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# A comparison of electron transfer reagents in the reductive opening of epoxides: reasons for the superiority of titanocene based complexes

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**Abstract**—Several commonly used electron transfer reagents were compared in their reactivity towards three epoxides. These substrates were designed to allow for a distinction between competing courses of the reaction. It was found that titanocene reagents were clearly superior due to their low Lewis acidity, high reduction tendency towards epoxides, and low reduction tendency towards the pivotal β-metal oxy radical intermediates. © 2002 Elsevier Science Ltd. All rights reserved.

## 1. Introduction

Epoxides are amongst the most frequently employed substrates in organic synthesis. This is due to the ease of their preparation from readily available precursors, e.g. olefins and carbonyl compounds, and their high reactivity.[1] The latter point arises mainly from the strain inherent in the three-membered ring that is released during ring opening. Epoxides, especially when prepared in high enantiomeric excess, have been very useful in $S_N2$ reactions in this respect. An alternative approach to exploiting the high reactivity of the strained epoxide is constituted by ring opening reactions utilizing electron transfer reagents.[2] In the light of the success of the Birch conditions for reducing organic compounds it is not surprising that epoxides can be opened by solvated electrons.[3] The initially formed radical is then further reduced to give carbanionic species. This concept has been extended by Bartmann,[4] Cohen,[5] and Yus[6] who have employed aromatic radical anions as the reducing agents in many synthetically useful applications.

With respect to the utilization of the intermediate radicals for organic synthesis the use of low valent metal complexes is more promising. The general idea of this concept was first outlined by Nugent and RajanBabu[7] as shown in Fig. 1 and constitutes an analogue of the well established opening of a cyclopropylcarbinyl radical.[7,8]

So far, only titanocene(III) reagents that were introduced by Nugent and RajanBabu in this field have been successfully

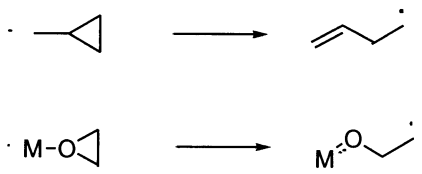


**Figure 1.** Analogy of epoxide opening and cyclopropylcarbinyl radical opening.

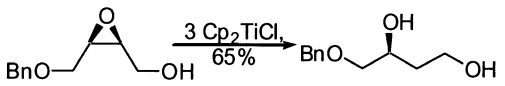


**Figure 2.** Chakraborty's epoxide opening for the synthesis of 1,3-diols.

employed in transformations that do not lead to deoxygenations of epoxides. An example is shown in Fig. 2.[2,9]

We have recently developed a catalytic system for conducting these reactions that has also allowed for the first enantioselective generation of radicals.[10]

Although the use of titanocene based reagents has a number of advantages it would clearly be attractive to use other metal complexes in order to establish novel reactivity patterns. In this contribution we describe our results in this area. We have concentrated on the use of single electron transfer reagents to avoid two electron processes via oxidative insertions or $S_N2$ type reactions with metals.[11]

## 2. Results

It is generally agreed that with the SET reagents the pivotal

*Keywords*: chromium; cyclization; epoxides; radical reaction; samarium; titanium; vanadium.

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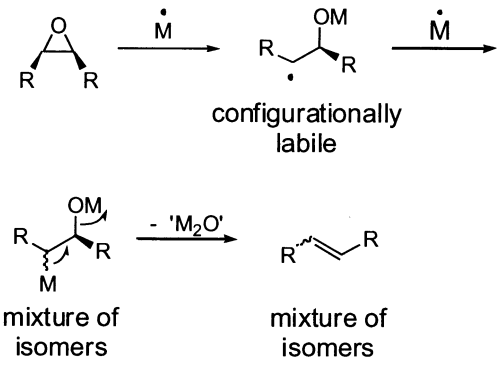



**Figure 3.** Deoxygenation of epoxides via electron transfer.

intermediates are indeed formed if the deoxygenation reaction of epoxides proceeds with low stereoselectivity to mixtures of the corresponding (*E*) and (*Z*) olefins as shown in Fig. 3.[7a,10]

This argument is based on the unselective trapping of the configurationally labile radical intermediate by the second equivalent of the SET reagent. The resulting diastereomeric mixture eliminates to give the depicted mixture of olefins.

The deoxygenation of simple unfunctionalized epoxides has already been investigated with titanocene[7] and samarium[12] reagents. Usually both complexes give mixtures of the isomers with low selectivity. The epoxide **1** investigated here is mechanistically more interesting because the organometallic intermediate formed after reductive trapping with a second equivalent of the low valent metal complex can give two different elimination products. Consequently, the issue of regioselectivity of the overall transformation and the factors controlling it are raised as shown in Fig. 4.

We have decided to use $SmI_2$, $CrCl_2$, $[V_2Cl_3(THF)_6]_2[Zn_2Cl_6]$ obtained by reduction of $VCl_3(THF)_3$[13] with Zn dust in THF, and $Cp_2TiCl$[14] as the actual reducing agents. The vanadium based reagent has to the best of our knowledge not been used in epoxide openings as yet. It has proven to give excellent results in pinacol type reactions

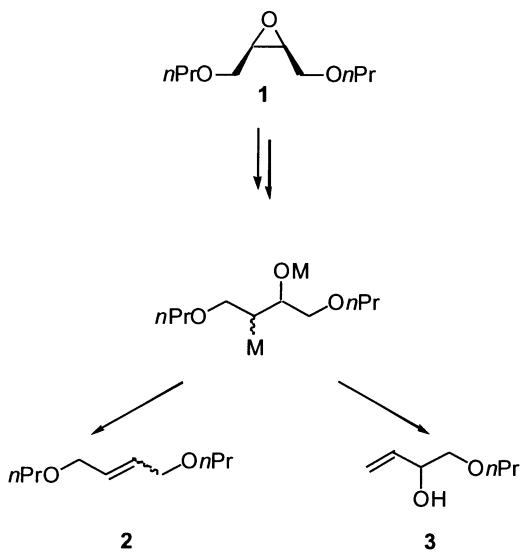
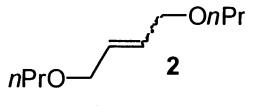
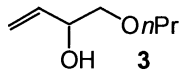
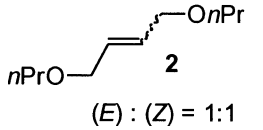
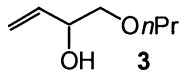
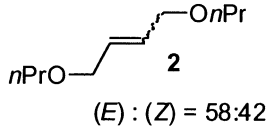
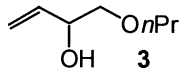



**Figure 4.** Competing modes of deoxygenation for epoxide **1**.

**Table 1**. Deoxygenation reactions of **1** in the presence of single electron transfer reagents

| Entry | ET-reagent | Product | Yield (%) |
|---|---|---|---|
| 1 | $CrCl_2$ |  **2** (*E*) : (*Z*) = 41:59 | 19[a] |
| | |  **3** | 16 |
| 2 | $VCl_3(THF)_3/Zn$ |  **2** (*E*) : (*Z*) = 1:1 | 73 |
| 3 | $SmI_2$ |  **3** | 53 |
| 4 | $Cp_2TiCl$ |  **2** (*E*) : (*Z*) = 58:42 | 19 |
| | |  **3** | 47 |

[a] 49% Substrate reisolated.

introduced by Pedersen.[15] $CrCl_2$ has, to the best of our knowledge, only been used in deoxygenation reactions of cyclohexene and styrene oxide where no problems of selectivity can occur.[16] Our results are summarized in Table 1.

Interestingly, $[V_2Cl_3(THF)_6]_2[Zn_2Cl_6]$ and $SmI_2$ react with complete albeit opposite selectivity. Whereas mixtures of the (*E*) and (*Z*) isomers (1:1) of **2** are formed in 73% yield with $[V_2Cl_3(THF)_6]_2[Zn_2Cl_6]$, $SmI_2$ gives only the product of propoxide elimination **3** in 53% yield. No other products were obtained. The rather low mass balance could be due to the noticeable volatility and water solubility of **3**. Surprisingly, the chromium reagent exhibited distinctly lower reactivity even when employed in DMF and in the presence of the diamine ligand ethylene diamine. Besides 49% of reisolated starting material, the deoxygenation products **2** and **3** were obtained in low yields. The titanocene reagent gave **2** in 19% yield as 58:42 mixture of (*E*) and (*Z*) isomers and **3** in 47% yield.

Although the reason for this different behavior is unclear at present it seems that the higher Lewis acidity of samarium could lead to a more efficient complexation of the propoxy group after reductive trapping. Elimination then occurs to yield the allylic alcohol. This experiment does, however, give no indication if the epoxide is opened via electron transfer directly or opened by nucleophilic substitution with iodide and ensuing reduction of the iodo compound.

The less Lewis acid vanadium species could react via ligand exchange to give a metalla oxetane that eliminates a vanadium oxo species to yield the allylic ether. An alternative explanation for this mode of deoxygenation could be the dimeric nature of the vanadium complex. The

second electron could then be transferred to the radical in an intramolecular manner. To justify this speculative thought a rigorous structural determination of the vanadium complex in solution would have to be carried out.

Titanocene chloride displays intermediate behavior with the product of propoxide elimination **3** being the major product. Thus, this reagent is expectedly less Lewis acidic than samarium diiodide.

The deoxygenation of epoxides with the metal complexes mentioned above all seem to proceed via intermediate β-metal oxy radicals. The reaction path after their trapping seems, however, to depend on the Lewis acidity of the electron transfer reagent.

With these results in hands we turned our attention to the decisive question for the desired use of the pivotal β-metal oxy radicals, the persistence of carbon-centered radicals in a reductive medium. Radical reactivity for CH and CC bond formation can only be exploited if the reduction of the radical is slower than the attempted ensuing radical transformation, e.g. a 5-*exo* cyclization.[17] For $SmI_2$ it is known that primary alkyl radicals are reduced with rate constants of about $6\times10^6\ M^{-1}\ s^{-1}$.[18] However, 5-*exo* cyclizations of radicals derived from $SmI_2$ mediated halide abstraction with alkenes and alkynes are well documented and must therefore be considered faster than reductive trapping.[17]

Therefore, we decided to investigate $SmI_2$ and the other electron transfer reagents mentioned above with suitably unsaturated epoxides. We chose epoxide **4** as substrate in these reactions for four reasons shown in Fig. 5.

Firstly, the ester groups can act as internal nucleophiles for Lewis acid assisted epoxide opening, secondly the mono-substituted epoxide is readily attacked by external nucleophiles, e.g. iodide, and thirdly the trisubstituted olefin is known to accelerate 5-*exo* cyclizations and should intercept radicals efficiently,[19] and last but not least the ester groups can trap alkoxides formed by $S_N2$ opening of the epoxide as acylating reagents.

Thus, substrate **4** should allow for an analysis of all effects especially when they occur with similar rates. Also the question of direct epoxide reduction and $S_N2$ opening followed by reduction of metallated iodohydrins should be resolved by analysis of the opening products.

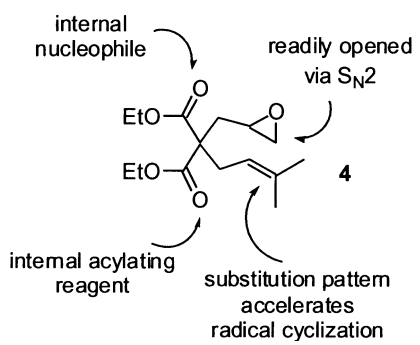



**Figure 5.** Possible side reactions during the opening of epoxide **4**.

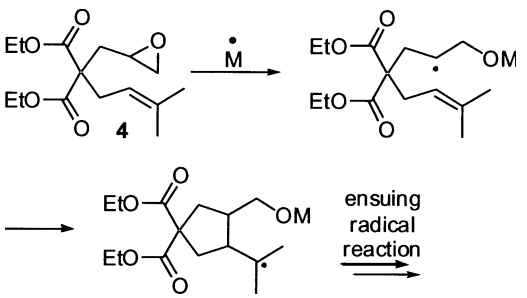
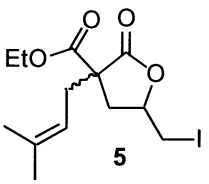
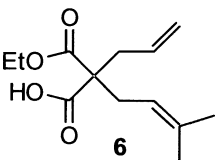
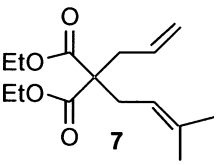
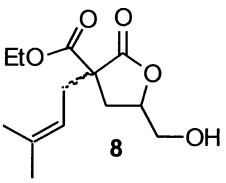
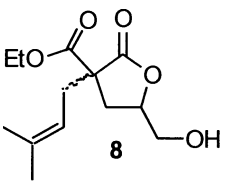
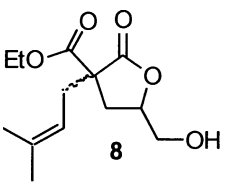
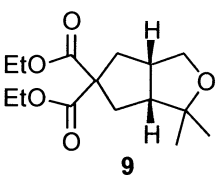



**Figure 6.** 5-*exo trig* radical cyclization after reductive opening of **4**.

**Table 2**. Reactions of **4** with single electron transfer reagents

| Entry | ET-reagent | Product | Yield (%) |
|---|---|---|---|
| 1 | $SmI_2$ |  | 31, dr=61:39 |
| | |  | 55 |
| 2 | $VCl_3(THF)_3/Zn$ |  | 59 |
| | |  | 7, dr=80:20 |
| 3 | $VCl_3/Zn$ |  | 48, dr=60:40 |
| 4 | $VCl_3(THF)_3$ |  | 25, dr=40:60 |
| 5 | $Cp_2TiCl$ |  | 57 |

The results of our investigations based on the opening shown in Fig. 6 are summarized in Table 2.

$SmI_2$ as electron transfer reagent resulted in the formation of two products in good combined yield. Lactone **5** is formed by epoxide opening with iodide via $S_N2$ and ensuing fast lactonization. The deoxygenation product **6** can only be formed by reduction of **5** with 2 equiv. of $SmI_2$ and β-elimination of a carboxylate. Thus, the epoxide ring is not opened via electron transfer at all and the $S_N2$ reaction with iodide must be considered much faster. In the case of the vanadium reagent different results were obtained. Expectedly, no chlorohydrins from external nucleophilic attack could be observed. Chloride is only a weak nucleophile. However, lactone **8** was isolated in low yield (7%). Thus, some vanadium or zinc species was Lewis acidic enough to promote an intramolecular nucleophilic epoxide opening. The main product is, however, constituted by the deoxygenation product **7** that could be isolated in 59% yield. This result was rather surprising for us because we expected a 5-*exo* cyclization to be faster than any second supposedly intermolecular trapping of the radical by vanadium. Because of the dimeric nature of the vanadium reagent in the solid state it could be that the second electron is transferred to the radical center in an intramolecular manner. This intramolecular process should be able to efficiently compete with the radical cyclization. This interpretation is in line with the 1:1 mixture of olefins obtained in the deoxygenation of **1** with vanadium via a radical intermediate (Table 1, entry 2). A rigorous confirmation of this presently speculative hypothesis could be obtained from solution studies of the vanadium reagent's structure. It should be noted, however, that preliminary kinetic investigations of the reaction of $[V_2Cl_3(THF)_6]_2[Zn_2Cl_6]$ with benzaldehyde have indicated that the reactive species in solution is $VCl_2$.[20]

Entries 4 and 5 readdress the issue of the intramolecular nucleophilic epoxide opening leading to the formation of **8**. The precursor to the vanadium(II) reagent, $VCl_3(THF)_3$ as well as $VCl_3$/Zn in THF result in the formation of **8** but in higher yields than with $[V_2Cl_3(THF)_6]_2[Zn_2Cl_6]$. Since both reagents constitute stronger Lewis acids than $[V_2Cl_3(THF)_6]_2[Zn_2Cl_6]$ vanadium(III) species are likely to be responsible for the undesired side reaction and not the vanadium(II) complex.

Titanocene chloride gave product **9** in 57% yield that arises through epoxide opening via electron transfer and the ensuing 5-*exo* cyclization. The second ring is closed through a radical substitution reaction. We are currently investigating the scope of the unprecedented and highly interesting reaction.[21]

Finally, we investigated the behavior of epoxide **10** under electron transfer conditions. Here, a tertiary radical would be formed after reductive opening that is more stable than the secondary radical obtained from **4** as depicted in Fig. 7. The results of the opening reactions are summarized in Table 3.

It is also well documented that tertiary radicals are only very slowly reduced even by potent electron transfer reagents,

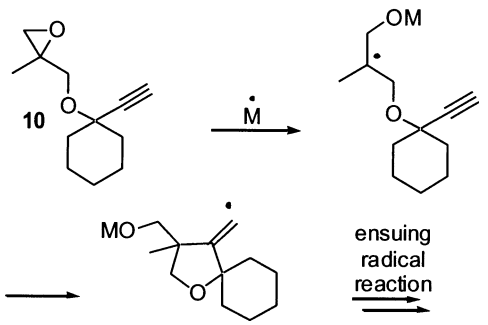
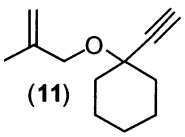
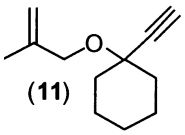
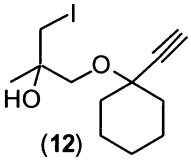
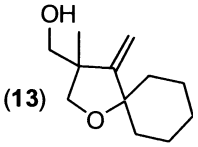
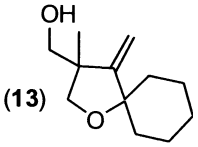



**Figure 7.** 5-*exo trig* radical cyclization after reductive opening of **10**.

**Table 3**. Reactions of **10** with single electron transfer reagents

| Entry | ET-reagent | Product | Yield (%) |
|---|---|---|---|
| 1 | $VCl_3(THF)_3$/Zn |  (11) | 57 |
| 2 | $SmI_2$ |  (11) | 36 |
| | |  (12) | 45 |
| 3 | $Cp_2TiCl$ |  (13) | 69–82 |
| 4 | $CrCl_2$ |  (13) | 38[a] |

[a] 37% Starting material reisolated.

e.g. $SmI_2$.[22] Therefore, we expected **10** to be a better substrate for cyclization than **4**. However, neither $[V_2Cl_3(THF)_6]_2[Zn_2Cl_6]$ nor $SmI_2$ gave any of the desired product. Utilizing vanadium, only the product of deoxygenation **11** could be obtained in significant amounts. Trace amounts of the chlorohydrins were detected in the crude reaction mixture. Thus, $[V_2Cl_3(THF)_6]_2[Zn_2Cl_6]$ constitutes a highly selective reagent for the deoxygenation of epoxides and does not allow for other synthetic applications of the pivotal β-metal oxy radical formed during reductive epoxide opening. $SmI_2$ gave a the primary iodohydrins in 45% yield and the deoxygenation product in 36% yield. As in the reactions of **4** nucleophilic opening of the epoxide is the main course of events. The Sm salt of iodohydrin **12** can be further reduced by $SmI_2$. The result obtained with $CrCl_2$ was rather surprising. As in the deoxygenation reaction the substrate **10** could be reisolated in substantial amounts.

However, the product of the radical cyclization **13** was also obtained in noticeable amounts (38%). Thus, $CrCl_2$, albeit being rather unreactive, is the only other reagent than $Cp_2TiCl$ that allows for the exploitation of the β-metal oxy radical in a carbon–carbon bond forming reaction. Our titanocene based protocol, on the other hand, gave the desired cyclization product **13** in good yield (69–82%) and once again demonstrates the superiority of the titanocene(III) reagents in reductive epoxide openings.

## 3. Conclusion

In summary our studies have revealed that $SmI_2$ is not a suitable reagent for the reductive opening of epoxides. The high Lewis acidity of this metal combined with the high nucleophilicity of the iodide ions leads to the formation of iodohydrins that are further reduced by samarium. The typical radical reactivity of β-metal oxy radicals as shown in Figs. 3, 6, and 7 could not be observed in the cases investigated here. In the case of $[V_2Cl_3(THF)_6]_2[Zn_2Cl_6]$ no other products than those of epoxide deoxygenation could be observed. Although it seems as if this reagent opens epoxides via electron transfer the resulting β-metal oxy radicals could not be intercepted by C–C bond forming reactions. This unexpected result can be tentatively rationalized by assuming a dimeric structure of the vanadium reagent in solution that would result in an intramolecular second electron transfer. These findings suggest that the reason for the superiority of $Cp_2TiCl$ reagents stems from their unique combination of low Lewis acidity preventing epoxide opening via $S_N2$ or $S_N1$ and low reducing power towards the β-metal oxy radical. The only other reagent allowing carbon carbon bond formation, $CrCl_2$, is unfortunately severely limited by its low reactivity. We are currently working on developing more reactive chromium reagents for these purposes.

## 4. Experimental

### 4.1. General methods

Unless otherwise indicated all reactions were performed in oven-dried (100 °C) glassware under argon. Solutions were transferred by means of teflon tubes. Liquid substances and solvents were added by means of plastic syringes. THF was dried over potassium and freshly distilled before use. DMF was used as received from Merck, just as ethylenediamine (p.a., abs.) obtained from Fluka. Chromium(II) chloride (anhydrous) was purchased from Alfa Aesar and stored under Argon. Samarium(II) iodide was prepared from samarium powder (40 mesh) with 1,2-diiodoethane.[21] Bis(cylopentadienyl)titanocenechloride was prepared in situ from bis(cyclopentadienyl)titanocenedichloride purchased from Aldrich and zinc or manganese dust. The reduction of the Vanadium–THF-complex was carried out in situ using zinc as reducing agent. Products were purified by flash chromatography on silica gel from Macherey-Nagel or Merck (particle size 43–60 μm, 230–400 mesh, ASTM). Eluents are given (MTBE refers to *tert*-butyl methyl ether, Cy refers to cyclohexane, EtOAc to ethyl acetate, $Et_2O$ to diethyl ether and PE to petrol ether, 40–60 °C fractions). Isomer ratios were determined from suitable $^1H$ NMR integrals of cleanly separated signals.

$^1H$ and $^{13}C$ NMR spectra were recorded on a Brucker AM 400 or DRX 300 instrument. For the $^1H$ NMR spectra chemical shifts are expressed relative to trichloromethane ($CHCl_3$: 7.26 ppm) and penta-deuterated benzene ($C_6HD_5$: 7.16 ppm) as internal standards in the corresponding fully deuterated solvents. For the $^{13}C$ NMR spectra the central signals of deuterotrichloromethane ($CDCl_3$: 77.16 ppm) and of deuterated benzene ($C_6D_6$: 128.06 ppm) were employed as internal standards. The integrals of the $^1H$ NMR signals are in accord with the assignment. Coupling constants are measured in Hz. Mass spectra were obtained on a Kratos MS 50 or a Thermoquest MAT 95XL operating at 70 eV. Infrared spectra were recorded on a Perkin–Elmer FT-IR spectrometer 1620. All substances were measured as neat film between KBr plates. Combustion analyses were performed by Mrs Martens at the Kekulé-Institut für Organische Chemie und Biochemie, Universität Bonn.

### 4.2. Preparation of starting materials: synthesis of the tris(tetrahydrofuran)vanadiumtrichloride

Under an argon atmosphere vanadium(III) chloride (5.04 g, 32 mmol) was extracted from a Soxhlet extractor with 150 ml dry THF until the extract becomes colorless. After reducing the solution volume to 40 ml the tris(tetrahydrofuran)vanadiumtrichloride was crystallized in the refrigerator by −38 °C over night. The complex was filtrated under argon and dried to obtain the pale red tris(tetrahydrofuran)vanadiumtrichloride (6.96 g, 58%). The complex was stored under argon in the refrigerator and used without further purification.

**4.2.1. (*Z*)-1,4-Dipropoxy-but-2-ene-oxide (1).** (*Z*)-1,4-Dipropoxy-but-2-ene[24] (12.7 g, 80 mmol), methyltrioxorhenium (100 mg, 0.4 mmol, 0.005 equiv.), $H_2O_2$ (16.2 ml, 30% solution in $H_2O$, 160 mmol, 2 equiv.) and 3-cyanopyridine (833 mg, 8 mmol, 0.1 equiv.) in $CH_2Cl_2$ (48 ml) were stirred 65 h at rt. The reaction was quenched with ice (8 g) and $MnO_2$ (10 mg), stirred for 1 h, poured into $H_2O$ (50 ml) and extracted with $CH_2Cl_2$ (3×50 ml). The organic layer was dried over $MgSO_4$ and evaporated under reduced pressure. The oil obtained was diluted with pentane (100 ml) and the white precipitate was filtered off. The solvent was evaporated and the residue distilled (b.p. 52–57 °C, 0.1 mbar). (*Z*)-1,4-Dipropoxy-but-2-ene-oxide (**1**) (11.3 g, 60 mmol) was obtained as colorless oil (75%).

(*Z*)-1,4-Dipropoxy-but-2-ene-oxide (**1**): $C_{10}H_{20}O_3$ (188.27 g/mol); $^1H$ NMR (400 MHz, $C_6D_6$): $\delta$=3.42 (dd, $J$=11.3, 3.9 Hz, 2H, A-part of an AB-system), 3.31 (dd, $J$=11.3, 6.4 Hz, 2H, B-part of an AB-system), 3.27 (dt, $J$=9.1, 6.6 Hz, 2H, A-part of an AB-system), 3.18 (dt, $J$=9.1, 6.6 Hz, 2H, B-part of an AB-system), 3.01 (m, 2H), 1.50 (qt, $J$=7.4, 6.6 Hz, 4H), 0.91 (t, $J$=7.3 Hz, 6H). $^{13}C$ NMR (100 MHz, $C_6D_6$): $\delta$=73.0, 68.22, 54.4, 23.4, 10.8. Anal. calcd for $C_{10}H_{20}O_3$: C, 63.80; H, 10.71. Found: C, 63.67; H, 10.86. IR (neat): $\nu$=2965, 2875, 1690, 1465, 1385, 1355, 1325, 1255, 1110, 1050, 955, 910, 845, 780 $cm^{-1}$

**4.2.2. 2-(3-Methyl-but-2-enyl)-2-oxiranylmethylmalonic acid diethylester (4).** 2-Oxiranylmethylmalonic acid diethylester (2.16 g, 10 mmol),[10c] NaH (288 mg, 12 mmol, 1.2 equiv.) and 1-bromo-3-methyl-2-butene (1.28 ml, 11 mmol, 1.1 equiv.) were stirred in THF (100 ml) at 0 °C for 2 h. MTBE was added and the solution washed with water (4×50 ml). The organic layer was dried over $MgSO_4$ and evaporated under reduced pressure. The purification of the residual oil by $SiO_2$ flash chromatography (PE/MTBE; 80:20) yielded 2-(3-methyl-but-2-enyl)-2-oxiranylmethylmalonic acid diethylester (**4**) (2.25 g, 7.9 mmol) as colorless oil (79%).

2-(3-Methyl-but-2-enyl)-2-oxiranylmethylmalonic acid diethylester (**4**): $C_{15}H_{24}O_5$ (284.35 g/mol); $R_f$ (89% Cy, 11% EE): 0.26; $^1$H NMR (400 MHz, $CDCl_3$): $\delta$=4.91 (tsept, $J$=7.4, 1.5 Hz, 1H), 4.14 (dq, $J$=14.1, 7.1 Hz, 1H, A-part of an AB-system), 4.13 (q, $J$=7.1 Hz, 2H), 4.11 (dq, $J$=14.2, 7.1 Hz, 1H, B-part of an AB-system), 2.90 (dddd, $J$=6.6, 5.1, 4.0, 2.6 Hz, 1H), 2.80–2.60 (m, *2H*), 2.66 (dd, $J$=4.9, 4.2 Hz, 1H, A-part of an AB-system), 2.36 (dd, $J$=5.2, 2.7 Hz, 1H, B-part of an AB-system), 2.04 (dd, $J$=14.8, 5.2 Hz, 1H, A-part of an AB-system), 1.95 (dd, $J$=14.6, 6.5 Hz, 1H, B-part of an AB-system), 1.62 (d, $J$=1.0 Hz, 3H), 1.56 (s, 3H), 1.19 (t, $J$=7.1 Hz, 3H), 1.19 (t, $J$=7.1 Hz, 3H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$=171.1 (2C), 135.9, 117.5, 56.4, 61.4, 61.3, 48.6, 46.9, 36.0, 32.1, 26.0, 18.0, 14.2, 14.0. HRMS (EI/70 eV) calcd for $M^{+\cdot}$: 284.1624; found: 284.1634; Anal. calcd for $C_{15}H_{24}O_5$: C, 63.36; H, 8.51. Found: C, 63.26; H, 8.74. IR (neat): $\nu$=2980, 2930, 1730, 1445, 1365, 1285, 1225, 1095, 1025, 935, 860 cm$^{-1}$.

**4.2.3. 2-(1-Ethynyl-cyclohexyloxymethyl)-2-methyloxirane (10).**[10g] 1-Ethynyl-1-(2-methylallyloxy)cyclohexane (2.27 g, 12.7 mmol), methyltrioxorhenium (30 mg, 0.1 mmol, 0.008 equiv.), $H_2O_2$ (6 ml, 30% solution in $H_2O$, 50 mmol, 3.9 equiv.), and 3-cyanopyridine (260 mg, 2.5 mmol, 0.2 equiv.) in $CH_2Cl_2$ (10 ml) were stirred at rt for 3 days. The reaction was quenched with ice and $MnO_2$ (a few mg), stirred for 1 h, poured into $H_2O$ (50 ml) and extracted with $CH_2Cl_2$ (3×50 ml). The organic layer was dried over $MgSO_4$ and evapurated under reduced pressure. The oil obtained was diluted with pentane and the white precipitate was filtered off. The solvent was evaporated and the residue purified by $SiO_2$ flash chromatography (Cy/EE 98:2) to afford 2-(1-ethynyl-cyclohexyloxymethyl)-2-methyloxirane (**10**) (2.41 g, 12.4 mmol) as a colorless oil (97%).

2-(1-Ethynyl-cyclohexyloxymethyl)-2-methyloxirane (**10**): $C_{12}H_{18}O_2$ (194.27 g/mol); $^1$H NMR (300 MHz, $CDCl_3$): $\delta$=3.58 (s, 2H), 2.78 (d, $J$=4.9 Hz, 1H), 2.64 (d, $J$=4.9 Hz, 1H), 2.46 (d, $J$=1.0 Hz, 1H), 1.91–1.84 (m, 2H), 1.71–1.28 (m, 8H), 1.39 (s, 3H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$=85.1, 73.8, 73.7, 67.0, 56.1, 52.3, 37.0 (2C), 25.4, 22.6, 18.8. Anal. calcd for $C_{12}H_{18}O_2$: C, 74.19; H, 9.34. Found: C, 73.97; H, 9.36. IR (neat): $\nu$=3290, 3045, 2935, 2860, 2100, 1450, 1150, 1090, 1030, 950, 905 cm$^{-1}$.

### 4.3. General synthetic procedures—general procedure 1 (GP1): epoxide openings with titanocene chloride

To a suspension of $Cp_2TiCl_2$ (548 mg, 2.2 mmol, 2.2 equiv.) in dry THF (20 ml) was added zinc or manganese powder (288 mg or 242 mg, 4.4 mmol, 4.4 equiv.) and the reaction mixture was stirred for 2 h to enable complete conversion to $Cp_2TiCl$. After the addition of the epoxide (1.0 mmol, 1.0 equiv.) the suspension was stirred for further 16 h at rt. The reaction was quenched by addition of HCl (2 N, 30 ml), then $CH_2Cl_2$ (30 ml) was added and the organic layer was separated. After extraction of the aqueous layer with $CH_2Cl_2$ (2×30 ml) the combined organic layers were washed with saturated aq. $NaHCO_3$ (30 ml), $H_2O$ (2×30 ml) and saturated aq. NaCl (30 ml) and dried over $MgSO_4$. The solvent was removed under reduced pressure and the residue purified by $SiO_2$ flash chromatography.

### 4.4. General procedure 2 (GP2): epoxide openings with chromium(II) chloride

A solution of ethylenediamine (0.5 ml) in DMF (40 ml) was degassed three times under vacuum in an ultrasonic bath. The solution was then added dropwise to a flask containing chromium(II) chloride (492 mg, 4 mmol, 4 equiv.) generating a blue-purple suspension. After addition of the epoxide (1.0 mmol, 1.0 equiv.) the reaction mixture was stirred for 70 h at rt. The reaction was quenched by addition of $H_2O$ (50 ml) and HCl (2 N, 20 ml) and the aqueous layer was extracted with $CH_2Cl_2$ (4×30 ml). The combined organic layers were washed with saturated aq. $NaHCO_3$ (30 ml), $H_2O$ (4×30 ml) and dried over $MgSO_4$. The solvent was removed under reduced pressure and the residue purified by $SiO_2$ flash chromatography.

### 4.5. General procedure 3 (GP3): epoxide openings with samarium(II) iodide

A deep blue solution of samarium(II) iodide (849 mg, 2.1 mmol, 2.1 equiv.) in dry THF (25 ml) was prepared according to Kagan et al.[23] from samarium (361 mg, 2.4 mmol, 2.4 equiv.) and 1,2-diiodoethane (592 mg, 2.1 mmol, 2.1 equiv.). After addition of the epoxide (1.0 mmol, 1.0 equiv.) the solution was stirred 60 h at rt. The reaction was quenched by addition of HCl (1 N, 30 ml) and the aqueous layer was extracted with $CH_2Cl_2$ (3×30 ml). The combined organic layers were washed with saturated aq. $Na_2S_2O_3$ (30 ml), $H_2O$ (3×30 ml) and saturated aq. NaCl (30 ml) and dried over $MgSO_4$. The solvent was removed under reduced pressure and the residue purified by $SiO_2$ flash chromatography.

### 4.6. General procedure 4 (GP4): epoxide openings with vanadium complexes

*Method A*: $VCl_3$/Zn: A solution of vanadiumtrichloride (300 mg, 2 mmol, 2 equiv.) in dry THF (10 ml) was reduced in situ with zinc dust (261 mg, 4 mmol, 4 equiv.) by stirring for 2 h to obtain a green-blue solution of the vanadium(II) complex ($[V_2Cl_3(THF)_6][Zn_2Cl_6]$). After addition of the epoxide (1 mmol, 1 equiv.) the solution was stirred for 16 h at rt. The reaction was quenched by addition of $H_2O$ (20 ml) and HCl (2 N, 10 ml) and the aqueous layer was extracted with $CH_2Cl_2$ (3×30 ml). The combined organic layers were washed with $H_2O$ (3×20 ml) and saturated aq. NaCl (30 ml) and dried over $MgSO_4$. The solvent was removed under

reduced pressure and the residue purified by $SiO_2$ flash chromatograph.

*Method B*: $V(THF)_3Cl_3$/Zn: A solution of tris(tetrahydrofuran)vanadiumtrichloride (747 mg, 2 mmol, 2 equiv.) in dry THF (10 ml) was reduced in situ with zinc dust (261 mg, 4 mmol, 4 equiv.) by stirring for 2 h to obtain a green-blue solution of the vanadium(II) complex ($[V_2Cl_3(THF)_6]_2$-$[Zn_2Cl_6]$). After addition of the epoxide (1 mmol, 1 equiv.) the solution was stirred for 16 h at rt. The reaction was quenched by addition of $H_2O$ (20 ml) and HCl (2 N, 10 ml) and the aqueous layer was extracted with $CH_2Cl_2$ (3×30 ml). The combined organic layers were washed with $H_2O$ (3×20 ml) and saturated aq. NaCl (30 ml) and dried over $MgSO_4$. The solvent was removed under reduced pressure and the residue purified by $SiO_2$ flash chromatography.

*Method C*: $V(THF)_3Cl_3$: To a red solution of tris(tetra hydrofuran)vanadiumtrichloride (747 mg, 2 mmol, 2 equiv.) in dry THF (10 ml) the epoxide (1 mmol, 1 equiv.) was added and the reaction mixture was stirred for 96 h at rt. The reaction was quenched by addition of $H_2O$ (30 ml) and the aqueous layer was extracted with MTBE (3×30 ml). The combined organic layers were washed with $H_2O$ (3×20 ml) and saturated aq. NaCl (30 ml) and dried over $MgSO_4$. The solvent was removed under reduced pressure and the residue purified by $SiO_2$ flash chromatography.

### 4.7. Opening of epoxide 1 in the presence of $Cp_2TiCl$ (Table 1, entry 4)

According to GP1: $Cp_2TiCl_2$ (548 mg, 2.2 mmol), Mn (242 mg, 4.4 mmol) and (*Z*)-1,4-dipropoxy-but-2-ene-oxide (188 mg, 1 mmol) in dry THF (20 ml) were reacted for 16 h at rt. After work-up and chromatography ($SiO_2$; PE/$Et_2O$, 93:7) (*E*/*Z*)-1,4-dipropoxy-but-2-ene[23] (**2**) (34 mg, 0.19 mmol) was obtained in 19% yield as colorless oil as a mixture of diastereoisomers (*Z*/*E* 42:58) and 1-propoxy-but-3-ene-2-ol[25] (**3**) (61 mg, 0.47 mmol) was obtained in 47% yield as colorless oil.

**4.7.1. (*E*/*Z*)-1,4-dipropoxy-but-2-ene (2).**[24] $C_{10}H_{20}O_2$ (172.27 g/mol); $R_f$ (89% Cy, 11% EE): 0.38; $^1H$ NMR (400 MHz, $CDCl_3$): $\delta$=5.80 (tt, *J*=2.9 Hz, 1.4, 2H)[a], 5.70 (ddd, *J*=4.7, 3.7, 0.9 Hz, 2H)[b], 4.03 (dm, *J*=4.8 Hz, 4H)[b], 3.96 (dd, *J*=2.9, 1.5 Hz, 4H)[a], 3.37 (t, *J*=6.8 Hz, 4H)[a], 3.37 (t, *J*=6.7 Hz, 4H)[b], 1.59 (sext, *J*=6.9 Hz, 4H)[a], 1.59 (sext, *J*=7.5 Hz, 4H)[b], 0.91 (t, *J*=7.5 Hz, 12H)[a,b]. [a,b]Signals of the two isomers. $^{13}C$ NMR (100 MHz, $CDCl_3$): $\delta$=129.6[a,*], 129.6[b,*], 72.3[a,**], 72.3[b,**], 70.9[a], 66.6[b], 23.1[a,b], 10.7[a,b]. [a,b]Signals of the two isomers. [*,**]Assignment interchangeable. HRMS (EI/70 eV) calcd for $M^{+\cdot}$: 172.1463; found: 172.1459; IR (neat): $\nu$=2960, 2855, 1465, 1360, 1260, 1100, 1040, 805 $cm^{-1}$.

**4.7.2. 1-Propoxy-but-3-ene-2-ol (3).**[25] $C_7H_{14}O_2$ (130.19 g/mol); $R_f$ (89% Cy, 11% EE): 0.16; $^1H$ NMR (400 MHz, $CDCl_3$): $\delta$=5.83 (ddd, *J*=17.3, 10.6, 5.7 Hz, 1H), 5.35 (dt, *J*=17.3, 1.6 Hz, 1H), 5.18 (dt, *J*=10.6, 1.5 Hz, 1H), 4.30 (m, 1H), 3.47 (dd, *J*=9.7, 3.5 Hz, 1H, A-part of an AB-system), 3.46 (dt, *J*=9.4, 6.7 Hz, 1H, A-part of an AB-system), 3.42 (dt, *J*=9.4, 6.7 Hz, 1H, B-part of an AB-system), 3.30 (dd, *J*=9.7, 8.0 Hz, 1H, B-part of an AB-system), 1.60 (sext, *J*=7.1 Hz, 2H), 0.92 (t, *J*=7.4 Hz, 3H). $^{13}C$ NMR (100 MHz, $CDCl_3$): $\delta$=136.9, 116.4, 74.6, 73.2, 71.6, 22.9, 10.6. IR (neat): $\nu$=3440, 3080, 2960, 2875, 1645, 1460, 1380, 1315, 1115, 990, 925, 670 $cm^{-1}$.

### 4.8. Opening of epoxide 1 in the presence of $CrCl_2$ (Table 1, entry 1)

According to GP2: $CrCl_2$ (492 mg, 4 mmol), ethylenediamine (0.5 ml) and (*Z*)-1,4-dipropoxy-but-2-ene-oxide (188 mg, 1 mmol) in DMF (40 ml) were reacted for 70 h at rt. After work-up and chromatography ($SiO_2$; PE/$Et_2O$, 90:10) (*E*/*Z*)-1,4-dipropoxy-but-2-ene (**2**) (33 mg, 0.19 mmol) was obtained in 19% yield as colorless oil as a mixture of diastereoisomers (*Z*/*E* 59:41). 1-Propoxy-but-3-ene-2-ol (**3**) (21 mg, 0.16 mmol) was obtained in 16% yield as colorless oil. Starting material was also recovered (92 mg, 0.49 mmol).

### 4.9. Opening of epoxide 1 in the presence of $VCl_3(THF)_3$/Zn (Table 1, entry 2)

According to GP4, Method B: $VCl_3(THF)_3$ (747 mg, 2 mmol), Zn (261 mg, 4 mmol) and (*Z*)-1,4-dipropoxy-but-2-ene-oxide (188 mg, 1 mmol) in dry THF (10 ml) were reacted for 16 h at rt. After work-up and chromatography ($SiO_2$; PE/$Et_2O$, 93:7) (*E*/*Z*)-1,4-dipropoxy-but-2-ene (**2**) (125 mg, 0.73 mmol) was obtained in 73% yield as colorless oil as a mixture of diastereoisomers (*Z*/*E* 50:50).

### 4.10. Opening of epoxide 1 in the presence of $SmI_2$ (Table 1, entry 3)

According to GP3: Sm (361 mg, 2.4 mmol), 1,2-diiodoethane (592 mg, 2.1 mmol) and (*Z*)-1,4-dipropoxy-but-2-ene-oxide (188 mg, 1 mmol) in dry THF (25 ml) were reacted for 16 h at rt. After work-up and chromatography ($SiO_2$; PE/$Et_2O$, 90:10) 1-propoxy-but-3-ene-2-ol (**3**) (69 mg, 0.53 mmol) was obtained in 53% yield as pale yellow oil.

### 4.11. Opening of epoxide 4 in the presence of $SmI_2$ (Table 2, entry 1)

According to GP3: Sm (361 mg, 2.4 mmol), 1,2-diiodoethane (592 mg, 2.1 mmol) and 2-(3-methyl-but-2-enyl)-2-oxiranylmethylmalonic acid diethylester (284 mg, 1 mmol) in dry THF (25 ml) were reacted for 50 h at rt. After work-up and chromatography ($SiO_2$; Cy/EE, 90:10) 5-iodomethyl-3-(ethoxycarbonyl)-3-(3-methyl-but-2-enyl)-2-oxotetrahydrofuran (116 mg, 0.31 mmol) (**5**) was obtained in 31% yield as pale yellow oil as a mixture of diasteroisomers (dr=61: 39). 2-Allyl-2-(3-methyl-but-2-enyl)-malonic acid monoethyl ester (133 mg, 0.55 mmol) was also obtained in 55% yield as colorless oil.

**4.11.1. 5-Iodomethyl-3-(ethoxycarbonyl)-3-(3-methyl-but-2-enyl)-2-oxo-tetrahydrofuran (5).** $C_{13}H_{19}IO_4$ (366.20 g/mol); $R_f$ (80% Cy, 20% EE): 0.45; $^1H$ NMR (400 MHz, $CDCl_3$): $\delta$=5.05–4.98 (m, 2H)[a,b], 4.52 (dddd,

$J$=8.4, 7.6, 6.6, 4.9 Hz, 1H)[a], 4.48 (dddd, $J$=9.6, 6.6, 6.5, 4.3 Hz, 1H)[b], 4.27–4.16 (m, 4H)[a,b], 3.41 (dd, $J$=10.1, 4.9 Hz, 1H)[a], 3.39 (dd, $J$=10.6, 4.4 Hz, 1H)[b], 3.29 (dd, $J$=10.6, 6.8 Hz, 1H)[b], 3.27 (dd, $J$=9.9, 8.6 Hz, 1H)[a], 2.80–2.67 (m, 2H)[a,b], 2.78 (dd, $J$=13.3, 6.3 Hz, 1H)[b], 2.62–2.53 (m, 2H)[a,b], 2.56 (dd, $J$=13.6, 6.7 Hz, 1H)[a], 2.43 (dd, $J$=13.8, 7.7 Hz, 1H)[a], 1.93 (dd, $J$=13.3, 9.5 Hz, 1H)[b], 1.71 (m, 6H)[a,b], 1.65 (m, 6H)[a,b], 1.29 (t, $J$=7.1 Hz, 3H)[a], 1.28 (t, $J$=7.1 Hz, 3H)[b]. [a,b]Signals of the two isomers. $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$=174.1[a], 173.4[b], 169.8[a], 169.5[b], 137.8[a], 137.4[b], 117.5[b], 117.0[a], 76.9[a], 76.4[b], 62.5[a,b], 56.8[b], 56.0[a], 37.8[b], 36.6[a], 33.2[a], 32.5[b], 26.1[a,b], 18.2[a,b], 14.1[a,b], 6.8[b], 6.3[b]. [a,b]Signals of the two isomers. HRMS (EI/70 eV) calcd for $M^{+\cdot}$: 366.0328; found: 366.0329; IR (neat): $\nu$=2965, 1780, 1730, 1445, 1365, 1340, 1160, 1095, 1010, 860, 800 cm$^{-1}$.

#### 4.11.2. 2-Allyl-2-(3-methyl-but-2-enyl)-malonic acid monoethyl ester (6).

$C_{13}H_{20}O_4$ (240.30 g/mol); $R_f$ (80% Cy, 20% EE): 0.05; $^1$H NMR (400 MHz, $CDCl_3$): $\delta$=5.67 (dddd, $J$=17.0, 10.1, 7.6, 7.0 Hz, 1H), 5.11 (dm, $J$=17.0 Hz, 1H), 5.09 (dm, $J$=10.2 Hz, 1H), 4.98 (tsep, $J$=7.5, 1.4 Hz, 1H), 4.24 (dq, $J$=10.8, 7.1 Hz, 1H, A-part of an AB-system), 4.21 (dq, $J$=10.8, 7.1 Hz, 1H, B-part of an AB-system), 2.73 (ddt, $J$=14.0, 7.0, 1.1 Hz, 1H), 2.68–2.57 (m, 2H), 2.61 (ddt, $J$=13.8, 7.8, 1.0 Hz, 1H), 1.69 (d, $J$=1.0 Hz, 3H), 1.61 (d, $J$=0.8 Hz, 3H), 1.29 (t, $J$=7.1 Hz, 3H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$=174.6, 173.5, 136.5, 132.3, 119.4, 117.3, 62.2, 57.9, 39.0, 33.7, 26.1, 18.1, 14.1. HRMS (EI/70 eV) calcd for $M^{+\cdot}$: 240.1362; found: 240.1360; IR (neat): $\nu$=2980, 1710, 1445, 1380, 1220, 1065, 920, 860, 655 cm$^{-1}$.

### 4.12. Opening of epoxide 4 in the presence of $VCl_3(THF)_3$/Zn (Table 2, entry 2)

According to GP4, Method B: $VCl_3(THF)_3$ (747 mg, 2 mmol), Zn (261 mg, 4 mmol) and 2-(3-methyl-but-2-enyl)-2-oxiranylmethylmalonic acid diethylester (284 mg, 1 mmol) in dry THF (10 ml) were reacted for 60 h at rt. After work-up and chromatography ($SiO_2$; Cy/EE, 93:7) 2-allyl-2-(3-methyl-but-2-enyl)-malonic acid diethyl ester (**7**)[26] (160 mg, 0.59 mmol) was obtained in 59% yield as colorless oil. 5-Hydroxymethyl-3-(3-ethoxycarbonyl)-3-(3-methyl-but-2-enyl)-2-oxo-tetrahydrofuran (**8**) (18 mg, 0.07 mmol) was obtained in 7% yield as colorless oil as a mixture of diastereoisomers (dr=80:20).

#### 4.12.1. 2-Allyl-2-(3-methyl-but-2-enyl)-malonic acid diethyl ester (7).

$C_{15}H_{24}O_4$ (268.35 g/mol); $R_f$ (89% Cy, 11% EE): 0.5; $^1$H NMR (400 MHz, $CDCl_3$): $\delta$=5.66 (ddt, $J$=16.3, 10.8, 7.4 Hz, 1H), 5.08 (dm, $J$=17.1 Hz, 1H), 5.07 (dm, $J$=10.4 Hz, 1H), 4.97 (tsep, $J$=7.4, 1.4 Hz, 1H), 4.18 (dq, $J$=10.9, 7.1 Hz, 1H, A-part of an AB-system), 4.15 (dq, $J$=10.8, 7.1 Hz, 1H, B-part of an AB-system), 2.61 (dt, $J$=7.4, 1.2 Hz, 2H), 2.59 (dm, $J$=7.6 Hz, 2H), 1.68 (d, $J$=1.1 Hz, 3H), 1.60 (s, 3H), 1.23 (t, $J$=7.1 Hz, 3H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$=171.3 (2C), 135.6, 132.9, 119.0, 117.8, 61.2 (2C), 57.8, 36.9, 31.1, 26.1, 18.1, 14.2 (2C). HRMS (EI/70 eV) calcd for $M^{+\cdot}$: 268.1675; found: 268.1674; IR (neat): $\nu$=2980, 2930, 1730, 1640, 1445, 1365, 1285, 1220, 1095, 1065, 920, 860 cm$^{-1}$.

#### 4.12.2. 5-Hydroxymethyl-3-(3-ethoxycarbonyl)-3-(3-methyl-but-2-enyl)-2-oxo-tetrahydro-furan (8).

$C_{13}H_{20}O_5$ (256.30 g/mol); $R_f$ (50% Cy, 50% EE): 0.35; $^1$H NMR (400 MHz, $CDCl_3$) (contains cyclohexan): $\delta$=5.07 (ddsept, $J$=9.3, 5.8, 1.5 Hz, 1H)[a], 5.01 (ddsept, $J$=8.2, 6.8, 1.4 Hz, 1H)[b], 4.64 (dddd, $J$=10.0, 6.4, 4.8, 2.8 Hz, 1H)[b], 4.53 (dddd, $J$=8.0, 7.1, 5.5, 3.2 Hz, 1H)[a], 4.23 (q, $J$=7.1 Hz, 3H)[a], 4.22 (qd, $J$=7.1, 0.3 Hz, 3H)[b], 3.92 (ddd, $J$=12.6, 5.8, 2.9 Hz, 1H)[b], 3.83 (ddd, $J$=12.5, 6.6, 3.2 Hz, 1H)[a], 3.69 (dt, $J$=12.2, 5.7 Hz, 1H)[a], 3.61 (ddd, $J$=12.5, 6.7, 4.9 Hz, 1H)[b], 2.78 (ddm, $J$=14.7, 8.2 Hz, 1H)[b], 2.72 (ddm, $J$=14.6, 8.1 Hz, 1H)[a], 2.65–2.51 (m, 2H)[a,b], 2.62 (dd, $J$=13.5, 7.2 Hz, 1H)[a], 2.56 (dd, $J$=13.1, 6.4 Hz, 1H)[b], 2.26 (dd, $J$=13.5, 8.0 Hz, 1H)[a], 2.15 (dd, $J$=13.1, 10.0 Hz, 1H)[b], 2.04 (m, OH)[a], 1.92 (m, OH)[b], 1.73 (q, $J$=1.2 Hz, 3H)[a], 1.70 (q, $J$=1.2 Hz, 3H)[b], 1.66 (d, $J$=1.3 Hz, 3H)[a], 1.64 (d, $J$=0.8 Hz, 3H)[b], 1.29 (t, $J$=7.1 Hz, 3H)[a], 1.28 (t, $J$=7.1 Hz, 3H)[b]. [a,b]Signals of the two isomers. $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$=174.7[a], 174.2[b], 170.3[a], 169.7[b], 137.7[a], 137.1[b], 117.5[b], 117.1[a], 78.8[b], 78.4[a], 64.4[a], 63.5[b], 62.5[b], 62.4[a], 56.3[b], 55.5[a], 33.4[a], 32.7[b], 32.1[b], 32.0[a], 26.1[a], 26.0[b], 18.2[a,b], 14.1[a,b]. [a,b]Signals of the two isomers. HRMS (EI/70 eV) calcd for $M^{+\cdot}$: 256.1311; found: 256.1306; IR (neat): $\nu$=3450, 2935, 1775, 1450, 1365, 1180, 1035, 915, 860 cm$^{-1}$.

### 4.13. Opening of epoxide 4 in the presence of a vanadium complex (Table 2, entry 3)

According to GP4, Method A: $VCl_3$ (150 mg, 1 mmol), Zn (130 mg, 2 mmol) and 2-(3-methyl-but-2-enyl)-2-oxiranylmethylmalonic acid diethylester (142 mg, 0.5 mmol) in dry THF (10 ml) were reacted for 20 h at rt. After work-up and chromatography ($SiO_2$; Cy/EE, 60:40) 5-hydroxymethyl-3-(3-ethoxycarbonyl)-3-(3-methyl-but-2-enyl)-2-oxo-tetrahydro-furan (**8**) (62 mg, 0.24 mmol) was obtained in 48% yield as colorless oil as a mixture of diastereoisomers (dr=60:40).

### 4.14. Opening of epoxide 4 in the presence of a vanadium complex (Table 2, entry 4)

According to GP4, Method C (Table 2, entry 5): $VCl_3$-$(THF)_3$ (747 mg, 2 mmol), Zn (261 mg, 4 mmol) and 2-(3-methyl-but-2-enyl)-2-oxiranylmethylmalonic acid diethylester (284 mg, 1 mmol) in dry THF (10 ml) were reacted for 60 h at rt. After work-up and chromatography ($SiO_2$; Cy/EE, 60:40) 5-hydroxymethyl-3-(3-ethoxycarbonyl)-3-(3-methyl-but-2-enyl)-2-oxo-tetrahydrofuran (**8**) (64 mg, 0.25 mmol) was obtained in 25% yield as colorless oil as a mixture of diastereoisomers (dr=40:60).

### 4.15. Opening of epoxide 4 in the presence of $Cp_2TiCl$ (Table 2, entry 5)

According to GP1: $Cp_2TiCl_2$ (249 mg, 1 mmol), Mn (110 mg, 2 mmol) 2-(3-methyl-but-2-enyl)-2-oxiranylmethylmalonic acid diethylester (284 mg, 1 mmol) in dry THF (10 ml) were reacted for 16 h at rt. After work-up and chromatography ($SiO_2$; Cy/EE, 80:20) (4,4-dimethyl-3-oxa-bicyclo[3.3.0]octane)-7,7-dicarboxylic acid diethyl ester (**9**) (162 mg, 0.57 mmol) was obtained in 57% yield as colorless oil.

**4.15.1. (4,4-Dimethyl-3-oxa-bicyclo[3.3.0]octane)-7,7-dicarboxylic acid diethyl ester (9).** $C_{15}H_{24}O_5$ (284.35 g/mol); $R_f$ (89% Cy, 11% EE): 0.14; $^1$H NMR (400 MHz, $CDCl_3$): $\delta$=4.19–4.08 (m, 4H), 3.89 (dd, $J$=9.4, 7.9 Hz, 1H, A-part of an AB-system), 3.51 (dd, $J$=9.1, 3.5 Hz, 1H, B-part of an AB-system), 2.84 (quintd, $J$=8.2, 3.3 Hz, 1H), 2.58 (ddd, $J$=13.3, 8.6, 2.0 Hz, 1H), 2.36 (ddd, $J$=10.6, 8.9, 7.8 Hz, 1H), 2.22 (ddd, $J$=12.8, 7.5, 2.1 Hz, 1H), 1.95 (dd, $J$=12.8, 11.1 Hz, 1H),), 1.82 (dd, $J$=13.4, 7.3 Hz, 1H), 1.20 (t, $J$=7.0 Hz, 3H), 1.20 (s, 3H), 1.18 (t, $J$=7.0 Hz, 3H), 1.09 (s, 3H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$=171.9, 171.2, 81.5, 71.9, 63.0, 61.4 (2C), 52.7, 43.4, 40.4, 36.0, 26.6, 23.7, 14.1 (2C). HRMS (EI/70 eV) calcd for $M^{+\cdot}$: 284.1624; found: 284.1625; Anal. calcd for $C_{15}H_{24}O_5$: C, 63.36; H, 8.51. Found: C, 63.17; H, 8.40. IR (neat): $\nu$=2975, 2870, 1730, 1465, 1445, 1365, 1295, 1260, 1180, 1100 cm$^{-1}$.

### 4.16. Opening of epoxide 10 in the presence of $VCl_3(THF)_3$/Zn (Table 3, entry 1)

According to GP4, Method B: $VCl_3(THF)_3$ (747 mg, 2 mmol), Zn (261 mg, 4 mmol) 2-(1-ethynyl-cyclohexyloxymethyl)-2-methyloxirane (194 mg, 1 mmol) in dry THF (15 ml) were reacted for 14 h at rt. After work-up and chromatography ($SiO_2$; PE) 1-ethynyl-1-(2-methyl-allyloxy)cyclohexane (**11**) (102 mg, 0.57 mmol) was obtained in 57% yield as colorless oil.

**4.16.1. Compound (11).** $C_{12}H_{18}O$ (178.27 g/mol); $R_f$ (100% PE): 0.05; $^1$H NMR (400 MHz, $CDCl_3$): $\delta$=5.02–5.00 (m, 1H), 4.86–4.84 (m, 1H), 4.01 (s, 2H), 2.45 (s, 1H), 1.93–1.88 (m, 2H), 1.77–1.76 (m, 3H), 1.71–1.61 (m, 4H), 1.58–1.46 (m, 3H), 1.36–1.26 (m, 1H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$=143.2, 111.5, 85.7, 73.8, 67.5, 37.4, 25.7, 22.9, 20.0. HRMS (EI/70 eV) calcd for $M^{+\cdot}$: 178.1358; found: 178.1358; IR (neat): $\nu$=3305, 2935, 2860, 1655, 1450, 1260, 1090, 895, 800, 655 cm$^{-1}$.

### 4.17. Opening of epoxide 10 in the presence of $SmI_2$ (Table 3, entry 2)

According to GP3: Sm (361 mg, 2.4 mmol), 1,2-diiodo-ethane (592 mg, 2.1 mmol) and 2-(1-ethynyl-cyclo-hexyloxymethyl)-2-methyloxirane (194 mg, 1 mmol) in dry THF (25 ml) were reacted for 50 h at rt. After work-up and chromatography ($SiO_2$; PE/$Et_2O$, 98:2) 1-ethynyl-1-(2-methyl-allyloxy)cyclohexane (**11**)[10g] (64 mg, 0.36 mmol) was obtained in 36% yield as colorless oil. 1-(1-Ethynyl cyclohexyloxy)-3-iodo-2-methyl-propan-2-ol (**12**) (147 mg, 0.45 mmol) was obtained in 45% yield as pale yellow oil.

**4.17.1. 1-(1-Ethynyl cyclohexyloxy)-3-iodo-2-methyl-propan-2-ol (12).** $C_{12}H_{19}IO_2$ (322.19 g/mol); $R_f$ (89% Cy, 11% EE): 0.35; $^1$H NMR (400 MHz, $CDCl_3$): $\delta$=3.68 (d, $J$=8.8 Hz, 1H, A-part of an AB-system), 3.53 (d, $J$=8.8 Hz, 1H, B-part of an AB-system), 3.35 (s, 2H), 2.52 (s, 1H), 2.48 (s, 1H), 1.89–1.82 (m, 2H), 1.69–1.60 (m, 4H), 1.58–1.44 (m, 3H), 1.40–1.28 (m, 1H), 1.36 (s, 3H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$=85.0, 74.3, 73.7, 70.7, 68.0, 37.2, 36.9, 25.4, 24.0, 22.6 (2C), 16.9. HRMS (EI/70 eV) calcd for $M^{+\cdot}$: 322.0430; found: 322.0414; IR (neat): $\nu$=3440, 3295, 2935, 2860, 1450, 1380, 1330, 1257, 1195, 1150, 1125, 1085, 950, 905, 850, 785, 625 cm$^{-1}$.

### 4.18. Opening of epoxide 7 in the presence of $Cp_2TiCl$ (Table 3, entry 3)

Collidine hydrochloride (394 mg, 2.5 mmol, 2.5 equiv.) was dried in vacuo before adding 2-(1-ethynyl-cyclohexyloxy-methyl)-2-methyloxirane (194 mg, 1 mmol), Mn powder (110 mg, 2 mmol, 2 equiv.), $Cp_2TiCl_2$ (24.9 mg, 0.1 mmol, 0.1 equiv.) and dry THF (10 ml). After stirring for 24 h at rt the reaction was quenched by addition of HCl (40 ml, 2 N), then MTBE was added (60 ml) and the organic layer was separated. It was further washed with sat. aq. $NaHCO_3$ (40 ml), $H_2O$ (40 ml), dried over $MgSO_4$ and evaporated under reduced pressure. Purification by $SiO_2$ flash chromatography (Cy/EE 92:8) afforded (3-methyl-4-methylene-1-oxa-spiro[4.5]dec-3-yl)-methanol (**13**)[10g] (135–162 mg, 0.69–0.82 mmol) as a colorless oil (69–82%).

**4.18.1. (3-Methyl-4-methylene-1-oxa-spiro[4.5]dec-3-yl)-methanol (13).**[10g] $C_{12}H_{20}O_2$ (196.29 g/mol); $R_f$ (80% Cy, 20% EE): 0.25; $^1$H NMR (300 MHz, $CDCl_3$): $\delta$=4.89 (s, 1H), 4.84 (s, 1H), 3.87 (d, $J$=9.0 Hz, 1H, A-part of an AB-system), 3.53 (d, $J$=9.0 Hz, 1H, B-part of an AB-system), 3.49 (dd, $J$=10.8, 7.0 Hz, 1H, A-part of an AB-system); 3.38 (dd, $J$=10.8, 5.6 Hz, 1H, B-part of an AB-system); 1.80–1.55, (m, 8H), 1.45–1.16 (m, 3H), 1.13 (s, 3H). $^{13}$C NMR (75 MHz, $CDCl_3$): $\delta$=162.4, 104.1, 84.6, 73.0, 68.3, 48.9, 37.1, 36.1, 25.6, 22.6 (2C), 21.3. HRMS (EI/70 eV) calcd for $M^{+\cdot}$: 196.1463; found: 196.1463; Anal. calcd for $C_{12}H_{20}O_2$: C, 73.43; H, 10.27. Found: C, 73.12; H, 10.06. IR (neat): $\nu$=3410, 2930, 2855, 1735, 1655, 1445, 1145, 1045, 935, 890 cm$^{-1}$.

### 4.19. Opening of epoxide 10 in the presence of $CrCl_2$ (Table 3, entry 4)

According to GP2: $CrCl_2$ (492 mg, 4 mmol), ethylene-diamine (0.5 ml) and 2-(1-ethynyl-cyclohexyloxymethyl)-2-methyloxirane (194 mg, 1 mmol) in DMF (40 ml) were reacted for 70 h at rt. After work-up and chromatography ($SiO_2$; PE/$Et_2O$, 60:40) (3-methyl-4-methylene-1-oxa-spiro[4.5]dec-3-yl)-methanol (**13**) (75 mg, 0.38 mmol) was obtained in 38% yield as colorless oil. Starting material was also recovered (73 mg, 37%).

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