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Metallocene-Catalyzed Diastereoselective Epoxidation of Allylic Alcohols

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Abstract—Allylic alcohols undergo an efficient process of diastereoselective epoxidation by *t*-butyl hydroperoxide (TBHP) in *n*-hexane solution in the presence of catalytic amounts of mono- and bis-cyclopentadienyl titanium(IV) and zirconium(IV) chlorides. © 2000 Elsevier Science Ltd. All rights reserved.

Introduction

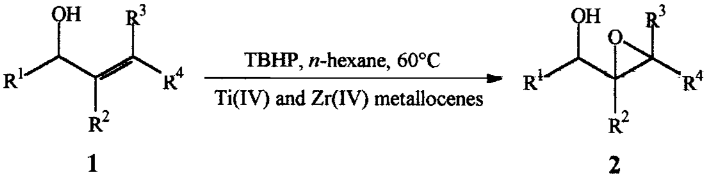
One of the typical procedures for the stereoselective synthesis of 2,3-epoxyalcohols **2**, well-known building blocks in preparative organic chemistry, is represented by oxidation of related allylic alcohols **1** by alkylhydroperoxides catalyzed by d^0 transition metal complexes (Scheme 1).[1]

In the past decades several studies were carried out on the mechanism of this metal-catalyzed epoxidation and some debates have arisen;[2] nowadays the preferred pathway, proposed by Sharpless (Scheme 2), involves a bidentate metal-alkylperoxidic intermediate **3**, formed as a consequence of a nucleophilic substitution on the metal centre conducted by hydroperoxide.[1,2] The role of the catalyst is to activate the coordinated hydroperoxide: because of the electron-withdrawing power of the d^0 metal site, the heterolysis of the O–O bond is considerably facilitated and so the oxygen atom covalently bonded to the metal is prone to nucleophilic attack. An alkene, usually, is a strong enough nucleophile to react with intermediate **3** when the metal is Mo(VI), W(IV), V(V) or Ti(IV). The following and generally slow step, then, is an O transfer to the incoming alkene generating a coordinated epoxide.

In accordance with this mechanism, some common features of good catalysts are strong Lewis acidity and lability with respect to ligands substitution.[1]

In general, the allylic alcohols are particularly reactive owing to the ability of the alcoholic oxygen to coordinate to the metal so that an intermediate such as **4** is formed in which the oxygen transfer is intramolecular.[1,2c] The preference for the oxidations of allylic alcohols compared with unfunctionalized alkenes is illustrated by the site-selective oxidation of geraniol (**1a**) promoted by a variety of metal catalysts.[3] Secondary allylic alcohols are epoxidized often with remarkable diastereoselectivity and the *threo–erythro* ratio depends on the metal and the type of ligands.[1b,2c,4]

Ti(IV)[4,5] alkoxides are largely employed as catalysts in CH_2Cl_2 for the epoxidation of allylic alcohols;[1b] Zr(IV)[3b,c] alkoxides are also reported to promote this reaction but they are less active than the former due to the lower Lewis acidity and thence scarcely used. Complexes of Ti(IV) and Zr(IV) other than alkoxides are very rarely employed with TBHP. Titanocene and zirconocene chlorides, for example, are very well-known and stable compounds and are widely used as catalysts in many homogeneous reactions; with regards to metallocene-catalyzed epoxidations of unfunctionalized



1

2

Scheme 1.

Keywords: diastereoselection; epoxidation; titanium and compounds; zirconium and compounds.

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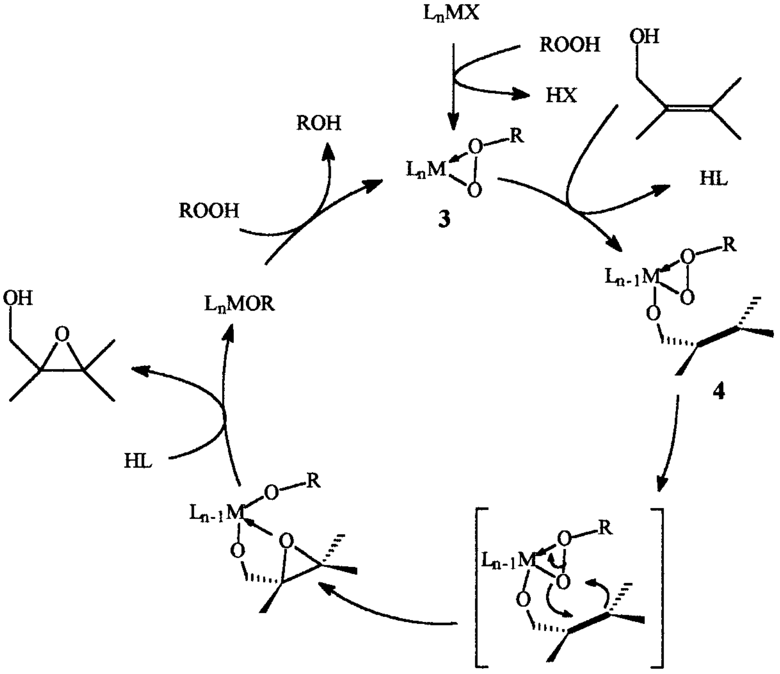


Scheme 2.

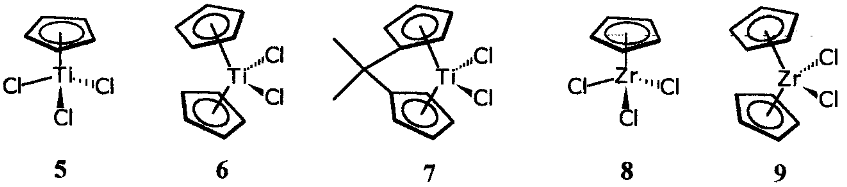
alkenes, the conversion is slow.[8] With polymer-supported Cp_2TiCl_2 and $CpTiCl_3$ the activity is slightly enhanced[9] as with the analogous Zr catalysts.[10] The lack of data about the metallocene-catalyzed epoxidations of allylic alcohols prompted us to undertake a study.

The switch of ligands from alkoxide to cyclopentadienyl was expected to affect the epoxidation rate because the latter is electron-rich and so the metal site is less Lewis acidic. The rate of chloride displacement by hydroperoxide is also, probably, slower than alkoxide displacement. Furthermore, the cyclopentadienyl is known to influence the level of molecular aggregation and the geometry of the metal centre, hence the diastereoselectivity for the chiral allylic alcohols.

In the present work we show that titanocene and zirconocene chlorides **5**–**9** (Scheme 3), in spite of their lower reactivity in comparison with alkoxides, prove to be valuable catalysts in the epoxidations of allylic alcohols provided that the reaction is carried out in hydrocarbon solvents instead of the generally used halogenated solvents.

Results and Discussion

As shown by some preliminary results on the epoxidation of geraniol (**1a**) reported in Table 1, the catalytic activities of metallocenes **6** and **9** in CH_2Cl_2 are rather low if compared with those observed in *n*-hexane (cf. entries 1–2 and 3–4, Table 1). The catalysts are insoluble in hydrocarbon solvents even at the temperatures employed (60°C), so there is a preference for an heterogenous system rather



5 **6** **7** **8** **9**

Scheme 3.

Table 1. Epoxidation of geraniol (**1a**) by TBHP catalyzed by Cp_2TiCl_2 (**6**) (**1a**/TBHP/catalyst 1/1/0.02 molar ratio was used) or Cp_2ZrCl_2 (**9**) (**1a**/TBHP/catalyst 1/1/0.08 molar ratio was used)

Entry	Catalyst	Solvent	Temperature (°C)	Reaction time (h)	Yield (%)[a]
1	**6**	CH_2Cl_2	40	4.0	35
2	**6**	*n*-hexane	60	4.0	82
3	**9**	CH_2Cl_2	40	7.0	–[b]
4	**9**	*n*-hexane	60	7.0	71[c]

[a] Unless otherwise noted all the yields of **2a** were determined by ^1H NMR analysis (400 MHz) on the crude reaction mixture.

[b] No amount of **2a** was detected by ^1H NMR analysis (400 MHz) on the crude reaction mixture.

[c] The yield of **2a** refers to isolated pure compound.

Table 2. Epoxidation of allylic alcohol **1b** by TBHP promoted by different titanium (IV) catalysts (in all entries **1b**/TBHP/catalyst 1/1/0.02 molar ratio was used. Solvent: *n*-hexane (similar results have been obtained in light petroleum); temperature: 60°C)

Entry	Catalyst	Reaction time (h)	Yield (%)[a]	Amount of ketone (%)[b]	*erythro*/*threo* d.r.
1	Ti(O*i*Pr)$_4$	4.0	47	2	76/24
2	TiCl$_4$	17	26	6	86/14
3	**5**	5.5	93	–[c]	88/12
4	**6**	1.0	92	–[d]	84/16
5	**7**	1.5	>95	–[d]	83/17

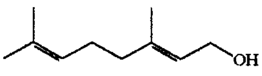
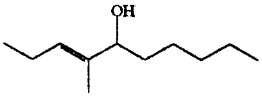
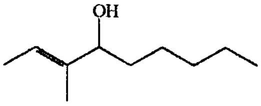
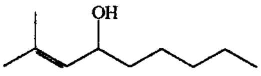
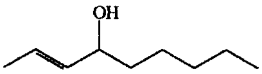
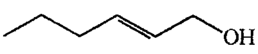
[a] All the yields of **2b** were determined by ^{1}H NMR analysis (400 MHz) on the crude reaction mixture.
[b] Determined by ^{1}H NMR analysis (400 MHz) on the crude reaction mixture.
[c] Amount of ketone not measured.
[d] Amount of ketone not detected.

than an homogeneous one. These outcomes are in contrast with those reported for Ti(IV)[4–6] and Zr(IV)[3c,7] alkoxides for which CH_2Cl_2 is the solvent of choice.

According to this observation we carried out all the subsequent tests in hydrocarbon solvents (*n*-hexane or light petroleum). As summarized in Table 2, catalysts **5–7** in these media proved to be more efficient than TiCl$_4$ and Ti(O*i*Pr)$_4$ in the epoxidation of the representative allylic alcohol **1b**: yields are much better and *erythro*-selectivity is significantly superior to that obtained with Ti(O*i*Pr)$_4$.

Prompted by these promising results we performed a set of experiments on different primary and secondary allylic alcohols (Table 3). Good yields of epoxyalcohol are obtained starting from trisubstituted and disubstituted substrates. Since the main undesired product recognized by NMR after the work-up was the unreacted starting material together with only a small amount of ketone, the yields may be roughly related to the degrees of conversion and so to the oxidation rates. According to a Sharpless-type mechanism (Scheme 2), shorter reaction times are required for the more nucleophilic trisubstituted allylic alcohols **1a–d** in comparison to disubstituted ones **1e**,**f**. Primary

Table 3. Epoxidation of allylic alcohols **1** by TBHP promoted by titanocenes **5–7** (unless otherwise noted **1**/TBHP/catalyst 1/1/0.02 molar ratio was used. Solvent: *n*-hexane (similar results have been obtained in light petroleum); temperature: 60°C)

Entry	Substrate	Catalyst	Reaction time (h)	Yield (%)[a]	Amount of ketone (%)[b]	*erythro*/*threo* d.r.
1	 **1a**	**5**	28	73	–[c]	–
2		**6**	4.0	82	–[c]	–
3		**7**	30	80	–[c]	–
4	 **1b**	**5**	5.5	93	–[c]	88/12
5		**6**	1.0	92	–[d]	84/16
6		**7**	1.5	> 95	–[d]	83/17
7		**5**	1.5	91	9	83/17
8	 **1c**	**6**	3.0	89	6	82/18
9		**6**[e]	6.0	60	10	76/24
10		7	3.0	70	–[c]	79/21
11		**7**[e]	22	81	–[c]	78/22
12	 **1d**	**5**	21	90	–[c]	6/94
13		**6**	3.0	90	–[c]	8/92
14		**7**	7.5	85	–[c]	8/92
15	 **1e**	**5**	23	40	–[c]	42/58
16		**6**	26	72	–[c]	43/57
17		**7**	28	80	8	44/56
18	 **1f**	**6**	46	24	–[c]	–
19		**7**	27	25	–[c]	–

[a] All the yields of **2** were determined by ^{1}H NMR analysis (400 MHz) on the crude reaction mixture.
[b] Determined by ^{1}H NMR analysis (400 MHz) on the crude reaction mixture.
[c] Amount of ketone not measured.
[d] Amount of ketone not detected.
[e] 0.1% mol of catalyst was used.

allylic alcohols **1a**,**f** are slightly less reactive than secondary ones **1b**–**e**. The coordinating role of the hydroxyl group, according to the hypothesis of Sharpless, is confirmed by the site-selective 2,3-epoxidation of geraniol (**1a**).

Reaction rates and yields are somehow dependent on the titanocene catalyst ($CpTiCl_3$ is the less active) but *erythro*–*threo* ratios are essentially unvaried along the series **5**–**7**. This means that the structure of the transition state in the oxygen transfer step, which determines the diastereoselectivity, is very similar in the three cases.

The activity of the bridged titanocene **7** is not significantly higher than that of Cp_2TiCl_2 although the former is expected to undergo a more rapid ligand displacement because of its greater electrophilicity.[11]

In a recent work,[4] Adam et al. resumed a concept, previously proposed by Sharpless, according to which, given a key intermediate such as **4**, the diastereoselectivity depends on the O–C–C═C dihedral angle value of the allylic frame in the transition state.

In the vanadium-catalyzed epoxidations the angle value is 40–50°; this implies a strong $A^{1,2}$ strain and a weak $A^{1,3}$ strain. When substrates **1** with $A^{1,2}$ strain are used (Scheme 1: R^1, R^2=alkyl; R^3=H) excellent *erythro*-selectivity is gained whereas with substrates with $A^{1,3}$ strain (Scheme 1: R^1, R^3=alkyl; R^2=H) only poor *threo*-selectivity is observed. In the peracid epoxidations the O–C–C═C dihedral angle value is estimated about 120°C and so the *threo*-selectivity for the $A^{1,3}$ strained substrates is larger than *erythro* selectivity for the $A^{1,2}$ strained ones. When $Ti(OiPr)_4$ in CH_2Cl_2 is employed as catalyst, $A^{1,2}$ and $A^{1,3}$ strains are intermediate to those of vanadium-catalyzed and peracid epoxidations; therefore the dihedral angle is probably between 50 and 120°.

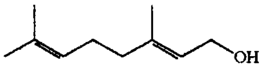
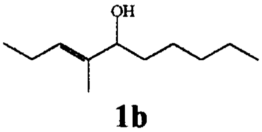
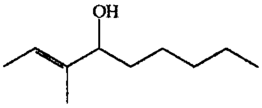
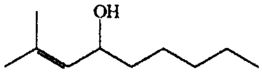
These considerations can also be made for titanocene-catalyzed epoxidations. The data previously reported for $Ti(OiPr)_4$ in CH_2Cl_2,[4] however, have to be regarded with care for any comparison because the present experiments are performed in different solvents and in a heterogeneous system. This fact may influence, as well as the different kind of ligands, the activity and the diastereoselectivity.

For the $A^{1,2}$ strained substrates **1b**,**c**, as expected, good *erythro*-selectivities were obtained (slightly better than $Ti(OiPr)_4$-catalyzed epoxidation);[4] for the $A^{1,3}$ strained allylic alcohol **1d** the *threo*-selectivity is very high (as large as with $Ti(OiPr)_4$). As for the other metal-catalyzed epoxidations, the effect of the alkyl group R^4 (Scheme 1) is almost negligible, slightly favouring the *threo* isomer.

It should be pointed out that good yields can be obtained in the presence of really reduced amounts of catalyst (0.1% mol) although a slightly lower diastereoselectivity is usually observed (cf. entries 8–9 and 10–11, Table 3).

Reaction times can be shortened by performing the oxidation under microwave irradiation (Table 4); under these conditions, less reactive alcohols, such as

Table 4. MW-assisted epoxidation of allylic alcohols **1** by TBHP catalyzed by Cp_2TiCl_2 (**6**) (in all entries **1**/TBHP/catalyst 1/1/0.02 molar ratio was used. MW power: 250 W)

Entry	Substrate	Reaction time (cycles × min)	Yield (%)[a]	Amount of ketone (%)[b]	*erythro*/*threo* d.r.
1	 **1a**	1×15 2×20	60	–[c]	–
2	 **1b**	1×15 2×20	>95	–[d]	83/17
3	 **1c**	1×15 1×20	90	6	80/20
4	 **1d**	1×15 1×20	82	–[c]	8/92
5	 **1f**	8×15	68	–[c]	–

[a] All the yields of **2** were determined by ^1H NMR analysis (400 MHz) on the crude reaction mixture.

[b] Determined by ^1H NMR analysis (400 MHz) on the crude reaction mixture.

[c] Amount of ketone not measured.

[d] Amount of ketone not detected.

trans-2-hexen-1-ol (**1f**), are transformed into the related epoxide with noticeably improved yields (Table 4, entry 5).

Zirconocene compounds **8–9** proved to be good catalysts, too. As expected, the activity is somewhat lower than that of titanocenes **5–7** and a larger amount of catalyst (8% mol) is often required. The epoxidations were carried out at 60°C in *n*-hexane. The yields are moderate, usually lower than for titanocene-catalyzed epoxidations and reaction times are longer (Table 5). Analogously to the related titanium compounds, the catalytic activity of bis-cyclopentadienyl derivative **9** is higher than that of the mono-cyclopentadienyl one **8**.

No great difference of diastereoselectivity is observed between **8** and **9** catalysts; this is somewhat dependent on amounts of zirconocene **9** (cf. entries 5–6, 8–9, 11–12, 14–15, Table 5). The *erythro–threo* ratios, however, are as large as or even better than those of titanocene-promoted oxidations. Once again, for the $A^{1,3}$ strained compound **1d** the *threo* isomer prevails whereas for the $A^{1,2}$ strained ones **1b**,**c** the *erythro* is more abundant. The effect of group R^4 is now reversed, being moderately *erythro*-directing.

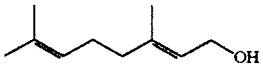
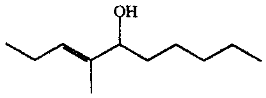
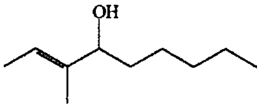
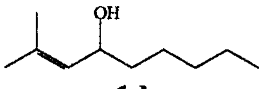
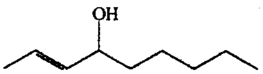
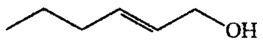
In summary, the previously unreported titanocene- and zirconocene-catalyzed epoxidations of allylic alcohols were accomplished in hydrocarbon solvents under mild conditions with good yields and diastereoselectivity. Two convenient aspects of the procedure are the cheapness of the catalysts and the easy work-up (only filtration of the insoluble catalyst is needed). The nucleophilicity of the substrates and the dependence of the *erythro–threo* ratios on the substitution pattern suggest a Sharpless-type mechanism involving a transition state in which the allylic alcohol and the hydroperoxide are simultaneously coordinated to the metal.

Experimental

General remarks

All reactions were carried out under a dry nitrogen atmosphere. Glassware was flame-dried (0.05 Torr) before use. Cyclopentadienyltitanium trichloride (**5**), cyclopentadienylzirconium trichloride (**8**), zirconocene dichloride (**9**), $TiCl_4$ and $Ti(OiPr)_4$ were all purchased from Aldrich

Table 5. Epoxidation of allylic alcohols **1** by TBHP promoted by zirconocenes **8–9**. (Unless otherwise noted **1**/TBHP/catalyst 1/1/0.08 molar ratio was used. Solvent: *n*-hexane (similar results have been obtained in light petroleum); temperature: 60°C)

Entry	Substrate	Catalyst	Reaction time (h)	Yield (%)[a]	Amount of ketone (%)[b]	*erythro*/*threo* d.r.
1	 **1a**	**8**	7.0	40	–[c]	–
2		**9**	7.0	71	–[c]	–
3		**9**[d]	43	70	–[c]	–
4	 **1b**	**8**	7.0	73	–[c]	88/12
5		**9**	6.5	84	–[c]	92/8
6		**9**[d]	22	82	18	94/6
7	 **1c**	**8**	8.0	80	–[c]	91/9
8		**9**	7.5	77	–[c]	94/6
9		**9**[d]	20	90	10	86/14
10	 **1d**	**8**	23	26	–[c]	9/91
11		**9**	29	48	–[c]	11/89
12		**9**[d]	30	58	5	12/88
13	 **1e**	**8**	25	59	5	67/33
14		**9**	22	70	10	66/34
15		**9**[d]	46	55	18	60/40
16	 **1f**	**8**	20	54[e]	–[f]	–
17		**9**	28	69[e]	–[f]	–
18		**9**[d]	46	59[e]	–[f]	–

[a] Unless otherwise noted all the yields of **2** refer to isolated pure compound.

[b] Unless otherwise noted the amount of ketone was determined by isolation of the pure compound.

[c] Amount of ketone not detected.

[d] 2% mol of catalyst was used.

[e] Yields determined by ^1H NMR analysis (400 MHz) on the crude reaction mixture.

[f] Amount of ketone not measured.

and used without further purifications. Titanocene dichloride (**6**) was prepared according to the procedure of Cardoso et al.;[12] the known catalyst (**7**)[13] was prepared as described below. Geraniol (**1a**) and *trans*-2-hexen-1-ol (**1f**) were purchased from Aldrich. Secondary allylic alcohols **1b–e** were prepared, according to the Grignard method,[14] from *n*-pentyl magnesium bromide and the corresponding aldehydes. All the solvents employed in the organometallic reactions were freshly distilled and dried: *n*-hexane and diethyl ether were distilled from calcium hydride and THF was distilled from sodium/benzophenone.

Epoxidations promoted by microwave irradiation were performed in an Ace pressure tube (Aldrich) which was placed inside a conventional MW kitchen oven (2450 MHz).

Reactions were monitored by thin layer chromatography (TLC) on Merck silica gel plates (0.25 mm) and visualized by UV light or by 10% H_2SO_4/ethanol spray test. Reaction temperatures were measured externally. Flash chromatography was performed on Merck silica gel (60, particle size: 0.040–0.063 mm). NMR spectra were recorded in $CDCl_3$ solutions on a Bruker DRX 400 spectrometer (400 MHz) at room temperature. Chemical shifts are reported relative to the residual solvent peak ($CHCl_3$: $\delta_H=7.26$). EIMS spectra were performed on VG TRIO 2000 spectrometer.

Yields of products **2** refer to isolated pure compounds or were determined by ^{1}H NMR analysis on the crude reaction mixtures. Products **2** were identified by comparison with the data reported in literature[15] and with ^{1}H NMR spectra of authentic samples prepared by an alternative procedure.[16] *erythro*/*threo* Ratios of epoxy alcohols **2b–e** were determined by integrating the characteristic peaks of the two diastereomers in the ^{1}H NMR spectra of the crude reaction mixtures.

Preparation of catalyst 7

Cyclopentadiene (41 ml, 0.5 mol) was added dropwise to a vigorously stirred suspension of powdered NaOH (50 g, 1.2 mol) and triethyl benzyl ammonium chloride (2.5 g, 0.011 mol) in dry THF (20 ml). Stirring was prolonged for 2 h. Then dry acetone (18 ml, 0.24 mol) was added and after 3 h the reaction was quenched by addition of brine (100 ml). After the usual work-up the solvent was removed. The crude oily residue was purified by distillation under reduced pressure to give 2,2-bis-cyclopentadienyl propane (23.0 g, 54% yield).

2.5N (*n*-hexane) *n*-butyllithium (14 ml, 0.035 mol) was slowly added at 0°C to a solution of 2,2-bis-cyclopentadienyl propane (3.0 g, 0.017 mol) in dry THF (180 ml). The solution was stirred at 60°C for 3 h. Then, at −78°C, a solution of $TiCl_4(THF)_2$ (5.8 g, 0.014 mol) in THF (150 ml) was added and stirring was prolonged overnight. After additional refluxing for 3 h, the solvent was removed under reduced pressure. The crude solid was extracted with dichloromethane (400 ml) and the organic phase was cooled at −20°C. After 16 h the catalyst **7**[13] was obtained as a dark green solid (2.3 g, 43% yield).

General procedure for the epoxidation of allylic alcohols 1 catalyzed by 5–9

A mixture of allylic alcohol **1** (2 mmol), TBHP (2 mmol) and the appropriate metallocene (see Tables for the amount) in *n*-hexane (2.5 ml) was stirred in a screw-cap bottle under the conditions reported in Tables 1–3 and 5. After completion of the reaction, the solid catalyst was removed by filtration under reduced pressure and the crude product obtained after the removal of the organic solvent was, unless otherwise noted, purified by flash-chromatography (eluent: light petroleum/ethyl acetate mixtures).

General procedure for the MW-assisted epoxidation of allylic alcohols 1 catalyzed by 5

A mixture of alcohol **1** (2 mmol), TBHP (2 mmol) and the catalyst **5** (0.04 mmol) in *n*-hexane (2.5 ml) was placed in the MW oven and irradiated until completion of the reaction. Then the reaction mixture was subjected to the usual work-up.

1-(3-Ethyl-2-methyl-oxiranyl)-hexan-1-ol (2b). (*erythro isomer*): [Found: C, 70.9; H, 11.6. $C_{11}H_{22}O_2$ requires C, 70.92; H, 11.90%]; R_f (25% Et_2O/light petroleum) 0.39; δ_H (400 MHz, $CDCl_3$) 3.61 (1H, dd, J=6.8, 2.6 Hz, $\mathrm{C}H\mathrm{OH}$), 2.99 (1H, dd, J=6.5, 6.5 Hz, $\mathrm{CH_3CH_2C}H\mathrm{O}$), 2.28 (1H, bs, $\mathrm{O}H$), 1.70–1.25 (13H, m), 1.03 (3H, t, J=7.6 Hz, $\mathrm{C}H_3\mathrm{CH_2CHO}$), 0.90 (3H, t, J=6.7 Hz, $\mathrm{(CH_2)_4C}H_3$); δ_C (100.6 MHz, $CDCl_3$) 72.5, 62.9, 60.4, 32.6, 31.8, 25.1, 22.5, 21.3, 14.0, 13.9, 10.3; *m*/*z* (EIMS) 186 (M^+). (*threo isomer*): [Found: C, 70.8; H, 12.0. $C_{11}H_{22}O_2$ requires C, 70.92; H, 11.90%]; R_f (25% Et_2O/light petroleum) 0.19; δ_H (400 MHz, $CDCl_3$) 3.21 (1H, m, $\mathrm{C}H\mathrm{OH}$), 2.79 (1H, dd, J=6.5, 6.5 Hz, $\mathrm{CH_3CH_2C}H\mathrm{O}$), 1.97 (1H, bs, $\mathrm{O}H$), 1.70–1.25 (13H, m), 1.03 (3H, t, J=7.6 Hz, $\mathrm{C}H_3\mathrm{CH_2CHO}$), 0.90 (3H, t, J=6.7 Hz, $\mathrm{(CH_2)_4C}H_3$); δ_C (100.6 MHz, $CDCl_3$) 77.0, 63.7, 63.4, 33.0, 31.8, 25.2, 22.5, 21.4, 13.9, 10.9, 10.4; *m*/*z* (EIMS) 186 (M^+).

1-(2,3-Dimethyl-oxiranyl)-hexan-1-ol (2c). (*erythro isomer*): [Found: C, 69.9; H, 11.3. $C_{10}H_{20}O_2$ requires C, 69.72; H, 11.70%]; R_f (25% Et_2O/light petroleum) 0.39; δ_H (400 MHz, $CDCl_3$) 3.62 (1H, dd, J=7.9, 3.0 Hz, $\mathrm{C}H\mathrm{OH}$), 3.15 (1H, q, J=5.6 Hz, $\mathrm{CH_3C}H\mathrm{O}$), 2.10 (1H, s, $\mathrm{O}H$), 1.54–1.16 (14H, m), 0.89 (3H, t, J=7.7 Hz, $\mathrm{(CH_2)_4C}H_3$); δ_C (100.6 MHz, $CDCl_3$) 72.6, 62.7, 54.9, 32.6, 31.8, 25.2, 22.5, 14.1, 14.0, 13.5; *m*/*z* (EIMS) 172 (M^+). (*threo isomer*): [Found: C, 69.8; H, 11.2. $C_{10}H_{20}O_2$ requires C, 69.72; H, 11.70%]; R_f (25% Et_2O/light petroleum) 0.30; δ_H (400 MHz, $CDCl_3$) 3.20 (1H, m, $\mathrm{C}H\mathrm{OH}$), 2.97 (1H, q, J=5.5 Hz, $\mathrm{CH_3C}H\mathrm{O}$), 2.13 (1H, s, $\mathrm{O}H$), 1.54–1.15 (14H, m), 0.89 (3H, t, J=7.7 Hz, $\mathrm{(CH_2)_4C}H_3$); δ_C (100.6 MHz, $CDCl_3$) 76.9, 63.6, 57.7, 33.0, 31.8, 25.3, 22.5, 14.1, 14.0, 13.5; *m*/*z* (EIMS) 172 (M^+).

1-(3,3-Dimethyl-oxiranyl)-hexan-1-ol (2d). (*Major isomer: threo*): [Found: C, 70.0; H, 11.6. $C_{10}H_{20}O_2$ requires C, 69.72; H, 11.70%]; R_f (50% Et_2O/light petroleum) 0.37; δ_H (400 MHz, $CDCl_3$) 3.47 (1H, dt, J=7.9, 5.2 Hz, $\mathrm{C}H\mathrm{OH}$), 2.70 (1H, d, J=7.9 Hz, $\mathrm{C}H\mathrm{OCHOH}$), 2.16 (1H, s, $\mathrm{O}H$), 1.75–1.16 (14H, m), 0.89 (3H, t, J=7.4 Hz, $\mathrm{(CH_2)_4C}H_3$); δ_C (100.6 MHz, $CDCl_3$) 70.2, 68.0, 59.6, 33.6, 31.7, 24.7, 24.5, 22.4, 19.2, 13.9; *m*/*z* (EIMS) 172 (M^+).

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References

1. (a) Jorgensen, K. A. *Chem. Rev.* **1989**, *89*, 431–458. (b) Hoveyda, A. H.; Evans, D. A.; Fu, G. C. *Chem. Rev.* **1993**, *93*, 1307–1365. (c) Sheldon, R. A., Kochi, J. A. *Metal-Catalyzed Oxidation of Organic Compounds*; Academic Press: New York, 1981.

2. (a) Chong, A. O.; Sharpless, K. B. *J. Org. Chem.* **1977**, *42*, 1587–1590. (b) Mimoun, H.; Mignard, M.; Brechot, P.; Saussine, L. *J. Am. Chem. Soc.* **1986**, *108*, 3711–3718. (c) Sharpless, K. B.; Verhoeven, T. R. *Adrichim. Acta* **1979**, *12*, 63–74. (d) Trost, M. K.; Bergman, R. G. *Organometallics* **1991**, *10*, 1172–1178.

3. (a) Sharpless, K. B.; Michaelson, R. C. *J. Am. Chem. Soc.* **1973**, *95*, 6136–6137. (b) Sharpless, K. B. *Chemtech.* **1985**, 692–700. (c) Krohn, K.; Vinke, I.; Adam, H. *J. Org. Chem.* **1996**, *61*, 1467–1472. (d) Kirshenbaum K. S. *Nouv. J. Chim.* **1983**, *7*, 699–701. (e) Jacobson, S. E.; Mares, F.; Zambri, P. M. *J. Am. Chem. Soc.* **1979**, *101*, 6946–6950. (f) Prat, D., Lett. R. *Tetrahedron Lett.* **1986**, *27*, 707–710. (g) Takai, K.; Oshima, K.; Nozaki, H. *Tetrahedron Lett.* **1980**, *21*, 1657–1660. (h) Kanemoto, S.; Nonaka, T.; Oshima, K.; Utimoto, K.; Nozaki, H. *Tetrahedron Lett.* **1986**, *27*, 3387–3390.

4. Adam, W.; Corma, A.; Reddy, T. I.; Renz, M. *J. Org. Chem.* **1997**, *62*, 3631–3637.

5. Isobe, M.; Kitamura, M.; Mio, S.; Goto, T. *Tetrahedron Lett.* **1982**, *23*, 221.

6. Woodard, S. S.; Finn, M. G.; Sharpless, K. B. *J. Am. Chem. Soc.* **1991**, *113*, 106–113.

7. Ikegami, S.; Katsuki, T.; Yamaguchi, M. *Chem. Lett.* **1987**, 83–84.

8. (a) Colletti, S. L.; Halterman, R. L. *Tetrahedron Lett.* **1992**, *33*, 1005–1008. (b) Colletti, S. L.; Halterman, R. L. *J. Organomet. Chem.* **1993**, *455*, 99–106.

9. Lau, C.-P.; Chang, B.-H.; Grubbs, R. H.; Brubaker, C. H. *J. Organomet. Chem.* **1981**, *214*, 325–331.

10. Chang, B.-H.; Grubbs, R. H.; Brubaker, C. H. *J. Organomet. Chem.* **1985**, *280*, 365–376.

11. Shaltout, R. M.; Corey, J. Y.; Rath, N. P. *J. Organomet. Chem.* **1995**, *503*, 205–212.

12. Cardoso, A. M.; Clark, R. J. M.; Moorhouse, S. J. *J. Chem. Soc., Dalton Trans.* **1980**, 1156–1160.

13. Nifant'ev, I. E.; Butakov, K. A.; Aliev, Z. G.; Urazowski, I. F. *Metalloorg. Khim.* **1991**, *4*, 1265.

14. Vogel, A. I. In *Vogel's Textbook of Practical Organic Chemistry*, 5th ed.; Furniss, B. S., Hannaford, A. J., Smith, P. W. G., Tatchell, A. R., Eds.; Wiley: New York, 1989; p 537.

15. Palombi, L.; Bonadies, F.; Scettri, A. *Tetrahedron* **1997**, *53*, 11369–11376.

16. Rossiter, B. E.; Verhoeven, T. R.; Sharpless, K. B. *Tetrahedron Lett.* **1979**, *20*, 4733–4736.