CHEMISTRY
A EUROPEAN JOURNAL

DOI: 10.1002/chem.200700873

An Investigation into the Allylic Imidate Rearrangement of Trichloroacetimidates Catalysed by Cobalt Oxazoline Palladacycles

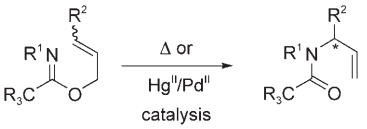
Hiroshi Nomura and Christopher J. Richards*[a]

Abstract: Dimeric palladacycles, di-μ-X-bis[{η^5-(*S*)-(*$_p$R*)-2-[2′-(4′-methylethyl)oxazolinyl]cyclopentadienyl,1-*C*,3′-*N*}(η^4-tetraphenylcyclobutadiene)cobalt]dipalladium (COP-X), containing bridging groups X = OAc, Cl, Br, I, O_2CCF_3, *p*-$O_2CC_6H_4F$, were synthesised and compared as catalysts for the asymmetric allylic imidate rearrangement of (*E*)-$Cl_3CC(=NH)OCH_2CH=CHR$ with R = *n*Pr. The enantiomeric excess of the product (*S*)-$Cl_3CC(=O)NHCHRCH=CH_2$ was essentially invariant of X (93–96%) and the yield increased in the sequence I < *p*-$O_2CC_6H_4F$ < OAc < $O_2CCF_3 \approx Br \approx Cl$. With X = Cl (COP-Cl), the catalyst loading was reduced to 0.25 mol% (CH_3CN/70 °C/48 h) and these conditions applied to various trichloroacetimidates (R = *n*Pr, Me, CH_2Ph, $CH_2CH=CH_2$, $CH_2OTBDMS$) to give the corresponding (*S*)-trichloroacetamides (68–88% yield, 84–94% *ee*; *ee* = enantiomeric excess). Addition of COP-Cl to triphenylphosphinobenzoyl NovaGel AM resin gave a recyclable catalyst in which the *ee* was maintained over three cycles (89–94%). Catalysis with COP-OAc displayed a small positive non-linear effect. The factors responsible for the activity of COP-X are discussed.

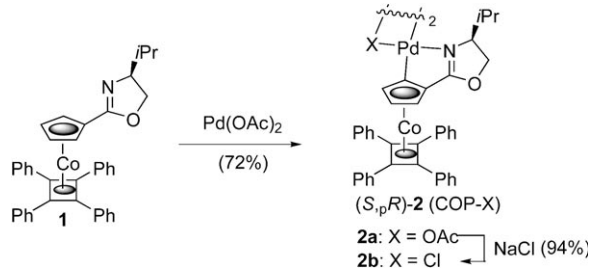
Keywords: allylic compounds · asymmetric catalysis · ligand effects · metallocenes · palladium

Introduction

The allylic imidate rearrangement was first reported by Overman in 1974 as a method for the conversion of allylic alcohols into higher value allylic amides and amines (Scheme 1).[1] This [3.3]-sigmatropic rearrangement was initially carried out by thermolysis of trichloroacetimidic esters of primary and secondary alcohols at a temperature of 140 °C. The resulting regio- and stereoselectivities observed, together with the measured activation parameters, were consistent with a concerted pericyclic process. Alternatively, addition of mercury(II) salts resulted in rate accelerations of up to 10^{12} for a reaction formulated as proceeding by means of a two-step iminomercuration–deoxymercuration mechanism. The discovery that palladium(II) complexes are superior catalysts for this reaction[2] led to the development of chiral non-racemic palladium(II) species as catalysts for the asymmetric allylic imidate rearrangement.[3] A major breakthrough in the practicality of this process was the discovery that cobalt oxazoline palladacycle **2b** (COP-Cl),[4] readily derived from **1** by diastereoselective palladation and ligand exchange (Scheme 2),[5] gave high enantioselectivities (typically > 90% *ee*; *ee* = enantiomeric excess) for the rearrange-



Scheme 1. The allylic imidate rearrangement.



Scheme 2. Diastereoselective synthesis of cobalt oxazoline palladacycles.

[a] H. Nomura, Dr. C. J. Richards
School of Biological and Chemical Sciences
Queen Mary, University of London
Mile End Road, London, E1 4NS (UK)
Fax: (+44) 207-882-7427
E-mail: c.j.richards@qmul.ac.uk

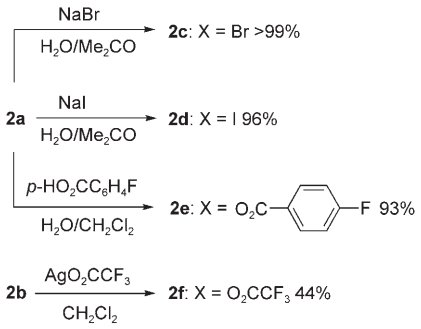
Supporting information for this article is available on the WWW under http://www.chemeurj.org/ or from the author.

ment of both (*E*)- and (*Z*)-trifluoroacetimidates (R = F, R^1 = *p*-$MeOC_6H_4$).[6] Crucially, and in contrast to previous applications of chiral palladacycle catalysts to the allylic imidate rearrangement, the halide-bridged palladacycle **2b** does not require activation by addition of one equivalent of silver trifluoroacetate. A subsequent report by Anderson and Overman that **2b** also catalyses the rearrangement of trichloroacetimidates (R = Cl, R^1 = H) with high enantioselectivies[7,8] is especially significant due to the relative ease with which the product trichloroacetamide may be hydrolysed to release an allylic amine. Palladcycles **2a** and **2b** have also been successfully applied as enantioselective catalysts of related reactions,[9] and **2a** as a reagent in enantioselective transcyclopalladation.[10]

In light of the observed differences in reactivity of these palladacycles as a function of the bridging ligand X, we were curious to investigate the effectiveness of other derivatives with the aim of minimising the catalyst loading of asymmetric trichloroacetimidate rearrangement. In addition, we anticipated that this and related studies may shed light on the factors responsible for catalyst activity. Our investigations to this effect are reported in this paper.[11]

Results and Discussion

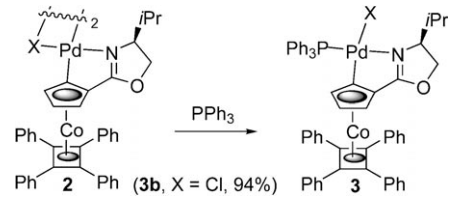
Synthesis of COP-X derivatives: A variety of COP-X derivatives were readily synthesised from **2a** and **2b** (Scheme 3). Bromide and iodide-containing compounds, **2c** and **2d**, respectively, were obtained in an analogous fashion to **2b** by simply adding the acetate-bridged complex **2a** to an aqueous acetone solution of the appropriate sodium halide. After stirring at room-temperature, the products were isolated by filtration. In common with chloride **2b**, the bromide and iodide-bridged complexes were obtained as mixtures of *cis*/*trans* isomers with respect to the alignment of the two carbon–nitrogen palladacycle chelates about the central (μ-$Cl)_2Pd_2$ moiety.[12] The *p*-fluorobenzoate derivative **2e** was obtained by dissolving **2a** and one equivalent of *p*-fluorobenzoic acid in dichloromethane, and driving the ligand metathesis reaction towards completion by repeatedly washing with water to remove the more water soluble acetic acid.



Scheme 3. Synthesis of additional derivatives of COP-X.

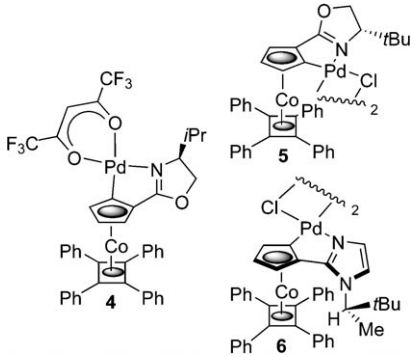
The pure complex **2e** was then obtained by recrystallisation. Finally the trifluoroacetate derivative **2f** was obtained by addition of one equivalent of silver trifluoroacetate to **2b** followed by filtration to remove the resulting precipitate of silver chloride. Although this[6] and related trifluoroacetate-bridged oxazoline-based palladacycles[3f,k] have previously been generated and used in situ, we found the isolated complex to be an air-stable non-hygroscopic complex, in common with all the related COP-X derivatives.

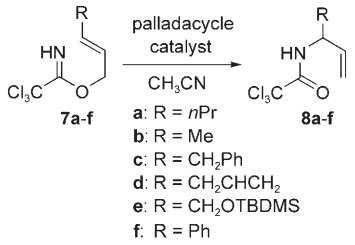
In addition to these palladium dimers, we also synthesised a monomeric complex (Scheme 4). Addition of one equivalent of triphenylphosphine to **2b** resulted in the rapid and essentially quantitative formation of adduct **3b**. The formulation of this as containing the ligated triphenylphosphine *cis* to the carbon–palladium bond is made by analogy to related non-metallocene aryl analogues.[13] In addition, the chemical shift of one of the cyclopentadienyl hydrogens in the ^{1}H NMR spectrum is smaller by approximately $\delta = 1$–1.5 ppm compared to the corresponding signal for **2b**. This difference is due to the proximity of the *cis*-coordinated phosphine to the hydrogen alpha to palladium, the upfield shift resulting from the positive anisotropic effect of the adjacent phenyl groups.



Scheme 4. Synthesis of palladacycle–triphenylphosphine adducts **3**.

Application of COP-X derivatives to the allylic imidate rearrangement: To compare the effectiveness of these palladacycles as allylic imidate rearrangement catalysts, complexes **2a–f** and **3b**, in addition to the related palladacycles **4**,[8b] **5**[14] and **6**,[15] were applied as catalysts for the rearrangement of trichloroacetimidate **7a** (R = *n*Pr, Scheme 5). Acetonitrile was chosen as the solvent for this investigation for two rea-





Scheme 5. Palladacycle-catalysed rearrangement of trichloroacetimidates **7**.

sons. Firstly, the boiling point (82 °C) is higher than that of dichloromethane (40 °C), the solvent generally used for this transformation.[7,16] It was anticipated that a higher boiling point could help to shorten the reaction time when low catalyst loadings were employed. Secondly, it was reasoned that this coordinating solvent[17] would aid the stability of the palladacycle at higher reaction temperatures.

Initially the new and known palladacycles were compared by employing a catalyst loading of 0.5 mol % (i.e. 1 mol %/Pd) in acetonitrile at 50 °C for 24 h (Table 1). This revealed

Table 1. Catalysis of the rearrangement of trichloroacetimidate **7a** to amide **8a** (R = *n*Pr).[a]

Entry	Cat.	*t* [h]	Yield [%][b]	*ee* [%][c] (config.)[c]
1	**2a** (X = OAc)	24	61	94 (*S*)
2	**2b** (X = Cl)	24	72	93 (*S*)
3	**2c** (X = Br)	24	69	96 (*S*)
4	**2d** (X = I)	24	11	93 (*S*)
5	**2e** (X = *p*-$O_2CC_6H_4F$)	24	28	94 (*S*)
6	**2f** (X = O_2CCF_3)	24	70	93 (*S*)
7	**3b**[d]	48	33	92 (*S*)
8	**4**[d]	24	79	94 (*S*)
9	**5**	48	25	28 (*R*)
10	**6**	24	9	86 (*S*)

[a] Compound **7a** (2.6 mmol), catalyst (0.5 mol %), CH_3CN (1 mL), 50 °C. [b] Isolated yield after chromatography. [c] Determined by HPLC analysis. [d] 1 mol % catalyst.

a small difference in yield between the acetate **2a** and chloride **2b**-bridged palladacycles (entries 1 and 2). The bromide-bridged species **2c** (entry 3) was similar to **2b**, and both were superior to the corresponding iodide **2d** (entry 4) such that the relationship between the halogen and the percentage yield obtained is Cl ≈ Br > I. The *para*-fluorobenzoate-bridged species **2e** was relatively ineffective (entry 5), and the trifluoroacetate derivative **2f** gave a similar yield to both **2b** and **2c** (entry 6). This latter result was surprising in light of the previous requirement to convert chloride bridged oxazoline-based palladacycles into their trifluoroacetate congeners in order to achieve catalysis.[3f,k] The lower than expected yield obtained with **2f** may be a consequence of the relative insolubility of this catalyst under the conditions employed, as apart from **2f**, all of the other catalysts completely dissolved once the substrate allylic imidate (2.6 M) had been added to a solution/suspension of the palladacycle in acetonitrile. In this respect, the hexafluoroacetylacetonate derivative **4**, which had previously been synthesised to increase catalyst solubility,[8b] offered no particular advantage over its synthetic precursors, either **2a** or **2b** (entry 8). The triphenylphosphine adduct **3b** gave a significantly reduced yield despite a longer reaction time (entry 7). A notable feature of all these reactions is the consistently high enantiomeric excesses obtained (92–96 %), revealing that enantioselectivity is essentially independent of the other ligand(s) coordinated to the palladacycle C–N chelate.

Finally, the two related palladacycles **5** and **6** were tested for comparison by using the same conditions. The former, which contains the opposite configuration of planar chirality (S_pS-**5** compared to S_pR-**2b**) resulted in a low yield of the opposite enantiomer of amide **8a** (entry 9). That the planar chirality is important to the enantioselectivity displayed by **2b** is supported by the result obtained with **6**. This was only marginally less selective in catalysing the formation of the same enantiomer of product as **2b**, despite the remoteness of the element of central chirality from palladium. However the low yield obtained with **6** precluded further investigations with this palladacycle.

Having identified that catalyst **2b** can be successfully used in acetonitrile, we next examined lowering the catalyst loading to 0.25 mol % and compensating for this by increasing the reaction temperature (Table 2). Examination of the

Table 2. Optimisation of time and temperature for the rearrangement of trichloroacetimidate **7a** to amide **8a** (R = *n*Pr) catalysed by 0.25 mol % of **2b** (COP-Cl).[a]

Entry	*t* [h]	*T* [°C]	Yield [%][b]	*ee* [%][c] (config.)[c]
1	24	60	65	95 (*S*)
2	48	60	71	90 (*S*)
3	24	70	67	93 (*S*)
4	48	70	79	92 (*S*)
5	24	80	63[d]	89 (*S*)
6	48	80	85[d]	92 (*S*)

[a] Compound **7a** (2.6 mmol), **2b** (0.25 mol %), CH_3CN (1 mL). [b] Isolated yield after chromatography. [c] Determined by HPLC analysis. [d] Calculated yield based on mass recovery, but HPLC analysis revealed the presence of an unidentified impurity.

crude reaction mixture by ^{1}H NMR spectroscopy revealed the reaction to be incomplete after both 24 and 48 h at 60 °C (entries 1 and 2) and 24 h at 70 °C (entry 3), but that a reaction time of 48 h at 70 °C resulted in essentially complete conversion (entry 4) and a yield of 79 % after isolation by column chromatography. Increasing the temperature to 80 °C further increased the rate of conversion as determined by ^{1}H NMR spectroscopy, but resulted in a reduction in the isolated yield due to the formation of an unidentified by-product (entries 5 and 6). A notable feature of these results is the consistency of the enantiomer ratio of **8a** over the range of temperatures employed, revealing that the differences in free energy between the two transition states

($\Delta\Delta G^{\neq} = 2.17$ Kcal mol^{-1} at 70 °C) must be dominated by the entropy term $T\Delta\Delta S^{\neq}$.

The lower catalyst loading of 0.25 mol % was then applied to a variety of other trichloroacetimidates to determine the general usefulness of these new conditions (Table 3). Methyl

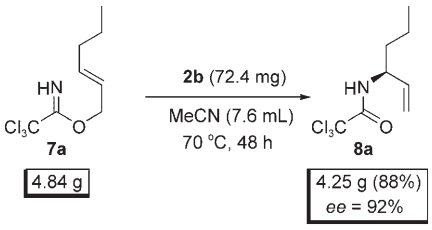
Table 3. Catalysis of the rearrangement in Scheme 5 by 0.25 mol % of **2b** (COP-Cl).[a]

Entry	Substrate (R)	*t* (h)	Product/yield [%][b]	*ee* [%] (config.)[c]
1	**7b** (R = Me)	48	**8b**/82	89 (*S*)[c]
2	**7c** (R = CH_2Ph)	48	**8c**/68	90 (*S*)[d]
3	**7d** (R = CH_2CHCH_2)[e]	72	**8d**/68	84 (*S*)[d]
4	**7e** (R = $CH_2OTBDMS$)	48	**8e**/72	94 (*S*)[c]
5	**7f** (R = Ph)[f]	96	**8f**/31	0
6	**9**	72	**8a**/21	67 (*R*)[c]

[a] Compound **7** or **9** (2.6 mmol), **2b** (0.25 mol %), CH_3CN (1 mL), 70 °C [b] Isolated yield after chromatography. [c] Determined by HPLC analysis. [d] Assigned by analogy. [e] Additional **2b** (0.5 mol %) added after 48 h and the reaction maintained at 70 °C for a further 24 h. [f] **2b** (0.5 mol % plus additional 0.5 mol % added after 48 h and the reaction maintained at 70 °C for a further 48 h).

(entry 1), benzyl (entry 2), allyl (entry 3) and protected hydroxymethyl (entry 4)-substituted trichloroacetimidates **7b**–**e** all gave the corresponding amides with enantioselectivities similar to, or just slightly less than, that obtained with **7a**. The additional double bond in substrate **7d** inhibited the reaction requiring the use of a higher catalyst loading. The phenyl-substituted trichloroacetimidate **7f** resulted in a low yield and no enantioselectivity (entry 5). It has been noted previously that a tertiary or phenyl substituent dramatically slows the reaction, as does the use of (*Z*)-trichloroacetimidates.[7] Although an example of the latter (**9**) gave (*R*)-**8a** in 67 % *ee* (entry 6), it is clear that the inherent lack of reactivity of these substrates could not be overcome.

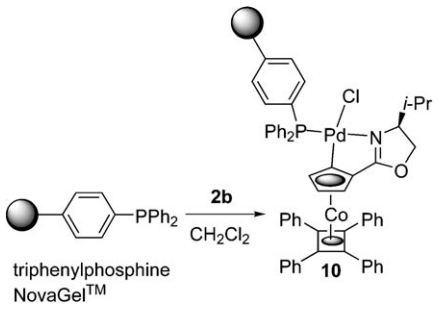
The applicability of the new conditions to a larger scale reaction was also examined (Scheme 6). Heating 4.84 g of



Scheme 6. Larger-scale rearrangement of **7a** with 0.25 mol % **2b** (COP-Cl).

7a with just 72.4 mg (i.e. 0.25 mol %) of COP-Cl **2b** led to the isolation of the product amide in 88 % yield and 92 % *ee*. Use of 0.25 mol % of COP-OAc **2a** with 4.73 g of **7a** resulted in a 62 % isolated yield and an 89 % *ee*. These results highlight the superior activity of the chloride-bridged palladacycle compared to the acetate analogue.

A solid-supported catalyst: On completion of this larger-scale reaction with COP-Cl **2b**, column chromatography was used to recover a mixture of yellow metallocene based compounds which contained a significant amount of **2b** (≈30 %). This prompted us to generate a solid-supported derivative with the potential to be more easily recycled and reused. Addition of triphenylphosphinobenzoyl NovaGel AM resin (0.4–0.7 mmol g^{-1})[18] (triphenylphosphine NovaGel) to **2b** in acetonitrile led to the isolation of **10**, the polymer supported analogue of the triphenylphosphine adduct **3b** (Scheme 7). The loading was determined by microanalysis to be approximately 0.6 mmol g^{-1}. As the catalytic activity of **3b** is somewhat less than that of **2b**, the catalysis potential of **10** for the rearrangement of trichloroacetimidate **7a** was tested with a loading of approximately 1.7 mol % of phosphine coordinated palladacycle monomer (Table 4). After heating at 50 °C for 48 h, the product **8a** was isolated



Scheme 7. Synthesis of a solid-supported palladacycle.

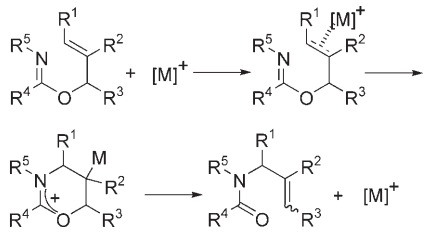
Table 4. Sequential application of **10** to the catalysed rearrangement of trichloroacetimidate **7a** to amide **8a** (R = *n*Pr).[a]

Run	*t* [h]	Yield [%][b]	*ee* [%] (config.)[c]
1	48	91	94 (*S*)
2	48	27	93 (*S*)
3	48	17	89 (*S*)

[a] Compound **7a** (2.6 mmol), **10** (0.120 g), CH_3CN (1 mL). [b] Isolated yield after chromatography. [c] Determined by HPLC analysis.

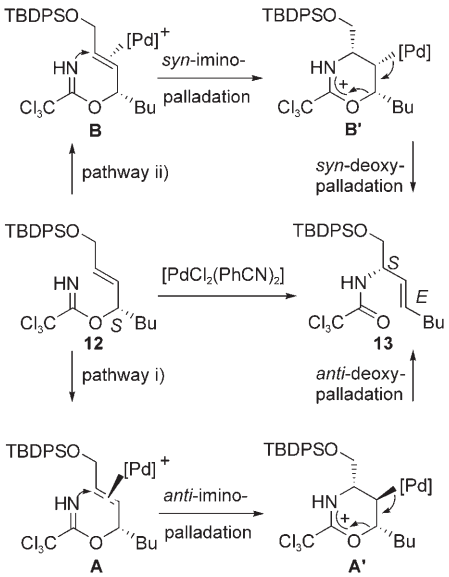
in 91 % yield and 94 % *ee* (entry 1). After filtering and washing the polymer it was again employed for the rearrangement of **7a** (entry 2), and although the yields of **8a** obtained in this and a subsequent run (entry 3) were rather low, the enantioselectivities obtained were consistently high. These results suggest that alternative modes of immobilisation, not involving deactivating palladium coordination, may lead to practical recyclable catalysts for the allylic imidate rearrangement and related reactions.

Rationalisation of reactivity trends: A mechanism for the palladium(II) and mercury(II)-catalysed rearrangement of allylic imidates has been proposed by Overman (Scheme 8).



Scheme 8. Cyclisation-induced rearrangement mechanism.

The evidence for cyclisation-induced rearrangement (CIR) catalysis in this and other [3,3] sigmatropic rearrangements has been reviewed[19] and followed its initial proposal by Henry as the mechanistic explanation of palladium acetate catalysed intramolecular allylic ester rearrangements.[20] Use of a chiral trichloroacetimidate substrate (*S*)-**12** (88% *ee*) with the achiral catalyst $[PdCl_2(NCPh)_2]$ resulted exclusively in the formation of (*S*,*E*)-**13**, also of 88% *ee* (Scheme 9).[2d]



Scheme 9. The possible pathways for the conversion of (*S*)-**13** into (*S*,*E*)-**13**.

There are two possible CIR mechanistic explanations of this outcome. In pathway (i), initial palladium coordination to give diastereoisomer **A** must be followed by *anti*-iminopalladation and *anti*-deoxypalladation to give (*S*,*E*)-**13**. In pathway (ii), formation of diastereoisomer **B** requires subsequent *syn*-iminopalladation and *syn*-deoxypalladation. Studies on the addition of amines[21] and other nucleophiles[22] to palladium coordinated alkenes have revealed these Wacker-type reactions to proceed with *anti* selectivity, outcomes that point to (i) as the pathway for allylic imidate rearrangement.[23] In support of this is the all-equatorial disposition of the substituents in the chair-like intermediate (e.g. **A′**) arising from (*E*)-allylic imidates.

Unlike ferrocene-based palladacycles, these cobalt systems do not require activation by addition of one equivalent of silver trifluoroacetate. The need for this in the ferrocene series may be due to the higher lability (with respect to ligand substitution) of the introduced trifluoroacetate group, but it could also be due to the oxidation of the ferrocene into a ferrocenium ion.[24] It has been noted that the cyclopentadienyl ligand of (η^4-tetraphenylcyclobutadiene)(η^5-cyclopentadienyl)cobalt is electron poor compared to ferrocene, as revealed by a comparison of ^{1}H NMR spectroscopic data, and the values of pK_a and pK_b for hydroxy and amino-substituted metallocenes respectively.[25] The electronic properties of the nitrogen ligand also appears to be important, as the higher activity observed with **2b** compared to **6** is likely due to differences between the coordinating nitrogen of the oxazoline and imidazole groups respectively, as reflected in the lower basicity of the former.[26]

We then considered whether the bridging groups, X, significantly influence the Lewis acidity of the metal in the palladacycles studied for catalyst activity. To investigate this, the same method used for the synthesis of triphenylphosphine adduct **3b** was used to generate small-scale samples of oxazoline complexes **3a**, **3c**, **3d** and **3f** (Scheme 4), together with a corresponding complex **11** derived from the imidazole analogue **6**. Examination of their ^{31}P NMR spectra revealed little difference in the chemical shifts of the coordinated phosphorus atoms (Table 5), and no correlation between chemical shift and catalyst activity. This suggests that there is little difference between the Lewis acidity of a chloride versus, for example, an iodide coordinated palladacycle. Instead, to account for the different yields observed with COP-X it was noted that the leaving group ability of the halogens in associative substitution reactions of square-planar palladium(II) complexes increases in the order Cl > Br > I.[27] Although the differences are relatively small, the nature of the entering group having a larger effect, the rate of substitution of [Pt(dien)Cl]Cl is about three and a half times faster than [Pt(dien)I]I.[28] Thus, although the relative electron deficiency of cobalt metallocenes appears to be important for the reactivity they display, the comparison of a series of COP-X derivatives points to the leaving group ability of the bridging ligand as another factor influencing activity.

Table 5. ^{31}P NMR spectroscopic chemical shifts for triphenylphosphine coordinated palladacycles.

Entry	Compound	Chemical shift [ppm]
1	**3a** (X = OAc)	32.88
2	**3b** (X = Cl)	33.87
3	**3c** (X = Br)	34.02
4	**3d** (X = I)	33.40
5	**3f** (X = O_2CCF_3)	32.49
6	**11**	34.02

To study the reaction further, COP-Cl was dissolved in CD_3CN and examined by ^{1}H NMR spectroscopy. The pres-

ence of *cis* and *trans* isomers (ratio = 1:0.5, it is not known which is which) revealed the maintenance of the chloride-bridged dimeric structures in this solvent. Following addition of COP-Cl **2b** to **7a** (0.016 M) in CD_3CN (**7a**/**2b** 3:1) and standing of the resulting solution at room temperature overnight, ^{1}H NMR spectroscopy revealed a 75% conversion of **7a** into **8a**, with unchanged COP-Cl **2b** (isomer ratio = 1:0.7) and no other palladacycle species present. This indicates that under these conditions, the resting state of the catalyst in the presence of the substrate and the product is as the chloride-bridged dimer.

The formation of dimeric and higher-order structures by bridging ligands such as halogens or alkoxides is associated with striking non-linear effects (NLEs) in asymmetric catalysis.[29] The possibility of this occurring in the palladacycle-catalysed allylic imidate rearrangement was examined with the acetate-bridged complex **2a** rather than the corresponding chloride **2b** in order to avoid possible complications arising from the presence of *cis* and *trans* isomers in the latter. For the conversion of **7a** into **8a**, the use of COP-OAc with enantiomeric excesses of 25 and 50% resulted in slightly higher values of product *ee* than calculated by linear extrapolation of the value of 89% *ee* obtained with enantiopure **2a** (Table 6). The origin of this outcome was investigated by

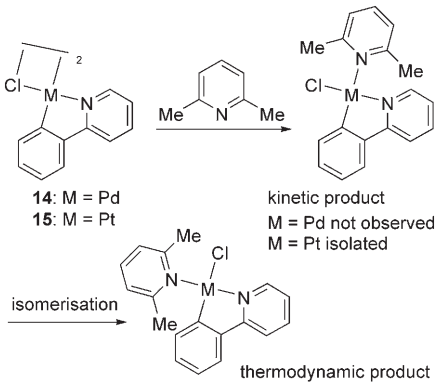
Table 6. Catalysis of the rearrangement of trichloroacetimidate **7a** to amide **8a** with non-enantiopure **2a** (COP-OAc).[a]

Entry	Cat. *ee* [%][b]	**8a** found *ee* [%]	**8a** expected *ee* [%][c]	Conv. [%][d]
1	100	89	–	–
2	75	66	67	>99
3	50	55	45	85
4	25	39	22	75

[a] Compound **7a** (2.6 mmol), **2a** (0.25 mol%), CH_3CN, (1 mL), 70°C, 48 h. [b] Obtained by combining ($S_p R$)-**2a** and ($R_p S$)-**2a** in appropriate amounts. [c] From linear extrapolation of 89%. [d] Determined by ^{1}H NMR spectroscopy.

examining the ^{1}H NMR spectrum of racemic COP-OAc which was found to be identical to the spectrum of enantiopure COP-OAc. This may be accounted for by either the absence of the S_pR/R_pS (*meso*) diastereoisomer, or by it producing an identical spectrum to the S_pR/S_pR *(or* R_pS/R_pS*)*-acetate-bridged dimer. Furthermore, no additional signals were observed in the ^{1}H NMR spectrum of 50% *ee* COP-OAc compared to enantiopure COP-OAc when the spectra were recorded in CD_3CN in the presence of excess **7a**. The observed small positive NLE may be accounted for by the operation of either an $(ML)_2$ system or the reservoir effect model, both of which require the formation of a *meso* isomer.[30] The former is consistent with dimeric COP-Cl as the actual catalyst, the later with an unobserved monomeric solvated species as the starting point of the catalytic cycle.

The substitution chemistry of chloride-bridged nitrogen coordinating palladacycles and platinacycles has been studied with complexes **14** and **15** (Scheme 10).[31] Reaction of



Scheme 10. Substitution chemistry in related palladacycles and platinacycles.[31]

the former with 2,6-dimethylpyridine gave a monomeric palladium complex with the chloride *trans* to the metal–carbon bond. This stereochemistry is the same as displayed by **3**, and has been observed with other monomeric adducts of palladacycles containing nitrogen donor ligands.[13,32] In contrast, the platinacycle **16** gave the monomeric adduct with the chloride *cis* to the metal–carbon bond. This outcome, in which the bridging chloride ligand *trans* to the metal–carbon bond has been substituted, is in agreement with the established order of kinetic *trans* effects.[33] Prolonged reaction of this kinetic product with 2,6-dimethylpyridine resulted in its conversion to the isomeric thermodynamic product.[31] That the kinetic product was not observed in the analogous palladium chemistry is consistent with the much greater kinetic lability of palladium compared to platinum complexes in ligand substitution and isomerisation reactions.

The crystal structure of **4**[8b] reveals the palladium–oxygen bond lengths of the hexafluoroacetylacetonate ligand *trans* to carbon and nitrogen as 2.102(4) and 2.020 Å(4) respectively. Thus, the metallocene ligand has a larger *trans* influence than the oxazoline and most likely a larger *trans* effect given: 1) the frequent correlation between these thermodynamic and kinetic effects and 2) the similarity of this C–N ligand to that in palladacycle **14**. Thus, the COP-X dimers react by introduction of either a solvent or substrate molecule to give a monomeric species initially containing this substituent *trans* to the metallocene ligand.[34] The lability of the bridging ligands X to substitution influences the yield obtained in a COP-X-catalysed allylic imidate rearrangement.

Conclusion

The screening of a range of COP-X-dimeric-bridged palladacycles as catalysts for the allylic imidate rearrangement of a trichloroacetimidate revealed an optimum group X to be chloride, the yield of the product trichloroacetamide increasing in the series $I < p\text{-}O_2CC_6H_4F < OAc < O_2CCF_3 \approx Br \approx Cl$. In contrast, the enantioselectivity was independent of the identity of X. With acetonitrile as the solvent, the enantiose-

lectivity of the COP-Cl-catalysed reaction was essentially invariant over the temperature range 50–80 °C, and with a catalyst loading of only 0.25 mol %, the optimum yield was obtained at 70 °C with a reaction time of 48 h. These conditions were successfully applied to a range of trichloroacetimidates to give the product amides (*S*)-$Cl_3CC(=O)NHCHRCH{=}CH_2$ in good yield and enantioselectivity (85–94 % *ee*). The potential for catalyst recycling was demonstrated by combination of COP-Cl with a polymer supported phosphine, triphenylphosphine NovaGel and isolation of the resulting adduct by filtration on completion of the reaction. The activity of the COP-Cl catalyst is ascribed to the relatively good leaving group ability of the chloride ligand, and to the relative electron deficiency of the cobalt metallocene and oxazoline components of the chelating palladium ligand. A small positive non-linear effect was observed with COP-OAc.

Experimental Section

General: Dichloromethane and acetonitrile were distilled from calcium hydride under an atmosphere of nitrogen. Petroleum ether refers to that fraction boiling in the range of 40–60 °C. Column chromatography was performed on silica gel (40–63 μm). All reactions were performed under an atmosphere of nitrogen. All NMR spectra were recorded on a Jeol JNM-EX 270 MHz spectrometer. Optical rotations were measured on a Jasco P-1010 instrument and IR spectra were recorded on a Shimadzu FTIR-8300 spectrometer. Melting points are uncorrected. Mass spectra were recorded by the EPSRC National Mass Spectrometry Service Centre and elemental analyses were performed at University College, London. Compounds **2a**,[5a] **2b**[6] **4**,[8b] **5**,[14] **6**[6] **7a**,[1b] **7b**,[1b] **7e**,[7] **7f**,[1b] **8a**,[1b] **8b**,[35] **8e**,[7] **8f**[1b] and **9**[9b] have been previously described. The enantiomeric excesses of **8a**, **8b** and **8e** were determined as previously reported.[7]

Di-μ-bromobis[{η⁵-(*S*)-(*pR*)-2-[2′-(4′-methylethyl)oxazolinyl]cyclopentadienyl,1-*C*,3′-*N*}(η⁴-tetraphenylcyclobutadiene)cobalt]dipalladium (2c): Aqueous sodium bromide (2 M, 0.5 mL, 1 mmol) was added to a flask containing **2a** (0.15 g, 0.1 mmol) and acetone (1 mL) and the resulting heterogeneous mixture was stirred at room temperature for 4 h. The resulting yellow solid was filtered, washed with water (2.1 mL) and acetone (0.3 mL) and dried in vacuo to give **2c** as a mustard-coloured solid (0.16 g, >99 %). M.p. 209–210 °C; $[\alpha]_D^{22}=+1137$ ($c=0.218$ in $CHCl_3$); exists as a 1.0:0.7 mixture of dimers in $CDCl_3$; ^{1}H NMR ($CDCl_3$): $\delta=$ 0.67–0.71 (m, 3H+2.1H), 0.74 (d, 3H, $J=6.8$ Hz), 0.80 (d, 2.1H, $J=$ 7.0 Hz), 2.10–2.33 (m, 1H+0.7H), 3.00–3.15 (m, 1H+0.7H), 3.30 (t, 1H, $J=9.0$ Hz), 3.40 (t, 0.7H, $J=8.9$ Hz), 4.16–4.22 (m, 1H+0.7H), 4.28 (t, 0.7H, $J=2.5$ Hz), 4.41 (t, 1H, $J=2.5$ Hz), 4.66 (d, 0.7H, $J=2.0$ Hz), 4.69 (d, 1H, $J=2.0$ Hz), 4.96 (d, 1H, $J=1.5$ Hz), 5.00 (d, 0.7H, $J=1.5$ Hz), 7.16–7.28 (m, 12H+8.4H), 7.56–7.66 ppm (m, 8H+5.6H); ^{13}C NMR ($CDCl_3$): $\delta=$14.0, 14.2, 18.8, 29.1, 29.3, 65.7, 71.2, 71.3, 76.3, 76.6, 80.3, 84.2, 84.5, 85.1, 85.2, 87.1, 88.2, 99.9, 126.2, 128.0, 129.2, 129.3, 135.2, 135.3, 170.8 ppm; IR (KBr): $\tilde{\nu}=$3060, 2960, 1602 (C=N), 1500, 1365, 1180 cm^{-1}; MS (MALDI): *m*/*z* (%): 1554.1 [M^+]; elemental analysis calcd (%) for $C_{78}H_{66}Br_2Co_2N_2O_2Pd_2{\cdot}H_2O$: C 59.60, H 4.36, N 1.78; found: C 59.24, H 4.24, N 1.71.

Di-μ-iodobis[{η⁵-(*S*)-(*pR*)-2-[2′-(4′-methylethyl)oxazolinyl]cyclopentadienyl,1-*C*,3′-*N*}(η⁴-tetraphenylcyclobutadiene)cobalt]dipalladium (2d): By using the same procedure for the synthesis of **2c**, **2a** (0.15 g, 0.1 mmol) and aqueous sodium iodide (2 M, 0.5 mL, 1 mmol) gave **2d** as a mustard-coloured solid (0.16 g, 96 %). M.p. 230–232 °C; $[\alpha]_D^{22}=+1325$ ($c=0.196$ in $CHCl_3$); exists as a 1.0:0.3 mixture of dimers in $CDCl_3$; ^{1}H NMR ($CDCl_3$): $\delta=0.65$ (d, 0.9H, $J=7.1$ Hz), 0.72 (d, 3H+0.9H, $J=$ 6.6 Hz), 0.80 (d, 3H, $J=6.9$ Hz), 2.40–2.19 (m, 1H+0.3H), 3.11–3.07 (m, 0.3H), 3.27–3.22 (m, 1H), 3.30 (t, 1H, $J=9.3$ Hz), 3.39 (t, 0.3H, $J=$ 8.1 Hz), 4.22–4.25 (m, 1H+0.3H), 4.38 (brt, 0.3H), 4.46 (brt, 1H), 4.64 (d, 0.3H, $J=2.2$, Hz), 4.68 (d, 1H, $J=2.2$ Hz), 4.95 (brs, 1H), 5.06 (brs, 0.3H), 7.16–7.26 (m, 12H+3.6H), 7.55–7.71 ppm (m, 8H+2.4H); ^{13}C NMR ($CDCl_3$): $\delta=$14.1, 19.0, 30.1, 66.8, 71.5, 76.3, 76.4, 80.6, 85.4, 86.7, 91.2, 103.1, 126.6, 128.4, 129.5, 129.6, 135.5, 135.7, 171.5 ppm; IR (KBr): $\tilde{\nu}=$3050, 2950, 1603 (C=N), 1500, 1365, 1180 cm^{-1}; MS (MALDI): *m*/*z* (%): 1648.0 [M^+]; elemental analysis calcd (%) for $C_{78}H_{66}Co_2I_2N_2O_2Pd_2{\cdot}2H_2O$: C 55.63, H 4.19, N 1.66; found: C 55.80, H 3.97, N 1.58.

Di-μ-4-fluorobenzoylatobis[{η⁵-(*S*)-(*pR*)-2-[2′-(4′-methylethyl)oxazolinyl]cyclopentadienyl,1-*C*,3′-*N*}(η⁴-tetraphenylcyclobutadiene)cobalt]dipalladium (2e): *p*-Fluorobenzoic acid (0.057 g, 0.4 mmol) was added in one portion to a solution of **2a** (0.30 g, 0.2 mmol) in CH_2Cl_2 (3 mL). The solution was stirred overnight at room temperature, washed with water (2× 3 mL), dried (Na_2SO_4), filtered and the solvent removed in vacuo to give **2e** as an orange crystalline solid (0.31 g, 93 %). M.p. 185–187 °C; $[\alpha]_D^{22}=$ +865 ($c=0.164$ in $CHCl_3$); ^{1}H NMR ($CDCl_3$): $\delta=0.03$ (d, 3H, $J=$ 6.6 Hz), 0.33 (d, 3H, $J=7.1$ Hz), 3.16 (m, 1H), 1.78 (m, 1H), 3.52 (t, 1H, $J=9.4$ Hz), 4.09–4.14 (m, 1H), 4.30 (t, 1H, $J=2.5$ Hz), 4.41 (d, 1H, $J=$ 1.5 Hz), 4.66 (d, 1H, $J=2.0$ Hz), 6.97, (t, 2H, $J=8.8$ Hz), 7.10–7.26 (m, 12H), 7.58–7.73 ppm (m, 10H); ^{13}C NMR ($CDCl_3$): $\delta=$13.2. 18.7, 28.9, 65.3, 71.1, 75.7, 78.5, 83.3, 85.6, 86.8, 99.2, 114.1, 114.5, 126.1, 128.0, 129.2, 131.6, 132.2, 135.9, 171.7, 174.3 ppm; IR (KBr) $\tilde{\nu}=$3060, 2950, 1600 (C= N), 1575, 1495, 1395, 1365, 1220, 1180, 1150, 1065 cm^{-1}; MS (FAB): *m*/*z* (%): 1672.4 [M^+]; elemental analysis calcd (%) for $C_{92}H_{74}Co_2F_2N_2O_6Pd_2$: C 66.08, H 4.46, N 1.68; found: C 66.03, H 4.66, N 1.56.

Di-μ-trifluoroacetatobis[{η⁵-(*S*)-(*pR*)-2-[2′-(4′-methylethyl)oxazolinyl]cyclopentadienyl,1-*C*,3′-*N*}(η⁴-tetraphenylcyclobutadiene)cobalt]dipalladium (2f): Silver trifluoroacetate (0.09 g, 0.41 mmol) was added to a solution of **2b** (0.30 g, 0.2 mmol) in CH_2Cl_2 (6 mL) in one portion and the reaction mixture was stirred overnight at room temperature. The resulting precipitate of silver chloride was removed by suction filtration and the solvent removed in vacuo to give **2f** as a brown glassy solid (0.15 g, 44 % yield). M.p. 232–235 °C (decomp); $[\alpha]_D^{22}=+712$ ($c=0.092$ in $CHCl_3$); ^{1}H NMR ($CDCl_3$): $\delta=-0.03$ (d, 3H, $J=6.6$ Hz), 0.44 (d, 3H, $J=7.1$ Hz), 1.58–1.63 (m, 1H), 2.90 (dt, 1H, $J=8.6$, 2.7 Hz, 3.37 (t, 1H, $J=9.1$ Hz), 4.09 (dd, 1H, $J=8.3$, 3.7 Hz), 4.26 (t, 1H, $J=2.7$ Hz), 4.72 (d, 1H, $J=2.0$, Hz), 4.79 (d, 1H, $J=1.7$ Hz), 7.17–7.28 (m, 12H), 7.56–7.59 ppm (m, 8H); ^{13}C NMR ($CDCl_3$) $\delta=$12.9, 13.0, 18.2, 29.4, 64.6, 71.3, 76.6, 79.5, 84.1, 84.5, 85.7, 96.7, 104.2, 126.4, 128.1, 129.1, 135.3, 171.0 ppm; IR (KBr): $\tilde{\nu}=$2960, 1680, 1600 (C=N), 1510, 1450, 1365, 1200, 1145 cm^{-1}; MS (FAB): *m*/*z* (%): 809.1 [1/2 M^+]; elemental analysis calcd (%) for $C_{82}H_{66}Co_2F_6N_2O_6Pd_2{\cdot}CH_2Cl_2$: C 58.47, H 4.02, N 1.64; found: C 58.13, H 3.94, N 1.53.

Chloro[{η⁵-(*S*)-(*pR*)-2-[2′-(4′-methylethyl)oxazolinyl]cyclopentadienyl,1-*C*,3′-*N*}(η⁴-tetraphenylcyclobutadiene)cobalt]triphenylphosphinepalladium (3): Triphenylphosphine (0.051 g, 0.19 mmol) was added to a solution of **2b** (0.14 g, 0.10 mmol) in CH_2Cl_2 (7.5 mL) in one portion and the reaction mixture was stirred for 3 h at room temperature. The solvent was removed in vacuo to give **3** as a red–brown glassy solid (0.18 g, 94 %). M.p. >250 °C; $[\alpha]_D^{22}=+761$ ($c=0.18$ in $CHCl_3$); ^{1}H NMR ($CDCl_3$): $\delta=0.79$ (d, 3H, $J=7.0$ Hz), 0.82 (d, 3H, $J=7$ Hz), 2.87 (m, 1H), 3.13 (d, 1H, $J=$ 1.5 Hz), 3.40 (t, 1H, $J=8.6$ Hz), 3.67 (dt, 1H, $J=9.1$, 3.7 Hz), 4.25 (t, 1H, $J=4.2$ Hz), 4.30 (t, 1H, $J=2.4$ Hz), 4.65 (d, 1H, $J=1.7$ Hz), 7.14–7.49 ppm (m, 35H); ^{13}C NMR ($CDCl_3$) $\delta=$14.0, 19.0, 28.8, 66.3, 71.4, 75.3, 80.3, 84.7, 87.6, 126.3, 127.9, 128.1, 129.1, 130.3, 131.5, 132.2, 135.1, 135.3, 135.4, 171.5 ppm; ^{31}P NMR ($CDCl_3$): $\delta=$33.87 ppm; IR (KBr): $\tilde{\nu}=$ 3050, 2950, 1605 (C=N), 1495, 1435, 1365, 1165 cm^{-1}; MS (FAB): *m*/*z* (%): 993.1 [M^+]; elemental analysis calcd (%) for $C_{57}H_{48}ClCoNOPPd$: C 68.82, H 4.86, N 1.41; found: C 68.52, H 4.71, N 1.29.

General method for the palladacycle-catalysed conversion of trichloroacetimidate 7a into trichloroacetamide 8a: Trichloroacetimidate **7a** (0.634 g, 2.6 mmol), the palladacycle catalyst (0.5 or 0.25 mol %) and acetonitrile (1 mL) were added to a round-bottomed flask containing a stir bar. The flask was sealed with a polyethylene stopper and placed in an oil bath preheated to the required temperature (50–80 °C). After either 24 or 48 h the flask was removed from the heating bath, cooled to room

temperature and concentrated in vacuo to give a brown oil. Column chromatography (3% EtOAc/hexanes) gave **8a** as a pale-yellow oil.

(*E*)-2,2,2-Trichloroacetimidic acid but-4-phenyl-2-enyl ester (7c): A solution of *trans*-4-phenyl-2-buten-1-ol[36] (1.90 g, 12.8 mmol) and DBU (DBU = 1,8-diazabicyclo[5.4.0]undec-7-ene; 0.38 mL, 2.5 mmol) in CH_2Cl_2 (97 mL) was cooled to 0 °C, and to this was added dropwise trichloroacetonitrile (1.92 mL, 19.2 mmol), maintaining the temperature of the reaction mixture below 5 °C. After stirring for 1 h at 0 °C, the solvent was removed in vacuo and the residue column chromatographed (neutral alumina, 2% EtOAc/petroleum ether) to give **7c** as a yellowish oil (2.76 g, 74%). ^{1}H NMR ($CDCl_3$): δ = 3.45 (d, 2H, J = 6 Hz,), 4.82 (d, 2H, J = 6 Hz,), 5.79 (m, 1H), 6.06 (m, 1H), 7.35–7.21 (m, 5H), 8.33 ppm (br s, 1H); ^{13}C NMR ($CDCl_3$): δ = 38.7, 69.6, 91.5, 124.6, 126.3, 128.60, 128.69, 135.0, 139.6, 162.6 ppm; IR (film) $\tilde{\nu}$ = 3340, 3030, 2940, 1660, 1490, 1450, 1380, 1290, 1080, 980, 910 cm^{-1}.

(*E*)-2,2,2-Trichloroacetimidic acid hex-2,5-dienyl ester (7d): A solution of (*E*)-hexa-2,5-dien-1-ol[37] (0.22 g, 2.2 mmol) and DBU (0.07 mL, 0.5 mmol) in CH_2Cl_2 (11 mL) was cooled to 0 °C, and to this was added dropwise trichloroacetnitrile (0.33 mL, 3.3 mmol), maintaining the temperature of the reaction mixture below 5 °C. The resulting orange solution was stirred for 1 h at 0 °C. The solvent was removed in vacuo and the residue column chromatographed (neutral alumina, 2% EtOAc/petroleum ether) to give **7d** as a colourless oil (0.18 g, 33%). ^{1}H NMR ($CDCl_3$): δ = 2.83 (t, 2H, J = 5.4 Hz), 4.75 (d, 2H, J = 8.9 Hz), 5.03 (dd, 1H, J = 8.9, 1.7 Hz), 5.05 (dd, 1H, J = 18.7, 1.7 Hz), 5.70 (m, 1H), 5.83 (m, 2H), 8.27 ppm (br s, 1H); ^{13}C NMR ($CDCl_3$): δ = 36.3, 69.7, 91.7, 115.9, 124.3, 134.0, 135.8, 162.6 ppm; IR (film): $\tilde{\nu}$ = 3344, 2947, 1662, 1450, 1290, 1070, 975, 920, 830, 795, 650 cm^{-1}.

General method for the COP-Cl-catalysed conversion of trichloroacetimidates 7b–c,e–f into trichloroacetamides 8b–c,e–f: Trichloroacetimidate **7** (2.6 mmol), (*S*)-COP-Cl (9.5 mg, 6.5 μmol) and acetonitrile (1 mL) were added to a round-bottomed flask containing a stir bar. The flask was sealed with a polyethylene stopper and placed in an oil bath preheated to 70 °C. After 48 h, the flask was removed from the heating bath, cooled to room temperature and concentrated in vacuo to give a brown oil. Column chromatography (3% EtOAc/hexanes) gave **8** as a pale-yellow oil.

(*S*)-2,2,2-Trichloro-*N*-(1-benzylallyl)acetamide (8c): Isolated as a pale-yellow oil (0.52 g, 68%). 94% *ee*; $[\alpha]_D^{22}$ = +17.4 (c = 0.228 in $CHCl_3$); ^{1}H NMR ($CDCl_3$): δ = 2.92 (dd, 1H, J = 13.6, 6.6 Hz), 3.01 (dd, 1H, J = 13.8, 6.6 Hz), 4.76–4.67 (m, 1H), 5.18 (dd, 1H, J = 17.7, 1.2 Hz), 5.19 (dd, 1H, J = 10.3, 1.2 Hz), 5.85 (ddd, 1H, J = 16.5, 10.8, 5.4 Hz), 6.56 (br s, 1H), 7.33–7.17 ppm (m, 5H); ^{13}C NMR ($CDCl_3$): δ = 40.5, 54.1, 92.7, 116.5, 127.1, 128.7, 129.5, 135.8, 136.0, 161.1 ppm; IR (film): $\tilde{\nu}$ = 3300, 3060, 2920, 1685, 1650, 1520, 1440, 1410, 1350, 1260, 1085, 1015, 990, 880, 820 cm^{-1}; MS (APCI): m/z (%): 309 (95) [M^++NH_3]; elemental analysis calcd (%) for $C_{12}H_{12}Cl_3NO$: C 49.26, H 4.13, N 4.79; found: C 49.40, H 4.21, N 4.64.

(*S*)-2,2,2-Trichloro-*N*-[1-(2-propenyl)allyl]acetamide (8d): Trichloroacetimidate **7d** (0.200 g, 0.82 mmol), (*S*)-COP-Cl **2b** (3.0 mg, 2 μmol) and acetonitrile (0.31 mL) were added to a round-bottomed flask containing a stir bar. The flask was sealed with a polyethylene stopper and placed in an oil bath preheated to 70 °C. After 48 h, additional (*S*)-COP-Cl **2b** (3.0 mg, 2 μmol) was added and heating at 70 °C was maintained for a further 24 h. After cooling to room temperature, the solvent was removed in vacuo and the residual brown oil column chromatographed (silica gel, 3% EtOAc/hexane) to give **8d** as a pale-yellow oil (0.08 g, 40%). 94% *ee*; $[\alpha]_D^{22}$ = +14.0 (c = 0.428 in $CHCl_3$); ^{1}H NMR ($CDCl_3$): δ = 2.50–2.33 (m, 2H), 4.56–4.47 (m, 1H), 5.16 (dd, 1H, J = 15.4, 1 Hz), 5.17 (dd, 1H, J = 10.7, 1 Hz), 5.22 (dd, 1H, J = 16.9, 1 Hz), 5.24 (dd, 1H, J = 6.6, 1 Hz), 5.89–5.68 (m, 2H), 6.63 ppm (br s, 1H); ^{13}C NMR ($CDCl_3$): δ = 38.5, 52.2, 92.8, 116.2, 119.5, 132.6, 135.9, 161.1 ppm; IR (film): $\tilde{\nu}$ = 3330, 2925, 1700, 1650, 1500, 1440, 1250, 990, 920, 820, 750, 680 cm^{-1}; MS (APCI): m/z (%): 259 (100) [M^++NH_3]; HRMS (ES$^+$): m/z: calcd for $C_8H_{14}Cl_3N_2O$: 259.0166 [M^++NH_4]; found: 259.0165.

Synthesis of 10 and application to the rearrangement of 7a: A mixture of (*S*)-COP-Cl **2b** (0.040 g, 27 μmol), triphenylphosphine NovaGel (0.080 g, 0.4–0.7 mmol g^{-1}, ≈44 μmol) and acetonitrile (5 mL) were stirred for 3 h at room temperature. Removal of the solvent in vacuo gave **10** (0.120 g) as brown beads: elemental analysis (%) NovaGel found: C 73.48, H 7.62, N 1.23; calcd for NovaGel + 0.6 mmol COP-Cl: C 70.57, H 6.68, N 1.44; found: C 70.77, H 6.46, N 1.68.

Conversion of trichloroacetimidate 7a into trichloroacetamide 8a with supported catalyst 10: Trichloroacetimidate **7a** (0.73 g, 3.0 mmol), the polymer supported catalyst **10** (120 mg, 0.05 mmol of palladacycle monomer) and acetonitrile (1 mL) were added to a round-bottomed flask containing a stir bar. The flask was sealed with a polyethylene stopper and placed in an oil bath preheated to 50 °C. After 48 h, the flask was removed from the heating bath, cooled to room temperature and the supernatant decanted from the polymer which was washed with additional acetonitrile (4 mL). Following combination of the acetonitrile solutions, the rearranged product **8a** was isolated as described above. After drying, the product was used in two further sequential reactions under the same conditions. Run 1 (**8b**: 91% yield, 94% *ee*); run 2 (27% yield, 93% *ee*); run 3 (17% yield, 89% *ee*).

General method for the synthesis of 3a, 3c, 3d, 3f and 11: Triphenylphosphine (5.3 mg. 0.02 mmol) was added to a solution of either **2a**, **2c**, **2d**, **2f** or **6** (0.01 mmol) in CH_2Cl_2 (0.7 mL) and the resulting solution was stirred at room temperature for 3 h prior to the removal of the solvent in vacuo.

Compound 3a (X = OAc): ^{1}H NMR ($CDCl_3$): δ = 0.73 (d, 3H, J = 7.1 Hz), 0.80 (d, 3H, J = 6.6 Hz), 1.42 (s, 1H), 2.38–2.30 (m, 1H), 3.21 (t, 1H, J = 8.9 Hz), 3.55 (d, 1H, J = 1.9 Hz), 3.82–3.75 (m, 1H), 4.12 (dd, 1H, J = 8.6, 4.9 Hz), 4.38 (br t, 1H), 4.61 (d, 1H, J = 2.4 Hz), 7.17–7.47 ppm (35H, m); ^{31}P NMR ($CDCl_3$): δ = 32.88 ppm.

Compound 3c (X = Br): ^{1}H NMR ($CDCl_3$): δ = 0.79 (d, 3H, J = 4.0 Hz), 0.81 (d, 3H, J = 4 Hz), 2.89 (m, 1H), 3.07 (d, 1H, J = 1.4 Hz), 3.33 (t, 1H, J = 9 Hz), 3.73 (m, 1H), 4.26 (t, 1H, J = 4.0 Hz), 4.30 (br t, 1H), 4.66 (d, 1H, J = 1.9 Hz), 7.13–7.41 ppm (m, 35H); ^{31}P NMR ($CDCl_3$): δ = 34.02 ppm.

Compound 3d (X = I): ^{1}H NMR ($CDCl_3$): δ = 0.79 (d, 3H, J = 3.4 Hz), 0.81 (d, 3H, J = 3.4 Hz), 2.92 (m, 1H), 3.08 (d, 1H, J = 1.9 Hz), 3.23 (t, 1H, J = 9 Hz), 3.86 (m, 1H), 4.29 (t, 1H, J = 3.2 Hz), 4.31 ppm (br t, 1H), 4.66 (d, 1H, J = 1.9 Hz), 7.19–7.48 ppm (m, 35H); ^{31}P NMR ($CDCl_3$) δ = 33.39 ppm.

Compound 3f (X = OCOCF$_3$): ^{1}H NMR ($CDCl_3$): δ = 0.72 (d, 3H, J = 7.1 Hz), 0.81 (d, 3H, J = 6.9 Hz), 2.27–2.21 (m, 1H), 3.19 (t, 1H, J = 9.1 Hz), 3.66–3.62 (m, 2H), 4.12 (dd, 1H, J = 8.6, 4.6 Hz), 4.41 (br t, 1H), 4.66 (d, 1H, J = 2.7 Hz), 7.44–7.16 ppm (m, 35H); ^{31}P NMR ($CDCl_3$): δ = 32.49 ppm.

Compound 11: ^{1}H NMR ($CDCl_3$): δ = 0.65 (d, 3H, J = 6.9 Hz), 0.72 (s, 9H), 3.10 (d, 1H, J = 2.2 Hz), 3.49 (q, 1H, J = 6.7 Hz), 3.89 (d, 1H, J = 2.5 Hz), 4.24 (t, 1H, J = 2.2 Hz), 7.14–7.49 ppm (m, 37H); ^{31}P NMR ($CDCl_3$): δ = 34.02 ppm.

Acknowledgement

We thank the EPSRC National Mass Spectrometry Service Centre, University of Wales, Swansea.

[1] a) L. E. Overman, *J. Am. Chem. Soc.* **1974**, *96*, 597–599; b) L. E. Overman, *J. Am. Chem. Soc.* **1976**, *98*, 2901–2910; c) L. E. Overman, *Acc. Chem. Res.* **1980**, *13*, 218–224.

[2] a) T. Ikariya, Y. Ishikawa, K. Hirai, S. Yoshikawa, *Chem. Lett.* **1982**, 1815–1818; b) T. G. Schenck, B. Bosnich, *J. Am. Chem. Soc.* **1985**, *107*, 2058–2066; c) P. Metz, C. Mues, A. Schoop, *Tetrahedron* **1992**, *48*, 1071–1080; d) M. Mehmandoust, Y. Petit, M. Larchevêque, *Tetrahedron Lett.* **1992**, *33*, 4313–4316; e) J. Gonda, A.-C. Helland, B. Ernst, D. Belluš, *Synthesis* **1993**, 729–734; f) L. E. Overman, G. G. Zipp, *J. Org. Chem.* **1997**, *62*, 2288–2291.

[3] a) M. Calter, T. K. Hollis, L. E. Overman, J. Ziller, G. G. Zipp, *J. Org. Chem.* **1997**, *62*, 1449–1456; b) T. K. Hollis, L. E. Overman, *Tetrahedron Lett.* **1997**, *38*, 8837–8840; c) Y. Uozumi, K. Kato, T.

Hayashi, *Tetrahedron: Asymmetry*, **1998**, *9*, 1065–1072; d) F. Cohen, L. E. Overman, *Tetrahedron: Asymmetry*, **1998**, *9*, 3213–3222; e) T. K. Hollis, L. E. Overman, *J. Organomet. Chem.* **1999**, *576*, 290–299; f) Y. Donde, L. E. Overman, *J. Am. Chem. Soc.* **1999**, *121*, 2933–2934; g) Y. Jiang, J. M. Longmire, X. Zhang, *Tetrahedron Lett.* **1999**, *40*, 1449–1450; h) P.-H. Leung, K.-H. Ng, Y. Li, A. J. P. White, D. J. Williams, *Chem. Commun.* **1999**, 2435–2436; i) J. Kang, K. H. Yew, T. H. Kim, D. H. Choi, *Tetrahedron Lett.* **2002**, *43*, 9509–9512; j) A. Moyano, M. Rosol, R. M. Moreno, C. López, M. A. Maestro, *Angew. Chem.* **2005**, *117*, 1899–1903; *Angew. Chem. Int. Ed.* **2005**, *44*, 1865–1869; k) C. E. Anderson, Y. Donde, C. J. Douglas, L. E. Overman, *J. Org. Chem.* **2005**, *70*, 648–657; l) R. Peters, Z. Xin, D. F. Fischer, W. B. Schweizer, *Organometallics*, **2006**, *25*, 2917–2920; m) M. E. Weiss, D. F. Fischer, Z. Xin, S. Jautze, W. B. Schweizer, R. Peters, *Angew. Chem.* **2006**, *118*, 5823–5827; *Angew. Chem. Int. Ed.* **2006**, *45*, 5694–5698; n) S. Jautze, P. Seiler, R. Peters, *Angew. Chem.* **2007**, *119*, 1282–1286; *Angew. Chem. Int. Ed.* **2007**, *46*, 1260–1264.

[4] COP = cobalt oxazoline palladacycle. For **2b** the abbreviation $[COP\text{-}Cl]_2$ has also been used to highlight the dimeric nature of this palladacycle.

[5] a) A. M. Stevens, C. J. Richards, *Organometallics* **1999**, *18*, 1346–1348; b) C. E. Anderson, L. E. Overman, C. J. Richards, M. P. Watson, N. White, *Org. Synth.* **2007**, *84*, 139–147; c) C. E. Anderson, S. F. Kirsch, L. E. Overman, C. J. Richards, M. P. Watson, *Org. Synth.* **2007**, *84*, 148–155.

[6] L. E. Overman, C. E. Owen, M. M. Pavan, C. J. Richards, *Org. Lett.* **2003**, *5*, 1809–1812.

[7] C. E. Anderson, L. E. Overman, *J. Am. Chem. Soc.* **2003**, *125*, 12412–12413.

[8] For other applications of cobalt oxazoline palladacycles as catalysts for the allylic imidate rearrangement see: a) J. Kang, T. H. Kim, K. H. Yew, W. K. Lee, *Tetrahedron: Asymmetry* **2003**, *14*, 415–418; b) S. F. Kirsch, L. E. Overman, M. P. Watson, *J. Org. Chem.* **2004**, *69*, 8101–8104.

[9] a) S. F. Kirsch, L. E. Overman, *J. Org. Chem.* **2005**, *70*, 2859–2861; b) S. F. Kirsch, L. E. Overman, *J. Am. Chem. Soc.* **2005**, *127*, 2866–2867; c) E. E. Lee, R. A. Batey, *J. Am. Chem. Soc.* **2005**, *127*, 14887–14893; d) S. F. Kirsch, L. E. Overman, N. S. White, *Org. Lett.* **2007**, *9*, 911–913.

[10] F. X. Roca, M. Motevalli, C. J. Richards, *J. Am. Chem. Soc.* **2005**, *127*, 2388–2389.

[11] During the preparation of this manuscript, a model for the enantioselectivity of COP-Cl-catalysed rearrangement of trichloroacetimidates was reported. See: M. P. Watson, L. E. Overman, R. G. Bergman, *J. Am. Chem. Soc.* **2007**, *129*, 5031–5044.

[12] Ratios: **2a** (1:0), **2b** (1:0.7), **2c** (1:0.7), **2d** (1:0.3), **2e** (1:0), **2f** (1:0). Isomer mixtures (*cis*/*trans*, also referred to as *syn*/*anti*) are a feature of many bridged palladacycles.

[13] a) T. Izumi. H. Watabe, A. Kasahara, *Bull. Chem. Soc. Jpn.* **1981**, *54*, 1711–1714; b) I. P. Smoliakova, K. J. Keuseman, D. C. Haagenson, D. M. Wellmann, P. B. Colligan, N. A. Kataeva, A. V. Churakov, L. G. Kuz′mina, V. V. Dunina, *J. Organomet. Chem.* **2000**, *603*, 86–97.

[14] R. S. Prasad, C. E. Anderson, C. J. Richards, L. E. Overman, *Organometallics* **2005**, *24*, 77–81.

[15] G. Jones, C. J. Richards, *Organometallics* **2001**, *20*, 1251–1254.

[16] Acetonitrile has been used with catalyst **4** (1 mol% loading) but only at 50 °C: see reference [8b].

[17] I. Persson, *Pure Appl. Chem.* **1986**, *58*, 1153–1161.

[18] Y. Uozumi, H. Danjo, T. Hayashi, *Tetrahedron Lett.* **1997**, *38*, 3557–3560.

[19] L. E. Overman, *Angew. Chem.* **1984**, *96*, 565–572; *Angew. Chem. Int. Ed. Engl.* **1984**, *23*, 579–586.

[20] a) P. M. Henry, *J. Am. Chem. Soc.* **1972**, *94*, 5200–5206; b) P. M. Henry, *Acc. Chem. Res.* **1973**, *6*, 16–24.

[21] a) B. Åkermark, J. E. Bäckvall, K. Siirala-Hansén, K. Sjöberg, K. Zetterberg, *Tetrahedron Lett.* **1974**, *15*, 1363–1366; b) B. Åkermark, J. E. Bäckvall, L. S. Hegedus, K. Zetterberg, K. Siirala-Hansén, K. Sjöberg, *J. Organomet. Chem.* **1974**, *72*, 127–138.

[22] a) J. K. Stille, R. Divakaruni, *J. Am. Chem. Soc.* **1978**, *100*, 1303–1304; b) J. E. Bäckvall, B. Åkermark, S. O. Ljunggren, *J. Am. Chem. Soc.* **1979**, *101*, 2411–2416; c) B. Åkermark, B. C. Söderberg, S. S. Hall, *Organometallics*, **1987**, *6*, 2608–2610.

[23] Examples of palladium-catalysed addition of nucleophiles to alkenes that proceed by means of *cis* palladation have recently been reported. Oxygen nucleophiles: a) T. Hayashi, K. Yamasaki, M. Mimura, Y. Uozumi, *J. Am. Chem. Soc.* **2004**, *126*, 3036–3037; b) M. B. Hay, A. R. Hardin, J. P. Wolfe, *J. Org. Chem.* **2005**, *70*, 3099–3107; c) R. M. Trend, Y. K. Ramtohul, B. M. Stoltz, *J. Am. Chem. Soc.* **2005**, *127*, 17778–17788. Nitrogen nucleophiles: d) J. E. Ney, J. P. Wolfe, *Angew. Chem.* **2004**, *116*, 3689–3692; *Angew. Chem. Int. Ed.* **2004**, *43*, 3605–3608; e) G. Liu, S. S. Stahl, *J. Am. Chem. Soc.* **2007**, *129*, 6328–6335.

[24] It has been noted that addition of an excess of silver trifluoroacetate to an iodide-bridged ferrocene oxazoline palladacycle results in the formation of a ferrocenium cation, see reference [3k].

[25] M. D. Rausch, R. A. Genetti, *J. Org. Chem.* **1970**, *35*, 3888–3897.

[26] The pK_a values for the conjugate acids of 2-methyloxazoline and imidazole are 5.5 and 7.75 respectively, see: a) M. A. Weinberger, R. Greenhalgh, *Can. J. Chem.* **1963**, *41*, 1038–1041; b) T. C. Bruice, G. L. Schmir, *J. Am. Chem. Soc.* **1958**, *80*, 148–156.

[27] D. F. Shriver, P. W. Atkins, C. H. Langford, *Inorganic Chemistry*, Oxford University Press, **1994**.

[28] F. Basolo, H. B. Gray, R. G. Pearson, *J. Am. Chem. Soc.* **1960**, *82*, 4200–4203.

[29] a) M. Avalos, R. Babiano, P. Cintas, J. L. Jiménez, J. C. Palacios, *Tetrahedron: Asymmetry* **1997**, *8*, 2997–3017; b) C. Girard, H. B. Kagan, *Angew. Chem.* **1998**, *110*, 3088–3127; *Angew. Chem. Int. Ed.* **1998**, *37*, 2922–2959.

[30] For a statistical distribution of $S_{,p}R/S_{,p}R$ (*R*,*R*) $R_{,p}S/R_{,p}S$ (*S*,*S*) and $S_{,p}R/R_{,p}S$ (*R*,*S*) dimers ($K=4$), $ee_{aux}=50\%$ gives $EE_{prod}=55\%$ (*EE* = extrapolated enantiomeric yield) with $g=0.5$ ($g=k_{RS}/k_{RR}$). Alternatively, for $g=0$ an EE_{prod} of 54% is calculated with $ee_{aux}=50\%$ if the component of the *meso* (*R*,*S*) diastereoisomer is 20%. See: D. Guillaneux, S.-H. Zhao, O. Samuel, D. Rainford, H. B. Kagan, *J. Am. Chem. Soc.* **1994**, *116*, 9430–9439.

[31] D. St. C. Black, G. B. Deacon, G. L. Edwards, *Aust. J. Chem.* **1994**, *47*, 217–227.

[32] a) B. N. Cockburn, D. V. Howe, T. Keating, B. F. G. Johnson, J. Lewis, *J. Chem. Soc. Dalton Trans.* **1973**, 404–410.

[33] *Trans* effect for Pt^{II}: $NH_3 \approx$ amine $< Cl^- \approx Br^- < SCN^- \approx I^- \approx NO_2^- \approx Ph^- < Me^-$, see: F. Basolo, R. G. Pearson, *Prog. Inorg. Chem.* **1962**, *4*, 381–453.

[34] Models for the origin of enantioselection have been proposed in which the alkene component of the allylic imidate substrate is coordinated *cis* to the metallocene.[3m,11] This is compatible with a mechanism in which initial coordination of the substrate is followed by isomerisation to the thermodynamic *cis* isomer, as presumably is also the case with phosphine adducts **3**.

[35] F. Cramer, N. Hennrich, *Chem. Ber.* **1961**, *94*, 976–989.

[36] P. Bulger, M. G. Moloney, P. C. Trippier, *Org. Biomol. Chem.* **2003**, *1*, 3726–3737.

[37] B. C. Ranu, A. Majee, *Chem. Commun.* **1997**, 1225–1226.

Received: June 8, 2007
Published online: September 24, 2007

