Desymmetrizing Hydroformylation of Dialkenylcarbinols with the Aid of a Planar-Chiral, Catalyst-Directing Group[‡]

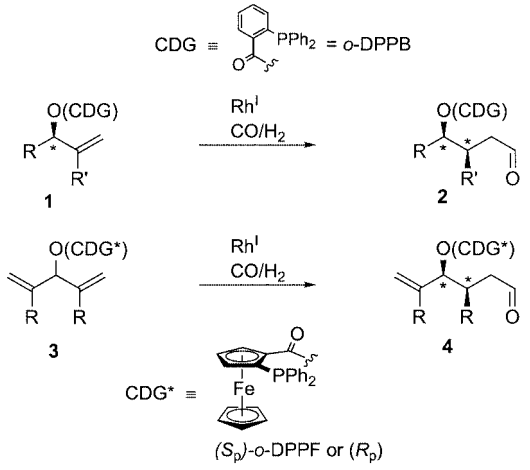
Bernhard Breit*[a] and Daniel Breuninger[a]

Keywords: Asymmetric synthesis / Catalysis / C–C coupling / Desymmetrization / Hydroformylation

The desymmetrizing hydroformylation of dialkenylcarbinols has been achieved with the aid of a planar-chiral, substrate-bound catalyst-directing group – the *ortho*-(diphenylphosphanyl)ferrocencylcarbonyl group (*o*-DPPF). This method allows the simultaneous construction of two new, vicinal stereogenic centers with high levels of stereocontrol. Optimization of the hydroformylation conditions, determination of the relative and absolute configuration of the product aldehydes (chemical derivatization and X-ray crystallographic studies), as well as conditions for removal and recovery of the catalyst-directing *o*-DPPF group are described. Furthermore, a model is presented that rationalizes the experimentally observed stereochemical result, and a new esterification protocol, which allows the formation of the sterically very hindered dialkenylcarbinol *o*-DPPF esters, is described.

Introduction

The addition of hydrogen and carbon monoxide across the carbon–carbon double bond of an alkene is referred to as the hydroformylation of alkenes. This reaction is catalyzed by metal complexes of group 9 and is one of the most important industrially applied processes relying on homogeneous catalysis.[1] The reaction is attractive from a synthetic point of view since a carbon–carbon bond is formed with simultaneous installation of the synthetically valuable aldehyde function while meeting the criteria of atom economy.[2] Despite extensive research efforts, the control of stereochemistry throughout the course of this reaction is still a challenge, although significant advances employing asymmetric catalysis with chiral phosphorus ligands have been made.[3] However, enantioselective catalysis of the hydroformylation is limited to a rather narrow substrate scope.[2] An alternative approach makes use of substrate-bound catalyst-directing groups (CDG), which allow for diastereoselective hydroformylation of chiral substrates.[4] For instance, installation of the *ortho*-(diphenylphosphanyl)benzoate function (*o*-DPPB) into 2-substituted allylic alcohol derivatives **1** leads to a regio- and stereoselective hydroformylation to give *syn*-aldehydes **2** (Scheme 1).[5] Hence, the chirality information residing in the substrate is transmitted efficiently (1,2-asymmetric induction) by passing through a highly ordered cyclic transition state for the selectivity-determining hydrometalation step, which is a result of the catalyst-binding properties and molecular architecture of the catalyst-directing *o*-DPPB group. However, if prochiral substrates are to be employed, the chirality information would have to be part of the catalyst-directing group.



Scheme 1. Concept of desymmetrizing hydroformylation with the aid of *o*-DPPF as a planar-chiral, substrate-bound catalyst-directing group (CDG*).

We report herein, in full detail, on a desymmetrizing hydroformylation of prochiral dialkenylcarbinols **3** employing a new planar-chiral, catalyst-directing group (*o*-DPPF) (Scheme 1).[6] Optimization of the experimental conditions, determination of the relative and absolute configuration of the products (chemical derivatization and X-ray crystallographic studies), as well as the conditions for removal and recovery of the catalyst-directing *o*-DPPF group are de-

[‡] Substrate-Directed Diastereoselective Hydroformylations, 5. Part 4: B. Breit, G. Heckmann, S. K. Zahn, *Chem. Eur. J.* **2003**, *9*, 425–434.

[a] Albert-Ludwigs-Universität Freiburg, Institut für Organische Chemie und Biochemie
Albertstr 21, 79104 Freiburg, Germany,
Fax: +49-761-203-8715
E-mail: bernhard.breit@organik.chemie.uni-freiburg.de

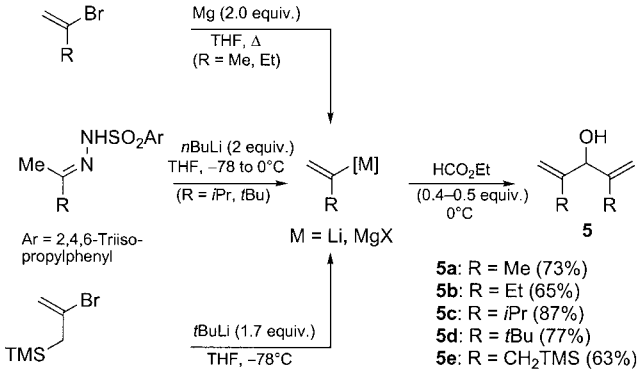
scribed. Furthermore, a model is presented that rationalizes the experimentally observed stereochemical result.

Previous investigations from our group have shown that the *o*-DPPB function has the ideal electronic and geometric properties to direct a transition metal catalyst into an allylic or homoallylic position and thus enables efficient face discrimination of a diastereotopic alkene.[4,5] To keep with these electronic and steric properties of the *o*-DPPB group, and to introduce an element of chirality, we envisioned the *ortho*-(diphenylphosphanyl)ferrocenylcarbonyl function (*o*-DPPF) to be an interesting candidate. As particularly attractive substrates, symmetrical dialkenylcarbinols (see following paper for diallylcarbinols) were chosen since a stereoselective monohydroformylation could form two stereogenic centers simultaneously. The resulting aldehydes are interesting building blocks for polyketide synthesis. However, hydroformylation of this particular class of substrates poses a difficult stereochemical challenge since diastereotopic alkene group discrimination and diastereotopic alkene face discrimination have to be managed simultaneously.[7]

Results

Preparation of Dialkenylcarbinol *o*-DPPF Esters

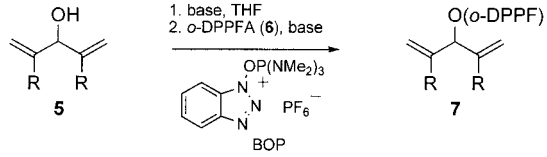
A literature survey revealed that symmetrical dialkenylcarbinols of type **5** are rare.[8] A general access to this interesting class of compounds furnishes the addition of 2 equiv. of an alkenylmetal species to ethyl formate. The corresponding dialkenylcarbinols **5a**–**e** were obtained in satisfactory to good yields (Scheme 2). The alkenylmetal reagent could be generated either by direct synthesis in a Shapiro reaction of the trisylhydrazone (trisyl = 2,4,6-triisopropylphenyl) or, alternatively, by halogen/metal exchange with *t*BuLi.



Scheme 2. Synthetic routes to dialkenylcarbinols.

Standard procedures for the esterification of alcohols **5** and *o*-DPPFA (**6**)[9] failed to give reasonable amounts of the desired *o*-DPPF esters **7** in our hands. This is presumably due to severe steric hindrance at the reaction centers of both reaction partners. Eventually, we found that a dual activation strategy of electrophile and nucleophile was successful. Thus, activation of the carboxylic acid with BOP[10] as the corresponding hydroxybenzotriazol ester, followed by treatment with the sodium or lithium alkoxide of **5**, furnished the *o*-DPPF esters **7** in good to reasonable yields (Table 1). Esterification failed when Hünig's base was employed (Table 1, Entry 3), which clearly indicates the importance of nucleophile activation as a metal alkoxide. In the case of **7d**, esterification failed with sodium as the counterion but proceeded smoothly when *t*BuLi was employed as the base (Table 1, Entries 8 and 9). Hence, the Lewis acidity of the metal counterion is a further important parameter for the success of these esterifications. When enantiomerically pure *o*-DPPFA was used, the corresponding *o*-DPPF esters were obtained in enantiomerically pure form (*ee* > 99%); this was confirmed in each case by HPLC analysis.

Table 1. Esterification of dialkenylcarbinols **5** with *o*-DPPFA (**6**) to give dialkenylcarbinol *o*-DPPF esters (**7**).



Entry	R	Product	Base	*ee* [%][a]	Yield [%][b]
1	Me	*rac*-**7a**	NaH	–	79
2	Me	(S_p)-**7a**	NaH	>99	68
3	Et	*rac*-**7b**	iPr$_2$NEt	–	–
4	Et	*rac*-**7b**	NaH	–	75
5	Et	(S_p)-**7b**	NaH	>99	70
6	*i*Pr	*rac*-**7c**	NaH	–	56
7	*i*Pr	(S_p)-**7c**	NaH	>99	65
8	*t*Bu	*rac*-**7d**	*t*BuLi	–	75
9	*t*Bu	(S_p)-**7d**	*t*BuLi	>99	75
10	CH_2TMS	*rac*-**7e**	*t*BuLi	–	60
11	CH_2TMS	(S_p)-**7e**	*t*BuLi	>99	80

[a] Determined by HPLC. [b] Isolated yield after chromatographic workup.

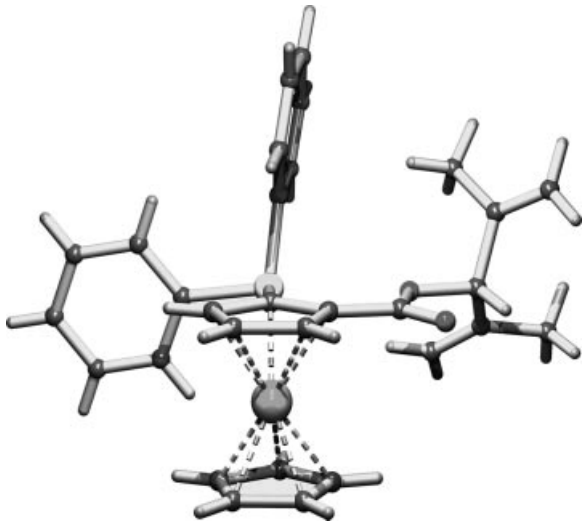


Figure 1. Structure of *rac*-**7a** in the solid state.

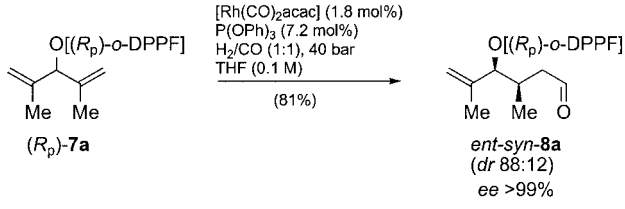
An X-ray crystal structure analysis was performed for *rac*-**7a**. Inspection of the X-ray plot of **7a** confirms severe steric hindrance around the ester function. The orientation of the two propenyl units is controlled by minimization of either A(1,3)- or A(1,2)-strain[11,12] (see Discussion and Model). The phenyl substituents of the PPh_2 unit are oriented so as to minimize steric repulsion with the ferrocene backbone. The ester function displays the typical preferred conformation of an ester of a secondary alcohol with a coplanar orientation of the ester carbonyl group and the C–H bond at C-3 due to the minimization of A(1,3) strain (Figure 1).[13]

Hydroformylation of Dialkenylcarbinol *o*-DPPF Esters

Since both alkenyl groups as well as both faces of each alkene unit of esters **7** are diastereotopic in nature, the regioselective monohydroformylation of dialkenylcarbinol *o*-DPPF esters **7** could, in principle, lead to four diastereomeric aldehydes **8** (Table 2). If racemic *o*-DPPF esters **7** are employed, the four diastereomeric aldehydes **8** will be formed as racemates. In the case of enantiomerically pure *o*-DPPF esters **7**, however, each of the four diastereomeric aldehydes will be formed as an enantiomerically pure isomer provided that racemization of the ferrocene backbone is precluded.

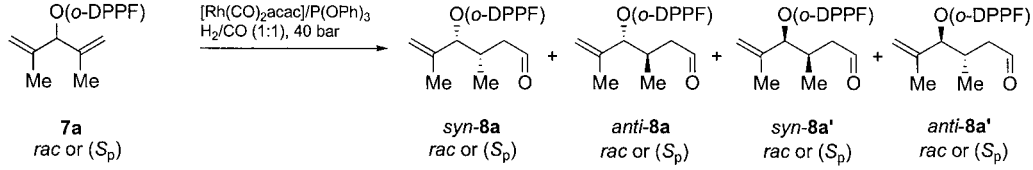
In order to identify the optimal reaction conditions, initial screening was done with dipropenyl ester **7a**. Subjection of **7a** to hydroformylation conditions employing 2 mol-% of rhodium catalyst precursor and 8 mol-% of triphenyl phosphite as the coligand at 90 °C and 40 bar of syngas in toluene for 96 h led to a 74% conversion into the monoaldehydes (Table 2, Entry 1). Interestingly, although the hydroformylation of **7a** proceeded rather slowly under these conditions, the NMR spectum of the crude product showed that of the four possible diastereomeric monoaldehydes **8a**, only two were formed in a ratio of 87:13. In an effort to optimize the hydroformylation rate, the coligand was changed to triphenylphosphane; the reaction rate was even lower (Table 2, Entry 2).[14] Finally, we found that when THF was employed as the solvent, the hydroformylation rate increased significantly. Complete conversion of the starting material into monoaldehydes was reached after 48 h employing 1.8 mol-% of catalyst. The diastereoselectivity under these conditions improved slightly to 88:12, and the pure diastereomers could be obtained by flash-chromatographic separation.

In order to probe substrate scope and diastereoselectivity as a function of substrate structure, esters **7b**–**e** were subjected to the optimized conditions of desymmetrizing hydroformylation (Table 2). The conversion and diastereomeric ratio of the aldehyde products were determined from the ^{1}H NMR spectrum of the crude product. The enantiomeric purity in the case of enantiomerically pure substrates **7** was determined after reduction of the aldehydes **8** to the corresponding primary alcohols **9**. The reduction step was necessary since aldehydes **8** proved unstable under the conditions of HPLC analysis. Hydroformylation proceeded smoothly to give, in all cases, essentially one major aldehyde diastereomer (*syn*-**8**), with diastereoselectivities ranging from 87:13 to >99:1. When enantiomerically pure esters (S_p)-**7a**–**e** (Table 3) were employed, the corresponding aldehydes *syn*-**8a**–**e** were obtained in enantiomerically pure form. (R_p)-**7a** led to the enantiomer *ent*-*syn*-**8a** as the major diastereomer in enantiomerically pure form [Equation (1)]. Hence, the absolute configuration of the *o*-DPPFA employed (R_p or S_p) determines the absolute configuration of the two new stereogenic centers formed in the monoaldehyde **8**.



(1)

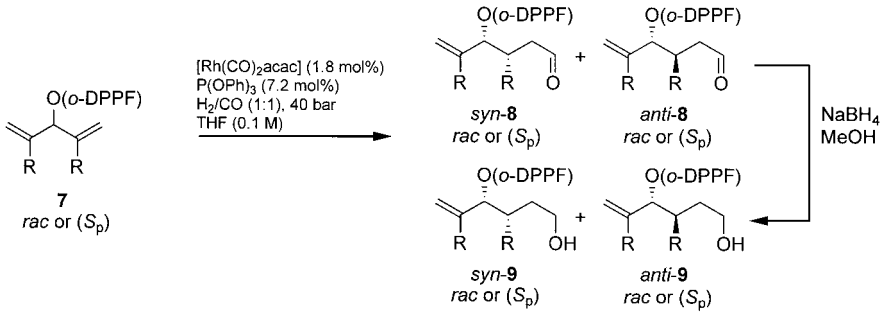
Table 2. Optimization of the hydroformylation conditions for substrate **7a**.



Entry	Substrate	[Rh]/P(OPh)$_3$ [mol-%]	Solvent	*T* [°C]	*t* [h]	Conv. [%][a]	*dr*[a] *syn*-**8a**/*anti*-**8a**	Yield [%][b]
1	*rac*-**7a**	2.0/8.0	Toluene (0.1 M)	90	89	74	86:14	92[c]
2	*rac*-**7a**	2.0/8.0[d]	Toluene (0.2 M)	90	84	45	86:14	87[c]
3	*rac*-**7a**	1.8/7.2	THF (0.1 M)	70	48	quant.	87:13	84[e]
4	(S_p)-**7a**	1.8/7.2	THF (0.1 M)	70	48	98	88:12	92

[a] Determined from the ^{1}H NMR spectrum of the crude product. [b] Isolated yield after chromatographic purification. [c] Based on recovered starting material. [d] PPh_3 was used as the coligand. [e] 6% of dialdehyde was also isolated as a mixture of stereoisomers.

Table 3. Results of the desymmetrizing hydroformylation of dialkenylcarbinol *o*-DPPF esters **7a**–**e**.

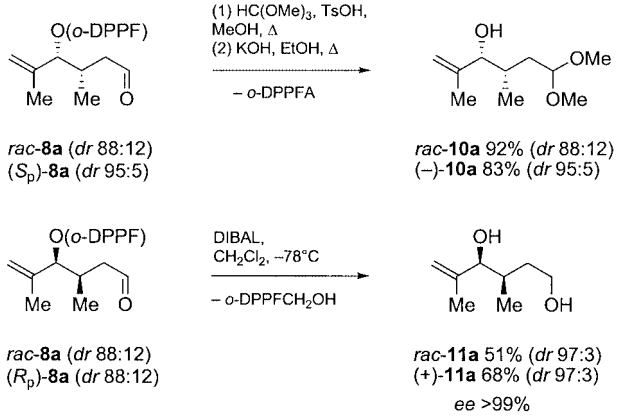


Entry	Substrate	*T* [°C]	*t* [h]	Conv.[a] [%]	*dr*[a] *syn*-**8**/*anti*-**8**	Yield[b] **8** [%]	Yield[b] **9** [%]	*ee* [%][c] of **9**
1	*rac*-**7a**	70	48	quant.	87:13	84	95	–
2	(S_p)-**7a**	70	48	98	88:12	92	76	>99[d]
3	*rac*-**7b**	70	48	quant.	93:7	86	87	–
4	(S_p)-**7b**	70	48	quant.	92:8	80	85	>99[d]
5	*rac*-**7c**	70	48	95	>97:3	77	96	–
6	(S_p)-**7c**	70	48	95	>98:2	80	85	>99[e]
7	*rac*-**7d**	70	48	30	>99:1	72[f]	–	–
8	*rac*-**7d**	90	72	61	>99:1	87[f]	88	–
9	(S_p)-**7d**	90	72	62	>99:1	82[f]	92	>99[e]
10	*rac*-**7e**	60	96	70	>99:1	68[f]	89	–
11	(S_p)-**7e**	60	96	56	>99:1	71[f]	97	>99[e]

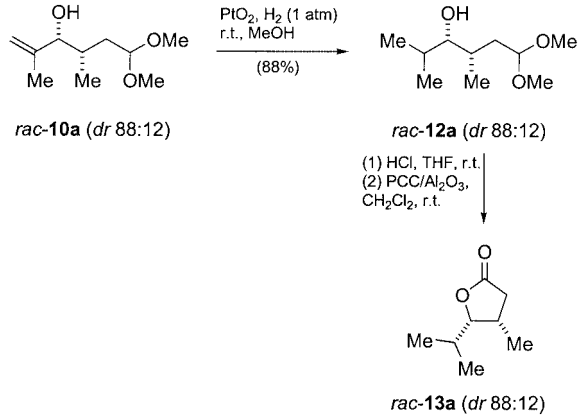
[a] Determined from the ^{1}H NMR spectrum of the crude product. [b] Isolated yield after chromatographic purification. [c] Determined by HPLC (AD or OD-H). [d] Major and minor diastereomer. [e] Major diastereomer. [f] Based on recovered starting material.

Removal and Recovery of the Catalyst-Directing *o*-DPPF Group

Removal of the substrate-bound catalyst-directing *o*-DPPF group was achieved by saponification with ethanolic potassium hydroxide after protection of the aldehydes as the dimethyl acetal. The alcohols *rac*-**10a** and (–)-**10a** were obtained in good yields, and the *o*-DPPFA could be recovered (Scheme 3). Alternatively, reductive removal of the *o*-DPPF group furnished the diols *rac*-**11a** and (+)-**11a**.



Scheme 3. Removal and recovery of the catalyst-directing *o*-DPPF group.



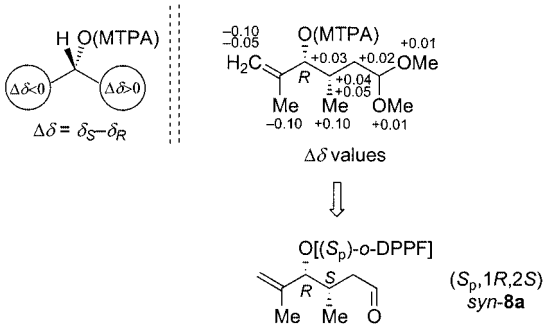
Scheme 4. Determination of relative configuration.

Determination of the Relative and Absolute Configuration of Product Aldehydes 8

Determination of the relative configuration of the major and minor diastereomeric aldehydes **8** proceeded from alcohol *rac*-**10a**. Alkene hydrogenation, aldehyde liberation, and oxidation gave the known γ-lactone *rac*-**13a** (Scheme 4).[15] NOESY NMR analysis allowed us to assign a *cis* relationship for the substituents of the major diastereomer and an *anti* relationship for the substituents of the minor diastereomer. Hence, the stereogenic centers of the major diastereomer of **8a** have a *syn* relationship (*syn*-**8a**) and the relative configuration of the minor diastereomer **8a** is *anti*.

In order to determine the absolute configuration of the hydroformylation products **8**, alcohol **12a** [*dr* = 95:5, obtained from the hydroformylation of (S_p)-**7a**] was subjected to a Mosher ester analysis.[16] Analysis of the chemical-shift differences of both diastereomeric Mosher esters allowed us

to assign the (*R*) configuration to the stereogenic center at C-3 (Scheme 5). Hence, the major diastereomeric aldehyde (*syn*-**8a**) obtained after hydroformylation of the dipropenylcarbinol *o*-DPPF ester (S_p)-**7a** has the configuration (S_p,1*R*,2*S*)-**8a**. The absolute and relative configuration of aldehydes **8b**–**e** was assigned in analogy.



Scheme 5. Determination of absolute configuration of (–)-**10a** by Mosher ester analysis [δ_S, δ_R: absolute configuration of the Mosher acid (MTPA) employed].

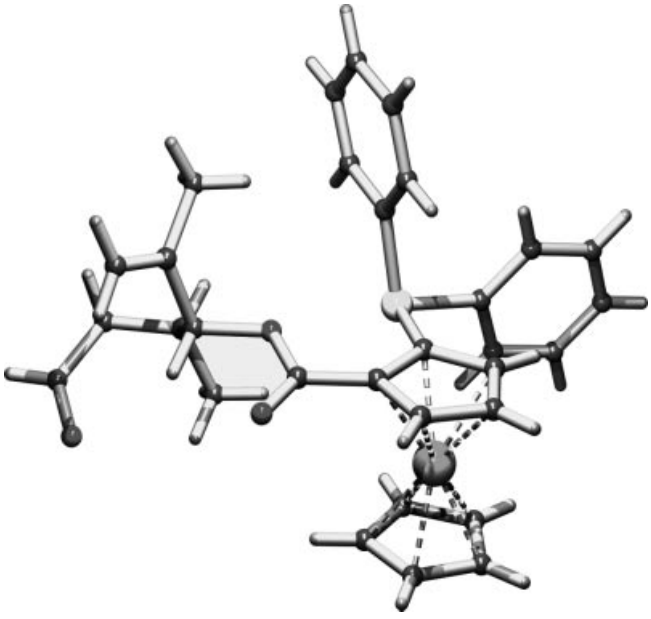


Figure 2. X-ray crystal structure analysis of *rac*-*syn*-**8a**.

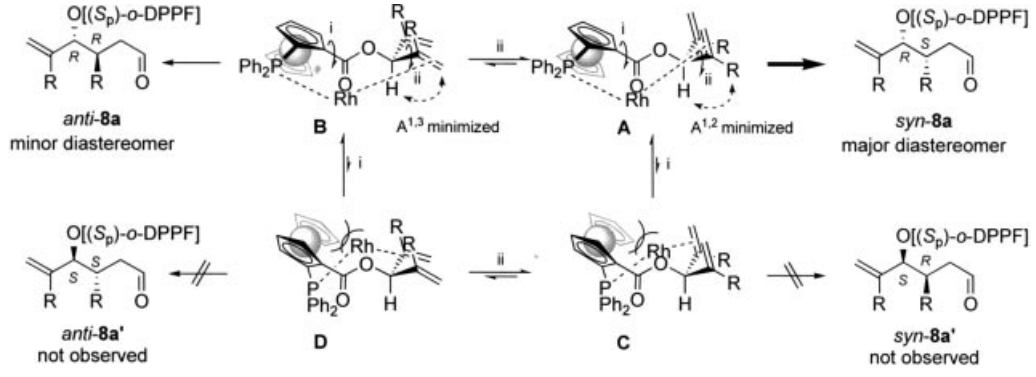
Final unequivocal proof of the relative configuration of the stereogenic centers at C-3 and C-4 came from an X-ray crystal structure analysis of *syn*-**8a** (Figure 2).

Discussion and Model for 1,2-Asymmetric Induction

From the absolute and relative configuration of monoaldehydes **8a** it follows that the hydroformylation of dialkenylcarbinol *o*-DPPF esters **7** occurs with good diastereotopic face discrimination and perfect diastereotopic group discrimination. Diastereotopic face discrimination increases with the size of the R substituent at the alkene. The same observation has been made previously for the *o*-DPPB-directed hydroformylation of chiral 2-substituted allylic alcohols (Scheme 1, **1** → **2**), for which a stereochemical model has been proposed.[5a] A similar model, modified by exchanging *o*-DPPB with the planar chiral *o*-DPPF group, allows us to rationalize the stereochemical outcome of the directed desymmetrizing hydroformylation (Scheme 6).

As discussed previously, comparison of the relative stability of the chelating (alkene)rhodium complexes **A**–**D**, which serve as models for the competing rate- and selectivity-determining hydrometalation transition states, allows us to predict the stereochemistry of the directed hydroformylation.[5a] Thus, for (S_p)-*o*-DPPF esters **7** the relative stabilities of the two diastereomeric complexes **A** and **B** and the corresponding transition states for hydrometalation decide the alkene face diastereoselection of the reaction. Minimization of A(1,2) strain in the alkene moiety leads, via **A**, to the major diastereomer *syn*-**8a**. The reaction via chelation mode **B**, in which the alkene conformation minimizes A(1,3) strain, leads to the minor diastereomer *anti*-**8a**. In fact, both conformational orientations of the alkene unit are possible in the ground state, as is obvious from the X-ray plot of the structure of **7a** in the solid state. Since A(1,2) strain is a function of the steric demand of the R substituent, it is obvious that face diastereoselectivity increases for derivatives **7b**–**d** (Table 2).[5a]

Group diastereoselectivity is determined by the relative stabilities of hydrometalation transition states resulting from chelation complexes **C** and **D** vs. **A** and **B**. Thus, coordination of the opposite diastereotopic alkene group re-



Scheme 6. Model for desymmetrizing hydroformylation of dialkenylcarbinol *o*-DPPF esters **7**.

quires a bond rotation process (i; Scheme 6). However, even a simple drawing makes clear that such a chelating bonding mode is prohibited because of severe steric hindrance between the ferrocene nucleus and the rhodium center. Hence, alkenyl group diastereoselection is perfect and neither diastereomer *syn*-**8a′** nor *anti*-**8a′** is observed.

Of course, we are fully aware that this simple model using ground-state conformational preferences for olefin coordination in order to explain reaction selectivity may oversimplify the overall kinetics of the hydroformylation.

Conclusions

The desymmetrizing hydroformylation of dialkenylcarbinols has been achieved with excellent levels of stereocontrol with the aid of the new chiral, substrate-bound, catalyst-directing *o*-DPPF group. Thus, two new, vicinal stereogenic centers are formed simultaneously. The catalyst-directing *o*-DPPF group can be removed and recovered easily, thus furnishing interesting chiral building blocks in enantiomerically pure form.

Experimental Section

General: Reactions were performed in flame-dried glassware under argon. The solvents were dried by standard procedures, distilled, and stored under argon. All temperatures quoted are not corrected. NMR spectra were obtained with a Varian Mercury spectrometer (300 MHz, 121.5 MHz, and 75.5 MHz for ^{1}H, ^{31}P, and ^{13}C respectively), a Bruker AMX 400 (400 MHz and 100.6 MHz for ^{1}H and ^{13}C respectively), or a Bruker DRX 500 (500 MHz and 125 MHz for ^{1}H and ^{13}C, respectively) and are referenced internally according to residual protio solvent signals (^{31}P NMR: 85% H_3PO_4 as external standard). Melting points: Melting point apparatus by Dr. Tottoli (Büchi). Elemental analyses: Elementar Vario EL (Elementar-Analysensysteme GmbH). Flash chromatography: Silica gel Si 60, E. Merck AG, Darmstadt, 40–63 μm. High-resolution mass spectra were obtained with a Finnigan MAT 8200 instrument. Enantiomeric excesses (*ee*) were determined by HPLC using Daicel Chiralpak AD, AD-H, and Chiralcel OD-H columns (wavelength: 245 nm) with 2-propanol/heptane as the eluent or by GC using a Supelco Betadex 110 (30 m × 0.25 mm; 0.25 μm film thickness) with helium 4.6 (Messer–Griesheim). Optical rotations were measured with a Perkin–Elmer 241 polarimeter. Hydroformylation reactions were performed in 50- and 100-mL stainless-steel autoclaves equipped with magnetic stirrers. Gases: carbon monoxide 3.7, hydrogen 4.3 (1:1, Messer–Griesheim). The following compounds were prepared according to literature procedures: 2,4-dimethylpenta-1,4-dien-3-ol (**5a**),[8] 3-methyl-2-butanone [(2,4,6-triisopropylphenyl)sulfonyl]hydrazone,[17] 3,3-dimethyl-2-butanone [(2,4,6-triisopropylphenyl)sulfonyl]hydrazone,[17] (2-bromoallyl)trimethylsilane,[18] and *o*-DPPFA (**6**).[19] MTBE = *tert*-butyl methyl ether; PE = petroleum ether; Cy = cyclohexane; EE = ethyl acetate; PCC = pyridinium chlorochromate.

Synthesis of Dialkenylcarbinols 5

3,5-Dimethyleneheptan-4-ol (5b): Freshly distilled 2-bromo-1-butene (2.525 g, 18.7 mmol) was added dropwise to a suspension of magnesium turnings (0.901 g, 37.1 mmol, 2.0 equiv.) in THF (40 mL). The resulting mixture was heated to reflux for 2 h, then cooled to 0 °C and a solution of ethyl formate (0.62 g, 8.4 mmol, 0.45 equiv.) in THF (5 mL) was added over 2 min. The mixture was allowed to warm to 25 °C and stirred for 1 h. Subsequently, the reaction mixture was quenched with satd. aqueous NH_4Cl solution (20 mL) and the aqueous phase was extracted with Et_2O (2 × 20 mL). The combined organic layers were washed with brine (20 mL), dried (Na_2SO_4), and the solvent was removed in vacuo. The crude product was dissolved in methanol (15 mL) and K_2CO_3 (3.654 g) was added. After stirring at 25 °C for 17 h, water (15 mL) and MTBE (20 mL) were added. The organic layer was washed with water (20 mL) and the combined aqueous layers were extracted with MTBE (20 mL). The combined organic layers were washed with brine (20 mL), dried (Na_2SO_4) and the solvents were removed in vacuo. The crude product was purified by flash chromatography (pentane/Et_2O, 5:1) to furnish **5b** (0.769 g, 5.5 mmol, 65%) as a colorless liquid. R_f (pentane/Et_2O, 5:1) = 0.25. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.03 (t, J = 7.3 Hz, 6 H), 1.77 (s, 1 H), 1.96 (m_c, 4 H), 4.55 (s, 1 H), 4.93 (s, 2 H), 5.11 (s, 2 H) ppm. ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 12.2 (2 C), 24.1 (2 C), 78.8, 109.6 (2 C), 151.3 (2 C) ppm.

2,6-Dimethyl-3,5-dimethyleneheptan-4-ol (5c): *n*-Butyllithium (17.4 mL, 1.51 M in hexane, 26.3 mmol, 2.0 equiv.) was added at –78 °C, over 20 min, with a syringe pump, to a solution of 3-methyl-2-butanone [(2,4,6-triisopropylphenyl)sulfonyl]hydrazone (4.807 g, 13.1 mmol) in THF (50 mL) and the resulting red solution was stirred at –78 °C for a further 30 min. Subsequently, the solution was warmed to 0 °C in an ice bath; at this point, a strong gas evolution (N_2) occurred and the color of the solution faded to yellow. After stirring for another 15 min, a solution of ethyl formate (0.43 g, 5.8 mmol, 0.44 equiv.) in THF (2 mL) was added, the solution was allowed to warm to 25 °C, and was stirred at this temperature for 1 h. After addition of aqueous satd. $NaHCO_3$ solution (30 mL), the aqueous layer was extracted with Et_2O (3 × 50 mL), the combined organic layers were washed with brine (30 mL), dried (Na_2SO_4), and concentrated. The crude product was purified by flash chromatography (PE/MTBE, 10:1) to furnish **5c** (0.848 g, 5.0 mmol, 87%) as a colorless liquid. R_f (PE/MTBE, 10:1) = 0.22. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.97 (d, J = 6.9 Hz, 6 H), 1.04 (d, J = 6.9 Hz, 6 H), 2.24 (sept, J = 6.9 Hz, 2 H), 4.46 (s, 1 H), 4.94 (s, 2 H), 5.14 (s, 2 H) ppm; OH signal not detected. ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 22.9 (2 C), 23.4 (2 C), 29.9 (2 C), 77.4, 108.5 (2 C), 157.0 (2 C) ppm. HRMS (EI; $C_{11}H_{20}O$, 168.3): calcd. 168.1514; found 168.1516.

2,2,6,6-Tetramethyl-3,5-dimethyleneheptan-4-ol (5d): *n*-Butyllithium (16.7 mL, 1.49 M in hexane, 24.9 mmol, 1.95 equiv.) was added at –78 °C, over 20 min, with a syringe pump, to a solution of 3,3-dimethyl-2-butanone [(2,4,6-triisopropylphenyl)sulfonyl]hydrazone (4.854 g, 12.8 mmol) in THF (25 mL) and the resulting red solution was stirred at –78 °C for a further 20 min. The solution was then warmed to 0 °C in an ice bath; at this point, a strong gas evolution (N_2) occurred and the color of the solution faded to yellow. After stirring for another 20 min, a solution of ethyl formate (0.43 g, 5.8 mmol, 0.46 equiv.) in THF (2 mL) was added, the solution was allowed to warm to 25 °C, and was stirred at this temperature for 90 min. After addition of satd. aqueous $NaHCO_3$ solution (100 mL), the aqueous layer was extracted with Et_2O (3 × 50 mL), the combined organic layers were washed with brine (50 mL), dried (Na_2SO_4), and concentrated. The crude product was purified by flash chromatography (PE/Et_2O, 20:1) to furnish **5d** (0.875 g, 4.5 mmol, 77%) as a white solid. R_f (Cy/EE, 5:1) = 0.42; m.p. 44 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.14 (s, 18 H), 1.41 (d, J = 5.8 Hz, 1 H), 4.97 (d, J = 5.8 Hz, 1 H), 5.19 (s, 2 H), 5.24 (s, 2 H) ppm. ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 30.7 (6C), 35.7 (2 C),

68.9, 111.2 (2 C), 158.9 (2 C) ppm. $C_{13}H_{24}O$ (196.3): calcd. C 79.53, H 12.32; found C 79.35, H 12.22.

2,4-Bis[(trimethylsilyl)methyl]penta-1,4-dien-3-ol (5e): *tert*-Butyllithium (33.0 mL, 1.55 M in pentane, 51.2 mmol, 1.7 equiv.) was added at –78 °C, over 15 min, to a solution of (2-bromoallyl)trimethylsilane (5.67 g, 29.4 mmol) in THF (30 mL). The mixture was stirred for 2 h, then a solution of ethyl formate (1.01 g, 13.6 mmol, 0.46 equiv.) in THF (5 mL) was added. After stirring at –78 °C for 15 min, the solution was allowed to warm to 25 °C, and stirring was continued for 60 min. After addition of satd. aqueous $NaHCO_3$ (20 mL), the aqueous layer was extracted with MTBE (3 × 50 mL) and the combined organic layers were dried (Na_2SO_4) and concentrated. The crude product was purified by flash chromatography (PE/MTBE, 50:1) to furnish crude **5e** (2.60 g). Purification was achieved by bulb-to-bulb distillation (60 °C/0.1 mbar to remove impurity; 120 °C/0.1 mbar for **5e**) to give **5e** (2.19 g, 8.6 mmol, 63%) as a colorless liquid. R_f (Cy/EE, 10:1) = 0.25. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.03 (s, 18 H), 1.38 (d, J = 14.2 Hz, 2 H), 1.55 (d, J = 14.2 Hz, 2 H), 1.69 (br. s, 1 H), 4.30 (s, 1 H), 4.75 (s, 2 H), 4.97 (s, 2 H) ppm. ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = –1.1 (s, 6C), 22.0 (2 C), 80.0, 109.4 (2 C), 147.3 (2 C) ppm.

Synthesis of Dialkenylcarbinol *o*-DPPF Esters 7

General Procedure 1 (GP1). Esterification Protocol 1: *o*-DPPFA (**6**) was dissolved in THF (10 mL per mmol of *o*-DPPFA) and the base was added (25 °C for NaH, –78 °C for *t*BuLi). In a separate flask under light protection, BOP[10] (1.0–1.1 equiv.) was dissolved in the same volume of THF and the sodium or lithium carboxylate was added over 30 min with a syringe pump at 25 °C and the mixture was stirred for 60 min. In a separate flask, the alcohol **5** (1.0–1.2 equiv.) was dissolved in THF (2 mL per mmol of alcohol), cooled (0 °C for NaH, –78 °C for *t*BuLi), the base was added and, after stirring for several minutes, the alkoxide mixture was added to the solution of the activated ester in one portion and the reaction mixture was again stirred for the indicated period of time at 25 °C. Subsequently, the reaction mixture was quenched with water (2 equiv.), silica gel was added, and all volatile material was removed in vacuo. Flash chromatography (the orange product fraction was collected in a flask under argon and the solvents were removed in an argon-purged rotary evaporator due to the air sensitivity of the *o*-DPPF esters) furnished the corresponding ester, which was dried at 60 °C/0.1 mbar overnight. **General Procedure 2 (GP2). Esterification Protocol 2:** *o*-DPPFA (**6**) and the alcohol **5** (1.0–1.2 equiv.) were dissolved in THF (10 mL per mmol of *o*-DPPFA) and deprotonated with *t*BuLi at –78 °C. The resulting mixture was then added to a solution of BOP (1.0–1.1 equiv.) in THF (10 mL per mmol of BOP) in a light-protected flask at 25 °C over 10 min and the mixture was stirred for the indicated period of time at 25 °C. The workup procedure was identical to that described in GP1. **General Procedure 3 (GP3). Esterification Protocol 3:** *o*-DPPFA **6** and the alcohol **5** were dissolved in THF (10 mL per mmol of *o*-DPPFA) and NaH (2.5–3.5 equiv.) was added. BOP (1.0–1.1 equiv.) was added to this mixture and the mixture was stirred for the indicated period of time at 25 °C. The workup procedure was identical to that described in GP1.

1-Isopropenyl-2-methylallyl 2-(Diphenylphosphanyl)ferrocenecarboxylate (7a). *rac*-7a: As described in GP3, *rac*-*o*-DPPFA (1.10 g, 2.66 mmol), alcohol **5a** (324 mg, 2.87 mmol, 1.08 equiv.), BOP (1.25 g, 2.83 mmol, 1.06 equiv.), and NaH (327 mg, 60% in mineral oil, 8.24 mmol, 3.11 equiv.) in THF (31 mL) gave, after a reaction time of 18 h, workup, and flash chromatography (PE/EE, 50:1), the title compound *rac*-**7a** (1.07 g, 2.10 mmol, 79%,) as an orange solid. **(S_p)-7a:** As described in GP3, (S_p)-*o*-DPPFA (573 mg, 1.38 mmol, *ee* > 99%), alcohol **5a** (156 mg, 1.39 mmol, 1.01 equiv.), BOP (650 mg, 1.47 mmol, 1.07 equiv.), and NaH (170 mg, 60% in mineral oil, 4.29 mmol, 3.11 equiv.) in THF (14 mL) gave, after a reaction time of 20 h, workup, and flash chromatography (PE/EE, 50:1), the title compound (S_p)-**7a** (477 mg, 0.94 mmol, 68%, *ee* > 99%) as an orange solid. **Data for 7a:** R_f (Cy/EE, 10:1) = 0.46; m.p. 75 °C. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.53 (s, 3 H), 1.73 (s, 3 H), 3.70 (br. s, 1 H), 4.20 (s, 5 H), 4.44 (pseudo t, J = 2.6 Hz, 1 H), 4.83 (pseudo t, J = 1.5 Hz, 1 H), 4.89 (s, 1 H), 4.98 (s, 1 H), 5.13 (br. s, 1 H), 5.20 (s, 1 H), 5.68 (s, 1 H), 7.13–7.17 (m, 2 H), 7.19–7.23 (m, 3 H), 7.33–7.37 (m, 3 H), 7.44–7.49 (m, 2 H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ = 18.2, 18.9 (d, $J_{C,P}$ = 2.4 Hz), 71.0 (s, 5 C), 71.9, 74.5, 75.5 (d, $J_{C,P}$ = 4.8 Hz), 75.7 (d, $J_{C,P}$ = 15.7 Hz), 79.1 (d, $J_{C,P}$ = 16.7 Hz), 79.9, 113.2 (d, $J_{C,P}$ = 2.4 Hz), 113.9, 128.0, 128.1 (d, $J_{C,P}$ = 6.7 Hz, 2 C), 128.2 (d, $J_{C,P}$ = 7.3 Hz, 2 C), 129.1, 132.3 (d, $J_{C,P}$ = 18.8 Hz, 2 C), 135.2 (d, $J_{C,P}$ = 21.5 Hz, 2 C), 138.5 (d, $J_{C,P}$ = 13.3 Hz), 139.6 (d, $J_{C,P}$ = 13.3 Hz), 141.6, 141.8, 170.3 ppm. ^{31}P NMR (121.5 MHz, $CDCl_3$): δ = –16.5 ppm. $C_{30}H_{29}FeO_2P$ (508.4): calcd. C 70.88, H 5.75; found C 70.83, H 5.76. HPLC [OD-H, heptane/2-propanol (95:5), 25 °C, 0.8 mL/min]: t_R[(S_p)-**7a**] = 8.41 min; t_R[(R_p)-**7a**] = 9.13 min. $[\alpha]_D^{20}$ = –142 (c = 0.46, $CHCl_3$).

2-Methylene-1-(1-methylenepropyl)butyl 2-(Diphenylphosphanyl)ferrocenecarboxylate (7b). *rac*-7b: *rac*-*o*-DPPFA (1.49 g, 3.6 mmol) dissolved in THF (35 mL) was treated with NaH (160 mg, 60% in mineral oil, 4.0 mmol, 1.12 equiv.), and then with BOP (1.69 g, 3.8 mmol, 1.06 equiv.) dissolved in THF (35 mL), as described in GP1. The alcohol **5b** (555 mg, 4.0 mmol, 1.14 equiv.) in THF (8 mL) was deprotonated with NaH (164 mg, 4.1 mmol, 1.14 equiv.) and the alkoxide was added to the reaction mixture. After stirring for 15 h, workup, and flash chromatography (PE/EE, 50:1), the title compound *rac*-**7b** (1.45 mg, 2.7 mmol, 75%) was obtained as an orange oil, which crystallized upon standing at 4 °C. **(S_p)-7b:** (S_p)-*o*-DPPFA (486 mg, 1.17 mmol, *ee* > 99%) dissolved in THF (11 mL) was treated with NaH (51 mg, 60% in mineral oil, 1.29 mmol, 1.10 equiv.) and subsequently with BOP (540 mg, 1.22 mmol, 1.04 equiv.) dissolved in THF (11 mL), as described in GP1. Then, alcohol **5b** (199 mg, 1.42 mmol, 1.22 equiv.) in THF (5 mL) was deprotonated with NaH (58 mg, 1.47 mmol, 1.25 equiv.) and the alkoxide was added to the reaction mixture. After stirring for 19 h, workup and flash chromatography (PE/EE, 50:1) furnished the title compound (S_p)-**7b** (439 mg, 0.82 mmol, 70%, *ee* > 99%) as an orange oil, which crystallized upon standing at 4 °C. **Data for 7b:** R_f (Cy/EE, 10:1) = 0.63; m.p. 139 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.92 (t, J = 7.3 Hz, 3 H), 1.07 (t, J = 7.3 Hz, 3 H), 1.84 (q, J = 7.3 Hz, 2 H), 2.06 (m_c, 2 H), 3.70 (ddd, J = 2.4, 1.5, 1.0 Hz, 1 H), 4.20 (s, 5 H), 4.45 (pseudo t, J = 1.7 Hz, 1 H), 4.84 (d, J = 1.7 Hz, 1 H), 4.98 (s, 1 H), 5.01 (d, J = 1.3 Hz, 1 H), 5.14 (ddd, J = 2.6, 1.5, 1.2 Hz, 1 H), 5.31 (s, 1 H), 5.80 (s, 1 H), 7.12–7.19 (m, 2 H), 7.20–7.24 (m, 3 H), 7.35–7.39 (m, 3 H), 7.45–7.51 (m, 2 H) ppm. ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 11.8, 12.0, 24.3, 25.0, 71.0 (5 C), 71.9, 74.6, 75.5 (d, $J_{C,P}$ = 5.8 Hz), 75.9 (d, $J_{C,P}$ = 16.0 Hz), 79.1 (d, $J_{C,P}$ = 17.4 Hz), 79.4, 110.9 (d, $J_{C,P}$ = 2.9 Hz), 111.6, 128.0, 128.1 (d, $J_{C,P}$ = 7.3 Hz, 2 C), 128.3 (d, $J_{C,P}$ = 8.7 Hz, 2 C), 129.1, 132.3 (d, $J_{C,P}$ = 18.9 Hz, 2 C), 135.3 (d, $J_{C,P}$ = 21.8 Hz, 2 C), 138.6 (d, $J_{C,P}$ = 14.6 Hz), 139.7 (d, $J_{C,P}$ = 13.1 Hz), 147.6, 147.8, 170.4 (d, $J_{C,P}$ = 2.9 Hz) ppm. ^{31}P NMR (121.5 MHz, $CDCl_3$): δ = –16.4 ppm. $C_{32}H_{33}FeO_2P$ (535.4): calcd. C 71.65, H 6.20; found C 71.64, H 6.34. HPLC [OD-H, heptane/2-propanol (500:1), 25 °C, 0.8 mL/min]: t_R[(R_p)-**7b**] = 11.78 min; t_R[(S_p)-**7b**] = 15.53 min. $[\alpha]_D^{20}$ = –142 (c = 0.64, $CHCl_3$).

3-Methyl-2-methylene-1-(2-methyl-1-methylenepropyl)butyl 2-(Diphenylphosphanyl)ferrocenecarboxylate (7c). *rac*-7c: *rac*-*o*-DPPFA

(592 mg, 1.43 mmol), dissolved in THF (10 mL) was treated with NaH (64 mg, 60% in mineral oil, 1.62 mmol, 1.13 equiv.) and subsequently with BOP (644 mg, 1.46 mmol, 1.02 equiv.) dissolved in THF (10 mL), as described in GP1. Then, alcohol **5c** (265 mg, 2.33 mmol, 1.63 equiv.) in THF (5 mL) was deprotonated with NaH (93 mg, 2.34 mmol, 1.64 equiv.) and the alkoxide was added to the reaction mixture. After stirring for 48 h, workup and flash chromatography (PE/EE, 50:1) gave the title compound *rac*-**7c** (452 mg, 0.80 mmol, 56%) as an orange solid. **(S_p)-7c:** (S_p)-*o*-DPPFA (420 mg, 1.01 mmol, *ee* > 99%) dissolved in THF (10 mL) was treated with NaH (53 mg, 60% in mineral oil, 1.34 mmol, 1.32 equiv.) and subsequently with BOP (461 mg, 1.04 mmol, 1.03 equiv.) dissolved in THF (10 mL), as described in GP1. Then, alcohol **5c** (171 mg, 1.02 mmol, 1.01 equiv.) in THF (5 mL) was deprotonated with NaH (98 mg, 2.48 mmol, 2.45 equiv.) and the alkoxide was added to the reaction mixture. After stirring for 48 h, workup and flash chromatography (PE/EE, 50:1) gave the title compound (S_p)-**7c** (372 mg, 0.66 mmol, 65%, *ee* > 99%) as an orange solid. **Data for 7c:** R_f (Cy/EE, 10:1) = 0.60; m.p. 96 °C. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.950 (d, J = 6.8 Hz, 3 H), 0.952 (d, J = 6.9 Hz, 3 H), 1.08 (d, J = 6.9 Hz, 6 H), 2.09 (sept, J = 6.8 Hz, 1 H), 2.29 (sept, J = 6.8 Hz, 1 H), 3.70 (ddd, J = 2.5, 1.5, 0.9 Hz, 1 H), 4.20 (s, 5 H), 4.44 (d pseudo t, J = 2.6, 0.5 Hz, 1 H), 4.90 (pseudo t, J = 1.1 Hz, 1 H), 4.93 (pseudo t, J = 1.1 Hz, 1 H), 5.07 (s, 1 H), 5.13 (quint, J = 1.3 Hz, 1 H), 5.29 (q, J = 0.6 Hz, 1 H), 5.86 (s, 1 H), 7.12–7.17 (m, 2 H), 7.19–7.23 (m, 3 H), 7.34–7.38 (m, 3 H), 7.45–7.50 (m, 2 H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ = 22.3, 22.5, 23.0, 23.2, 30.96, 30.99, 71.2 (5 C), 72.1, 74.7, 75.7 (d, $J_{C,P}$ = 4.8 Hz), 76.2 (d, $J_{C,P}$ = 15.8 Hz), 77.2, 79.6 (d, $J_{C,P}$ = 17.3 Hz), 110.8, 111.0 (d, $J_{C,P}$ = 3.3 Hz), 128.2, 128.3 (d, $J_{C,P}$ = 6.4 Hz, 2 C), 128.5 (d, $J_{C,P}$ = 7.0 Hz, 2 C), 129.3, 132.7 (d, $J_{C,P}$ = 19.1 Hz, 2 C), 135.4 (d, $J_{C,P}$ = 21.5 Hz, 2 C), 138.9 (d, $J_{C,P}$ = 14.2 Hz), 140.0 (d, $J_{C,P}$ = 13.6 Hz), 152.9, 153.2, 170.6 (d, $J_{C,P}$ = 3.0 Hz) ppm. ^{31}P NMR (121.5 MHz, $CDCl_3$): δ = –16.7 ppm. $C_{34}H_{37}FeO_2P$ (564.5): calcd. C 72.34, H 6.61; found C 72.24, H 6.65. HPLC [OD-H, heptane/2-propanol (1000:1), 24 °C, 0.8 mL/min]: t_R[(S_p)-**7c**] = 15.20 min; t_R[(R_p)-**7c**] = 16.80 min. $[\alpha]_D^{20}$ = –141 (c = 0.46, $CHCl_3$).

1-(2,2-Dimethyl-1-methylenepropyl)-3,3-dimethyl-2-methylenebutyl [2-(Diphenylphosphanyl)ferrocenecarboxylate (7d). *rac*-7d: *rac*-*o*-DPPFA (545 mg, 1.32 mmol) and alcohol **5d** (269 mg, 1.37 mmol, 1.04 equiv.) in THF (20 mL) were treated with *t*BuLi (1.60 mL, 1.66 M in pentane, 1.94 mmol) and then with BOP (608 mg, 1.38 mmol, 1.04 equiv.) in THF (14 mL), as described in GP2. After stirring for 2 h, workup and flash chromatography (PE/EE, 50:1) gave the title compound *rac*-**7d** (582 mg, 0.98 mmol, 75%) as an orange solid. **(S_p)-7d:** (S_p)-*o*-DPPFA (426 mg, 1.03 mmol, *ee* > 99%) and alcohol **5d** (205 mg, 1.04 mmol, 1.01 equiv.) in THF (10 mL) were treated with *t*BuLi (1.25 mL, 1.66 M in pentane, 2.08 mmol) and then with BOP (461 mg, 1.04 mmol, 1.01 equiv.) in THF (10 mL), as described in GP2. After stirring for 2 h, workup and flash chromatography (PE/EE, 50:1) gave the title compound (S_p)-**7d** (458 mg, 0.77 mmol, 75%, *ee* > 99%) as an orange solid. **Data for 7d:** R_f (Cy/EE, 10:1) = 0.45; m.p. 191 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.95 (s, 9 H), 1.11 (s, 9 H), 3.65 (br. s, 1 H), 4.22 (s, 5 H), 4.41 (pseudo t, J = 2.6 Hz, 1 H), 5.03 (s, 1 H), 5.07 (s, 1 H), 5.09 (br. s, 1 H), 5.28 (s, 1 H), 5.52 (s, 1 H), 6.10 (s, 1 H), 7.09–7.17 (m, 2 H), 7.18–7.24 (m, 3 H), 7.33–7.37 (m, 3 H), 7.42–7.49 (m, 2 H) ppm. ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 30.2 (3 C), 30.5 (3 C), 35.78, 35.83, 70.9 (5 C), 71.4, 71.5, 74.4, 75.3 (d, $J_{C,P}$ = 4.4 Hz), 76.2 (d, $J_{C,P}$ = 14.5 Hz), 79.7 (d, $J_{C,P}$ = 17.4 Hz), 113.3, 113.8 (d, $J_{C,P}$ = 5.8 Hz), 128.04 (d, $J_{C,P}$ = 5.8 Hz, 2 C), 128.05, 128.2 (d, $J_{C,P}$ = 5.8 Hz, 2 C), 128.9, 132.9 (d, $J_{C,P}$ = 20.4 Hz, 2 C), 134.9 (d, $J_{C,P}$ = 21.8 Hz, 2 C), 138.6 (d, $J_{C,P}$ = 14.5 Hz), 139.3 (d, $J_{C,P}$ = 14.5 Hz), 154.2, 154.8, 170.2 (d, $J_{C,P}$ = 2.9 Hz) ppm. ^{31}P NMR (121 MHz, $CDCl_3$): δ = –18.0 ppm. $C_{36}H_{41}FeO_2P$ (592.5): calcd. C 72.97, H 6.97; found C 72.96, H 7.01. HPLC (OD-H, *n*-hexane, 30 °C, 0.8 mL/min): t_R[(S_p)-**7d**] = 17.11 min; t_R[(R_p)-**7d**] = 19.40 min. $[\alpha]_D^{20}$ = –157 (c = 0.805, $CHCl_3$).

2-[(Trimethylsilyl)methyl]-1-{1-[(trimethylsilyl)methyl]vinyl}allyl 2-(Diphenylphosphanyl)ferrocenecarboxylate (7e). *rac*-7e: *rac*-*o*-DPPFA (554 mg, 1.34 mmol) and alcohol **5e** (362 mg, 1.41 mmol, 1.06 equiv.) in THF (15 mL) were treated with *t*BuLi (1.76 mL, 1.56 M in pentane, 2.75 mmol, 2.04 equiv.) and then with BOP (650 mg, 1.47 mmol, 1.10 equiv.) in THF (15 mL), as described in GP2. After stirring for 1 h, work-up and flash chromatography (PE/EE, 25:1) gave the title compound *rac*-**7e** (529 mg, 0.81 mmol, 60%) as an orange solid. **(S_p)-7e:** (S_p)-*o*-DPPFA (790 mg, 1.91 mmol, *ee* > 99%) in THF (20 mL) was treated with *t*BuLi (1.19 mL, 1.65 M in pentane, 1.91 mmol, 1.00 equiv.) and subsequently with BOP (889 mg, 2.01 mmol, 1.05 equiv.) in THF (10 mL), as described in GP1. Then, alcohol **5e** (504 mg, 1.96 mmol, 1.03 equiv.) in THF (5 mL) was deprotonated with *t*BuLi (1.19 mL, 1.96 mmol, 1.03 equiv.) and the alkoxide was added to the reaction mixture. After stirring for 1 h, workup and flash chromatography (PE/EE, 25:1) gave the title compound (S_p)-**7e** (993 mg, 1.52 mmol, 80%, *ee* > 99%) as an orange solid. **Data for 7e:** R_f (Cy/EE, 10:1) = 0.50; m.p. 99 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.01 (s, 9 H), 0.03 (s, 9 H), 1.18 (d, J = 14.6 Hz, 1 H), 1.25 (d, J = 14.6 Hz, 1 H), 1.42 (d, J = 14.2 Hz, 1 H), 1.59 (d, J = 14.2 Hz, 1 H), 3.68 (br. s, 1 H), 4.22 (s, 5 H), 4.44 (pseudo t, J = 2.6 Hz, 1 H), 4.68 (s, 1 H), 4.85 (s, 1 H), 4.88 (s, 1 H), 5.15 (pseudo quint, J = 1.3 Hz, 1 H), 5.24 (s, 1 H), 5.57 (s, 1 H), 7.12–7.17 (m, 2 H), 7.18–7.22 (m, 3 H), 7.35–7.39 (m, 3 H), 7.45–7.51 (m, 2 H ppm. ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = –1.02 (3 C), –0.98 (3 C), 22.3, 22.9, 71.1 (5 C), 71.8, 74.4, 75.4 (d, $J_{C,P}$ = 5.8 Hz), 76.0 (d, $J_{C,P}$ = 16.0 Hz), 79.6 (d, $J_{C,P}$ = 17.4 Hz), 80.1, 111.3, 111.5 (d, $J_{C,P}$ = 4.4 Hz), 127.9, 128.1 (d, $J_{C,P}$ = 7.3 Hz, 2 C), 128.2 (d, $J_{C,P}$ = 7.3 Hz, 2 C), 129.0, 132.4 (d, $J_{C,P}$ = 18.9 Hz, 2 C), 135.2 (d, $J_{C,P}$ = 21.8 Hz, 2 C), 138.7 (d, $J_{C,P}$ = 14.5 Hz), 139.7 (d, $J_{C,P}$ = 14.6 Hz), 143.6, 143.7, 170.1 ppm. ^{31}P NMR (121.5 MHz, $CDCl_3$): δ = –17.1 ppm. $C_{36}H_{45}FeO_2PSi_2$ (652.7): calcd. C 66.24, H 6.95; found C 66.29, H 7.03. HPLC [AD, heptane/2-propanol (200:1), 15 °C, 0.5 mL/min]: t_R[(R_p)-**7e**] = 10.53 min; t_R[(S_p)-**7e**] = 13.27 min. $[\alpha]_D^{20}$ = –95 (c = 0.805, $CHCl_3$).

Rhodium-Catalyzed Desymmetrizing Hydroformylation of Dialkenylcarbinol *o*-DPPF Esters 7

General Procedure 4 (GP4). Hydroformylation Protocol: The catalyst precursor [$Rh(CO)_2$acac] was added to a solution of *o*-DPPF ester **7** in toluene or THF (a small gas evolution of CO was visible). After addition of the coligand, the resulting orange solution was transferred with a syringe into an oven-dried (70 °C), stainless-steel tube autoclave; the flask and syringe were rinsed twice with the solvent (final substrate concentration was 0.1 M). The argon in the autoclave was removed by a pressurizing/depressurizing cycle (three times 20 bar H_2/CO), and finally the autoclave was pressurized with 40 bar H_2/CO (1:1) and heated in an oil bath to the reaction temperature for the indicated period of time. Subsequently, the autoclave was cooled to 25 °C, depressurized, and the solution was filtered through a plug of Celite, washed with MTBE, and the solvents were removed in vacuo. Conversion and diastereoselectivity were determined by NMR analysis of the crude mixture (NMR in $CDCl_3$, conversion was determined by integration of the aldehyde proton NMR signals relative to the NMR signals of the olefinic

protons of the starting material; diastereoselecitivity was determined by integration of aldehyde proton NMR signals). Crude products were purified by flash chromatography (the orange fraction was collected in a flask under argon and the solvents were removed in an argon-purged rotary evaporator) followed by drying of the product aldehyde **8** at 60 °C/0.1 mbar for several hours.

(1*R*,2*S*)-1-Isopropenyl-2-methyl-4-oxobutyl (S_p)-2-(Diphenylphosphanyl)ferrocenecarboxylate (8a)

***rac*-8a. Variation 1:** According to GP4, hydroformylation of *rac*-**7a** (170.6 mg, 0.34 mmol) was carried out with [$Rh(CO)_2$acac] (1.7 mg, 6.6 μmol, 0.02 equiv.) and $P(OPh)_3$ (7.0 μL, 0.027 mmol, 0.08 equiv.) in toluene (3.4 mL) at 90 °C for 89 h. The NMR spectrum of the crude product showed a conversion of 74% and the resulting aldehydes were obtained in a diastereomeric ratio of 86:14. Flash chromatography (PE/EE, 5:1) furnished starting material *rac*-**7a** (49.6 mg, 0.10 mmol, 29%) and the product aldehydes *rac*-**8a** (116.7 mg, 0.22 mmol, 92% relative to reisolated starting material, *dr* 86:14) as an orange foam. **Variation 2:** According to GP4, hydroformylation of *rac*-**7a** (260.8 mg, 0.51 mmol) was carried out with [$Rh(CO)_2$acac] (2.7 mg, 10 μmol, 0.02 equiv.) and PPh_3 (10.8 mg, 0.041 mmol, 0.08 equiv.) in toluene (2.6 mL) at 90 °C for 89 h. The NMR spectrum of the crude product showed a conversion of 45% and the resulting aldehydes were obtained in a diastereomeric ratio of 86:14. Flash chromatography (PE/EE, 10:1) furnished starting material (143.2 mg, 0.28 mmol, 55%) and the product aldehydes *rac*-**8a** (109.6 mg, 0.20 mmol, 87% relative to reisolated starting material, *dr* 86:14) as an orange foam. **Variation 3:** According to GP4, hydroformylation of *rac*-**7a** (675 mg, 1.33 mmol) was carried out with [$Rh(CO)_2$acac] (6.2 mg, 24 μmol, 0.018 equiv.) and $P(OPh)_3$ (25.1 μL, 0.096 mmol, 0.072 equiv.) in THF (13.3 mL) at 70 °C for 48 h. The NMR spectrum of the crude product showed a quantitative conversion and the resulting aldehydes were obtained in a diastereomeric ratio of 87:13. Flash chromatography (PE/EE, 5:1) furnished the product aldehydes *rac*-**8a** (603 mg, 1.12 mmol, 84%, *dr* 87:13) as an orange solid.

(S_p)-8a: According to GP4, hydroformylation of (S_p)-**7a** (230.0 mg, 0.45 mmol) was carried out with [$Rh(CO)_2$acac] (2.1 mg, 8.1 μmol, 0.018 equiv.) and $P(OPh)_3$ (8.5 μL, 0.032 mmol, 0.072 equiv.) in THF (4.5 mL) at 70 °C for 48 h. The NMR spectrum of the crude product showed a conversion of 98% and the resulting aldehydes were obtained in a diastereomeric ratio of 88:12. Flash chromatography (PE/EE, 5:1) furnished the product aldehydes (S_p)-**8a** (219.0 mg, 0.41 mmol, 90%, *dr* 88:12) as an orange solid. The minor diastereomer could be separated by flash chromatography (PE/EE, 25:1) to afford essentially pure aldehyde (S_p)-**8a** (*dr* > 95:5).

(R_p)-8a: According to GP4, hydroformylation of (R_p)-**7a** (320.0 mg, 0.63 mmol) was carried out with [$Rh(CO)_2$acac] (2.9 mg, 11.2 μmol, 0.018 equiv.) and $P(OPh)_3$ (11.9 μL, 0.045 mmol, 0.072 equiv.) in THF (6.3 mL) at 70 °C for 48 h. The NMR spectrum of the crude product showed a conversion of 93% and the resulting aldehydes were obtained in a diastereomeric ratio of 88:12. Flash chromatography (PE/EE, 5:1) furnished the product aldehydes (R_p)-**8a** (276.3 mg, 0.51 mmol, 81%, *dr* 88:12) as an orange foam.

Data for 8a: R_f (Cy/EE, 10:1) = 0.24; m.p. 65 °C. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.04 (d, J = 6.8 Hz, 3 H), 1.47 (s, 3 H), 2.29 (ddd, J = 18.0, 9.5, 2.0 Hz, 1 H), 2.40–2.48 (m, 2 H), 3.69 (br. s, 1 H), 4.19 (s, 5 H), 4.44 (pseudo t, J = 2.4 Hz, 1 H), 4.74 (s, 1 H), 4.82 (t, J = 1.5 Hz, 1 H), 5.10 (pseudo quint, J = 1.2 Hz, 1 H), 5.16 (d, J = 6.2 Hz, 1 H), 7.14–7.18 (m, 2 H), 7.20–7.23 (m, 3 H), 7.33–7.37 (m, 3 H), 7.42–7.47 (m, 2 H), 9.70 (dd, J = 2.1, 1.1 Hz, 1 H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ = 15.7 (d, $J_{C,P}$ = 3.9 Hz), 18.6, 29.8, 47.6, 71.0 (5 C), 72.0, 74.6, 75.4 (d, $J_{C,P}$ = 15.8 Hz), 75.6 (d, $J_{C,P}$ = 4.5 Hz), 79.2 (d, $J_{C,P}$ = 16.4 Hz), 80.2, 114.3, 128.1, 128.2 (d, $J_{C,P}$ = 4.8 Hz, 2 C), 128.3 (d, $J_{C,P}$ = 5.4 Hz, 2 C), 129.1, 132.4 (d, $J_{C,P}$ = 19.1 Hz, 2 C), 135.1 (d, $J_{C,P}$ = 21.8 Hz, 2 C), 138.2 (d, $J_{C,P}$ = 13.6 Hz), 139.6 (d, $J_{C,P}$ = 13.3 Hz), 141.8, 170.8 (d, $J_{C,P}$ = 3.0 Hz), 201.4 ppm. ^{31}P NMR (121 MHz, $CDCl_3$): δ = –16.8 ppm. $C_{31}H_{31}FeO_3P$ (538.4): calcd. C 69.16, H 5.80; found C 69.35, H 6.04. $[\alpha]_D^{20}$ = –121 (c = 0.31, $CHCl_3$, *dr* > 95:5).

(1*R*,2*S*)-2-Ethyl-1-(1-methylenepropyl)-4-oxobutyl (S_p)-2-(Diphenylphosphanyl)ferrocenecarboxylate (8b). *rac*-8b: According to GP4, hydroformylation of *rac*-**7b** (346.9 mg, 0.65 mmol) was carried out with [$Rh(CO)_2$acac] (3.0 mg, 11.6 μmol, 0.018 equiv.) and $P(OPh)_3$ (12.2 μL, 0.046 mmol, 0.072 equiv.) in THF (6.5 mL) at 70 °C for 48 h. The NMR spectrum of the crude product showed a quantitative conversion and the resulting aldehydes were obtained in a diastereomeric ratio of 93:7. Flash chromatography (PE/EE, 10:1) furnished the product aldehydes *rac*-**8b** (313.5 mg, 0.55 mmol, 86%, *dr* 93:7) as an orange solid. **(S_p)-8b:** According to GP4, hydroformylation of (S_p)-**7b** (326.0 mg, 0.61 mmol) was carried out with [$Rh(CO)_2$acac] (2.8 mg, 10.9 μmol, 0.018 equiv.) and $P(OPh)_3$ (11.5 μL, 0.044 mmol, 0.072 equiv.) in THF (6.0 mL) at 70 °C for 48 h. The NMR spectrum of the crude product showed a quantitative conversion and the resulting aldehydes were obtained in a diastereomeric ratio of 92:8. Flash chromatography (PE/EE, 10:1) furnished the product aldehydes (S_p)-**8b** (275.3 mg, 0.49 mmol, 80%, *dr* 92:8) as an orange solid. **Data for 8b:** R_f (Cy/EE, 10:1) = 0.22; m.p. 99 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.911 (t, J = 7.5 Hz, 3 H), 0.915 (t, J = 7.5 Hz, 3 H), 1.43–1.52 (m, 1 H), 1.60–1.83 (m, 3 H), 2.31–2.45 (m, 3 H), 3.70 (ddd, J = 2.5, 1.5, 0.7 Hz, 1 H), 4.21 (s, 5 H), 4.46 (d pseudo t, J = 2.5, 0.6 Hz, 1 H), 4.837 (s, 1 H), 4.841 (s, 1 H), 5.10 (ddd, J = 2.6, 1.6, 1.2 Hz, 1 H), 5.29 (d, J = 6.0 Hz, 1 H), 7.15–7.21 (m, 2 H), 7.22–7.26 (m, 3 H), 7.35–7.39 (m, 3 H), 7.43–7.49 (m, 2 H), 9.68 (pseudo t, J = 1.6 Hz, 1 H) ppm. ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 11.2, 11.6, 22.5 (d, $J_{C,P}$ = 3.8 Hz), 24.3, 36.4, 44.5, 71.0 (5 C), 72.0, 74.5, 75.4 (d, $J_{C,P}$ = 15.4 Hz), 75.6 (d, $J_{C,P}$ = 4.9 Hz), 78.8, 79.2 (d, $J_{C,P}$ = 16.7 Hz), 112.0, 128.1, 128.2 (d, $J_{C,P}$ = 6.7 Hz, 2 C), 128.3 (d, $J_{C,P}$ = 7.3 Hz, 2 C), 129.1, 132.4 (d, $J_{C,P}$ = 19.4 Hz, 2 C), 135.1 (d, $J_{C,P}$ = 21.5 Hz, 2 C), 138.3 (d, $J_{C,P}$ = 13.9 Hz), 139.6 (d, $J_{C,P}$ = 13.3 Hz), 147.7, 170.7 (d, $J_{C,P}$ = 2.7 Hz), 201.7 (CHO) ppm. ^{31}P NMR (121.5 MHz, $CDCl_3$): δ = –17.3 ppm. $C_{33}H_{35}FeO_3P$ (566.5): calcd. C 69.97, H 6.23 found C 69.71, H 6.36. $[\alpha]_D^{20}$ = –103 (c = 0.59, $CHCl_3$, *dr* = 92:8).

(1*R*,2*R*)-3-Methyl-1-(2-methyl-1-methylenepropyl)-2-(2-oxoethyl)butyl (S_p)-2-(diphenylphospanyl)Ferrocenecarboxylate (8c). *rac*-8c: According to GP4, hydroformylation of *rac*-**7c** (186.6 mg, 0.33 mmol) was carried out with [$Rh(CO)_2$acac] (1.5 mg, 5.8 μmol, 0.018 equiv.) and $P(OPh)_3$ (6.2 μL, 0.024 mmol, 0.071 equiv.) in THF (3.4 mL) at 70 °C for 48 h. The NMR spectrum of the crude product showed a conversion of 95% and the resulting aldehydes were obtained in a diastereomeric ratio of >97:3. Flash chromatography (PE/EE, 20:1) gave the product aldehydes *rac*-**8c** (151.9 mg, 0.26 mmol, 77%, *dr* > 97:3) as an orange solid. **(S_p)-8c:** According to GP4, hydroformylation of (S_p)-**7c** (314.7 mg, 0.56 mmol) was carried out with [$Rh(CO)_2$acac] (2.6 mg, 10.1 μmol, 0.018 equiv.) and $P(OPh)_3$ (12.4 μL, 0.047 mmol, 0.085 equiv.) in THF (5.6 mL) at 70 °C for 48 h. The NMR spectrum of the crude product showed a conversion of 95% and the resulting aldehydes were obtained in a diastereomeric ratio of >98:2. Flash chromatography (PE/EE, 20:1) furnished the product aldehydes (S_p)-**8c** (264.2 mg, 0.44 mmol, 80%, *dr* > 98:2) as an orange solid. **Data for 8c:** R_f (Cy/EE, 10:1) = 0.30; m.p. 156 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ

= 0.80 (d, J = 6.9 Hz, 3 H), 0.93 (d, J = 6.5 Hz, 6 H), 1.00 (d, J = 6.8 Hz, 3 H), 1.98–2.06 (m, 1 H), 2.13–2.29 (m, 3 H), 2.41–2.48 (m, 1 H), 3.72 (br. s, 1 H), 4.20 (s, 5 H), 4.45 (pseudo t, J = 2.6 Hz, 1 H), 4.93 (s, 1 H), 4.95 (s, 1 H), 5.06 (br. s, 1 H), 5.36 (d, J = 8.2 Hz, 1 H), 7.17–7.26 (m, 5 H), 7.35–7.38 (m, 3 H), 7.45–7.50 (m, 2 H), 9.54 (t, J = 1.7 Hz, 1 H) ppm. ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 17.2, 22.0, 22.6, 23.0, 26.8 (d, $J_{C,P}$ = 2.9 Hz), 30.6, 40.6, 40.7, 71.1 (5 C), 71.8, 74.0, 75.4 (d, $J_{C,P}$ = 4.4 Hz), 75.5 (d, overlapped), 77.2, 80.0 (d, $J_{C,P}$ = 17.4 Hz), 111.6, 128.1, 128.2 (d, $J_{C,P}$ = 7.3 Hz, 2 C), 128.3 (d, $J_{C,P}$ = 8.7 Hz, 2 C), 129.1, 132.6 (d, $J_{C,P}$ = 18.9 Hz, 2 C), 135.0 (d, $J_{C,P}$ = 21.8 Hz, 2 C), 138.4 (d, $J_{C,P}$ = 14.5 Hz), 139.7 (d, $J_{C,P}$ = 13.1 Hz), 153.3, 170.4 (d, $J_{C,P}$ = 2.9 Hz), 201.8 ppm. ^{31}P NMR (121.5 MHz, $CDCl_3$): δ = –17.4 ppm. $C_{35}H_{39}FeO_3P$ (594.5): calcd. C 70.71, H 6.61; found C 70.56, H 6.67. $[\alpha]_D^{20}$ = –71 (c = 0.55, $CHCl_3$, dr > 98:2).

(1*R*,2*R*)-1-(2,2-Dimethyl-1-methylenepropyl)-3,3-dimethyl-2-(2-oxoethyl)butyl (S_p)-2-(Diphenylphospanyl)ferrocenecarboxylate (8d)

***rac*-8d. Variation 1:** According to GP4, hydroformylation of *rac*-**7d** (295.6 mg, 0.50 mmol) was carried out with [$Rh(CO)_2$acac] (2.3 mg, 8.9 μmol, 0.018 equiv.) and $P(OPh)_3$ (9.4 μL, 0.036 mmol, 0.072 equiv.) in THF (5.0 mL) at 70 °C for 48 h. The NMR spectrum of the crude product showed a conversion of 30% and only one aldehyde could be detected. After flash chromatography (PE/EE, 50:1), starting material (186.7 mg, 0.32 mmol, 63%) could be reisolated; increasing the polarity of the eluent (PE/EE, 5:1) furnished the aldehyde *rac*-**8d** (84.0 mg, 0.13 mmol, 72% based on recovered starting material, dr > 99:1) as an orange solid. **Variation 2:** According to GP4, hydroformylation of *rac*-**7d** (373.7 mg, 0.63 mmol) was carried out with [$Rh(CO)_2$acac] (2.9 mg, 11.2 μmol, 0.018 equiv.) and $P(OPh)_3$ (11.9 μL, 0.045 mmol, 0.072 equiv.) in THF (6.3 mL) at 90 °C for 72 h. The NMR spectrum of the crude product showed a conversion of 61% and only one aldehyde could be detected. After flash chromatography (PE/EE, 50:1), starting material (139.9 mg, 0.24 mmol, 37%) could be reisolated; increasing the polarity of the eluent (PE/EE, 5:1) furnished the aldehyde *rac*-**8d** (210.2 mg, 0.34 mmol, 87% based on recovered starting material, dr > 99:1) as an orange solid.

(S_p)-8d: According to GP4, hydroformylation of (S_p)-**7d** (408.3 mg, 0.69 mmol) was carried out with [$Rh(CO)_2$acac] (3.2 mg, 12.4 μmol, 0.018 equiv.) and $P(OPh)_3$ (13.0 μL, 0.050 mmol, 0.072 equiv.) in THF (7.0 mL) at 90 °C for 72 h. The NMR spectrum of the crude product showed a conversion of 62% and only one aldehyde could be detected. After flash chromatography (PE/EE, 50:1), starting material (120.7 mg, 0.20 mmol, 30%) could be reisolated; increasing the polarity of the eluent (PE/EE, 5:1) then delivered the aldehyde (S_p)-**8d** (251.6 mg, 0.40 mmol, 82% based on recovered starting material, dr > 99:1) as an orange solid.

Data for 8d: R_f (Cy/EE, 5:1) = 0.26; m.p. 160 °C (decomp.). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.95 (s, 9 H), 1.10 (s, 9 H), 2.32 (ddd, J = 18.1, 6.0, 1.7 Hz, 1 H), 2.40 (ddd, J = 18.1, 5.2, 1.3 Hz, 1 H), 2.66 (dt, J = 2.6 Hz, 1 H), 3.67 (br. s, 1 H), 4.19 (s, 5 H), 4.43 (pseudo t, J = 2.6 Hz, 1 H), 4.70 (s, 1 H), 5.01 (s, 1 H), 5.07 (br. s, 1 H), 5.58 (d, J = 7.7 Hz, 1 H), 7.15–7.20 (m, 2 H), 7.21–7.25 (m, 3 H), 7.34–7.39 (m, 3 H), 7.44–7.50 (m, 2 H), 9.54 (pseudo t, J = 1.5 Hz, 1 H) ppm. ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 28.7 (3 C), 30.4 (3 C), 34.4, 36.0, 44.0, 46.6, 70.8 (5 C), 71.6, 73.2, 74.4, 75.2 (d, $J_{C,P}$ = 4.4 Hz), 76.6 (d, $J_{C,P}$ = 14.4 Hz), 79.3 (d, $J_{C,P}$ = 17.4 Hz), 114.6, 128.1, 128.18 (d, $J_{C,P}$ = 5.8 Hz, 2 C), 128.25 (d, $J_{C,P}$ = 5.8 Hz, 2 C), 129.1, 132.6 (d, $J_{C,P}$ = 18.9 Hz, 2 C), 135.1 (d, $J_{C,P}$ = 21.8 Hz, 2 C), 138.5 (d, $J_{C,P}$ = 13.1 Hz), 139.6 (d, $J_{C,P}$ = 13.1 Hz), 157.9, 169.8 (d, $J_{C,P}$ = 2.9 Hz), 202.8 ppm. ^{31}P NMR (121.5 MHz, $CDCl_3$): δ = –18.1 ppm. $C_{37}H_{43}FeO_3P$ (622.6): calcd. C 71.38, H 6.96; found C 71.34, H 6.97. $[\alpha]_D^{20}$ = –50 (c = 0.67, $CHCl_3$, dr > 99:1).

(1*R*,2*R*)-4-Oxo-2-[(trimethylsilyl)methyl]-1-{1-[(trimethylsilyl)methyl]vinyl}butyl (S_p)-2-(Diphenylphosphanyl)ferrocenecarboxylate (8e). *rac*-8e: According to GP4, hydroformylation of *rac*-**7e** (254.9 mg, 0.39 mmol) was carried out with [$Rh(CO)_2$acac] (1.8 mg, 7.0 μmol, 0.018 equiv.) and $P(OPh)_3$ (7.4 μL, 0.028 mmol, 0.072 equiv.) in THF (4.0 mL) at 60 °C for 96 h. The NMR spectrum of the crude product showed a conversion of 70% and only one aldehyde could be detected. After flash chromatography (PE/EE, 50:1, stationary phase neutral Al_2O_3 deactivated with 10% water), starting material (71.5 mg, 0.11 mmol, 28%) could be reisolated; increasing the polarity of the eluent (PE/EE, 20:1) furnished the aldehyde *rac*-**8e** (130.8 mg, 0.19 mmol, 68% based on recovered starting material, dr > 99:1) as an orange solid. **(S_p)-8e:** According to GP4, hydroformylation of (S_p)-**7e** (330.6 mg, 0.51 mmol) was carried out with [$Rh(CO)_2$acac] (2.4 mg, 9.3 μmol, 0.018 equiv.) and $P(OPh)_3$ (9.6 μL, 0.037 mmol, 0.072 equiv.) in THF (5.1 mL) at 60 °C for 96 h. The NMR spectrum of the crude product showed a conversion of 56% and only one aldehyde could be detected. After flash chromatography (PE/EE, 50:1, stationary phase neutral Al_2O_3 deactivated with 10% water), starting material (142.5 mg, 0.22 mmol, 43%) could be reisolated; increasing the polarity of the eluent (PE/EE, 20:1) furnished the aldehyde (S_p)-**8e** (141.1 mg, 0.21 mmol, 71% based on recovered starting material, dr > 99:1) as an orange solid. **Data for 8e:** R_f (Cy/EE, 10:1) = 0.35; m.p. 122 °C. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.01 (s, 9 H), 0.06 (s, 9 H), 0.57 (ddd, J = 15.2, 11.2, 1.1 Hz, 1 H), 0.70 (dd, J = 15.2, 2.3 Hz, 1 H), 1.31 (d, J = 14.1 Hz, 1 H), 1.46 (d, J = 14.1 Hz, 1 H), 2.37 (dd, J = 17.5, 3.5 Hz, 1 H), 2.45–2.52 (m, 1 H), 2.64 (ddd, J = 17.5, 9.5, 1.5 Hz, 1 H), 3.69 (ddd, J = 2.5, 1.5, 0.8 Hz, 1 H), 4.22 (s, 5 H), 4.36 (s, 1 H), 4.46 (d pseudo t, 1 H, J = 2.5, 0.5 Hz), 4.51 (s, 1 H), 5.15 (pseudo quint, J = 1.4 Hz, 1 H), 5.25 (s, 1 H), 7.14–7.19 (m, 2 H), 7.22–7.25 (m, 3 H), 7.36–7.40 (m, 3 H), 7.45–7.50 (m, 2 H), 9.64 (d, J = 0.9 Hz, 1 H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ = –1.14 (3C), –0.79 (3C), 15.0 (d, $J_{C,P}$ = 4.2 Hz), 23.7, 30.5, 47.7 (d, $J_{C,P}$ = 2.4 Hz), 71.1 (5 C), 72.0, 74.8, 75.5 (d, $J_{C,P}$ = 4.5 Hz), 75.7 (d, $J_{C,P}$ = 15.7 Hz), 78.5, 79.1 (d, $J_{C,P}$ = 16.4 Hz), 108.8, 128.12, 128.14 (d, $J_{C,P}$ = 6.7 Hz, 2 C), 128.3 (d, $J_{C,P}$ = 7.3 Hz, 2 C), 129.1, 132.6 (d, $J_{C,P}$ = 18.8 Hz, 2 C), 135.1 (d, $J_{C,P}$ = 21.3 Hz, 2 C), 138.4 (d, $J_{C,P}$ = 13.6 Hz), 139.5 (d, $J_{C,P}$ = 13.3 Hz), 143.6, 170.6 (d, $J_{C,P}$ = 2.7 Hz), 201.7 ppm. ^{31}P NMR (121.5 MHz, $CDCl_3$): δ = –16.8 ppm. $C_{37}H_{47}FeO_3PSi_2$ (682.8): calcd. C 65.09, H 6.94; found C 65.13, H 6.93. $[\alpha]_D^{20}$ = –83 (c = 0.83, $CHCl_3$, dr > 99:1).

Determination of Enantiomeric Purity of Hydroformylation Products

General Procedure 5 (GP5). $NaBH_4$ Reduction of Aldehydes 7: $NaBH_4$ (1.1–1.3 equiv.) was added to a suspension of aldehyde **7** in methanol. After stirring at 25 °C for the indicated period of time, the reaction was quenched with water (4 equiv.), all volatile components were removed in vacuo, and the residue was purified by flash chromatography to furnish the alcohol **9**.

(1*R*,2*S*)-4-Hydroxy-1-isopropenyl-2-methylbutyl (S_p)-2-(Diphenylphosphanyl)ferrocenecarboxylate (9a). *rac*-9a: The aldehyde *rac*-**8a** (99.0 mg, 0.184 mmol, dr 84:16) in methanol (5 mL) was treated with $NaBH_4$ (7.6 mg, 0.201 mmol, 1.1 equiv.) for 35 min as described in GP5. Flash chromatography (Cy/EE, 2:1) furnished the title compound *rac*-**9a** (94.4 mg, 0.175 mmol, 95%, dr 84:16) as an orange oil, which crystallized upon standing at 4 °C. **(S_p)-9a:** The aldehyde (S_p)-**8a** (46.6 mg, 0.087 mmol, dr 88:12) in methanol (3 mL) was treated with $NaBH_4$ (4.3 mg, 0.114 mmol, 1.3 equiv.)

for 30 min as described in GP5. Flash chromatography (Cy/EE, 2:1) furnished the title compound (S_p)-**9a** (35.6 mg, 0.066 mmol, 76%, *dr* 88:12, *ee* > 99%) as an orange oil, which crystallized upon standing at 4 °C. **Data for 9a:** R_f (Cy/EE, 5:1) = 0.08; m.p. 75 °C. ^{1}H NMR (500 MHz, C_6D_6): δ = 1.10 (d, J = 6.8 Hz, 3 H), 1.33–1.41 (m, 1 H), 1.41 (s, 3 H), 1.63–1.70 (m, 1 H), 2.00–2.08 (m, 1 H), 3.44 (dt, J = 10.3, 6.8 Hz, 1 H), 3.51 (dt, J = 10.3, 6.8 Hz, 1 H), 3.64 (ddd, J = 2.5, 1.5, 0.9 Hz, 1 H), 4.06 (dt, J = 2.5 Hz, 1 H), 4.15 (s, 5 H), 4.73 (s, 1 H), 4.76 (s, 1 H), 5.18 (ddd, J = 2.5, 1.5, 1.1 Hz, 1 H), 5.46 (d, J = 6.0 Hz, 1 H), 6.97–7.03 (m, 3 H), 7.05–7.10 (m, 3 H), 7.26–7.33 (m, 2 H), 7.50–7.57 (m, 2 H, Ar-H) ppm; OH signal not detected. ^{13}C NMR (125 MHz, C_6D_6): δ = 15.1 (d, $J_{C,P}$ = 4.8 Hz), 18.9, 31.5, 36.3, 60.4, 71.3 (5 C), 72.0, 75.3, 75.7 (d, $J_{C,P}$ = 4.8 Hz), 76.8 (d, $J_{C,P}$ = 16.0 Hz), 79.2 (d, $J_{C,P}$ = 17.3 Hz), 80.5, 113.2, 128.2, 128.3 (d, $J_{C,P}$ = 7.0 Hz, 2 C), 128.4 (d, $J_{C,P}$ = 6.3 Hz, 2 C), 129.1, 132.8 (d, $J_{C,P}$ = 18.9 Hz, 2 C), 135.5 (d, $J_{C,P}$ = 21.8 Hz, 2 C), 139.2 (d, $J_{C,P}$ = 14.8 Hz), 140.4 (d, $J_{C,P}$ = 14.5 Hz), 142.9, 170.4 (d, $J_{C,P}$ = 2.7 Hz) ppm. ^{31}P NMR (121.5 MHz, C_6D_6): δ = –17.3 ppm. $C_{31}H_{33}FeO_3P$ (540.4): calcd. C 68.90, H 6.16; found C 68.95, H 6.36. HPLC [AD, heptane/2-propanol (95:5), 25 °C, 1 mL/min]: t_R[(S_p,3*S*,4*R*)-**9a**] = 27.35 min; t_R[(R_p,3*R*,4*S*)-**9a**] = 31.21 min. $[\alpha]_D^{20}$ = –106 (c = 0.25, $CHCl_3$, *dr* = 88:12).

(1*R*,2*S*)-2-Ethyl-4-hydroxy-1-(1-methylenepropyl)butyl (S_p)-2-(Diphenylphosphanyl)ferrocenecarboxylate (9b). *rac*-9b: The aldehyde *rac*-**8b** (62.4 mg, 0.110 mmol, *dr* 93:7) in methanol (4 mL) was treated with $NaBH_4$ (4.4 mg, 0.116 mmol, 1.1 equiv.) for 35 min as described in GP5. Flash chromatography (Cy/EE, 2:1) furnished the title compound *rac*-**9b** (54.2 mg, 0.095 mmol, 87%, *dr* 93:7) as an orange solid. **(S_p)-9b:** The aldehyde (S_p)-**8b** (168 mg, 0.295 mmol, *dr* 92:8) in methanol (10 mL) was treated with $NaBH_4$ (12.3 mg, 0.325 mmol, 1.1 equiv.) for 90 min as described in GP5. Flash chromatography (Cy/EE, 2:1) furnished the title compound (S_p)-**9b** (143 mg, 0.252 mmol, 85%, *dr* 92:8, *ee* > 99%) as an orange solid. **Data for 9b:** R_f (Cy/EE, 5:1) = 0.08; m.p. 111 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.92 (t, J = 7.7 Hz, 3 H), 0.94 (t, J = 7.3 Hz, 3 H), 1.30 (t, J = 5.2 Hz, 1 H), 1.45–1.60 (m, 4 H), 1.68–1.88 (m, 3 H), 3.64 (m_c, 2 H), 3.69 (br. s, 1 H), 4.21 (s, 5 H), 4.44 (pseudo t, J = 2.6 Hz, 1 H), 4.81 (br. s, 2 H), 5.11 (br. s, 1 H), 5.37 (d, J = 6.0 Hz, 1 H), 7.15–7.20 (m, 2 H), 7.21–7.26 (m, 3 H), 7.34–7.39 (m, 3 H), 7.43–7.50 (m, 2 H) ppm. ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 11.2, 11.8, 21.7 (d, $J_{C,P}$ = 2.9 Hz), 24.6, 32.4, 37.8, 61.0, 71.0 (5 C), 71.8, 74.4, 75.4 (d, $J_{C,P}$ = 4.4 Hz), 75.8 (d, $J_{C,P}$ = 15.9 Hz), 78.4, 79.3 (d, $J_{C,P}$ = 17.4 Hz), 110.9, 128.1, 128.2 (d, $J_{C,P}$ = 7.3 Hz, 2 C), 128.3 (d, $J_{C,P}$ = 7.3 Hz, 2 C), 129.1, 132.5 (d, $J_{C,P}$ = 18.9 Hz, 2 C), 135.1 (d, $J_{C,P}$ = 21.8 Hz, 2 C), 138.4 (d, $J_{C,P}$ = 13.1 Hz), 139.6 (d, $J_{C,P}$ = 13.1 Hz), 148.2, 170.8 (d, $J_{C,P}$ = 2.9 Hz) ppm. ^{31}P NMR (121.5 MHz, $CDCl_3$): δ = –17.3 ppm. $C_{33}H_{37}FeO_3P$ (568.5): calcd. C 69.72, H 6.56; found C 69.41, H 6.76; HPLC [OD-H, heptane/2-propanol (98:2), 25 °C, 0.8 mL/min]: t_R[(S_p,3*S*,4*R*)-**9b**] = 22.30 min; t_R[(R_p,3*R*,4*S*)-**9b**] = 25.31 min. $[\alpha]_D^{20}$ = –81 (c = 0.44, $CHCl_3$, *dr* = 92:8).

(1*R*,2*R*)-2-(2-Hydroxyethyl)-3-methyl-1-(2-methyl-1-methylenepropyl)butyl (S_p)-2-(Diphenylphosphanyl)ferrocenecarboxylate (9c). *rac*-9c: The aldehyde *rac*-**8c** (47.8 mg, 0.080 mmol, *dr* > 98:2) in methanol (3 mL) was treated with $NaBH_4$ (3.3 mg, 0.087 mmol, 1.1 equiv.) for 40 min as described in GP5. Flash chromatography (Cy/EE, 2:1) furnished the title compound *rac*-**9c** (45.9 mg, 0.077 mmol, 96%, *dr* > 98:2) as an orange solid. **(S_p)-9c:** The aldehyde (S_p)-**8c** (94.8 mg, 0.159 mmol, *dr* > 98:2) in methanol (6 mL) was treated with $NaBH_4$ (7.0 mg, 0.185 mmol, 1.2 equiv.) for 40 min as described in GP5. Flash chromatography (Cy/EE, 2:1) furnished the title compound (S_p)-**9c** (81.4 mg, 0.136 mmol, 86%, *dr* > 98:2, *ee* > 99%) as an orange solid. **Data for 9c:** R_f (Cy/EE, 5:1): 0.13; m.p. 71 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.87 (d, J = 6.9 Hz, 3 H), 0.91 (d, J = 7.0 Hz, 3 H), 1.04 (d, J = 6.9 Hz, 3 H), 1.07 (d, J = 6.9 Hz, 3 H), 1.08–1.27 (m, 2 H), 1.41–1.58 (m_c, 1 H), 1.68–1.77 (m_c, 1 H), 2.03–2.15 (m, 2 H), 3.42–3.53 (m, 2 H), 3.73 (ddd, J = 2.5, 1.5, 0.9 Hz, 1 H), 4.22 (s, 5 H), 4.43 (d pseudo t, 1 H, J = 2.5, 0.4 Hz), 4.99 (d, J = 0.7 Hz, 1 H), 5.04 (ddd, J = 2.5, 1.5, 1.0 Hz, 1 H), 5.06 (t, J = 1.3 Hz, 1 H), 5.54 (d, J = 5.3 Hz, 1 H), 7.17–7.26 (m, 5 H), 7.34–7.39 (m, 3 H), 7.44–7.51 (m, 2 H) ppm. ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 17.8, 22.2, 22.4, 23.3, 26.6, 28.2, 30.8, 41.9, 61.8, 71.0 (5 C), 71.7, 73.3, 75.2 (d, $J_{C,P}$ = 4.4 Hz), 75.5 (d, $J_{C,P}$ = 13.1 Hz), 76.3, 80.6 (d, $J_{C,P}$ = 17.4 Hz), 108.8, 128.06, 128.13 (d, $J_{C,P}$ = 7.3 Hz, 2 C), 128.3 (d, $J_{C,P}$ = 7.3 Hz, 2 C), 129.1, 132.6 (d, $J_{C,P}$ = 18.9 Hz, 2 C), 135.0 (d, $J_{C,P}$ = 21.8 Hz, 2 C), 138.4 (d, $J_{C,P}$ = 13.1 Hz), 139.7 (d, $J_{C,P}$ = 13.1 Hz), 154.2, 170.5 (d, $J_{C,P}$ = 2.9 Hz) ppm ^{31}P NMR (121.5 MHz, $CDCl_3$): δ = –17.2 ppm. $C_{35}H_{41}FeO_3P$ (596.5): calcd. C 70.47, H 6.93; found C 70.55, H 7.13; HPLC [AD, heptane/2-propanol (96:4), 20 °C, 1 mL/min]: t_R[(S_p,3*R*,4*R*)-**9c**] = 16.69 min; t_R[(R_p,3*S*,4*S*)-**9c**] = 18.69 min. $[\alpha]_D^{20}$ = –51 (c = 0.52, $CHCl_3$, *dr* > 98:2).

(1*R*,2*R*)-1-(2,2-Dimethyl-1-methylenepropyl)-2-(2-hydroxyethyl)-3,3-dimethylbutyl (S_p)-2-(Diphenylphosphanyl)ferrocenecarboxylate (9d). *rac*-9d: The aldehyde *rac*-**8d** (100.0 mg, 0.161 mmol) in methanol (5 mL) and THF (2 mL) was treated with $NaBH_4$ (6.7 mg, 0.177 mmol, 1.1 equiv.) for 80 min as described in GP5. Flash chromatography (PE/EE, 5:1) furnished the title compound *rac*-**9d** (88.7 mg, 0.142 mmol, 88%, *dr* > 99:1) as an orange solid. **(S_p)-9d:** The aldehyde (S_p)-**8d** (107.3 mg, 0.172 mmol, *dr* > 99:1) in methanol (5 mL) was treated with $NaBH_4$ (7.1 mg, 0.188 mmol, 1.1 equiv.) for 40 min as described in GP5. Flash chromatography (PE/EE, 5:1) furnished the title compound (S_p)-**9d** (98.5 mg, 0.158 mmol, 92%, *dr* > 99:1, *ee* > 99%) as an orange solid. **Data for 9d:** R_f (Cy/EE, 5:1) = 0.14; m.p. 148 °C (decomp.). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.99 (s, 9 H), 1.11 (s, 9 H), 1.32 (t, J = 5.6 Hz, 1 H), 1.36–1.46 (m, 1 H), 1.53–1.67 (m, 2 H), 3.44–3.51 (dt, J = 7.5, 5.6 Hz, 2 H), 3.66 (br. s, 1 H), 4.21 (s, 5 H), 4.42 (pseudo t, J = 2.6 Hz, 1 H), 4.74 (s, 1 H), 5.00 (s, 1 H), 5.07 (quint, J = 1.3 Hz, 1 H), 5.59 (d, J = 6.4 Hz, 1 H), 7.15–7.20 (m, 2 H), 7.22–7.26 (m, 3 H), 7.34–7.38 (m, 3 H), 7.43–7.49 (m, 2 H) ppm. ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 28.9 (3 C), 30.8 (3 C), 31.7, 34.8, 36.0, 48.4, 64.0, 70.8 (5 C), 71.5, 73.8, 74.4, 75.1 (d, $J_{C,P}$ = 4.4 Hz), 76.9, 79.1 (d, $J_{C,P}$ = 16.0 Hz), 113.0, 128.08, 128.17 (d, $J_{C,P}$ = 5.8 Hz, 2 C), 128.24 (d, $J_{C,P}$ = 6.6 Hz, 2 C), 129.1, 132.6 (d, $J_{C,P}$ = 18.9 Hz, 2 C), 135.1 (d, $J_{C,P}$ = 21.8 Hz, 2 C), 138.4 (d, $J_{C,P}$ = 13.1 Hz), 139.5 (d, $J_{C,P}$ = 13.1 Hz), 157.8, 170.0 (d, $J_{C,P}$ = 2.9 Hz) ppm ^{31}P NMR (121 MHz, $CDCl_3$): δ = –17.2 ppm. $C_{37}H_{45}FeO_3P$ (624.6): calcd. C 71.15, H 7.26; found C 70.95, H 7.35; HPLC [AD, heptane/2-propanol (95:5), 20 °C, 0.8 mL/min]: t_R[(R_p,3*S*,4*S*)-**9d**] = 11.33 min; t_R[(S_p,3*R*,4*R*)-**9d**] = 12.89 min. $[\alpha]_D^{20}$ = –65 (c = 0.725, $CHCl_3$, *dr* > 99:1).

(1*R*,2*R*)-4-Hydroxy-2-[(trimethylsilyl)methyl]-1-{1-[(trimethylsilyl)methyl]vinyl}butyl (S_p)-2-(Diphenylphosphanyl)ferrocenecarboxylate (9e). *rac*-9e: The aldehyde *rac*-**8e** (115.1 mg, 0.169 mmol, *dr* > 99:1) in methanol (6 mL) was treated with $NaBH_4$ (6.9 mg, 0.182 mmol, 1.1 equiv.) for 60 min as described in GP5. Flash chromatography (PE/EE, 5:1) furnished the title compound *rac*-**9e** (103.0 mg, 0.150 mmol, 89%, *dr* > 99:1) as an orange solid. **(S_p)-9e:** The aldehyde (S_p)-**8e** (85.6 mg, 0.125 mmol, *dr* > 99:1) in methanol (5 mL) was treated with $NaBH_4$ (5.5 mg, 0.145 mmol, 1.2 equiv.) for 60 min as described in GP5. Flash chromatography (PE/EE, 5:1) furnished the title compound (S_p)-**9e** (83.5 mg, 0.122 mmol, 97%, *dr* > 99:1, *ee* > 99%) as an orange solid. **Data for 9e:** R_f (Cy/EE,

10:1) = 0.14; m.p. 130 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.02 (s, 9 H), 0.07 (s, 9 H), 0.59 (dd, J = 15.5, 11.6 Hz, 1 H), 0.68 (dd, J = 15.5, 2.4 Hz, 1 H), 1.20 (t, J = 5.2 Hz, 1 H), 1.23 (d, J = 14.2 Hz, 1 H), 1.47 (d, J = 14.2 Hz, 1 H), 1.55–1.72 (m, 2 H), 1.95–2.04 (m, 1 H), 3.58–3.67 (m, 2 H), 3.69 (br. s, 1 H), 4.22 (s, 5 H), 4.35 (br. s, 1 H), 4.46 (pseudo t, J = 2.5 Hz, 1 H), 4.49 (br. s, 1 H), 5.16 (pseudo quint, J = 1.3 Hz, 1 H), 5.39 (s, 1 H), 7.14–7.19 (m, 2 H), 7.21–7.25 (m, 3 H), 7.35–7.39 (m, 3 H), 7.44–7.50 (m, 2 H) ppm. ^{13}C NMR (100.6 MHz, $CDCl_3$): δ = –1.0 (3 C), –0.7 (3 C), 15.6 (d, $J_{C,P}$ = 4.4 Hz), 24.0, 32.5, 36.2, 60.9, 71.1 (5 C), 71.9, 74.7, 75.4 (d, $J_{C,P}$ = 4.4 Hz), 75.8 (d, $J_{C,P}$ = 14.5 Hz), 77.4, 79.4 (d, $J_{C,P}$ = 16.0 Hz), 108.3, 128.11, 128.15 (d, $J_{C,P}$ = 7.2 Hz, 2 C), 128.3 (d, $J_{C,P}$ = 7.3 Hz, 2 C), 129.1, 132.7 (d, $J_{C,P}$ = 18.9 Hz, 2 C), 135.1 (d, $J_{C,P}$ = 20.3 Hz, 2 C), 138.5 (d, $J_{C,P}$ = 13.1 Hz), 139.6 (d, $J_{C,P}$ = 12.9 Hz), 144.1, 170.8 (d, $J_{C,P}$ = 2.9 Hz) ppm. ^{31}P NMR (121.5 MHz, $CDCl_3$): δ = –16.8 ppm. $C_{37}H_{49}FeO_3PSi_2$ (684.8): calcd. C 64.90, H 7.21; found C 64.94, H 7.16; HPLC [OD-H, hexane/2-propanol (150:1), 20 °C, 0.8 mL/min]: t_R[(S_p,3*S*,4*R*)-**9e**] = 16.26 min; t_R[(R_p,3*R*,4*S*)-**9e**] = 18.61 min. $[\alpha]_D^{20}$ = –82 (c = 0.825, $CHCl_3$, *dr* > 99:1).

Cleavage and Recovery of the Catalyst-Directing Group

General Procedure 6 (GP6). Aldehyde Protection and Alkaline Ester Hydrolysis: The aldehyde **7** was suspended in methanol (10 mL/mmol), trimethyl orthoformate (5 equiv.) and *para*-toluenesulfonic acid monohydrate (0.05 equiv.) were added and the mixture was heated to reflux for 2 h. After cooling to 25 °C, all volatile components were removed in vacuo (0.1 mbar). Saturated KOH/EtOH (10 mL/mmol, degassed) was added to the resulting red-brown solid residue. This mixture was heated to reflux for several hours. After cooling to room temp., satd. aqueous $NaHCO_3$ solution (30 mL/mmol) and Et_2O (30 mL/mmol) were added and the mixture was stirred until a brown solid precipitated. The solid material was collected by filtration and washed several times with water and Et_2O. Subsequently, the solid was suspended in 1 N HCl (20 mL/mmol) and CH_2Cl_2 (20 mL/mmol) and the mixture was stirred until the solid had completely dissolved in the organic layer. The aqueous phase was separated and extracted with CH_2Cl_2 (10 mL/mmol). The combined organic layers were dried (Na_2SO_4) and the solvent was removed in vacuo (argon-purged rotary evaporator) to give *o*-DPPFA (**6**) as an orange-brown solid (partially oxidized). The aqueous layer of the filtrate obtained above was extracted three times with Et_2O (10 mL/mmol each), the combined organic layers were dried (Na_2SO_4), and the solvent was removed in vacuo. Flash chromatography of the residue furnished the pure dimethyl acetal **10**.

(3*S*,4*R*)-6,6-Dimethoxy-2,4-dimethylhexen-3-ol (10a). *rac*-10a: The aldehyde *rac*-**7a** (795 mg, 1.48 mmol, *dr* 88:12) in methanol (15 mL) was treated with trimethyl orthoformate (0.81 mL, 7.40 mmol, 5.0 equiv.) and *p*-toluenesulfonic acid monohydrate (14.0 mg, 0.07 mmol, 0.05 equiv.) and heated to reflux for 2 h as described in GP6. After evaporation of all volatile material, satd. KOH/EtOH (15 mL, degassed) was added and the mixture was heated to reflux for 5 h. After workup, *rac*-*o*-DPPFA (449 mg, 1.08 mmol, 74%) was recovered as an orange-brown solid (partially oxidized) and the acetal **10a** (256 mg, 1.36 mmol, 92%, *dr* 88:12) was obtained after flash chromatography (pentane/Et_2O, 3:1) as a slightly yellow liquid. **(3*S*,4*R*)-10a:** The aldehyde (S_p)-**7a** (103.0 mg, 0.191 mmol, *dr* 95:5) in methanol (2 mL) was treated with trimethyl orthoformate (0.11 mL, 1.005 mmol, 5.3 equiv.) and *p*-toluenesulfonic acid monohydrate (1.8 mg, 0.009 mmol, 0.05 equiv.) and heated to reflux for 2 h as described in GP6. After evaporation of all volatile material, satd. KOH/EtOH (2 mL, degassed) was added and the mixture was refluxed for 3.5 h. After workup and flash chromatography (pentane/Et_2O, 3:1), the acetal **10a** (30.0 mg, 0.159 mmol, 83%, *dr* 95:5) was obtained as a slightly yellow liquid. **Data for 10a:** R_f (pentane/Et_2O, 3:1) = 0.09. ^{1}H NMR (400 MHz, C_6D_6): δ = 0.94 (d, J = 6.5 Hz, 3 H), 1.45–1.56 (m, 1 H), 1.58 (s, 3 H), 1.79–1.90 (m, 2 H), 3.11 (s, 3 H), 3.12 (s, 3 H), 3.74 (d, J = 4.3 Hz, 1 H), 4.43 (dd, J = 6.4, 4.7 Hz, 1 H), 4.83 (s, 1 H), 4.99 (s, 1 H) ppm; OH signal not detected. ^{13}C NMR (100.6 MHz, C_6D_6): δ = 14.0, 18.7, 32.3, 36.8, 52.1, 52.4, 78.3, 103.5, 111.1, 146.9 ppm. HRMS (EI; $C_{10}H_{20}O_3$, 188.3): calcd. for [M – MeOH] 156.1151; found 156.1150. $[\alpha]_D^{20}$ = –6.5 (c = 1.10, CH_2Cl_2, *dr* 95:5).

DIBAL Reduction of *o*-DPPF Ester 8a

(3*R*,4*S*)-3,5-Dimethyl-5-hexene-1,4-diol (11a). *rac*-11a: DIBAL (1.4 mL, 1 M in cyclohexane, 1.40 mmol, 3.7 equiv.) was added dropwise, at –78 °C, to a solution of *o*-DPPF ester *rac*-**8a** (202.4 mL, 0.38 mmol, *dr* 87:13) in CH_2Cl_2 (4 mL). After stirring for 2.5 h at this temperature, the solution was allowed to warm to 25 °C and saturated aqueous NH_4Cl (4 mL) and aqueous HCl (1 M, 5 mL) were added. The aqueous phase was extracted with CH_2Cl_2 (4 × 8 mL), the combined organic phases were dried (Na_2SO_4), and the solvent was removed in vacuo. Flash chromatography (PE/MTBE, 1:5) furnished *rac*-**11a** (27.9 mg, 0.19 mmol, 51%, *dr* 97:3) as a colorless liquid. **(3*R*,4*S*)-11a:** The aldehyde (R_p)-**8a** (130.0 mg, 0.24 mmol, *dr* 95:5) in CH_2Cl_2 (4 mL) was treated with DIBAL (0.85 mL, 1 M in cyclohexane, 0.85 mmol, 3.5 equiv.) as described above for the racemate. Flash chromatography (PE/MTBE, 1:2) furnished (3*R*,4*S*)-**11a** (23.6 mg, 0.14 mmol, 68%, *dr* 97:3, *ee* > 99%) as a colorless liquid. **Data for 11a:** R_f (PE/MTBE, 1:5) = 0.16. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.88 (d, J = 6.8 Hz, 3 H), 1.51 (m_c, 1 H), 1.71 (s, 3 H), 1.67–1.74 (m, 1 H), 1.87 (m_c, 1 H), 2.01 (br. s, 2 H), 3.64–3.71 (m, 1 H), 3.73–3.81 (m, 1 H), 3.96 (d, J = 4.6 Hz, 1 H), 4.91 (s, 1 H), 4.97 (s, 1 H ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ = 13.2, 19.0, 32.8, 36.7, 60.7, 78.7, 111.3, 146.5 ppm. HRMS (EI; $C_8H_{16}O_2$, 144.2) calcd. for [M – OH] 126.1043; found 126.1045. GC (Supelco BetaDex 110, 120° isotherm, 18 psi): t_R[(3*S*,4*R*)-**11a**] = 23.7 min; t_R[(3*R*,4*S*)-**11a**] = 25.9 min. $[\alpha]_D^{20}$ = +2.3 (c = 1.05, $CHCl_3$, *dr* 97:3).

Determination of Relative and Absolute Configuration of Product Aldehydes 8

(3*S,4*S**)-1,1-Dimethoxy-3,5-dimethylhexan-4-ol (*rac*-12a):** PtO_2 (36.9 mg, ca. 80%, 0.130 mmol, 0.12 equiv.) was added to the allylic alcohol *rac*-**10a** (204.3 mg, 1.085 mmol, *dr* 88:12) in methanol (11 mL). Then, a balloon of hydrogen (1 bar) was connected and the mixture was stirred for 2.5 h at 25 °C. The solids were removed by filtration through Celite; after washing with methanol, removal of the solvent, and flash chromatography (pentane/Et_2O, 3:1), *rac*-**12a** (181.1 mg, 0.952 mmol, 88%, *dr* 88:12) was obtained as a colorless liquid. **Data for *rac*-12a:** R_f (pentane/Et_2O, 3:1) = 0.06. ^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.87 (d, J = 6.8 Hz, 3 H), 0.89 (d, J = 6.8 Hz, 3 H), 0.99 (d, J = 6.6 Hz, 3 H), 1.56 (ddd, J = 14.0, 7.4, 4.8 Hz, 1 H), 1.65–1.76 (m, 3 H), 1.85 (m_c, 1 H), 3.32 (s, 3 H), 3.33 (s, 3 H), 4.47 (dd, J = 6.6, 4.9 Hz, 1 H) ppm; OH signal not detected. ^{13}C NMR (125 MHz, $CDCl_3$): δ = 12.7, 19.23, 19.27, 30.9, 31.5, 37.1, 52.4, 53.0, 79.8, 103.3 ppm.

(4*S,5*S**)-5-Isopropyl-4-methyldihydrofuran-2-one (*rac*-13a):** Aqueous HCl (3 M, 3 mL) was added, at room temperature, to a solution of dimethylacetal *rac*-**12a** (42.5 mg, 0.223 mmol, *dr* 88:12) in THF (3 mL) and stirred for 24 h. Subsequently, satd. aqueous $NaHCO_3$ (6 mL) and Et_2O (10 mL) were added. The aqueous phase was extracted with Et_2O (2 × 15 mL), the combined organic layers were dried ($MgSO_4$), and the solvents were removed in vacuo. Without further purification, the crude product was dissolved in CH_2Cl_2

(3 mL), PCC on Al_2O_3 (451.0 mg, 1 mmol PCC/g, 0.451 mmol, 2.0 equiv.) and NaOAc (12.4 mg, 0.151 mmol, 0.7 equiv.) were added, and the mixture was stirred at 25 °C for 21 h. After removal of the solids by filtration through silica gel, washing with Et_2O, removal of the solvents, and flash chromatography (pentane/Et_2O, 5:1) gave *rac*-**13a** (23.0 mg, 0.162 mmol, 73%, *dr* 88:12) as a colorless oil. **Data for *rac*-13a:** R_f (pentane/Et_2O, 5:1) = 0.09. ^1H NMR (500 MHz, $CDCl_3$): δ = 0.89 (d, J = 6.6 Hz, 3 H), 0.99 (d, J = 6.9 Hz, 3 H), 1.07 (d, J = 6.5 Hz, 3 H), 1.88 (dsept, J = 10.2, 6.6 Hz, 1 H), 2.19 (dd, J = 16.9, 1.1 Hz, 1 H), 2.54 (m_c, 1 H), 2.72 (dd, J = 16.9, 7.4 Hz, 1 H), 3.93 (dd, J = 10.2, 4.8 Hz, 1 H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ = 13.5, 17.8, 20.2, 28.2, 32.3, 39.0, 89.1, 177.0 ppm. HRMS (EI; $C_8H_{14}O_2$, 142.2): calcd. 142.0995; found 142.0994.

Determination of Absolute Configuration of (–)-10a. Preparation of (*R*) Mosher Ester: (+)-(*R*)-α-Methoxy-α-(trifluoromethyl)phenylacetic acid (16.0 mg, 0.068 mmol, 1.2 equiv.), DCC (15.1 mg, 0.073 mmol, 1.25 equiv.), and DMAP (7.1 mg, 0.058 mmol, 1.0 equiv.) were added to a solution of (3*S*,4*R*)-**10a** (11.0 mg, 0.058 mmol) in CH_2Cl_2 (2.4 mL and the mixture was stirred at 25 °C for 48 h. After removal of the solvent and flash chromatography (pentane/Et_2O, 3:1), the (*R*) Mosher ester (3.9 mg, 0.010 mmol, 17%) was obtained as a colorless liquid. R_f (pentane/Et_2O, 3:1) = 0.30. ^1H NMR (400 MHz, $CDCl_3$): δ = 0.84 (d, J = 6.5 Hz, 3 H), 1.31 (ddd, J = 13.8, 9.5, 4.7 Hz, 1 H), 1.63 (ddd, J = 13.8, 7.3, 4.7 Hz, 1 H), 1.73 (s, 3 H), 1.97 (m_c, 1 H), 3.29 (s, 3 H), 3.30 (s, 3 H), 3.53 (d, J = 0.9 Hz, 3 H), 4.42 (dd, J = 7.3, 4.4 Hz, 1 H), 4.98 (s, 1 H), 5.01 (pseudo t, J = 1.3 Hz, 1 H), 5.24 (d, J = 6.9 Hz, 1 H), 7.35–7.44 (m, 3 H, Ar-H), 7.49–7.54 (m, 2 H, Ar-H) ppm. **Preparation of (*S*) Mosher Ester:** (–)-(*S*)-α-Methoxy-α-(trifluoromethyl)phenylacetic acid (17.6 mg, 0.075 mmol, 1.3 equiv.), DCC (15.1 mg, 0.073 mmol, 1.25 equiv.) and DMAP (7.1 mg, 0.058 mmol, 1.0 equiv.) were added to a solution of (3*S*,4*R*)-**10a** (11.0 mg, 0.058 mmol) in CH_2Cl_2 (2.4 mL) and the mixture was stirred at 25 °C for 48 h. After removal of the solvent and flash chromtaography (pentane/Et_2O, 3:1), the (*S*) Mosher ester (4.0 mg, 0.010 mmol, 17%) was obtained as a colorless liquid. R_f (pentane/Et_2O, 3:1) = 0.42. ^1H NMR (400 MHz, $CDCl_3$): δ = 0.94 (d, J = 6.5 Hz, 3 H), 1.36 (ddd, J = 13.7, 9.0, 4.7 Hz, 1 H), 1.63 (s, 3 H), 1.67 (ddd, J = 13.7, 7.3, 4.7 Hz, 1 H), 2.00 (m_c, 1 H), 3.30 (s, 3 H), 3.31 (s, 3 H), 3.55 (d, J = 1.3 Hz, 3 H), 4.44 (dd, J = 7.3, 4.7 Hz, 1 H), 4.88 (s, 1 H), 4.96 (s, 1 H), 5.18 (d, J = 6.5 Hz, 1 H), 7.37–7.43 (m, 3 H, Ar-H), 7.50–7.54 (m, 2 H, Ar-H) ppm.

Crystal Structure Analysis of *rac*-7a: $C_{30}H_{29}FeO_2P$, M_r = 508.35, monoclinic, space group: $P2_1/n$, a = 9.4923(2), b = 20.3927(6), c = 13.2997(3) Å, β = 103.6766(15)°, V = 2501.47(11) Å^3, $\rho_{calcd.}$ = 1.350 g cm^{-3}, Z = 4, F(000) = 1064, crystal dimensions: 0.25 × 0.24 × 0.22 mm. A total of 20079 reflections were collected at 100 K with a Nonius Kappa CCD area detector diffractometer using ω scans in the θ range 2.00–30.03°, 7306 reflections were unique (R_{int} = 0.0424). The structure was solved by direct methods.[20] Full-matrix least-squares refinement[21] was based on F^2, with all non-hydrogen atoms anisotropic and hydrogen atoms isotropic. The refinement converged at R_1 = 0.0611, wR_2 = 0.0921 for all data; final GOF: 0.992; largest peak/hole in the final difference Fourier map: 0.445/–0.630 e Å^{-3}.

Crystal Structure Analysis of *rac*-8a: $C_{31}H_{31}FeO_3P$, M_r = 538.38, monoclinic, space group: $P2_1/n$, a = 9.6863(4), b = 19.9872(9), c = 14.0443(3) Å, β = 105.414(2)°, V = 2621.20(17) Å^3, $\rho_{calcd.}$ = 1.364 g cm^{-3}, Z = 4, F(000) = 1128, crystal dimensions: 0.20 × 0.16 × 0.14 mm. A total of 10535 reflections were collected at 100 K with a Nonius Kappa CCD area detector diffractometer using ω scans in the θ range of 2.96–27.84°, 6216 reflections were unique (R_{int} = 0.0316). The structure was solved by direct methods.[20] Full-matrix least-squares refinement[21] was based on F^2, with all non-hydrogen atoms anisotropic and hydrogen atoms isotropic. The refinement converged at R_1 = 0.0649, wR_2 = 0.0993 for all data; final GOF: 1.017; largest peak/hole in the final difference Fourier map: 0.626/–0.382 e Å^{-3}.

CCDC-270160 (*rac*-**7a**) and -240401 (*rac*-**8a**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Center via www.ccdc.cam.ac.uk/data_request/cif.

Acknowledgments

This work was supported by the Fonds der Chemischen Industrie and the Alfried-Krupp Award for young university teachers. We thank M. Lutterbeck and S. Preuss for technical assistance, Dr. R. Krieger and G. Fehrenbach for analytical assistance, and Dr. M. Keller, Universität Freiburg, for the X-ray crystal structure analysis of compounds **7a** and **8a**.

[1] a) C. D. Frohning, C. W. Kohlpaintner, in *Applied Homogeneous Catalysis with Organometallic Compounds* (Eds.: B. Cornils, W. A. Herrmann) Wiley-VCH, Weinheim, **2000**, pp. 29–104; b) K. Weissermel, H.-J. Arpe, *Industrial Organic Chemistry*, Wiley-VCH, Weinheim, **2003**, pp. 127–141; c) *Rhodium Catalyzed Hydroformylation* (Eds.: P. W. N. van Leeuwen, C. Claver), Kluwer, Dordrecht, The Netherlands, **2000**.
[2] B. Breit, W. Seiche, *Synthesis* **2001**, 1–36.
[3] a) K. Nozaki, I. Ojima, in *Catalytic Asymmetric Synthesis*, 2nd ed. (Ed.: I. Ojima), Wiley-VCH, New York, **2000**, pp. 429–463; b) M. Diéguez, O. Pàmies, C. Claver, *Tetrahedron: Asymmetry* **2004**, *15*, 2113–2122; c) F. Agbossou, J. F. Carpentier, A. Mortreux, *Chem. Rev.* **1995**, *95*, 2485–2506.
[4] a) B. Breit, *Acc. Chem. Res.* **2003**, *36*, 264–275; b) I. J. Krauss, C. C.-Y. Wang, J. L. Leighton, *J. Am. Chem. Soc.* **2001**, *123*, 11514–11515; c) R. W. Jackson, P. Perlmutter, E. E. Tasdelen, *J. Chem. Soc., Chem. Commun.* **1990**, 763–764; d) S. D. Burke, J. E. Cobb, *Tetrahedron Lett.* **1986**, *27*, 4237–4240.
[5] a) B. Breit, G. Heckmann, S. K. Zahn, *Chem. Eur. J.* **2003**, *9*, 425–434; b) B. Breit, *Chem. Eur. J.* **2000**, *6*, 1519–1524; c) B. Breit, *Liebigs Ann./Recueil* **1997**, 1841–1851; d) B. Breit, *Angew. Chem.* **1996**, *108*, 3021–3023; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 2835–2837.
[6] B. Breit, D. Breuninger, *J. Am. Chem. Soc.* **2004**, *126*, 10244–10245.
[7] a) C. S. Poss, S. L. Schreiber, *Acc. Chem. Res.* **1994**, *27*, 9–17; b) M. C. Willis, *J. Chem. Soc., Perkin Trans. 1* **1999**, 1765–1787; c) D. S. La, J. B. Alexander, D. R. Cefalo, D. D. Graf, A. H. Hoveyda, R. R. Schrock, *J. Am. Chem. Soc.* **1998**, *120*, 9720–9721; d) K. Mikami, S. Narisawa, M. Shimizu, M. Terada, *J. Am. Chem. Soc.* **1992**, *114*, 6566–6568; e) K. Tamao, T. Tohma, N. Inui, O. Nakayama, Y. Ito, *Tetrahedron Lett.* **1990**, *31*, 7333–7336.
[8] N. Boccara, P. Maitte, *Bull. Soc. Chim. Fr.* **1972**, 1448–1462.
[9] a) S.-L. You, Y.-M. Luo, W.-P. Deng, X.-L. Hou, L.-X. Dai, *J. Organomet. Chem.* **2001**, *637–639*, 845–849; b) P. Stepnicka, *New J. Chem.* **2002**, *26*, 567–575.
[10] BOP: (benzotriazol-1-yloxy)tris(dimethylamino)phosphonium hexafluorophosphate (Fluka).
[11] R. W. Hoffmann, *Chem. Rev.* **1989**, *89*, 1841–1860.
[12] F. Johnson, *Chem. Rev.* **1968**, *68*, 375–413.
[13] G. J. Karabatsos, D. J. Fenoglio, *Top. Stereochem.* **1970**, *5*, 167–203.
[14] For the influence of a coligand on reaction rate and diastereoselectivity for the *o*-DPPB-directed hydroformylation see ref.[5c]

[15] J. Rojo, M. García, J. C. Carretero, *Tetrahedron* **1993**, *49*, 9787–9800.
[16] I. Ohtani, T. Kusumi, Y. Kashman, H. Kakisawa, *J. Am. Chem. Soc.* **1991**, *113*, 4092–4096.
[17] K. Avasthi, T. Baba, S. Tsutomu, *Tetrahedron Lett.* **1980**, *21*, 945–946; M. Julia, C. Marzano, *Tetrahedron* **1985**, *41*, 3717–3724.
[18] In analogy to: B. M. Trost, T. A. Grese, D. M. T. Chan, *J. Am. Chem. Soc.* **1991**, *113*, 7350–7362; A. Hosomi, Y. Sakata, H. Sakurai, *Carbohydr. Res.* **1987**, *171*, 223–232.
[19] B. Breit, D. Breuninger, *Synthesis*, submitted.
[20] G. M. Sheldrick, *SHELXS-97, Program for Solving Crystal Structures*, University of Göttingen, **1997**.
[21] G. M. Sheldrick, *SHELXL-97, Program for Refining Crystal Structures*, University of Göttingen, **1997**.

Received April 26, 2005
Published Online: August 1, 2005

