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RESEARCH ARTICLE

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Regioselective cycloruthenation of *N*-(benzylidene) benzylamines: Enantiopure catalysts for transfer hydrogenation

Albert Martinez-Segura[1] | **Javier Eusamio**[1,2] | **Yaiza M. Medina**[1,2] | **Katherine Ariz**[3] | **Albert Gutiérrez**[1,2] | **Joan Albert**[1] | **Jaume Granell**[1] | **Mercè Font-Bardia**[4] | **Arnald Grabulosa**[1,2]

[1]Departament de Química Inorgànica i Orgànica, Secció de Química Inorgànica, Universitat de Barcelona, Martí i Franquès, 1-11, Barcelona, Spain

[2]Institut de Nanociència i Nanotecnologia (IN2UB), Universitat de Barcelona, Barcelona, Spain

[3]Laboratory of Organometallic Chemistry and Catalysis, Institute of Chemistry and Biochemistry, University of Valparaíso, Valparaíso, Chile

[4]Unitat de Difracció de Raigs X, Centres Científics i Tecnològics de la Universitat de Barcelona (CCiTUB), Solé i Sabarís 1-3, Barcelona, Spain

Correspondence
Arnald Grabulosa, Departament de Química Inorgànica i Orgànica, Secció de Química Inorgànica, Universitat de Barcelona, Martí i Franquès, 1-11, E-08028 Barcelona, Spain.
Email: arnald.grabulosa@qi.ub.es

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The reaction between *N*-(benzylidene)benzylamines (p-$RC_6H_4CH{=}NCH_2C_6H_5$; R = Cl, H, NO_2, F, OMe), $[RuCl_2(\eta^6\text{-}p\text{-cymene})]_2$ and potassium acetate has cleanly furnished the corresponding cycloruthenated complexes **C1–C5**. The process is completely regioselective, with the formation in all cases of the *endo*-derivative, independently of the substituent of the aromatic ring. The five-membered *endo*-metallacycles **C6** and **C7** can also be obtained from the enantiopure imines (R_C)-p-$RC_6H_4CH{=}NCHMeC_{10}H_7$ (R = Cl, H, respectively) working under similar conditions. The crystal structures of the seven metallated compounds have been determined by X-ray diffraction. These complexes are active as catalyst precursors for the reduction of acetophenone and benzophenone by transfer hydrogenation. An enantiomeric excess of up to 77% at room temperature has been obtained with the complex **C7** in the reduction of acetophenone.

KEYWORDS
chiral imines, cycloruthenation, regioselectivity, stereogenic metal, transfer hydrogenation

1 | INTRODUCTION

Cycloruthenation is a very interesting process, as cycloruthenated derivatives display important applications.[1,2] Cyclometallated ruthenium complexes have been used as efficient precursors in homogeneous catalysts for several processes[3–6] and some of them show promising anticancer activity.[7] Besides this, some complexes have found

use as sensitizers for solar cells[8] or in redox-catalysed processes as electron shuttles.[9,10]

In recent times, ruthenium-catalysed *ortho*- or *meta*-C—H bond functionalization has become a very active field,[11,12] and the cycloruthenation reaction is also a fundamental step in these processes. Knowledge of the factors that give rise to a regioselective activation of C—H bonds by ruthenium complexes can be useful to improve these processes and to find new ruthenium catalysts or new experimental conditions.

Many cycloruthenated compounds with nitrogen ligands have been described[1,7] but those containing imines have been understudied, even though they can be very useful given the easy synthesis of these *N*-donor ligands and the large diversity of organic structures they can contain, including a wide range of optically pure compounds. Figure 1 shows the Schiff-base cycloruthenated derivatives described so far in the literature.[13–18]

This contribution (Figure 1, bottom right) reports the cycloruthenation of *N*-(benzylidene)benzylamines, *p*-$RC_6H_4CH{=}NCH_2C_6H_5$ (R = Cl, H, NO_2, F, OMe). It should be noted that, unlike what has been published so far, these Schiff bases could afford, by activation of $C_{aromatic}$—H bonds, two distinct five-membered metallacycles. We have found that the cycloruthenation process is completely regioselective with the formation in all cases of the *endo*-derivative (i.e., that in which the ruthenacycle contains the C=N bond), independently of the substitution at the aromatic ring. The study has been extended to chiral imines derived from 1-naphthylethylamine (R_C)-*p*-$RC_6H_4CH{=}NCHMeC_{10}H_7$ (R = Cl, H) to obtain enantiopure ruthenated imines. Furthermore, these metallacycles have been explored in the catalytic, enantioselective reduction of acetophenone and benzophenone by transfer hydrogenation.

2 | RESULTS AND DISCUSSION

2.1 | Cycloruthenated complexes C1–C5

In general, the cyclometallation of Schiff bases (imines) can occur in different carbon atoms, furnishing two isomeric cyclometallated compounds: *endo*-metallacycles if the metallacycle contains the C=N bond, or *exo*-derivatives if it does not contain it (Figure 2). In addition, imines are known to exist as *E* and *Z* isomers, although *N*-substituted aldimines generally favour the more stable *E* form in most cases. Five-membered *endo*- or *exo*-

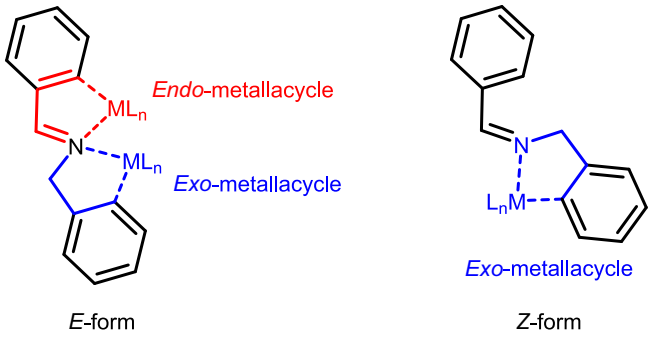

FIGURE 2 Cyclometallation positions of the imine.

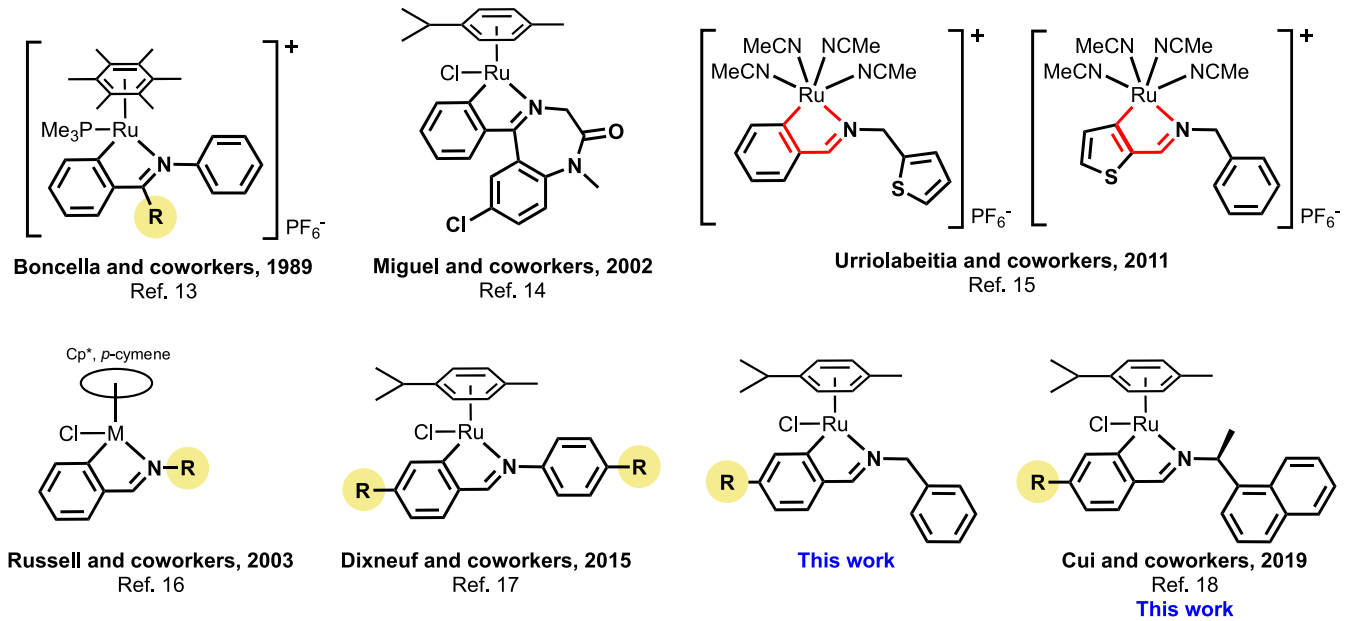

FIGURE 1 Selected examples of relevant cycloruthenated complexes with imines.

metallacycles can be formed from *N*-(benzylidene)benzylamines in the *E*-form, but the *Z*-isomer exclusively forms *exo*-metallacycles. The *endo* effect—the strong tendency of imines towards the formation of *endo*-metallacycles—is known for cyclopalladation reactions[19–21] and it has also been reported for the cycloruthenation of thiophene-based imines.[15]

The *N*-(benzylidene)benzylamines **L1–L5**, *p*-$RC_6H_4CH{=}NCH_2C_6H_5$ (R = Cl [**L1**], H [**L2**], NO_2 [**L3**], F [**L4**] and OMe [**L5**]) were treated in the presence of potassium acetate with the precursor $[RuCl(\mu\text{-}Cl)(\eta^6\text{-}p\text{-cymene})]_2$ in methanol for 4 h at rt. Under these conditions, the cycloruthenation process is completely regioselective, with the formation in all cases of the *endo*-derivatives regardless of the substituent of the aromatic ring (Figure 3). This synthetic procedure is very convenient because it was found that the complexes spontaneously precipitated in methanol.

After elimination of methanol, the crude was analysed by ^{1}H NMR; an additional quantity of the *endo*-derivative was found, as well as small amounts of the corresponding benzaldehyde, benzylamine and the starting ruthenium dimer, but in none of the cases any trace of the *exo*-metallacycle was observed.

In an attempt to prepare an *exo*cyclic derivative, the reaction was performed using the imine $2,6\text{-}Cl_2C_6H_3CH{=}NCH_2C_6H_5$, with substituted benzylidene *ortho* positions that prevent the HC activation process, but again the *exo*-ruthenacycle was not observed. Instead, decomposition of the imine with the formation of the corresponding ruthenated benzylamine could be detected, a compound previously described by Pfeffer and coworkers.[22]

The obtained complexes (**C1–C5**) were fully characterised by ^{1}H, $^{13}C\{^1H\}$, ^{19}F (for **C4**) NMR, IR and mass spectrometry. ^{1}H NMR confirmed that cyclometallation had taken place because four distinct H peaks, assignable to the four aromatic H atoms of the *p*-cymene moiety, were observed, in agreement with the stereogenic nature of the pseudotetrahedral Ru atom after cyclometallation. The aromatic part of the spectrum showed three different resonances of the aromatic protons of the *para*-substituted benzylidene group, proving that the *endo*-metallacycle is formed (Figure 2).

The most relevant peak in mass spectroscopy, $[M - Cl]^+$, confirmed the identity of the compounds. In addition, peaks assigned to dimeric ruthenium metallacyclic compounds ($[2\ M - Cl]^+$) were also observed.

Monocrystals appropriate for X-ray measurements of the five metallated complexes (**C1–C5**) could be obtained by dissolving the complex in dichloromethane and adding hexane to induce crystallisation. The five crystal structures could be resolved, and the structures are given in Figure 4.

The five compounds show similar values of the most interesting metrical parameters (Table 1). It should be noted that upon metallation of the imine, the compounds bear a stereogenic (pseudotetrahedral) ruthenium atom, which in our case is racemic as all complexes crystallise in centrosymmetric space groups. The bond distances fall in the normal ranges: Ru—$C_{metallated}$ (2.053–2.043 Å), Ru—Cl (2.053–2.043 Å) and Ru—N (2.081–2.093 Å), and the bite angles of Ru-$C_{metallated}$—N (77.52–77.97°) differ considerably from the ideal 90° and are in accordance with those observed for other cycloruthenated *N*-donor derivatives.[17,22–26] The structures confirm that the cycloruthenation had taken place by $C_{aromatic}$—H activation of the benzylidene group of the imine, forming the *endo*-metallacycle. The complexes exhibit the typical *three-legged piano stool* geometry, with the metal coordinated to the chloride, nitrogen and carbon of the benzylidene group, forming a five-membered ruthenacycle. Interestingly, the Ru-centroid distance is longer for complexes with an electron-poor metallated phenyl ring (**C4** and especially **C3**) and shorter for **C5**, with an electron-rich metallated phenyl ring. This suggests that the more electronically rich the metallated phenyl ring is, the stronger the Ru-arene bonds are. In addition, all the structures show that the *p*-cymene group is flipped 90° in relation to the cyclometallated imine, having the *p*-cymene methyl directed towards the chloride group. This could be helpful for the activation of the complex as it provides a catalyst with an open space to interact with the substrate.

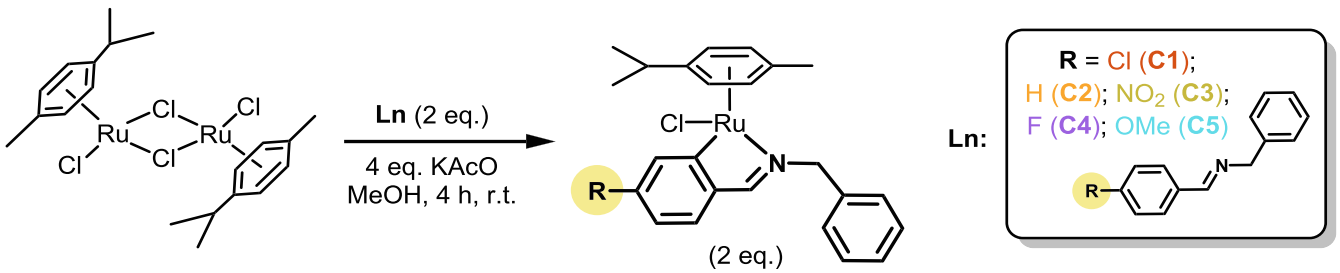

FIGURE 3 Cycloruthenation of *N*-(benzylidene)benzylamines to give complexes **C1–C5**.

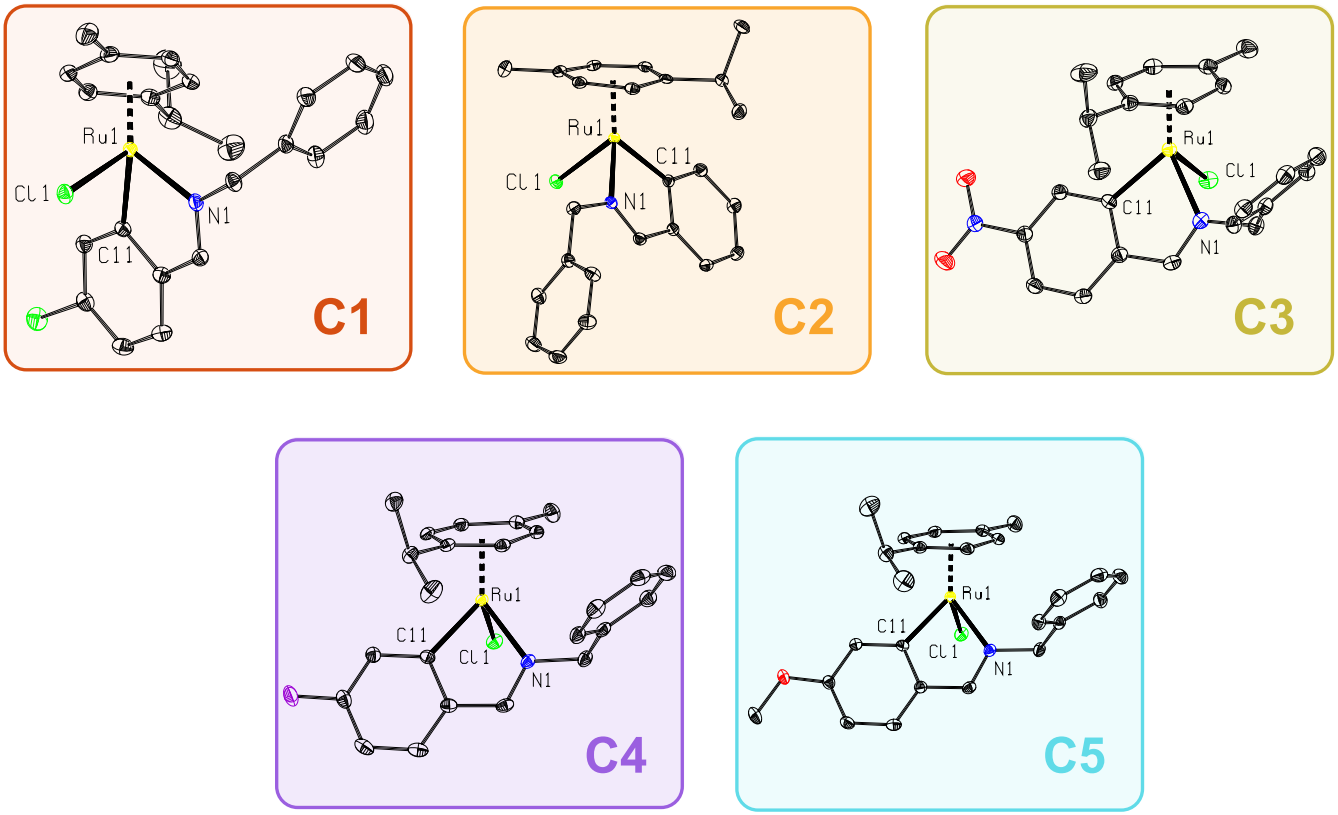

FIGURE 4 Oak Ridge Thermal-Ellipsoid Plot Program (ORTEP) plots (drawn at 50% probability level) of complexes **C1**–**C5**. Hydrogen atoms are not shown for the sake of clarity.

	C1	C2	C3	C4	C5
Ru—C11	2.0507 (15)	2.0515 (13)	2.044 (2)	2.0531 (16)	2.0529 (13)
Ru—N1	2.0843 (14)	2.0850 (11)	2.0806 (19)	2.0929 (13)	2.0900 (12)
Ru—Cl1	2.4209 (4)	2.3989 (3)	2.4190 (6)	2.4212 (10)	2.4222 (5)
Ru—Centroid	1.711	1.709	1.724	1.716	1.708
C11—Ru—N1	77.86 (6)	77.91 (5)	77.52 (8)	77.99 (6)	77.97 (5)
C11—Ru—Cl1	86.84 (4)	83.29 (3)	88.33 (6)	93.26 (6)	83.48 (3)
N1—Ru—Cl1	84.54 (4)	87.02 (4)	81.47 (5)	84.01 (4)	87.44 (4)

TABLE 1 Selected distances (Å) and angles (deg) of complexes **C1**–**C5**.

2.2 | Catalytic transfer hydrogenation

The ruthenium complexes **C1**–**C5** were explored as precatalysts for the reduction of ketones under transfer hydrogenation conditions.[27] Two ketones were selected as substrates: acetophenone and benzophenone. The catalytic runs were performed under an inert atmosphere in refluxing isopropanol (82°C) after an activation period of 15 min at the same temperature to form the Ru-hydride complex, which acts as the active catalytic species.[28,29] The catalyses were carried out using a catalyst loading of 0.5 mol% and 5 mol% of potassium *tert*-butoxide as a base, with 2-propanol acting as the solvent and the hydrogen donor (Figure 5).

The reaction was monitored by taking aliquots at regular intervals (0, 30, 60, 90 and 120 min) and analysing them by gas chromatography (GC). The conversion profiles are given in Figures 6 and 7 for acetophenone and benzophenone, respectively. It should be noted that the reduction of acetophenone is faster than the reduction of benzophenone, in accordance with steric factors. Indeed, with the former substrate, all the precursors yield full conversion after 2 h. Besides this, both reactions are faster when the precursor **C1** (R = Cl) and especially the parent complex **C2** (R = H) are used. This is more evident in the reduction of the less reactive benzophenone, in which the **C2** is much more active than the other complexes.

When the precatalyst **C1** was treated with 5 eq of potassium *tert*-butoxide in isopropanol-d_8 at reflux for 15 min and the resulting solution was analysed by ^{1}H NMR, signals corresponding to the coordinated *p*-cymene (5.2–3.7 ppm) and to the cyclometallated imine (8.4–7.2 ppm) were observed, confirming that both ligands remain intact after the activation.

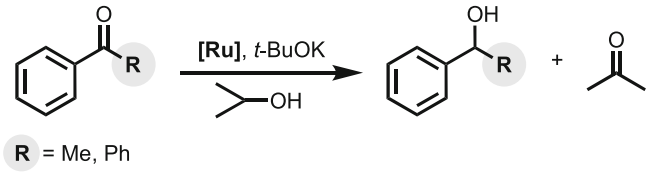

FIGURE 5 Ruthenium-catalysed reduction of acetophenone and benzophenone.

2.3 | Optically pure cycloruthenated complexes C6 and C7

In the enantioselective transfer hydrogenation reaction, acetophenone acts as the benchmark substrate, rendering a chiral alcohol upon reduction.[30] Given the good results obtained with catalysts **C1**–**C5**, it was deemed interesting to prepare chiral imines and explore their

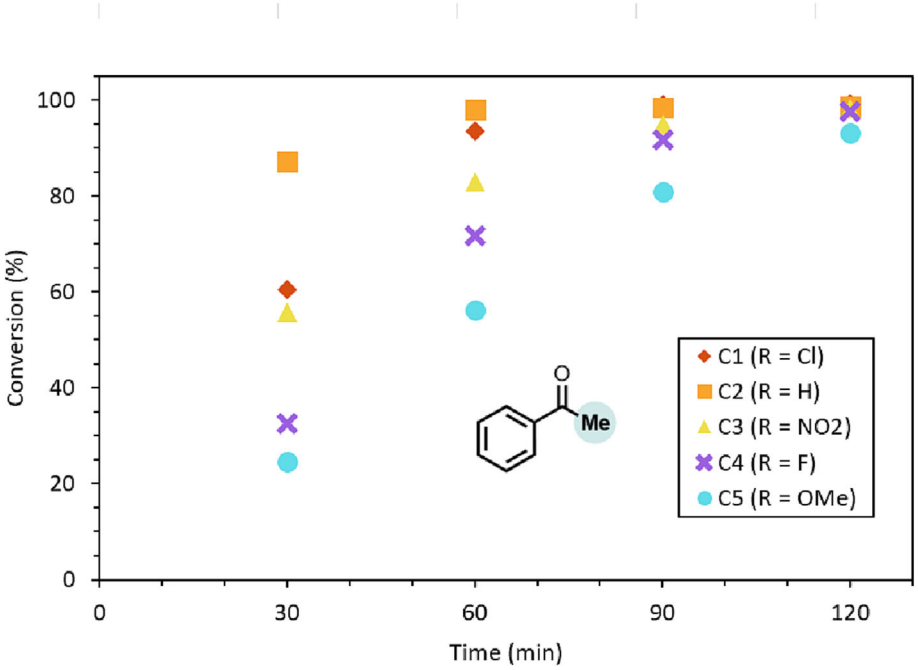

FIGURE 6 Acetophenone conversion versus time for complexes **C1**–**C5**.

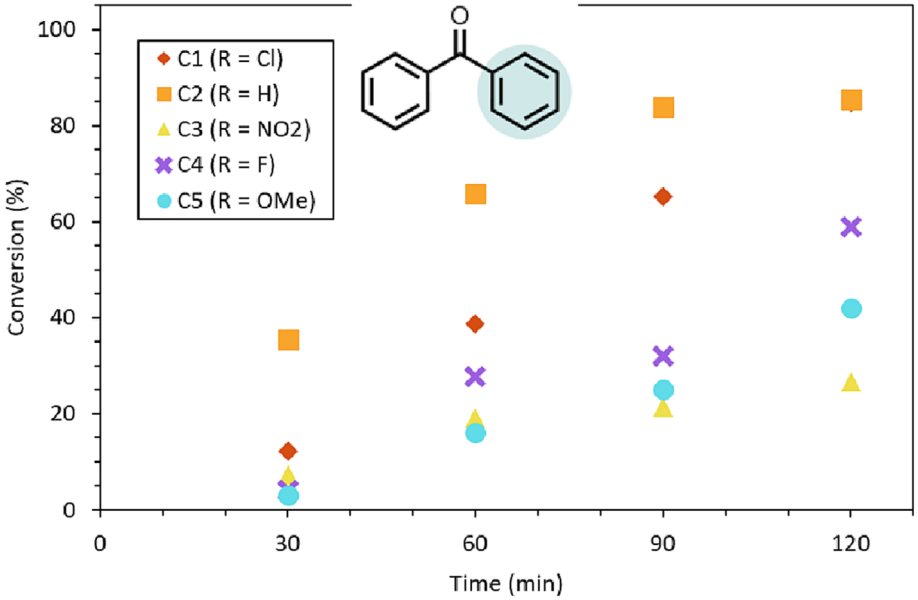

FIGURE 7 Benzophenone conversion versus time for complexes **C1**–**C5**.

cyclometallation. The cycloruthenation of some optically pure amines has been reported[22,31–34] but, to the best of our knowledge, only one example of the synthesis of ruthenacycles containing enantiopure imines has been reported until now: the ruthenation of imine (R_C)-*p*-$RC_6H_4CH{=}NCHMeC_{10}H_7$ (the ligand **L6** of this manuscript), which was described by Cui and coworkers in their study of enantioselective C—H activation reactions.[18] The synthesis of the chiral imines (**L6** and **L7**) (Figure 8) was carried out following a similar procedure to that of **L1**–**L5**, reacting the primary amine (R_C)-1-(1-naphthyl)ethylamine and the corresponding aldehyde.[35,36]

The substituents of the phenyl ring (Cl and H) for the ligands were selected based on the catalytic results with complexes **C1**–**C5**. These enantiopure imines (R_C)-*p*-$RC_6H_4CH{=}NCHMeC_{10}H_7$ were treated with $[RuCl_2(\eta^6\text{-}p\text{-cymene})]_2$ and potassium acetate in methanol for 24 h at rt. Under these conditions, the process is again completely regioselective, with the formation in both cases of the *endo*-derivatives **C6** (previously reported by Cui and coworkers)[18] and **C7** (Figure 9).

The ruthenacycles **C6** and **C7** were fully characterised by the usual techniques. ^{1}H NMR confirmed that cyclometallation had taken place because four proton signals corresponding to the magnetically inequivalent protons of the *p*-cymene group were observed. The aromatic zone of both spectra confirms that the *endo*-metallacycle has been formed. The most relevant peak in mass spectroscopy, assigned to $[M - Cl]^+$, confirms the molecular formulae of the compounds.

Crystals suitable for X-ray diffraction could be successfully grown for **C6** and **C7,** and both crystal structures are shown in Figure 10.[37]

The structures show similar data to the five structures of **C1**–**C5** described in the previous section and again confirm the cycloruthenation by $C_{aromatic}$—H activation of the iminic benzylidene group, forming the *endo*-metallacycle (Table 2). Again, the two structures show that the *p*-cymene group is flipped 90° in relation to the cyclometallated imine, with the methyl substituent of the *p*-cymene group directed to the chloride. The free imine ligand is optically pure and has an R_C absolute configuration, and it is found that only one diastereomer of the complex appears in the crystal with an R_{Ru} absolute configuration, which can be considered a pseudotetrahedral

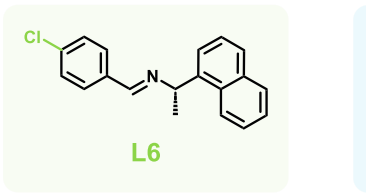

FIGURE 8 Chiral imines **L6** and **L7**.

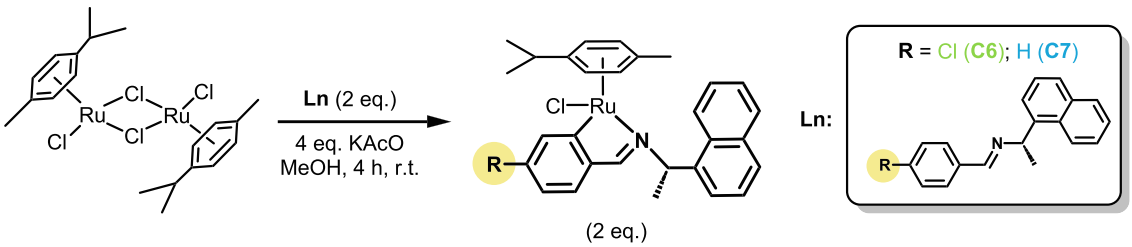

FIGURE 9 Synthesis of complexes **C6** and **C7**.

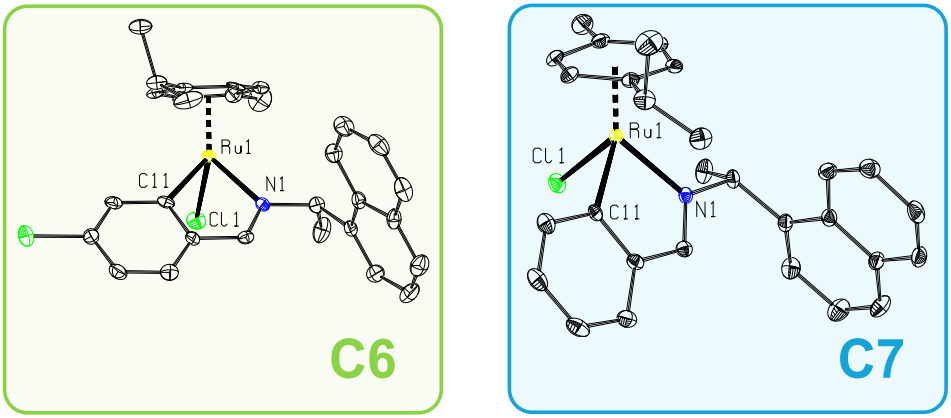

FIGURE 10 Oak Ridge Thermal-Ellipsoid Plot Program (ORTEP) plots (drawn at the 50% probability level) of **C6** and **C7**. Hydrogen atoms are not shown for the sake of clarity.

centre. The absolute configuration of the ruthenium atom is confirmed by the Flack[38] parameters of 0.015 (18) and 0.012 (13) for **C6** and **C7**, respectively.

Pfeffer and coworkers have reported the cycloruthenation of different enantiopure primary amines, including (R_C)-1-(1-naphthyl)ethylamine, and they found, by ^{1}H NMR studies at room temperature, the presence of mixtures of (R_C,R_{Ru}) and (R_C,S_{Ru}) diastereomers.[22] Cui and coworkers[18] observed via ^{1}H NMR that crude **C6** contained both diastereomers in a 90:10 ratio from which the major diastereomer could be isolated, a result matching our own findings. Interestingly, we found that in the case of **C7** (with the non-substituted chiral imine), there is already less than 5% of the minor diastereomer present in the crude and virtually none in the recrystallised product.

TABLE 2 Selected distances (Å) and angles (deg) of complexes **C6** and **C7**.

	C6	C7
Ru—C11	2.042 (5)	2.045 (3)
Ru—N1	2.098 (4)	2.101 (3)
Ru—Cl1	2.4214 (13)	2.4194 (7)
Ru—Centroid	1.705	1.705
C11—Ru—N1	77.91 (19)	77.94 (12)
C11—Ru—Cl1	88.69 (13)	84.54 (9)
N1—Ru—Cl1	85.49 (14)	88.15 (7)

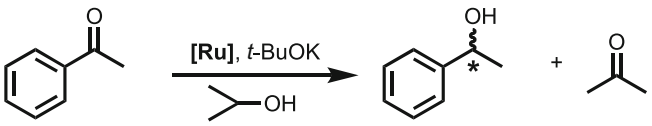

FIGURE 11 Enantioselective transfer hydrogenation of acetophenone.

2.4 | Catalytic enantioselective transfer hydrogenation

The complexes **C6** and **C7** were tested as catalysts in the enantioselective transfer hydrogenation of acetophenone, producing 1-phenylethanol, a chiral alcohol. The runs were performed in the same manner as in the previous section: 0.5 mol% of the ruthenium complex, 5 mol% of potassium *tert*-butoxide as a base, isopropanol as the solvent and hydrogen donor in an inert atmosphere at 82°C (Figure 11). The results with precursors **C6** and **C7** are given in Figure 12.

The figure shows that both complexes are competent in the reduction of acetophenone, giving full conversions after 2 h at 82°C. It should be noted that the enantioselectivity remains almost constant throughout the process, leading to 50% enantiomeric excess in all the reactions, favouring the *S* enantiomer of 1-phenylethanol. The unsubstituted complex **C7** is the most active complex for the asymmetric reduction of the ketone analogously to **C2**, although complex **C6** follows a similar pattern and presents a full conversion after 2 h.

In order to increase the enantioselectivity, a catalytic run with **C7** was repeated at 40°C, both for the activation

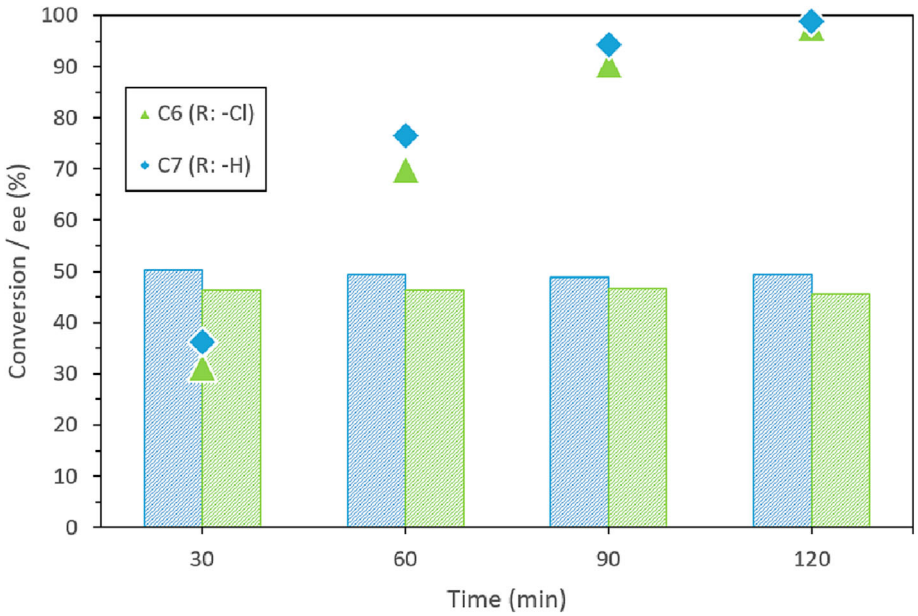

FIGURE 12 Acetophenone conversion (points) and enantiomeric excess (*ee*) (bars) versus time for complexes **C6** and **C7**.

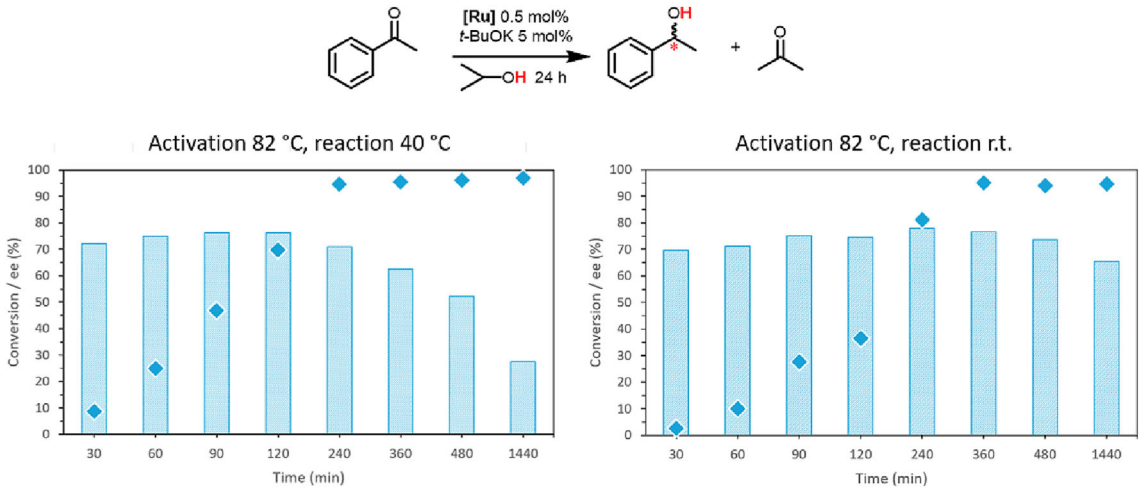

FIGURE 13 Acetophenone conversion (points) and enantiomeric excess (bars) versus time for **C7** carrying out the activation at 82°C and the reaction at 40°C and at rt.

and for the catalysis. Under these conditions, the enantioselectivity improved considerably (up to 75% *ee*), but the conversion was only 29% after 24 h. Much better results were obtained when the activation was performed at reflux of isopropanol (82°C) and the catalysis at 40°C (Figure 13, bottom left). Under these conditions, a conversion of 95% and an *ee* of 76% were obtained after 4 h. Finally, when the reaction was performed at rt while keeping the activation temperature at 82°C, the reaction was slower, but still, an almost full conversion of 95% with a 77% *ee* was obtained after 6 h (Figure 13, bottom right).

These results show that the enantioselectivity reaches a maximum value of near 80% *ee* when the catalysis is performed at low temperatures, but that the activation of the catalyst must be carried out at 82°C to achieve good conversions. The enantioselectivity decreases after 2 h at 40°C (Figure 13, left), reaching a low value at 24 h, but it remains mostly unchanged when performing the reaction at rt (Figure 13, bottom right). This shows that catalyst decomposition is probably taking place at 40°C, forming catalytically active but achiral ruthenium species. A catalytic run with **C6** was performed under the same conditions, and similar results were observed (Figure **S1**, page S25), although the decrease of the enantioselectivity over time was more pronounced.

It has been reported that a cycloruthenated derivative of *(R)*-1-(1-naphthyl)ethylamine (Figure 14) can also be used as a catalysts for the reduction of acetophenone with a conversion of 95% at 20 min and an *ee* of 60%.[34] The higher rigidity and bulkiness of the complexes in this paper probably gives a more definite chiral environment, which accounts for the better enantioselectivities obtained.

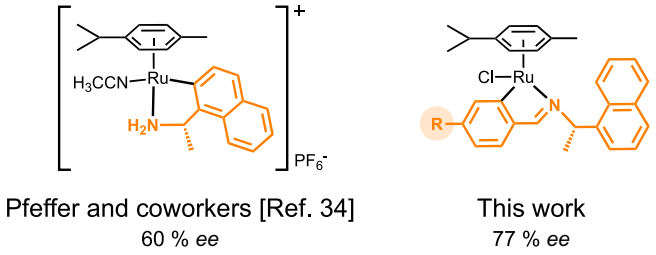

FIGURE 14 Chiral cycloruthenated catalytic precursors for the enantioselective reduction of acetophenone.

3 | CONCLUSIONS

This paper has demonstrated that *N*-(benzylidene)benzylamines are excellent cyclometallating ligands for Ru (II)-arene complexes under very mild conditions, affording regioselectively the *endo* derivative regardless of the substitution at the aromatic ring of the benzylidene moiety of the ligands. This result can be useful to design new, more efficient C—H bond functionalization processes catalysed by ruthenium compounds. Besides this, it has been shown that the obtained *endo*-cycloruthenated derivatives are very active precursors in the reduction by transfer hydrogenation of ketones and that the enantiopure derivatives **C6** and **C7** are stereoselective, despite containing the chiral fragment outside of the metallacycle. The robustness of the complexes and the large diversity of chiral imines that can be prepared should allow for an easy access to a wide range of chiral cycloruthenated compounds to be applied in transfer hydrogenation,[34] and other catalytic reactions,[39] contemplating even biological applications.[1] Studies in all

of these applications are in due course and will hopefully be reported in future publications.

4 | EXPERIMENTAL PART

4.1 | General methods

NMR spectra were recorded in $CDCl_3$ at 298 K with 400 or 500 MHz spectrometers. Chemical shifts are given in δ values (ppm) relative to $SiMe_4$ and coupling constants are given in Hz. The IR spectra were recorded in an ATR spectrophotometer, and the most important bands are given in cm^{-1}. High-resolution mass spectrometry (HRMS) analyses were performed with electrospray ionisation (ESI). ESI (+) spectra were acquired on a mass-selective detector–time-of-flight (MSD–TOF) instrument using an H_2O:CH_3CN (1:1, v/v) eluent mixture at a potential of 175 V. GC analyses to determine conversions and enantioselectivities were carried out on a FID-detector gas chromatograph equipped with a 30 m Chiraldex β-DM column. Examples of chromatograms are given in Figure **S2** (page S26). The imines **L1–L7** were prepared following the procedure described in previous reports.[35,36]

4.2 | Ruthenium complexes

4.2.1 | Synthesis of C1

Imine **L1** (115 mg, 0.50 mmol) was reacted with the dinuclear complex $[RuCl(\mu\text{-}Cl)(\eta^6\text{-}p\text{-cymene})]_2$ (153 mg, 0.25 mmol) at room temperature in 10 mL of methanol for 4 h in the presence of an excess of potassium acetate (98 mg, 1.0 mmol). The precipitate obtained was filtered and dried to obtain an orange solid, **C1**. The product was purified by recrystallisation in dichloromethane/diethyl ether. Yield: 59% (146 mg).

^{1}H NMR (400 MHz): 0.8 (doublet, J = 6.9, CH_3iPr, 3H), 1.0 (doublet, J = 6.9, CH_3iPr, 3H), 2.0 (singlet, CH_3[*p*-cymene], 3H), 2.4 (heptuplet, J = 6.9, CHiPr, 1H), 4.6 (doublet, J = 5.9, p-cymene, 1H), 4.7 (doublet, J = 5.9, p-cymene, 1H), 5.2–5.3 (multiplet, CH_2N, 2H), 5.4 (doublet, J = 5.9, p-cymene, 1H), 5.5 (doublet, J = 5.9, p-cymene, 1H), 6.9 (doublet, J = 8.1, 2.0, aryl, 1H), 7.3 (doublet, J = 8.0, 1H), 7.3–7.5 (multiplet, aryl, 5H), 7.9 (br, HC=N, 1H), 8.1 (doublet, J = 2.0, aryl, 1H). **^{13}C{^{1}H} NMR (125 MHz):** 18.9 (singlet, CH_3, 1C), 21.3 (singlet, CH_3, 1C), 23.1 (singlet, CH_3, 1C), 30.9 (singlet, CH [iPr], 1C), 68.9 (singlet, CH_2N, 1C), 79.7 (singlet, p-cymene, 1C), 80.6 (singlet, p-cymene, 1C), 90.1 (singlet, p-cymene, 1C), 90.9 (singlet, p-cymene, 1C), 102.6 (singlet, p-cymene, 1C), 103.3 (singlet, p-cymene, 1C), 122.0–144.0 (multiplet, aryl, 11C), 171.8 (singlet, HC=N, 1C), 190.5 (singlet, C–Ru, 1C). **IR**, ν = 581, 722, 755, 811, 864, 1035, 1522, 1603, 2909, 2961, 3054. **HRMS (ESI):** m/z found (calc.) for $C_{24}H_{25}ClNRu^+$ ($[M - Cl]^+$); 464.0715 (464.0713).

4.2.2 | Synthesis of C2

Cycloruthenated compound **C2** was prepared from imine **L2** (105 mg, 0.54 mmol) following the same experimental procedure described for **C1**. Yield 135 mg (54%).

^{1}H NMR (400 MHz): 0.7 (doublet, J = 6.9, CH_3iPr, 3H), 1.0 (doublet, J = 6.9, CH_3iPr, 3H), 2.0 (singlet, CH_3[*p*-cymene], 3H), 2.4 (heptuplet, J = 6.9, CHiPr, 1H), 4.5 (doublet, J = 5.9, p-cymene, 1H), 4.6 (doublet, J = 5.9, p-cymene, 1H), 5.2–5.4 (multiplet, CH_2N, 2H), 5.4 (doublet, J = 5.9, p-cymene, 1H), 5.5 (doublet, J = 5.9, p-cymene, 1H), 6.9 (triplet, J = 7.4, aryl, 1H), 7.1 (triplet, J = 7.4, aryl, 1H), 7.3–7.5 (multiplet, aryl, 6H), 7.9 (singlet, HC=N, 1H), 8.2 (doublet, J = 7.6, aryl, 1H). **^{13}C{^{1}H} NMR (125 MHz):** 18.9 (singlet, CH_3, 1C), 21.3 (singlet, CH_3, 1C), 23.1 (singlet, CH_3, 1C), 30.8 (singlet, CH [iPr], 1C), 68.8 (singlet, CH_2N, 1C), 79.0 (singlet, p-cymene, 1C), 80.1 (singlet, p-cymene, 1C), 90.0 (singlet, p-cymene, 1C), 90.8 (singlet, p-cymene, 1C), 102.3 (singlet, p-cymene, 1C), 102.7 (singlet, p-cymene, 1C), 122.2–145.2 (multiplet, aryl, 11C), 172.7 (singlet, HC=N, 1C), 189.1 (singlet, C–Ru, 1C). **IR**, ν = 699, 728, 745, 858, 1541, 1601, 2908, 2958, 3030. **HRMS (ESI)**: m/z found (calc.) for $C_{24}H_{26}NRu^+$ ($[M - Cl]^+$) 430.1114 (430.1103).

4.2.3 | Synthesis of C3

Cycloruthenated compound **C3** was prepared from imine **L3** (118 mg, 0.50 mmol) following the same experimental procedure described for **C1**. Yield 86 mg (35%).

^{1}H NMR (400 MHz): 0.7 (doublet, J = 6.9, CH_3iPr, 3H), 1.0 (doublet, J = 6.9, CH_3iPr, 3H), 2.0 (singlet, CH_3, 3H), 2.4 (heptuplet, J = 7.0, CHiPr, 1H), 4.7 (doublet, J = 6.0, p-cymene, 1H), 4.8 (doublet, J = 6.0, p-cymene, 1H), 5.3–5.4 (multiplet, CH_2N, 2H), 5.5 (doublet, J = 6.0, p-cymene, 1H), 5.7 (doublet, J = 6.4, p-cymene, 1H), 7.3–7.5 (multiplet, aryl, 5H), 7.5 (doublet, J = 8.30, aryl, 1H), 7.8 (doublet, J = 8.3, 2.2, aryl, 1H), 8.0 (singlet, HC=N, 1H), 8.9 (doublet, J = 2.2, aryl, 1H). **^{13}C{^{1}H} (125 MHz):** 18,9 (singlet, CH_3, 1C), 21.3 (singlet, CH_3, 1C), 23.2 (singlet, CH_3, 1C), 31.0 (singlet, CH [iPr], 1C), 69.6 (singlet, CH_2N, 1C), 80.3 (singlet, p-cymene, 1C), 81.4 (singlet, p-cymene, 1C), 90.6 (singlet, p-cymene, 1C), 91.4 (singlet,

p-cymene, 1C), 103.3 (singlet, p-cymene, 1C), 104.2 (singlet, p-cymene, 1C), 117.0–151.0 (multiplet, aryl, 11C), 171.4 (singlet, HC=N, 1C), 189.9 (singlet, C–Ru, 1C). **IR**, ν = 711, 746, 843, 1304, 1371, 1442, 1507, 2965, 3055. **HRMS (ESI):** m/z found (calc.) for $C_{24}H_{25}N_2O_2Ru^+$ ($[M - Cl]^+$) 475.0967 (475.0954).

4.2.4 | Synthesis of C4

Cycloruthenated compound **C4** was prepared from imine **L4** (112 mg, 0.54 mmol) following the same experimental procedure described for **C1**. Yield 157 mg (63%).

^{1}H NMR (400 MHz): 0.7 (doublet, 3H, J = 6.9, CH_3iPr), 1.0 (doublet, J = 6.9, CH_3iPr, 3H), 2.4 (heptuplet, J = 7.0, CHiPr, 1H), 4.5 (doublet, J = 5.9, p-cymene, 1H), 4.6 (doublet, J = 5.7, p-cymene, 1H), 5.2–5.3 (multiplet, CH_2N, 2H), 5.4 (doublet, J = 6.3, p-cymene, 1H), 5.5 (doublet, J = 5.9, p-cymene, 1H), 6.6 (triplet of doublets, J = 8.8, 2.3, aryl, 1H), 7.3–7.5 (multiplet, aryl, 6H), 7.8 (doublet of doublets, J = 9.2, 2.5, aryl, 1H), 7.9 (singlet, HC=N, 1H). **^{13}C {^{1}H} (125 MHz):** 18.9 (singlet, CH_3, 1C), 21.3 (singlet, CH_3, 1C), 23.1 (singlet, CH_3, 1C), 30.8 (singlet, CH [iPr], 1C), 68.7 (singlet, CH_2N, 1C), 79.4 (singlet, p-cymene, 1C), 80.6 (singlet, p-cymene, 1C), 90.0 (singlet, p-cymene, 1C), 90.8 (singlet, p-cymene, 1C), 102.5 (singlet, p-cymene, 1C), 103.1 (singlet, p-cymene,1C), 110.0–163.2 (multiplet, aryl, 11C), 171.5 (singlet, HC=N, 1C), 192.2 (singlet, C–Ru, 1C). **^{19}F{^{1}H} NMR (376.5 MHz):** −109.3 (s). **IR**, ν = 587, 728, 745, 810, 858, 1233, 1438, 1551, 1607, 2915, 2958, 3044. **HRMS (ESI):** m/z found (calc.) for $C_{24}H_{25}FNRu^+$ ($[M - Cl]^+$) 448.1011 (448.1009).

4.2.5 | Synthesis of C5

Cycloruthenated compound **C5** was prepared from imine **L5** (114 mg, 0.51 mmol) following the same experimental procedure described for **C1**. Yield 147 mg (59%).

^{1}H NMR (400 MHz): 0.7 (doublet, J = 6.9, CH_3iPr, 3H), 1.0 (doublet, J = 6.9, CH_3iPr, 3H), 2.0 (singlet, CH_3, 3H), 2.4 (heptuplet, J = 6.9, CHiPr, 1H), 3.9 (singlet, OMe, 3H), 4.55 (doublet, J = 5.9, p-cymene, 1H), 4.6 (doublet, J = 5.9, p-cymene, 1H), 5.2–5.3 (multiplet, CH_2N, 2H), 5.4 (doublet, J = 5.9, p-cymene, 1H), 5.5 (doublet, J = 5.8, p-cymene, 1H), 6.5 (doublet of doublets, J = 8.3, 2.4, aryl, 1H), 7.3–7.5 (multiplet, aryl, 6H), 7.8 (doublet, J = 2.4, aryl, 1H), 7.9 (br, HC=N, 1H). **^{13}C{^{1}H} (125 MHz):** 18.9 (singlet, CH_3, 1C), 21.3 (singlet, CH_3, 1C), 23.2 (singlet, CH_3, 1C), 30.8 (singlet, CH [iPr], 1C), 55.2 (singlet, MeO, 1C), 68.5 (singlet, CH_2N, 1C), 78.9 (singlet, p-cymene, 1C), 80.1 (singlet, p-cymene, 1C), 89.8 (singlet, p-cymene, 1C), 90.6 (singlet, p-cymene, 1C), 102.0 (singlet, p-cymene, 1C), 102.6 (singlet, p-cymene, 1C), 107.0–160.0 (multiplet, aryl, 11C), 171.5 (singlet, HC=N, 1C), 191.2 (singlet, C–Ru, 1C). **IR,** ν = 708, 756, 850, 1035, 1211, 1536, 1581, 2831, 2956, 3044. **HRMS (ESI):** m/z found (calc.) for $C_{25}H_{28}NORu^+$ ($[M - Cl]^+$) 460.1213 (460.1208).

4.2.6 | Synthesis of C6

Imine **L6** (157 mg, 0.54 mmol) reacted with the dinuclear derivative $[RuCl(\mu\text{-}Cl)(\eta^6\text{-}p\text{-cymene})]_2$ (163 mg, 0.27 mmol) at room temperature in 10 mL of methanol overnight in the presence of excess potassium acetate (105 mg, 1.10 mmol). The precipitate obtained was filtered and dried to obtain an orange solid, **C6**. The product was purified by recrystallisation in dichloromethane/diethyl ether. Yield: 33% (98 mg).

^{1}H NMR (400 MHz): 0.6 (doublet, J = 6.9, CH_3iPr, 3H), 1.0 (doublet, J = 6.9, CH_3iPr, 3H), 1.9 (doublet, J = 6.9, NCHMe, 3H), 2.0 (singlet, CH_3, 3H), 2.4 (heptuplet, J = 6.9, CHiPr, 1H), 4.0 (doublet, J = 5.8, p-cymene, 1H), 4.4 (doublet, J = 6.1, p-cymene, 1H), 4.9 (doublet, J = 6.1, p-cymene, 1H), 5.3 (doublet, J = 6.1, p-cymene,1-H), 6.4 (q, J = 7.0, NCHMe, 1H), 6.9 (doublet of doublets, J = 8.0, 2.0, aryl, 1H), 7.3 (doublet, J = 8.0, aryl, 1H), 7.4 (doublet, J = 8.0, aryl, 1H), 7.5 (multiplet, aryl, 1H), 7.6 (triplet of doublets, J = 8.1, 1.3, aryl, 1H), 7.7 (triplet of doublets, J = 8.4, 1.5, aryl, 1H), 7.9 (doublet, J = 8.1, aryl, 1H), 8.0 (doublet, J = 8.0, aryl, 1H), 8.1 (doublet, J = 2.0, aryl, 1H), 8.2 (doublet, J = 8.7, aryl, 1H), 8.3 (singlet, HC=N, 1H). **^{13}C{^{1}H} NMR (125 MHz):** 18.8 (singlet, CH_3, 1C), 20.5 (singlet, CH_3, 1C), 23.5 (singlet, CH_3, 1C), 23.9 (singlet, CH_3, 1C), 30.7 (singlet, CH [iPr], 1C), 67.7 (singlet, NCHMe, 1C), 76.6 (singlet, p-cymene, 1C), 81.4 (singlet, p-cymene, 1C), 89.2 (singlet, p-cymene, 1C), 92.8 (singlet, p-cymene, 1C), 102.52 (singlet, p-cymene, 1C), 104.4 (singlet, p-cymene, 1C), 122–144 (multiplet, aryl, 15C), 169.3 (singlet, HC=N, 1C), 190.5 (singlet, C–Ru, 1C). **IR,** ν = 786, 804, 1065, 1224, 1526, 1564, 1597, 2959, 3059. **HRMS (ESI):** m/z found (calc.) for $C_{29}H_{29}ClNRu^+$ ($[M - Cl]^+$) 528.1035 (528.1026).

4.2.7 | Synthesis of C7

Cycloruthenated compound **C7** was prepared from imine **L7** (147 mg, 0.57 mmol). following the same experimental procedure described for **C6**. Yield 221 mg (74%).

^{1}H NMR (400 MHz): 0.9 (doublet, J = 7.0, CH_3iPr, 3H), 1.9 (doublet, J = 6.9, NCHMe, 3H), 2.0 (singlet, CH_3, 3H), 2.4 (heptuplet, J = 7.0, CHiPr, 1H), 4.1 (doublet, J = 5.8, p-cymene, 1H), 4.4 (doublet, J = 6.1, p-

cymene, 1H), 4.9 (doublet, J = 6.1, p-cymene, 1H), 5.2 (doublet, J = 6.1, p-cymene, 1H), 6.5 (q, J = 6.8, NCHMe, 1H), 7.0 (triplet of doublets, J = 7.4, 1.5, aryl, 1H), 7.1 (triplet of doublets, J = 7.4, 1.5, aryl, 1H), 7.3 (doublet, J = 8.0, aryl, 1H), 7.4–7.5 (multiplet, aryl, 2H), 7.6–7.7 (multiplet, aryl, 1H), 7.7–7.8 (multiplet, aryl, 1H), 7.9 (doublet, J = 7.9, aryl, 1H), 8.0 (doublet, J = 8.1, aryl, 1H), 8.1 (doublet, J = 8.0, aryl, 1H), 8.2 (doublet, J = 8.7, aryl, 1H), 8.3 (singlet, HC=N, 1H). **^{13}C{1H} NMR (125 MHz):** 18.8 (singlet, CH_3, 1C), 20.5 (singlet, CH_3, 1C), 23.5 (singlet, CH_3, 1C), 23.8 (singlet, CH_3, 1C), 30.6 (singlet, CH [iPr], 1C), 67.5 (singlet, NCHMe, 1C), 76.0 (singlet, p-cymene, 1C), 80.9 (singlet, p-cymene, 1C), 89.1 (singlet, p-cymene, 1C), 92.8 (singlet, p-cymene, 1C), 102.3 (singlet, p-cymene, 1C), 103.9 (singlet, p-cymene, 1C), 122.2–145.7 (multiplet, aryl, 15C), 170.2 (singlet, HC=N, 1C), 189.0 (singlet, C–Ru, 1C). **IR**, ν = 781, 802, 1032, 1222, 1541, 1591, 2928, 3041. **HRMS (ESI):** m/z found (calc.) for $C_{29}H_{30}NRu^+$ ([M − Cl]$^+$) 494.1416 (494.1411).

4.3 | Catalytic experiments

4.3.1 | General procedure for Ru-catalysed transfer hydrogenation

Transfer hydrogenation runs were performed in 100 mL Schlenk flasks. In a purified dinitrogen atmosphere, the flask was charged with 0.02 mmol (0.5 mol%) of the ruthenium precatalyst and 0.10 mmol of potassium *tert*-butoxide. After purging the system, 25 mL of isopropanol were added, and the solution was stirred for 15 min at reflux (82°C) to activate the precatalyst. At this point, 4.0 mmol of acetophenone or benzophenone were added. At regular intervals of time, aliquots were extracted and analysed by GC.

4.4 | Associated content

Supporting Information: ^{1}H and ^{13}C{^{1}H} NMR spectra of the compounds **C1–C7** (pages S1–S24), graphics of a catalytic run with **C6** (Figure **S1**, page S25) and examples of GC traces (Figure **S2**, page S26). CCDC 2222768–2222774 contain supplementary crystallographic data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

AUTHOR CONTRIBUTIONS

Albert Martinez-Segura: Formal analysis; investigation; visualization; writing—original draft; writing—review and editing. **Javier Eusamio:** Data curation; investigation; validation; writing—review and editing. **Yaiza M. Medina:** Investigation; validation. **Katherine Ariz:** Investigation. **Albert Gutierrez:** Investigation; validation. **Joan Albert:** Conceptualization; writing—review and editing. **Jaume Granell:** Conceptualization; project administration; resources; writing—original draft. **Merce Font-Bardia:** Formal analysis; investigation. **Arnald Grabulosa:** Funding acquisition; methodology; project administration; resources; supervision; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

There are no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the Supporting Information of this article.

ORCID

Albert Martinez-Segura https://orcid.org/0000-0001-5385-8797
Javier Eusamio https://orcid.org/0000-0002-2348-2941
Yaiza M. Medina https://orcid.org/0000-0002-6156-0787
Katherine Ariz https://orcid.org/0000-0002-3394-1961
Albert Gutiérrez https://orcid.org/0000-0003-4724-8356
Joan Albert https://orcid.org/0000-0002-8256-2650
Jaume Granell https://orcid.org/0000-0001-6360-7043
Mercè Font-Bardia https://orcid.org/0000-0002-7892-8744
Arnald Grabulosa https://orcid.org/0000-0003-0198-4139

REFERENCES

[1] J.-P. Djukic, J.-B. Sortais, L. Barloy, M. Pfeffer, *Eur. J. Inorg. Chem.* **2009**, *2009*, 817.
[2] P. B. Arockiam, C. Bruneau, P. H. Dixneuf, *Chem. Rev.* **2012**, *112*, 5879.
[3] S. D. Drouin, D. Amoroso, G. P. A. Yap, D. E. Fogg, *Organometallics* **2002**, *21*, 1042.
[4] M. E. van der Boom, D. Milstein, *Chem. Rev.* **2003**, *103*, 1759.
[5] A. Hijazi, K. Parkhomenko, J.-P. Djukic, A. Chemmi, M. Pfeffer, *Adv. Synth. Catal.* **2008**, *350*, 1493.
[6] G. C. Vougioukalakis, R. H. Grubbs, *Chem. Rev.* **2010**, *110*, 1746.
[7] C. Gaiddon, M. Pfeffer, *Eur. J. Inorg. Chem.* **2017**, *2017*, 1639.
[8] P. G. Bomben, K. C. D. Robson, B. D. Koivisto, C. P. Berlinguette, *Coord. Chem. Rev.* **2012**, *256*, 1438.

[9] A. D. Ryabov, V. S. Sukharev, L. Alexandrova, R. Le Lagadec, M. Pfeffer, *Inorg. Chem.* **2001**, *40*, 6529.
[10] A. D. Ryabov, R. Le Lagadec, H. Estevez, R. A. Toscano, S. Hernandez, L. Alexandrova, V. S. Kurova, A. Fischer, C. Sirlin, M. Pfeffer, *Inorg. Chem.* **2005**, *44*, 1626.
[11] N. Kuhl, M. N. Hopkinson, J. Wencel-Delord, F. Glorius, *Angew. Chem., Int. Ed.* **2012**, *51*, 10236.
[12] N. Hofmann, L. Ackermann, *J. Am. Chem. Soc.* **2013**, *135*, 5877.
[13] G. C. Martin, J. M. Boncella, *Organometallics* **1989**, *8*, 2968.
[14] J. Pérez, V. Riera, A. Rodríguez, D. Miguel, *Organometallics* **2002**, *21*, 5437.
[15] L. Cuesta, I. Maluenda, T. Soler, R. Navarro, E. P. Urriolabeitia, *Inorg. Chem.* **2011**, *50*, 37.
[16] D. L. Davies, O. Al-Duaij, J. Fawcett, M. Giardiello, S. T. Hilton, D. R. Russell, *Dalton Trans.* **2003**, 4132.
[17] B. Li, C. Darcel, T. Roisnel, P. H. Dixneuf, *J. Organomet. Chem.* **2015**, *793*, 200.
[18] Z.-Y. Li, H. H. C. Lakmal, X. Qian, Z. Zhu, B. Donnadieu, S. J. McClain, X. Xu, X. Cui, *J. Am. Chem. Soc.* **2019**, *141*, 15730.
[19] J. Albert, M. Gomez, J. Granell, J. Sales, X. Solans, *Organometallics* **1990**, *9*, 1405.
[20] J. Albert, R. M. Ceder, M. Gomez, J. Granell, J. Sales, *Organometallics* **1992**, *11*, 1536.
[21] J. Granell, M. Martínez, *Dalton Trans.* **2012**, *41*, 11243.
[22] J.-B. Sortais, N. Pannetier, A. Holuigue, L. Barloy, C. Sirlin, M. Pfeffer, N. Kyritsakas, *Organometallics* **2007**, *26*, 1856.
[23] P. Steenwinkel, S. L. James, R. A. Gossage, D. M. Grove, H. Kooijman, W. J. J. Smeets, A. L. Spek, G. van Koten, *Organometallics* **1998**, *17*, 4680.
[24] R. Le Lagadec, L. Rubio, L. Alexandrova, R. A. Toscano, E. V. Ivanova, R. Meškys, V. Laurinavičius, M. Pfeffer, A. D. Ryabov, *J. Organomet. Chem.* **2004**, *689*, 4820.
[25] V. Martínez Cornejo, J. Olvera Mancilla, S. López Morales, J. A. Oviedo Fortino, S. Hernández-Ortega, L. Alexandrova, R. Le Lagadec, *J. Organomet. Chem.* **2015**, *799–800*, 299.
[26] W. A. O. Altalhi, A. I. McKay, B. Spyrou, A. J. Canty, P. S. Donnelly, R. A. J. O'Hair, *J. Organomet. Chem.* **2021**, *950*, 121973.
[27] D. Wang, D. Astruc, *Chem. Rev.* **2015**, *115*, 6621.
[28] A. Grabulosa, A. Mannu, E. Alberico, S. Denurra, S. Gladiali, G. Muller, *J. Mol. Catal. A: Chem.* **2012**, *363–364*, 49.
[29] A. Grabulosa, A. Mannu, A. Mezzetti, G. Muller, *J. Organomet. Chem.* **2012**, *696*, 4221.
[30] S. Gladiali, E. Alberico, *Chem. Soc. Rev.* **2006**, *35*, 226.
[31] H. C. L. Abbenhuis, M. Pfeffer, J. P. Sutter, A. de Cian, J. Fischer, H. L. Ji, J. H. Nelson, *Organometallics* **1993**, *12*, 4464.
[32] L. Leyva, C. Sirlin, L. Rubio, C. Franco, R. Le Lagadec, J. Spencer, P. Bischoff, C. Gaiddon, J.-P. Loeffler, M. Pfeffer, *Eur. J. Inorg. Chem.* **2007**, *2007*, 3055.
[33] N. Gül, J. H. Nelson, *Polyhedron* **1999**, *18*, 1835.
[34] J.-B. Sortais, L. Barloy, C. Sirlin, A. H. M. de Vries, J. G. de Vries, M. Pfeffer, *Pure Appl. Chem.* **2006**, *78*, 457.
[35] J. Albert, J. M. Cadena, J. R. Granell, X. Solans, M. F. Bardia, *Tetrahedron: Asymmetry* **2000**, *11*, 1943.
[36] J. Albert, J. M. Cadena, J. Granell, X. Solans, M. Font-Bardia, *J. Organomet. Chem.* **2004**, *689*, 4889.
[37] It should be noted that Cui et al. (Ref. 18) previously reported the crystal structure of **C6** containing one molecule of dichloromethane per unit cell in contrast to our structure, which contains one molecule of methanol. As expected, there are no significant differences in the values of bond distances and angles of both X-ray determinations of **C6**.
[38] H. D. Flack, G. Bernardinelli, *Chirality* **2008**, *20*, 681.
[39] M. T. Findlay, P. Domingo-Legarda, G. McArthur, A. Yen, I. Larrosa, *Chem. Sci.* **2022**, *13*, 3335.

SUPPORTING INFORMATION

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