Transposition of Allylic Alcohols into Carbonyl Compounds Mediated by Transition Metal Complexes

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Received July 15, 2002

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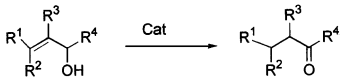
I. Introduction

The conversion of allylic alcohols to saturated carbonyl compounds is a useful synthetic process and would conventionally require a two-step sequential oxidation and reduction reactions. A one-pot catalytic transformation (Scheme 1), equivalent to an internal

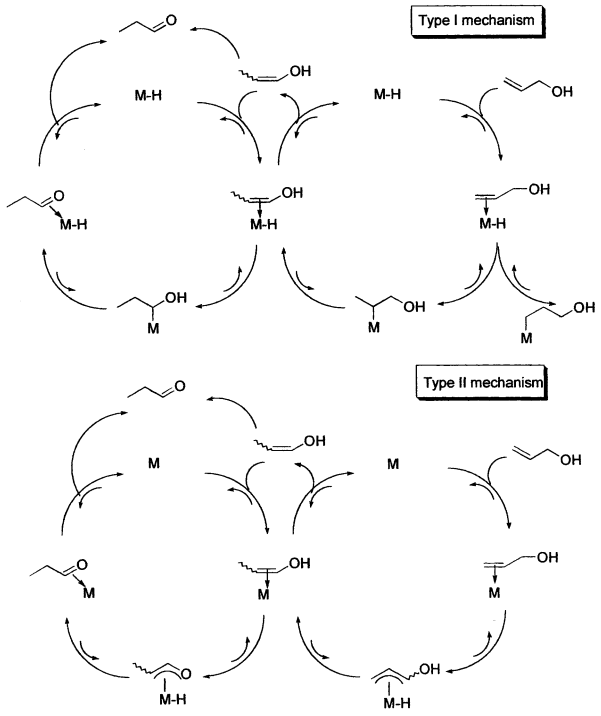
Scheme 1



redox process, is a conceptually attractive strategy.[1−3] Apart from maintaining total atom economy in the process,[4] it could also avoid the use of costly and/or toxic reagents, especially in the oxidation reactions. In this regard, a number of methods have been developed harnessing the ability of transition metal complexes to migrate double bonds. Such a migration in the case of an allylic alcohol would result in the formation of an enol (or enolate) intermediate which on tautomerization can afford the saturated carbonyl compound.[5]

Interestingly, with the exception of a handful, in particular Mo, group 8, 9, and 10 transition metal complexes have been predominantly employed for this transposition. Two main mechanisms have been proposed for this reaction (Scheme 2):

Scheme 2



(i) The type I mechanism, via alkylmetal intermediates. In this case, the catalyst is a metal-hydride M−H, either isolated or generated in situ. After π complexation to the allylic alcohol, insertion reaction can lead to σ-complexes. These reactions are usually reversible, and therefore, the abstraction of the hydrogen α to the OH group leads to the enol η-2 complexed to the metal hydride. A final decomplexation (via a dissociative mechanism) gives back the catalyst and the enol, which then tautomerizes to the carbonyl derivative. Interestingly, an associative mechanism could also be envisaged for this last step; particularly attractive would be the reaction with a second molecule of allylic alcohol thereby directly generating the initial η-2 intermediate. Yet another alternative pathway can be considered for this last step. Insertion of the metal-hydride on the enol double bond can give a σ-complex with the metal linked to the carbon bearing the alcohol function. At this stage, migration of the hydrogen from the OH

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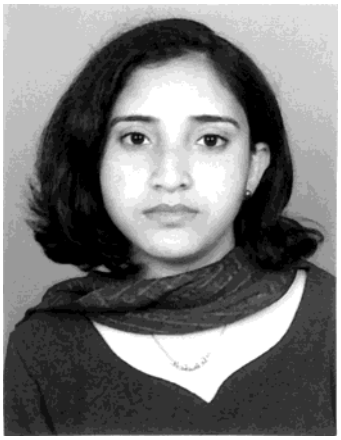
10.1021/cr0103165 CCC: $44.00
Published on Web 11/28/2002



Ramalinga Uma was born in Trichy (Tamilnadu), India. She obtained her M.Sc. degree from the University of Poona in 1991. Subsequently, she joined the School of Chemistry, University of Hyderabad, for doctoral studies under the supervision of Professor Goverdhan Mehta and was awarded her Ph.D degree in 1999. Later, she pursued postdoctoral studies (1999–2001) with Dr. René Grée at the Ecole Nationale Supérieure de Chimie de Rennes, France, where she worked on developing novel aldol-type reactions mediated by transition metal complexes. She is currently a postdoctoral fellow with Dr. Jeffrey Karpen at the University of Colorado Health Sciences Center, CO, working on the design and synthesis of polymer linked multivalent ligands and selective blockers for cyclic nucleotide gated ion channels.

Christophe Crévisy obtained his "diplôme d'ingénieur" in chemistry from the Ecole Nationale Supérieure de Chimie de Clermond-Ferrand in 1988 and received his Ph.D. degree in 1992 from the University of Orléans. His Ph.D. studies on the synthesis of antitumor enediynes were carried out under the direction of Dr. Jean-Marie Beau. From 1992 to 1993, he did a postdoctoral work with Pr. Pierre Deslongchamps at the University of Sherbrooke (Canada). Since 1994, he has been a senior lecturer at the Ecole Nationale supérieure de Chimie de Rennes. He is currently working in the research group of Dr. René Grée and his main research interests are the development of new synthetic methodologies such as transition metal catalyzed aldol reactions, [4+3] cycloaddition reactions as well as synthesis on polymer supports.

group to the metal would lead to the carbonyl η-2 complexed to the M−H. A final decoordination can furnish the carbonyl and regenerate the catalyst. Regardless of the exact nature of the final step of the reaction, it is important to note that type I mechanism is *intermolecular*.

(ii) The type II mechanism, via π-allyl intermediates. The reaction starts again with a η-2 complexation of the allylic alcohol on the transition metal catalyst M. In this case, it is followed by the migration of the hydrogen linked to the carbinol center onto

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the metal leading to a π-allyl metal hydride intermediate. Readdition of this hydrogen on the other side of the allylic system leads to the enol complexed in an η-2 manner to the catalyst. As in the previous mechanism, decomplexation regenerates the catalytic species M and gives the enol that tautomerizes to the carbonyl. Here again, an associative mechanism could be considered for this last step. Alternatively, it is possible to consider another 1,3-shift of the OH hydrogen, with a first migration onto the metal followed by another migration to the carbon vicinal to the carbonyl leading to a η-2 complex that can then regenerate the catalyst M and give the transposed product. It is important to note that type II mechanism involves an *intramolecular* hydrogen transfer.

In both, type I and type II mechanisms, steric as well as electronic factors are expected to play significant roles in the formation of key intermediates such as the σ-bonded complexes or the π-allyl derivatives. Therefore, such factors could strongly influence the scope and limitation of the isomerization reaction.

A third mechanism involving dehydrogenation of the alcohol, to give an unsaturated ketone, followed by readdition of the metal hydride to the double bond has been proposed for some ruthenium complexes (see Scheme 21).

It has been shown that the nitrogen atom plays a key role in the transition metal mediated isomerization of allylamines.[6] Likewise, for allylic alcohols, alternative mechanisms involving the oxygen moiety at some stage of the catalytic cycle (either at the alcohol or at the alcoholate stage) has also been suggested.[3,7] However, more data seem to be necessary to clarify the exact role of the oxygen atom in such isomerizations.

The purpose of this article is to review this reaction, mainly from the synthetic chemist's standpoint. For each family of catalyst, we have carefully considered the scope and limitation aspects with regard to the type of allylic alcohols that can be used in the transformation.[2] Furthermore, this isomerization reaction can potentially lead to the creation of one (or two) new stereogenic centers (Scheme 1). Therefore, it is suitable for extension to asymmetric catalysis and this important aspect has been discussed in the last part of this review.

Information regarding the nature of the catalyst, data on their turnover frequencies (TOF) as well as their turnover numbers (TON) have been furnished. When reliable data were available, the mechanistic details such as type I or type II mechanism have also been discussed. In this review, we have essentially considered homogeneous catalysts but complementary data from heterogeneous systems have been incorporated in a few cases where they seemed useful. Finally, extension to allylic ethers or amines has also been covered in selected cases.[8,9] This appeared especially important in the case of asymmetric catalysis where it can be considered as a useful alternative pathway.

II. Isomerization Reactions

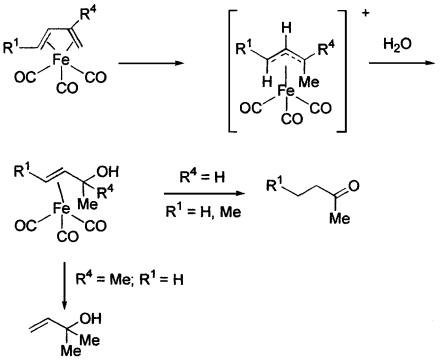
Several transition metal catalysts have been utilized to effect the isomerization reaction. This review is organized based on the metal complexes and the scope and limitations with respect to the allylic alcohol substrate. A separate section deals with the asymmetric catalysis.

A. Iron Complexes

Emerson and Pettit proposed the first example of an isomerization reaction catalyzed by iron complexes during their studies on the hydrolysis of π-allyl-iron tricarbonyl cations salts.[10] On reaction with water, the salt derived from butadiene-$Fe(CO)_3$ gave rise to appreciable quantities of 2-butanone; likewise, the piperylene complex gave 2-pentanone.

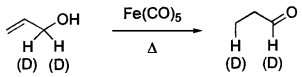
The formation of these products was rationalized by a probable attack of water to give substituted allyl alcohol complex and subsequent isomerization via π-allyl-hydridoiron tricarbonyl complexes to give the unstable enol-$Fe(CO)_3$ complexes, which could decompose to give the enols and then the corresponding ketones (Scheme 3). Support for this mechanism

Scheme 3



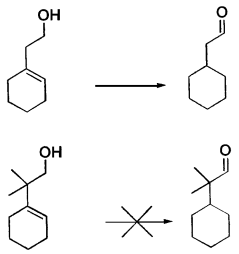
came from the results of the salt derived from isoprene-$Fe(CO)_3$ which mainly gave dimethylvinylcarbinol. In this case, the isomerization did not occur because of the absence of hydrogen on the carbon atom bearing the hydroxyl group. Further, on heating allyl alcohol with $Fe(CO)_5$, isomerization to propionaldehyde was observed, consistent with the mechanism of isomerization (Scheme 4).

Scheme 4



A little later, Rosenberg et al. have shown further evidence for such a mechanism.[11] Rearrangement of [1,1 $-^2H_2$] allyl alcohol with $Fe(CO)_5$ produced propionaldehyde with deuterium appearing in the methyl but not in the methylene group which was consistent with the mechanism involving a 1,3-hydrogen transfer. Further, it was found that there was no significant equilibrium between the intermediates as there was no significant aldehyde proton (by ^1H NMR) in the propionaldehyde formed. Such a mechanism suggested the requirement of at least one hydrogen on each carbon between the double bond and the carbinol group. This was indirectly confirmed using homoallylic alcohols (Scheme 5): while 2-(1-

Scheme 5

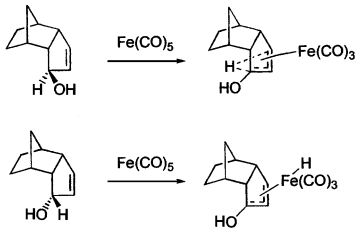


cyclohexenyl)ethanol underwent isomerization to the corresponding aldehyde as consecutive 1,3-hydrogen shifts are possible, no aldehyde was observed in the reaction of 2-methyl-2-(1-cyclohexenyl)propanol with $Fe(CO)_5$.

However, the data were also consistent with hydrogen migration occurring through a concerted suprafacial pathway not requiring the intermediacy of a π-allyl-hydridoiron tricarbonyl. Elegant experiments were designed by Rosenberg et al. to differentiate between the two mechanisms exploiting the well-defined topology of *endo*-α-1-hydroxy-5,6-dihydrodicyclopentadiene and *endo*-β-1-hydroxy-5,6-dihydrodicyclopentadiene systems.[12] In both the epimers, a mechanism operating through a 1,3-suprafacial hydrogen shift is possible. But, as the approach of $Fe(CO)_5$ from the least hindered *exo* side was considered reasonable, the π-allyl-hydroiron tricarbonyl mechanism is only possible in the case of the α-alcohol. The migrating hydrogen is indeed positioned to allow the formation of a π-allyl-hydroiron tricarbonyl complex. Whereas, in the β-alcohol, such a complex formation is sterically not possible and the reaction could proceed only through a concerted, sigmatropic 1,3-hydrogen shift. On heating,

at 130 °C for 16 h with 10 mol % $Fe(CO)_5$ under nitrogen, the α-alcohol underwent isomerization to the ketone. Whereas, under similar conditions the *β*-alcohol exhibited no detectable rearrangement. This result is in favor of a mechanism involving a *π*-allyl-hydroiron tricarbonyl complex (Scheme 6).

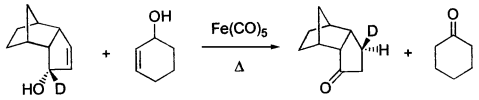
Scheme 6



However, a mechanism involving suprafacial 1,3-hydrogen shift occurring on the same face as the metal was also not ruled out wherein, a discrete Fe−H intermediate was not involved.

Strauss and Ford prepared the deutero-labeled *endo*-α-1-hydroxy-5,6-dihydrodicyclopentadiene and subjected it to the $Fe(CO)_5$ catalyzed isomerization to investigate the stereospecificity of the deuterium in the corresponding ketone as well as to probe the inter/intramolecular nature of the hydrogen migration.[13] It was found that when the deutero alcohol was heated in the presence of 2-cyclohexen-1-ol, only the deutero ketone and unlabeled cyclohexanone were obtained showing that crossover had not occurred (Scheme 7).

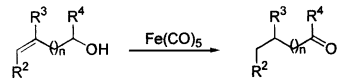
Scheme 7



These results in conjunction with those of Rosenberg's demonstrate conclusively that the transformation catalyzed by $Fe(CO)_5$ occurs with overall intramolecular 1,3-suprafacial shift of hydrogen on the same side of the molecule as the iron atom. Primary kinetic isotope effect values ranging from 1.12 to 1.46 with an average of 1.23 were obtained for the isomerization of endo-α-1-hydroxy-5,6-dihydrodicyclopentadiene at 136 °C with conversions ranging from 10 to 40%.[13] On the other hand, the dodecacarbonyl triiron catalyzed isomerization of 3-ethyl-1-pentene, considered to proceed through a *π*-allyl metal hydride intermediate, showed no primary kinetic isotopic effect.[14] As most 1,3-hydrogen shift reactions catalyzed by iron carbonyls are believed to involve the same catalytically active unsaturated iron carbonyl species, these results suggested that the introduction of a hydroxyl group had changed the rate determining step of the rearrangement and made possible a concerted suprafacial 1,3-hydrogen migration, with the migrating H atom on the same face as the metal atom.

A first study dealing with the scope and limitations of these reactions in synthesis was performed by Damico and Logan who screened half a dozen allylic alcohols toward isomerization mediated by $Fe(CO)_5$.[15]

Table 1



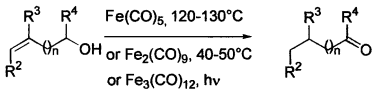
entries	R^2	R^3	R^4	n	cat. (%)	time (h)	conditions	GC yield (%)
a	H	H	C_3H_7	1	10	4	neat, 110 °C	80
b	H	H	C_9H_{19}	0	20	6	124 °C	60
c	H	Me	C_4H_9	0	20	6	124 °C	75
d	H	H	C_5H_{11}	0	3	1	*hν*, 20 °C	70
e	$-(CH_2)_2-$	H	$-CH_2-$	0	20	6	124 °C	20
f	$-(CH_2)_2-$	H	$-CH_2-$	0	3	4	*hν*, 20 °C	40
g	C_2H_5	H	H	1	10	6	neat, 110 °C	8
h	H	H	H	7	10	5	124 °C	∼10
i	H	H	H	7	5	5	*hν*, 20 °C	54

It was shown that heating secondary allylic alcohols either neat or in hydrocarbon solvents at 110−125 °C with 10−20 mol % $Fe(CO)_5$ for 2−6 h gave 60−80% conversions to isomerized ketones of greater than 95% purity (Table 1). Attempts to apply the above conditions to the isomerization of unsaturated nonconjugated primary alcohols or cyclic olefinic alcohols gave poor yields of the corresponding aldehydes or ketones. The decrease in yield was explained in terms of $Fe(CO)_5$ catalyzed dimerization of the resulting aldehyde during the prolonged heating. Therefore, alternative experimental conditions using $Fe(CO)_5$ in combination with ultraviolet light at room temperature was explored for the first time. Under irradiation with a 200-W high-pressure mercury lamp at 20 °C with 3−5% $Fe(CO)_5$ in pentane, the reaction of cyclic and primary allylic alcohols afforded higher yields, ranging from 40 to 60%, within 1−6 h of irradiation. Even alcohols with very remote double bonds, such as 9-decenol, could be isomerized under these reaction conditions. This result was consistent with the known migration of double bonds in monolefins, induced by iron carbonyls.[16]

Iranpoor et al. studied the nonacarbonyl diiron catalyzed conversion of unsaturated alcohols, ethers, and esters to their corresponding aldehydes, ketones, enol ethers, and enol esters. The same set of substrates as in the previous study were screened for nonacarbonyl diiron catalyst (2−7 mol %) in benzene at 40−50 °C and the results were compared with those obtained from pentacarbonyl iron catalyst at 120−130 °C (Table 2).[17]

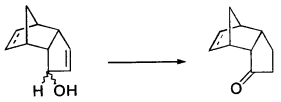
Examples of simple allylic alcohol, 1,1-disubstituted allylic alcohol, homoallylic alcohol, long chain primary alcohol with double bond remote from the carbinol moiety, cyclic allylic alcohols as well as their corresponding ethers and esters were shown to undergo efficient isomerization. In each case, $Fe_2(CO)_9$ proved to be a better catalyst as the reaction could be performed at a lower temperature with higher yields of the product and faster reaction rates. They extended their studies on isomerization by employing substoichiometric amounts of dodecacarbonyl triiron under photochemical activation ($\lambda \geq 560$ nm) in *n*-hexane at 25−30 °C. The same set of primary and secondary allylic and non allylic alcohols and ethers were isomerized to the corresponding saturated aldehydes, ketones, and enol ethers.[18]

Table 2



entries	R^2	R^3	R^4	n	catalyst (mol %)	time (h)	yield (%)
a	H	H	C_3H_7	1	$Fe(CO)_5$ (10)	4	80
b	H	H	C_3H_7	1	$Fe_2(CO)_9$ (20)	1.75	90
c	H	H	C_3H_7	1	$Fe_3(CO)_{12}$ (30)	1.67	88
d	H	H	H	7	$Fe(CO)_5$ (10)	5	10
e	H	H	H	7	$Fe_2(CO)_9$ (20)	2	75
f	H	H	H	7	$Fe_3(CO)_{12}$ (30)	2	78
g	H	H	H	0	$Fe_2(CO)_9$ (20)	2	85
h	H	H	H	0	$Fe_3(CO)_{12}$ (20)	1.33	90
i	H	Me	Me	0	$Fe(CO)_5$ (20)	6	75
j	H	Me	Me	0	$Fe_2(CO)_9$ (20)	2.5	90
k	H	Me	Me	0	$Fe_3(CO)_{12}$ (30)	2	88
l	$-(CH_2)_2-$	H	$-CH_2-$	0	$Fe(CO)_5$ (20)	6	20
m	$-(CH_2)_2-$	H	$-CH_2-$	0	$Fe_2(CO)_9$ (20)	1.5	85
n	$-(CH_2)_2-$	H	$-CH_2-$	0	$Fe_3(CO)_{12}$ (20)	2	90

Table 3

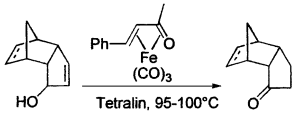


entries	C8−C9	OH	catalyst (mol %)	time (h)	yield (%)
a	CH_2CH_2	α	$Fe(CO)_5$ (10)	16	40
b	CH_2CH_2	α	$Fe_2(CO)_9$ (40)	6	85
c	CH_2CH_2	α	$Fe_3(CO)_{12}$ (25)	1	94
d	CH=CH	α	$Fe(CO)_5$ (70)	10	5
e	CH=CH	α	$Fe_2(CO)_9$ (70)	5	58
f	CH=CH	α	$Fe_3(CO)_{12}$ (30)	6	60
g	CH_2CH_2	β	$Fe(CO)_5$ (100)	16	0
h	CH_2CH_2	β	$Fe_2(CO)_9$ (100)	6	0
i	CH_2CH_2	β	$Fe_3(CO)_{12}$ (25)	2	0

Tricyclic allylic alcohols and the related ethers and esters were also isomerized in moderate to good yields with 25−80 mol % of the catalyst (Table 3).

To establish the active species (viz. $Fe(CO)_3$ or $Fe(CO)_4$) involved in the reaction, benzylideneacetone tricarbonyl was used as a source of $Fe(CO)_3$ free from $Fe(CO)_4$. It was shown that when benzylidenacetone tricarbonyl (40 mol %) was treated with allylic alcohols, ethers, or cycloocta-1,5-diene at 95−100 °C in tetralin, rapid double bond migration occurred giving rise to the isomerized products (Scheme 8). As

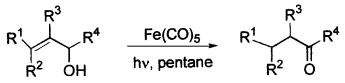
Scheme 8



$Fe(CO)_3$ is the only reactive species present under these conditions, it was deduced that it should be the active catalyst responsible for the double bond migration in these compounds.

Though the initial isomerization studies began with $Fe(CO)_5$ under thermal conditions, this catalyst was not explored as much due to rather slow reaction rates, low yields, high temperature, and toxicity. More recently, Grée et al. studied a wide variety of allylic alcohols and developed the scope and limitation of this cheap and readily available catalyst.[19] In

Table 4



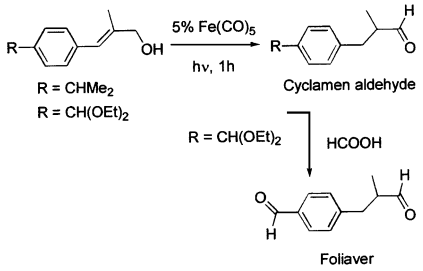
R^1	R^2	R^3	R^4	catalyst (%)	time (h)	yield (%)
H	H	H	n-C_5H_{11}	1	1	95
Me	H	H	n-C_5H_{11}	2	2	86
H	H	Me	n-C_5H_{11}	2	2	95
H	H	H	Ph	5	1.5	84
Me	H	H	Ph	5	5	64
Me	Me	H	n-C_5H_{11}	5	4	37[a]
Ph	H	H	n-C_5H_{11}	5	2	93
Ph	H	H	Ph	10	1.5	90
Ph	H	H	Me	5	1.5	85
Ph	H	Me	n-C_5H_{11}	5	5	80
Ph	H	H	H	5	2	38
Ph	H	Me	H	5	1	90
CO_2Me	H	H	n-C_4H_9	5	1	70
H	H	CO_2Me	Ph	5	1	87
COPh	H	H	n-C_4H_9	5	3	70
CN	H	H	n-C_4H_9	10	6	40
H	CN	H	n-C_4H_9	10	1.5	90

[a] 2-Methyl-1-nonen-4-ol was also isolated (21%); under the same reaction conditions, it could be transformed, albeit more slowly, into the target ketone.

the presence of 1−10 mol % of $Fe(CO)_5$ under photochemical activation in pentane, it was shown that allylic alcohols with various types of substituents as well as various substitution patterns underwent efficient isomerization usually in good to excellent yields (Table 4).

It was established that substrates bearing either alkyl or aryl groups on the carbinol center (R^4) underwent smooth transposition. Furthermore, this reaction was compatible with alkyl, aryl as well as electronwithdrawing groups on the double bond (R^1 or R^3). It was demonstrated for the first time that sterically hindered trisubstituted olefins could be successfully isomerized under these reaction conditions. Finally, the above results led to a short and efficient synthesis of two perfume components, the cyclamen aldehyde and foliaver (Scheme 9).

Scheme 9



Nevertheless, the following appear to be some of the limitations to this $Fe(CO)_5$ mediated isomerization:[19]

(i) In agreement with previous results, primary allylic alcohols without an α-substituent, such as cinnamyl alcohol gave low yields.[15] This appears to be due to competitive reactions at the aldehyde function, such as aldolization reactions.

(ii) Allylic alcohols on polyunsaturated systems either gave the expected η-4 diene tricarbonyliron complexes or did not react at all.

Table 5

R^1	R^2	R^3	R^4	catalyst	substrate/metal	V_{org}/V_{aq}	TOF (h^{-1})
H	H	H	Me	$Rh_2(SO_4)_3$	120	2	2520
H	H	H	*n*-Pr	$Rh_2(SO_4)_3$	120	2	490
H	H	H	*n*-Pent	$Rh_2(SO_4)_3$	120	2	30
H	H	H	Et	$RhCl_3$	210	1	540
Me	H	H	Me	$RhCl_3$	200	1	36
H	H	H	*n*-Pr	$RhCl_3$	40	4.4	31
H	*n*-Pr	H	H	$RhCl_3$	40	4.4	3.2
n-Pr	H	H	H	$RhCl_3$	40	4.4	3.1
Me	$-CH_2)_2-$	H	$-CH_2-$	$RhCl_3$	60	1	150
$-CH_2-CH_2-CH=CMe_2$	Me	H	H	$RhCl_3$	80	1	4.8
H	H	H	*n*-Pr	$RhCl_3$	41	1/0	60
H	H	H	Et	$RhCl_3$	39	1/0	63
H	H	H	*n*-Pent	$RhCl_3$	50	1/0	60

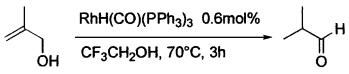
(iii) Finally, alcohols with a strong electron withdrawing substituent such as a CF_3 group on the carbinol center did not react. The inhibition of the 1,3-hydride shift by the CF_3 group could be a plausible explanation for this result.

In conclusion, several iron carbonyl reagents appear to be useful catalysts for this transformation despite the fact that in some cases relatively high quantities of catalyst have been used.[20] With those derivatives, there is adequate evidence for the reaction occurring via π-allyl intermediates (type II mechanism). Extensive studies have shown that these catalysts bring about transposition in a relatively broad range of substrates, with some well-recognized limitations. Nevertheless, these $Fe(CO)_x$ catalysts are not suitable for asymmetric transposition of allylic alcohols. Finally, it is worth mentioning that these studies eventually led to the development of a novel tandem isomerization−aldolization reaction mediated by iron carbonyls.[21]

B. Rhodium Complexes

In 1975, Strohmeier et al demonstrated that $RhH(CO)(PPh_3)_3$ (0.6 mol %) quantitatively isomerized methallyl alcohol to isobutyraldehyde in 3 h at 70 °C in trifluoroethanol (Scheme 10).[22]

Scheme 10



On changing to dioxan the transposition required 20 h indicating that the solvent had a strong effect on the kinetics of the reaction. $RhCl_3 \cdot 3H_2O$ also proved to be a catalyst but gave the aldehyde only in 30% yield after 3 h at 90 °C in dioxan since a competitive decarbonylation also occurred.[22,23] Better results were obtained under biphasic conditions (benzene−water) in the presence of onium salts; 2 mol % $RhCl_3$ gave a complete conversion of 1-octen-3-ol to 3-octanone in less than 2 h at 80 °C.[24]

Very recently, a more systematic study was performed using $RhCl_3$ or $Rh_2(SO_4)_3$ as catalysts with water soluble sulfonated triphenylphosphine (TPPS) in biphasic (*n*-heptane/water) systems.[25] The reaction was also performed under homogeneous conditions (THF) in a few cases for comparison purposes. This catalytic system appears very promising and, from the results given in Table 5, several interesting observations could be made.

(i) Except for geraniol, that gave citronellal in 44% yield along with two dehydration byproducts, most other reactions were quantitative. This is especially interesting in the case of the primary allylic alcohols (both the *E* and *Z* isomers) and for the sterically hindered 3-methyl-2-cyclohexenol.

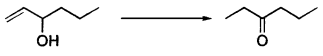
(ii) Using 1-hexen-3-ol as a model, it was possible to recycle the catalyst several times.

(iii) A decrease in TOF was observed as a function of the chain length (C_4 to C_8). This is probably due to the corresponding decrease in solubility of these alcohols in the aqueous catalytic phase. In agreement with this proposal, the reactions performed in THF gave similar TOFs for the different alcohols.

As an extension, the same authors recently reported on the use of microreactors for high throughput screening of catalytic reactions.[26] They have used this novel technology for the screening of different rhodium and ruthenium based catalysts in the isomerization of 1-hexen-2-ol to ethylpropyl ketone (Table 6). It was found that under these conditions, the $RhCl_3$/TPPTS system was the most efficient one in agreement with their previous results. They could also screen different substrates with the latter catalyst and establish that the reaction was very sensitive to the chain length leading to a rapid decrease in conversion on addition of substituents on both sides.

Another interesting biphasic isomerization of five allylic alcohols employing $[Rh(CO)_2Cl]_2$ (2−4 mol %) under catalytic phase transfer conditions was reported. Good to excellent yields of carbonyl derivatives were obtained after 6−10 h at room temperature (Table 7).[27] Though a phase transfer catalyst was not absolutely essential for the reaction to proceed, its presence resulted in cleaner reactions. The complex $[Rh(CO)_2(OH)]_2$ was postulated to be the true active species and a type II mechanism, via π-allyl hydride intermediate was proposed. Since the latter study only covers allylic alcohols that are not steri-

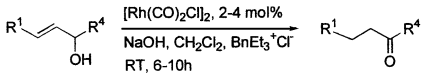
Table 6



catalyst[a]	ligand/metal	conversion (%)
$RhCl_3$/TPPTS	4.6/1	53
Rh_2SO_4/TPPTS	4.1/1	34
$[Rh(COD)Cl]_2$/DPPBTS	1.1/1	36
$[Rh(COD)Cl]_2$/BDPPTS	1.1/1	1.5
$[Rh(COD)Cl]_2$/CBDTS	1.3/1	1
$RuCl_3$/TPPTS	4.0/1	61
$PdCl_2$/DPPBTS	2.6/1	3.5

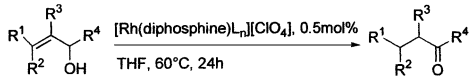
[a] Catalyst concentration: 1−2 mol % TPPTS = tris(*m*-sulfophenyl)phosphane, DPPBTS = di(sulfophenylphosphanyl)butane, BDPPTS = sulfonated (2S,4S)−(−)-2,4-bis(diphenylphosphanyl)pentane, CBDTS = sulfonated (S,S)-1,2-bis(diphenylphosphanylmethyl) cyclobutane.

Table 7



R^1	R^4	$BnEt_3^+Cl^-$	yield (%)
H	n-C_3H_7	+	100
H	n-C_3H_7	−	90−93
Me	Me	+	98
Me	Me	−	80
H	Ph	−	71
Ph	Me	+	94

Table 8



R^1	R^2	R^3	R^4	diphosphine	conversion	selectivity
Me	Me	H	H	BINAP[a]	64	80
Me	Me	H	H	BINAP[b]	88	61
Me	Me	H	H	DPPB[b]	50	24
Me	Me	H	H	DIPB[b]	42	20
H	H	Me	H	BINAP[b]	99	90
Me	H	H	H	BINAP[b]	87	93
Me	Me	H	Me	BINAP[b]	88	34
H	$-CH_2-$	H	$-(CH_2)_2-$	BINAP[b]	82	98

[a] (COD) was used as a ligand. [b] Solvent molecules act as ligands to themetal complex. DPPB = $Ph_2P(CH_2)_4PPh_2$; DIPB = $(i\text{-}Pr)_2P(CH_2)_4P(i\text{-}Pr)_2$.

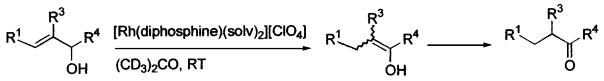
cally hindered, the scope and limitations of this reaction toward the substituted derivatives remain to be established.

In parallel to their studies on the asymmetric catalytic isomerization of allylic amines, Tani et al. have demonstrated that the Rh^I (diphosphine) derivatives were also very efficient catalysts for the transposition of allylic alcohols (Table 8).[28]

Employing small amounts of the catalyst (0.5 mol %) good to excellent conversions were obtained even for the more challenging examples, noteworthy are the derivatives with two alkyl groups in the terminal position ($R^1 = R^2 =$ Me) and 2-cyclohexen-1-ol.

It was proposed quite early that the transposition of an allylic alcohol by transition metal complexes might involve an enol intermediate. An important progress toward this direction was made when it was

Table 9



R^1	R^3	R^4	enol production time[a]	enol isomerization time[b]
H	H	H	14 min	(Z) 120 min (E) 40 min
H	Ph	H	330 min	
H	H	Me	9 min	(Z) 180 min (E) 50 min
H	H	Ph	124 min	(Z) 5.5 h
Ph	H	H	167 min	(Z) ∼8 h (E) ∼6 h
H	OEt	H	50 h	
H	Me	H	16 min	8 days
$-CH_2-$	$-(CH_2)_2-$	H	27 h	5 days

[a] Time required to convert ∼98% of the allylic alcohol. [b] Time required to transpose ∼98% of the enol into the carbonyl compound.

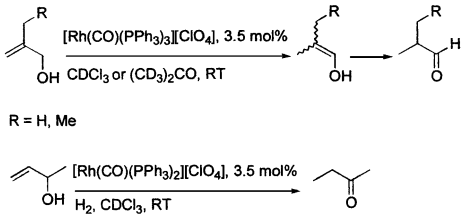
Table 10

diphosphine	time[a](min)	enol (%)	ketone (%)
$Ph_2P(CH_2)_2PPh_2$	14	89	11
$Cy_2P(CH_2)_2PCy_2$	<5	0	100
$Ph_2P(CH_2)_3PPh_2$	45	0	100
$Ph_2P(CH_2)_4PPh_2$	19	25	75
BINAP	21	80.4	19.6

[a] Time required for ∼98% conversion of allyl alcohol to propanal in $(CD_3)_2CO$ at 25°C.

possible to characterize the enol for the first time by NMR during the transposition of methallyl alcohol to isobutyraldehyde by $[Rh(CO)(PPh_3)_3][ClO_4]$ at room temperature (Scheme 11).[29] The same catalyst

Scheme 11



was also able to isomerize 2-ethylprop-2-en-1-ol and prop-2-en-1-ol to their corresponding enols. Similar results were obtained with $[Rh(CO)(PPh_3)_2][ClO_4]$ after activation with H_2. In the case of *cis*-2-buten-1,4-diol, these catalysts led to 2-hydroxytetrahydrofuran. In agreement with D labeling experiments, this reaction probably proceeded through 4-hydroxybutanal as an intermediate corresponding to the allylic alcohol isomerization.[30]

At about the same period, a very extensive and detailed study of Rh^+ mediated isomerization was completed in Bosnich's group.[31] They demonstrated that mono- and disubstituted allylic alcohols could be efficiently transposed to the corresponding carbonyls. Considering the very mild conditions involved (1 mol % catalyst at room temperature or below), these results are indeed interesting from a synthetic point of view (Table 9). Furthermore, the nature of the ligands on the Rh^+ catalyst has a strong effect on the kinetics of the reaction (Table 10). For instance, with $[Rh(CYPHOS)]^+$ catalyst the isomer-

ization occurs just upon mixing at 25 °C, and the reaction is quite rapid even at −80 °C.

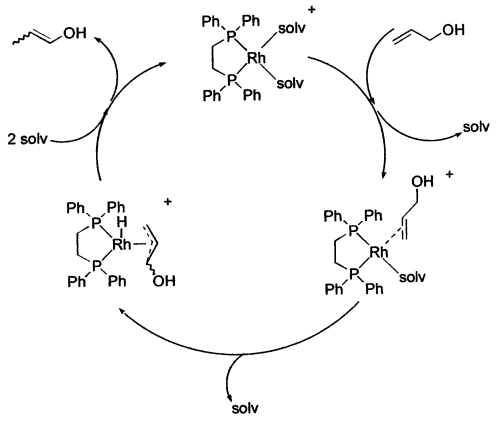
From a mechanistic viewpoint, these studies afforded many important results:

(i) It was possible to fully characterize a large number of intermediate enols by NMR (Table 9). In some cases, these enols could be isolated by bulb-to-bulb distillation, although some ketonization occurred under these conditions.

(ii) The stability of these enols were studied, and it was demonstrated that the kinetics of their isomerization to carbonyl derivatives was strongly dependent upon the number and nature of substituents on the double bond, as well as their geometry. Further, these studies indicated that the enols were less stable in the presence of the Rh^+ catalysts than in their absence. As expected, the carbonyl derivatives were instantaneously obtained from the enols by acid or base catalysis.[32]

(iii) A type II mechanism was proposed for this transposition (Scheme 12). Using selective D labeling,

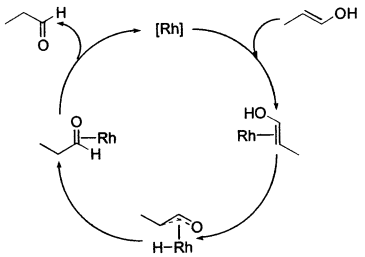
Scheme 12



both at the alcohol and at the enol stage, it was shown that the different steps of the catalytic cycle were irreversible. Using similar arguments, it was shown that the equilibration of the π-allyl intermediates via a $\sigma-\pi-\sigma$ mechanism was not favored.

(iv) For the last step of the isomerization reaction it was proposed that the η-2 complexed enol leads to the η-2 complexed carbonyl derivative via a rhodium mediated 1,2-hydride shift (Scheme 13). The use of

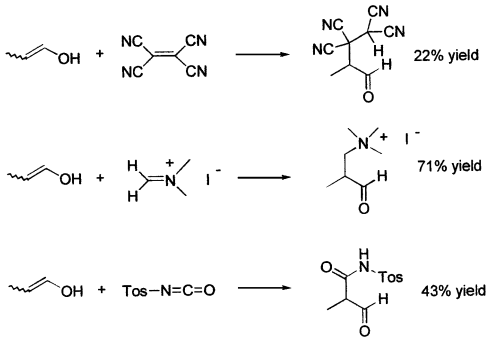
Scheme 13



chiral ligands on the metal led to a small, but significant (18% ee) asymmetric induction in the isomerized ketone furnishing evidence for such a mechanism.

(v) Further, the intermediate enols were trapped in an *ene*-type reaction using strong electrophiles, such as TCNE, iminium salts, or tosyl isocyanate (Scheme 14).

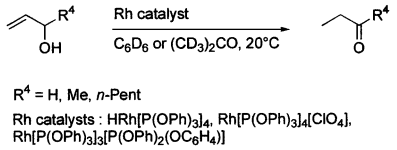
Scheme 14



(vi) In contrast to the iron carbonyl catalysis, no transposition was observed in the case of homoallylic alcohols. This was explained by the formation of stable rhodium intermediates, which could interrupt the catalytic cycle.

Further, using isomerization of allyl alcohol to propanal as a model, studies revealed that rhodium complexes with triphenyl phosphite derived ligands also served as useful catalysts (Scheme 15). The most

Scheme 15

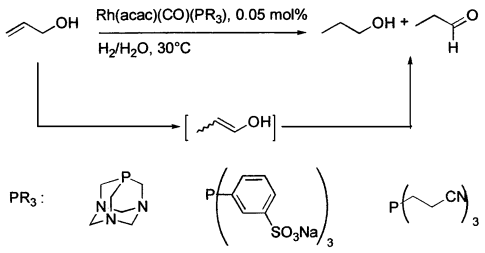


efficient one among them was the orthometalated complex, which gave a quantitative conversion after 70 min at 20 °C.[33]

Here again, the corresponding enols were characterized by NMR. Additionally, using deuterium labeling studies a 1,3-shift was established. Finally, the reaction was extended to 3-buten-1-ol and 1-octen-3-ol with similar results. However, no reaction was obtained with derivatives having other substituents on the double bond, indicating strong limitations by steric factors.

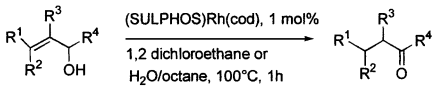
Rhodium (I) acetylacetonato complexes with three different functionalized phosphines have been studied in the hydrogenation of allyl alcohol to propanol (Scheme 16).[34]

Scheme 16



It was proposed that, in the presence of these catalysts, the alcohol was partly isomerized to enol before the hydrogenation to propanol occurred. This was supported by identification of small amounts (1−

Table 11



R^1	R^2	R^3	R^4	yield (%)[a]	yield (%)[b]
H	H	H	H	95	100
H	H	Me	H	38	73
H	H	H	Me	98	100
Me	H	H	H	62	30
Me	Me	H	H	4	<1

[a] Homogeneous conditions (dichloroethane as the solvent). [b] Biphasic conditions (1/1 water/octane mixture). SULPHOS: $^{-}O_3S(C_6H_4)CH_2C(CH_2PPh_2)_3$.

10%) of propanal and also by deuterium labeling experiments.

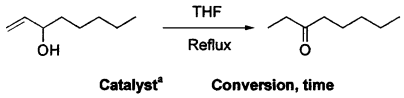
As part of a search for catalysts that could be used under biphasic conditions, the zwitterionic Rh(SULPHOS)(COD) derivative was studied.[35] Starting with allyl alcohol and using only 1 mol % catalyst, a quantitative yield of propanal was obtained within 1 h at 100 °C (Table 11). After separation of the product, the catalyst could be recycled three times with a slight deactivation after each run. In a homogeneous solution, an excellent yield was obtained (90%), but the catalyst could not be reused. Once again, this reaction appears to be limited to sterically less hindered alcohols. This system also isomerized a homoallylic alcohol via two successive hydrogen shifts. A type II mechanism was proposed with these catalysts.

It is known that Wilkinson's catalyst does not efficiently isomerize allylic alcohols or allylic ethers; for instance, at high temperature (130 °C) cinnamyl alcohol gave only low yields of 2-phenyl propanol (8%) and cinnamaldehyde (11%) along with their decarbonylation products.[36] It has also been shown that $[Rh(PPh_3)_3][PF_6]$ (easily prepared in situ from Wilkinson's catalyst and $AgPF_6$ in methanol) efficiently promotes the isomerization of 1-octen-3-ol to 3-octanone.[37]

During a search for deprotection protocols for allylic ethers of sugar derivatives, Boons et al. found that $Rh(PPh_3)_3Cl$ on its reaction with ^{n}BuLi resulted in the hydrido complex $RhH(PPh_3)_3$ that proved to be highly efficient for the isomerization of allylic ethers.[38] On the basis of this result, a more systematic study of a number of related rhodium complexes was performed. Using the isomerization of 1-octen-3-ol as a model, it was demonstrated that various hydride, alkyl as well as aryl rhodium complexes could catalyze this transformation (Table 12).[37]

The catalyst $RhH(PPh_3)_3$, which was easily prepared and used in situ, was selected for further studies to probe the scope and limitation of the various allylic alcohols that could be isomerized. Using 5 mol % catalyst in refluxing THF, a wide range of secondary alcohols could be efficiently isomerized (Table 13). Among them, highly sterically hindered derivatives (such as $R^1 = R^2 = Me$, $R^4 =$ *n*-pentyl) and allylic alcohols with different 1,2- or 1,1-disubstitution patterns on the double bond are particularly interesting. Furthermore, the reactions

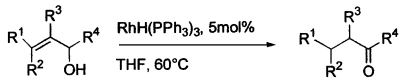
Table 12



catalyst[a]	conversion, time
$RhH(PPh_3)_3$ [b]	100, 30−40 min
$RhH(PPh_3)_3$ [c]	100, 45 min
$RhMe(PPh_3)_3$	100, 30−40 min
$RhPh(PPh_3)_3$	100, 30−40 min
$RhTMP(PPh_3)_3$ [d]	100, 30−40 min
$RhPhCO(PPh_3)_2$	100, 40−50 min
$RhHCO(PPh_3)_2$	40, 4 h
$RhHCO(PPh_3)_3$	100, 60−70 min
$Rh(PPh_3)_3^+, PF_6^-$ [e]	100, <10 min

[a] In all experiments, 5 mol % of the catalyst was used. [b] Prepared from $RhCl(PPh_3)_3$ and *n*Buli. [c] Prepared from $RhCl(PPh_3)_3$ and LDA. [d] TMPA = 2,6-tetramethylpiperidinamide. [e] MeOH was used as the solvent.

Table 13



R^1	R^2	R^3	R^4	yield (%)
H	H	H	*n*-C_5H_{11}	91
Me	H	H	*n*-C_5H_{11}	92
H	H	Me	*n*-C_5H_{11}	96
Me	Me	H	*n*-C_5H_{11}	89
Ph	H	H	*n*-C_5H_{11}	89
Ph	H	Me	*n*-C_5H_{11}	96
H	H	H	Ph	92
Ph	H	H	CF_3	69
Me	H	H	(*E*)-CH=CHPh	78
Me	$Me_2C{=}CH(CH_2)_2-$	H	H	61[a]
H	H	H	$-C(Me)_2COOC_2H_5$	88

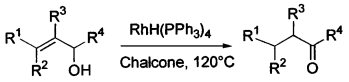
[a] On the basis of recovered starting material (50% conversion).

of the trifluoromethyl alcohol and the dienyl alcohol are quite noteworthy since these two derivatives could not be transposed into the carbonyl compounds using ironcarbonyl catalysts. Although 100% conversion in the case of geraniol to citronellal was not achieved, it is worth mentioning that this catalyst brings about partial conversion in this challenging example.

Another rhodium hydride, $RhH(PPh_3)_4$, has been successfully employed for such allylic alcohol isomerizations. However, it is worth noting that the transpositions have been performed under unusual reaction conditions; slow addition of the reagents to the catalyst dissolved in a high boiling solvent such as chalcone. Further, the reactions were performed under vacuum to remove the products immediately. Such conditions were designed to displace the equilibrium and also to limit the secondary reactions. It would be interesting to establish if such reaction conditions could broaden the scope of other catalysts. In that way, $RhH(PPh_3)_4$ (at around 0.1 mol %) could isomerize a wide range of primary and secondary allylic alcohols (Table 14) as well as glycols to diketones (Table 15) or to hydroxyketones (Table 16) generally in good to excellent yields.[39]

Notwithstanding its high sensitivity to oxygen and moisture, this rhodium hydride appears to be a very versatile catalyst.

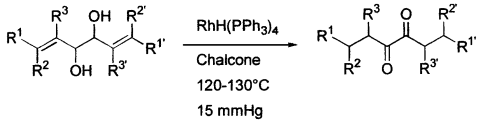
Table 14



R^1	R^2	R^3	R^4	yield (%)
H	H	H	H	95
Me	H	H	H	87
H	H	Me	H	75
Ph	H	H	H	36
H	H	H	Me	95
Me	H	H	Me	93
H	H	Me	Me	87
Me-CH=CH	H	H	Me	90[a]

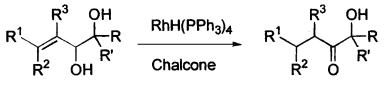
[a] Et-CH=CH−CH_2−CO-Me + Pr−CH=CH−CO-Me.

Table 15



R^1	R^2	R^3	$R^{1'}$	$R^{2'}$	$R^{3'}$	yield (%)
H	H	H	H	H	H	94
Me	H	H	Me	H	H	97
H	H	Me	H	H	H	93
H	H	H	Me	H	H	98

Table 16



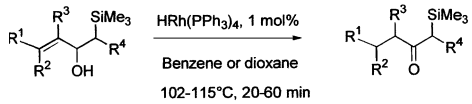
R^1	R^2	R^3	R	R′	P (mmHg)	T (°C)	yield (%)
H	H	H	Me	−CH=CH_2	15	130	98
Me	H	H	Me	−CH=CH_2	15	160	94
H	H	Me	Me	−CH=CH_2	15	160	0
H	H	H	H	Ph	0.01	140	92
Me	H	H	H	Ph	0.01	140	0
H	H	Me	H	Ph	0.01	140	0
H	H	H	H	furyl−2−	0.01	130	89
Me	H	H	H	furyl−2−	0.01	130	88
H	H	Me	H	furyl−2−	0.01	130	82

More recently, it could be successfully used for the isomerization of different type of silicon containing allylic alcohols. For instance, starting from various β-trimethylsilyl alcohols excellent yields of β-silyl carbonyl compounds were obtained, despite the possible β-elimination of Me_3SiOH (Table 17).[40]

However, no reaction was observed for the alcohol with $R^1 = R^2 = Me$, indicating again the role of steric hindrance around the double bound. In the case of α-silyl allylic alcohols the same catalyst was also efficient but only in the presence of a α-silyl enone as a cocatalyst (Table 18).

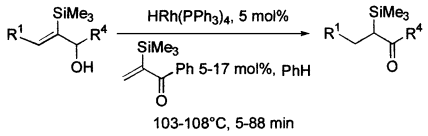
It was suggested that a fast Michael addition of the hydride on this enone affords a rhodium enolate, which is the real promoter for the isomerization of these allylic alcohols. This interesting result raises intringing questions such as: what could be the detailed mechanism of the reaction of such rhodium enolates with these alcohols? Would it work with other allylic alcohols? Would other enones give similar results? The same $RhH(PPh_3)_4$ performs the

Table 17



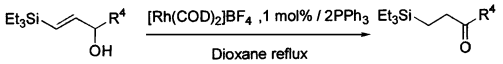
R^1	R^2	R^3	R^4	isolated yield (%)
H	H	H	H	95
H	H	H	H	82
H	H	H	H	88
Me	H	H	H	67
H	H	Me	H	65
n-C_3H_7	H	H	H	90
n-C_5H_{11}	H	H	H	88
n−C_5H_{11}	H	H	H	95
Me	Me	H	H	0
n−C_3H_7	H	H	Me	99
H	H	H	n−C_5H_{11}	92
Me	H	H	n−C_5H_{11}	95
H	H	Me	n−C_5H_{11}	90
n−C_3H_7	H	H	n−C_5H_{11}	99

Table 18



R^1	R^4	isolated yield (%)
H	n-C_5H_{11}	60
H	n-C_5H_{11}	98
H	n-C_8H_{17}	90
H	n-$C_{10}H_{21}$	96
H	2-phenylethyl	94
H	Ph	56
H	1-ethylphenyl	82
H	cyclohexyl	81
H	1-pentenyl	82
Me	n-C_5H_{11}	72
n-C_4H_9	n-C_5H_{11}	87
n-C_4H_9	H	0
	−$(CH_2)_3$-	0

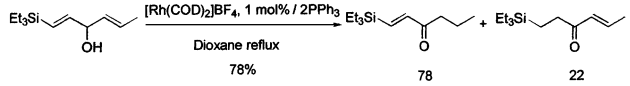
Scheme 17



R^4 = Cyclohexyl 97%
R^4 = CH_2CH_2Ph 96%
R^4 = Ph 85%
R^4 = n-Pent 100%

isomerization of β-silyl allylic alcohols. However, for latter derivatives the most effective catalyst proved to be $[Rh(COD)_2]BF_4/2PPh_3$: it afforded β-silyl carbonyl compounds in good yields (Scheme 17) and proved to be efficient as well for a β-bis allylic alcohol (Scheme 18).[41]

Scheme 18



An interesting aspect of this reaction was the development of a tandem hydrosilylation−isomerization process, starting from propargylic alcohols.

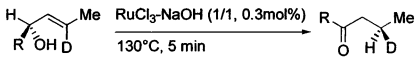
This one-pot procedure afforded β-silyl ketones in moderate yields.

In conclusion, these rhodium-derived complexes are among the most versatile and efficient catalysts for this transposition. They can be used at low catalyst loading (in some cases < 1%) and at low temperatures (RT or below). Furthermore, due to the presence of phosphine ligands, extension to asymmetric catalysis could be achieved, as discussed later in this review. However, some progress is still awaited, especially for the sterically more hindered allylic alcohols. Finally, the isolation and characterization of the enol intermediates with these Rh^+ catalysts have led to very important results from a mechanistic standpoint. Furthermore, in the case of alcoholates, the transposition led to enolates which could be trapped in situ, for instance in aldolisation reactions.[42]

C. Ruthenium Complexes

A variety of ruthenium derivatives have been employed in this isomerization. Early experiments with $RuCl_3$ and allyl alcohol gave complex mixtures.[43a] However, for the transposition of methallyl alcohol to isobutyraldehyde, the latter salt (at 0.6 mol %) appears to be a good catalyst when the reaction was performed in trifluoroethanol at 70 °C.[22] It was also employed for the isomerization of various allylic alcohols and glycols.[43b] When a 1:1 mixture of $RuCl_3$ and NaOH was used, the reaction was quantitative after 5 min at 130 °C. Furthermore, on using chiral nonracemic alcohols, the transposition occurred with a significant chirality transfer (from 37.6 to 40.7%) (Scheme 19).[44]

Scheme 19



R = Me, Et

$Ru(acac)_3$ also proved to be an effective catalyst for the isomerization of a wide range of 1-substituted propenes, including a few allylic alcohols such as 1-phenyl-3-propen-1-ol.[45] Using 1 mol % catalyst, the reaction was complete after 15 min at 100 °C. On the basis of deuterium labeling experiments, a mechanism via π-allyl intermediates was proposed.

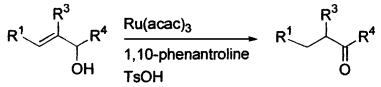
$Ru(acac)_3$ can be also used in combination with other reagents. Noteworthy are the very interesting studies by Drent et al:[46]

(i) They have shown that a (2:1) mixture of Ph_3P and $Ru(acac)_3$ isomerized 3-buten-2-ol to methylethyl ketone.

(ii) They have demonstrated that combination of some Bronsted acids (such as TsOH) with cationic ruthenium complexes (obtained for instance from $Ru(acac)_3$ with 2 equiv of 1,10-phenanthroline) led to efficient isomerization of sterically less hindered allylic alcohols (Table 19)

(iii) More importantly, it was established that, for allylic alcohols with R_3=H, such a process could be performed even in the presence of butadiene. Since allylic alcohols can be obtained by hydration of dienes, the latter result appears important: it opens a new and a very attractive route to the direct one-pot transformation of butadiene to methylethyl ketone with possible extension to other dienes.

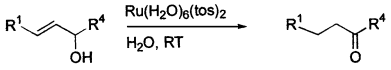
Table 19



R^1	R^3	R^4	yield (%) with butadiene	yield (%) without butadiene
H	Me	H	85	92
H	Me	Me	82	90
H	H	Me	91	98
Me	H	Me	7	63
Me	H	H	trace	40
H	H	Et	76	n.c.

The ruthenium complex $Ru(H_2O)_6(tos)_2$ proved to be an efficient catalyst for the rearrangement of simple allylic ethers and alcohols (five examples, including cyclohexenol) (Scheme 20).[7,47] Such reactions occurred under mild conditions (5−10% catalyst in water at room temperature or 45 °C) and gave good yields of carbonyl compounds even if oxidation products was observed in some cases. The homoallylic alcohols were stable under these conditions. It is important to note that very detailed mechanistic studies, using labeled compounds, have been carried out using this catalyst. The main conclusions were the following:

Scheme 20



a : $R^1 = R^4 = H$; b : $R^1 = H$, $R^4 = Me$; c : $R^1 = H$, $R^4 = Et$, d : $R^1 = Me$, $R^4 = H$

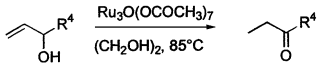
(i) The crossover experiments have unambiguously established that, in that case, the reaction was intermolecular.

(ii) A modified metal hydride addition−elimination mechanism was proposed that involved the exclusive Markovnikov addition to the double bond. This regiocontrol was considered as a strong indication for the oxygen playing an important role to direct the addition of the metal hydride species.

The closely related catalyst $Ru(H_2O)_6(trif)_2$ also gave similar results, and this could be further extended to allyl phenyl ether.[48]

The oxoruthenium complex $Ru_3O(OCOCH_3)_7$ was found to be an interesting catalyst for the transposition of simple secondary alcohols (Scheme 21). Its solubility in ethylene glycol permitted its use under biphasic conditions; the ketone being insoluble in ethylene glycol was isolated by decantation and the catalytic system could be recycled several times. However, this system appeared limited to allylic alcohols that were unsubstituted on the double bond,

Scheme 21



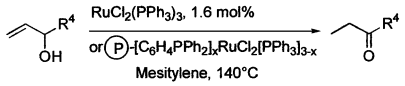
R^4 = Me, Et, *n*-Pr, *n*-Bu

while sterically more hindered alcohols appeared to be less reactive.[49] It could also be used under biphasic (heptane-water) reaction conditions.[50]

$Ru(CO)_3(PPh_3)_2$ was also found to be a good catalyst for the double bond migration of various alkenes and a single example of an allylic alcohol. Employing 1 mol % of the catalyst the isomerization of 1-phenyl-2-propen-1-ol was complete after 6 h at 80°C. On the basis of deuterium labeling experiments, a π-allyl type mechanism was proposed.[51]

A wide range of organometallic ruthenium chloride complexes, especially $RuCl_2(PPh_3)_3$ and a few closely related derivatives have been studied. Early experiments have demonstrated that three simple secondary allylic alcohols rearrange with this soluble catalyst. Furthermore, an interesting comparison was made with the corresponding catalyst anchored to an insoluble resin (Scheme 22).[52]

Scheme 22

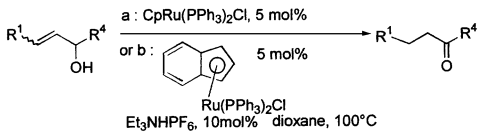


Quite expectedly, the soluble catalyst had higher initial rates of reaction (around 4 times). However, it also promoted some allyl alcohol disproportionation and often deterioration to inactive material occurred. On the contrary, the supported catalyst had good advantages in offering cleaner reactions and the possibility of multiple recycling. However, it would be interesting to verify the possible use of this type of catalyst with more challenging allylic alcohols.

A very extensive study of the scope and limitations of the rearrangement of allylic alcohols with $CpRu(PPh_3)_2Cl$ and the corresponding indenyl complex was accomplished by B. Trost et al (Table 20).[53]

Under standard reaction conditions (5 mol % cat in dioxane at 100 °C), the isomerization proceeded in good yield for cinnamyl alcohol as well as for a wide range of allylic secondary alcohols. Furthermore, this catalyst exhibits a remarkable chemoselectivity since non-allylic alcohols did not undergo oxidation, while substrates with remote double bonds very often did not migrate in the presence of these catalysts. However, more recent results have shown that remote double bonds can indeed migrate, but at very low rates compared to allyl alcohols.[54] With these catalysts, limitations seem to appear essentially in the case of sterically hindered alcohols; for instance, geraniol was not isomerized. In the case of cyclic alcohols, the results depend on the ring size. While the six-membered substrates did not react, the eight-membered derivative was transposed albeit more slowly than the corresponding acyclic alcohols. The indenyl complex showed enhanced reactivity (shorter reaction times as well as higher yields) in the case of cyclic derivatives. A mechanism was proposed for the catalytic cycle and is outlined in Scheme 21. After ionization to a ruthenium cationic species, its reaction with the allylic alcohol led to a bis-coordinated ruthenium alkoxide intermediate. A hydride migration at this stage resulted in a ruthenium hydride intermediate and a subsequent 1,4-hydride addition led to the final carbonyl derivative coordinated (in a π-oxallyl or a σ-enolate manner) to the ruthenium catalyst. This mechanism accounts for the experimental results and was also confirmed by labeling studies.

Table 20



R^1	R^4	cat	time (h)	yield (%)	
Ph	H	a	8	90	
H	Cy	a	1.5	92	
H	$Ph(CH_2)_2$	a	2	81	
Ph	n-C_4H_9	a	9	23	
Ph	n-C_4H_9	b	2	83	
H	CH_2=CH−$(CH_2)_8$−	a	1	87	
H	$HOCH_2$−$(CH_2)_9$−	a	1	52	
H	HOCH(Me)−$(CH_2)_8$−	a	1.5	90	
H	Me−$(CH_2)_{10}$−	a	2.5	91	
n-$C_{10}H_{21}$	$Ph(CH_2)_2$	a	24	53	
n-$C_{10}H_{21}$	$Ph(CH_2)_2$	b	3	81	
H	CH_2=CHCH(OH)−$(CH_2)_8$−	a	1.5	73	
H	CH_2=CHCH(OMe)−$(CH_2)_8$−	a	1	93	
	−$(CH_2)_5$−	a	24	31	
	−$(CH_2)_5$−	b	3	47	
	−$(CH_2)_9$−	a	9	84	
	−$(CH_2)_9$−	b	2.5	87	
n-C_5H_{11}	CH_2=C(Me)−$(CH_2)_2$−	b	3	82	
n-C_4H_9	CH_2=CH−$(CH_2)_2$−	b	8	77	(2 isomers)
n-C_4H_9	Me−CH(OH)−$(CH_2)_8$−	b	10	69	
	−CH(OH)−$(CH_2)_8$−	b	4	35	
	−CH(OAc)−$(CH_2)_8$−	b	3	86	
	−CH_2OCO−$(CH_2)_6$−	b	6.5	28	

In efforts to obtain more efficient catalysts, modifications of ligands and/or reaction conditions have been explored. For instance, in the isomerization of 3-buten-2-ol to methylethyl ketone with $RuClCp(PPh_3)_2$ as the catalyst, a strong increase in reactivity was observed (with a turnover frequency of over 200 000 h^{-1}) when the reaction was carried out using AgOTs instead of Et_3NHPF_6 for sequestering the chloride anion and in the absence of a solvent.[54] As this catalyst is highly active, it would be very interesting to try out its use with some more challenging, allylic alcohols. It is worth mentioning that this type of ruthenium catalyst could also lead to the formation of ethers both via homo- and heterocoupling reactions. The complex $RuCl_2(PPh_3)_3$ on reaction with $AgPF_6$ in methanol also resulted in a very active cationic species. This species very quickly isomerized 1-octen-3-ol to 3-octanone. However, this catalyst has a strong Lewis acid character often leading to products resulting from competitive nucleophilic addition by the solvent. Interestingly, in the case of a primary allylic alcohol (3-dodecen-1-ol), this catalyst led to a one-pot isomerization and protection of the resulting aldehyde as the dimethyl acetal.[37]

Once again starting from the same ruthenium derivative $RuCl_2(PPh_3)_3$ or from $[RuCl_2(p\text{-cymene})]_2$, a strong rate enhancement by a catalytic amount of base such as K_2CO_3 was reported. The dimetallic

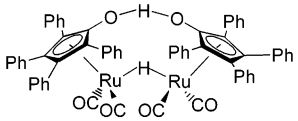
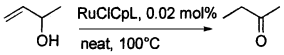


Figure 1.

Table 21[a]



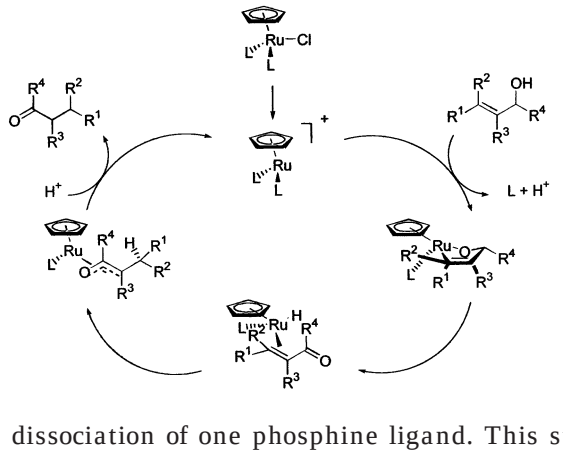
L	TOF[b] (h^{-1})
2 PPh_3[c]	>200000
DPPM[d]	2000
DPPM	530
DPPE	1675
DPPP	5500
DPPB	18000
DCPE	20000
DPPPH	0
cis-DPPV	0

[a] DPPM = bis(diphenylphosphino)methane. DPPE= 1,2-bis(diphenylphosphino)ethane. DPPP = 1,3-bis(diphenylphosphino)propane. DPPB = 1,4-bis(diphenylphosphino)butane. DCPE = 1,2-bis(dicyclohexylphosphino)ethane. DPPPH = 1,2-bis(diphenylphosphino)benzene. DPPV = *cis*-1,2-bis(diphenylphosphino)ethene. [b] Activity determined after 158 min. [c] Activity determined after 2 min. [d] Activity determined after 5 min.

catalyst representated in Figure 1, which can itself serve as a base, proved to be an efficient catalyst (0.2−0.5 mol %) as well.[55] Excellent yields were obtained in the case of 1-octen-3-ol, 2-cyclohepten-1,4-diol, and 2-cycloocten-1,4-diol. Lower yields were obtained in the case of 1-cyclohexen-3-ol and 2-cyclohexen-1,4-diol.

On the contrary, the replacement of the two triphenylphosphines by various bidentate ligands led to a decrease in the reactivity (Table 21).[54] This was in agreement with the mechanism (Scheme 23) involv-

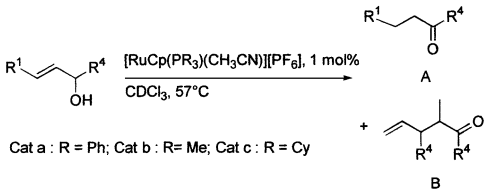
Scheme 23



ing dissociation of one phosphine ligand. This step becomes quite difficult in the case of diphosphines with flexible linkers and even more for those possessing rigid systems, to the extent that in the latter case no catalytic activity was observed.

In yet another study, a series of [$RuCp(PR_3)(CH_3CN)_3$][PF_6] type complexes were tested.[56] Such derivatives have more labile ligands and therefore, would generate the 14 e^- cationic ruthenium species more readily. The reaction of simple disubstituted

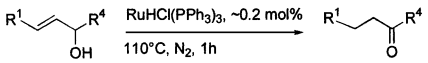
Table 22



R^1	R^4	cat	time	A (%)[a]	B (%)
H	H	a	10 min	82	7
H	H	b	15 min	67	21
H	H	c	3 min	86	4
H	Me	a	3 min	>98	
H	Me	b	5 min	>98	
H	Me	c	3 min	>98	
H	*p*-MeC_6H_4	a	30 min	23	74
H	*p*-MeC_6H_4	b	8 min	60	38
H	*p*-MeC_6H_4	c	5 min	67	29
Ph	H	a	17 h	91*	
Ph	H	b	15 h	87*	
H	*n*-Hex	a	3 min	>98	
H	*n*-Hex	b	90 min	>98	
H	*n*-Hex	c	3 min	>98	

[a] Yields are calculated from NMR spectra except * where isolated yields are given.

Table 23



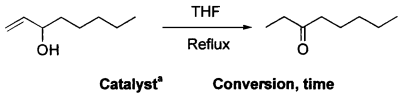
R^1	R^4	yield (%)
H	Me	91
H	Et	92
H	*n*-Pr	92
H	*n*-Bu	90
H	*n*-Pent	93
Me	Me	75
	$-(CH_2)_3-$	81

allylic alcohols with these catalysts (1 mol %) at 57 °C gave the corresponding carbonyls in good yields (Table 22). These are efficient catalysts and relatively high turnover frequency numbers (up to 30 000) were obtained. However, from a synthetic point of view, there appears to be strong limitations since neither C_1 nor C_3 disubstituted alcohols could be transposed under these conditions. Furthermore, in some cases a competitive reaction leading to γ,δ-unsaturated carbonyl compounds was observed.

Several ruthenium hydride type complexes form another class of active catalysts for this isomerization. For instance, it was recognized very early that $RuHCl(PPh_3)_3$ could transpose simple allylic alcohols (Table 23).[49] Good yields were obtained with secondary allylic alcohols and for a homoallylic alcohol, but the reaction failed in the case of a primary allylic alcohol such as 2-butenol.

This ruthenium hydride complex, as well as the corresponding methyl and phenyl derivatives, could be generated and used in situ and were found to be efficient catalysts (5 mol %) in refluxing THF.[37] Although less active than their rhodium counterparts, all catalysts isomerized 1-octen-3-ol to 3-octanone in high yields (Table 24). This reaction could be extended to several other simple allylic alcohols (results for $RuH_2(PPh_3)_3$ are given in Table 25).

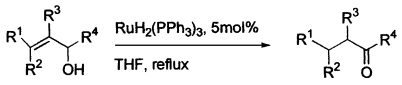
Table 24



catalyst[a]	conversion, time
$RuClH(PPh_3)_3$[b]	100, 60−70 min
$RuClH(PPh_3)_3$[c]	100, 45 min
$RuClMe(PPh_3)_3$	100, 60−70 min
$RuClPh(PPh_3)_3$	100, 60−70 min
$RuH_2(PPh_3)_3$	100, 30−40 min
$RhMe_2(PPh_3)_3$	100, 30−40 min
$RuPh_2(PPh_3)_3$	100, 30−40 min
$RuH_2(PnBu_3)_4$	100, 30−40 min
$[RuCl(PPh_3)_3][PF_6]$[d]	100, <10 min

[a] In all experiments 5 mol % of the catalyst was used. [b] Generated from $RuCl_2(PPh_3)_3$ and *n*-BuLi. [c] Generated from $RuCl_2(PPh_3)_3$ and LDA. [d] MeOH was used as the solvent.

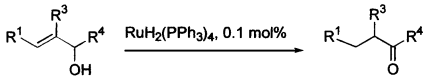
Table 25



R^1	R^2	R^3	R^4	yield (%)
H	H	H	*n*-C_5H_{11}	91
Me	H	H	*n*-C_5H_{11}	92
H	H	Me	*n*-C_5H_{11}	95
Me	Me	H	*n*-C_5H_{11}	0
Ph	H	H	*n*-C_5H_{11}	95
Ph	H	Me	*n*-C_5H_{11}	98
H	H	H	Ph	90
Me	H	H	(*E*)-CH=CHPh	0
H	H	H	$-C(Me)_2COOC_2H_5$	71[a]

[a] On the basis of recovered starting material (75% conversion).

Scheme 24

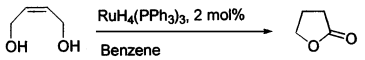


a : $R^1 = R^3 = H$, R^4 = *n*-Pr; quant. yield after 5 min at 110°C

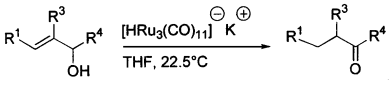
b : $R^1 = R^4$ = Me, R^3 = H; 16% conversion after 1 h at 140°C

c : R^1 = H, R^3-R^4 = $(CH_2)_4$; 62% conversion after 30 min at 175°C

Scheme 25



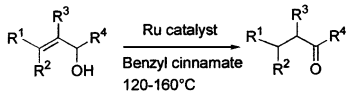
Scheme 26



a : $R^1 = R^3 = R^4 = H$; b : R^1 = Me, $R^3 = R^4 = H$; c : $R^1 = R^3 = H$, R^4 = Et.

A few polyhydride ruthenium complexes have also been reported as active catalysts in this isomerization (Schemes 24,[57] 25,[58] and 26[59]). In the case of *Z*-butenediol, the isomerization was followed by an intramolecular condensation to form a hemiacetal and a dehydrogenation (a known process for such a catalyst) affording the butyrolactone. This reaction could be extended as well to 2-butyn-1,4-diol.[58] However, these catalysts appear limited in scope to simple, sterically less hindered allylic alcohols.

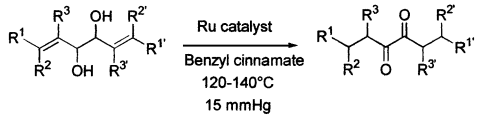
Table 26



R^1	R^2	R^3	R^4	yield (%) $RuCl_2(PPh_3)_3$	yield (%) $RuClH(PPh_3)_3$
H	H	H	Me	83	84
Me	H	H	Me	88	70
H	H	Me	Me	13−14	60
Me−CH=CH	H	H	Me	polymers	71[a]

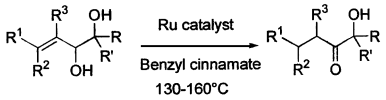
[a] Et-CH=CH−CH_2−CO-Me + Pr−CH=CH−CO-Me.

Table 27



R^1	R^2	R^3	$R^{1'}$	$R^{2'}$	$R^{3'}$	yield (%) $RuCl_2$-$(PPh_3)_3$	yield (%) RuClH-$(PPh_3)_3$	yield (%) RuH_2-$(PPh_3)_3$
H	H	H	H	H	H	95	60	94
Me	H	H	Me	H	H	95	85	97
H	H	Me	H	H	H	40	52	78
H	H	H	Me	H	H	95	96	96
H	H	H	H	H	Me	95		

Table 28

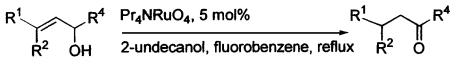


R^1	R^2	R^3	R	R′	*P* (mm Hg)	yield (%) $RuCl_2$-$(PPh_3)_3$	yield (%) RuClH-$(PPh_3)_3$	yield (%) RuH_2-$(PPh_3)_3$
H	H	H	Me	−CH=CH_2	15	95	38	94
Me	H	H	Me	−CH=CH_2	15	95	42	94
H	H	Me	Me	−CH=CH_2	15	0	0	0
H	H	H	H	Ph	0.01	95	96	96
Me	H	H	H	Ph	0.01	0	0	0
H	H	Me	H	Ph	0.01	0	0	0
H	H	H	H	furyl−2−	0.01	95	40	90
Me	H	H	H	furyl−2−	0.01	95	64	88
H	H	Me	H	furyl−2−	0.01	95	24	84

The approach developed by Dedieu and Pascal appears more fruitful from a synthetic point of view. They studied three related catalysts $RuCl_2(PPh_3)_3$, $RuHCl(PPh_3)_3$, and $RuH_2(PPh_3)_4$.[39] The reactions were performed under the conditions previously reported for $RhH(PPh_3)_4$: slow addition of the alcohol to a solution of catalyst in a high boiling solvent with simultaneous removal of the carbonyl compound under vacuum. Except for primary alcohols, moderate to excellent yields of carbonyl compounds were obtained using this technique, and starting from allylic alcohols (Table 26) or glycols (Tables 27 and 28). From these results, $RuCl_2(PPh_3)_2$ appears to be the most convenient catalyst since it is both stable and readily available.

In a completely different approach, it has been demonstrated recently that 5% of the well-known oxidant tetrapropylammonium perruthenate (TPAP), in the presence of a stoichiometric amount of a

Table 29

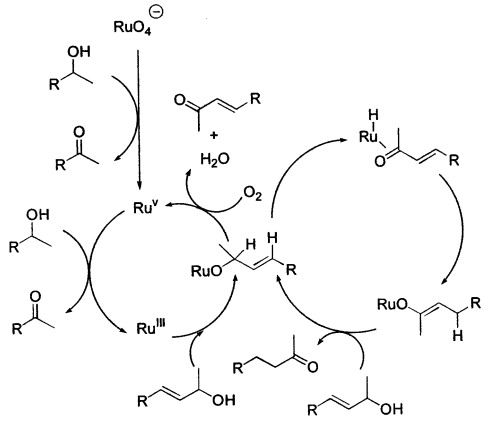


R^1	R^2	R^4	yield (%)
H	H	Ph	90
H	H	$PhCH_2CH_2$	92
H	H	*p*-Cl−Ph	87
n-C_9H_{19}	H	H	41
Ph	H	Et	71
Ph	H	H	48
Me	$Me_2C{=}CH{-}(CH_2)_2$-	H	52
H	$-(CH_2)_3-$		89

primary alcohol such as 1-decanol or 2-undecanol, could efficiently perform the isomerization of allylic alcohols to their corresponding carbonyls (Table 29).[60]

Moderate to good yields were obtained with these allylic alcohols and further studies would be necessary to gain information on the scope and limitations. However, it already appears to be a promising system since it gave a complete isomerization in the challenging case of geraniol. A mechanism for this transformation has been proposed (Scheme 27). The

Scheme 27

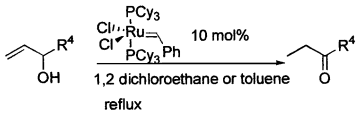


reaction starts with a sequential reduction of the Ru^{VII} complex (mediated by the saturated alcohol) to the catalytically active Ru^{III} species. This species on interaction with the allylic alcohol generates the ruthenium alkoxide and a subsequent β-hydride elimination followed by a 1,4-hydride addition leads to the metal enolate. A final ligand exchange affords the saturated carbonyl derivative and regenerates the catalyst.

Finally, it is noteworthy that the ring closing methathesis catalysts, such as Grubb's catalyst (10 mol % in refluxing toluene), was also able to effect this transposition (Table 30).[61] Only unsubstituted allylic alcohols have been tested, but it is interesting to note that both ester and ether functionalities appear compatible with these reaction conditions. It was recently extended to the isomerization of allyl ethers and amines.[62]

In conclusion, the ruthenium derived complexes also appear very promising in catalyzing this transposition. They can be used at low loading capacity ($\leq$ 1%) and in some cases, furnish high turnover frequencies. However, some progress is still awaited in terms of reactivity and expansion of their synthetic

Table 30



R^4	Time (h)	Yield (%)
$PhCH_2$	2	70
n-C_7H_{15}	2	80
MeOOC-$(CH_2)_4$-	3	67
$TBSOCH_2$	4	67
	2	70
$CH_2{=}CH{-}CH(OH){-}(CH_2)_6$-	1	81[a]
BnO-$(CH_2)_2$-	1	52

[a] In this case, both double bond migrate and the dicarbonyl compound is obtained.

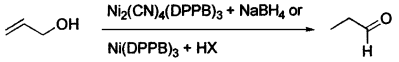
potential, especially with regard to the sterically more hindered and/or more functionalized systems. Finally, due to the presence of phosphine ligands, extension to asymmetric catalysis is possible as discussed later.

D. Other Metals

1. Nickel Complexes

It has been recognized early that nickel complexes can isomerize olefins by migration of the double bonds, and this was extended to a few allylic alcohols. The first reported example was a system obtained by reaction of $Ni_2(CN)_4(DPPB)_3$ with $NaBH_4$. It proved to be an efficient catalyst for the conversion of allyl alcohol to propionaldehyde (Scheme 28).

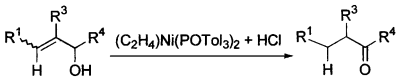
Scheme 28



Using only 0.5 mol % catalyst, 80% conversion to the aldehyde was obtained after 25 min in CH_2Cl_2 at room temperature.[63]

Further, the effect of the cocatalyst on the reactivity of the systems $Ni(DPPB)_2$/HX in the isomerization of olefins was also probed by the same group.[64] For the allyl alcohol, HCN was found to be the best acid. A quantitative transformation to propanal was observed after 25 min at room temperature with only 1% nickel catalyst and 4% of HCN in benzene. No nickel hydride could be detected in the isomerization mixture, and a mechanism via π-allyl intermediates (general type II) was suggested. It is important to note that, while CF_3CO_2H was also a good cocatalyst for the isomerization of various olefins, Corain et al. found that it was completely inefficient to bring about double bond transposition in an allylic alcohol (Scheme 28). However, recent studies by Mortreux et al.[65] demonstrates that a catalyst obtained by the combination of CF_3CO_2H (4 equiv) with either isolated $Ni(DPPB)_2$ or more conveniently an in situ preparation of $Ni(DPPB)_2$ from $Ni(COD)_2$ and DPPB (2 equiv) gave the best results for the isomerization of geraniol

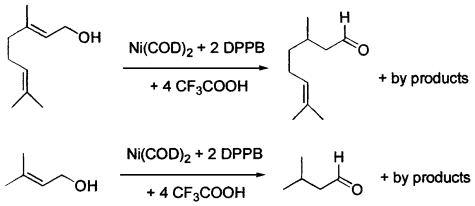
Table 31



entries	R1	R3	R4	time/temp (°C)	solvent	ROH/Ni/HCl	% conv	% yield
a	H	H	H	5 days/45	xylene	20.0/1.0/0.8	100	100
b	H	H	*n*-C_3H_7	2 days/25	xylene	2.0/1.0/0.8	100	81
c	$-(CH_2)_5-$	H	$-(CH_2)-$	1 h/25	pentane	2.0/1.0/1.0	26	51
d	H	Me	H	1 h/25	toluene	2.0/1.0/0.8	65	30
e	Me	H	Me	1 h/25	pentane	2.0/1.0/1.0	92	64
f	Me	H	H	2 h/25	ether	2.0/1.0/1.4	98	80
g	H	H	$CH=CH_2$	1 h/25	hexane	2.0/1.0/0.8	63	20

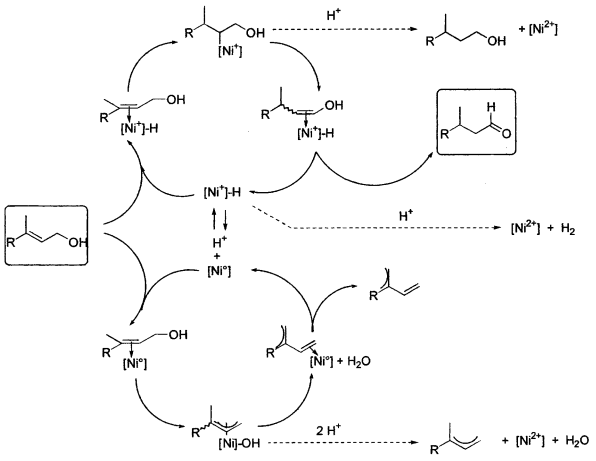
to citronellal as well as for prenol to isovaleraldehyde in toluene at 80 °C (Scheme 29).

Scheme 29



Careful optimization was necessary to minimize the various side reactions such as esterification, acetalization, and acid promoted cyclizations due to the presence of the acid catalyst. Under the best conditions, the reaction stops after ca. 50% conversion and citronellal was isolated in 45% yield. In the presence of 1,2-butanediol, the reaction gave the corresponding acetal with a higher yield (90% in the case of prenol for instance). A catalytic cycle was suggested for this reaction (Scheme 30).

Scheme 30



Several pathways were proposed for the catalyst deactivation:[65]

(i) The aldehyde formed in the reaction could reversibly coordinate to Ni° to form inactive species. This is in agreement with the fact that various nickel coordination complexes of carbonyl compounds have been reported.[66]

(ii) The protonolysis of either the hydrido nickel species or the π-allyl or alkyl nickel intermediates.

This first series of catalysts were successfully used with either very simple models (such as allyl alcohol) or only with limited success in more challenging examples such as geraniol. Therefore, the scope and limitation of such catalysts remain to be established.

Another nickel-derived catalytic system, the ethylenebis (tri-*o*-tolyl phosphite) nickel(0) activated by HCl has also been reported. It performed the isomerization of alkenes bearing polar functional groups, including various simple primary and secondary allylic alcohols (Table 31).[67]

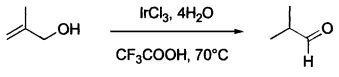
The reactions occurred between 25 and 50 °C but high catalyst loading (usually 20−50 mol %) were necessary to obtain good rates and conversions. This appears to be due to the deactivation of the catalyst system during the first 2 h of the reaction. A type II mechanism has been proposed which is supported by the generation of an enol ether from the corresponding allyl phenyl ether. Another nickel hydride complex $NiH(Ph_2P\ CH_2\ CH_2\ SEt)_2$ has been reported to isomerize allyl alcohol to propanal.[68]

It is notable that chiral nickel catalysts have been used for the asymmetric isomerization of allylic ethers, as discussed later in this review. Furthermore, the complex $(Cy_3P)_2NiCl_2$ proved to be a good catalyst for the isomerization of allylic lithium alkoxides to the corresponding enolates even in the case of the more difficult di- and trisubstituted derivatives. Such enolates could be trapped subsequently for instance, in aldol reactions.[69]

2. Iridium Complexes

It has been noticed, as early as in 1975, that $IrCl_3$, $4H_2O$ (10 mol %) promotes the rearrangement of isobutenol to isobutyraldehyde (Scheme 31). The

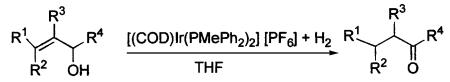
Scheme 31



transformation is quantitative after 3 h at 70 °C, affording the aldehyde although contaminated by about 10% of unidentified byproducts.[22]

At the same period, it was discovered that the catalyst $[(COD)Ir(PMePh_2)_2][PF_6]$ was not only very efficient in hydrogenation of olefins but also could promote the isomerization of allylic alcohols.[70] This observation led Felkin's group to study the isomerization of various substrates. Indeed, after activation with molecular hydrogen, this catalyst proved to be very efficient (0.1−0.5 mol %) in the case of sterically less hindered alcohols (Table 32).[71]

Table 32

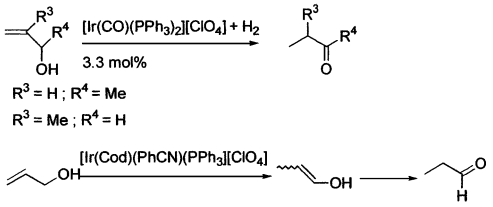


entries	R^1	R^2	R^3	R^4	time (h)	temp (°C)	yield (%)
a	H	H	H	H	0.5	20	100
b	H	H	H	Me	1	20	100
c	H	H	Me	H	0.5	20	100
d	Me	H	H	H	24	20	88
e	Me	H	H	Me	15	20	15
	Me	H	H	Me	18	65	80
f	H	H	Me	Me	2	20	4
g	H	$-(CH_2)_5-$	H	$-(CH_2)-$	2	65	6
h	Me	$Me_2C{=}CH-(CH_2)_2$	H	H	15	65	12
i	Me	Me	H	H	15	65	12
j	Me	Me	H	Me	15	65	0

The reaction was fast at room temperature and gave high yields in the corresponding carbonyl compounds. However, the reaction became very slow and low yielding for sterically more hindered alcohols. These examples confirm the importance of the substitution pattern on the olefin. Even the disubstituted systems were difficult to isomerize, and trisubstituted derivatives gave only very poor yields with this catalyst.

Two closely related cationic iridium catalysts have been reported to isomerize allylic alcohols (Scheme 32). In one case, it was possible to characterize the intermediate enol by NMR.[29c,29f]

Scheme 32

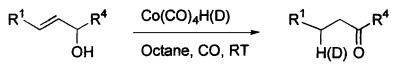


Finally, it must be noted that the iridium derived catalysts proved to be very efficient in the isomerization of allylic ethers;[72] less than 3 mol % of the catalyst at room temperature gave the enol ethers in good yields and with an excellent stereoselectivity. Very recently, a polymer supported iridium catalyst has also been reported to be active in the isomerization of allyl ethers.[73] Such a system that can in principle be recycled would find some applications in allyl ether deprotection.

3. Cobalt Complexes

The isomerization of allyl alcohols to saturated carbonyls by $HCo(CO)_4$ was one of the earliest reports on the use of transition metal complexes for this reaction (Scheme 33).[74]

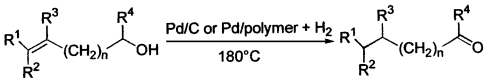
Scheme 33



a : $R^1 = R^4 = H$; **b** : $R^1 = Me$, $R^4 = H$; **c** : $R^1 = H$, $R^4 = Me$

Although the reaction was fast (10 min) at room temperature, the amount of catalyst employed was quite high (20−50 mol %) apart from the low isolated yields in carbonyl compounds (3−21%). This was attributed to competitive hydroformylation reactions giving rise to complex mixtures of products. An interesting aspect of this reaction was the use of the corresponding deutero cobalt carbonyl. It led to propanal exclusively deuterated on the carbon in the β-position. However, at least one equivalent of the catalyst must have been used to explain this result. From a mechanistic point of view, a 1,3-hydrogen shift, similar to those observed during the isomerization of olefins, was proposed. A little later, it was demonstrated that in the reaction of allyl alcohols with $Co_2(CO)_8$ under CO atmosphere, there was a competing carbonylation reaction in addition to the isomerization reaction leading to carbonyls.[75] However, the harsh reaction conditions (240 °C, 230−300 atm CO) resulted in poor yields of carbonyls along with contamination by various side products.

Table 33



entries	R^1	R^2	R^3	R^4	*n*	cat	conv[a](%)
a	H	H	H	H	0	Pd/C	95
b	H	H	H	H	1	Pd/C	40
c	H	H	H	H	2	Pd/C	15
d	H	H	Me	H	0	Pd/C	90
e	H	H	Et	H	0	Pd/C	85
f	Me	H	H	H	0	Pd/C	40
g	Me	Me	H	H	0	Pd/polymer	80
h	Me	H	Me	H	0	Pd/C	35
i	Me	H	H	Me	0	Pd/polymer	100

[a] These reactions give also small amount (<5%) of saturated alcohols and of dehydration products (<5%).

4. Palladium/Platinum Complexes

It has been recognized as early as 1926 that warming 4-penten-3-ol on Pd black induced transposition to afford 3-pentanone.[76] Subsequent studies confirmed this observation with other metals such as platinum.[77,78] A more systematic study was performed with palladium (Table 33).[79]

It must be noted that the Pd catalyst needs to be activated first with hydrogen. Furthermore, this reaction was studied in the gaseous phase using a flow apparatus. Allyl alcohol on a preparative scale (31 g) resulted in 81% isolated yield of propanal, under the conditions mentioned above. However, with these catalysts all attempts to isomerize allyl alcohol in the liquid-phase failed.

A comparative study was made on the reactivity of various unsaturated alcohols in this transformation. This was measured by their conversion to corresponding carbonyl compounds under standard conditions. Several observations were made:

(i) Due to sequential bond shifts, it is possible to start from unsaturated but non-allylic alcohols. However, as expected, the rate of the reaction decreases when the distance to the double bond increases (see entries a, b, and c).

(ii) This reaction gives good results for primary alcohols without substituents on the terminal carbon of the double bond (entries d and e).

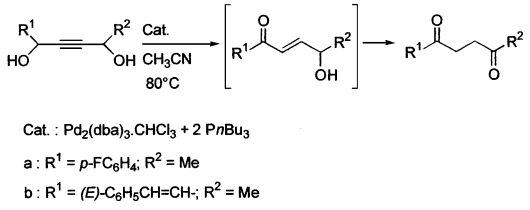
(iii) On the contrary, substitutions on the olefinic part decreases the rate of the transformation (entries f and h). Low yields of isomerized product were obtained starting from secondary alcohols (e.g., 2-cyclohexen-1-ol or 3-penten-2-ol) and using Pd/C as the catalyst.

(iv) In two cases (entries g and i), an intriguing result was obtained on changing the support. Under usual reaction conditions (Pd on charcoal), mainly dehydration of the starting material was observed. On the other hand, when the catalyst was supported on a polymer carrier, it gave 80% isomerization and 20% dehydration in the case of g and a quantitative transposition for i. The gem disubstituted example g is particularly notable since such olefins are usually difficult to isomerize. No explanation was given for this intriguing result that appears to be potentially useful from a synthetic perspective.

The complex *cis*-$PdCl_2(PPh_3)_2$ was reported to perform the isomerization of 1-aryl-3-butene 1,2 diols into 1-aryl-1-butanol-2-ones.[80]

Various γ-hydroxy-α,β-unsaturated ketones have been proposed as intermediates in the isomerization of alkyne diols to 1,4-diketones mediated by palladium complexes (Scheme 34).[81] In two cases, these

Scheme 34

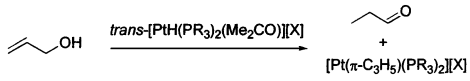


intermediates have been isolated, and it has been demonstrated that they could be transformed into the 1,4-dicarbonyl derivatives. Therefore, this family of catalyst could also be of synthetic use, even if the scope and limitations remain to be established.

It must be noticed that the palladium-catalyzed reaction of aromatic halides with allylic alcohols can lead to the formation of β-aromatic carbonyl compounds.[82] This reaction has strong analogies with the isomerization of allylic alcohols; furthermore, similar intermediates (σ or π) have been proposed in the mechanism.[83]

Catalytic platinum hydride complexes react with allyl alcohol at room temperature to give equimolar amounts of propionaldehyde and corresponding π-allyl derivatives (Scheme 35).[84]

Scheme 35

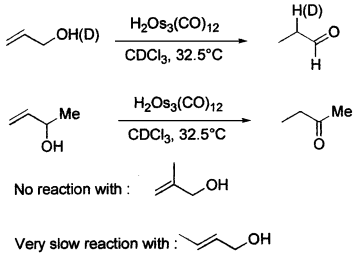


Although the mechanism of this reaction, which involves chelate intermediates, is interesting, it seems of limited synthetic application at this stage.

5. Osmium Complexes

It was recognized early that $H_2Os_3(CO)_{10}$ could catalyze the isomerization of simple allylic alcohols.[85] The corresponding products were not isolated, and only kinetic data were available, indicating similar rates for allyl alcohol and 1-buten-3-ol. However, further substitution on the double bond completely inhibited the reaction (Scheme 36). Isomerization of

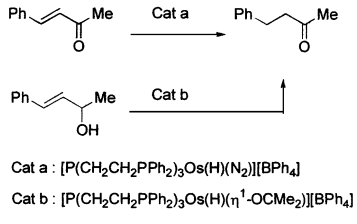
Scheme 36



the deuterated alcohol led to the α-deuterated aldehyde (NMR control).

More recently, it was demonstrated that some osmium complexes catalyzed the reduction of α,β-unsaturated ketones via isomerization of the initially formed allylic alcohols.[86] For instance, reduction of benzylidene acetone with catalyst b (1 mol %, dichloroethane, 80 °C, 1 h) gave over 90% conversion to the saturated ketone. Using the closely related catalyst a (10 mol %, CD_2Cl_2, 3 h, RT), a complete isomerization of the allylic alcohol to the corresponding saturated ketone was observed by NMR (Scheme 37).

Scheme 37

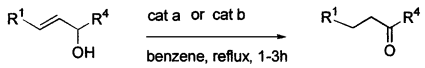


A type I mechanism, via σ-alkyl ligands was proposed for this transformation. From a synthetic point of view, the scope and limitations remain to be established for this family of catalysts.

6. Molybdenum Complexes

The molybdenum complexes *trans*-$Mo(N_2)_2(DPE)_2$ and $MoH_4(DPE)_2$ (1−5 mol % in refluxing benzene) could effect the transposition of allylic alcohols to carbonyl compounds. The yields were good for the secondary and lower in the case of primary allylic alcohols (Table 34).[87]

Table 34[a]



entries	R^1	R^4	catalyst (%)	yield (%)	ref
a	H	Me	a (2)	100	84
b	H	Me	a (1)	69	84
c	H	Me	b (5)	95	84
d	H	H	a (5)	20	84
e	H	H	b (5)	27	84
f	Me	Me	a (20)	98−100[b]	85
g	H	$(CH_2)_3-CH=CH_2$	a (20)	98−100[b]	85

[a] cat a : *trans*-$Mo(N_2)_2(DPE)_2$. cat b: $MoH_4(DPE)_2$. [b] Conversion.

This appears to be due to the decarbonylation of propanal by these complexes. Migration of allylic ethers have also been reported with these catalysts. Using higher catalyst loading (20 mol %), this could be extended with success to 3-penten-2-ol and 1,7-octadien-3-ol. The latter derivative is interesting since no migration of the second, remote double bond was observed.[88] However, for cyclic derivatives such as 2-cyclopenten-1-ol or 2-cyclohexen-1-ol, complex mixtures of products were obtained. A type II mechanism via π-allyl hydrido complexes was suggested, and this is in agreement with the formation of a π-allyl molybdenum hydride during the reaction of the same catalyst with propene.[87] It is worth mentioning that some stereocontrol was observed during the reaction of this catalyst with cyclic allylic alcohol substrates. In the more reactive cis isomer, the CH bond that cleaved was parallel to the π orbital of the double bond η-2 complexed to the transition metal and thus closer to it. Whereas, in the trans isomer the CH bond was far removed and in a bad alignment, leading to a lower rate of isomerization.[89]

Among the other metals, it is worth mentioning that 20 mol % (naphthalene)$Cr(CO)_3$ in acetone at room temperature has been used to isomerize dienylsilylenol ethers in good yields.[90] However, to the best of our knowledge, this reaction has not been extended to dienyl or allylic alcohols. It is also known that different metal-oxo complexes (in the V, W, Mo, and Re series) isomerize allylic alcohols, but in a very different process since it involves a 1,3-transposition of the hydroxyl group.[91]

In conclusion to this part, the nickel and iridium complexes appear to have synthetic potentialities that still need to be developed. However, most of the other transition metal complexes seem to be of relatively limited synthetic usefulness at this stage.

III. Asymmetric Catalysis

The transposition of allylic amines, mediated by chiral rhodium BINAP complexes was a major discovery in the field of asymmetric catalysis.[6] This was not only an important breakthrough from a fundamental point of view, but also led to very useful industrial processes for the preparation of menthol and other terpenes.[28]

On the other hand, in the case of allylic alcohols, similar reactions have met with limited success both in terms of yield and enantiomeric excess. In principle, the transposition of allylic alcohols to saturated carbonyls could open up the scope for asymmetric catalysis in the following instances:

(i) When the terminal carbon of the double bond on the allyl alcohol has two different substituents: in this case, the newly formed stereogenic center would be β to the carbonyl (eq 1 Scheme 38).

Scheme 38

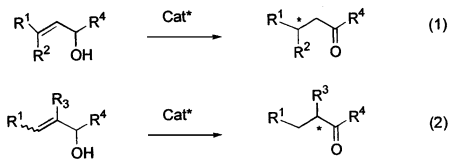
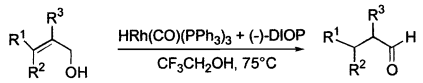


Table 35



entries	R^1	R^2	R^3	time (h)	conv (%)	ee (%)	configuration
a	Me	H	Me	55	98	4	S
b	H	H	Et	55	100	3	R
c	Me	Et	H	400	63	2	R
d	Ph	Me	H	180	0		

(ii) When the two substituents on the vicinal position of the allylic alcohol are different ($R^1CH_2 \neq R^3$; eq 2 Scheme 38): in this case, the newly created asymmetric center would be α to the carbonyl and keto−enol isomerization could be the enantioselectivity determining step. Therefore, if some selectivity is observed, the transition metal catalyst should play other roles than only inducing the double bond migration.

(iii) Certainly, it would be possible to envisage the control of both stereocenters on a single molecule. However, to the best of our knowledge, there is no report to date on such a challenging case.

Another obvious possible use of this transition metal mediated isomerization is to achieve resolution of allylic alcohols. A few examples have been reported and will be discussed later.

The earliest studies in asymmetric catalysis of allyl alcohol isomerization, reported by Botteghi and Giacomelli in 1976, were not very encouraging as the ee's obtained were very low (Table 35).[92]

These reactions were performed with a catalyst prepared from $HRh(CO)(PPh_3)_3$ modified by DIOP ligand and using trifluoroethanol or diglyme as the solvent. The reaction requires a relatively high temperature and long time for obtaining good conversions. Further, the reaction proceeded only in the case of sterically less hindered alcohols and the ee's obtained were very low (2−4%). It is worth mentioning that 2-vinylbutan-1-ol (entry b) is the only example of a derivative leading to a carbonyl with a stereogenic center in the vicinal position and the enantiomeric excess obtained with this was very low (3%). Several explanations are possible for this result, but a low selectivity in the keto−enol isomerization and/or the racemization of the aldehyde under the reaction conditions appear very likely.

In parallel to the development of the isomerization of allylic amines by cationic BINAP−Rh complexes, Tani et al. also reported the transposition of two allylic alcohols.[28] In the latter case, the yields (47 and 70%) and the ee's (37 and 53%) were obviously lower as compared to the excellent results obtained in the case of the corresponding allylic amines (Scheme 39). This was in agreement with detailed mechanistic

Scheme 39

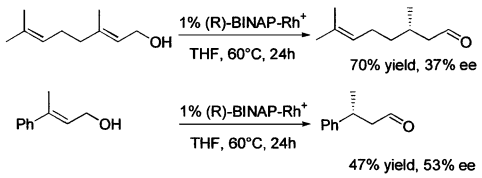
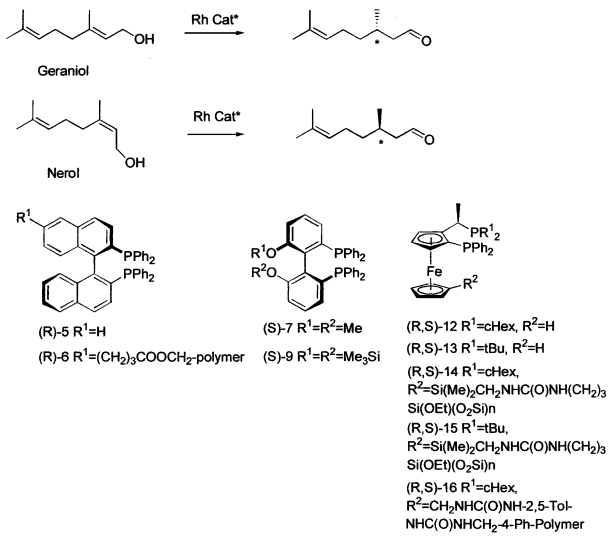


Table 36



					Geraniol as Substrate				
ligand	(*R*)-5	(*R*)-6	(*S*)-7	(*S*)-9	(*R*,*S*)-12	(*R*,*S*)-13	(*R*,*S*)-14	(*R*,*S*)-15	(*R*,*S*)-16
conv. (%)	88	46	75	74	62	85	63	72	62
ee (%)	60	61	44	51	9	22	21	20	4
sign	(−)	(−)	(+)	(+)	(+)	(−)	(−)	(−)	(−)
					Nerol as Substrate				
ligand	(*R*)-5	(*R*)-6	(*S*)-7	(*S*)-9	(*R*,*S*)-12	(*R*,*S*)-13	(*R*,*S*)-14	(*R*,*S*)-15	(*R*,*S*)-16
conv. (%)	90	72	85	78	70	96	54	95	19
ee (%)	51	50	32	37	16	31	20	21	11
sign	(+)	(+)	(−)	(−)	(−)	(+)	(+)	(+)	(+)

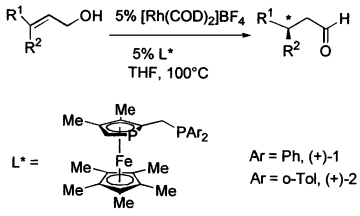
studies establishing the key role of the nitrogen atom in the isomerization of allylamines.[6b]

In the case of geraniol, more recent studies have shown that changing the counterion from perchlorate to triflate with same catalyst resulted in an increased enantioselectivity (from 37 to 60% ee).[93] The same group have also studied the effect of other ligands on this rhodium mediated isomerization for both geraniol and nerol (Table 36).

The selectivities were lower in the case of the biphep ligands (32−51%) and the enantioselectivities further deteriorated with ferrocene derived ligands (4−31%).

In this regard, recent studies by G. Fu et al using similar Rh^+ complexes but with new phosphaferrocene ligands, are more promising.[94] Starting from β,β-disubstituted allyl alcohols, optically active aldehydes were obtained not only in fair to good yields, but more importantly in good to excellent ee's (57−94%, Table 37). The *Z* allyl alcohols gave slightly higher ee's than their corresponding *E* isomers. A correlation could be established between the geometry of the double bond and the absolute configuration of the aldehyde. Furthermore, the catalyst could be recovered and reused. Detailed mechanistic studies have established an intramolecular 1,3-migration pathway and using D-labeled derivatives, it was shown that the differentiation between the enantiotopic H (or D) during CH activation was a key issue for the stereocontrol. This isomerization was applied to a formal synthesis of 7-hydroxycalamenene and 7-hydroxycalamenal, two naturally occurring sesquiterpenes in the cadinene family.

Table 37



R^1	R^2	L*	yield (%)	ee (%)
Me	Ph	(+)−2	91	75
Et	Ph	(+)−2	96	76
i-Pr	Ph	(+)−2	98	92
i-Pr	*p*-ClPh	(+)−2	86	92
i-Pr	*p*-Tol	(+)−2	90	91
i-Pr	*o*-Tol	(+)−2	86	92
Me	Cy	(+)−2	74	94
Ph	Me	(+)−2	80	59
Ph	Et	(+)−2	78	57
Ph	*i*-Pr	(+)−2	82	82
Ph	*t*-Bu	(+)−2	90	90
o-Tol	*i*-Pr	(+)−2	60	81
p-Tol	*i*-Pr	(+)−2	83	77
p-ClPh	*i*-Pr	(+)−2	83	85
Cy	Me	(+)−2	80	87

Not much data are available for the kinetic resolution of acyclic allyl alcohols. In the case of rac-3-buten-2-ol, the first experiments gave only very low ee's (1.7%).[95] More recently, better results were obtained using [Ru (*R*)-BINAP)(H)(MeCN)$(THF)_2$]-$[BF_4]$ as catalyst (2 mol %, in THF/CH_2Cl_2), at 50% conversion the (*S*) alcohol could be isolated in a 42% ee.[96]

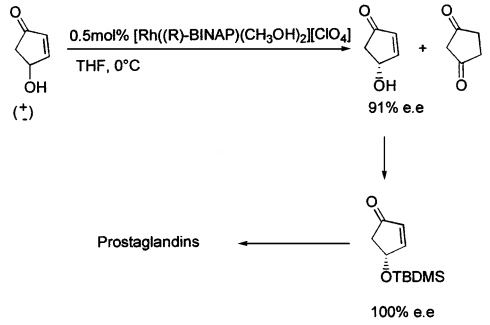
It is noteworthy that higher ee's have been obtained on a cyclic derivative. Using a similar rhodium

Table 38

entries	R (*n*)	C2−C3	cat (%)	temp (°C)	*t* (h)	product sign	yield (%)	ee (%)
1	H (1)		5.0	25	15	(+)	∼100	43.3
2	H (1)		2.0	25	100	(+)	28.0	38.3
3	H (1)		2.0	reflux	15	(+)	99.6	16.9
4	TMS (1)	CH=CH	2.0	reflux	14	(−)	∼100	93.5
5	TMS (2)	CH=CH	2.0	reflux	11	(−)	96.8	93.6
6	TES (1)	CH=CH	2.0	reflux	16	(−)	85.8	97.5
7	TES (2)	CH=CH	2.0	reflux	12	(−)	94.0	96.0
8	TBDMS (1)	CH=CH	2.0	reflux	17	(−)	94.9	96.1
9	TBDMS (2)	CH=CH	2.0	reflux	12	(−)	78.6	96.0
10	Me (1)	CH=CH	2.0	50	12	(−)	91.4	73.0
11	Bn (1)	CH=CH	2.0	50	40	(−)	66.6	72.8
12	TBDMS (1)	CH_2-CH_2	2.0	reflux	20	(−)	88.7	93.7
13	TBDMS (2)	CH_2-CH_2	2.0	reflux	16	(−)	85.2	93.9

catalyzed isomerization, an efficient kinetic resolution of 4-hydroxy-2-cyclopentenone has been reported.[97] It occurred with a 5:1 discrimination rate between the two enantiomers (in a 91% ee at 72% conversion) and led to the preparation of an useful intermediate in prostaglandin synthesis (Scheme 40).

Scheme 40

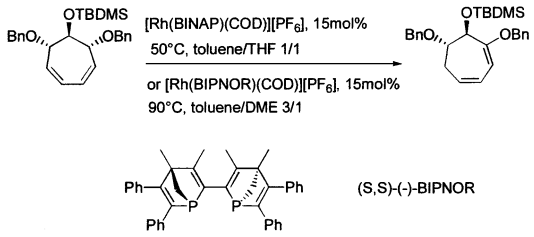


More recently, the same type of catalyst (5 mol %) has been used for the desymmetrization of meso 2-ene-1,4-diols.[98] After 40 h at room temperature, the corresponding hydroxyketones were obtained in quantitative yield and in 43.3% ee (Table 38).

Under similar conditions, the corresponding ethers gave good to excellent results in terms of yields and selectivities. Among them, the silyl ethers appeared especially useful; after isomerization and desilylation, the hydroxyketones were obtained in 93−98% ee's. However, the reactions of the bisacetates and bis(methoxymethyl) ethers did not give any isolable products. On the basis of deuterium labeling experiments a mechanism involving a suprafacial 1,3-hydrogen shift was proposed. This strategy could be extended to a cycloheptenediol to afford the expected hydroxyketone in 71% ee.[99] The latter derivative was transformed in a two step sequence to (−)-(*S*)-physoperuvine.

A similar desymmetrization process was followed in the case of the dienyl ether shown in Scheme 41.[100]

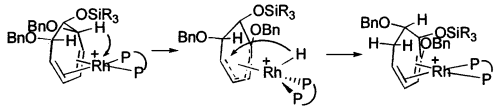
Scheme 41



An interesting aspect of this reaction was the comparison between the BINAP and the BIPNOR chiral ligands on the rhodium catalysts. While the rate of the reaction was higher with the BINAP derived catalyst, the enantioselectivity was strongly improved in the case of BIPNOR (92% ee versus 31% ee for BINAP). The solvent was also shown to play an important role on the enantioselectivity. An oxygen containing cosolvent was necessary, and the best results were obtained with a 3:1 mixture of toluene and DME.

A mechanism involving first a η-4 complexation on the face opposite to the bulky benzyloxy substituents followed by insertion of rhodium into one of the two syn C−H bonds to give the η-5 pentadienyl complex was proposed (Scheme 42). The chiral BIPNOR

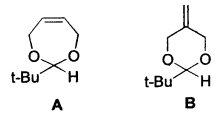
Scheme 42



ligand controls the choice of this C−H bond and therefore the enantioselectivity of the isomerization. This is followed by the hydride migration to give the final dienyl ether.

Cylic allyl acetals such as 2-substituted 4,7-dihydrodioxepins or 5-methylene 1,3-dioxanes have also proven to be excellent models for desymmetrization studies. Using various transition metal catalysts, it

Table 39

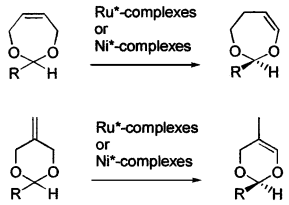


substrate	catalytic system[a]	temp (°C)	time (h)	yield (%)	ee
A	$NiCl_2$[(−)−CHIRAPHOS] + RMgX	0−20	72	21	22
A	$NiCl_2$[(−)−CHIRAPHOS] + $LiBHEt_3$	20	48	72	67
A	$NiCl_2$[(−)−DIOP] + RMgX	0	0.5	86	22
A	$NiCl_2$[(−)−DIOP] + $LiBHEt_3$	−57	16	79	45
A	$NiBr_2$[(−)−DIOP] + $LiBHEt_3$	−55	24	83	39
B	$NiCl_2$[(−)-CHIRAPHOS] + $LiBHEt_3$	66	120	84	16
B	$NiCl_2$[(−)-DIOP] + RMgX	0	0.5	86	73
B	$NiCl_2$[(−)−DIOP] + $LiBHEt_3$	0	24	83	63
B	$NiBr_2$[(−)−DIOP] + RMgX	0	0.5	86	72
B	$NiBr_2$[(−)−DIOP] + $LiBHEt_3$	−57	24	86	89
B	$NiBr_2$[(−)−DIOP] + $LiBHEt_3$	−70	144	86	92

[a] All reactions performed with 4 mol % catalyst in THF except last entry (ether).

was possible to promote their asymmetric transposition to the corresponding vinyl ethers (Scheme 43).

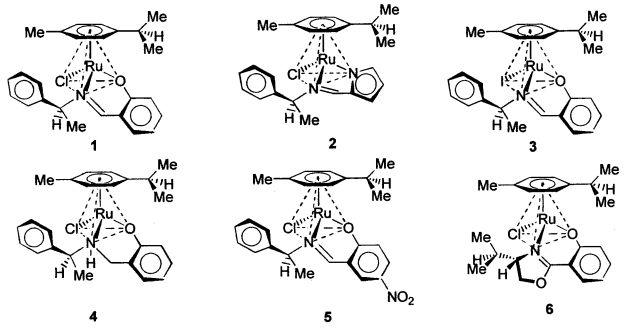
Scheme 43



In a first series of experiments, hydridic ruthenium complexes modified by optically active ligands such as DIOP were used (0.5 mol % of $Ru_2Cl_4(DIOP)_3$ and $NaBH_4$ or H_2). The yields in the isomerized products were good (74−99%), but the ee's obtained were low to moderate (3−25% for the oxepins and 12.8−37.6% for the dioxins).[101] Later on, the same group reported the use of new and more efficient catalysts after activation with lithium triethylborohydride (Super-Hydride). With dihalogenonickel complexes, enantioselectivities of up to 92% for the isomerization of dioxanes were obtained (Table 39) and DIOP proved to be the best ligand.[102] Furthermore, it was observed that the nature of the halogen was important; nickel bromide was found to be superior to nickel chloride. Finally, lowering the temperature gave better ee's. On the contrary, in the case of the dioxepins, the chiraphos ligand proved to be superior to the DIOP ligand giving the highest enantioselectivity (67%). For this family of dioxepins, a further important improvement has been reported recently. Starting from nickel iodide and the Me-DuPHOS ligand (5 mol %) and after activation with $LiBHEt_3$, quantitative conversions and ee's of up to 98% were obtained.[103] These optically active 4,5-dihydro-1,3 dioxepins appear to be excellent building blocks for the synthesis of compounds such as dioxan-4-carboxaldehydes or 2-hydroxy-γ-butyrolactone.

A different approach was followed by the group of Brunner.[104] Using the same dioxepins as models (Scheme 43), they studied the catalytic properties of chiral metal complexes. Six different (η-6-arene) ruthenium complexes were studied (Table 40). Only

Table 40



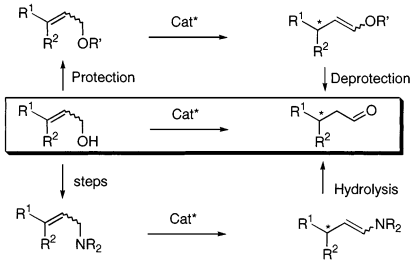
catalyst[a]	conv (%)	yield (%)	ee (sign)
1	100	96−99	49.8(+)−53.2(+)
2	17	15−16	0.5(−)−1.2(+)
3	95−100	91−95	60.1(+)−61.0(+)
4	100	86−87	26.0(+)−30.3(+)
5	18	16	3.9(+)−4.1(+)
6	13	11	0.3(+)−0.7(+)

[a] Cat:$NaBH_4$:substrate = 1:26:200; THF/MeOH as solvent.

three of them gave good conversions and good yields in the corresponding enol product. However, these catalysts gave at best moderate (61% ee) enantioselectivities.

In conclusion, though very good results have been obtained for the asymmetric isomerization of allylic ethers in the case of cyclic models, this needs to be further extended to acyclic and more flexible systems. Apart from the recent results from G. Fu's group, the asymmetric transposition of allylic alcohols have furnished only low to moderate ee's. Hence, the need to develop novel and efficient catalysts would continue to be a challenging problem for the future. While it has been demonstrated that the use of enamine type intermediates gave a very efficient synthesis of optically pure derivatives that are extremely important synthetic intermediates (Scheme 44),[6] an approach using the same type of reactions but starting from the corresponding allylic alcohols would give a more direct synthesis of these derivatives. Furthermore, it would lead to a complete atom economy type reaction.[4]

Scheme 44

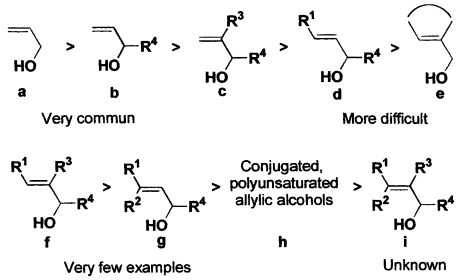


IV. Conclusions

The isomerization of allylic alcohols to saturated carbonyls, mediated by homogeneous transition metal catalysts, has been known for around 40 years. Over 50 different catalytic systems have been prepared from 10 metals and corresponding studies have led to important contributions in coordination chemistry as well as in the chemistry of enols. In many cases this isomerization requires relatively high quantities of catalysts, leading to low TOFs and TONs. This, coupled with rather harsh reaction conditions has limited the use of most of them in this transformation. More active catalysts (at 1 mol % or less) have also been reported, but the corresponding metals (for instance Rh, Ru, Ir) are expensive and therefore issues concerning recycling need to be addressed.

As far as the allylic alcohols are concerned, there is a strong dependence upon the substitution (Scheme 45): most of the catalysts readily isomerize allyl

Scheme 45



alcohol (type a), the corresponding secondary alcohols (type b) and also often the α-substituted derivatives c.

However, the reaction becomes more difficult as the number of substituents increases on the double bond: only a limited number of catalysts give good yields with type d or e alcohols. As far as the trisubstituted alcohols are concerned (such as f or g), very few examples are known. If we consider for instance the isomerization of geraniol (a reaction that is potentially of much economic importance), only six catalytic systems have been reported to date and they have met only with limited success in terms of conversions and yields. For conjugated and polyunsaturated allylic alcohols only three examples of catalysts have been reported. Whereas, to the best of our knowledge, no example has been described yet for the isomerization of type i polysubstituted allylic alcohols.

It has to also be noticed that only limited studies have dealt with addressing the functional group compatibility in this reaction and therefore more systematic studies will be necessary to get a better picture of the scope and limitations of the catalysts.

From a mechanistic viewpoint, several elegant studies have been reported. In such a case, excellent indications have been obtained about the inter/intramolecular characteristics of the isomerization. Furthermore, they allowed choices between the type I or type II mechanisms and discussions about the possible role of the oxygen atom in these reactions. However, it is very clear that in many reported examples, complementary studies appear necessary to allow in depth understanding of their mechanisms.

The asymmetric version of the allylic alcohol isomerization is still far behind the corresponding reaction starting from allylic amines; however, the recently described Rh^+ catalysts appear to open new and interesting perspectives in this area.

In conclusion, it can be expected that novel and more efficient generation of catalysts would be developed soon.[105] Such derivatives could allow a routine use of this atom economical and powerful transformation in synthesis especially for the multistep preparation of natural, as well as nonnatural, products.

V. Acknowledgments

R.U. thanks CNRS and MENRT for foreign research associate positions. R.G. thanks Professor K. N. Houk and his group for their hospitality during a sabbatical leave at UCLA, where this review article was started. We thank Professor A. Mortreux for fruitful exchange of information.

VI. References and Notes

(1) For an early review on the isomerization of allylic alcohols seeYanovskaya, L. A.; Shakhidayatov, Kh. *Russ. Chem. Rev.* **1970**, *39*, 859.
(2) When we were completing this review another article was published (see ref 3). However, this latter review appears mostly oriented towards the nature of the catalysts and the mechanism of the reactions. Therefore, both the articles appear highly complementary.
(3) Van der Drift, R. C.; Bouwman, E.; Drent, E. *J. Organomet. Chem.* **2002**, *650*, 1.
(4) For a discussion on the atom economy concept see (a) Trost, B. M. *Science* **1991**, *254*, 1471. (b) Trost, B. M. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 259.
(5) Herrmann, W. A. In *Applied Homogeneous Catalysis with Organometallic Compounds*; Cornils, B., Herrmann, W. A., Eds.; VCH: Weinheim, 1996; vol 2, 980. Davies, S. G. *Organotransition Metal Chemistry. Applications to Organic Synthesis*; Pergamon Press: UK, 1982; p 266.
(6) (a) Tani, K.; Yamagata, T.; Akutagawa, S.; Kumobayashi, H.; Taketomi, T.; Takaya, H.; Miyashita, A.; Noyori, R.; Otsuka, S. *J. Am. Chem. Soc.* **1984**, *106*, 5208. (b) Noyori, R. *Asymmetric Catalysis in Organic Synthesis*; John Wiley: New York, 1994; p 98.
(7) McGrath, D. V.; Grubbs, R. H. *Organometallics* **1994**, *13*, 224.
(8) The use of transition metal complexes for the deprotection of allylic ethers is a classical reaction (see ref 9), which will not be discussed in this review.
(9) (a) Corey, E. J.; Suggs, J. W. *J. Org. Chem.* **1973**, *38*, 3224. (b) Greene, T. W.; Wuts, P. G. M. *Protective Groups in Organic Synthesis*, 2nd Ed.; John Wiley and Sons: New York, 1991.
(10) Emerson, G. F.; Pettit, R. *J. Am. Chem. Soc.* **1962**, *84*, 4591.
(11) Hendrix, W. T.; Cowherd, F. G.; von Rosenberg, J. L. *Chem. Commun.* **1968**, 97.
(12) Cowherd, F. G.; von Rosenberg, J. L. *J. Am. Chem. Soc.* **1969**, *91*, 2157.
(13) Strauss, J. U.; Ford, P. W. *Tetrahedron Lett.* **1975**, *33*, 2917.
(14) Casey, C. P.; Cyr, C. R. *J. Am. Chem. Soc.* **1973**, *95*, 2248.
(15) Damico, R.; Logan, T. J. *J. Org. Chem.* **1967**, *32*, 2356.

(16) Manuel, T. A. J. *J. Org. Chem*. **1962**, *27*, 3941.
(17) Iranpoor, N.; Imanieh, H.; Forbes, E. J. *Synth. Commun*. **1989**, *19*, 2955.
(18) Iranpoor, N.; Mottaghinejad, E. *J. Organomet. Chem*. **1992**, *423*, 399.
(19) Cherkaoui, H.; Soufiaoui, M.; Grée, R. *Tetrahedron* **2001**, *57*, 2379.
(20) Recent results from our laboratory demonstrate that, under similar reaction conditions, (COT) $Fe(CO)_3$ is also a catalyst for this reaction.
(21) Crévisy, C.; Wietrich, M.; Le Boulaire, V.; Uma, R.; Grée, R. *Tetrahedron Lett*. **2001**, *42*, 395.
(22) Strohmeier, W.; Weigelt, L. *J. Organomet. Chem*. **1975**, *86*, C17.
(23) In methanol, a different reaction pathway was observed, see Bright, A.; Malone, J. F.; Nicholson, J. K.; Powell, J.; Shaw, B. L. *Chem. Commun*. **1971**, 712.
(24) Sasson, Y.; Zoran, A.; Blum, J. *J. Mol. Cat*. **1981**, *11*, 293.
(25) de Bellefon, C.; Caravieilhes, S.; Kuntz, E. G. *C. R. Acad. Sci. Paris, IIc, Chem*. **2000**, *3*, 607.
(26) de Bellefon, C.; Tanchoux, N.; Caravieilhes, S.; Grenouillet, P.; Hessel, V. *Angew. Chem., Int. Ed*. **2000**, *39*, 3442.
(27) Alper, H.; Hachem, K. *J. Org. Chem*. **1980**, *45*, 2269.
(28) (a) Tani, K. *Pure & Appl. Chem*. **1985**, *57*, 1845. (b) Otsuka, S.; Tani, K. *Synthesis* **1991**, 665.
(29) (a) Park, J.; Chin, C. S. *J. Chem. Soc., Chem. Commun*. **1987**, 1213. (b) Chin, C. S.; Lee, S. Y.; Park, J.; Kim, S. *J. Am. Chem. Soc*. **1988**, *110*, 8244. (c) Chin, C. S.; Park, J.; Kim, C.; Lee, S. Y.; Shin, J. H.; Kim, J. B. *Catal. Lett*. **1988**, *1*, 203. (d) Chin, C. S.; Park, J.; Lee, S. Y.; Kim, C. *J. Organomet. Chem*. **1988**, *352*, 379. (e) Chin, C. S.; Park, J.; Kim, C. *Bull. Korean Chem. Soc*. **1989**, *10*, 102. (f) Chin, C. S.; Lee, B.; Kim, S.; Chun, J. *J. Chem. Soc., Dalton Trans*. **1991**, 443.
(30) Chin, C. S.; Lee, B.; Hong, K. *Bull. Korean Chem. Soc*. **1990**, *11*, 162.
(31) Bergens, S.; Bosnich, B. *J. Am. Chem. Soc*. **1991**, *113*, 958.
(32) It has been shown that impurities in $CDCl_3$ (most likely DCl) also catalyzed the ketonisation step: Chin, C. S.; Lee, S. Y.; Lee, B. *Bull. Korean Chem. Soc*. **1990**, *11*, 176.
(33) Trzeciak, A. M.; Ziolkowski, J. J. *Gazz. Chim. Ital*. **1994**, *124*, 403.
(34) Pruchnik, F. P.; Smolenski, P.; Wadja-Hermanowicz, K. *J. Organomet. Chem*. **1998**, *570*, 63.
(35) Bianchini, C.; Meli, A.; Oberhauser, W. *New J. Chem*. **2001**, *25*, 11.
(36) Lee, D.-Y.; Moon, C. W.; Jun, C.-H. *J. Org. Chem*. **2002**, *67*, 3945.
(37) Uma, R.; Davies, M. K.; Crévisy, C.; Grée, R. *Eur. J. Org. Chem*. **2001**, 3141.
(38) Boons, G. J.; Burton, A.; Isles, S. *Chem. Commun*. **1996**, 141.
(39) Dedieu, M.; Pascal, Y.-L. *J. Mol. Cat*. **1980**, *9*, 71.
(40) (a) Sato, S.; Matsuda, I.; Izumi, Y. *Tetrahedron Lett*. **1983**, *24*, 3855. (b) Sato, S.; Matsuda, I.; Izumi, Y. *Tetrahedron Lett*. **1984**, *25*, 769. (c) Sato, S.; Matsuda, I.; Izumi, Y. *Tetrahedron Lett*. **1985**, *26*, 4229. (d) Sato, S.; Matsuda, I.; Izumi, Y. *J. Organomet. Chem*. **1988**, *344*, 71.
(41) Takeuchi, R.; Nitta, S.; Watanabe, D. *J. Org. Chem*. **1995**, *60*, 3045.
(42) Gazzard, L. J.; Motherwell, W. B.; Sandham, D. A. *J. Chem. Soc., Perkin Trans. 1* **1999**, 979.
(43) (a) Nicholson, J. K.; Shaw, B. L. *Proc. Chem. Soc*. **1963**, 282. (b) Dedieu, M.; Pascal, J.-Y. *J. Mol. Catal*. **1980**, *9*, 59.
(44) Smadja, W.; Ville, G.; Georgoulis, C. *J. Chem. Soc., Chem. Commun*. **1980**, 594.
(45) (a) Georgoulis, C.; Valery, J. M.; Ville, G. *Synth. Comm*. **1984**, *14*, 1043. (b) Krompiec, S.; Suwinski, J. *Pol. J. Chem*. **1990**, *64*, 505. (c) Krompiec, S.; Suwinski, J.; Grobelny, R. *J. Mol. Cat*. **1994**, *89*, 303.
(46) Stunnenberg, F.; Niele, F. G. M.; Drent, E. *Inorg. Chim. Acta* **1994**, *222*, 225.
(47) McGrath, D. V.; Grubbs, R. H.; Ziller, J. W. *J. Am. Chem. Soc*. **1991**, *113*, 3611.
(48) Karlen, M.; Ludi, A. *Helv. Chim. Acta* **1992**, *75*, 1604.
(49) Sasson, Y.; Rempel, G. L. *Tetrahedron Lett*. **1974**, *47*, 4133.
(50) Sasson, Y.; Zoran, A.; Blum, J. *J. Mol. Cat*. **1979**, *6*, 289.
(51) Krompiec, S.; Suwinski, J.; Grobelny, J. *Pol. J. Chem*. **1996**, *70*, 813.
(52) Zoran, A.; Sasson, Y.; Blum, J. *J. Org. Chem*. **1981**, *46*, 255.
(53) (a) Trost, B. M.; Kuliawec, R. J. *Tetrahedron Lett*. **1991**, *32*, 3039. (b) Trost, B. M.; Kuliawec, R. J. *J. Am. Chem. Soc*. **1993**, *115*, 2027.
(54) van der Drift, R. C.; Vailati, M.; Bouwman, E.; Drent, E. *J. Mol. Catal. A: Chem*. **2000**, *159*, 163.
(55) Bäckvall, J.-E.; Andreasson, U. *Tetrahedron Lett*. **1993**, *34*, 5459.
(56) Slugovc, C.; Rüba, E.; Schmid, R.; Kirchner, K. *Organometallics* **1999**, *18*, 4230.
(57) Felföldi, K.; Bartok, M. *J. Organomet. Chem*. **1985**, *297*, C37.
(58) Lin, Y.; Zhu, X.; Zhou, Y. *J. Organomet. Chem*. **1992**, *429*, 269.
(59) Langenbahn, M.; Bernauer, K.; Süss-Fink, G. *J. Organomet. Chem*. **1989**, *379*, 165.
(60) Marko, I. E.; Gautier, A.; Tsukazaki, M.; Llobet, A.; Plantalech-Mir, E.; Urch, C. J.; Brown, S. M. *Angew. Chem., Int. Ed*. **1999**, *38*, 1960.
(61) (a) Gurjar, M. K.; Yakambram, P. *Tetrahedron Lett*. **2001**, *42*, 3633. See also: (b) Hoye, T. R.; Zhao, H. *Org. Lett*. **1999**, *1*, 1123.
(62) Cadot, C.; Dalko, P. I.; Cossy, J. *Tetrahedron Lett*. **2002**, *43*, 1839.
(63) Corain, B. *Gazz. Chim. Ital*. **1972**, *102*, 687.
(64) Corain, B.; Puosi, G. *J. Catalysis* **1973**, *30*, 403.
(65) Bricout, H.; Monflier, E.; Carpentier, J.-F.; Mortreux, A. *Eur. J. Inorg. Chem*. **1998**, 1739.
(66) (a) Huang, Y.-H.; Gladysz, J. A. *J. Chem. Educ*. **1988**, *65*, 298; (b) Kim, Y.-J.; Osakada, K.; Yamamoto, A. *Bull. Chem. Soc. Jpn*. **1989**, *62*, 964.
(67) Lochow, C. F.; Miller, R. G. *J. Org. Chem*. **1976**, *41*, 3020.
(68) Rigo, P.; Bressan, M.; Basato, M. *Inorg. Chem*. **1979**, *18*, 860.
(69) Motherwell, W. B.; Sandham, D. A. *Tetrahedron Lett*. **1992**, *33*, 6187.
(70) Crabtree, R. H.; Felkin, H.; Morris, G. E. *J. Organomet. Chem*. **1977**, *141*, 205.
(71) Baudry, D.; Ephritikhine, M.; Felkin, H. *Nouv. J. Chim*. **1978**, *2*, 355.
(72) (a) Baudry, D.; Eephritikhine, M.; Felkin, H. *J. Chem. Soc., Chem. Comm*. **1978**, 694. (b) Moriya, T.; Suzuki, A.; Miyaura, N. *Tetrahedron Lett*. **1995**, *36*, 1887. (c) Ohmura, T.; Shirai, Y.; Yamamoto, Y.; Miyaura, N. *Chem. Commun*. **1998**, 1337. (d) Ohmura, T.; Yamamoto, Y.; Miyaura, N. *Organometallics* **1999**, *18*, 413.
(73) Baxendale, I. R.; Lee, A.-L.; Ley, S. V. *Synlett* **2002**, 516.
(74) Goetz, R. W.; Orchin, M. *J. Am. Chem. Soc*. **1963**, *85*, 1549.
(75) Falbe, J.; Schulze-Steinen, H.-J.; Korte, F. *Chem. Ber*. **1965**, *98*, 886.
(76) Delaby, R. *Compt. Rend*. **1926**, *182*, 140.
(77) Simonik, J.; Beranek, J. *Collect. Czech. Chem. Commun*. **1972**, *37*, 353.
(78) for a recent study on various Pt catalysts see: Hoang-Van, C.; Zegaoui, O. *Applied Catalysis A: General* **1997**, *164*, 91.
(79) Kraus, M. *Collect. Czech. Chem. Commun*. **1972**, *37*, 460.
(80) Marbach, A.; Pascal, Y. L. *C. R. Hebd. Seances Acad. Sci., Paris, Ser. C* **1969**, *268*, 1074.
(81) Lu, X.; Ji, J.; Ma, D.; Shen, W. *J. Org. Chem*. **1991**, *56*, 5774.
(82) (a) Melpolder, J. B.; Heck, R. F. *J. Org. Chem*. **1976**, *41*, 265. (b) Jeffery, T. *Tetrahedron Lett*. **1991**, *32*, 2121 and references therein.
(83) Heck, R. F. *Organic Reactions*; John Wiley: New York, 1982; Vol 27, p 345.
(84) Clark, H. C.; Kurosawa, H. *J. Chem. Soc., Chem. Commun*. **1972**, 150.
(85) Deeming, A. J.; Hasso, S. *J. Organomet. Chem*. **1976**, *114*, 313.
(86) Bianchini, C.; Farnetti, E.; Graziani, M.; Peruzzini, M.; Polo, A. *Organometallics* **1993**, *12*, 3753.
(87) Tatsumi, T.; Hashimoto, K.; Tominaga, H.; Mizuta, Y.; Hata, K.; Hidai, M.; Uchida, Y. *J. Organomet. Chem*. **1983**, *252*, 105.
(88) Lin, Y.; Lu, X. *J. Organomet. Chem*. **1983**, *251*, 321.
(89) Fiaud, J. C.; Aribi-Zouioueche, L. *J. Chem. Soc., Chem. Commun*. **1986**, 390.
(90) Sodeoka, M.; Yamada, H.; Shibasaki, M. *J. Am. Chem. Soc*. **1990**, *112*, 4906.
(91) (a) Bellemin-Laponnaz, S.; Gisie, H.; Le Ny, J.-P.; Osborn, J. A. *Angew. Chem., Int. Ed. Engl*. **1997**, *36*, 976. (b) Bellemin-Laponnaz, S.; Le Ny, J.-P.; Osborn, J. A. *Tetrahedron Lett*. **2000**, *41*, 1549. (c) Bellemin-Laponnaz, S.; Le Ny, J.-P.; Dedieu, M. *Chem. Eur. J*. **1999**, *5*, 57. (d) Narasaka, K.; Kusama, H.; Hayashi, Y. *Chem. Lett*. **1991**, 1413.
(92) Botteghi, C.; Giacomelli, G. *Gazz. Chim. Ital*. **1976**, *106*, 1131
(93) Chapuis, C.; Barthe, M.; de Saint Laumer, J.-Y. *Helv. Chim. Acta* **2001**, *84*, 230.
(94) (a) Tanaka, K.; Qiao, S.; Tobisu, M.; Lo, M. M.-C.; Fu, G. C. *J. Am. Chem. Soc*. **2000**, *122*, 9870. (b) Tanaka, K.; Fu, G. C. *J. Org. Chem*. **2001**, *66*, 8177.
(95) Ohkubo, K.; Ohgushi, T.; Kusaga, T.; Yoshinaga, K. *Inorg. Nucl. Chem. Lett*. **1977**, *13*, 631.
(96) Wiles, J. A.; Lee, C. E.; McDonald, R.; Bergens, S. H. *Organometallics* **1996**, *15*, 3782.
(97) Kitamura, M.; Manabe, K.; Noyori, R.; Takaya, H. *Tetrahedron Lett*. **1987**, *28*, 4719.
(98) Hiroya, K.; Kurihara, Y.; Ogasawara, K. *Angew. Chem., Int. Ed*. **1995**, *34*, 2287.
(99) Hiroya, K.; Ogasawara, K. *J. Chem. Soc., Chem. Commun*. **1995**, 2205.
(100) Faitg, T.; Soulie, J.; Lallemand, J.-Y.; Mercier, F.; Mathey, F. *Tetrahedron* **2000**, *56*, 101.
(101) (a) Frauenrath, H.; Philipps, T. *Angew. Chem., Int. Ed*. **1986**, *25*, 274. (b) Frauenrath, H.; Kaulard, M. *Synlett* **1994**, 517.
(102) Frauenrath, H.; Reim, S.; Wiesner, A. *Tetrahedron: Asymmetry* **1998**, *9*, 1103.
(103) Frauenrath, H.; Brethauer, D.; Reim, S.; Maurer, M.; Raabe, G. *Angew. Chem., Int. Ed*. **2001**, *40*, 177.
(104) Brunner, H.; Prommesberger, M. *Tetrahedron: Asymmetry* **1998**, *9*, 3231.

(105) It should be mentioned that these catalysts could, in principle, perform similar 1,3-hydrogen shifts in the case of propargylic alcohols: such a reaction should lead in an atom economy manner to corresponding enals and enones. However, to the best of our knowledge, such isomerization are relatively rare: they have been reported only for a few Pd,[81,106] Ir,[58,107] and Ru[108] catalysts. Furthermore, it appears that, at least for the latter complex, the mechanism can be different from that involved in the case of allylic alcohols.[108c] Finally, in the case of propargylic alcohols, other reaction pathways could be also involved such as for instance metal mediated 1,3-OH shifts (see ref 91d and references therein).

(106) (a) Minn, K. *Synlett* **1991**, 115. (b) Lu, X.; Ji, J.; Guo, C.; Shen, W. *J. Organomet. Chem.* **1992**, *428*, 259. (c) Guo, C.; Lu, X. *Synlett* **1992**, 405. (d) Guo, C.; Lu, X. *J. Chem. Soc., Perkin Trans. 1* **1993**, 1921.

(107) Ma, D.; Lu, X. *Tetrahedron Lett.* **1989**, *30*, 2109.

(108) (a) Shvo, Y.; Blum, Y.; Reshef, D. *J. Organomet. Chem.* **1982**, *238*, C79. (b) Ma, D.; Lu, X. *J. Chem. Soc., Chem. Commun.* **1989**, 890. (c) Trost, B. M.; Livingston, R. C. *J. Am. Chem. Soc.* **1995**, *117*, 9586. (d) Trost, B. M.; Lee, C. *J. Am. Chem. Soc.* **2001**, *123*, 12193.

CR0103165