation via the heterofunctionalization of unsaturated substrates. Furthermore, owing to uncertainties relating to the chemical composition of the active species, applications of complexes of Group II alkoxides as bases for asymmetric carbon–carbon bond-forming reactions are not covered by this review article (Yamada & Shibasaki 1998; Kumaraswamy et al. 2001, 2003; Suzuki et al. 2001; Saito et al. 2007).

While the coordination chemistry of heavier Group II metals has been reviewed numerous times (see the introductory paragraph for references) and several recent papers have highlighted results in heavier Group II catalysis...
(Coles 2008; Smith 2009; Westerhausen 2009), there are no extensive review articles that discuss the catalytic reactivity of calcium, strontium and barium reagents.

2. Heterofunctionalization catalysis

(a) \(\sigma\)-bond metathesis and insertion reactivity at heavier Group II centres

Several precedents exist in stoichiometric heavier Group II chemistry that are consistent with the fundamental reaction types observed for trivalent organo-lanthanide complexes. Westerhausen, for example, has observed the insertion of both 1,4-diphenylbutadiyne and benzonitrile into the metal–phosphorus bond of a series of homolectic heavier alkaline earth phosphides, \([\text{M}{\text{P(SiMe}_3\text{)}_2(\text{THF})_4}]\) (\(\text{M} = \text{Ca, Sr and Ba}; \text{THF} = \text{tetrahydrofuran}; \text{Westerhausen et al. 1997, 1998c, 1999, 2000b}\)). In a related study, it has been demonstrated that the analogous amide complexes \([\text{M}\{\text{N(SiMe}_3\text{)}_2\}_2(\text{THF})_2]\) also undergo insertion reactions with benzonitrile (Westerhausen & Schwarz 1992). Although in all cases, the initial reaction products underwent decomposition with silyl group migration, the isolated products can be rationalized in terms of the insertion step. This work parallels early studies by Gilman and Coles, which showed that ill-defined heavier alkaline earth complexes, proposed to contain metal–carbon \(\sigma\)-bonds, react with unsaturated substrates such as CO\(_2\), benzonitrile and 1,1-diphenylethene (Gilman et al. 1943, 1945; Gilman & Woods 1945; Coles & Hart 1971). Mingos and coworkers have demonstrated the insertion of carbonyl sulphide, carbon disulphide and sulphur dioxide into Group II metal–alkoxide bonds (Arunasalam et al. 1994, 1995, 1998; Bezugoli et al. 1997, 1998a,b). Feil et al. reported the insertion of 1,3-dicyclohexyl carbodiimide into the calcium amide bonds of \([\text{Ca}\{\text{N(SiMe}_3\text{)}_2\}_2]\) (Feil & Harder 2005). Perhaps more importantly, the work of Harder has shown that highly reactive heavier Group II benzyl complexes are suitable initiators for the polymerization of styrene. These reactions have been shown to occur through multiple insertions of the alkene into the metal–carbon \(\sigma\)-bond of intermediate organometallic species (Weeber et al. 2000).

Further to these observations, \(\sigma\)-bond metathesis (or protonolysis) has been frequently employed in stoichiometric heavier Group II chemistry to synthesize new organometallic complexes. Examples include the reaction of heavier Group II metal amides \([\text{M}\{\text{N(SiMe}_3\text{)}_2\}_2(\text{THF})_n]\) (\(\text{M} = \text{Ca, Sr and Ba}; \ n = 0 \text{ or } 2\)) with alcohols, thiols, selenols and tellurols, pyroles and pyrazoles, terminal alkynes, cyclopentadiene and derivatives, phosphines or arsines to yield the corresponding metal alkoxide (Westerhausen et al. 2003; Sarazin et al. 2006; Davidson et al. 2007), thiolate (Chadwick et al. 1998), selenolate and tellurate (Gindelberger & Arnold 1992, 1994), pyrrolide and pyrazolide (Vargas et al. 2002; Hitzbleck et al. 2004), acetylide (Burkey & Hanusa 1996; Green et al. 1999; Avent et al. 2005a; Barrett et al. 2008b; Schumann et al. 2009), cyclopentadienide (Tanner & Hanusa 1994; Tanner et al. 1995; Westerhausen et al. 1995; Hays et al. 1996; Avent et al. 2006), phosphide (Westerhausen & Schwarz 1993; Westerhausen 1994; Westerhausen et al. 1996a,b, 1998b, 2000a,c) or arsenide (Westerhausen & Schwarz 1995; Westerhausen et al. 1998a, 2001) species, \(\text{MX}_2\), along with the reaction by-product \(\text{HN(SiMe}_3\text{)}_2\). In many cases,
homoleptic organometallic complexes commonly demonstrate low solubility in hydrocarbon solvents and are often isolated with the addition of a charge neutral, chelating ligand.

(b) The Schlenk equilibrium

An underlying challenge in the development of catalytic reagents based upon the heavier alkaline earths is the propensity of heteroleptic compounds of the form LMX\(_1^1\) to undergo Schlenk-like solution redistribution reactions to the homoleptic compounds L\(_2^2\)M and MX\(_2^1\) (figure 2). The latter species are often polymeric and of low solubility in non-coordinating solvents, and the former species are kinetically stabilized and unreactive. This solution redistribution reaction results in the formation of a mixture from a potentially catalytically active species and may result in the loss of any ligand control over reactivity.

This problem becomes increasingly important for the heavier alkaline earth congeners, as ionic radius increases and Lewis acidity decreases on descending the group and, for a given ancillary ligand set, the tendency towards solution redistribution of heteroleptic Group II organometallics, LMX\(_1^1\), to MX\(_1^1\) and L\(_2^2\)M increases across the series M = Mg < Sr < Ca < Ba.

To overcome this problem, we, and others, have proposed that the application of sterically demanding monoanionic ligand sets to the kinetic stabilization of heteroleptic alkaline earth complexes should slow the rate of the redistribution reaction, allowing subsequent study of the σ-bonded substituent in the heteroleptic complexes. Work by Hanusa has shown that a number of heteroleptic heavier alkaline earth complexes including halides (McCormick et al. 1989; Burkey et al. 1994; Harvey & Hanusa 2000), acetylides (Burkey & Hanusa 1996), amides (Sockwell et al. 1992) and a calcium borohydride (Harvey et al. 2000; figure 3; X\(_1^1\) = I, C≡CR, NR\(_2^2\), HBR\(_3^3\)) may be kinetically stabilized by the application of bulky cyclopentadienyl ligands allowing their synthesis and characterization in the solid state. Many of these compounds, however, have

\[
2 \text{LMX}^1 \rightleftharpoons \text{L}_2\text{M} + \text{MX}^1_2, \; M = \text{Mg, Ca, Sr, Ba}
\]

Figure 2. The Schlenk equilibrium of heavier Group II complexes.

Figure 3. Selected examples of well-defined, kinetically stabilized, heteroleptic heavier Group II complexes. Empirical formulae only (many compounds are of higher nuclearity in the solid state).
proven unstable in solution and readily undergo Schlenk-like equilibria, and it is notable that little or no further reaction chemistry has been forthcoming from this approach.

Chisholm et al. (2003, 2004) reported the isolation and characterization of the \( \beta \)-diketiminato stabilized calcium amide 1 and a tris(pyrazolylborate) stabilized analogue (figures 3 and 4), along with their application to the ring-opening polymerization of rac-lactide to form heterotactic polylactide.

This paper represented a breakthrough in heteroleptic heavier Group II chemistry; demonstrating controlled reactivity at an alkaline earth centre supported by a mono-anionic spectator ligand, it paved the way for the application of heavier Group II catalysts in small molecule transformations. To date, the majority of catalytic applications are based upon heteroleptic complexes of the form \( \text{LMX}^1 \) containing kinetically stabilizing \( \beta \)-diketiminato, triazenide, aminotropiniminato, bis(imidazolin-2-ylidene-1-yl)borate and tris(imidazolin-2-ylidene-1-yl)borate spectator ligands, and reactive \( \sigma \)-bonded amide, hydride or alkyl ligands (\( \text{X}^1 = \text{N(SiMe}_3\text{)}_2, \text{H or benzyl} \)). A number of homoleptic complexes of the form \( \text{MX}^1_2 \), however, have also been reported as pre-catalysts for heterofunctionalization of unsaturated substrates.

\( \text{c) Hydroamination (C–N) bond formation} \)

(\( i \)) Intramolecular hydroamination of aminoalkenes

In 2005, the intramolecular hydroamination of a number of aminoalkenes catalysed by 1 was reported (Crimmin et al. 2005, 2009). Reactions were shown to proceed in high yield under mild conditions (25–80°C, 0.25–132 h), allowing the synthesis of pyrrolidines, piperidines and hexahydroazepines from the \( n \)-exo-trig (\( n = 5, 6, 7 \)) cyclization of 1-amino-4-pentenes, 1-amino-5-hexenes and 1-amino-6-heptenes, respectively (figure 5). Reactions at higher temperatures were found to proceed with the Schlenk-like solution redistribution of 1 to the homoleptic complexes \( \left[ \text{Ca}\{\text{N(SiMe}_3\text{)}_2\}_2(\text{THF})\}_2 \right] \) and \( \left[ \{\text{ArNC(Me)CHC(Me)NAr}\}_2\text{Ca} \right] \) (\( \text{Ar} = 2,6\text{-di-iso-propylphenyl} \)). This work set a precedent for heterofunctionalization catalysis at heavier Group II metal centres.

As a point of comparison, the authors also synthesized the magnesium pre-catalyst \( \left[ \{\text{ArNC(Me)CHC(Me)NAr}\}_2\text{MgMe(THF)} \right] \) (2) and studied its reaction with aminoalkenes. While side-by-side kinetic analysis showed that the calcium pre-catalyst was more active than the magnesium analogue for the cyclization of...
(1-allylcyclohexyl)methylamine (for reactions conducted at an initial aminoalkene concentration of 0.44 M, turn over frequency (TOF) 1, 146 h⁻¹; 2, 48.5 h⁻¹), the synthetic utility of the calcium complex proved more limited. Not only were reactions of 2,2-disubstituted 1-amino-5-hexene substrates accompanied by alkene isomerization products, but also the cyclization of 1-amino-2,2-diphenyl-6-heptene could not be achieved with this catalyst. Nevertheless, both 1 and 2 demonstrated activities commensurate with those reported for the organo(III)lanthanides (Hong & Marks 2004) and in vast excess of those reported for organozinc complexes (Dochnahl et al. 2006, 2007; Meyer et al. 2006).

The reaction scope is currently limited to the hydroamination cyclization of 1° and 2° aminoalkenes incorporating the olefin at the terminal position. The reaction is reported to be influenced greatly by the substitution pattern of the aminoalkene. Typically, geminal disubstituted alkenes gave the fastest reaction times and could be cyclized using just 2 mol% of 1 or 2–5 mol% of 2. These substrates benefit from a favourable kinetic effect owing to the geminal groups decreasing the conformational freedom of the aminoalkene and favouring reactive conformations (Jung & Piizzi 2005). For a given catalyst, both loadings and reaction times decreased with the increasing steric demands of the geminal substituents. Substitution about the C=C bond lengthened reaction times, and the intramolecular hydroamination of aminoalkenes possessing internal olefins catalysed by either 1 or 2 is yet to be reported. The inclusion of alkyl groups on the terminal position of the alkene can be expected to disfavour the hydroamination reaction owing to the need to form an insertion transition state with partial tertiary Group II alkyl character. Similar observations have been made in organolanthanide chemistry, and a number of coordinatively unsaturated ansa-bridged metalloocene and half-sandwich organolanthanide catalysts have been designed to effect the hydroamination/cyclization of highly substituted aminoalkenes (Molander & Dowdy 1999). Consistent with Baldwin’s (1976) guidelines for ring formation, the ease of the catalytic reactions increases with decreasing ring size (5 > 6 > 7-membered ring closures). In all cases, more forcing reaction conditions (higher reaction temperatures, higher catalyst loadings) were reported for the hydroamination of aminoalkenes to 6- and 7-membered rings.
The cyclization of aminoalkenes possessing two pro-chiral centres potentially results in the formation of a mixture of diastereoisomeric products. Although substitution on the β-position of the aminoalkene had little effect upon the diastereoselectivity of the reaction, α-substituted aminoalkenes underwent a diastereoselective intramolecular hydroamination cyclization reaction. Thus, the catalytic reaction of 1-amino-1-phenylpent-4-ene with both 1 and 2 yielded the corresponding trans-pyrrolidine in a diastereoisomeric excess of 90 and 98 per cent, respectively. A similar reaction of 2-aminohex-5-ene catalysed by 20 mol% 1 was reported to proceed to give the trans-pyrrolidine in 78 per cent diastereoisomeric excess (figure 6). Similar selectivities have been observed in the organolanthanide series, and reaction of 2-aminohex-5-ene with [{(C₅Me₄)₂SiMe₂}La(CH(SiMe₃)₂)] has been reported to yield a 8:1 mixture of trans: cis heterocyclic products at 0°C (Gagne et al. 1992).

The observed diastereoselectivity is most readily explained by consideration of the energetically dissimilar diastereoisomeric transition states to carbon–nitrogen bond formation in the insertion step. Of the four 7-membered diastereoisomeric transition states that can be envisaged for the carbon–nitrogen-bonding forming step, transition states A and D (figure 6), leading to the cis-pyrrolidine, possess a potentially destabilising 1,3-diaxial steric interaction. This latter conformation may raise the activation energy to carbon–nitrogen bond formation and, hence, favour the trans-diastereoisomer via transition states B and C. In this regard, it appears that substitution at the β-position of the aminoalkene does not suffer from similar unfavourable non-bonding interactions and does not affect the diastereoselectivity of the reaction. By analogy to the organo(III)lanthanide system, the improved diastereoselectivity in the case of the magnesium catalyst can be attributed to the shorter M–N and M–C bond lengths in magnesium-containing relative to calcium-containing complexes tightening the transition state of the insertion reaction and therefore increasing any effects exerted by non-bonding interactions.
While the stoichiometric protonolysis reaction of an analogue of 2, [{ArNC(Me)CHC(Me)NAr}Mg\textsubscript{\textit{n}}/\textit{t}-Bu], with benzyamine, 2-methoxyethylamine and pyrrolidine to yield the corresponding dimeric magnesium amides and methane has been reported (Barrett \textit{et al.} 2009\textit{b}) to proceed rapidly and non-reversibly at room temperature, the reaction of 1 with benzyamine forms a quantifiable equilibrium between monomeric bis(trimethylsilyl)amide and dimeric benzylamide reaction products (figure 7). A van’t Hoff analysis of this equilibrium mixture allowed the derivation of \(\Delta G^\circ (298\text{K})\) as 11.3 kJ mol\(^{-1}\), consistent with facile pre-catalyst activation via protonolysis with a primary amine (Barrett \textit{et al.} 2008\textit{d}). Further reactions of 1 with 2-methoxyethylamine and 2,6-di-iso-propylaniline demonstrated that the equilibrium could be effectively perturbed to the reaction products in the presence of chelating or more acidic substrates. (Avent \textit{et al.} 2004, 2005\textit{b}; figure 7). These studies, along with a report by Harder and coworkers upon the addition of ammonia to 1, have demonstrated that \(\beta\)-diketiminato calcium 1\textsuperscript{\circ} amide complexes undergo facile external amine/amide exchange along with intramolecular site exchange between amide and amine ligands (Ruspic & Harder 2007; Crimmin \textit{et al.} 2009).

Although products of the intramolecular insertion of alkenes into M–N bonds have not been directly observed, a deuterium labelling experiment has implied their formation. Thus, the cyclization of (1-allylcyclohexyl)methylamine-d\(_2\) with either 1 or 2 has been reported to yield the corresponding hydroamination product with deuterium incorporation upon the carbon framework solely at the exo-cyclic methyl group. Crimmin \textit{et al.} proposed that the two pre-catalysts 1 and 2 give rise to two distinct catalytic systems proceeding via non-reversible and reversible catalyst initiation, respectively (figure 8). Data were reported that are consistent with rate-determining insertion of the alkene into the metal–nitrogen bond of a coordinatively unsaturated monomeric metal amido reaction intermediate. Kinetic studies upon the magnesium pre-catalyst allowed the derivation of the rate law \(v \approx k_{d1}k_3[\text{Cat}]_0/\textit{k}_a[\text{Sub}]_0 + k_3\), where \(k_{d1}\) is a dissociation rate constant of ligand dissociation from a coordinatively saturated catalyst resting state, \(\textit{k}_a\) is an association rate constant of a ligand with the coordinatively unsaturated resting state (i.e. the reverse of \(k_{d1}\)), \(k_{il}\) is the rate constant of alkene insertion into a coordinatively unsaturated resting state, Cat is catalyst and Sub is substrate. In line with the findings of Hultzsch and coworkers for lanthanide(III) systems
(Gribkov et al. 2006), it was suggested that both substrate and product inhibit the reaction to similar extents; hence, reaction-rate constants are dependent upon the substrate concentration at \( t_0 \).

While Crimmin et al. refrained from application of heavier analogues of 1 and 2 (\( M = \text{Sr}, \text{Ba}; \) Avent et al. 2005b) in hydroamination catalysis owing to their propensity to undergo Schlenk-like redistribution under the reaction conditions, Datta et al. (2007, 2008a, b) reported aminotroponoate and aminotroponiminate supported calcium and strontium amide complexes 3–5 as competent catalysts for the intramolecular hydroamination of aminoalkenes (figure 9). Although, in most instances, selectivities and catalyst activities were commensurate with those reported for the \( \beta \)-diketiminato-stabilized calcium amide 1, it is noteworthy that Datta et al. reported not only that 4 mol\% 4 was effective for the intramolecular hydroamination of an aminoalkyne to the corresponding imine in more than 90 per cent after 22 h at room temperature, but also that both 4 and 5 affect the cyclization of the internal (activated) alkene \( \text{trans-1-amino-2,2-dimethyl-5-phenyl-4-pentene} \) to the corresponding pyrrolidine in 80 per cent yield after 10 min at room temperature (figure 10). Despite side-by-side experiments suggesting that the strontium compound 5 is less active than the calcium analogue 4, the kinetic stability of the Group II catalytic intermediates with respect to Schlenk-like solution redistribution was not discussed.

Based upon initial studies upon the coordination chemistry of N-heterocyclic carbenes to Group II metal centres (Barrett et al. 2008c; Arrowsmith et al. 2009c) and inspired by Chisholm’s et al. (2003, 2004) application of tripod ligand sets in Group II lactide polymerization catalysis, Arrowsmith et al. (2009a, b) have reported the application of calcium and strontium-based bis(imidazolin-2-ylidene-1-yl)borate complexes 6–7 and calcium, strontium and barium tris(imidazolin-2-ylidene-1-yl)borate complexes 8–10 to the intramolecular
Figure 9. Aminotroponate, aminotropiniminate, bis(imidazolin-2-ylidene-1-yl)borate, tris (imidazolin-2-ylidene-1-yl)borate and triazenide supported Group II pre-catalysts for intramolecular hydroamination.

Figure 10. Scope of hydroamination catalysis with complexes 3–9 and 11–12.
hydroamination of aminoalkenes. Although in all cases, reactions proceeded with no evidence for the Schlenk-like redistribution of the pre-catalysts or reaction intermediates, these complexes have been reported to be rather thermally labile and susceptible to B–N bond cleavage. Indeed, while bis(imidazolin-2-ylidene-1-yl)borate complexes proved robust under catalytic conditions, their tripodal analogues proved fragile with ligand cleavage reactions occurring not only during their synthesis, resulting in their isolation as imidazole solvates, but also under protic reaction conditions at temperatures above 50°C. The current scope of hydroamination catalysis with these complexes is limited to 1° aminoalkenes incorporating terminal olefins (figure 10). Although the poor performance of tris(imidazolin-2-ylidene-1-yl)borate Group II bis(trimethylsilyl)amide complexes 8–10 in hydroamination catalysis limited the reaction scope to the cyclization of 1-amino-2,2-diphenyl-4-pentene and (1-allylcyclohexyl)methylamine, it has been reported that bis(imidazolin-2-ylidene-1-yl)borate Group II complexes 6–7 effect the cyclization of a number of substrates, allowing the formation of 5-, 6- and 7-membered heterocycles. It is noteworthy that the β-diketiminato calcium amide 1 was reported to be ineffective for the cyclization of 1-amino-2,2-diphenyl-6-heptene to the corresponding 7-membered heterocycle. In all cases, strontium-based catalysts were reported to be more active than the lighter calcium analogues. The barium complex 10 proved ineffective for hydroamination catalysis of aminoalkenes.

Barrett et al. (2008a) have also reported the application of calcium and strontium amidine catalysts supported by sterically demanding triazenide ligand sets 11–12 to the intramolecular hydroamination of 1-amino-2,2-diphenyl-4-pentene. While the pre-catalysts were shown to be highly sensitive to Schlenk equilibrium in solution, in this instance, kinetic experiments were conducted and, in contrast to the findings of Arrowsmith et al. but consistent with Datta et al., the calcium species 11 provided higher turnover frequencies than the strontium analogue 12 (for reactions conducted at an initial aminoalkene concentration of 0.4 M, TOF 11, 500 h⁻¹; 12, 75 h⁻¹).

The discrepancies in the reported activities of calcium and strontium-based catalysts are indicative of the difficulties in studying heavier Group II reaction chemistry resulting from facile exchange of both neutral and mono-anionic ligand sets (Schlenk equilibration). To further complicate this issue, current reports of Group II hydroamination catalysis are plagued by discussion of ‘rates’ of reaction based upon reaction times and conditions; unless discussion is supported by reaction-rate constants, turnover frequencies derived from kinetic data or reaction half-lives at known concentrations of the reactants, it is likely to be more misleading than informative. The current observed decrease in reactivity across the series Ca/Sr > Mg/Ba, however, is consistent with density functional theory studies upon intermolecular hydroamination catalysis (vide infra).

While the different coordination environment at the metal centres of 1–12 undoubtedly influence reactivity, the development of an ‘intrinsic’ reaction scale through interpretation of experimental data has, to date, been complicated by the facile exchange processes at Group II metal centres (figure 11). In this regard, it is noteworthy that initial attempts to achieve the stereocontrolled intramolecular hydroamination of 1-amino-2,2-diphenyl-4-pentene by use of a chiral calcium amide catalyst 13, based upon the
(S)-Ph-pybox ligand, have provided non-racemic products, but in extremely low enantioselectivity (less than 10% enantiomeric excess (e.e.)). In this study, it was proposed that the pre-catalyst $L^*M(X^1)$ is unstable with respect to Schlenk-like solution equilibria with the formation of homoleptic calcium complexes $(L^*)_2M$ and $M(X^1)_2$. Furthermore, the latter bis(trimethylsilyl) amide complex $[Ca\{N(SiMe_3)_2\}_2(THF)_2]$ is proposed to be catalytically active, giving rise to an achiral background reaction (Buch & Harder 2008).

(ii) **Intermolecular hydroamination of alkenes**

Barrett *et al.* (2009a) reported a combined computational and experimental study upon the addition of amines to alkenes catalysed by coordination complexes of the heavier alkaline earths. The reaction of benzylamine, pyrrolidine and piperidine with styrene, 4-methylstyrene, 4-methoxystyrene and 4-chlorostyrene catalysed by 5 mol% $[M\{N(SiMe_3)_2\}_2]$ ($M=Ca, Sr$) was reported to proceed

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<td>168 (50°C)</td>
<td>5</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>0.25</td>
<td>99</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>1</td>
<td>99</td>
</tr>
</tbody>
</table>

Figure 11. Side-by-side comparison of reaction conditions for the intramolecular cyclization of 1-amino-2,2-diphenyl-4-pentene.

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\[
\begin{align*}
&\text{X} \quad + \quad \text{R}_1\text{R}_2\text{NH} \quad \text{R}_1 = \text{R}_2 = -(\text{CH}_2)_4-, -(\text{CH}_2)_5-; \quad \text{R} = \text{H}, \text{R}_2 = \text{Bn} \\
&\quad \quad \quad \text{X} = \text{Cl, H, Me, OMe} \\
&\quad \quad \quad \text{M} = \text{Ca, Sr} \\
&\quad \quad \quad \text{60°C, neat, 1–144 h} \\
&\quad \quad \quad \text{5 mol\%} \\
&\quad \quad \quad \text{5 examples 63–92% conversion}
\end{align*}
\]

Figure 12. Intermolecular hydroamination mediated by Group II complexes.

\[\text{NR}_1\text{R}_2\]

\[\text{M} = \text{Ca, Sr} \]

under mild solvent-free reaction conditions at 60°C (figure 12). While the products were readily isolable following the reaction, current data upon reaction yields are reported for \textit{in situ} conversions only.

In all cases, reactions are reported to proceed with an anti-Markovnikov or 2,1-addition of the amine to the alkene. Similar observations have been made in organo(III)lanthanide catalysis and the preferential anti-Markovnikov or 2,1-addition to styrene can be attributed to the organization of the transition state to N–C bond formation. Factors that stabilize the developing anionic charge upon the atom adjacent to the metal centre in the transition state to N–C bond formation will be expected to lower the activation energy of the insertion step. In the case of the 2,1-insertion of styrene into the Ca–N bond, the phenyl group may stabilize the adjacent anionic centre. In the case of a 1,2-insertion, no such stabilization exists (figure 13). Despite the strontium-based catalyst demonstrating superior reactivity (lower reaction times and higher reaction yields) to the calcium analogue, the magnesium and barium analogues of these catalysts (M = Mg, Ba) effected the hydroamination of styrene in very low yields.

Density functional theory calculations of the model reaction of ethylene with ammonia catalysed by the model complexes \([\{\text{HNC(Me)CHC(Me)NH}\}M(\text{NH}_2)\]] in the gas phase using B3LYP theory employing the LANL2DZ basis set provided

\[\text{not observed}\]

Figure 14. Free energy profiles for the reaction of ethylene with ammonia catalysed by [{HNC(Me)CHC(Me)NH}M(NH2)]. Dot, Mg; filled circle, Ca; filled triangle, Sr; filled square, Ba. TS is transition state.

Figure 15. Electron density difference maps for the alkene insertion (a) transition state and (b) intermediate for the Mg-mediated cycle. Density difference is relative to a pro-molecule composed of spherical atoms, solid lines indicate areas of build up in electron density, and dotted lines indicate areas of depletion. Slice taken in the plane of atoms C1–C2–N3 and contours at intervals of 0.003.

considerable insight into the observed reactivity (figures 14 and 15). In line with experimental findings upon the intramolecular hydroamination of aminoalkenes, results were consistent with rate-determining alkene insertion within a catalytic cycle dominated by Coulomb interactions. Alkene insertion into the M–N bond

was reported to occur via a four-centre transition state that is highly polarized; electron density equivalent to almost an entire electron is polarized onto the carbon adjacent to the metal and occurs with simultaneous depletion of electron density in the nitrogen-based lobe, with electron density being directed to the newly forming carbon–nitrogen bond. Examination of the barrier heights of insertion ($M = Mg, 87.9 \text{kJ mol}^{-1}; Ca, 69.9 \text{kJ mol}^{-1}; Sr, 64.9 \text{kJ mol}^{-1}; Ba, 77.8 \text{kJ mol}^{-1}$) and protonolysis ($M = Mg, 82.8 \text{kJ mol}^{-1}; Ca, 36.0 \text{kJ mol}^{-1}$) steps revealed a series of data consistent with the experimental observations. Barrett et al. suggest that the relative barrier heights for alkene insertion into a $M–N$ bond may be viewed as a result of a balance of the polarity of the $M–N$ bond (i.e. the ability of the $M–N$ bond to induce a dipole in the non-polarized alkene) and the polarizability of the $M^{2+}$ cation.

Eyring analysis of kinetic reaction data upon the addition of piperidene to styrene catalysed by $[M\{N(SiMe_3)2\}2]$ ($M = Ca, Sr$) provided activation energies of $\Delta G^\ddagger = 100.8$ and $97.9 \text{kJ mol}^{-1}$ for calcium and strontium, respectively. Although these data are overestimated somewhat compared with those calculated on the model system, it was suggested that the strontium and calcium reagents provide the ideal balance of polarization and polarizability that allow facile insertion reactions with alkene substrates. Furthermore, the increased activity of the strontium catalyst was attributed to an influential entropic advantage, with the calcium catalyst providing data consistent with a much tighter and more ordered transition state in the insertion step than the strontium system ($\Delta S^\ddagger = -167.8 \text{J mol}^{-1} \text{K}^{-1}$ and $-22.0 \text{J mol}^{-1} \text{K}^{-1}$ for calcium and strontium, respectively).

With regard to the free-energy diagram presented in figure 14, it is noteworthy that, while the metal alkyl intermediates have been implied by deuterium labelling studies upon the intramolecular hydroamination of alkenes, recent studies by Wiecko et al. (2008) and Schumann et al. (2004) have provided experimental evidence for the formation of Group II alkene adducts. In both these studies, metallocene complexes of the heavier alkaline earth metals bearing pendent alkenyl groups (tethered to the cyclopentadienyl ring) were shown to demonstrate metal coordination to the $\pi$-system of unsaturated carbon–carbon bonds in solid state. The importance of crystal-packing effects in these latter interactions, however, cannot be underestimated.

(iii) Intermolecular hydroamination of carbodiimides

In contrast to the unstable reaction intermediates implied in the intra- and intermolecular hydroamination of alkenes (vide supra), products derived from the insertion of carbodiimides into heavier alkaline earth metal–nitrogen bonds, i.e. Group II guanidinates, are kinetically and thermodynamically stable and readily isolable. Several stoichiometric reaction studies have documented these insertion products. Feil & Harder (2005) reported the insertion of 1,3-dicyclohexyl carbodiimide into the calcium amide bonds of $[Ca\{N(SiMe_3)2\}2]$. Based upon this finding, Barrett et al. (2008c) reported that a number of analogues of 1, in which the bis(trimethylsilylamide) ligand had been replaced by a less basic amide ligand, readily react with dialkyl carbodiimides to yield calcium complexes containing both $\beta$-diketiminate and guanidinate ligands (figure 16).
Review. Group II catalysis

Figure 16. Insertion of 1,3-dialkyl carbodiimides into the Ca–N bonds of derivatives of 1. NMR is nuclear magnetic resonance.

While in all cases, the insertion reaction products in the aforementioned studies were characterized by multi-nuclear nuclear magnetic resonance (NMR) and single-crystal X-ray diffraction, application of this stoichiometric reactivity in the Group II catalysed hydroamination of carbodiimides was reported by Lachs et al. (2008). The reaction of electron-deficient and electron-rich primary arylamines with 1,3-dialkyl carbodiimides was reported to proceed rapidly at room temperature catalysed by 2–4 mol% $[\text{M}\{\text{N(SiMe}_3\}_2\}_2(\text{THF})_2]$ (M = Ca, Sr, Ba) to yield the corresponding guanidines, $[\text{ArNC(NHR)}_2]$ (figure 17). The reaction scope included sterically encumbered amines (e.g. 2,6-di-iso-propylaniline) and carbodiimides (e.g. 1,3-di-tert-butyl carbodiimide) and, in most cases, the reaction products were reported to crystallize directly from preparations in hexane solvent (0.15 M concentration of substrates), allowing their isolation by simple filtration. Characterization of the hydroamination products by multinuclear NMR spectroscopy and, in one instance, single-crystal X-ray diffraction revealed that the guanidines form with a concomitant 1,3-proton shift (figure 17). Lachs et al. explored the limit of this catalysis and, by conducting the reaction of aniline with 1,3-dicyclohexyl carbodiimide in hexane on a 60 mmol scale, demonstrated that catalysis shutdown below a 0.5 mol% loading of $[\text{Ca}\{\text{N(SiMe}_3\}_2\}_2(\text{THF})_2]$. In this instance, the product was isolated in 86 per cent yield.

Through a series of stoichiometric reactions, Lachs et al. suggested that the calcium-mediated hydroamination of carbodiimides proceeds via a catalytic cycle incorporating a dimeric calcium guanidinate intermediate. It was reported that

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Figure 17. Scope of Group II mediated hydroamination of carbodiimides.
Figure 18. (a) Proposed mechanism of the Group II mediated hydroamination of carbodiimides and (b) ORTEP representation of $\text{13}$ thermal ellipsoids at 40% probability; H atoms are omitted for clarity.

the reaction of $[\text{Ca}\{\text{N(SiMe}_3)\}_2(\text{THF})_2]$ with either two equivalents of aniline and two equivalents of 1,3-di-$\text{iso}$-propyl carbodiimide or two equivalents of $[\text{PhNC(NH}^\text{iPr})_2]$ yielded a compound that gave identical spectroscopic data in benzene-$d_6$ solution to that formed from the addition of four equivalents of $[\text{PhNC(NH}^\text{iPr})_2]$ to $[\text{Ca}\{\text{N(SiMe}_3)\}_2]$. Complex $\text{13}$ was isolated from this latter reaction following crystallization from hexane solution and was characterized by variable temperature NMR spectroscopy, along with single-crystal X-ray diffraction (figure 18). While site exchange between the terminal and bridging ligands of $\text{13}$ ($\Delta G^\dagger = 67.8$ kJ mol$^{-1}$) was observed in $d_8$-toluene solution, this latter dimeric complex proved kinetically competent for the catalytic hydroamination of 1,3-di-$\text{iso}$-propyl carbodiimide with aniline. Based upon this reactivity, the stoichiometric insertion studies and by analogy to the hydroamination of aminoalkenes, the authors proposed that the reaction proceeds via a catalytic cycle constructed with insertion and protonolysis steps (figure 18).

(iv) Intermolecular hydroamination of isocyanates

In 2008, Barrett et al. reported that the hydroamination of 2,6-di-$\text{iso}$-propylphenyl isocyanate and 1-adamantyl isocyanate with diphenylamine could be catalysed by 5–6 mol% $\text{1}$ or $[\text{M}\{\text{N(SiMe}_3)\}_2]_2$ ($\text{M} = \text{Ca}$, $\text{Sr}$ and $\text{Ba}$) in benzene or toluene solution. Although the aryl-substituted isocyanate was reported to undergo hydroamination at room temperature, the alkyl-substituted analogue required slightly more forcing conditions ($60^\circ\text{C}$). In both cases, the urea products were readily isolable by crystallization from hydrocarbon solution and isolated in 48–93% yield. The reported reaction scope is currently very restricted, being limited to these two preparations (figure 19). The catalytic reaction, however, does offer distinct advantages over the uncatalysed variant, and a background experiment demonstrated no reaction between diphenylamine and 1-adamantyl isocyanate over a period of four weeks at room temperature or 16h at 80$^\circ\text{C}$. Kinetic analysis upon this latter reaction catalysed by 5 mol% $[\text{Ca}\{\text{N(SiMe}_3)\}_2]_2$ at room temperature demonstrated that both starting materials were consumed at the same rate, indicative of a clean heterofunctionalization of the isocyanate without deleterious (polymerization) side reactions.

In line with this observation, Barrett et al. demonstrated that the controlled insertion of 1-adamantyl isocyanate into the metal–nitrogen bond of \([\{\text{ArNC(Me)CHC(Me)NAr}\}\text{Ca}(\text{NPh}_2)(\text{THF})]\) occurs upon reaction in a 1:1 stoichiometry in hydrocarbon solution at room temperature. The resulting ureido complex 14 was isolated in an unoptimized yield of 36 per cent, crystallographically charaterized, and proven to be catalytically competent for the hydroamination of 2,6-di-i Propylphenyl isocyanate with diphenylamine (figure 20). In contrast to a report by Crimmin et al. (2009) documenting the intramolecular hydroamination of aminoalkenes, hydroamination reactions of isocyanates with diphenylamine were reported to yield kinetic data consistent with significant product inhibition of catalysis. Barrett et al. ascribe the observed product inhibition to the urea product effectively binding Group II metal centres
and preventing substrate coordination and activation. Initial attempts to quantify the effect of the metal centre upon the rate of reaction were reported to be complicated by the insolubility of intermediate barium ureido species in hydrocarbon solvents. A cross-over reaction conducted in C₆D₆ between one equivalent of the urea derived from 1-adamantyl isocyanate and one equivalent of 2,6-di-iso-propylphenyl isocyanate catalysed by 5 mol% [Ca{N(SiMe₃)₂}₂] demonstrated the potential reversibility in the insertion step. Thus, it was proposed that catalytic turnover occurs via reversible σ-bond metathesis and insertion reaction steps (figure 20a).

(d) Hydrophosphination (C–P) bond formation

(i) Intermolecular hydrophosphination of alkenes, alkynes and dienes

In 2007, Hill and coworkers reported the catalytic hydrophosphination of a series of unhindered activated alkenes and an alkyne with diphenylphosphine mediated by 10–20 mol% of 1 (figure 21). The structures of the isolated products were consistent with an anti-Markovnikov, syn-addition of the P–H bond across the least hindered, unsaturated C–C bond of the substrate. The reaction proved to be highly dependent upon the steric demands of the alkene and more hindered substrates, such as α-methylstyrene, 1,2-diphenylethene and trans-stilbene, did not readily undergo hydrophosphination under these reaction conditions. Similar observations have been made in the hydrosilylation of styrenes with calcium benzyl complexes, with α-methylstyrene being less reactive towards hydrosilylation than styrene itself (vide infra). Despite the precedent in lanthanide(III) chemistry for the intermediate species to initiate polymerization reactions (Kawaoka & Marks 2005), oligomeric or polymeric reaction by-products were not reported.

The observed regio- and stereo-selectivity were consistent with the precedent set by not only organo(III)lanthanide (Hong & Marks 2004), but also calcium-mediated intermolecular hydroamination (§2c). As in the case of the hydroamination of styrenes, the preferential anti-Markovnikov or 2,1-addition of diphenylphosphine to styrene can be attributed to the organization of the transition state to P–C bond formation. Factors that stabilize the developing anionic charge upon the atom adjacent to the metal centre in the transition state to P–C bond formation will be expected to lower the activation energy of the insertion step. In the case of the 2,1-insertion of styrene into the Ca–P bond, the phenyl group may stabilize the adjacent anionic centre (figure 22). In the case of a 1,2-insertion, no such stabilization exists. Furthermore, the almost exclusive syn-addition of diphenylphosphine to diphenylacetylene can be attributed to a concerted insertion of the alkyne into the Ca–P σ-bond of an intermediate phosphide complex.

The stoichiometric reaction between 1 and diphenylphosphine was conducted on an NMR scale, and monitoring of the reaction by $^1$H and $^{31}$P NMR spectroscopy revealed the consumption of diphenylphosphine with concurrent production of HN(SiMe$_3$)$_2$ and a single new product peak at $-21.3$ ppm in the $^{31}$P NMR spectrum owing to the formation of heteroleptic β-diketiminate-stabilized phosphide 15. The half-life of this reaction under pseudo-first-order conditions (15 equivalent HPPh$_2$) was reported as approximately 200 min. To eliminate the possibility that the slow σ-bond metathesis step was due to steric factors, the authors conducted a competition experiment between 1 and a 1:1 mixture of HNPh$_2$ and HPPh$_2$. After 30 min at room temperature, exclusive formation of the calcium diphenylamide in preference to 15 was observed, despite the fact diphenylphosphine has a lower pKa than diphenylamine (Li et al. 2006). This disparity in the rate of the reaction of 1 with diphenylphosphine compared with diphenylamine was attributed to the fact that a coordination of the substrate to the metal is required for the σ-bond metathesis (protonolysis) step to occur, and that the soft phosphine is a poorer ligand than the amine for the hard calcium centre.
Support for the postulated mechanism of intermolecular hydrophosphination was provided by the reactivity of 15. The reaction of diphenylphosphine with styrene could be catalysed by 10 mol% 15, demonstrating that the latter is kinetically active in the proposed catalytic cycle. More importantly, the reaction of 15 with an excess of diphenylacetylene and a single equivalent of HN(SiMe)_3 in C_6D_6 at 75°C for 45 min gave a 1:1 mixture of (E)-PhC(H)=C(PPh_2)Ph, observed at 8.9 ppm in the 31P NMR, and 1 in near quantitative yield. This latter experiment can be explained by considering the concerted insertion of the alkyne into the Ca–P bond of 15 to generate a highly unstable calcium vinyl intermediate that then undergoes a subsequent σ-bond metathesis with hexamethyldisilazane to liberate the hydrophosphinated product and regenerate 1 (figure 23). Thus, it was proposed that the reaction proceeds via (i) catalyst initiation by the reaction of 1 with diphenylphosphine to form the analogous phosphide, (ii) the concerted insertion of the unsaturated carbon–carbon bond into the Ca–P sigma bond, and (iii) a facile σ-bond metathesis (protonolysis) reaction of the calcium alkyl intermediate.

Hill and coworkers attempts to catalyse the hydrophosphination of alkenes with [Ca{N(SiMe_3)_2}]_2(THF)_2] in benzene solution met with limited success, and the reaction was reported to be accompanied by the precipitation of a small amount of a yellow insoluble solid, which was later confirmed to be [Ca(PPh_2)_2(THF)_4] by independent synthesis (Crimmin et al. 2007a; Gartner et al. 2007a). Despite this observation, Westerhausen and coworkers have reported that [Ca(PPh_2)_2(THF)_4] in THF is an excellent catalyst for the hydrophosphination of diphenylacetylene and 1,4-diphenylbutadiene with diphenylphosphine (Al-Shboul et al. 2008). Reactions proceeded to high yield in less than 2 h at room temperature with 5–6 mol% catalyst loading and, in the instance of the latter substrate, the product was trans,trans-1,4-diphenyl-1,4-bis(diphenylphosphanyl)buta-1,3-diene (formed from addition of two molecules of phosphine to the diyne; figure 24). While the discrepancy between the two catalyst systems is
likely due to the solubility properties of \([\text{Ca}(\text{PPh}_2)_2(\text{THF})_4]\), further studies employing the analogous strontium and barium phosphides have yet to be reported.

(ii) Intermolecular hydrophosphination of carbodiimides

In 2008, Hill and coworkers demonstrated that phosphaguanidines could be synthesized in high yield by the Group II catalysed hydrophosphination of carbodiimides. A series of heavier alkaline earth-based catalysts including the heteroleptic calcium amide 1 and the homoleptic alkaline earth amides \([\text{Ca}\{\text{N(SiMe}_3)_2\}_2]\), \([\text{Ca}\{\text{N(SiMe}_3)_2\}_2(\text{THF})_2]\), \([\text{Sr}\{\text{N(SiMe}_3)_2\}_2(\text{THF})_2]\) and \([\text{Ba}\{\text{N(SiMe}_3)_2\}_2(\text{THF})_2]\) were applied to the hydrophosphination of carbodiimides with diphenylphosphine, di-p-tolylphosphine and dicyclohexylphosphine (figure 25).

The hydrophosphination of a number of symmetric and unsymmetric carbodiimides with secondary arylphosphines was reported to proceed at room temperature using catalyst loadings as low as 1.5 mol\%. While 1 was found to catalyse this reaction, the simpler homoleptic alkaline earth amides proved more active. The reaction products were isolated as colourless solids by crystallization from hexane solution at low temperature. Under these reaction conditions, the hydrophosphination of carbodiimides with dicyclohexylphosphine could not be achieved with either the homoleptic or heteroleptic alkaline earth-based catalysts, and it was postulated that, in these cases, catalyst activation did not occur.
Additionally, the hydrophosphination of sterically demanding carbodiimides such as 1,3-di-tert-butyl carbodiimide with Group II amides was not catalysed under the reported reaction conditions.

Based upon a series of stoichiometric reactions, and in contrast to the previously discussed hydrophosphination reactions (vide supra), it was postulated that unsaturated homoleptic heavier alkaline earth phosphides are unlikely to be long-lived intermediates in the catalytic hydrophosphination of carbodiimides conducted in C_6D_6 solutions. Rather, it was proposed that the phosphaguanidinate product was acting as a ligand for the Lewis acidic metal centre. The individual reaction steps for the reaction of diphenylphosphine with 1,3-di-iso-propyl carbodiimide catalysed by the model complex 1 were followed by ^31P NMR spectroscopy. Following the reaction of diphenylphosphine (δ^31P = −40.1 ppm) with 1 to form the calcium phosphide 15 (δ^31P = −21.3 ppm), an insertion reaction with the carbodiimide to form the phosphaguanidinate 16 (δ^31P = −21.1 ppm) was observed. The reaction product was characterized by single-crystal X-ray diffraction and shown to exist in the solid state as a mononuclear five-coordinate calcium complex in which the phosphaguanidinate ligand binds via a symmetric−NCN−chelate with auxiliary coordination at calcium provided by the β-diketiminate spectator ligand and a single molecule of THF. Consistent with previous studies upon the coordination chemistry of phosphaguanidine ligands (Mansfield et al. 2006), the phosphorus lone pair is not delocalized across the amidinate moiety, and there is a significant degree of pyramidalization at phosphorus.

Further studies demonstrated that, while 16 was kinetically competent for hydrophosphination catalysis, the addition of diphenylphosphine to this isolated complex did not result in the formation of the phosphide complex 15 as monitored by ^1H and ^31P NMR spectroscopy. Catalytic turnover was observed, however, upon addition of a mixture of diphenylphosphine and carbodiimide to 16. The authors explained these observations in terms of the Curtin–Hammett principle, and suggest that an equilibrium between 16/HPPh₂ and the phosphide 15/phosphaguanidine product exists in solution. Thus, complex 15 is formed in low concentration, but readily reacts with the carbodiimide to reform 16 achieving catalytic turnover. While these experiments suggested a degree of reversibility in the σ-bond metathesis step, the potential for reversibility in the insertion step was demonstrated by a cross-over experiment. The reaction of one equivalent of [Ph₂P{NHCy}{NCy}] (δ^31P = −18.1 ppm) and one equivalent of 1,3-di-iso-propyl carbodiimide catalysed by either 10 mol% 1 or 5 mol% [Ca{N(SiMe₃)₂}] in C_6D_6 resulted in the formation of the cross-over products [Ph₂P{NH−i-Pr}{N−i-Pr}] (δ^31P = −18.5 ppm) and 1,3-dicyclohexyl carbodiimide, as observed by NMR spectroscopy. Based upon these experiments, Hill and coworkers suggested that the catalytic reaction proceeds via fast catalyst initiation, with turnover proceeding via σ-bond metathesis and insertion reaction steps, with both steps being reversible under the catalytic conditions (figure 26).

(e) Hydrosilylation (C–Si) bond formation
(i) Intermolecular hydrosilylation of alkenes and dienes

In 2006, Harder and coworkers described the application of the heavier alkaline earth benzyl complexes, [{{2-(Me₂N)C₆H₄}CHSiMe₃}₂M(THF)₂] (M=Ca, Sr), to the intermolecular hydrosilylation of vinylarenes and dienes with phenylsilane
Figure 26. (a) Proposed mechanism of Group II mediated hydrophosphination of carbodiimides. (b) ORTEP representation of 16; thermal ellipsoids at 20% probability; H atoms are omitted for clarity.

Figure 27. Scope of Group II mediated hydrosilylation of alkenes and dienes.

and phenylmethylsilane (figure 26; Buch et al. 2006). Reactions proceeded with low catalyst loadings (0.5–10 mol%) under relatively mild conditions (50°C, 0.5–16 h), with the strontium catalyst providing shorter reaction times than the calcium analogue (figure 27). The reaction scope is limited to activated alkenes, and norbornene and allylbenzene were reported to not undergo hydrosilylation with Group II catalysts. Despite the possibility that \([\{2-(Me_2N)C_6H_4\}CHSiMe_3\}_2M(THF)_2]\) may initiate the anionic polymerization of styrene, clean hydrosilylation reactivity was observed.

The regiochemistry of the isolated products proved solvent dependent for the hydrosilylation of diphenylethene; while preparations in benzene gave products deriving from 2,1-insertion of the alkene into the M-H σ-bond, preparations in THF gave the opposite regioisomer proposed to derive from a similar 2,1-insertion into an M-Si σ-bond. Despite the possible formation of CaH₂ upon catalyst
initiation via reaction of \([\{2-(\text{Me}_2\text{N})\text{C}_6\text{H}_4\}\text{CHSiMe}_3\}_2\text{M(THF)}\}_2\) with \(\text{R}_n\text{SiH}_{4-n}\) (vide infra), commercially available \(\text{CaH}_2\) proved inactive for the hydrosilylation of alkenes under these reaction conditions.

While not directly observed, Buch et al. suggest that the catalyst resting state may be by hydride-rich clusters of the general formulae \([\{2-(\text{Me}_2\text{N})\text{C}_6\text{H}_4\}\text{CHSiMe}_3\}_\geq 1\text{MH}_1\leq n\] . Detailed mechanistic studies have not been conducted, but the stoichiometric reaction of phenylsilane with \(\text{I}\) has been shown to yield the corresponding molecular calcium hydride complex \([\{\text{ArNC(Me)CHC(Me)NAr}\text{CaH(THF)}\}_2\) (\(\text{Ar}=2,6\text{-di-iso-propylphenyl}, \text{17}; \text{Harder} \& \text{Brettar} 2006; \text{figure 28}).

Based upon this evidence and the observed reaction products, Harder has proposed two distinct ‘lanthanide-mimetic’ catalytic cycles, proceeding via either a metal hydride (figure 29, cycle A) or silanide intermediate (figure 9, cycle B). Furthermore, it has been suggested that more polar solvents favour the formation of charge-separated species of the form \([\text{LM}]^+\text{[H}_4\text{SiPh}]^-\) that, in turn, decompose to yield the metal silanide \([\text{LM(SiPh}_2\text{H})]\) with liberation of \(\text{H}_2\). Although this rationale neatly accounts for the observed solvent-dependent regiochemistry, it remains a possibility that the two regio-isomeric transition states of the \(\sigma\)-bond metathesis step between \(\text{LMX}^1\) (\(X^1\text{= alkyl, M}=\text{Ca, Sr}\) and \(\text{R}_n\text{SiH}_{4-n}\) have similar activation energies that may be perturbed by solvent polarity.

Figure 28. Reaction of \(\text{I}\) with \(\text{PhSiH}_3\) to yield the molecular hydride \(\text{17}\).

Figure 29. Proposed mechanisms of the Group II mediated hydrosilylation of alkenes.
As with intramolecular hydroamination catalysis (§2c), initial attempts to achieve a catalytic asymmetric hydrosilylation of substrates containing unsaturated carbon–carbon bonds has met with limited success (Buch & Harder 2008). While a number of chiral calcium catalysts based upon non-racemic β-diketiminate (derived from acetylacetone and (S)-α-Me-benzylamine) and (S)-Ph-pybox ligands have proven catalytically active for the hydrosilylation of styrene, in all instances reaction products were isolated with low enantioselectivities (5–10% e.e.). These results have been explained in terms of the loss of ligand control over reactivity, and Buch et al. suggest that, as with intramolecular hydroamination catalysis, under the catalytic reaction conditions, the Schlenk equilibrium is operative with non-racemic catalysts $L^\ast MX$ forming inactive chiral species $L^\ast 2M$ and racemic active catalysts $MX_2$.

More recently, the grafting of calcium reagents onto silica supports, as a means to control this deleterious solution equilibrium, has been achieved. The hydrosilylation catalysts $[\{2-(Me_2N)C_6H_4\}CHSiMe_3\}_2Ca(THF)_2$ and $[Ca\{N(SiMe_3)_2\}_2(THF)_2$ have been reported to react with silica, prepared by dehydroxylation at 700°C, to afford materials that bear solid supported (bound to the solid surface via a silanol group) calcium complexes which still contain a single reactive $\sigma$-bonded substituent (i.e. $[\equivSiO–Ca\{N(SiMe_3)_2\}$ and $[\equivSiO–Ca\{\{2-(Me_2N)C_6H_4\}CHSiMe_3\}$]). Characterized by IR spectroscopy and one- and two-dimensional solid-state NMR spectroscopy, these materials proved catalytically active for the hydrosilylation of styrene, 1,3-cyclohexadiene and 1,1-diphenylethylene with PhSiH$_3$, albeit with lower activities than those reported for homogeneous catalysis, particularly for the hydrosilylation of 1,1-diphenylethylene. While it is unclear whether the active catalyst is bound to the silica surface, the authors suggested that the sensitivity of the reaction to substrate size is an indication of a heterogeneous process (Gauvin et al. 2009).

(ii) Intermolecular hydrosilylation of ketones

The scope of the hydrosilylation reactivity has been extended to incorporate ketones and the intermolecular hydrosilylation of cyclohexanone, benzophenone, adamantone and acetophenone with phenylsilane catalysed by the molecular calcium hydride 17 to afford the corresponding silyl-ethers was reported in 2008 (figure 30; Spielmann & Harder 2008). Reactions were reported to proceed under mild conditions (50°C, 0.2–34 h), and by-products originating from competitive carbonyl enolization reactions are only observed in low yield (less than 5%). It is noteworthy that, irrespective of the initial silane:ketone ratio, the major
reaction products are those derived from a 1:2 reaction stoichiometry, i.e. $[\text{PhHSi}(OCHR_1R_2)_2]$. At low silane : ketone ratios, small amounts of the trialkoxy product could also be obtained.

The pre-catalyst 17 has been shown to react with ketones to yield the corresponding dimeric β-diketiminato calcium alkoxide products derived from the insertion of the ketone into the Ca–H bond of the molecular hydride. These latter species have been shown to be kinetically competent for the hydrosilylation of ketones. Stoichiometric preparations included the reaction of 17 with benzophenone, acetophenone, cyclohexanone, 1,3-diphenylacetone and 2-adamantone to yield the corresponding alkoxides in 9–73% yield following crystallization from hydrocarbon solutions. Quenching the reaction mixtures with $\text{Me}_3\text{SiCl}$ showed, in addition to the expected reduction products, moderate to significant amounts of substrate enolization and aldol condensation products. Despite this observation, under the catalytic reaction conditions, these side reactions are apparently largely inhibited.

Despite a report by Spielmann & Harder (2007) documenting that 17 readily reacts with alternative substrates, including benzonitrile, cyclohexene oxide, 2-methylpropene oxide, 1,1,3,3-tetramethylbutyl isonitrile and diphenylmethylnitrogen–oxygen bonds into the calcium–hydride bond of the organometallic reagent, catalytic preparations for the hydrosilylation (or hydrogenation) of these substrates with Group II reagents have yet to be reported.

(f) Hydrogenation (C–H) bond formation

Based upon their studies of the calcium-mediated hydrosilylation of alkenes, Spielmann et al. (2008) reported the calcium-catalysed hydrogenation of styrene, 1,1-diphenylethylene, 1,3-cyclohexadiene, $\alpha$-methylstyrene and 1-phenylcyclohexene. Reactions were reported to proceed under mild conditions ($20^\circ\text{C}, 20 \text{ bar H}_2$) and while both 17 and $\{\{2-(\text{Me}_2\text{N})\text{C}_6\text{H}_4\}\text{CHSiMe}_3\}_2\text{M(THF)}_2$ proved catalytically active, finely ground commercially available CaH$_2$ was an ineffective catalyst under these reaction conditions. As with the previously reported hydrosilylation catalysis ($\S 2d(i)$), reactions proved to be sensitive to solvent polarity. Although preparations in THF or a THF/HMPA mixture
proceeded rapidly, in most instances, the reaction products were accompanied by side products derived from the dimerization/hydrogenation of the alkene (figure 31). In the case of styrene, while a reaction in THF/HMPA led to a calcium-mediated polymerization of this substrate, changing the solvent to benzene gave the hydrogenation product in 80 per cent yield. Spielmann et al. suggested that the side products derive from single or multiple insertions of the alkene substrate into the Group II alkyl intermediate. As with hydrosilylation, hydrophosphination and hydroamination catalysis, the reaction scope is currently limited to activated alkenes.

Stoichiometric studies demonstrated that 17 readily undergoes insertion reactions with 1,1-diphenylacetylene and myrcene (7-methyl-3-methylene-1,6-octadiene), a terpene that contains three double bonds. In both reactions, the insertion products were isolated and fully characterized, including single-crystal X-ray diffraction studies. In the case of myrcene, the reaction proved highly selective, with 17 adding to the least hindered end of the diene. Experimental evidence for the metathesis step was provided by not only the reaction of the calcium complexes isolated from these latter reactions, but also the exchange reaction of 17 with D2. Treatment of the calcium deuteride 17-d2 with 1 bar H2 at 20°C led to complete H/D exchange after 20 min at room temperature, as evidenced by NMR spectroscopy. The reaction of H2 with Ca–C bonds required slightly more forcing reactions conditions and, consistent with those reported for the catalytic reaction, could be achieved at 20 bar H2 at 20°C in either benzene or THF solution. Based upon the reactivity of the observed reaction intermediates, it was suggested that alkene hydrogenation occurs via the catalytic cycle outlined in figure 32.

3. Concluding remarks

In the past few years, well-defined coordination complexes of the heavier Group II metals have been applied to the heterofunctionalization of unsaturated substrates, including the hydroamination, hydrophosphination, hydrosilylation
and hydrogenation of substrates containing unsaturated carbon–carbon, carbon–nitrogen and carbon–oxygen bonds. Organometallic reagents derived from these elements have shown a versatile reaction chemistry and are beginning to emerge from merely lanthanide-mimetic applications. Noteworthy recent studies have demonstrated not only C–F bond activation at calcium (Barrett et al. 2007), but also the dehydrocoupling of silanes with amines and terminal alkynes mediated by a calcium catalyst (Buch & Harder 2007). These studies, in addition to a recent report upon the facile synthesis of Group II alkyl complexes through salt-metathesis reactions (Crimmin et al. 2008), are likely to provide a key starting point to extend the rapidly growing field of Group II catalysis beyond the heterofunctionalization of unsaturated substrates.

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References


Bezougli, I. K., Bashall, A., Mcpartlin, M. & Mingos, D. M. P. 1998b Insertion of CS2 into the Group 2 metal–alkoxide bonds of [M(OR)2]n (M = Mg, Ca, Sr Or Ba; R = Et, i-Pr); crystal structures of [Ca(S2CO-i-Pr)2(i-PrOH)3] and [Ba(S2COEt2)]∞. J. Chem. Soc., Dalton Trans. 2671–2677.


Gindelberger, D. E. & Arnold, J. 1992 Preparation of stable magnesium, calcium, strontium, and barium tellurolates and the X-ray crystal-structures of [Mg{TeSi(SiMe_3)_3}_2(THF)_2] and [Ca{TeSi(SiMe_3)_3}_2(THF)_4]. J. Am. Chem. Soc. 114, 6242–6243.


Harder, S. 2004 The chemistry of Ca-II and Yb-II: astoundingly similar but not equal! Angew. Chem., Int. Ed. 43, 2714–2718. (doi:10.1002/anie.200353557)


Sockwell, S. C., Hanusa, T. P. & Huffman, J. C. 1992 Formation and reactions of mono(peralkylcyclopentadienyl) and bis(peralkylcyclopentadienyl) complexes of calcium and barium—the X-ray crystal-structure of \([\{\text{Me}_4\text{EtC}_5\}\text{Ca(NSiMe}_2\text{CH}_2\text{CH}_2\text{SiMe}_2\}\}_2\). *J. Am. Chem. Soc.* **114**, 3393–3399. (doi:10.1021/ja00035a035)


Tanner, P. S., Burkey, D. J. & Hanusa, T. P. 1995 Cyclopentadienyl ring metathesis with bis(pentamethylcyclopentadienyl) calcium as a route to mixed ring organolanthane complexes—the crystal-structure of \([\{\text{C}_5\text{Me}_5\}_2\text{Nd}(\text{C}_5\text{H}_5)\] . *Polyhedron* **14**, 331–333. (doi:10.1016/0277-5387(94)00316-7)


Vargas, W., Englich, U. & Ruhlandt-Senge, K. 2002 A novel group of alkaline earth metal amides: syntheses and characterization of \([\text{M}\{\text{N}(2,6-(\text{i-Pr}_2\text{C}_6\text{H}_3)(\text{SiMe}_3)\}_2(\text{THF})_2 ((\text{M}=\text{Mg, Ca, Sr, Ba})\) and the linear, two-coordinate \([\text{Mg}\{\text{N}(2,6-(\text{i-Pr}_2\text{C}_6\text{H}_3)(\text{SiMe}_3)\}_2(\text{THF})_2\])\) . *Inorg. Chem.* **41**, 5602–5608. (doi:10.1021/ic0203668)


Westerhausen, M., Hartmann, M. & Schwarz, W. 1996a Synthesis of tris(1,2-dimethoxyethane-o,o′)barium bis(2,2,5,5-tetramethyl-2,5-disilaphosphanolate) and the monomer dimer equilibrium in toluene solution. Inorg. Chem. 35, 2421–2426. (doi:10.1021/ic950854y)


Westerhausen, M., Hartmann, M. & Schwarz, W. 1997a Synthesis of tris(1,2-dimethoxyethane-o,o′)barium bis(2,2,5,5-tetramethyl-2,5-disilaphosphanolate) and the monomer dimer equilibrium in toluene solution. Inorg. Chem. 36, 521–527. (doi:10.1021/ic960887t)


