Selective catalytic oxidations by palladium and manganese

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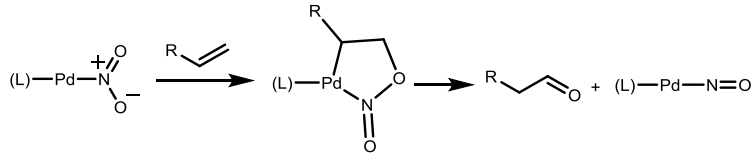
Chapter 4

Mechanistic insight into the *anti*-Markovnikov oxidation of alkenes

In this chapter the mechanism by which the *anti*-Markovnikov oxidation of alkenes catalysed by Pd(II) proceeds is explored through a combination of spectroscopy and variation in reaction conditions. It is shown that although alkenes can form complexes with Pd(II) readily, the first step in the reaction appears to be the formation of a complex between Pd(II) and benzoquinone and that the oxidation state of Pd(II) do not necessarily change during the reaction. Furthermore it is apparent that formation of Pd(0) in the reaction is unlikely.

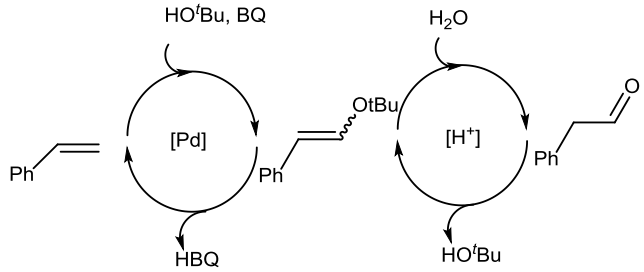
4.1 Introduction

The Palladium(II) catalysed oxidation of alkenes to ketones or acetaldehyde (also known as the Waker-Tsuji and Wacker processes, respectively), has been known for over 60 years.[1] As discussed in the introductory chapter, discovering methods for the Pd(II) catalysed *anti*-Markovnikov selective oxidation of terminal alkenes has been a challenge for almost as long a period of time. The first successful example was reported by Feringa[2] in 1986, in the oxidation of styrene to phenylacetaldehyde using $[PdCl(NO_2)(MeCN)_2]$, CuCl and oxygen in *tert*-butanol. Despite excellent selectivity towards the AM product, the reaction was effectively single turnover (10% yield from 10% catalyst loading). The nitro ligand was proposed to be non-innocent in the reaction and was in fact shown later by Grubbs and co-workers [3] as being the source of oxygen in the aldehyde product (Scheme 1).



Scheme 1. Proposed mechanism of aldehyde formation catalysed by $PdCl(NO_2)(MeCN)_2$.[2, 3]

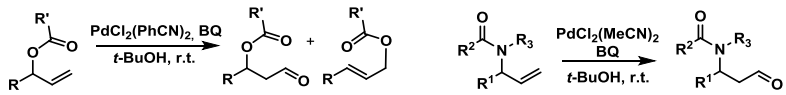
More recently, Grubbs and co-workers[4] reported the synthesis of terminal alcohols from alkenes, *i.e.* a formally *anti*-Markovnikov hydration, via oxidation of styrene to phenylacetaldehyde using $[PdCl_2(MeCN)_2]$ as catalyst and benzoquinone as terminal oxidant and subsequent reduction of the aldehyde using Shvo's catalyst. From a mechanistic perspective, the selectivity was ascribed to the formation of a *tert*-butyl enol ether, which underwent hydrolysis to the aldehyde in the presence of water (Scheme 2).



Scheme 2. Proposed mechanism of aldehyde formation by hydrolysis of enol ether.[4]

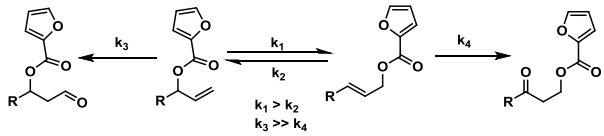
As described in chapters 2 and 3, the oxidation of both terminal allylic esters and amines can be achieved with excellent AM selectivity at ambient temperatures using catalysts such as $[CH_3CN)_2PdCl_2]$, *p*-benzoquinone as oxidant and *t*-butanol as solvent (Scheme 3). In contrast to styrene, however, the presence of water impacted the selectivity negatively and indeed water is not necessary to obtain the aldehyde product. This and several other observations raise questions regarding the mechanism by which these reactions take place, not least that, for example, a NO_2 ligand was not required (Scheme 3). Indeed such ligands (*i.e.* in $[PdCl(NO_2)(MeCN)_2]$) show reduced reaction rates in

comparison with $[CH_3CN)_2PdCl_2]$ in the oxidation of allylic esters and amides. In chapter 3, it was shown that alcohols serve as nucleophile in the reaction and the absence of incorporation of deuterium from solvent indicates that an α-hydrogen is transferred to the β-position during the reaction (Chapter 3, scheme 10).



Scheme 3. Oxidation of allylic esters and allylic amides (chapters 2 and 3).

The AM oxidation of allylic alcohols presents opportunities as an alternative to aldol condensations in the synthesis of protected β-hydroxy aldehydes. In chapter 2 it was shown that such regioselectivity could be achieved through the Pd(II) catalysed oxidation of ester-protected allylic alcohols using BQ as oxidant in *t*-butanol. Furthermore, catalyst loading could be decreased to 0.5 mol% and relatively mild conditions (*i.e.* neutral conditions and at ambient temperature) could be employed. Again, a key strength of palladium(II)-catalysed oxidations in allowing for orthogonal reactions to proceed simultaneously was demonstrated. A palladium-catalysed rearrangement of ester-protected linear allylic esters to the corresponding branched isomers was found to proceed under the reaction conditions employed,[5] which enabled the same product to be obtained as for the protected β-hydroxy terminal alkenes (Scheme 4). Hence both linear and branched allylic esters can be used as starting material to obtain the same protected β-hydroxy aldehydes (Scheme 4). Reaction monitoring by ^{1}H NMR spectroscopy indicated that the Curtin–Hammett principle [6] applied in this case with the selectivity towards the branched aldehyde product due to the low rate at which the thermodynamically more stable linear allylic ester underwent oxidation and the relatively rapid Pd(II) catalysed isomerisation between the branched and linear allylic alcohols. The absence of substitution of the acetyl protecting group with CD_3CO- (*i.e.* originating from CD_3CO_2H added to the reaction mixture) and the partial retention of enantiomeric excess at the allylic position when starting from a single enantiomer of the branched allylic ester suggests that, at least in the oxidation step (k_3 and k_4 in Scheme 4), a Pd(II) allyl species is not formed as an intermediate.



Scheme 4. Pd(II)-catalysed equilibration between linear and branched allylic esters and competing oxidation reactions.

In this chapter, the mechanisms by which the reactions described in chapters 2 and 3 proceed will be discussed and in particular the roles played by, and interplay of, the catalyst ($[PdCl_2(RCN)_2]$, where R = CH_3, iPr or Ph), the oxidant (in particular *p*-benzoquinone), solvent and substrates: allylic esters and allylic amides.

In both the oxidation of allylic esters and allylic amides, a key complication in mechanistic studies is the occurrence of competing reactions, some of the more important of which are catalysed by Pd(II). The occurrence of these additional reactions makes a detailed kinetic analysis impractical, in regard to extraction of reaction order.

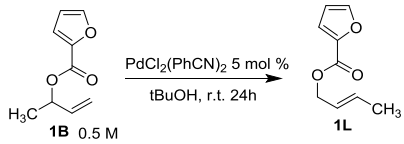
Nevertheless, these side reactions also open up many opportunities in both achieving greater reactivity/substrate scope as demonstrated in chapter 2 and 3 and in exploring how the catalyst achieves such high *anti*-Markovnikov selectivity.

In exploring the mechanisms by which the oxidation of terminal alkenes proceeds several key aspects need to be addressed; i) the nature of the interactions between the catalyst, substrate and oxidant, ii) whether or not benzoquinone reoxidises Pd(0) to Pd(II) as is often proposed or facilitates a Pd(II) - Pd(IV) cycle or engages in a concerted intramolecular electron transfer between substrate and terminal oxidant, and (iii) the relation to other reactions that can occur, *e.g.*, Overman rearrangement, enamine formation, *i.e.* are there common intermediates with Pd(II) formed or do these other pathways compete with the oxidation. Finally, a key question needs to be addressed into the role of ligands in regard to controlling selectivity further.

4.2 Results and discussion

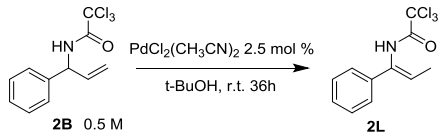
4.2.1 Reaction of the $PdCl_2(CH_3CN)_2$ with alkenes

As discussed in chapter 2, even in the absence of oxidant, allylic esters such as **1B** (Scheme 5) underwent rapid (in comparison to the rate of oxidation) isomerisation to the linear allylic ester **1L**. The rate of the rearrangement was reduced when the catalyst was first stirred with benzoquinone to the extent that (30%) enantiomeric excess was retained in the product. Omission of benzoquinone resulted in rearrangement of branched linear allylic ester **1B** to linear allylic ester **1L** with only trace amounts (< 5%) of oxidation products formed (Scheme 5).



Scheme 5. Rearrangement of allylic ester**1B** to **1L** catalysed by Pd(II).

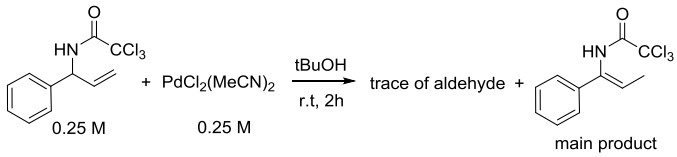
Similarly, when allylic amide **2B** was allowed to react with 2.5 mol% of the Pd catalyst, in the absence of *p*-benzoquinone, only trace amounts of the aldehyde product were formed. Instead, rearrangement to form the corresponding enamine **2L** was observed with > 75% yield (Scheme 6).



Scheme 6. Isomerisation of allylic amide to enamine catalysed by Pd(II).

Furthermore, with stoichiometric [$PdCl_2(MeCN)_2$], less than 5% conversion of styrene was observed even over several days (Figure 3) and with 2,2,2-trichloro-N-(1-phenylallyl)acetamide no oxidation and >95 % conversion to the enamine was observed (Scheme 7). The lack of conversion is particularly important since, in the presence of oxidant (benzoquinone), full conversion and AM selectivity was achieved.

These data suggests that although Pd(II) can, and indeed does (vide infra), bind alkenes readily, these Pd(II) alkene complexes are unlikely to be involved in the catalytic cycle and are instead a resting state for the catalyst and an initial step in isomerisation.



Scheme 7. Reaction between an allylic amide and stiochiometric Pd(II) in the absence of benzoquinone.

The possibility of formation of alkene Pd(II) complexes was explored with styrene and an allylic amide. Both styrene[7] and allylic amides form complexes with [$PdCl_2$(MeCN)] in benzene. Removal of solvent *in vacuo*, yielded a red solid and tacky solid, respectively. The Raman spectra (λ_{exc} 785nm) of both compounds show clear shifts in the olefinic and, in the case of allylic amides, the carbonyl stretching modes, confirming complexation to Pd(II). In the case of styrene, the loss of one of the two intense bands at ca. 1620 cm^{-1} is consistent with η_2-complexation of the alkene. The alkenes were released upon dissolution in DMSO-d_6 (Figure 1).

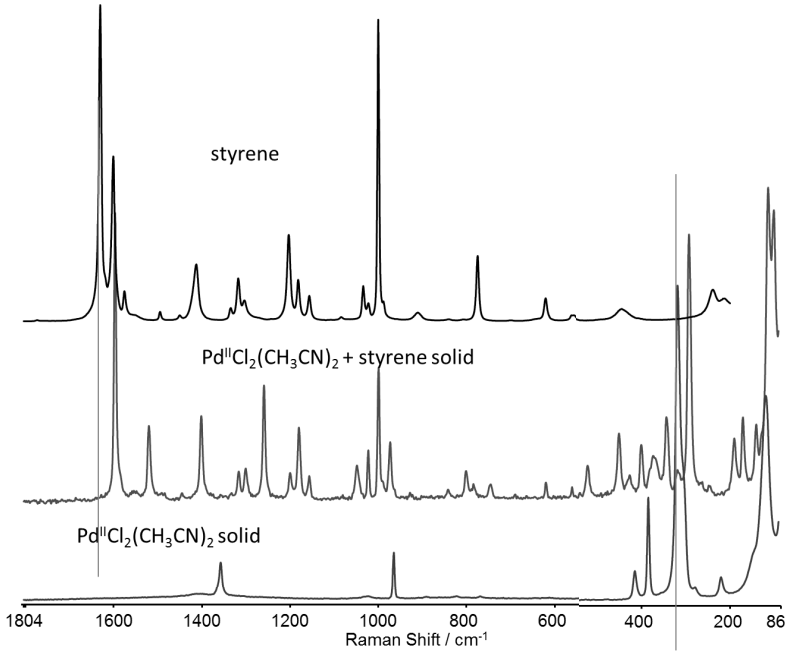


Figure 1. Raman spectra (λ_{exc} 785nm) of styrene, the catalyst and the complex isolated from a mixture of styrene and catalyst in benzene.

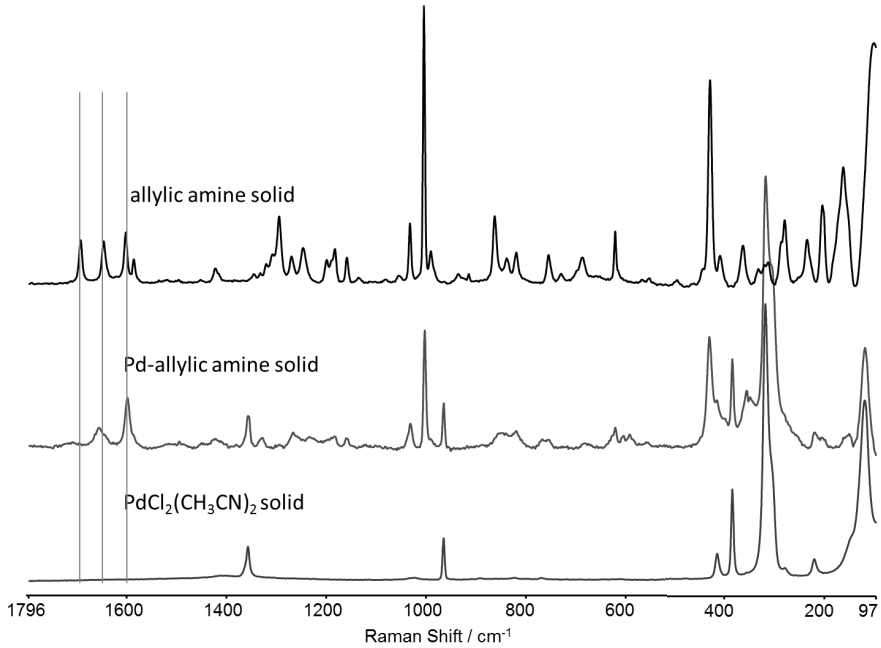


Figure 2. Raman spectra of 2,2,2-trichloro-N-(1-phenylallyl)acetamide, the complex isolated from benzene and the catalyst.

The reaction of styrene and of allylic amines with sub-stoichometric [Pd(II)Cl_2(CH_3CN)$_2$] was investigated in the absence of terminal oxidant. In the case of styrene, although within one hour the reaction mixture turned from orange to dark green and a precipitate formed, and indeed little conversion was observed even after 2 days. The ^{1}H NMR spectrum obtained of the liquid phase is similar to that of styrene (Figure 3i) with minor broadening (Figure 3ii). In contrast the spectrum obtained from the solid formed (Figure 3iii) shows broadening of the β-H of the alkene and the ortho-hydrogens of the phenyl ring. This latter spectrum returns to that of styrene upon addition of DMSO (Figure 3iv) indicating that a styrene-Pd(II) complex had formed. The lack of conversion to the aldehyde under stoichiometric conditions is in contrast to the report of Spencer et al. in which, 2 eq. of $PdCl_2$, in DMF/H_2O provided 58% conversion of styrene to aldehyde after 5 h,[8] and may indicate that water is necessary as nucleophile in order for the reaction to proceed, however it is more probable that the primary reason for a lack of reaction in *t*-BuOH is that the Pd(II) catalyst is precipitated as a 1:1 complex with styrene and therefore cannot catalyse the reaction.

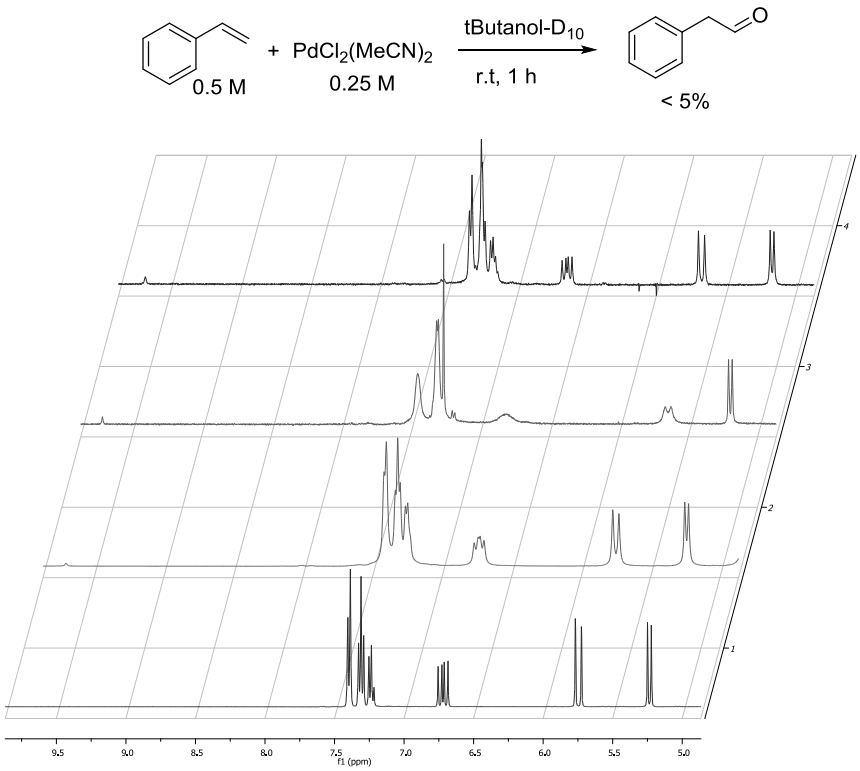


Figure 3. ^{1}H NMR spectrum (from bottom to top) (i) of styrene, (ii) of the liquid phase obtained from an equimolar mixture of $[PdCl_2(CH_3CN)_2]$ and styrene in *t*ert-butanol-D_{10} after stirring for 1 h at room temperature, (iii) of the solid formed (dissolved in $CDCl_3$) and (iv) after addition of DMSO to solution (iii).

In contrast to styrene, however, the solid formed upon from mixture of allylic amide and $[PdCl_2(CH_3CN)_2]$ in *t*-BuOH does not show obvious difference from the allylic amide and a significant amount of enamine formation was observed (Figure 4). These data indicate that although the allylic amide forms a complex with Pd(II), its association constant is likely to be lower than that of styrene. Furthermore, although $PdCl_2(MeCN)_2$ forms relatively stable complexes with the alkenes, it is not itself capable of rapid oxidation of the alkene and, where possible, engages in isomerisation processes instead.

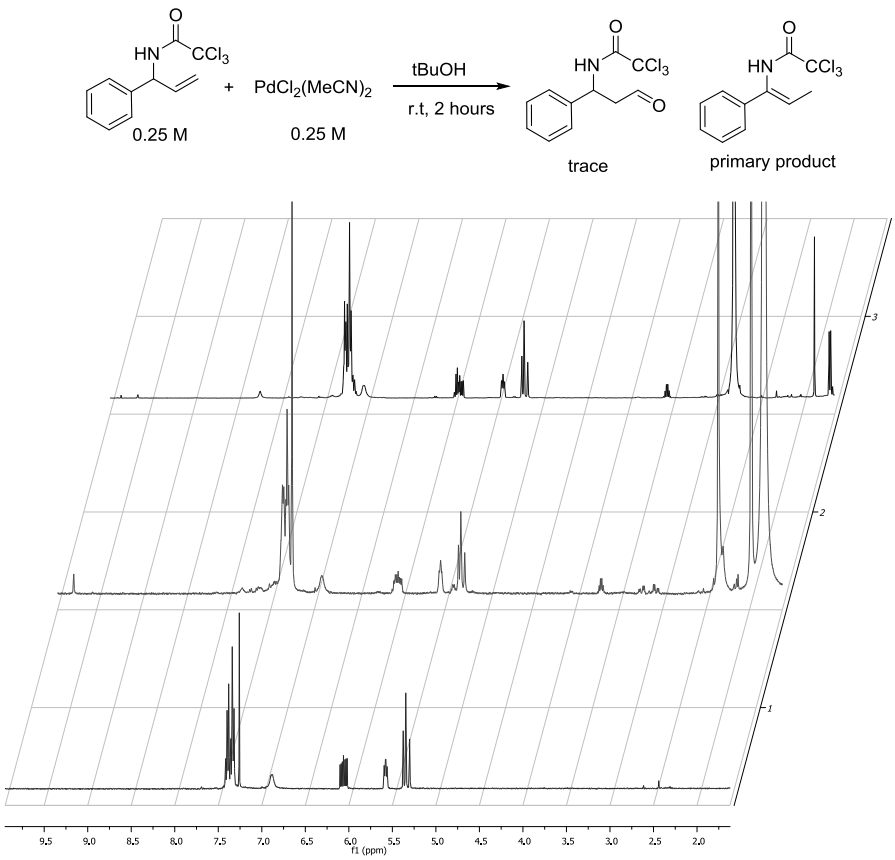


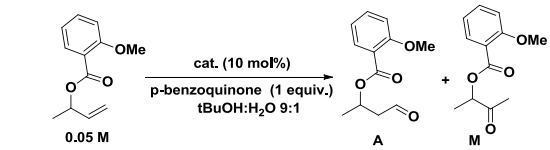
Figure 4. ^{1}H NMR spectrum (bottom to top) of (i) 2,2,2-trichloro-*N*-(1-phenylallyl)acetamide in $CDCl_3$, (ii) of solid (dissolved in $CDCl_3$) (iii) solution (diluted in $CDCl_3$) obtained after 1 h at room temperature from a mixture of $[PdCl_2(CH_3CN)_2]$ and 2,2,2-trichloro-*N*-(1-phenylallyl)acetamide.

The effect of variation in catalyst on the selectivity and conversion achieved in the oxidation of allylic esters was explored. Although $PdCl_2$ is the catalyst used primarily for the Wacker oxidation, it provides only modest to good reactivity under the present conditions (Table 1, entries 1 and 7), in comparison to the nitrile based catalysts such as $[PdCl_2(MeCN)_2]$. Hence, although additional nitrile ligands are not essential, they increase reactivity possibly due to catalyst solubility (Table 1, entries 2, 8 and 9); it should be noted that $PdCl_2$ shows limited solubility in *t*-BuOH. In the case of $PdBr_2$, some rearrangement products were observed but, as with PdI_2, oxidation was not observed (Table 1, entries 12 and 13). Notably, although in the presence of nitrile ligands full conversion is achieved, addition of 1 to 10 equiv of acetonitrile resulted in a near complete loss of activity towards oxidation but did not supress isomerisations.

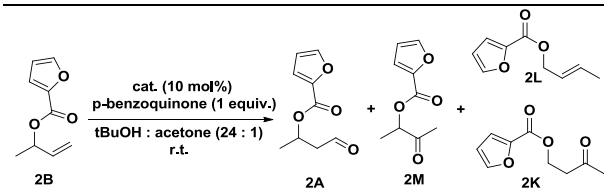
Similar reactivity as with $[PdCl_2(MeCN)_2]$ was observed with allyl complexes, *e.g.*, $(\eta^3\text{-}C_3H_5)_2Pd_2Cl_2$, (Table 1, entry 11). Importantly, the presence of less labile ligands, such as trisubstituted phosphine and 1,5-cyclodiene, resulted in a complete loss of oxidation activity and minor amounts of isomerisation products formed (Table 1, entries 4,5 and

11). Indeed, in the case of the two step one pot enantioselective conversion of linear allylic imidate to protected β-amino-aldehydes (see chapter 3), although a Pd(II) catalyst was used for the first isomerisation step, additional $PdCl_2(MeCN)_2$ was required in order for the subsequent oxidation to take place (see chapter 4 for details). In the case of $Pd(OAc)_2$, conversion was not observed even with addition of KCl. Similar results were obtained in the case of allylic amides also (see chapter 3).

Table 1. Dependence of conversion and selectivity on catalyst used



entry	catalyst	Conv.	**A : M**
1	$PdCl_2$	full	2.1 : 1
2	$PdCl_2(MeCN)_2$	full	3 : 1
3	$Pd(OAc)_2$	0 %	-
4	$PdCl_2(o\text{-}tolyl_3P)_2$	0 %	-
5	$PdCl_2(COD)$	0 %	-



entry	catalyst	Conv.	**2A : 2M : (2L+2K)**
6	none	0 %	---
7	$PdCl_2$	68 %	19 : 7 : 42
8	$PdCl_2(MeCN)_2$	full	83 : 11 : 6
9	$PdCl_2(PhCN)_2$	full	84 : 10 : 6
10	$(\eta^3\text{-}C_3H_5)_2Pd_2Cl_2$	full	75 : 9 : 16
11	$PdCl_2(PPh_3)_2$	0 %	---
12	$PdBr_2$	ca. 5%	---
13	PdI_2	0 %	---

4.2.2 Role of oxidant in the Pd(II) catalysed oxidation of alkenes and suppression of isomerisation reactions

As discussed above, the presence of the oxidant, benzoquinone, has an important role not only as an electron sink but also in reducing the rate of isomerisation reactions, in

particular the Overman rearrangement[5] in the case of allylic esters and enamine formation in the case of allylic amides. Furthermore, as shown above, the catalyst cannot oxidise the substrate on its own even where the catalyst is used stoichiometrically. These observations raise questions as to the roles played by the oxidant over and above its role as electron sink. It is notable however, that although an increase in catalyst concentration results in an increase in the rate of reaction with stoichiometric benzoquinone, using excess benzoquinone does not have a similar effect, and with 50 mol% oxidant 60% conversion (with 50% oxidised products and 10% rearrangement products) was obtained after 1 h. Such behaviour is consistent with a rapid prior equilibrium, for example of a benzoquinone/palladium complex that lies in favour of the complex.

Overall, the conversion to oxidised products achieved is limited by the amount of benzoquinone available and not the palladium catalyst; *i.e.* the catalyst itself even under normal reaction conditions does not serve as a terminal electron sink.

Formation of complexes between the allylic amide and $[PdCl_2(MeCN)_2]$ is manifested in the formation of precipitates under reaction conditions and indeed a mixture of 1:1 and 2:1 alkene:Pd(II) complexes can be expected to be present in solution.[7] The complexation of alkenes to the Pd(II) would be expected to compete with coordination of benzoquinone. If benzoquinone needs to coordinate during the catalytic cycle then such complexation would be expected to inhibit the reaction. This possibility was probed through reactions in which the order of addition of alkene (0.15 M) and benzoquinone (1.0 M) to a solution of $[PdCl_2(MeCN)_2]$ (0.025 M) in *t*-butanol-D_{10} was varied. Full conversion was obtained with high selectivity to aldehyde within 55 min when the alkene and benzoquinone were added simultaneously or benzoquinone added first. By contrast when the when the alkene was stirred with $[PdCl_2(MeCN)_2]$ for 15 min prior to addition of benzoquinone, although 95% conversion was observed a substantial amount of enamine (doublet at 1.6 ppm in Figure 5) was obtained also. These data support the hypothesis that complexation between the alkene and Pd(II) leads to isomerisation while in the presence of oxidant this pathway is effectively shut down. Notably, isomerisation of the substrates as well as oxidation was prevented by addition of a small amount of DMSO.

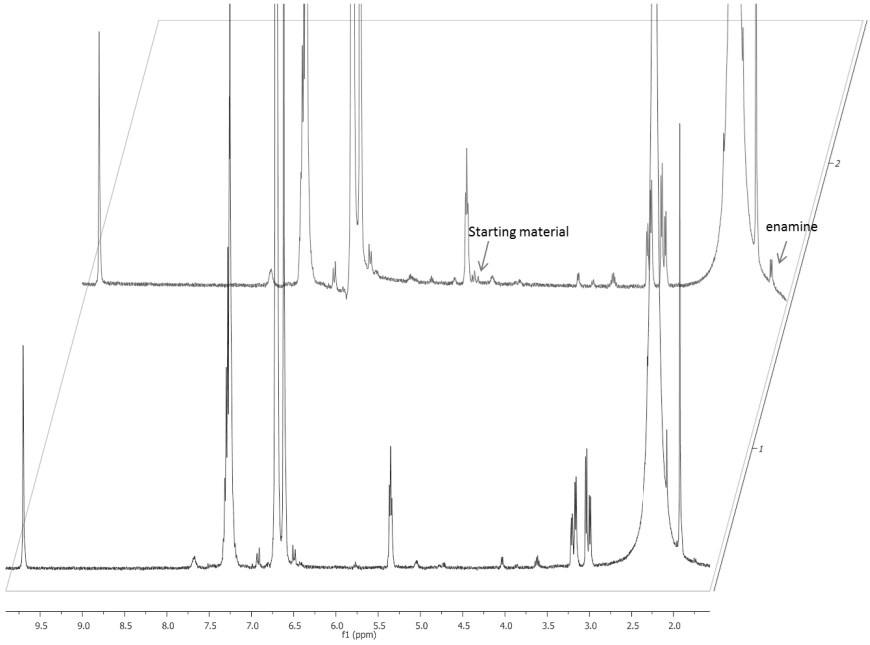
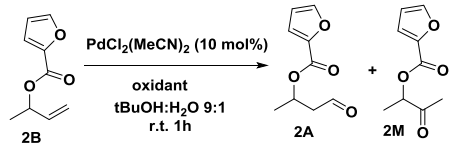


Figure 5. ^{1}H NMR spectra of the reaction mixture (2,2,2-trichloro-N-(1-phenylallyl)acetamide, benzoquinone and ($PdCl_2(CH_3CN)_2$])and in *t*-butanol-D_{10}) diluted in $CDCl_3$ after 55 min. bottom: all reagents added simultaneously, top: allylic amide added 15 min prior to benzoquinone.

Although benzoquinone was the oxidant of choice in the methods described in chapters 2 and 3, the effectiveness of other oxidants was examined in the oxidation of allylic esters. Dichlorobenzoquinone shows similar activity and selectivity as BQ in the oxidation of allylic esters. Notably, only 4% conversion to a rearrangement product was obtained using 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) as oxidant as well as 3,3',5,5'-tetra-*tert*-butyl-4,4'-diphenoquinone (TBD) and $K_3[Fe(CN)_6]$ (Table 2).

Table 2. Pd(II) catalysed oxidation of allylic esters with various oxidants



Entry	oxidant	conversion	**A : M**
1	benzoquinone (100 mol%)	full	2.9 : 1
2	benzoquinone (200 mol%)	full	2.9 : 1
3	benzoquinone (50 mol%)	60%	2.5 :1
4	dichloro-benzoquinone (100 mol%)	full	2.9 : 1
5	2,3-dichloro-5,6-dicyano-1,4-benzoquinone (100 mol%)	4 %	--
6	3,3',5,5'-tetra-*tert*-butyl-4,4'-diphenoquinone	3 %	--
7	*t*-BuOOH(70%wt in H_2O) (100 mol%)	50 %	1 : 1
8	$K_3[Fe(CN)_6]$ (100 mol%)	3 %	--

The differences in reactivity between the various substituted benzoquinones and other electron and oxygen transfer oxidants indicates that the coordination of BQ to Pd(II) is likely to be a key step in the catalytic cycle since the tetrasubstituted BQ (DDQ), despite having a similar redox potential, is less likely to coordinate to Pd(II) due to the steric hindrance. However, it is notable that the rearrangement is also suppressed.

4.2.3 Evidence for complexation of Pd(II) with p-benzoquinone

Benzoquinone was employed as an oxidant in most of the reactions carried out in chapters 2 and 3. In principle, the role of the oxidant could be expected to reoxidise Pd(0) to Pd(II) after the substrate has undergone oxidation. However, as discussed above, the Pd(II) catalysts do not oxidise, spontaneously, the alkenes despite forming η_2-alkene complexes.

When only 0.3 equiv. of *p*-benzoquinone with respect to substrate were added to **2B** in *t*-BuOH in the presence of 2.5 mol% [$PdCl_2(MeCN)_2$], 80% conversion was observed, albeit with 30 % yield of the aldehyde product and ca. 50% yield of the isomerised substrate **2L**. Hence, we postulate that benzoquinone coordinates to the Pd(II) catalyst prior to reaction of the catalyst with the alkene substrate. Indeed, for the reaction to proceed efficiently, it was found necessary to stir the Pd(II) catalyst with *p*-benzoquinone in *t*-BuOH, for 10 to 20 minutes before addition of substrate. Spectroscopy was employed to support this hypothesis.

Stoichiometric [$PdCl_2(MeCN)_2$] (5 mM) was stirred with benzoquinone (5 mM) in *t*-BuOH for 2 h after which the solvent was removed *in vacuo*. The ^{1}H NMR and Raman spectra of the residue were recorded. The spectra showed the formation of hydroquinone by ^{1}H NMR and semiquinone by Raman spectroscopy. (BQ δ in $CDCl_3$ is at 6.79 ppm and for hydroquinone at 6.71ppm, Figure 6).

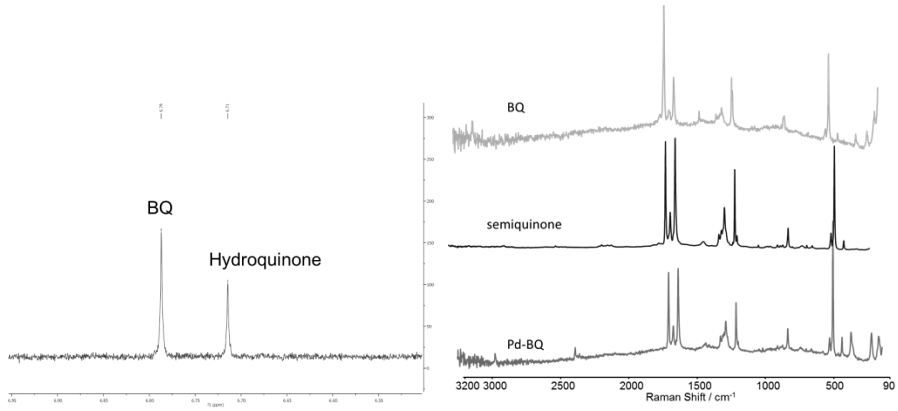
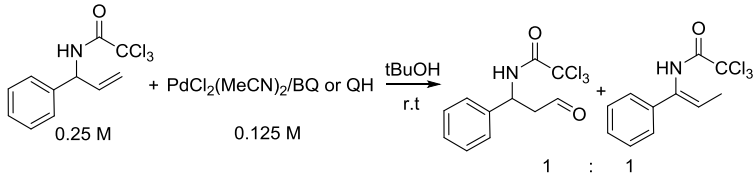


Figure 6. Left: ^{1}H NMR and right: Raman spectrum (785 nm) of the solid obtained from a 1:1 mixture of $Pd(II)(Cl)_2(CH_3CN)_2$ and BQ (**1**) in *t*-BuOH.

Since quinhydrone (QH) was formed during the reaction, QH was prepare from a 1 : 1 mixture of BQ and hydroquinone. The dark red solid QH (5 mM) was mixed with an equimolar amount of $PdCl_2(MeCN)_2$ (5 mM) for 2 h in *t*-BuOH, the solvent was removed

in vacuo and the isolated product $PdCl_2(MeCN)_2$ / QH (**2**) obtained was characterised by ^1H NMR and Raman spectroscopy.

When a solid sample of **1** (50 mol%) was used in the oxidation of styrene, ca. 50% conversion was obtained with the aldehyde as the main product within 2 h. Longer reaction times did not lead to further conversion of the styrene. Under these conditions, allylic amide was also oxidised to the corresponding aldehyde together with formation of enamine. Although the formation of enamine is slower than that of aldehyde, a 1 : 1 ratio of both products were obtained after full conversion was reached. The same results were obtained using residue **2** (Scheme 8).

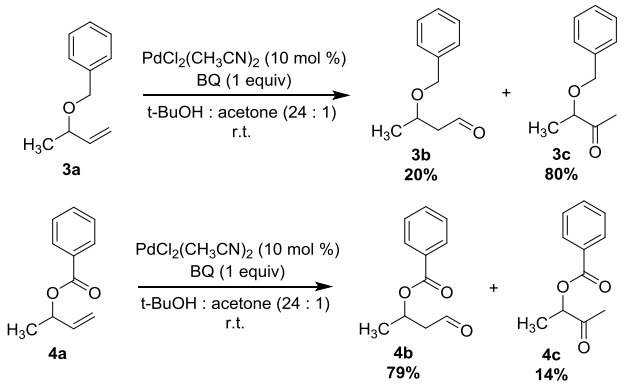


Scheme 8. Oxidation of allylic amide with substoichiometric oxidant/catalyst.

These data suggest that the oxidation of styrene and allylic amides is catalysed by either a palladium species in a higher oxidation state than Pd(II) or a by a concerted electron transfer to the benzoquinone from the substrate mediated by Pd(II), while the formation of enamines is catalysed by Pd(II). This interpretation is further confirmed by reaction of an equimolar mixture of allylic amide (0.05 M), $PdCl_2(MeCN)_2$ and BQ in *t*-BuOH. This reaction only gave corresponding aldehyde as main product without formation of enamine.

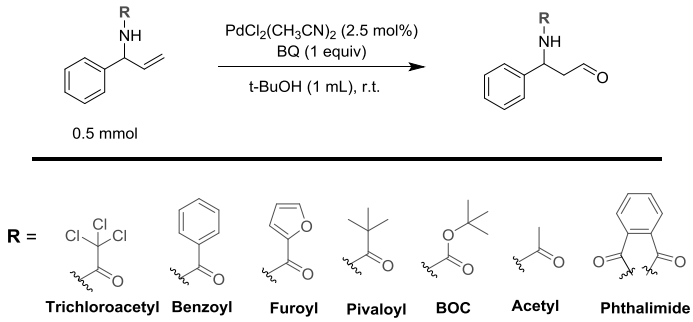
4.2.4 Insight into the mechanism from substrate scope

In summary, in the first instance the functional groups of allylic alcohols and amines were protected to form the corresponding allylic esters and allylic amides in order to prevent oxidation of the alcohol and amine functional groups. A number of protecting groups (PG) were investigated in the present study. In the case of the allylic alcohols, it was found that protecting groups containing carbonyl functionalities resulted in a significant increase in the AM selectivity of the aldehyde product, over the Markovnikov (ketone) product (Scheme 9). These data suggest that the presence of the carbonyl moiety directs the nucleophile to attack the terminal carbon of the α-olefin, thereby forming the aldehyde product. Such phenomena could be a consequence of an effect of the carbonyl group on the coordination mode of the Pd catalyst to the substrate. As such, it is possible that the Pd catalyst coordinates to both the PG carbonyl moiety and the alkene group, simultaneously.



Scheme 9. Effect of protecting group on selectivity.

In the case of the protected allylic amines, a range of protecting groups was investigated also. 1-phenylprop-2-en-1-amine was protected with carbonyl containing groups, where the R substituent was varied, as shown in Scheme 10. Most of the protecting groups allowed for the aldehyde to be formed as the main product with excellent selectivity with respect to ketone (See chapter 3, scheme 3). These data confirm the importance of a carbonyl group in achieving regioselectivity.



Scheme 10. Variation in protecting group.

4.3 Summary and conclusions

The experimental data reported in this chapter indicate that although Pd(II) can bind to alkenes, such complexation actually retards their oxidation rather than accelerates it. Coordination of the oxidant prior to attack on the substrate is therefore most likely to occur. These results hold important implications with regard to the standard mechanism proposed for the Wacker Tsuji reaction in that an intramolecular electron transfer from alkene to benzoquinone mediated by the Pd(II) ion is involved rather than a more classical Pd(II)/Pd(0) cycle. This conclusion implies that efforts towards extending the method to a system in which oxygen is the terminal oxidant should focus on regeneration of a mediator such as benzoquinone rather than attempting to reoxidise a putative Pd(0) intermediate that is unlikely to be present in fact.

4.4 Experimental section

General Procedures and methods

All reagents are of commercial grade and used as received unless stated otherwise. Chromatography: Merck silica gel type 9385 230-400 mesh, TLC: Merck silica gel 60, 0.25 mm, with visualisation by UV and potassium permanganate staining. ^{1}H-NMR spectra were recorded on a Varian AMX400 (400 MHz). Mass spectra were recorded on an AEI-MS-902 mass spectrometer (EI+) or a LTQ Orbitrap XL (ESI+). Raman spectra were recorded at 785 nm on a Perkin Elmer Raman station. For details of reaction conditions and characterisation of products for allylic alcohols see chapter 2, for allylic amines see chapter 3.

4.5 Bibliography

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