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FULL PAPER

One-pot controlled reduction of conjugated amides by sequential double hydrosilylation catalyzed by an iridium(III) metallacycle

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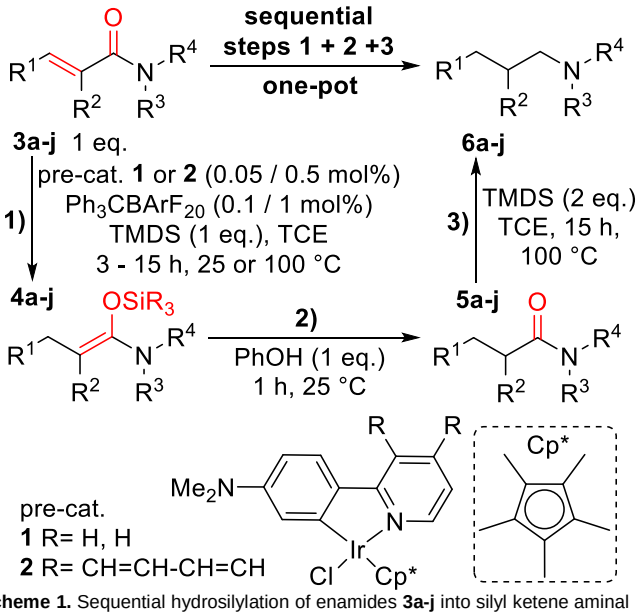
Abstract: A single and accessible cationic iridium^{III} metallacycle catalyzes effectively the one-pot sequential double hydrosilylation of challenging α,β-unsaturated secondary and tertiary amides to afford in a controlled and straightforward way the corresponding reduced products, that is to say the related secondary and tertiary amides and amines. The catalytic hydrosilylations of the conjugated amides described herein proceeded in good yields and high chemoselectivities. The critical silyl enolate, in other words silyl ketene aminal intermediate, has been observed and characterized by using control experiments, mass spectrometry and state of the art Nuclear Magnetic Resonance analyses. The present achievements indicate a promising potential of catalysts based on metallacycles for future significant developments in one-pot multicatalytic synthesis and therefore the production of highly functionalized and complex organic molecules.

Introduction

The quests for chemically effective syntheses of commodity and complex chemicals with lower waste production, minimal physical separation operations and catalyst's recyclability are now the major challenges in the domain of homogenous catalysis for economic and environmental benefits. These challenges are embodied nowadays into new strategies of research wherein efficiency, selectivity as well as modularity and adaptivity of catalytic systems are the main goals.[1] Sequential multimetallic catalysis,[2] cooperative and non-cooperative dual catalysis[3] as well as tandem catalysis[4] are presently some of the developed approaches towards one-pot multicatalytic synthesis.[1,5] Among those, sequential double hydrofunctionalization of alkynes has recently received a rising interest. Consecutive reactions like hydroamination-hydrogenation, hydroboration-hydrogenation, hydroboration-hydrosilylation have allowed powerful and selective pot-economical conversions of bulk materials to highly functionalized molecules.[6]

The selective reduction of carbon–carbon double bonds in α,β-unsaturated carbonyl compounds still remains challenging in hydrogenation[7] and hydrosilylation[8] due to several competing reactions: 1,2-addition, 1,4-additions, α- or β-additions to the alkene, de-oxygenation or even polymerizations. Interestingly, among the possible 1,4-addition products, metal- (or silyl-) enol ethers or ketene acetals, are versatile nucleophiles in Mukaiyama aldol, Michael reactions, allylic alkylations, asymmetric protonations and haloketone or ketol formations.[9]



Scheme 1. Sequential hydrosilylation of enamides **3a-j** into silyl ketene aminal **4a-j**, amides **5a-j** and amines **6a-j** using iridacycle catalyst **1** or **2**.

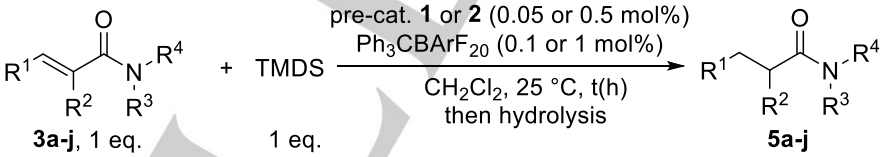
Although there have been efforts made to achieve chemoselective C-C hydrosilylation of α,β-unsaturated ketones and esters,[8] there are, to the best of our knowledge, very few examples of chemoselective hydrosilylation of α,β-unsaturated amides[10] and no sequential hydrofunctionalization of enamides. Moreover, the catalytic carbon-carbon and carbon-heteroatom bond formation at the α-position of amides remains challenging.[11] Because of the hydrogens of amides or esters being much less acidic than those of aldehydes or ketones, amides are relunctant to form enolates, i.e. silyl ketene aminals. Up to now, only few catalytic methods have been able to form such a critical intermediate and enable alkylation,[11b] 1,4-addition,[11c] Mannich-type reaction[11d] and α-amination.[11e] Following our ongoing interest in metal catalyzed hydrosilylation reactions of C-C and C-heteroatom unsaturated compounds,[12] we report herein the application of an accessible iridium^{III} metallacycle like **1** or **2** to catalyze the first one-pot sequential double hydrosilylation of secondary and tertiary α,β-unsaturated amides **3a-j** to afford in a controlled and chemoselective way the related silyl ketene aminal **4a-j**, amides **5a-j** and amines **6a-j** (Scheme 1).

Results and Discussion

Our investigations on the double reduction of α,β-unsaturated amides started by studying the first step of the targeted sequential reaction, i.e. the hydrosilylation of the conjugated CC double bond. The use of iridium^{III} catalyst precursors, additives and reaction conditions was directly inspired by our previous study on hydrosilylation reactions of secondary and tertiary amides using chlorinated iridium^{III} metallacycles **1** and **2** as pre-catalysts, trityltetra(pentafluorophenyl)borate (Ph_3CBArF_{20}) as the dechlorination agent, 1 equivalent of inexpensive 1,1,3,3-tetramethyldisiloxane (TMDS) as reducing agent and dichloromethane as a solvent (Scheme 1, Table 1).[12h]

The chlorinated iridium^{III} metallacycles **1** and **2** were respectively based on 2-phenylpyridine and 1-phenylisoquinoline chelating ligands, both functionalized by a NMe_2- electron donating group. As already demonstrated in our previous studies, such a feature is critical in order to get a higher hydricity for the transient metal-hydride species (i.e. a feature of strong hydride donor) and therefore a faster reduction of the organic unsaturation for a highest catalytic activity.[12h] At first, the hydrosilylation of tertiary conjugated amides **3a** was performed using 0.05 mol% of catalyst **1** or **2** in combination with 0.1 mol% of Ph_3CBArF_{20} and 1 equivalent of TMDS (entries 1, 2). Whereas reduced amide **5a** was rapidly obtained in a high yield using pre-catalyst **1** at 25 °C, no reaction was observed with pre-catalyst **2**. Though the catalytic reaction could proceed at 100 °C in 1,1',2,2'-tetrachloroethane (TCE), the lower reactivity of iridacycle **2** at 25 °C was rather surprising in reference to its high performances in the hydrosilylation of challenging bulky secondary and tertiary amides.[12h] The scope of the hydrosilylation reaction was then studied with aromatic and aliphatic tertiary conjugated amides **3b–f** (Table 1). Under the optimized conditions described above, the corresponding amides **5b–f** were obtained generally in high to quantitative yields (entries 3-7). By comparison to conjugated amides **3a** and **3d**, substrate **3e** issued from *trans*-2-methyl-2-butenoic acid and dibenzylamine led to a moderate yield of **5e** (entry 6). This indicated possible limitations of the 1,4-addition reaction to trisubstituted substrates. Afterwards, the scope of the hydrosilylation reaction was studied with aromatic and aliphatic secondary conjugated amides **3g–j** (Table 1, entries 8-11). Due to the lower reactivity of secondary amides,[12h,13] higher loadings of catalyst **1** (0.5 mol%) and Ph_3CBArF_{20} (1 mol%) were required in order to allow the reaction to proceed smoothly and get high yields of amides **5g-j**. With the exception of **3g** which required a 15 hours reaction time, other conjugated amides **3h-j** were effectively reduced in few hours at 25 °C.

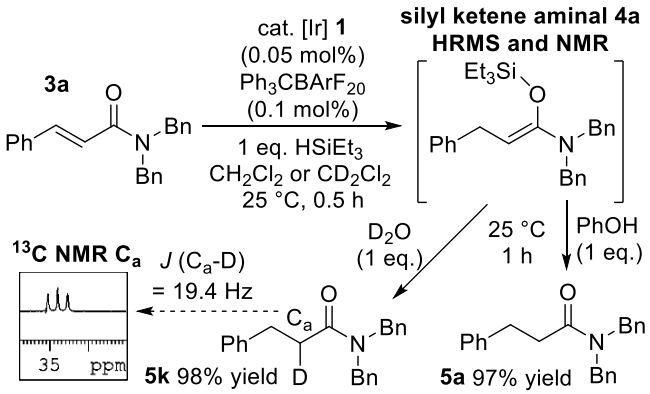
Table 1. Hydrosilylation of enamides **3a-j** into amides **5a-j** using catalyst **1** or **2**.



3a-j, 1 eq. 1 eq. **5a-j**

Entry	Enamide **3**	R^1	R^2	R^3	R^4	pre-cat (mol%)	t (h)	Yield (%)[a] (isolated yield %)[b]
1[c]	**3a**	Ph	H	Bn	Bn	**1** (0.05)	0.5	**5a** 100 (90)
2	**3a**	Ph	H	Bn	Bn	**2** (0.05)	14	**5a** 0 (-)[c]
3	**3b**	Ph	H		-$(CH_2)_2$-O-$(CH_2)_2$-	**1** (0.05)	14	**5b** 100 (61)
4	**3c**	Ph	H	Me	Me	**1** (0.05)	14	**5c** 100 (77)
5	**3d**	H	Me	Bn	Bn	**1** (0.05)	0.5	**5d** 98 (98)
6	**3e**	Me	Me	Bn	Bn	**1** (0.05)	24	**5e** 37 (31)
7	**3f**	Ph	H	Me	Ph	**1** (0.05)	2	**5f** 98 (76)
8	**3g**	Ph	H	H	*n*-Bu	**1** (0.5)	15	**5g** 88[d] (84)
9	**3h**	Ph	H	H	Bn	**1** (0.5)	6	**5h** 100 (89)
10	**3i**	Ph	H	H	Ph	**1** (0.5)	0.5	**5i** 100 (90)
11	**3j**	Ph	H	H	-CH_2-1-thiophene	**1** (0.05)	4	**5j** 100 (100)

[a] yield (%) measured by GC; Ph_3CBArF_{20}: trityl tetra(pentafluorophenyl)borate; TMDS: 1,1,3,3-tetramethyldisiloxane.
[b] isolated yield (%) after flash chromatography or recrystallisation. [c] 90 % yield of **5a** at 100 °C in 1,1',2,2'-tetrachloroethane (TCE).
[d] along with 12% of the related secondary amine.



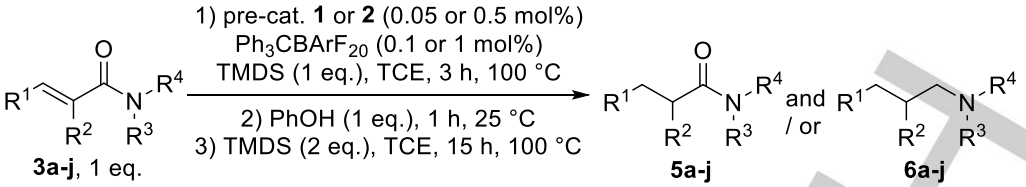
Scheme 2. Sequential hydrosilylation of enamides **3a** into silyl ketene aminal **4a** and amide **5a.**

We next focused on the characterization of the silyl ketene aminal **4a** (Schemes 1 and 2). At first, the hydrosilylation of enamide **3a** was studied using pre-catalyst **1**, Ph_3CBArF_{20} and 1 equivalent of Et_3SiH in CH_2Cl_2 at 25°C during 30 minutes (Scheme 2). In the prospect of performing a second hydrosilylation reaction, we had to exclude water due to the high sensitivity of the catalytic system. Therefore, we found the silyl enolate / silyl ketene aminal **4a** resulting from a hydrosilylation through a 1,4-addition was smoothly protonated by an equivalent of phenol to afford amide **5a**. Three different alcohols, i.e. Gaiacol, isopropanol and phenol, were tested for the protodesilylation of **4a** (Table S1). Phenol, the most acidic and the less coordinating reagent, led to **5a** in 97 % yield after 30 minutes of reaction. The silyl ketene aminal **4a** was first evidenced by a reaction with D_2O and formation of deuterated amide **5k** (Scheme 2). After purification by flash chromatography, product **5k** was characterized by ^1H and ^{13}C NMR (Figure S1 and Figure S2) as well as by HRMS ESI (+) (Figure S3). It was worth to compare the coupling of benzylic protons of deuterated amide **5k** with those of **5a** (see Figure S1). While a triplet was observed for **5a**, a doublet was observed for **5k** due to the neighboring deuterium. Moreover, the ^{13}C NMR spectrum of **5k** confirmed the presence of a deuterium because a triplet resulting from the coupling of deuterium (spin 1) and carbon nuclei C_a (spin ½) (J C_a-D = 19.4 Hz) was observed at 34.8 ppm (Scheme 2, Figure S2).

In another experiment, the hydrosilylation of enamide **3a** was performed under the same reaction conditions, i.e. in CD_2Cl_2 using pre-catalyst **1**, Ph_3CBArF_{20} additive and 1 equivalent of Et_3SiH at 25°C during 30 minutes (Schemes 2 and S2). The mass spectrometry ESI-(+) analysis of a reaction mixture aliquot diluted in dry acetonitrile showed evidence of the silyl ketene aminal **4a** and the related sodium ketene aminal **4b** along with amide **5a** and several side products issued from a bimolecular 1,4-addition[14] and a Diels-Alder [4+2]-cycloaddition (Figure S4, Scheme S3). Furthermore, the crude solution of silyl enolate / silyl ketene aminal **4a** was transfered in a dry NMR Young tube under argon in order to be studied. ^1H and ^1H-^1H COSY NMR analyses confirmed the molecular structure of **4a** (Figures S5 and S7). We could identify the scalar couplings between some key spin systems like: an ethyl, a benzyl and a Ph-CH_2-CH system (Scheme S4). The conventional correlations were observed through the ^3J(H,H) coupling constants (ethyl, CH_2-H) as well as through the weak ^4J(H,H) of the benzylic systems. This defined the chemical shifts of the ortho aromatic protons and supported the molecular structure of silyl ketene aminal **4a**. The latter was further confirmed by ^{13}C and ^1H-^{13}C HSQC NMR experiments (Figures S6 and S8). Among the observed ^{13}C and ^1H NMR chemical shifts, the most significants were the non-aromatic olefin carbon at 90.5 ppm and the related proton at 3.75 ppm, which were typical of an enolate system like **4a** (Scheme S4). A further NMR analysis by NOESY ^1H-^1H confirmed the molecular structure of silyl ketene aminal **4a**. The ethyl, benzyl and Ph-CH_2-CH spin systems which were observed by ^1H-^1H COSY were part of the same molecule as confirmed by unambiguous NOEs (Scheme S4). The two benzyl groups on the nitrogen and the three ethyl of the silicon were all in fast exchange and led to single couplings. The three phenyl groups were on free rotation. The NOE between the olefin proton and those of the benzyl groups of the nitrogen (-CH_2-) was hardly observed due to the close chemical shifts (3.75 and 3.91 ppm). There was no NOE observed between the olefin proton (3.75 ppm) and the ortho- aromatic protons (7.15 ppm) of the Ph-CH_2-CH spin system, these protons being not close to each other. Finally, the last NMR experiment by ^{29}Si HSQC highlighted the main correlation observed through the ^2J(Si-H) and ^3J(Si-H) with a ^{29}Si chemical shift of +21.0 ppm and could be in agreement with a silicon atom bound to three carbons and one oxygen, the ^{29}Si chemical shift for $HSiEt_3$ being of +0.2 ppm.[15]

Once the protodesilylation of silyl ketene aminal **4** had been set in anhydrous conditions, we studied the scope of the sequential double hydrosilylation reaction of aromatic and aliphatic conjugated amides **3a-j** into amines **6a-j** (Table 2). Similar to the hydrosilylation of the conjugated CC double bond, the double hydrosilylation of the conjugated CC and CO double bonds was performed using: 0.05 mol% of catalyst **1** or **2** and 0.1 mol% of Ph_3CBArF_{20} for tertiary amides **3a-f** and, using 0.5 mol% of catalyst **1** or **2** and 1 mol% of Ph_3CBArF_{20} for secondary amides **3g-j**.[12h,13] All reactions were run according to a one-pot and 3 steps procedure. The first step accomplished the hydrosilylation of the conjugated CC double bond using one equivalent of TMDS. In order to accelerate these catalytic reactions, they were run at 100 °C in 1,1',2,2'-tetrachloroethane (TCE) for 3 hours. After cooling, the second step, i.e. the protodesilylation of silyl ketene aminals **4a-j**, proceeded by reaction with one equivalent of recrystallized phenol dissolved in dry TCE at 25 °C for 1 hour. Afterwards, the third step, i.e. the hydrosilylation of the amide CO bonds, was performed based on our previous study on hydrosilylation of secondary and tertiary amides.[12h] Two additional equivalents of TMDS were added to the reaction mixture which was subsequently heated to 100 °C for 15 hours. At the exception of reagent **3a** which was better reduced using catalyst **1**, the sequential double hydrosilylations of tertiary conjugated amides **3b-f** were conducted along with catalyst **2** (entries 1-12). The desired amines **6a-f** were isolated in fair to high yields. We noticed the reaction of substrates **3b,d,e** bearing donor substituents led to the expected amines **6b,d,e** as major products along with some amounts of amides **5b,d,e** (entries 3-4,7-10). Regarding the sequential double hydrosilylation of secondary conjugated amides **3g-j**, the corresponding amines **6h-j** were obtained in good yields with minor amounts of amides **5h-j** (entries 15-20). It was worth to note that substrate **3g** bearing a *n*-butyl substituent on the amide nitrogen led to almost equal amounts of amide and amine products with catalyst **1** or **2** (entries 13,14). While catalyst **1** performed better with substrates **3h,j** bearing benzyl groups on the nitrogen (entries 15-16, 19-20),

Table 2. Sequencial hydrosilylation of enamides **3a-j** into amides **5a-j** and amines **6a-j** using catalysts **1** or **2**.

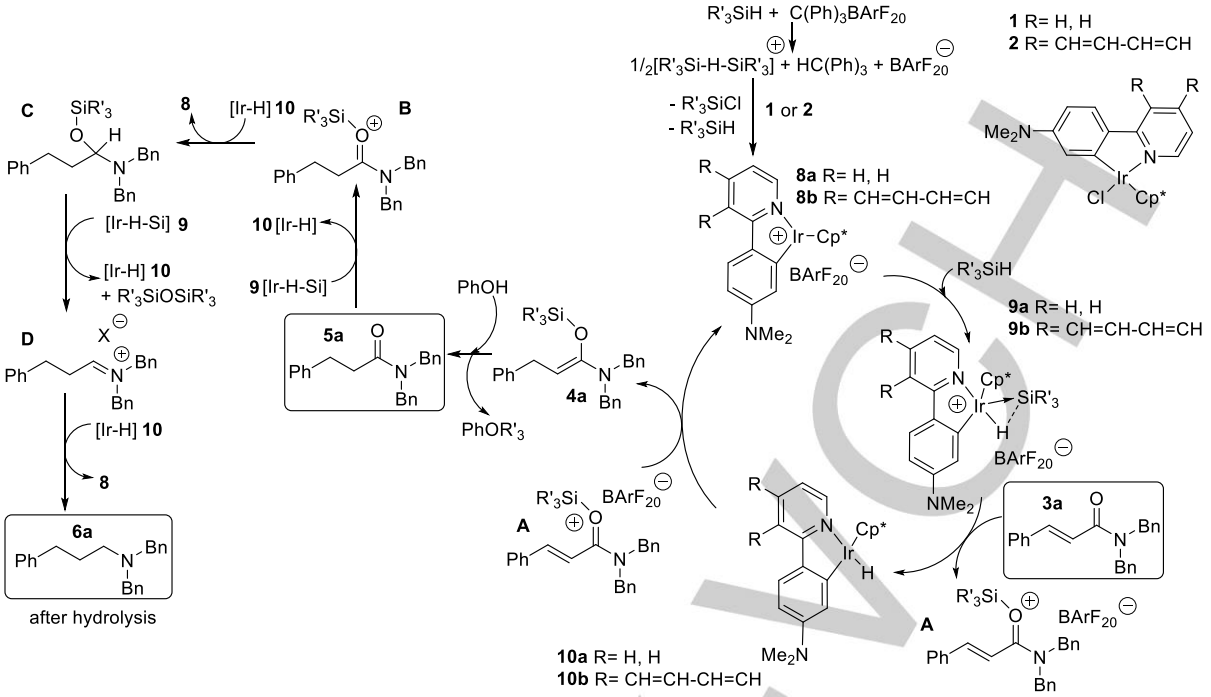


Entry	Enamide **3**	R^1	R^2	R^3	R^4	pre-cat (%)	Yield (%, isolated)[a]
1[c]	**3a**	Ph	H	Bn	Bn	**1** (0.05)	**6a** (93)
2	**3a**	Ph	H	Bn	Bn	**2** (0.05)	**6a** (72)
3	**3b**	Ph	H	-$(CH_2)_2$-O-$(CH_2)_2$-		**1** (0.05)	**5b** (36) + **6b** (10)
4	**3b**	Ph	H	-$(CH_2)_2$-O-$(CH_2)_2$-		**2** (0.05)	**5b** (16) + **6b** (63)
5	**3c**	Ph	H	Me	Me	**1** (0.05)	**6c** (67)
6	**3c**	Ph	H	Me	Me	**2** (0.05)	**6c** (83)
7	**3d**	H	Me	Bn	Bn	**1** (0.05)	**5d** (35) + **6d** (31)
8	**3d**	H	Me	Bn	Bn	**2** (0.05)	**5d** (17) + **6d** (61)
9	**3e**	Me	Me	Bn	Bn	**1** (0.05)	**5e** (27) + **6e** (46)
10	**3e**	Me	Me	Bn	Bn	**2** (0.05)	**5e** (21) + **6e** (51)
11	**3f**	Ph	H	Me	Ph	**1** (0.05)	**6f** (74)
12	**3f**	Ph	H	Me	Ph	**2** (0.05)	**6f** (91)
13	**3g**	Ph	H	H	*n*-Bu	**1** (0.5)	**5g** (32) + **6g** (21)
14	**3g**	Ph	H	H	*n*-Bu	**2** (0.5)	**5g** (26) + **6g** (34)
15	**3h**	Ph	H	H	Bn	**1** (0.5)	**5h** (11) + **6h** (68)
16	**3h**	Ph	H	H	Bn	**2** (0.5)	**5h** (28) + **6h** (53)
17	**3i**	Ph	H	H	Ph	**1** (0.5)	**5i** (8) + **6i** (64)
18	**3i**	Ph	H	H	Ph	**2** (0.5)	**5i** (9) + **6i** (83)
19	**3j**	Ph	H	H	-CH_2-1-thiophene	**1** (0.5)	**5j** (5) + **6j** (82)
20	**3j**	Ph	H	H	-CH_2-1-thiophene	**2** (0.5)	**5j** (21) + **6j** (43)

[a] isolated yield (%) after flash chromatography or recrystallisation; Ph_3CBArF_{20}: trityl tetra(pentafluorophenyl)borate; TMDS: 1,1,3,3-tetramethyldisiloxane; TCE: 1,1',2,2'-tetrachloroethane.

catalyst **2** was more effective with conjugated amide **3i** substituted by a phenyl (entries 17,18).

Regarding the reaction mechanism (Scheme 3), an ionic hydrosilylation[16] pathway could be presumed. However, Djukic et al. had already shown through a combination of organometallic syntheses and DFT calculations a cohesive hydridoiridium(III)→silylium donor−acceptor complex could exist.[12h,17] Hence, we assumed our reaction pathway may differentiate from the others by the activation mode of the silane. As already calculated before by us, the necessary dechlorination of precatalyst **1** or **2** to yield putative electron deficient cationic intermediate **8** results from a reaction with an in-situ-produced form of a stabilised silylium cation generated by the reaction of the tritylium cation with the silane reagent (Scheme 3).[12h,18] For instance, the reaction of Et_3SiH with Ph_3C^+ is expected to produce triphenylmethane and cation $[Et_3Si\text{-}H\text{-}SiEt_3]^+$ according to Heinekey,[18a] and our previous DFT-D computations.[12h] In the framework of the mechanism depicted in Scheme 3, cationic complexes **8a-b** and silane reagent form adducts **9a-b** which are sources of hydrido-iridium intermediates **10a-b** and silylium cation R_3Si^+.[12h,18-20] The latter may activate the carbonyl group of amide substrate **3a** and generate silyloxy carbonium species **A**. Reaction with the first equivalent of the iridium hydride complex **10** affords silyl ketene aminal **4** resulting from a 1,4-addition addition as well as the cationic iridium complex **8**. Afterwards, the addition of one equivalent of phenol allows the protodesilylation of the enolate **4** and affords amide **5a**. Reaction with the second equivalent of silylium cation and iridium hydride complex **10** leads first to silyloxy carbonium species **B** which is then reduced into silyl hemiacetal **C**. At this stage, elimination of a silyloxide fragment may be helped by any electrophilic species present in the medium to lead to the iminium intermediate **D** which we evidenced by mass spectrometry in a previous study.[12h] The latter can then react with the third equivalent of the iridium hydride complex **10** and affords the amine product **6a** along with the cationic iridium catalytic species **8** (Scheme 3).



Scheme 3. Reaction mechanism of the sequential hydrosilylation of enamide **3a** into amide **5a** and amine **6a** catalyzed by iridium(III) complex **1** or **2** and Ph_3CBArF_{20}, trityl tetra(pentafluorophenyl)borate.

Conclusion

We have shown accessible cationic iridium^{III} metallacycles catalyze effectively the one-pot sequential double hydrosilylation of challenging α,β-unsaturated secondary and tertiary amides to afford in a controlled and selective way the corresponding reduced products, that is to say the related secondary and tertiary amides and amines. The catalytic hydrosilylation reactions described herein proceeded with low catalyst loadings, in good yields and high chemoselectivities. The critical silyl ketene aminal intermediate has been observed and characterized by using control experiments, mass spectrometry and state of the art Nuclear Magnetic Resonance analyses. The present achievements indicate a promising potential of catalysts based on metallacycles for future significant developments in one-pot multicatalytic synthesis and therefore the production of highly functionalized and complex organic molecules.

Experimental Section

General procedure for the synthesis of amides[21]
In a Schlenk, a solution of trimethylphosphite ($P(OMe)_3$) (0.7 mL, 1.5 eq.) in dichloromethane (CH_2Cl_2) (20 mL) is cooled at 0°C under nitrogen gas. After addition and solvation of iodine (I_2) (1.52 g, 1.5 eq.), the carboxylic acid reagent (1.5 eq.) was added followed by triethylamine (NEt_3) (1.4 mL, 2.5 eq.). After 10 minutes of stirring, the amine reagent (1 eq.) was added to the reaction. The resulting mixture was first stirred at 0°C for 10 minutes and then for 14 hours at room temperature. The reaction was then hydrolyzed using a saturated aqueous solution of sodium bicarbonate ($NaHCO_3$) and extracted three times with dichloromethane. The organic phase was subsequently washed with HCl 1M, water and brine. After drying over magnesium sulfate ($MgSO_4$), solvents were evaporated and the residu was purified by flash chromatography over silica gel using a mixture of petroleum ether and ethyl acetate. Evaporation of solvents led to the desired amide as a solid or an oil.

General procedure for the hydrosilylation of conjugated amides 3 into amides 5
In a Schlenk tube, conjugated amide reagent **3** (1.54 mmol, 1 eq.) and iridium^{III} catalyst **1** (0.05 mol% / 0.0005 eq. / 0.34 mg for a tertiary enamide or 0.1 mol% / 0.001 eq. / 0.68 mg for a secondary enamide) are introduced. Ph_3CBArF_{20} salt (0.1 mol% / 1.42 mg or 1 mol% / 14.2 mg) is then added in a glovebox. Under nitrogen, 1 mL of CH_2Cl_2 and TMDS (1 eq., 0.272 mL) are transferred by syringe and the reaction mixture is heated at 25 °C under stirring for 0.5 to 24 h (the Schlenk tube being closed under N_2). Afterwards, the solvent is evaporated under vacuum (using a Schlenk line) to afford the desired amide **5** which was further purified by recrystallization or flash chromatography using mixtures of petroleum ether and ethyl acetate.

General procedure for the sequential hydrosilylation of conjugated amides 3 into amines 6.
In a Schlenk tube, enamide reagent **3** (1.54 mmol, 1 eq.) and iridium^{III} catalyst **1** or **2** (0.05 mol% / 0.0005 eq. / 0.34 mg of **1** or 0.38 mg of **2** for a tertiary enamide as well as 0.1 mol% / 0.001 eq. / 0.68 mg of **1** or 0.76 mg of **2** for a secondary enamide) are introduced. BArF salt (0.1 mol% / 1.42 mg or 1 mol% / 14.2 mg) is then added in a glovebox. Under nitrogen, 1 mL of TCE and TMDS (1 eq., 0.272 mL) are transferred by syringe and the reaction is heated to 100 °C under stirring for 3 hours (the Schlenk tube being closed under N_2). After cooling to 25°C, a solution of recrystallized phenol in TCE (1.54 mmol, 1 eq. in 1 mL TCE) was transferred by canula to the reaction mixture and the resulting solution was allowed to react for 1 hour. Afterwards, TMDS (2 eq., 0.545 mL) was added and the reaction was heated to 100 °C for 15 hours. The solvent is then evaporated under vacuum (using a Schlenk line) and the reaction mixture is hydrolysed using dichloromethane (3 mL) and NaOH 1M (5 mL). The resulting solution is stirred vigorously at 20°C during 1 hour. After extraction with dichloromethane and brine, the organic phase was dried with $MgSO_4$ and evaporated to afford the desired amine **6** which was further purified by flash chromatography using mixtures of petroleum ether and ethyl acetate with 5% NEt_3.

5a *N,N*-dibenzyl-3-phenylpropanamide CAS [180747-56-2][22]
Isolated as a solid after recrystallisation using a dichloromethane/cyclohexane solvent mixture (0.457 g, 90% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 2.73 (t, J = 7.6 Hz, 2H), 3.06 (t, J = 7.9 Hz, 2H), 4.38 (bs, 2H), 4.62 (bs, 2H), 7.07 (d, J = 6.5 Hz, $2H_{Ar}$), 7.19 (m, $5H_{Ar}$), 7.29 (m, $8H_{Ar}$).
^{13}C NMR (75 MHz, $CDCl_3$): δ 31.8 (CH_2), 35.2 (CH_2), 48.5 (CH_2), 50.0 (CH_2), 126.3 (CH), 126.5 (2CH), 127.5 (CH), 127.7 (CH), 128.5 (2CH), 128.6 (2CH), 128.7 (2CH), 128.8 (2CH), 129.1 (2CH), 136.6 (C), 137.5 (C), 141.3 (C), 172.9 (CO).

5b 1-morpholino-3-phenylpropan-1-one CAS [17077-46-2][22,23]
Isolated as an oil by flash chromatography on silica gel using a (60/35/5) petroleum ether / ethyl acetate / triethylamine solvent mixture (Rf = 0.4) (0.206 g, 61% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 2.61 (t, J = 6.0 Hz, 2H), 2.98 (t, J = 6.0 Hz, 2H), 3.35 (t, J = 6.0 Hz, 2H), 3.51 (t, J = 6.0 Hz, 2H), 3.62 (bs, 4H), 7.21 (m, $3H_{Ar}$), 7.30 (m, $2H_{Ar}$).
^{13}C NMR (75 MHz, $CDCl_3$): δ 31.6 (CH_2), 34.9 (CH_2), 42.1 (CH_2), 46.1 (CH_2), 66.6 (CH_2), 67.0 (CH_2), 126.4 (CH), 128.6 (2CH), 128.7 (2CH), 141.2 (C), 171.0 (CO).

5c *N,N*-dimethyl-3-phenylpropanamide CAS [5830-31-9][22,23]
Isolated as a solid after flash chromatography on silica gel using a (1/1) mixture of petroleum ether and ethyl acetate (Rf = 0.3) (0.210 g, 77% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 2.61 (t, J = 7.5 Hz, 2H), 2.93 (s, 3H, Me), 2.95 (s, 3H, Me), 2.99 (t, J = 7.2 Hz, 2H), 7.25 (m, $5H_{Ar}$).
^{13}C NMR (75 MHz, $CDCl_3$): δ 31.5 (CH_2), 35.4 (CH_2), 35.5 (CH_2), 37.3 (CH_2), 126.2 (CH), 128.5 (2CH), 128.6 (2CH), 141.6 (C), 172.3 (CO).

5d *N,N*-dibenzylisobutyramide CAS [6284-09-9][24]
Isolated as a solid after recrystallisation using a mixture of dichloromethane and cyclohexane (0.404 g, 98% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 1.19 (d, J = 9.0 Hz, 6H, $2CH_3$), 2.84 (pent, J = 6.0 Hz, 1H), 4.47 (bs, 1H), 4.59 (bs, 1H), 7.18 (m, $4H_{Ar}$), 7.32 (m, $6H_{Ar}$).
^{13}C NMR (75 MHz, $CDCl_3$): δ 19.9 (CH_3), 30.6 (CH_3), 48.2 (CH_2), 49.8 (CH_2), 126.4 (2CH), 127.4 (CH), 127.7 (CH), 128.3 (2CH), 128.7 (2CH), 129.1 (2CH), 137.0 (C), 137.9 (C), 177.8 (CO).

5e *N,N*-dibenzyl-2-methylbutanamide CAS [138943-74-5][25]
Isolated as an oil after flash chromatography over silica gel using a (7/3) mixture of petroleum ether and ethyl acetate (Rf = 0.2) (0.134 g, 31% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 1.51 (d, J = 6.6 Hz, 3H), 1.58 (s, 3H), 2.80 (s, 2H), 3.39 (bs, 4H), 5.35 (m, 1H), 7.13 (m, 2H), 7.21 (t, J = 8.1 Hz, $4H_{Ar}$), 7.29 (d, J = 8.7 Hz, $4H_{Ar}$).
^{13}C NMR (75 MHz, $CDCl_3$): δ 13.4 (CH_3), 14.7 (CH_3), 32.8 (CH), 58.0 ($2CH_2$), 62.9 (CH_2), 122.0 (CH), 126.8 (2CH), 128.2 (2CH), 128.3 (2CH), 128.9 (2CH), 129.0 (CH), 134.4 (C), 140.3 (C), 178.0 (CO).

5f N-methyl-N,3-diphenylpropanamide CAS [18859-20-6][26]
Isolated as a solid after chromatography on silica gel using a (6/4) mixture of petroleum ether and ethyl acetate (Rf = 0.7) (0.280 g, 76% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 2.37 (t, J = 7.7 Hz, 2H), 2.92 (t, J = 7.8 Hz, 2H), 3.25 (s, 3H), 7.04 (m, 4H), 7.18 (m, 3H), 7.28 (m, 3H).
^{13}C NMR (75 MHz, $CDCl_3$): δ 31.9 (CH_2), 36.1 (CH_2), 37.4 (CH_3), 126.1 (2CH), 127.4 (CH), 127.8 (CH), 128.4 (2CH), 128.5 (2CH), 129.8 (2CH), 141.4 (C), 144.1 (C), 172.3 (CO).

5g N-butyl-3-phenylpropanamide CAS [10264-11-6][27]
Isolated as an oil after chromatography on silica gel using a (8/2) mixture of petroleum ether and ethyl acetate (Rf = 0.2) (0.266 g, 84% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 0.88 (t, J = 6.0 Hz, 3H), 1.25 (m, 2H), 1.40 (m, 2H), 2.45 (t, J = 7.5 Hz, 2H), 2.96 (t, J = 7.8 Hz, 2H), 3.20 (q, J = 6.0 Hz, 2H), 5.36 (bs, 1H), 7.20 (m, $3H_{Ar}$), 7.27 (m, $2H_{Ar}$).
^{13}C NMR (75 MHz, $CDCl_3$): δ 13.8 (CH_3), 20.1 (CH_2), 31.8 (CH_2), 31.9 (CH_2), 38.7 (CH_2), 39.3 (CH_2), 126.3 (CH), 128.5 (2CH), 128.6 (2CH), 141.1 (C), 172.4 (CO).

5h *N*-benzyl-3-phenylpropanamide CAS [10264-10-5][28]
Isolated as a solid after recrystallization using a dichloromethane / cyclohexane mixture (0.328 g, 89% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 2.52 (t, J = 7.9 Hz, 2H), 3.00 (t, J = 7.9 Hz, 2H), 4.39 (d, J = 5.7 Hz, 2H), 5.48 (bs, 1H, NH), 7.21 (m, $5H_{Ar}$), 7.27 (m, $5H_{Ar}$).
^{13}C NMR (75 MHz, $CDCl_3$): δ 31.8 (CH_2), 38.5 (CH_2), 43.6 (CH_2), 126.3 (CH), 127.5 (CH), 127.8 (2CH), 128.5 (2CH), 128.6 (2CH), 128.7 (2CH), 138.3 (C), 140.9 (C), 172.1 (CO).

5i *N*,3-diphenylpropanamide CAS [3271-81-6][28]
Isolated as a solid after recristallisation using a dichloromethane/cyclohexane mixture (0.312 g, 90% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 2.65 (t, J = 7.6 Hz, 2H), 3.05 (t, J = 7.6 Hz, 2H), 7.14 (m, NH+$1H_{Ar}$), 7.29 (m, $7H_{Ar}$), 7.43 (d, J = 7.9 Hz, $2H_{Ar}$).
^{13}C NMR (75 MHz, $CDCl_3$): δ 31.7 (CH_2), 39.6 (CH_2), 120.1 (CH), 124.4 (CH), 126.5 (2CH), 128.5 (2CH), 128.8 (2CH), 129.1 (2CH), 137.9 (C), 140.8 (C), 170.5 (CO).

5j 3-phenyl-*N*-(thiophen-2-ylmethyl)propanamide CAS [546097-42-1][29]
Isolated as an oil after recrystallization using a dichloromethane / cyclohexane mixture (0.378 g, 100% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 2.49 (t, J = 7.2 Hz, 2H), 2.98 (t, J = 7.5 Hz, 2H), 4.57 (d, J = 5.7 Hz, 2H), 5.72 (bs, 1H, NH), 6.88 (m, $1H_{Ar}$), 6.92 (m, $1H_{Ar}$), 7.20 (m, $4H_{Ar}$), 7.27 (m, $2H_{Ar}$).
^{13}C NMR (75 MHz, $CDCl_3$): δ 31.6 (CH_2), 38.2 (CH_2), 38.3 (CH_2), 125.1 (CH), 125.9 (CH), 126.3 (CH), 126.9 (CH), 128.4 (2CH), 128.6 (2CH), 140.8 (C), 141.0 (C), 171.7 (CO).

5k *N,N*-dibenzyl-3-phenylpropanamide-2-d
Isolated as a white solid after recrystallisation using a dichloromethane/cyclohexane solvent mixture (0.499 g, 98% yield). Melting point: 104°C.
^{1}H NMR (300 MHz, $CDCl_3$): δ 2.73 (t, J = 7.6 Hz, 2H), 3.08 (d, J = 7.7 Hz, 2H), 4.40 (s, 2H), 4.64 (s, 2H), 7.10 (d, J = 6.6 Hz, $2H_{Ar}$), 7.22 (m, $5H_{Ar}$), 7.31 (m, $8H_{Ar}$).
^{13}C NMR (75 MHz, $CDCl_3$): δ 31.6 (CH_2), 34.8 (t, J = 19.4 Hz ,CDH), 48.4 (CH_2), 49.9 (CH_2), 126.2 (CH), 126.4 (2CH), 127.5 (CH), 127.7 (CH), 128.4 (2CH), 128.5 (2CH), 128.6 (2CH), 128.7 (2CH), 129.0 (2CH), 136.6 (C), 137.5 (C), 141.3 (C), 172.8 (CO). HRMS (ESI+) m/z calculated for $C_{23}H_{25}NO$ [MH+]: 331.19307, measured 331.19098.

6a *N,N*-dibenzyl-3-phenylpropan-1-amine CAS [27376-59-6][30]
Isolated as an oil by chromatography on silica gel using a (85/10/5) mixture of petroleum ether, ethyl acetate and triethylamine (Rf = 0.8) (0.452 g, 93% yield).
^{1}H NMR ($CDCl_3$, 300 MHz): δ 1.85 (quin, J = 7.4 Hz, 2H, CH_2), 2.51 (t, J = 6.9 Hz, 2H, CH_2), 2.61 (t, J = 9.0 Hz, 2H, CH_2), 3.60 (s, 4H, $2CH_2$), 7.10 (m, $2H_{Ar}$), 7.17 (t*, J = 7.7 Hz, $1H_{Ar}$), 7.25 (t*, J = 7.5 Hz, $4H_{Ar}$), 7.33 (t*, J = 7.5 Hz, $4H_{Ar}$), 7.40 (d*, J = 6.6 Hz, $4H_{Ar}$).
^{13}C NMR ($CDCl_3$, 75 MHz): δ 29.2 (CH_2), 33.7 (CH_2), 53.1 (CH_2), 58.5 ($2CH_2$), 125.7 (2CH), 126.9 (CH), 128.3 (4CH), 128.4 (2CH), 128.5 (2CH), 129.0 (4CH), 140.0 (C), 142.7 (2C).

6b 4-(3-phenylpropyl)morpholine CAS [25262-57-1][31]
Isolated as an oil by chromatography on silica gel using a (60/35/5) mixture of petroleum ether, ethyl acetate and triethylamine (Rf = 0.4) (0.199 g, 63% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 7.14 (m, $5H_{Ar}$), 3.62 (t, J = 4.7 Hz, 4H), 2.56 (t, J = 7.7 Hz, 2H), 2.34 (t, J = 4.7 Hz, 4H), 2.27 (t, J = 7.5 Hz, 2H), 1.75 (m, 2H).
^{13}C NMR (75 MHz $CDCl_3$): δ 142.1 (C), 128.5 (2CH), 128.4 (CH), 125.9 (2CH), 67.1 ($2CH_2$), 58.4 (CH_2), 53.8 ($2CH_2$), 33.7 (CH_2), 28.3 (CH_2).

6c *N,N*-dimethyl-3-phenylpropan-1-amine CAS [1199-99-1][32]
Isolated as an oil by chromatography on silica gel using a (85/10/5) mixture of petroleum ether, ethyl acetate and triethylamine (Rf = 0.5) (0.168 g, 67% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 7.20 (m, $3H_{Ar}$), 7.12 (m, $2H_{Ar}$), 2.57 (t, J = 7.8 Hz, 2H), 2.24 (t, J = 7.5 Hz, 2H), 2.17 (s, 6H),1.73 (tt, J = 7.8-7.4 Hz, 2H).
^{13}C NMR (75 MHz, $CDCl_3$): δ 139.4 (C), 128.9 (2CH), 128.5 (2CH), 126.8 (CH), 57.5 (CH_2), 43.1 ($2CH_3$), 32.7 (CH_2), 25.7 (CH_2).

6d *N,N*-dibenzyl-2-methylpropan-1-amine CAS [121238-79-7][32]
Isolated as a solid by chromatography on silica gel using a (90/5/5) mixture of petroleum ether, ethyl acetate and triethylamine (Rf = 0.8) (0.238 g, 61% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 7.20 (m, $10H_{Ar}$), 3.43 (s, 4H), 2.08 (t, J = 7.3 Hz, 2H), 1.77 (m, 1H), 0.78 (d, J = 6.6 Hz, 6H).
^{13}C NMR (75 MHz, $CDCl_3$): δ 140.2 (C), 129.0 (4CH), 128.2 (4CH), 126.8 (2CH), 60.7 (CH_2), 59.0 ($2CH_2$), 32.8 (CH), 17.8 ($2CH_3$).

6e *N,N*-dibenzyl-2-methylbutan-1-amine CAS [1620971-05-2][33]
Isolated as an oil by chromatography on silica gel using a (99/1) mixture of petroleum ether and ethyl acetate (Rf = 0.8) (0.210 g, 51% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 7.20 (m, $10H_{Ar}$), 3.42 (q, J = 14.9 Hz, 4H), 2.16 (m, 1H), 2.06 (m, 1H), 1.56 (m, 1H), 1.41 (m, 1H), 0.93 (m, 1H), 0.75 (m, 6H).
^{13}C NMR (75 MHz, $CDCl_3$): δ 140.2 (2C), 130.0 (4CH), 128.2 (4CH), 126.8 (2CH), 60.8 (CH_2), 59.0 ($2CH_2$), 32.8 (CH), 27.6 (CH_2), 17.8 (CH_3), 11.4 (CH_3).

6f N-methyl-N-(3-phenylpropyl)aniline CAS [29514-68-9][34]
Isolated as an oil by chromatography on silica gel using a (85/10/5) mixture of petroleum ether, ethyl acetate and triethylamine (Rf = 0.9) (0.316 g, 91% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 7.13 (m, $7H_{Ar}$), 6.58 (m, $3H_{Ar}$), 3.23 (t, J = 7.5 Hz, 2H), 2.80 (s, 3H), 2.55 (t, J = 7.7 Hz, 2H), 1.80 (tt, J = 7.7-7.5 Hz, 2H).

^{13}C NMR (75 MHz, $CDCl_3$): δ 149.4 (C), 141.9 (C), 129.3 (2CH), 128.5 (2CH), 128.4 (2CH), 126.0 (2CH), 116.2 (CH), 112.4 (CH), 52.4 (CH_2), 38.4 (CH_3), 33.5 (CH_2), 28.3 (CH_2).

6g N-(3-phenylpropyl)butan-1-amine CAS [92111-13-2][35]
Isolated as an oil by chromatography on silica gel using a (55/40/5) mixture of petroleum ether, ethyl acetate and triethylamine (Rf = 0.8) (0.1 g, 34% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 9.43 (bs, NH), 7.10 (m, 5H_{Ar}), 2.81 (m, 4H), 2.60 (t, J = 7.2 Hz, 2H), 2.16 (m, 2H), 1.75 (m, 2H), 1.26 (q, J = 7.3 Hz, 2H), 0.80 (t, J = 7.3 Hz, 3H).
^{13}C NMR (75 MHz, $CDCl_3$): δ 139.8 (C), 128.6 (2CH), 128.4 (2CH), 126.4 (CH), 47.7 (CH_2), 47.2 (CH_2), 32.8 (CH_2), 27.7 (CH_2), 27.2 (CH_2), 20.0 (CH_2), 13.4 (CH_3).

6h N-benzyl-3-phenylpropan-1-amine CAS [32861-51-1][23]
Isolated as a solid by chromatography on silica gel using a (80/15/5) mixture of petroleum ether, ethyl acetate and triethylamine (Rf = 0.3) (0.236 g, 68% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 1.30 (bs, 1H), 1.79 (hept, J = 9.0 Hz, 1H), 2.63 (m, 4H, CH_2), 3.73 (s, 2H, CH_2), 7.14 (m, 3H_{Ar}), 7.22 (m, 3H_{Ar}), 7.33 (m, 4H_{Ar}).
^{13}C NMR (75 MHz, $CDCl_3$): δ 31.9 (CH_2), 33.8 (CH_2), 49.1 (CH_2), 54.1 (CH_2), 125.9 (CH), 127.0 (CH), 128.2 (2CH), 128.4 (2CH), 128.5 (4CH), 140.7 (C), 142.3 (C).

6i *N*-(3-phenylpropyl)aniline CAS [1738-99-4][36]
Isolated as a solid by chromatography on silica gel using a (80/15/5) mixture of petroleum ether, ethyl acetate and triethylamine (Rf = 0.5) (0.270 g, 83% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 7.15 (m, 7H_{Ar}), 6.66 (t, J = 7.4 Hz, 1H_{Ar}), 6.58 (d, J = 8.7 Hz, 2H_{Ar}), 3.08 (t, J = 7.1 Hz, 2H), 2.65 (t, J = 7.6 Hz, 2H), 1.90 (dt, J = 7.6-7.1 Hz, 2H).
^{13}C NMR (75 MHz, $CDCl_3$): δ 148.5 (C), 141.8 (C), 129.3 (2CH), 128.6 (2CH), 128.5 (2CH), 126.1 (CH), 117.3 (CH), 112.9 (2CH), 43.5 (CH_2), 33.5 (CH_2), 31.2 (CH_2).

6j 3-phenyl-N-(thiophen-2-ylmethyl)propan-1-amine CAS [1038212-86-0][37]
Isolated as an oil by chromatography on silica gel using a (75/20/5) mixture of petroleum ether, ethyl acetate and triethylamine (Rf = 0.6) (0.292 g, 82% yield).
^{1}H NMR (300 MHz, $CDCl_3$): δ 7.14 (m, 6H_{Ar}), 6.84 (m, 2H_{Ar}), 3.90 (d, J = 1.0 Hz, 2H, CH_2), 2.60 (m, 4H), 1.76 (m, 2H), 1.77 (bs, NH).
^{13}C NMR (75 MHz, $CDCl_3$): δ 144.2 (C), 142.2 (C), 128.5 (2CH), 128.4 (2CH), 126.7 (CH), 125.9 (CH), 125.0 (CH), 124.4 (CH), 48.7 (CH_2), 48.4 (CH_2), 33.7 (CH_2), 31.7 (CH_2).

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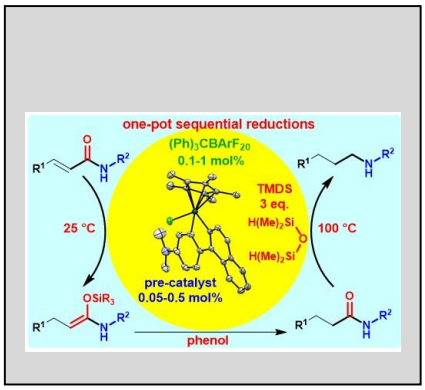
FULL PAPER

Silyl Ketene Aminals



A single cationic iridium^{III} metallacycle catalyzes effectively the one-pot sequential double hydrosilylation of challenging α,β-unsaturated secondary and tertiary amides to afford in a controlled and selective way the corresponding amides and amines. The critical silyl ketene aminal intermediate has been characterized by using control experiments, mass spectrometry and state of the art Nuclear Magnetic Resonance analyses.