180. Preparation and Structural Analysis of Several New α,α,α′,α′-Tetraaryl-1,3-dioxolane-4,5-dimethanols (TADDOL's) and TADDOL Analogs, Their Evaluation as Titanium Ligands in the Enantioselective Addition of Methyltitanium and Diethylzinc Reagents to Benzaldehyde, and Refinement of the Mechanistic Hypothesis

by **Yoshio N. Ito**[1]), **Xavier Ariza**[2]), **Albert K. Beck**, **Andrej Boháč**[3a]), **Camille Ganter**, **Robert E. Gawley**[4]), **Florian N. M. Kühnle**[5]), **Juraj Tuleja**[3b]), **Yan Ming Wang**[5]), and **Dieter Seebach***

Laboratorium für Organische Chemie der Eidgenössischen Technischen Hochschule, Universitätstrasse 16, CH–8092 Zürich

(24. VIII. 94)

Preparation and screening of twenty new ligands, all analogs of α,α,α′,α′-tetraaryl-1,3-dioxolane-4,5-dimethanol (TADDOL), for the Ti-catalyzed asymmetric addition of methyltri(isopropoxy)titanium and diethylzinc to benzaldehyde are described. These ligands have the dioxolane ring of the TADDOL's replaced by cyclobutane, cyclopentane, cyclohexene, cyclohexane, bicyclo[2.2.1]heptene and -heptane and bicyclo[2.2.2]octene and -octane moieties; several have H-atoms or alkyl groups in place of the aryl groups, and nine of them have C_2 symmetry. X-Ray crystallography and molecular mechanics are used to analyze the structure of the ligands, and two structural features appear to correlate with selectivity: *i*) the torsion angle for the chelating O-atom and the *ortho*-C-atom of the axial Ph group (a small, *ca.* 19°, angle is optimum, *Fig. 8*) and *ii*) the 'degree of perpendicularity' of the axial Ph group (*Fig. 9*). Competition experiments indicate that TADDOL **1a** catalyzes both the methyltitanium and diethylzinc additions ≥ 50 times faster than the related dioxolane analogs **12a**, **12c**, and **12e** (*Scheme 7*), indicating that both axial and equatorial aryl groups (see *Footnote 6*) are necessary for ligand-accelerated catalysis of these reactions. A refined mechanistic hypothesis is presented (*Fig. 10*) to explain the selectivities observed for these new ligands. Our analysis suggests that a combination of structural features appear necessary for good catalytic efficiency and high selectivity. These features, especially the rather subtle conformational effects, appear to be optimized (among the ligands tested) in the TADDOL's.

Introduction. – The stereoselective addition of organometallics to the heterotopic faces of a carbonyl group has been the subject of intense study for over forty years, ever since *Curtin* [1], *Cram* [2], and *Prelog* [3] first began rationalizing the selective addition of nucleophiles to diastereotopic faces of aldehydes and ketones. Of particular interest has been the gradual development of theories regarding the factors that are responsible for facial selectivity. *E.g.*, following *Cram*'s original postulate, notable contributions to the theory were made over the years by *Karabatsos* [4], *Felkin* [5], *Dunitz* [6], *Anh* [7], and *Heathcock* [8] and coworkers, among others.

---

[1]) Visiting Professor (1993–1994) from the Department of Chemistry, Faculty of Science, Kyushu University 33, Hakozaki, Higashi-ku, Fukuoka 812, Japan.

[2]) Visiting student (1993) from the University of Barcelona, Spain.

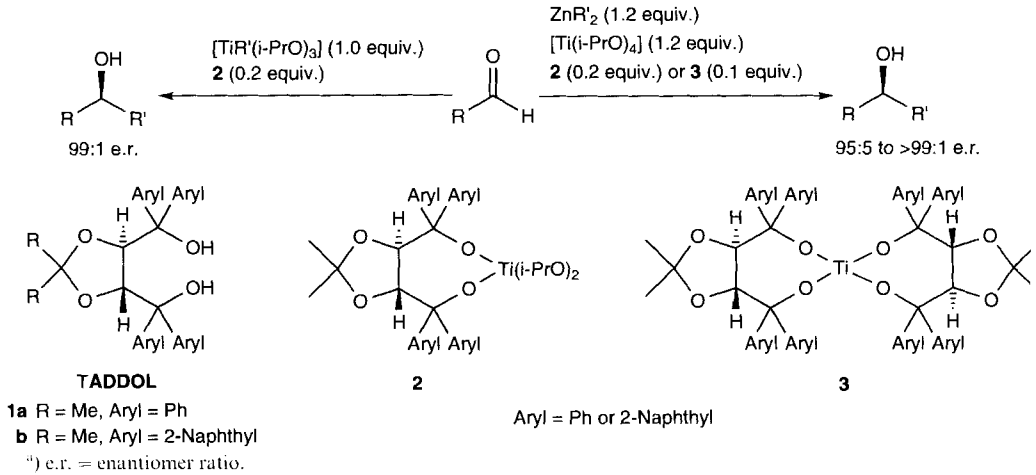
[3]) Postdoctoral associates in the group of *C. G.*: a) from the Comenius University, Bratislava, Slovakia (since 1993); b) from the Research Institute of Chemical Technology, Bratislava, Slovakia (1992–1994).

[4]) Fogarty Senior International Fellow (1993–1994), on leave from the Department of Chemistry, University of Miami, Coral Gables, Florida 33124-0431, USA.

[5]) Parts of the projected Ph. D. Theses of *F. N. M. K.* and *Y. M. W.*

Recently, a number of efforts have focussed on the selective addition of nucleophiles to enantiotopic faces of achiral carbonyl compounds [9–11]. *E.g.*, contributions from this laboratory have described the use of chiral titanium complexes [12–14] as catalysts in the addition of dialkylzinc [15] and alkyltitanium [16] reagents in high yield and excellent enantioselectivity. The most selective ligands we have found to date are α,α,α′,α′-*t*etra*a*ryl-1,3-*d*ioxolane-4,5-*d*imethan*ol*s (TADDOL's; aryl = Ph, substituted Ph, or naphthyl) [17] [18]. *E.g.*, TADDOL's **1a** and **1b** afford 95 to over 99% enantioselectivity in the asymmetric addition of organozinc reagents to a variety of aldehydes, as shown in *Scheme 1* [18–20]. Additionally, TADDOL **1a** mediates the asymmetric addition of a variety of alkyl- and aryltitanium reagents to aryl-, alkyl-, vinyl-, and alkynylaldehydes with enantioselectivities of up to 99.5% (*Scheme 1*) [16]. The very best enantioselectivities are observed, when a mixture of the chiral titanium TADDOLate **2** and excess titanium tetraisopropoxide ([Ti(i-PrO)$_4$]) is employed.

Scheme 1. *Highly Enantioselective Addition of [TiR′(i-PrO)$_3$]* [16] [21] *or ZnR$_2$* [15] [18–21] *to Aldehydes, Catalyzed by 10–20 mol-% Chiral Ti-TADDOLates* **2** *or* **3** *and [Ti(i-PrO)$_4$]*[a])



[a]) e.r. = enantiomer ratio.

The mechanism of the alkylzinc additions involves acceleration of the asymmetric catalytic process by the TADDOL ligand over the competing (achiral) catalyst, [Ti(i-PrO)$_4$]. We have concluded that the rate enhancement by the TADDOL ligands is due to an increase in the rate of ligand exchange in the TADDOLate complex over the isopropoxy complex due to the steric bulk of the TADDOLate compared to two isopropoxides (ligand-accelerated catalysis) [21]. The role of [Ti(i-PrO)$_4$] in this process is to remove (chiral) product alkoxides from the titanium TADDOLate complex by ligand exchange [21]. Based on the results of X-ray crystal-structure analysis of several ligands, we have also formulated a hypothesis to explain the face selectivity of Ti-TADDOLate-mediated reactions [21]. This hypothesis is based on the observation that four aryl groups in the seven-membered metallocycle are situated in axial[6]) and equatorial positions that

[6]) The axial Ph (or other substituent) is defined as that which is antiperiplanar to the angular H-atom when the ligand is part of a ring formed by either a metal or an intramolecular H-bond.

approximate C_2 symmetry. A generalized representation of this arrangement is shown in *Fig. 1a*, with an aldehyde also coordinated to the metal. In this presentation, the metal is in the foreground and the dioxolane (in the rear) is deleted for clarity. The aldehyde is illustrated in two (superimposed) conformations, the solid lines indicating the more favorable orientation. Note that the conformation indicated by the dashed lines is disfavored by a steric interaction with a pseudoaxial aryl group. Assuming that the attack of a nucleophile comes from the direction of the viewer, this hypothesis accounts for the *Si*-face selectivity observed in both reactions mentioned above, and in all other known Ti-TADDOLate-mediated nucleophilic additions to aldehydes (see discussion in our previous paper [21]). Since we do not know anything about the structure of the transition state (intramolecular or intermolecular attack, mononuclear or binuclear complex, *etc.*), it is important to note that this analysis is valid, independent of the coordination number of the metal. The model only involves the coordination of the chiral ligand and the aldehyde, and will be valid (although with somewhat different steric energies for the two conformers) whether the metal is square pyramidal or octahedral. The topicity sense of the enantioselective additions for the TADDOL ligands can be expressed in general terms as follows: if the conformation of the Ti–O–C–$Aryl_{axial}$ torsion angle is *P* (*Fig. 1b*) [22], then the nucleophile adds to the *Si* face of the aldehyde.

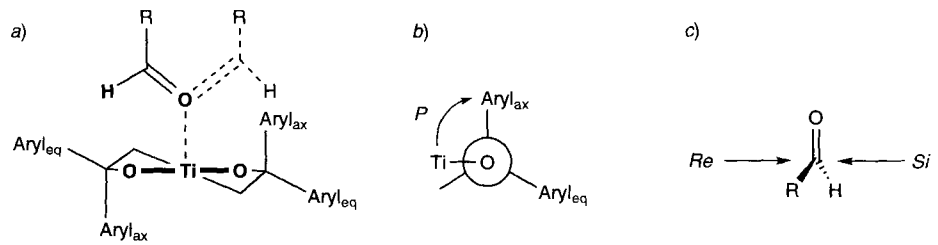
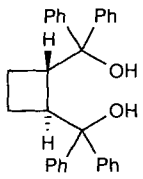


Fig. 1. a) *Transition-state model for predicting face selectivity in Ti-TADDOLate-mediated nucleophilic additions to aldehydes*, b) *definition of conformation for predicting topicity* (see text), *and* c) *definition of enantiotopic faces*

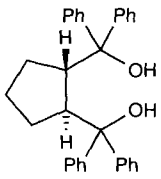
In spite of the successes outlined above, we continued to screen a number of new ligands for these reactions, hoping to find even more versatile ligands for these or other asymmetric processes currently under study in our laboratories [23–27][7]). Additionally, by comparing the selectivities of these new ligands, we hoped to learn more about the structural factors that influence the enantioselectivity, so as to refine the working hypothesis shown in *Fig. 1*. Toward this end, we prepared a number of TADDOL analogs (**4**–**12**) and evaluated their enantioselectivities in the asymmetric addition of triisopropoxy(methyl)titanium ([TiMe(i-PrO)$_3$]) and diethylzinc ($ZnEt_2$) to benzaldehyde. We also evaluated three pairs of catalysts (**1a**/**12a**/, **1a**/**12c**, and **1a**/**12e**) in competition experiments as a means of measuring relative rates for these catalysts. As part of this study, we determined the X-ray crystal structure of several ligands and completed a conformational analysis of a number of ligands using molecular mechanics. Analysis of the collected data was consistent with the face-selectivity hypothesis presented in *Fig. 1*, which could be refined based on the results reported herein.

---

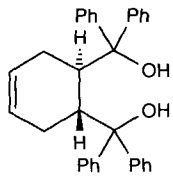
[7]) For a review of TADDOL's in organic synthesis, see [28a]. For a review of titanium reagents in organic synthesis, see [28b].



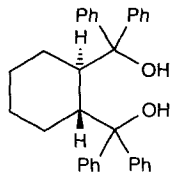
4



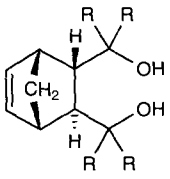
5



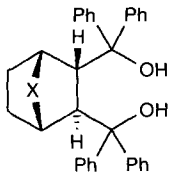
6



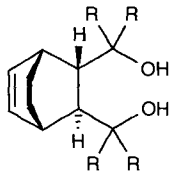
7



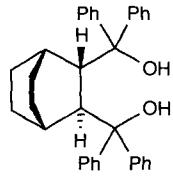
8a R = Ph
b R = Me



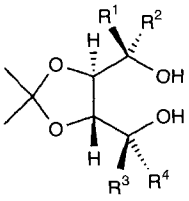
9a X = CH_2
b X = O



10a R = Ph
b R = Me
c R = H



11



1a $R^1 = R^2 = R^3 = R^4$ = Ph
12a $R^1 = R^4$ = Ph, $R^2 = R^3$ = Me
12b $R^1 = R^3$ = Ph, $R^2 = R^4$ = Me
12c $R^1 = R^4$ = Me, $R^2 = R^3$ = Ph
12d $R^1 = R^3$ = Ph, $R^2 = R^4$ = 1-Naphthyl

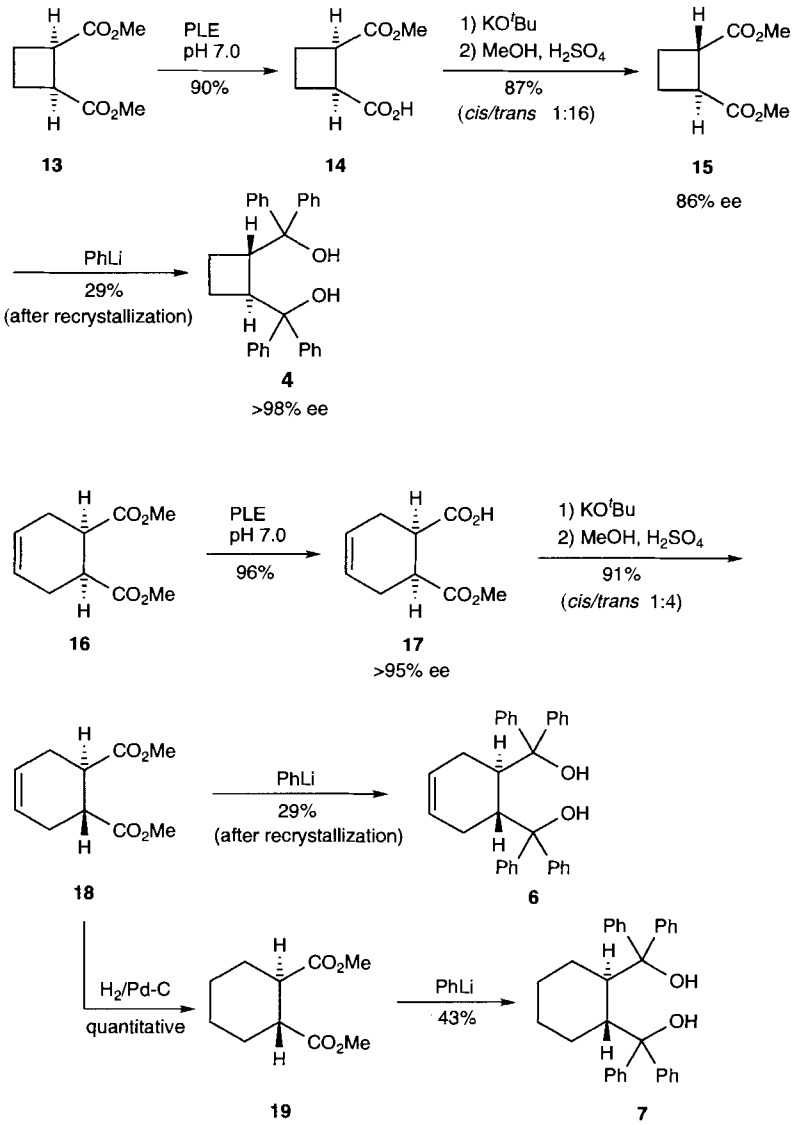
12e $R^1 = R^2 = R^3 = R^4$ = Me
f $R^1 = R^2 = R^3 = R^4 = CH_2Ph$
g $R^1 = R^2 = R^3 = R^4$ = *cyclo*-C_6H_{11}
h $R^1 = R^2$ = H, $R^3 = R^4$ = Ph

Preparation of TADDOL Analogs. – The preparation of TADDOL analogs **4**–**12** was accomplished as described in *Schemes 2*–*6*. First, for the synthesis of **4** [29], **6** and **7** (*Scheme 2*), pig-liver esterase catalyzed asymmetric hydrolysis of *meso*-diesters **13** and **16** [30] [31][8]), followed by epimerization of the ester moieties of **14** and **17** was used to generate *trans*-dicarboxylates **15** and **18** after esterification. Chiral-stationary-phase (CSP) GC analysis showed 86% ee for cyclobutane-dicarboxylate **15**, while **18** was enantiomerically pure. Treatment of **15** and **18** with PhLi afforded the desired benzhydryl alcohols **4** and **6**. At this stage, the enantiomeric purity of **4** could be increased by recrystallization. Cyclohexane derivative **7** was also prepared from **18** by hydrogenation (→ **19**) followed by addition of PhLi. The configuration of **4**, **14**, and **17** was established using literature data [29–31].

For the preparation of the cyclopentane analog **5**, a similar enzyme-catalyzed hydrolysis was reported to afford product of only 17% ee [30a, b] [31], so we decided to devise another asymmetric synthesis of *trans*-cyclopentane-1,2-dicarboxylic acid. In unpublished work [32], we have recently developed a new chiral auxiliary, 2-(*tert*-butyl)-5,5-

[8]) For a review article on work with pig-liver esterase, see [31].

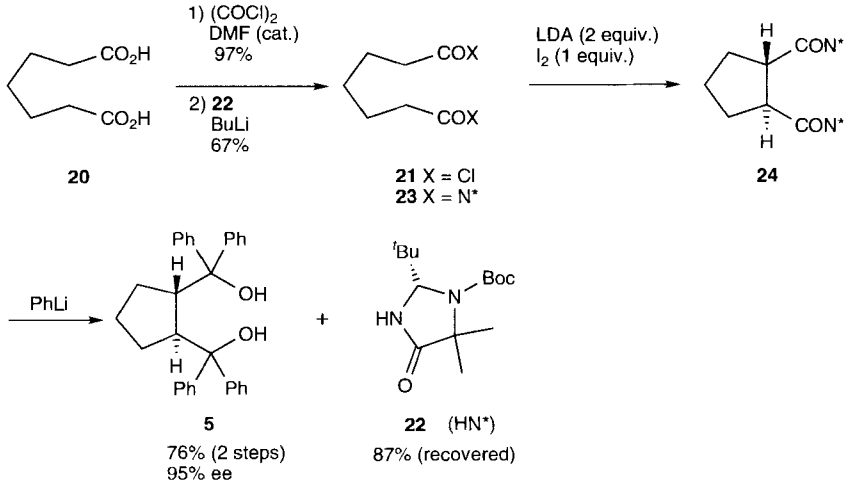
Scheme 2. *Synthesis of TADDOL Analogs* **4**, **6**, *and* **7** *by Using Enantioselective Enzymatic Hydrolysis of* meso-*Diesters*



dimethylimidazolidin-4-one **22** (HN*, *Scheme 3*), for asymmetric alkylations of enolates. Both enantiomers of **22** are available easily from (*S*)-alanine and show excellent asymmetric induction in the alkylation of corresponding propionyl- or Boc-protected glycine derivatives [32]. Thus, the chiral auxiliary **22** was acylated with pimeloyl dichloride (**21**), obtained from the corresponding diacid **20** (*Scheme 3*). The resulting diamide **23** was treated with 2 equiv. of lithium diisopropylamide (LDA) and then with 1 equiv. of I_2 at −78°. The intramolecular coupling reaction, probably a radical process [33],

proceeded smoothly, and cyclopentane derivative **24** was obtained in high yield[9]). Without purification, **24** was treated with PhLi to afford **5** in 76% yield (for the two steps), accompanied by recovery of the chiral auxiliary in 87% yield. The enantiomeric purity of **5** was determined to be 95% ee by CSP HPLC. The configurational assignment rests upon methanolysis of **24** to the known dimethyl ester and comparison of its optical rotation with literature data [30e].

Scheme 3. *Asymmetric Synthesis of TADDOL Analog* **5** *by Oxidative Intramolecular Coupling of Chiral Diamide* **23**



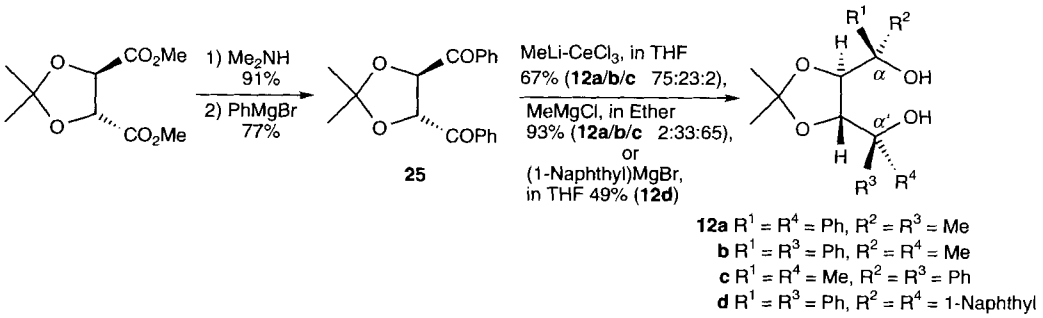
Dioxolanes **12a–d** were prepared from tartaric acid as shown in *Scheme 4*. Successive treatment of dimethyl isopropylidenetartrate with Me_2NH [34] and PhMgBr produced diketone **25**[10]). Addition of MeLi in Et_2O to **25** resulted in a mixture of the three possible stereoisomers **12a–c**. Chromatography afforded 13% of **12a**, 37% of **12b**, and 25% of **12c**. However, significant racemization had occurred: the products showed only 65% ee. A more selective synthesis of **12a** and **12c**, without racemization, resulted when either methylcerium or methyl-*Grignard* reagents were used. Thus, $MeCeCl_2$ [35] afforded a mixture **12a**/**12c** in a 98:2 ratio (51% yield, along with 16% of **12b**), while MeMgCl gave **12a**/**12c** in a 2:98 ratio (63% yield, along with 30% of **12b**)[11]). The relative configuration of the C_2-symmetrical isomer to which we assign structure **12a** was determined by X-ray crystal-structure analysis (*vide infra*). Since the diastereoisomer **12c** is also C_2-symmetric but **12b** is not, the remaining two structures were easily assigned from their NMR spectra. Addition of (1-naphthyl)magnesium bromide to **25** afforded a single addition product **12d**, the NMR spectrum of which did not exhibit the characteristics expected of a C_2-symmetric derivative (even at 80° in (D_6)DMSO), so **12d** was assigned the C_1-symmetric structure shown. The preparation of the diols **12e,f** has been published [14]

[9]) Intramolecular and intermolecular couplings of the dienolates of chiral pimelamides have been examined in the laboratory of Prof. *G. Helmchen* (Organisch-Chemisches Institut, Universität Heidelberg). We thank Prof. *Helmchen* for communicating his results to us prior to publication.

[10]) A small amount (3%) of a side product, tentatively identified as (4*R*,5*R*)-4-benzoyl-5-[hydroxy(diphenyl)methyl]-2,2-dimethyl-1,3-dioxolane, was also obtained in this reaction.

[11]) These mixtures were easier to separate, since **12a**/**12c** were readily separated from **12b**.

Scheme 4. *Synthesis of TADDOL Analogs* **12a–d** *by Addition of Organometallics to Dibenzoyldioxolane* **25**



12a $R^1 = R^4 = Ph$, $R^2 = R^3 = Me$
b $R^1 = R^3 = Ph$, $R^2 = R^4 = Me$
c $R^1 = R^4 = Me$, $R^2 = R^3 = Ph$
d $R^1 = R^3 = Ph$, $R^2 = R^4 =$ 1-Naphthyl

[21]. Catalytic hydrogenation of the original TADDOL **1a** afforded the tetracyclohexyl derivative **12g**[12]). Details for the preparation of the diphenyl-substituted diol **12h** will be published elsewhere [37].

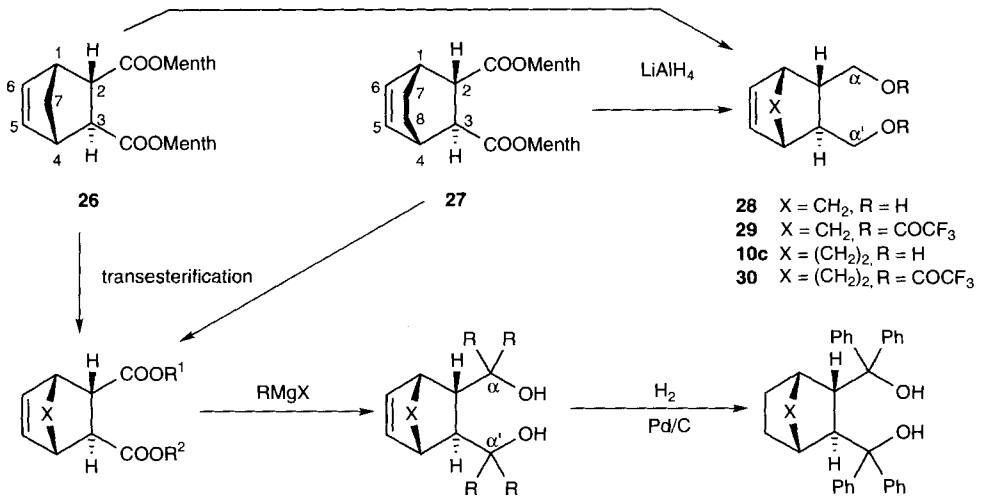
Bicyclic TADDOL analogs were prepared as shown for bicyclo[2.2.1]heptane analogs **8a, b** and **9a** and bicyclo[2.2.2]octane analogs **10a–c** and **11** in *Scheme 5* and for 7-oxabicyclo[2.2.1]heptane analog **9b** in *Scheme 6*. *Diels-Alder* reaction, according to a method described by *Yamamoto* and coworkers [38], of di[(1*R*,2*S*,5*R*)-menthyl] fumarate with either cyclopentadiene or cyclohexadiene proceeded in both cases with high diastereoselectivity (> 96:4 diastereoisomer ratio; see also [39] for similar diastereoselectivities obtained with di[(*S*)-ethyllactyl] fumarate). After recrystallization, **26** and **27** were obtained as pure diastereoisomers. This was determined by reduction with $LiAlH_4$ to the corresponding diols **28** [38a] [40] and **10c**, trifluoroacetylation to **29** and **30**, and CSP-GC analysis. Transesterification of **26** with either MeOH or EtOH and of **27** with MeOH gave the corresponding diesters **31–33**, which in all cases were accompanied by the mixed esters **34/35** (see also [38b]) (85:15), **36/37** (75:25), and **38/39** (10:90). Addition of methyl-*Grignard* reagent to the dimethyl esters **31** and **33** led to the tetramethyldiols **8b** and **10b**, whereas addition of phenyl-*Grignard* reagent to the diethyl ester **32** yielded the tetraphenyldiol **8a**, and addition to the dimethyl ester **33** gave **10a**. Subsequent hydrogenation afforded the corresponding saturated TADDOL analogs **9a** and **11**.

A slightly different approach was chosen for the preparation of the 7-oxabicyclo-[2.2.1]heptane TADDOL analog **9b** (*Scheme 6*). The racemic *Diels-Alder* adduct **40**/*ent*-**40** [41], obtained from furan and fumaryl dichloride, was esterified with (−)-(1*R*,2*S*,5*R*)-menthol to give the diastereoisomeric esters **41/42**. They were separated by flash chromatography (FC) and subsequently hydrogenated to the saturated ester **43** and **44**, respectively. However, due to the low stability of **41** and **42**, it was preferable to first reduce **41/42** to **43/44** which were then separated by FC. Transesterification of **43** with MeOH led to a mixture of mixed menthyl methyl diester **45** and dimethyl ester **46**. Interestingly, **45** was the only one of the two possible mixed esters that was detected. X-Ray analysis of **45**[13]) revealed both the absolute configuration and the fact that the *exo*-menthyl ester had been transesterified preferentially. Also, its partial reduction gave exclusively the ester alcohol **47**. The enantiomeric purity of diester **46** was determined by

[12]) Ligand **12g** was a gift from Dr. *R. O. Duthaler* (*Ciba*, Basel) [36]. The crystal structure has been determined and will be published elsewhere [27].

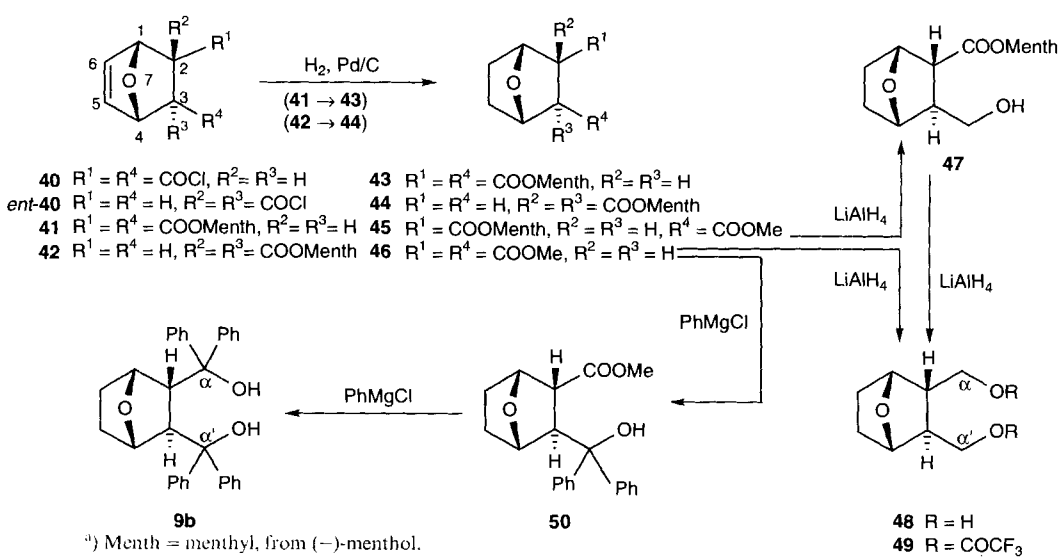
[13]) The coordinates of this structure have been deposited with the *Cambridge Crystallographic Data Centre*.

Scheme 5. *Preparation of the Bicyclo[2.2.1]heptane and Bicyclo[2.2.2]octane TADDOL Analogs* **8a**, **b**, **9a**, **10a**–**c**, *and* **11**[a])



[a]) Menth = menthyl, from (−)-menthol.

Scheme 6. *Preparation of the 7-Oxabicyclo[2.2.1]heptane TADDOL Analog* **9b**[a])



[a]) Menth = menthyl, from (−)-menthol.

reduction with $LiAlH_4$ to the corresponding diol **48** [42], trifluoroacetylation to **49**, and CSP-GC analysis. Addition of phenyl-*Grignard* reagent to **46** led to a mixture of **50** and the TADDOL analog **9b**.

Two features of bicyclic TADDOL analogs have to be mentioned explicitly: *a*) highly characteristic chemical-shift values can be observed in the ^{1}H-NMR spectra (see *Table 1*), which, in combination with the results of the X-ray analysis of **45**, allow unequivocal configurational assignments of the position of the ester groups at C(2) and C(3); *b*) the preferred reactivity of functional groups in the *exo*-position at C(3) over those in the *endo*-position at C(2) in the bicyclo[2.2.1]heptanes, which, in the bicyclo[2.2.2]octane series, corresponds to substituents at C(2) oriented towards C(6) ($R^{C(6)}$–C(2)) and at C(3) oriented towards the ethylene-bridge atom C(8) ($R^{C(8)}$–C(3)), respectively. The influence of steric hindrance by the bridge atoms on the attack of a reagent is almost negligible for an O-atom, small for a CH_2 group, and significant for a CH_2CH_2 group as illustrated by the transesterifications of **43**, **26**, and **27** (**43** → **45** exclusively, **26** → **34**/**35** (85:15), **26** → **36**/**37** (75:25), and **27** → **38**/**39** (10:90)), the $LiAlH_4$ reduction of the mixed ester **45** to **47**, and the addition of *Grignard* reagent to the dimethyl ester **46** (→ **50**).

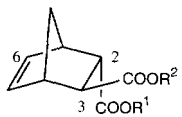
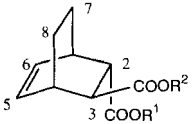
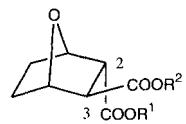
Structural Studies. – During our efforts to gain structural information about these catalysts, we were able to determine the crystal structures of **4**, **7**, and **12a**. They were compared with the previously determined [17] X-ray crystal structure of TADDOL **1a** (*Fig. 2a*). The cyclobutane derivative **4** gave crystals suitable for X-ray analysis only in its racemic form, and it crystallized in the monoclinic space group $P2_1/n$ as a H-bonded dimer (*Fig. 2b*). Both enantiomers are symmetry-connected *via* a glide plane. The four OH groups of this dimer form an eight-membered ring containing two intra- and two intermolecular H-bonds. The cyclobutane ring slightly deviates from planarity and two of the four bond angles in the ring are smaller than 90° (88.7° and 87.6°). The torsion angle between the diphenylmethanol groups is 95.8°, which is in the range observed for other *trans*-disubstituted cyclobutane rings [43]. The four Ph groups occupy equatorial and axial positions[6]) on the seven-membered ring produced by the intramolecular H-bond, which conforms to the mechanistic model shown in *Fig. 1* [21]. The least-squares superimposition of the crystal structure of **4** with that of **1a**[14]) shows very similar conformations for the 'chelating arms' of the two ligands, with only very small deviations in the planes of the Ph groups, as indicated by the HO–C–C–C_{ortho} torsion angles.

Single crystals of the cyclohexanedimethanol **7** were obtained by crystallization from hexane/AcOEt. The cyclohexane ring of **7** is in the chair conformation (*Fig. 2c*). The $C(Ph)_2OH$ substituents are *trans*-diaxial, with the dihedral angle compressed to −143.2°. The two OH groups are situated above and below the cyclohexane ring, which places two of the Ph substituents right on top of each other (closest C–C distance 3.84 Å). This conformation is reminescent of the solvent and host-free crystal structures of the hexaphenyl- [44] and tetrakis(2-methoxyphenyl)-substituted [45] 1,3-dioxolanedimethanols. As this conformation of ligand **7** cannot accomodate a metal by chelation, and because we wanted structural information about a chelating conformer, we crystallized **7** in the presence of piperidine, hoping that this secondary amine, being a strong H-bond acceptor, would be able to 'reinstall' a H-bonded ring. Single crystals were obtained (see *Exper. Part*), but the conformation of **7** in its clathrate with piperidine turned out to be unchanged.

---

[14]) Rigid superimposition of the four C-atoms and the two O-atoms of the chelate.

Table 1. *Assignment of Selected ^{1}H-NMR Chemical Shifts of Diesters*

R^1	R^2									
				δ [ppm]			δ [ppm]			δ [ppm]
Menth	Menth	**26**	H_{exo}–C(2)	3.35	**27**[a])	$H^{C(7)}$–C(2)	3.15	**43**	H_{exo}–C(2)	3.48
			H_{endo}–C(3)	2.67		$H^{C(5)}$–C(3)	2.88		H_{endo}–C(3)	3.05
			H–C(6)	6.03		H–C(6)	6.15			
			H_{ax}–C(1′)OOC_{endo}–C(2)	4.58		H_{ax}–C(1′)$OOC^{C(6)}$–C(2)	4.60		H_{ax}–C(1′)OOC_{endo}–C(2)	4.66
			H_{ax}–C(1′)OOC_{exo}–C(3)	4.69		H_{ax}–C(1′)$OOC^{C(8)}$–C(3)	4.69		H_{ax}–C(1′)OOC_{exo}–C(3)	4.69
Menth	Me	**34**	H_{exo}–C(2)	3.33	**38**[a])	$H^{C(7)}$–C(2)	3.12	**45**	H_{exo}–C(2)	3.48
			H_{endo}–C(3)	2.71		$H^{C(5)}$–C(3)	2.84		H_{endo}–C(3)	3.09
			H–C(6)	6.00		H–C(6)	6.13			
			H_{ax}–C(1′)OOC_{endo}–C(2)	4.58		H_{ax}–C(1′)$OOC^{C(6)}$–C(2)	4.60		H_{ax}–C(1′)OOC_{endo}–C(2)	4.65
			$MeOOC_{exo}$–C(3)	3.71		$MeOOC^{C(8)}$–C(3)	3.71		$MeOOC_{exo}$–C(3)	3.72
Me	Menth	**35**	H_{exo}–C(2)	3.37	**39**[a])	$H^{C(7)}$–C(2)	3.19			
			H_{endo}–C(3)	2.67		$H^{C(5)}$–C(3)	2.84			
			H–C(6)	6.07		H–C(6)	6.20			
			$MeOOC_{endo}$–C(2)	3.64		$MeOOC^{C(6)}$–C(2)	3.63			
			H_{ax}–C(1′)OOC_{exo}–C(3)	4.70		H_{ax}–C(1′)$OOC^{C(8)}$–C(3)	4.68			
Me	Me	**31**	H_{exo}–C(2)	3.38	**33**[a])	$H^{C(7)}$–C(2)	3.17	**46**	H_{exo}–C(2)	3.51
			H_{endo}–C(3)	2.69		$H^{C(5)}$–C(3)	2.86		H_{endo}–C(3)	3.08
			H–C(6)	6.07		H–C(6)	6.20			
			$MeOOC_{endo}$–C(2)	3.65		$MeOOC^{C(6)}$–C(2)	3.65		$MeOOC_{endo}$–C(2)	3.73
			$MeOOC_{exo}$–C(3)	3.72		$MeOOC^{C(8)}$–C(3)	3.73		$MeOOC_{exo}$–C(3)	3.72

[a]) The superscripts indicate toward which C-atom a substituent or H-atom is oriented.

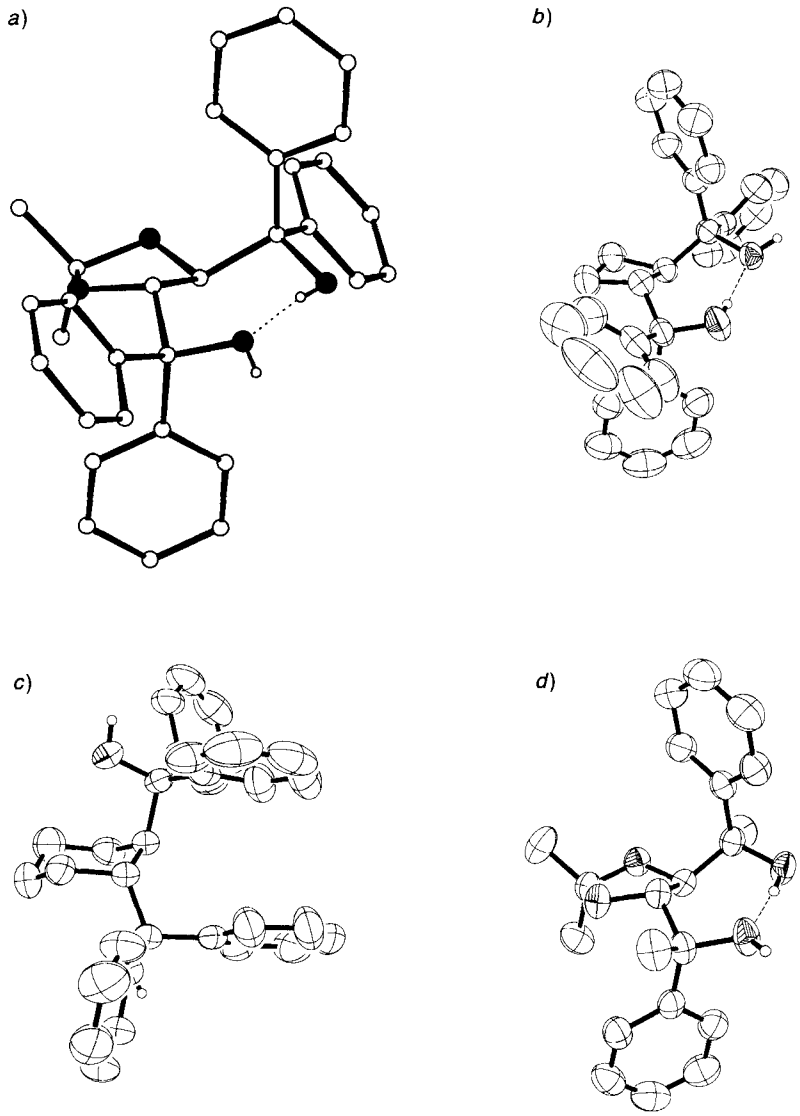


Fig. 2. *X-Ray crystal structures of*: a) *TADDOL* **1a** *taken from* [17], b) *cyclobutane ligand* **4**, c) *cyclohexane ligand* **7**, *and* d) *dioxolane ligand* **12a**

Among the different isomers of the dimethyl-diphenyl-substituted diols **12**, only **12a** could be crystallized. The X-ray crystal structure (*Fig. 2d*) shows a nearly identical conformation to that of **1a** (*Fig. 2a*), the Me C-atoms in the methanol unit of **12a** occupying the positions of the C_{ipso} atoms of the equatorial[6]) Ph rings in **1a**. The HO–C–C–C_{ortho} torsion angles of the axial[6]) Ph rings in **12a** slightly differ from those in **1a**, but the overall agreement is nearly perfect.

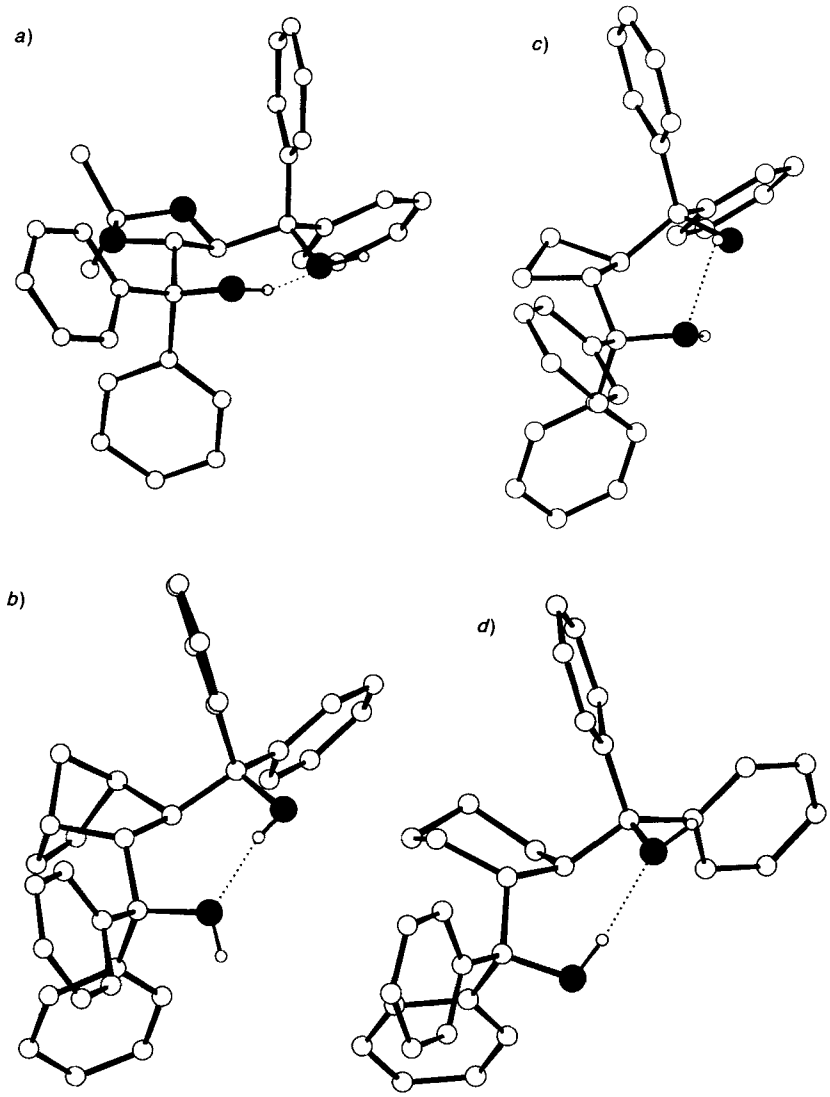


Fig. 3. *MM2*-Calculated* [46] *structures of ligands*: a) *TADDOL* **1a**, b) *cyclobutane ligand* **4**, c) *trinorbornene ligand* **8a**, *and* d) *cyclohexane ligand* **7** (*trans*-diaxial conformer shown)

In addition to the X-ray studies, a molecular-mechanics study of these ligands was undertaken to try to find a correlation between some structural feature and the enantioselectivity in these model reactions[15]). To be assured of obtaining structures that approximate the conformation of the ligand bound to a metal, an intramolecular H-bond was

[15]) Molecular-mechanics calculations were done with the MM2* force field contained in the MacroModel program (version 4.0). For a literature description of an earlier version of MacroModel, see [46].

used to keep the ligand in a 'cyclic' conformation[16]). Crystal structures of all but one TADDOL contain this feature, the exception being the cyclohexane derivative **7**, described above (*Fig. 2c*). Several of the calculated structures are depicted in *Fig. 3*. Comparison with X-ray data show a close similarity (*cf. Fig. 2a,b* with *Fig. 3a, b*, see also *Fig. 7* below), the major difference being variations in the HO–C–C–C_{ortho} torsion angles of the Ph substituents. Our calculations indicate that the potential surface for small ($< 30°$) rotations around these bonds is rather shallow; thus, these differences are not surprising. The cyclohexane ligand **7** exhibits a conformation in the crystal (*Fig. 2c*) that cannot possibly accomodate a metal, since the OH groups are oriented above and below the cyclohexane ring. Using molecular mechanics, we compared this conformation with two that contain intramolecular H-bonds. The conformation found in the crystal is the most stable of these three conformations. A conformation in which the $C(Ph)_2OH$ substituents are antiperiplanar (*i.e. trans*-diaxial, *Fig. 3d*), but which contains an intramolecular H-bond, is 3.0 kcal/mol higher in energy, and a synclinal (diequatorial) conformation containing an intramolecular H-bond is 4.08 kcal/mol less stable than the conformation in *Fig. 2c*.

Conformational analysis of bicyclooctane ligand **11** revealed two nearly isoenergetic isomers ($\Delta E = 230$ cal) that differ in the conformation of the bicyclooctane nucleus. *Fig. 4* illustrates the two conformers in a side view that shows the differences in the torsions due to different conformations of the bicyclooctane nucleus[17]). The two conformers differ in the chirality sense of the three torsions connecting the bridgehead C-atoms. In both, the CH–CHR–CHR–CH torsion is *M* [22]. In one conformer, the other two bridges ($CH–CH_2–CH_2–CH$) have *P* torsion angles, but in the other conformer, these other bridges have *M* torsion angles. In further discussions (below), these two conformers are distinguished as *MPP*-**11** (or *PMM-ent*-**11**) and *MMM*-**11** (or *PPP-ent*-**11**). The (slightly) more stable of the two is conformer *MPP*-**11** ($\Delta E = 230$ cal/mol)[15]). *Fig. 5* shows these two conformers (now for *ent*-**11** so that the chirality sense corresponds to

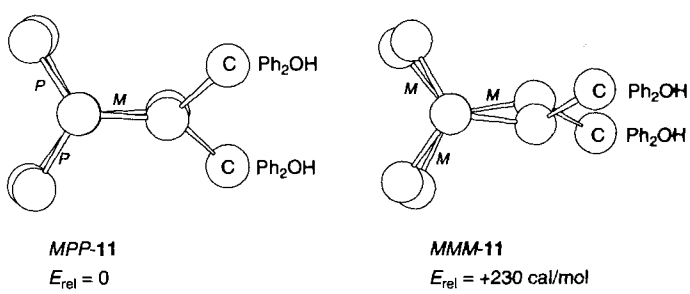


Fig. 4. *Two conformations of the bicyclooctane nucleus of ligand* **11**, *which differ in the chirality sense* (*M*, *P* [22]) *of the torsion angles of the bridges connecting the bridgehead atoms*

[16]) Clearly, the torsion and bond angles in the Ti-catalyst will differ somewhat from the X-ray or computationally derived structures of the free ligands with OH···O H-bonds. Nevertheless, the calculations reveal the inherent conformational preferences of the ligand; the forces responsible for these preferences will persist, when the ligand is bound to the metal (*cf.* the discussion in the next section).

[17]) None of the other bicyclic ligands (**8a, b**, **9a, b**, and **10a–c**) showed this type of conformational motion. All had torsions of *ca.* 0° for the bridges other than the one containing the methanol substituents.

that of **1a** and to the following discussion) in a least-squares superimposition of the eight atoms of the bicyclooctane nucleus. Note the large difference in the placement of the two OH groups. With such a small energy difference, we assume that both these conformers are populated when the ligand is bound to the catalytic center, and that the selectivities observed are due to averaged effects.

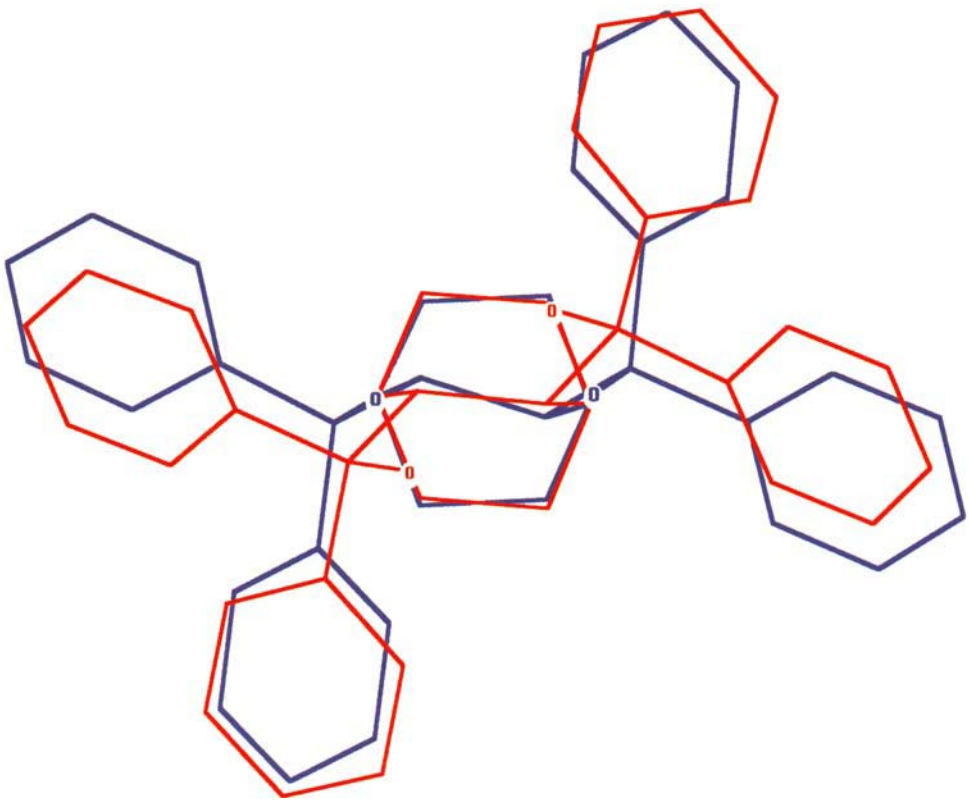


Fig. 5. *Least-squares superimposition of the eight atoms of the two conformations of the bicyclooctane nucleus of ligand* ent-**11**. The chirality sense is inverted so that it is the same as that of TADDOL **1a**. *PPP-ent-***11** is in blue and *PMM-ent-***11** in red.

Evaluation of Enantioselective Additions to Benzaldehyde. – The ligands **4**–**12** were evaluated in two reactions: the addition of $[TiMe(i\text{-}PrO)_3]$ and of $ZnEt_2$ to benzaldehyde (*Scheme 7*). For each set of data, all experiments were done under the same conditions and by the same experimentalist (with one exception)[18]), so that the structural effects of the various ligands could be compared directly. The $[TiMe(i\text{-}PrO)_3]$ additions were conducted in toluene, warming from −78° to −10° overnight (*Scheme 7a*, *Table 2*). These conditions differ from those published previously [16] [21]. For simplicity, the catalysts were prepared *in situ* by mixing 1 equiv. of ligand with 3 equiv. of $[TiMe(i\text{-}PrO)_3]$ prior to addition of benzaldehyde. The conditions chosen for the $ZnEt_2$ reaction (*Scheme 7b*, *Table 3*)

[18]) *Table 2*: *Y. N. I.*, except for ligand **11** (*Y. M. W.*). *Table 3*: *Y. M. W.*

Scheme 7. *Addition of* a) *[TiMe(i-PrO)$_3$] and of* b) *ZnEt$_2$ to Benzaldehyde* (see *Tables 2* and *3*)

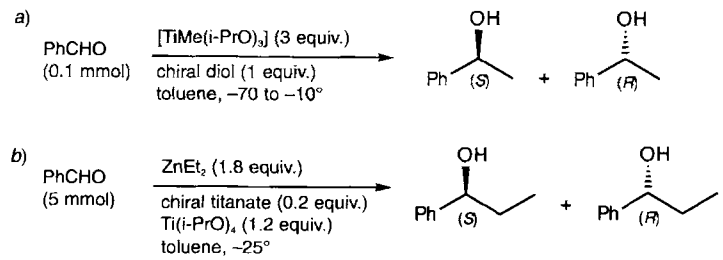


Table 2. *Addition of [TiMe(i-PrO)$_3$] to PhCHO in the Presence of TADDOL Titanate and Their Analogs Which Were Prepared from Chiral Diols* **1a**, **4–7**, *or* **12a–e**, **h** *and [TiMe(i-PrO)$_3$]* in situ[a])

	1a	**4**	**5**	**6**	**7**	**11**	**12a**
E.r.[b])	99:1	4:96	4:96[c])	83:17	93:7	94:6	94:6[d])
Yield [%][e])	72	57	60	57	43	61	81
	12a[f])	**12a[g])**	**12b**	**12c**	**12d**	**12e**	**12h**
E.r.[b])	88:12[h])	82:18[i])	59:41	24:76[j])	99:1	48:52	43:57
Yield [%][e])	53	70	82	90	66	66	60

[a]) [TiMe(i-PrO)$_3$] + diol→[Ti(diolate)] + [Ti(i-PrO)$_4$] + 2 CH_4. [b]) E.r. = enantiomer ratio (*S*)/(*R*). [c]) Corrected for the enantiomeric purity of the ligand (95% ee): actually observed ratio 6:94. [d]) When run with ligand of 65% ee, the observed ratio was 78.5:21.5 (94:6 corrected), 70% yield. [e]) Yield of purified and isolated product, except for ligand **11** (% conversion as determined by GC). [f]) 20 mol-% of **12a** were used for this reaction. [g]) 7 mol-% of **12a** were used for this reaction. [h]) Corrected for the enantiomeric purity of the ligand (65% ee): actually observed ratio 74.5:25.5. [i]) Corrected for the enantiomeric purity of the ligand (65% ee): actually observed ratio 71:29. [j]) When run with ligand of 65% ee, the observed ratio was 33:67 (24:76 corrected), 61% yield.

Table 3. *Addition of ZnEt$_2$ to PhCHO in the Presence of TADDOL Titanate and Their Analogs Which Were Prepared from Chiral Diol* **1a**, **4**, *or* **6–12** *and [Ti(i-PrO)$_4$]*

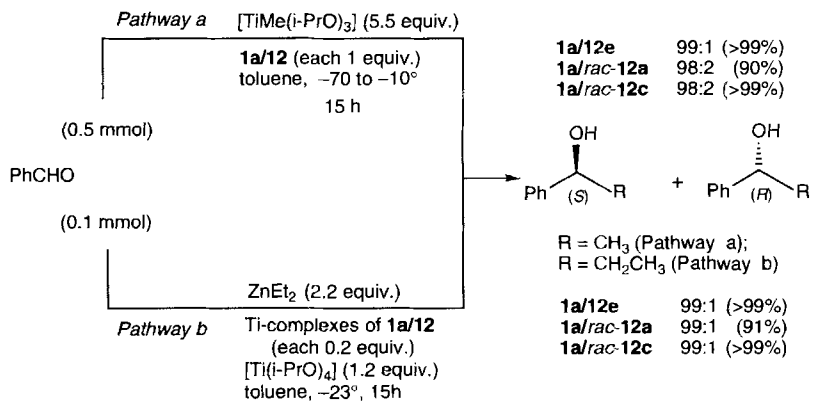
	1a	**4**	**6**	**7**	**8a**	**8b**	**9a**
E.r.[a])	99:1[b])	6:94	61:39	60:40	20:80	53:47	15:85
Yield [%][c])	99	79	53	79	99	73	90
	9b	**10a**	**10b**	**10c**	**11**	**12a**	**12b**
E.r.[a])	15:85	15:85	51:49	50:50	16:84	76:24[d])	57:43
Yield [%][c])	42	91	71	37	60	95	94
	12c	**12d**	**12e**	**12f**	**12g[f])**	**12h**	
E.r.[a])	44:56[e])	97:3	50:50	54:46	70:30	36:64	
Yield [%][c])	99	94	97	98	85	98	

[a]) E.r. = enantiomer ratio (*S*)/(*R*). [b]) Taken from [21]. [c]) Yield of purified and actually isolated product. [d]) Corrected for the enantiomeric purity of the ligand (65% ee): actually observed ratio 67:33. [e]) Corrected for the enantiomeric purity of the ligand (65% ee): actually observed ratio 46:54. [f]) Taken from [15].

were those previously optimized for TADDOL **1a** (toluene at –25° overnight) [15] [21][19]). Note that for the three ligands **5**, **12a**, and **12c**, the experiments were run with ligand that was not enantiomerically pure. However, for the [TiMe(i-PrO)$_3$] addition using ligands **12a** and **12c**, repetition of the experiment using enantiomerically pure ligand afforded the same result. In the $ZnEt_2$ addition, we have previously shown [18] that, for ligand **1b**, the enantiomeric purity of the addition product is linear as a function of the enantiomeric purity of **1b**. Thus, we are confident that the corrected values listed in *Tables 2* and *3* accurately reflect inherent selectivities due to the ligands.

To evaluate the relative rates of additions catalyzed by TADDOL **1a** and three other C_2-symmetric dioxolane ligands (**12a**, **12c**, and **12e**), competition experiments were carried out as described in *Scheme 8*. Note that tetramethyl ligand **12e** showed (within experimental error) no enantioselectivity, neither in the [TiMe(i-PrO)$_3$] nor in the $ZnEt_2$ additions (*Tables 2* and *3*); if catalysts derived from the two ligands **1a** and **12e** would react at equal rates, a product of *ca.* 75:25 enantiomer ratio, would be obtained (*vide infra*). The diphenyl-dimethyl-substituted ligands **12a** and **12c** were selective, so the competition experiments were performed between enantiomerically pure TADDOL **1a** and racemic diphenyldimethyl ligands **12a** and **12c**. The results of these competition experiments for the [TiMe(i-PrO)$_3$] and $ZnEt_2$ additions are shown in *Scheme 8*.

Scheme 8. *Addition of Organometallics to Benzaldehyde in the Presence of Competing Catalysts:* Pathway a: *Addition of [TiMe(i-PrO)$_3$]*; Pathway b: *Addition of $ZnEt_2$*. Selectivities (ratios) and percent conversions are determined by CSP-GC.



Discussion[20]). – The primary aim of this study was to evaluate the enantioselectivities of a number of structurally diverse ligands and to try to correlate structural features with the observed selectivities. *The most striking feature of these results is the clear superiority*

[19]) We have recently learned that other groups have also tested two of these ligands (**9** and **11**) in the $ZnEt_2$ reaction [47] [48]. In both cases, optimized conditions were found that afforded excellent selectivities, although sometimes only when low temperatures were maintained for extended periods. We are grateful to Profs. *Wandrey* and *Waldmann* for informing us of their results prior to publication.

[20]) To simplify the following discussion, the chirality sense of some of the ligands is inverted so that all ligands are homochiral, and have the Ti–O–C–Ph_{axial} torsion angle in the *P*-configuration.

of TADDOL **1a** *over all the other ligands*, including several (**4**, **6**, **7**, **11**, and **12a**, **c**, **e**, **f**, **g**) that also have C_2 symmetry. It is also interesting to note that in most instances when the selectivity of a ligand is evaluated in both reactions, the [TiMe(i-PrO)$_3$] addition is more selective. This is true for ligands **4**, **6**, **7**, **11**, and **12a**, **c**, **d**; ligands **1a** and **12b**, **e**, show the same selectivity in the two reactions within experimental error, while ligand **12h** is slightly more selective in the $ZnEt_2$ reaction.

We evaluated the structural features that might explain the differences in selectivities. Thus, the dihedral angle between the two methanol ring substituents in the ligands (*Fig. 6*) was examined, on the assumption that changes in this angle would affect the strength of the Ti–O bonds, which might have a bearing on the dynamics of ligand exchange (a crucial component of the catalytic cycle [21]), but no straightforward correlation was found. Specifically, pairs of ligands with very similar dihedral angles show very different selectivities: TADDOL **1a** ($\alpha = 87°$ (calc.) and 90° (X-ray)) is 99% enantioselective in the $ZnEt_2$ reaction, whereas the bicyclic ligands **9** and **10a**, with $\alpha = 89°$ (calc.) are only 85% selective. Similarly, the cyclobutane ligand **4** ($\alpha = 97°$ (calc.) and 96° (X-ray)) is 96% selective, while the trinorbornene ligand **8a** ($\alpha = 95°$ (calc.)) is only 80% selective.

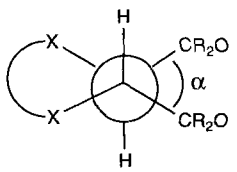


Fig. 6. *The dihedral angle α between the two methanol substituents*

Analysis of two other structural features is presented. First, we examined the features of selected ligands having C_2 symmetry, since the top and bottom faces of the metal chelate ring are homotopic for these ligands, which were chosen based on two criteria: they all have four Ph substituents on the chelate ring (and can, therefore, be directly compared with TADDOL **1a**), and they all have low-energy conformations with approximate C_2 symmetry. Second, we compared the selectivities of several other ligands (having both C_1 and C_2 symmetry) and evaluated their structural features in the context of a refined mechanistic hypothesis.

In the first comparison, we will illustrate significant structural features by looking at ligands **1a**, **4**, and **11**[21]). This analysis is predicative on the assumption that the conformation of the free ligand and the ligand bound to Ti are similar. That this assumption is valid (to a first approximation) is demonstrated by the superimposed structures in *Fig. 7*, which shows a least-squares superimposition of the five atoms of the dioxolane ring of TADDOL **1a** as found in the crystal structure of the free ligand (*i.e. Fig. 2a*) [17] and as found in the crystal structures of two Ti complexes [21] [49], along with the MM2*-calculated structure from *Fig. 3a*. Particularly relevant to the following discussion is the nearly

[21]) The MM2*-calculated structures of cyclobutane ligand **4** and cyclopentane ligand **5** are very similar, so only **4** is discussed in detail. Two of the tetraphenyl ligands having formal C_2 symmetry are disqualified from this analysis: the cyclohexene ligand **6** has a minimum-energy boat conformation (*i.e.*, lacks C_2 symmetry), and the cyclohexane ligand **7** has two very different C_2-symmetric conformations.

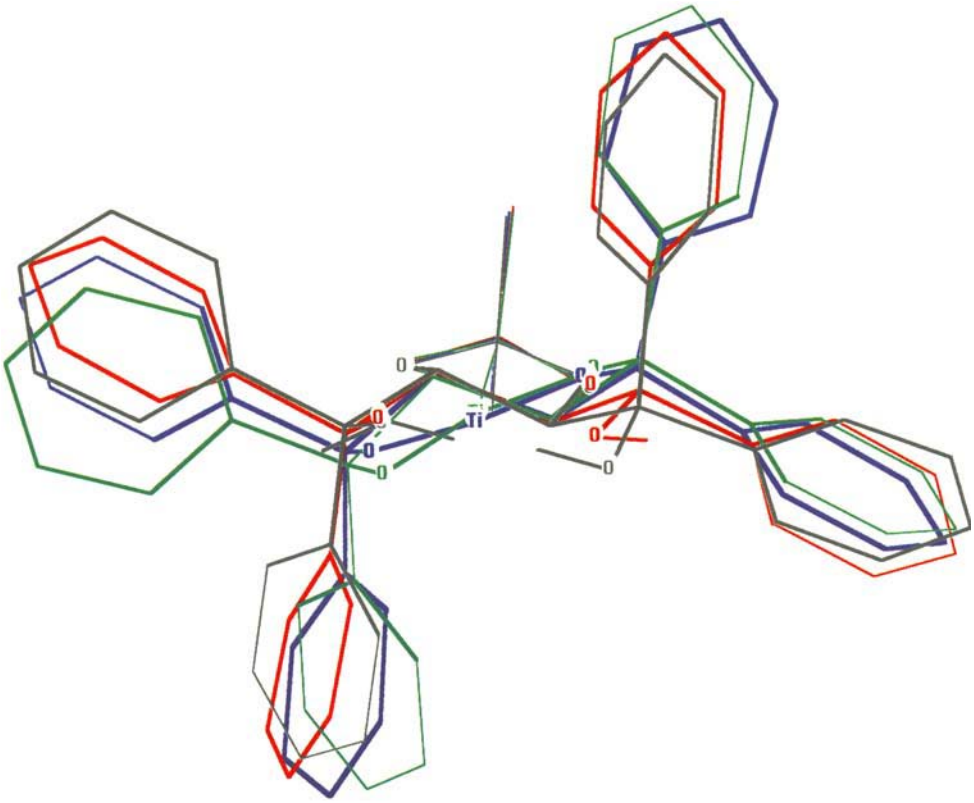


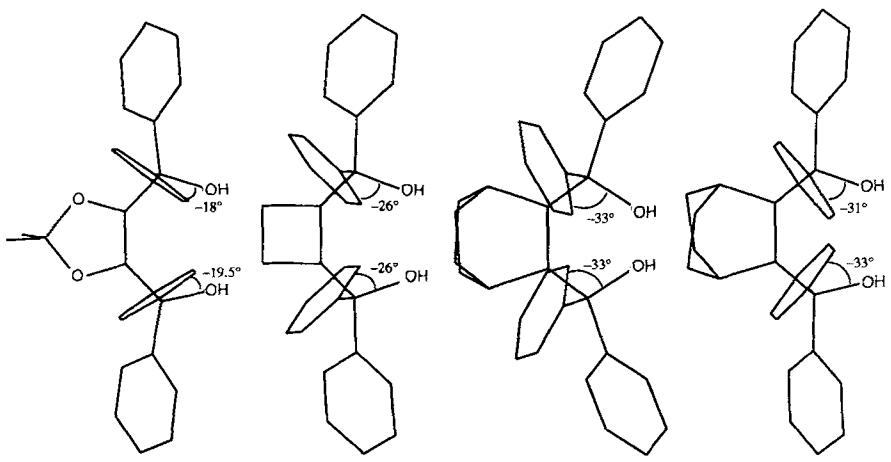
Fig. 7. *Least-squares superimposition of the five atoms of the dioxolane ring of ligand* **1a** *as found in X-ray crystal structures of* **1a** *alone* (black) [17], *in a spirotitanate* (green) [21], *and in a [TiX_2(Cp)] complex* (blue) [49], *along with the MM2*-calculated conformation* (red)

parallel alignment of the bonds to the axial[6]) and equatorial Ph groups, independent of whether the O-atoms are connected by a chelated Ti-atom or a H-bond.

Two aspects of the orientation of the Ph groups in MM2*-calculated conformations of **1a**, **4**, and **11** appear to correlate with selectivity. *Fig. 8* shows projections of **1a**, **4**, and the two conformers of **11**, which are oriented so as to highlight the HO–C–C–CH_{ortho} torsion angles. Comparison of enantioselectivities (expressed as relative rates) observed for these ligands in the two additions studied show that, as these angles increase, the selectivity decreases, *i.e.*, the lower selectivities are found when the preferred position of C_{ortho} of the axial Ph ring rotates away from the site of metal coordination[22]). We had previously hypothesized that large axial groups are critical for high enantioselectivity in nucleophilic additions to aldehydes [21], and the differences in preferred torsions may play a role in determining the effective size of the axial Ph group.

---

[22]) Recognize that these torsions represent the preferred conformation at the bottom of a rather shallow energy well. Nevertheless, calculations indicate that rotation of one of the axial Ph's to a torsion of *ca.* −19° would 'cost' *ca.* 150 and 220–310 cal/mol, respectively, for ligands **4** and **11** (for *PPM-ent*-**11**, the value is 220 cal/mol, whereas for *PPP-ent*-**11** it is 310 cal/mol).



	1a	*ent*-**4**	*PPM-ent*-**11**	*PPP-ent*-**11**
Selectivity of the [TiMe(i-PrO)$_3$] reaction:	99:1	24:1	16:1	
Selectivity of the $ZnEt_2$ reaction:	99:1	16:1	5:1	

Fig. 8. *Projections of ligands* **1a**, ent-**4**, *and* ent-**11**, *showing the* O–C–C–C_{ortho} *torsions and the selectivities* (as relative rates) *for these ligands in the [TiMe(i-PrO)$_3$] and $ZnEt_2$ reactions.* The configuration of ligands **4** and **11** are inverted so that the three ligands are homochiral and, therefore, have the same sign for the indicated torsions.

A second feature of the structures of **1a**, **4**, and **11** that correlates with selectivity is revealed by examination of the superimposition shown in *Fig. 9*. This figure was generated by a least-squares superimposition of the MM2*-calculated [46] atomic coordinates of the atoms indicated in the inset for ligands **1a**, *ent*-**4**, and the two conformers of *ent*-**11**. The projection is shown analogously to that of *Fig. 1*, that is with the O-atoms (and the Ti-atom) in the foreground and the chelate in an approximate horizontal plane. The superimposed structures are oriented so that TADDOL **1a** (shown in blue) has its axial[6]) Ph's aligned vertically (*cf. Fig. 1*). Note that the position of the axial Ph's in the other two ligands tilts progressively more towards the horizontal plane, which nearly bisects the Ph–C–Ph bond angle of *PMM-ent*-**11**[23]). Note that conformer *PPP-ent*-**11** closely resembles TADDOL **1a**. It appears, therefore, that the lowering of the selectivity observed for **11** (*Fig. 8*) may be due to the averaged effects of two nearly equally populated conformational isomers of the chiral ligand working in competition. One conformer might be considerably more selective than the other, while their catalytic rates are probably similar (*vide infra*).

---

[23]) Note that this effect would be exaggerated, if a vector connecting the two O-atoms of *PMM-ent*-**11** were rotated clockwise to correspond more closely to the position of the O-atoms in **1a** and **4**. This rotation would move the *equatorial* Ph's in *PMM-ent*-**11** closer to the vertical, *but opposite* those of **1a**. If this were strictly the case, and if *PMM* were the only conformer, **11** might be expected to afford the opposite sense of enantioselectivity from that generalized in *Fig. 1*.

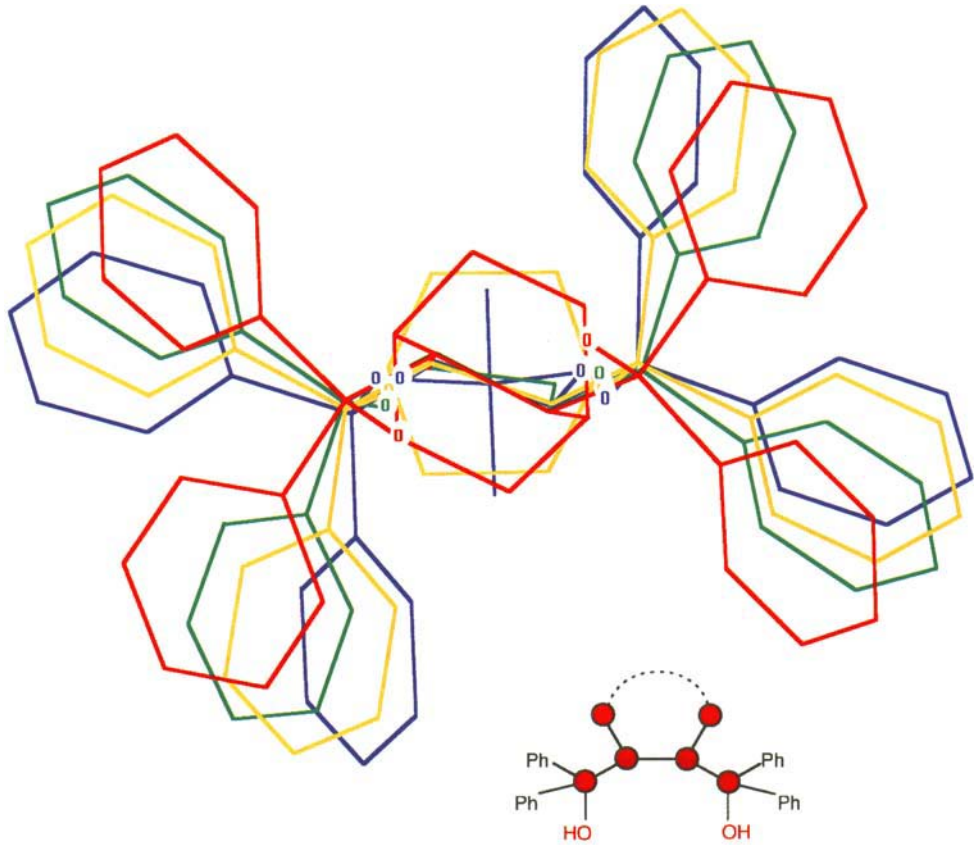


Fig. 9. *Least-squares superimposition of the atoms indicated by the red circles in the inset for ligands* **1a** (blue), ent-**4** (green), *and the two conformers of* ent-**11**, PPP (yellow) *and* PMM (red)

We have previously noted that the reaction catalyzed by Ti-TADDOLate derived from **1a** is considerably faster than that by [Ti(i-PrO)$_4$], which is also present in the reaction mixture [21]. We now have solid evidence (in the form of competition experiments described in *Scheme 8*) that the tetraphenyl ligand **1a** catalyzes the nucleophilic additions of the organometallic reagents considerably faster than tetramethyl ligand **12e**, or the C_2-symmetric dimethyl-diphenyl-substituted ligands **12a** and **12c**.

If two assumptions are made, a relationship can be derived that gives the relative rates for the reaction of each catalyst[24]). The assumptions are: *i*) the selectivity of the reaction(s) is (are) constant throughout the reaction[25]), and *ii*) the mechanisms are similar, and the rate-determining step for each catalyst acting alone and in competition is the same. Under these conditions, the relative rate for two catalysts is given by *Eqn. 1*, were r_A and r_B are the rates for catalysts A and B, respectively; ee_A and ee_B are the enantiomer

[24]) We thank Dr. *M. Garland* of this department for a helpful discussion and for the derivation of *Eqn. 1*.

[25]) This assumption need not be met if the reactions are stopped at low conversion.

excesses observed separately with catalysts A and B, and ee_{obs} is the enantiomer excess observed when catalysts A and B compete.

$$\frac{r_A}{r_B} = \frac{ee_B - ee_{obs}}{ee_{obs} - ee_A} \quad (1)$$

Regarding the first assumption, the selectivity of these reactions as a function of percent conversion has not been explicitly tested. However, we know [21] that the $ZnEt_2$ reaction with TADDOL catalysts affords lower selectivities unless extra $[Ti(i\text{-}PrO)_4]$ is present. This is due to the accumulation of chiral alkoxide that accumulates in the reaction mixture as the reaction proceeds, and which makes a catalyst that is less selective. The extra mol-equiv. of $[Ti(i\text{-}PrO)_4]$ is included in the recipe to introduce 4-fold excess of isopropoxide ligand that serves to dilute the accumulating chiral alkoxide by ligand exchange. We also know that the enantioselectivity of the $ZnEt_2$ addition using ligand **1b** is linear with respect to the enantiomeric purity of the ligand [18]. Furthermore, since the enantioselectivity of TADDOL **1a** is 99% at > 99% conversion, it cannot have fallen (or risen) very much as the reaction proceeds. In the $[TiMe(i\text{-}PrO)_3]$ reactions as described here, there is also 1 mol-equiv. of $[Ti(i\text{-}PrO)_4]$ present[26]), and the 99% selectivity at > 99% conversion for this reaction leaves little room for doubt that the selectivity remains constant as the reaction proceeds.

The competition experiments were set up in such a way that ee_B is always equal (or nearly equal) to zero. For tetramethyl ligand **12e**, this is true in both reactions; the C_2-symmetric dimethyl-diphenyl ligands **12a** and **12c** were used in racemic form to insure 0% ee[27]). *Scheme 8* shows enantiomer-ratio data rounded off to two significant figures, an operation that was judged necessary, because we were evaluating small differences between two large numbers[28]). The data in *Scheme 8* (*Pathway b*) for the $ZnEt_2$ reaction cannot be used in the above equation, because the answer has a zero in the denominator. The same problem arises with the competition between TADDOL **1a** and tetramethyl ligand **12e** in the $[TiMe(i\text{-}PrO)_3]$ addition. However, *rac*-**12a** and *rac*-**12c** compete measurably with TADDOL **1a** in the $[TiMe(i\text{-}PrO)_3]$ addition, with observed relative rates of *ca.* 50:1. In the absence of more reliable data, then, we feel safe in estimating that TADDOL **1a** catalyzes the addition of $[TiMe(i\text{-}PrO)_3]$ or $ZnEt_2$ to benzaldehyde at a rate that is ≥ 50-times faster than in the case of ligands **12a**, **12c**, or **12e**.

Given the structural similarity observed between the X-ray crystal structures of **1a** and **12a** (*cf. Fig. 2* and accompanying discussion), the large difference in rates and selectivities for the two ligands is striking. In the context of the mechanistic hypothesis, we interpret the results of the competition experiments as follows. The rate of exchange of an isopropoxy ligand for the aldehyde was previously found to be critical for enantioselectivity, and we proposed that this exchange is faster in metal complexes where steric crowding is great [21][29]). The TADDOLs **1a** (tetraphenyl) and **1b** (tetranaphthyl) are

---

[26]) The chiral catalyst is made by addition of 1 equiv. of diol ligand to 2 equiv. of $[TiMe(i\text{-}PrO)_3]$, which should afford (after ligand exchange), a mixture of titanium diolate (*e.g.* **2**) and $[Ti(i\text{-}PrO)_4]$.

[27]) Note that the chirality sense of the enatioselectivity of ligand **12c** is opposite to that of **1a** and **12a**.

[28]) *E.g.* 98.6:1.4 or 99.1:0.9. For the signal to noise ratio observed in our chromatograms, these numbers are, within experimental error, the same.

[29]) However, it also appears that if steric crowding becomes too great, the selectivity drops off again. *E.g.*, the catalyst **2** (aryl = 1-naphthyl), exhibits a selectivity of 64:36 in the $ZnEt_2$ reaction [21].

fairly crowded ligands and are also the most selective. The tetramethyl analog **12e** is considerably less crowded, and its catalytic rate is much slower than that of **1a**. Two possibilities may explain the low selectivity observed for this ligand: one is that there is little or no inherent facial bias for this ligand (*vide infra*); the other is that the reaction catalyzed by **12e** may actually be slower than that catalyzed by [Ti(i-PrO)$_4$]. Ligand **12a**, with Ph's in the axial position[6]) and a structure that is very similar to **1a**, is selective (with the same chirality sense as **1a**) but reacts at a considerably slower rate. Thus, the equatorial Ph's are *necessary* to increase the steric crowding required for fast aldehyde/isopropoxy exchange. They are not *sufficient*, however, as seen in the competition between **1a** and *rac*-**12c**, which clearly shows that equatorial Ph's alone do not accelerate the reaction through crowding.

The chirality sense of the enantioselectivities observed for all the tetraphenyl ligands included in this study (**1a**, **4**–**7**, **8a**, **9a**, **b**, **10a**, and **11**) is consistent with the mechanistic model of *Fig. 1*: if the Ti–O–C–Ph$_{axial}$ torsion angle is *P* (*cf. Fig. 1b*), then the organometallic reagent adds to the *Si* face of the aldehyde; if, on the other hand, it is *M*, *Re* addition occurs. Transition-state model **A** (*Fig. 10*) illustrates the situation for a tetraphenyl-substituted chelate, where the nucleophile approaches from the direction of the viewer and the favored orientation of the aldehyde is indicated by solid-line structure and the disfavored orientation by the dashed-line structure. The selectivities of many of the other ligands can be rationalized on the basis of slight modifications of this model. *E.g*, ligand **12h** (see **B**) has an axial[6]) Ph group that would tend to favor attack on the aldehyde *Si* face, if the aldehyde were bound to the top face of the catalyst, but the less hindered bottom face of the catalyst appears to favor *Re*-face attack, as observed. The selectivity of the additions mediated by catalysts containing the two C_2-symmetric methyl-phenyl-substituted ligands **12a** and **12c** can be interpreted in the following way: the topicity of the additions using ligand **12a**, having axial[6]) Ph's and equatorial Me's (see **C**), is the same as with all the tetraphenyl ligands and indicates a greater steric hinderance by an axial Ph than by an equatorial Me. The rate of reaction is slower than for the tetraphenyl ligands (*vide supra*), which may mean that the addition catalyzed by [Ti(i-PrO)$_4$] is competitive, especially for the $ZnEt_2$ addition, which shows only *ca.* 3:1 selectivity. On the other hand, ligand **12c**, having equatorial Ph's and axial[6]) Me's (see **D**) shows a preference for *Re*-face addition, which is consistent with a greater steric demand imposed by an equatorial Ph over an axial Me. Here again, the rate of reaction is not as fast as with a tetraphenyl ligand, and the low selectivity may be due to a combination of low facial bias in the catalyst as well as competition by [Ti(i-PrO)$_4$].

For the C_1-symmetrical ligand **12b**, the observed selectivity is slightly in favor of *Si*-face attack, as would be expected from the preferred orientation when the ligand is bound to the bottom face of the catalyst (see **E**). Finally, the C_1-symmetrical ligand **12d** is also selective for *Si*-face attack as would be expected whether the aldehyde binds to the top or the bottom face of the catalyst, although the bottom face is probably preferred for steric reasons (see **F**).

The kinetic experiments described in *Scheme 8* indicate that the tetramethyl ligand **12e** reacts at least 50 times more slowly than TADDOL **1a**, and the lack of selectivity observed in reactions using catalysts having this ligand or one of the other tetramethyl ligands (**8b**, **10b**) may be due to competition from an addition catalyzed by [Ti(i-PrO)$_4$] and also from a simple lack of facial bias due to the catalyst (see **G**). The tetrabenzyl-

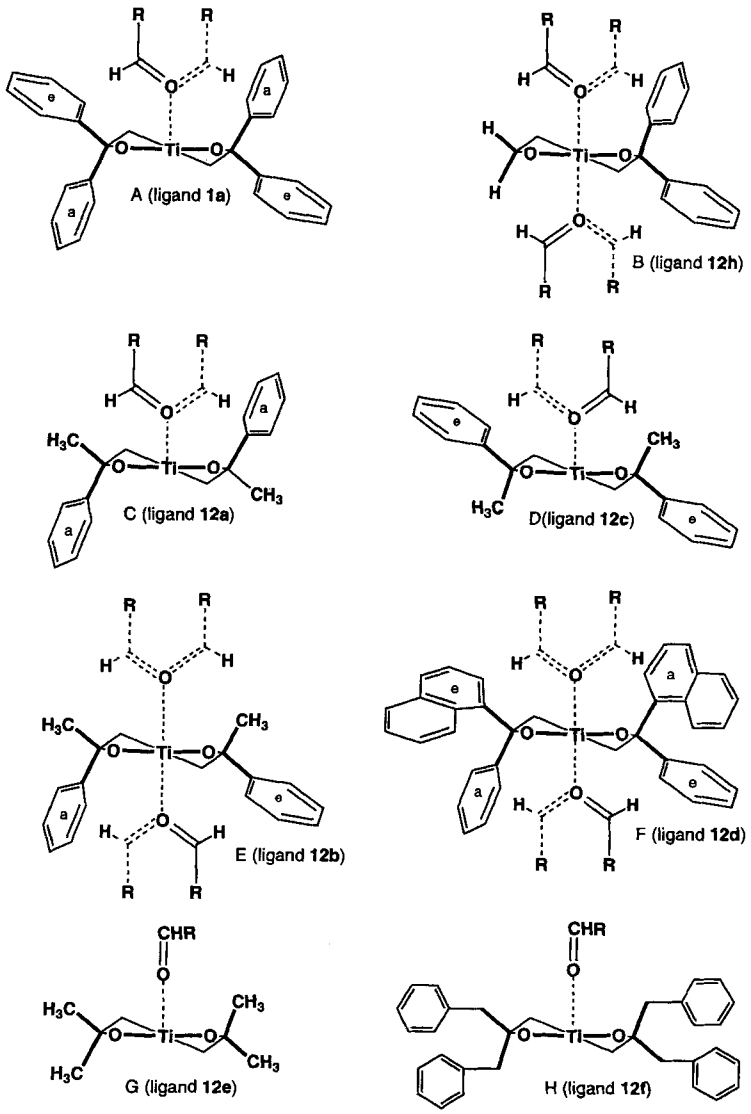


Fig. 10. *Transition-state models for rationalizing the face selectivity of dioxolane ligands* **1a** *and* **12**

substituted ligand **12f** (see **H**) is not much different, probably because the Ph's can orient away from the coordinated aldehyde. The tetracyclohexyl ligand, **12g**, also shows low selectivity [15], most likely due to steric inhibition to binding of the aldehyde, similar to that observed for the tetra(1-naphthyl)-substituted TADDOL[29]). The X-ray structure of **12g** [27] supports this view.

In summary, analysis of the structural features of a number of TADDOL analogs and comparison of these structural features with the selectivities observed in the addition of organometallics to benzaldehyde, mediated by the Ti-complexes of these ligands, indi-

cates that a combination of structural features are necessary for good catalytic efficiency and high selectivity. These features, especially the rather subtle conformational effects, appear to be optimized (among the ligands tested) in the TADDOL's.

We thank Prof. *G. Helmchen* and Dr. *M. Garland* for helpful discussions, Prof. *F. Diederich* for the use of computer facilities, Prof. *H. Waldmann* and *C. Wandrey* for sharing information prior to publication, and Dr. *W. B. Schweizer* (X-ray service, Laboratorium für Organische Chemie, ETH-Zürich) for the X-ray analysis of **45**. We thank the following for financial support: *Sandoz AG, Swiss National Science Foundation, Overseas Research Fund of the Ministry of Education, Science, and Cultur*, Japan fellowship to *Y.N.I. United States National Institutes of Health* (Fogarty Senior International Fellowship to *R.E.G.* (F06 TWO1926-01)), *Stiftung Stipendienfonds der Chemischen Industrie*, Frankfurt a.M. (fellowship to *F.N.M.K.*), Ministerio de Educatión y Ciencia, Spain, fellowship to *X.A.*, *Witco GmbH* (donation of $ZnEt_2$), *Hüls AG* (donation of $[Ti(i\text{-}PrO)_4]$), and *Chemische Fabrik Uetikon* (donation of dimethyl tartrate).

Experimental Part

1. *General.* Abbrevations: h.v. (high vacuum, 0.01–0.001 Torr), t_R (retention time). Cyclohexadiene, cyclopentadiene, fumaric dichloride, furan (–)-(1*R*,2*S*,5*R*)-menthol, PhMgCl (1M in CH_2Cl_2), and $(CF_3CO)_2O$ were from *Fluka AG*; pig-liver esterase (PLE) from *Sigma*, and all were used as received. The molarity of the solns. of MeLi, BuLi, and PhLi (*Chemetall GmbH*) were determined by titration [50]. A 2M stock soln. of $ZnEt_2$ was prepared according to the reported method [15] [21]. A 1M toluene soln. of $[TiMe(i\text{-}PrO)_3]$ was prepared from $[TiCl(i\text{-}PrO)_3]$ and MeLi according to [13]. All other commercially available chemicals used were of *p.a.* quality or purified or dried according to standard methods. TLC: precoated silica gel *60* F_{254} plates (*Merck*); visualization by I_2 or detection by phosphomolybdic acid soln. (phosphomolybdic acid (25 g), $Ce(SO_4)_2 \cdot 4\,H_2O$ (10 g), H_2SO_4 (60 ml), H_2O (940 ml)). Flash chromatography (FC): SiO_2 *60* (0.04–0.063 mm, *Fluka*). HPLC: *Kontron Uvikon LCD 725*; chiral stationary phase (CSP), *Chiracel/OD* 4.6 × 250 mm (*Daicel*): λ 232 or 254 nm; flow 1 ml/min, i-PrOH/hexane, isostatic. Capillary gas chromatography (GC): *HGRC* (*Carlo Erba*); column (*Macherey-Nagel*): heptakis(2,3,6-tris-*O*-ethyl)-β-cyclodextrin in *OV 1701 Vi* (40:60), 20 m × 0.27 mm, glass capillary, or heptakis(2,3,6-tri-*O*-methyl)-β-cyclodextrin in *OV 1701 Vi* (40:60), 50 m × 0.25 mm [51]; injector temp. 250°, detector temp. 250°, heating rate 80°/0.5° per min, pressure 0.5 kPa H_2. Bulb-to-bulb distillation (of the isolated products): *Büchi GKR-50*; b.p. correspond to uncorrected air-bath temp. M.p.: open glass capillaries; *Büchi 510* or *SMP-20*. $[\alpha]_D$ at r.t. (*ca.* 20°); *Perkin-Elmer-241* polarimeter; *p.a.* solvents. IR ($CHCl_3$ or KBr): *Perkin-Elmer 298*; $\tilde{\nu}$ in cm^{-1}. NMR Spectra: *Varian Gemini 200* (200 MHz (^1H), 50 MHz (^{13}C)) or *Bruker WM 300* (300 MHz (^1H), 75 MHz (^{13}C)); δ in ppm rel. to $SiMe_4$ (= 0 ppm), J in Hz; unless stated otherwise, $CDCl_3$ solns.; some of the chemical-shift assignments are based on 2D-HETCOR experiments; the superscripts indicate toward which C-atom a substituent or H-atom is orientated. MS: *VG-Tribrid* spectrometer; fragment ions in m/z with rel. intensities (%) in parentheses. Elemental analyses were performed by the Microanalytical Service of the Laboratorium für Organische Chemie, ETH.

2. *(1S,2S)-α,α,α′,α′-Tetraphenylcyclobutane-1,2-dimethanol* (**4**). Following [30a,b], a suspension of PLE in 3.2M $(NH_4)_2SO_4$ (0.58 ml, containing 17 mg of enzyme) was added to a suspension of dimethyl *cis*-cyclobutane-1,2-dicarboxylate (**13**; 13.7 g, 78 mmol) in phosphate buffer (pH 7.0, 250 ml) at r.t. The mixture was stirred vigorously for 2 d maintaining the pH at 7.0 by pH-stat controlled addition of 1M NaOH. Subsequently, the pH of the mixture was adjusted to 9.0 by adding 1M NaOH. After washing with Et_2O, the mixture was acidified (pH 2) with 6M HCl, saturated with NaCl, and extracted with Et_2O. The Et_2O soln. was dried ($MgSO_4$) and evaporated: *1-methyl 2-hydrogen (1R,2S)-cyclobutane-1,2-dicarboxylate* (**14**; 10.7 g, 90%) which was used without further purification. $[\alpha]_D^{r.t.} = +4.4$ ($c = 0.89$, EtOH; [30b]: *ent*-**14**, $[\alpha]_D^{25} = -3.0$ ($c = 2.11$, $CHCl_3$)).

A soln. of K(*t*-BuO) (7.41 g, 66 mmol) in THF (100 ml) was added to a soln. of **14** (8.73 g, 55 mmol) in THF (30 ml) at 0°. After stirring at r.t. for 1 h, the mixture was cooled to 0°, and conc. HCl soln. (7.0 ml) and ice (*ca.* 30 g) were added. Extraction with Et_2O, drying ($MgSO_4$), and evaporation gave a residue which was diluted with MeOH (150 ml). After adding conc. H_2SO_4 (3 g, 30 mmol), the soln. was refluxed for 8 h. Evaporation, dilution with aq. $NaHCO_3$ soln., extraction with AcOEt, drying ($MgSO_4$), concentration, and distillation *in vacuo* gave **15**/**13** 16:1 (by ^1H-NMR: 3.67 (*s*, Me of **15**); 3.68 (*s*, Me of **13**)). Purification by FC (hexane/AcOEt 1:0→25:1) and distillation *in vacuo* gave **15** as colorless oil (7.47 g, 78% from **14**). CSP GC: 86% ee; t_R 71.7 (**15**), 70.8 min (*ent*-**15**). $[\alpha]_D^{r.t.} = +120$ ($c = 0.85$, acetone); $[\alpha]_D^{r.t.} = +119$ ($c = 1.48$, $CHCl_3$). IR ($CHCl_3$): 3545*m* (br.), 3026*s*, 3001*s*, 2955*m*, 1732*s*, 1437*s*, 1377*m*, 1323*m*, 1246*m*, 1211*m*, 1173*m*, 1026*m*, 957*m*. ^1H-NMR (200 MHz): 3.67 (*s*, 2 Me); 3.40 (*m*, 2 CH); 2.16 (*m*, 2 CH_2).

To a soln. of **15** (2.27 g, 13 mmol) in THF (50 ml), 1.73M PhLi in benzene (36.6 ml, 63 mmol) was added at 0°. After stirring for 1 d, the mixture was diluted with sat. aq. NH_4Cl soln. and extracted with Et_2O. The org. layer was washed with sat. aq. NaCl soln., dried ($MgSO_4$), and evaporated and the residue crystallized from hexane/AcOEt: **4** (3.69 g, 65%). The filtrate was purified by FC (hexane/toluene/AcOEt 6:3:0.5) to afford another crop of **4** (1.08 g, 19%). The combined material (4.77 g, total yield 84%) was recrystallized twice from hexane/AcOEt to afford pure **4** (1.65 g, 29%). Colorless crystals. CSP-HPLC: > 98% ee. M.p. 170–171° ([52]: m.p. 174–175.5°). $[\alpha]_D^{r.t.} = +57.9$ ($c = 0.54$, acetone; [52]: *ent*-**4**, $[\alpha]_D^{29} = -59$ ($c = 0.5$, acetone)); $[\alpha]_D^{r.t.} = +153$ ($c = 1.60$, $CHCl_3$). IR ($CHCl_3$): 3592*s* (br.), 3381*s* (br.), 3061*m*, 3013*s*, 1493*m*, 1447*m*, 1317*w*, 984*w*. ^{1}H-NMR (200 MHz): 7.15–7.40 (*m*, 20 arom. H); 3.46 (*s*, 2 OH); 3.26 (*m*, 2 CH); 1.70–2.00 (*m*, 2 CH_2). MS: 404 (100, $[M - OH]^+$), 220 (58), 207 (30), 193 (11), 183 (89). Anal. calc. for $C_{30}H_{28}O_2$ (420.55): C 85.68, H 6.71; found: C 85.83, H 6.87.

3. *(1S,2S)-α,α,α′,α′-Tetraphenylcyclopentane-1,2-dimethanol* (**5**). Oxalyl chloride (6.48 ml, 68 mmol) and DMF (0.124 ml, 1.6 mmol) were added to a soln. of pimelic acid (**20**; 5.00 g, 31 mmol) in CH_2Cl_2 (31 ml). After stirring for 4 h, the mixture was diluted with hexane (10 ml) and filtered. The filtrate was concentrated and distilled to give pimeloyl chloride (**21**; 6.0 g, 97%). ^{1}H-NMR (200 MHz): 2.91 (*t*, $J = 6.1$, 2 $COCH_2$); 1.73 (*m*, 2 $COCH_2CH_2$); 1.42 (*m*, 2 H–C(4)).

A soln. of 1.55M BuLi in hexane (2.38 ml, 3.69 mmol) was added to a soln. of (2*S*)-1-[(*tert*-butoxy)carbonyl]-2-(*tert*-butyl)-5,5-dimethylimidazolidin-4-one [32] (**22**; 0.993 g, 3.7 mmol) in THF (25 ml) at −18°. At −15°, **21** (0.302 ml, 1.8 mmol) was added to this soln. After stirring for 15 min at r.t., the mixture was diluted with phosphate buffer (pH 7) and extracted with AcOEt. The org. layer was washed with sat. aq. $NaHCO_3$ and NaCl soln., dried ($MgSO_4$), and evaporated. FC (hexane/AcOEt 19:1 to 9:1) gave *(2S,2′S)-1,1′-(1,7-dioxohexane-1,7-diyl)bis{1-[(*tert*-butoxy)carbonyl]-2-(*tert*-butyl)-5,5-dimethylimidazolidin-4-one}* (**23**; 0.828 g, 67% based on **22**). Colorless caramel. ^{1}H-NMR (300 MHz): 6.04, 5.87 (2*s*, CH conformational isomers); 2.7–3.0 (*m*, 2 CH_2CO); 1.4–1.8 (*m*, 3 CH_2); 0.93, 0.91 (2*s*, 2 *t*-Bu).

A soln. of 0.69M LDA (2.94 ml, 2.0 mmol; prepared from BuLi and $(i\text{-}Pr)_2NH$) in THF was added to a soln. of **23** (0.659 g, 1.0 mmol) in THF (15 ml) at −78° and stirred for 2 h. A soln. of I_2 (0.253 g, 1.0 mmol) in THF (3 ml) was then added at −90°. After stirring at −75° for 3 h, the mixture was warmed gradually to r.t., and stirring was continued overnight. A phosphate buffer (pH 7) was added and the mixture extracted with Et_2O, washed with NaCl, dried ($MgSO_4$), and evaporated to give *(2S,2′S)-1,1′-[(1S,2S)-cyclopentane-1,2-dicarbonyl]bis{1-[(*tert*-butoxy)carbonyl]-2-(*tert*-butyl)-5,5-dimethylimidazolidin-4-one}* (**24**)[30]. ^{1}H-NMR (300 MHz): 6.01, 5.85 (2*s*, CH, conformational isomers); 4.25 (br., 2 CH); 1.3–1.8 (*m*, 3 CH_2); 0.94, 0.93, 0.91 (3*s*, 2 *t*-Bu).

The crude **24** was dissolved in THF (10 ml) and 1.7M PhLi in benzene (4.71 ml, 8.0 mmol) added at −78°. After stirring at r.t. overnight, the mixture was diluted with sat. aq. NH_4Cl soln., extracted with AcOEt, dried ($MgSO_4$), and evaporated. FC (hexane/toluene/AcOEt 8:1:1 to 4:0:1) afforded **22** (0.468 g, 87% recovery) and **5** (0.329 g, 76%). Colorless caramel. CSP HPLC: 95% ee. $[\alpha]_D^{r.t.} = +17.8$ ($c = 1.16$, $CHCl_3$). IR ($CHCl_3$): 3600*s* (br.), 3383*s* (br.), 2955*m*, 1599*w*, 1492*m*, 1447*m*, 1321*w* (br.), 1223*s*, 1161*w*, 1001*w*, 980*w*, 916*w*. ^{1}H-NMR (300 MHz): 7.15–7.65 (*m*, 20 arom. H); 3.39 (*m*, 2 CH); 3.15 (*s*, 2 OH); 1.5–1.7 (*m*, 2 $CHCH_2$); 0.91 (*m*, $CH_2CH_2CH_2$). MS: 418 (93, $[M - OH]^+$), 400 (100), 339 (20), 321 (24), 235 (93). Anal. calc. for $C_{31}H_{30}O_2$ (434.58): C 85.68, H 6.96; found: C 85.67, H 7.13.

4. *(1R,2R)-α,α,α′,α′-Tetraphenylcyclohex-4-ene-1,2-dimethanol* (**6**). As described for **4**, with PLE in 3.2M $(NH_4)_2SO_4$ soln. (0.60 ml containing 17 mg of enzyme) and dimethyl *cis*-cyclohex-4-ene-1,2-dicarboxylate (**16**; 11.7 g, 59 mmol) in phosphate buffer (pH 7.1; 250 ml; 4 d, pH maintained at 7.1–7.3 by addition of 2M NaOH; pH then adjusted to 9.0 by adding 2M NaOH): *1-methyl 2-hydrogen (1S,2R)-cyclohex-4-ene-1,2-dicarboxylate* (**17**; 10.5 g 96%). $[\alpha]_D^{r.t.} = +14.9$ ($c = 1.49$, EtOH; [30c]: $[\alpha]_D^{20} = +17.7$ ($c = 1.0$, EtOH)).

A soln. of **17** (2.88 g, 16 mmol) in THF (30 ml) was added to a soln. of K(*t*-BuO) (2.63 g, 23 mmol) in THF (10 ml) at 0°. After stirring at r.t. for 1 h, the mixture was concentrated and acidified with 6M HCl (8 ml). Extraction of the mixture with Et_2O, drying ($MgSO_4$), and evaporation gave a residue which was diluted with MeOH (150 ml). After adding conc. H_2SO_4 (3 g, 30 mmol), the soln. was refluxed for 8 h. Evaporation, dilution with aq. $NaHCO_3$ soln., extraction with AcOEt, drying ($MgSO_4$), concentration, and distillation *in vacuo* gave **16**/**18** 4:1 (by ^{1}H-NMR: 3.69 (*s*, Me of **16**); 3.70 (*s*, Me of **18**)). FC (hexane/AcOEt 1:0 to 50:1) and distillation gave **18**. Colorless oil. $[\alpha]_D^{r.t.} = -140$ ($c = 1.49$, $CHCl_3$). IR ($CHCl_3$): 3600*s* (br.), 3030*s*, 2954*s*, 2849*s*, 1734*s*, 1438*s*, 1350*m*, 1313*m*, 1263*w*, 1232*w*, 1199*m*, 1177*m*. ^{1}H-NMR (200 MHz): 5.68 (*m*, 2 olef. H); 3.70 (*s*, 2 Me); 2.87 (*m*, 2 COCH); 2.1–2.5 (*m*, 2 CH_2).

---

[30]) We have experienced difficulties in reproducing this procedure. By using $CuCl_2$ instead of I_2, **24** could, however, be isolated reproducibly in *ca.* 65% yield [32].

To a soln. of **18** (0.637 g, 3.2 mmol) in THF (13 ml), 1.73M PhLi in benzene (8.93 ml, 15 mmol) was added at 0°. After stirring for 1 d, the mixture was diluted with sat. aq. NH_4Cl soln. and extracted with Et_2O, the org. layer washed with sat. aq. NaCl soln., dried ($MgSO_4$), and evaporated, and the residue recrystallized from hexane/AcOEt: **6** (0.409 g, 29%). Colorless crystals. CSP HPLC: > 98% ee. M.p. 207–208°. $[\alpha]_D^{r.t.} = +62.7$ ($c = 0.84$, acetone); $[\alpha]_D^{r.t.} = +111$ ($c = 1.13$, $CHCl_3$). IR ($CHCl_3$): 3576*s* (br.), 3063*s*, 1596*w*, 1493*m*, 1448*m*, 1348*m* (br.), 982*w*. ^{1}H-NMR (200 MHz): 7.09–7.32 (*m*, 20 arom. H); 5.91 (*m*, 2 olef. H); 2.89 (*s*, 2 OH); 2.75 (*m*, 2 CH, 2 H of CH_2); 2.0–2.2 (*m*, 2 H of CH_2). MS: 429 (21, $[M - OH]^+$), 351 (21), 249 (21), 246 (68), 243 (19), 235 (27), 225 (15), 209 (11), 184 (100). Anal. calc. for $C_{32}H_{30}O_2$ (446.59): C 86.06, H 6.77; found: C 86.06, H 6.90.

5. *(1R,2R)-α,α,α′,α′-Tetraphenylcyclohexane-1,2-dimethanol* (**7**). A mixture of **18** (0.942 g, 4.8 mmol) and 10% Pd/C (0.1 g) in AcOEt (10 ml) was stirred vigorously under H_2 for 1 d. The mixture was filtered and evaporated. The residue (**19**) was diluted with THF (12 ml), and 1.73M PhLi in benzene (11.8 ml, 20 mmol) was added at 0°. After stirring for 1 d, the mixture was diluted with sat. aq. NH_4Cl soln. and extracted with Et_2O. The org. layer was washed with sat. aq. NaCl soln., dried ($MgSO_4$), and evaporated. FC (hexane/toluene/AcOEt 50:10:3) and recrystallization from hexane/AcOEt gave **7** (0.917 g, 43%). Colorless crystals. CSP HPLC: > 98% ee. M.p. 189–190°. $[\alpha]_D^{r.t.} = +131$ ($c = 1.05$, acetone); $[\alpha]_D^{r.t.} = +152$ ($c = 1.17$, $CHCl_3$). IR ($CHCl_3$): 3550*m* (br.), 2945*s* (br.), 1597*m*, 1493*s*, 1147*s*, 1222*s*, 704*w*. ^{1}H-NMR (200 MHz): 7.01–7.38 (*m*, 20 arom. H); 2.88 (*m*, 2 CH); 2.43 (*s*, 2 OH); 1.7–2.1, 1.3–1.6 (2*m*, 4 CH_2). MS: 431 (13, $[M - OH]^+$), 353 (7), 248 (49), 183 (100). Anal. calc. for $C_{32}H_{32}O_2$ (448.60): C 85.68, H 7.19; found: C 85.88, H 7.32.

6. *Bicyclo[2.2.1]hept-5-ene-2-*endo,*3-*exo*-dimethanols* **8a** *and* **8b**. *Di[(1′R,2′S,5′R)-menthyl] (2S,3S)-Bicyclo[2.2.1]hept-5-ene-2-*endo,*3-*exo*-dicarboxylate* (**26**). As described in [38], $SnCl_4$ (11.4 g, 45 mmol) was added at −78° under Ar to a soln. of di[(1′*R*,2′*S*,5′*R*)-menthyl] fumarate (8.84 g, 22.5 mmol) in toluene (80 ml). After 15 min of stirring, cyclopentadiene (3.0 g, 45 mmol) was added dropwise at −78°, and stirring was continued for 2 h. The mixture was slowly warmed up to r.t. overnight, hydrolyzed with sat. $KHCO_3$ soln. (90 ml), and extracted with Et_2O. The org. phase was filtered through *Celite*, dried ($MgSO_4$), and evaporated. The crude product (97% de) was recrystallized from EtOH: 8.91 g (86%) of **26**. ^{1}H-NMR and CSP-HPLC: > 99% de. M.p. 78–79°. $[\alpha]_D^{r.t.} = +0.6$, ($c = 1.1$, $CHCl_3$). IR ($CHCl_3$): 2915*s*, 2860*s*, 1708*s*, 1448*m*, 1367*m*, 1304*m*, 1260*m*, 1173*m*, 1110*m*, 1092*w*, 990*m*, 955*m*, 908*w*, 860*w*. ^{1}H-NMR (500 MHz): 6.29 (*dd*, $J(5,6) = 5.6$, $J(4,5) = 3.2$, H–C(5)); 6.03 (*dd*, $J(5,6) = 5.6$, $J(1,6) = 2.8$, H–C(6)); 4.69, 4.58 (2*ddd*, $J(1'ax,2'ax) = J(1'ax,6'ax) = 10.9$, $J(1'ax,6'eq) = 4.3$, H_{ax}–C(1′)OOC_{exo}–C(3) and H_{ax}–C(1′)OOC_{endo}–C(2′), resp.); 3.35 (*dd*, $J(2exo,3endo) = 4.5$, $J(1,2exo) = 3.8$, H_{exo}–C(2)); 3.26 (*m*, $w_{1/2} \approx 8$, H–C(1)); 3.10 (*m*, $w_{1/2} \approx 7$, H–C(4)); 2.67 (*dd*, $J(2exo,3endo) = 4.5$, $J(3endo,7^{C(5)}) \approx 1.5$, H_{endo}–C(3)); 2.01–1.88 (*m*, 2 H_{eq}–C(6′), 2 Me_2CH–C(2′)); 1.69–1.64 (*m*, 4 menth. H); 1.61 (*dm*, $J_{gem} = 8.7$, $w_{1/2} \approx 4$ each, $H^{C(2)}$–C(7)); 1.53–1.36 (*m*, 4 menth. H); 1.45 (*dddd*, $J_{gem} = 8.7$, $J(1,7^{C(5)}) = J(3endo,7^{C(5)}) = J(4,7^{C(5)}) \approx 1.5$, $H^{C(5)}$–C(7)); 1.12–0.82 (*m*, 6 menth. H); 0.91, 0.90 (2*d*, $J = 7.0$ each, 2 *Me*CH–C(2′)); 0.89, 0.88 (2*d*, $J = 6.5$ each, 2 Me–C(5′)); 0.74, 0.76 (2*d*, $J = 7.0$ each, 2 *Me*CH–C(2′)). ^{13}C-NMR (125 MHz): 174.05, 172.83 (2*s*, 2 C=O); 137.66, 134.88 (2*d*, C(5), C(6)); 74.64, 74.55 (2*d*, 2 C(1′)); 48.13, 47.72, 47.02, 45.90 (4*d*, C(1), C(2), C(3), C(4)); 47.42 (*t*, C(7)); 47.38, 47.07 (2*d*, 2 C(2′)); 40.92, 40.89 (2*t*, 2 C(6′)); 34.30 (*t*, 2 C(4′)); 31.42, 31.38 (2*d*, 2 C(5′)); 26.30, 26.12 (2*d*, 2 Me_2CH–C(2′)); 23.32, 23.23, (2*t*, 2 C(3′)); 22.02, 22.01 (2*q*, *Me*–C(5′)); 20.85, 20.84, 16.12, 16.10 (4*q*, 2 Me_2CH–C(2′)). MS: 458 (0.2, M^+), 183 (60), 182 (49), 165 (22), 139 (59), 138 (100), 137 (14), 117 (47), 95 (31), 83 (59), 81 (27), 69 (21), 67 (12), 66 (28), 57 (12), 55 (20). Anal. calc. for $C_{29}H_{46}O_4$ (458.68): C 75.94, H 10.11; found: C 75.68, H 9.86.

*(2S,3S)-Bicyclo[2.2.1]hept-5-ene-2-*endo,*3-*exo*-dimethanol* (**28**). A soln. of **26** (702 mg, 1.53 mmol) in dry Et_2O (5 ml) was added dropwise to a stirred suspension of $LiAlH_4$ (145 mg) in dry Et_2O (10 ml). The suspension was stirred for 0.5 h at r.t. Sat. NH_4Cl soln. (0.2 ml) was added and the suspension filtered through *Celite*. The crude product was purified by FC (Et_2O/MeOH 15:1, silica gel (85 g)): 177 mg (75%) of **28** [40]. CSP-GC (after trifluoroacetylation (→ **29**)): > 99% ee. B.p. 130–131°/0.05 Torr. $[\alpha]_D^{r.t.} = -23.5$ ($c = 1.0$, $CHCl_3$). IR ($CHCl_3$): 3595*w*, 3360*s* (br.), 2917*s*, 2867*s*, 1628*w*, 1566*w*, 1420*m*, 1330*m*, 1090*m*, 1013*s*, 975*m*, 900*w*, 870*w*. ^{1}H-NMR (500 MHz): 6.23 (*dd*, $J(5,6) = 5.7$, $J(4,5) = 3.2$, H–C(5)); 5.98 (*dd*, $J(5,6) = 5.7$, $J(1,6) = 2.9$, H–C(6)); 3.78 (*dd*, $J_{gem} = 9.9$, $J(3endo,\alpha'a) = 5.5$, H_a–$C(\alpha')_{exo}$); 3.66 (*dd*, $J_{gem} = 9.8$, $J(2exo,\alpha a) = 5.0$, H_a–$C(\alpha)_{endo}$); 3.42 (*dd*, $J_{gem} = 9.9$, $J(3endo,\alpha'b) = 9.9$, H_b–$C(\alpha')_{exo}$); 3.04 (*dd*, $J_{gem} = 9.8$, $J(2exo,\alpha b) = 9.8$, H_b–$C(\alpha)_{endo}$); 3.06–2.89 (*m*, OH); 2.82 (*m*, $w_{1/2} \approx 8$, H–C(1)); 2.59 (*m*, $w_{1/2} \approx 7$, H–C(4)); 1.94 (*dddd*, $J(2exo,\alpha b) = 9.8$, $J(2exo,\alpha a) = 5.0$, $J(2exo,3endo) = 5.0$, $J(1,2exo) = 3.3$, H_{exo}–C(2)); 1.86 (*m*, $w_{1/2} \approx 16$, OH); 1.46 (*dm*, $J_{gem} = 8.6$, $w_{1/2} \approx 4$ each, $H^{C(2)}$–C(7)); 1.45 (*dddd*, $J_{gem} = 8.6$, $J(1,7^{C(5)}) = J(3endo,7^{C(5)}) = J(4,7^{C(5)}) \approx 1.6$, $H^{C(5)}$–C(7)); 1.32 (*dddd*, $J(3endo,\alpha'b) = 9.9$, $J(3endo,\alpha'a) = 5.5$, $J(2exo,3endo) = 5.0$, $J(3endo,7^{C(5)}) = 1.1$, H_{endo}–C(3)). ^{13}C-NMR (125 MHz): 137.99, 133.43 (2*d*, C(5), C(6)); 66.62, 66.10 (2*t*, C(α), C(α′)); 47.95, 46.94, 44.66, 44.56 (4*d*, C(1), C(2), C(3), C(4)); 47.15 (*t*, C(7)). MS: 154 (0.5, M^+), 136 (4), 118 (4), 117 (7), 105 (7), 91 (11), 87 (6), 79 (12), 77 (10), 67 (20), 66 (100). Anal. calc. for $C_9H_{14}O_2$ (154.21): C 70.10, H 9.15; found: C 69.81, H 9.04.

*(2S,3S)-Bicyclo[2.2.1]hept-5-ene-2-*endo,*3-*exo-*dimethyl Bis(trifluoroacetate)* (**29**). In analogy to [53], the following general procedure was applied: Diol **28** (0.02 mmol) was added to a soln. of $(CF_3CO)_2O$ (100 µl) in CH_2Cl_2 (250 µl) under Ar. The mixture was stirred overnight at r.t., the solvent removed, the residue dissolved in CH_2Cl_2 (1 ml), and the soln. analyzed by CSP GC: > 99% ee. B.p. 62–65°/0.05 Torr. $[\alpha]_D^{r.t.} = +35.2$ ($c = 0.72$, $CHCl_3$). IR ($CHCl_3$): 2948*w*, 2864*w*, 1780*s*, 1454*w*, 1398*w*, 1350*m*, 1338*m*, 1230*w*, 1150*s* (br.), 938*w*. ^{1}H-NMR (300 MHz): 6.32 (*dd*, $J(5,6) = 5.7$, $J(4,5) = 3.2$, H–C(5)); 6.11 (*dd*, $J(5,6) = 5.7$, $J(1,6) = 2.9$, H–C(6)); 4.45 (*dd*, $J_{gem} = 10.9$, $J(3endo,\alpha'a) = 6.6$, H_a–C(α′)$_{exo}$); 4.32 (*dd*, $J_{gem} = 10.9$, $J(3endo,\alpha'b) = 8.4$, H_b–C(α′)$_{exo}$); 4.14 (*dd*, $J_{gem} = 10.7$, $J(2exo,\alpha a) = 7.1$, H_a–C(α)$_{endo}$); 4.08 (*dd*, $J_{gem} = 10.7$, $J(2exo,\alpha b) = 8.8$, H_b–C(α)$_{endo}$); 2.95 (*m*, $w_{1/2} \approx 7$, H–C(1)); 2.78 (*m*, $w_{1/2} \approx 6$, H–C(4)); 2.14 (*dddd*, $J(2exo,\alpha b) = 8.8$, $J(2exo,\alpha a) = 7.1$, $J(2exo,3endo) = 4.7$, $J(1,2exo) = 3.3$, H_{exo}–C(2)); 1.61 (*dddd*, $J_{gem} = 9.1$, $J(1,7^{C(5)}) = J(3endo,7^{C(5)}) = J(4,7^{C(5)}) \approx 1.7$, $H^{C(5)}$–C(7)); 1.52 (*dm*, $J_{gem} = 9.1$, $w_{1/2} \approx 4$ each, $H^{C(2)}$–C(7)); 1.44 (*dddd*, $J(3endo,\alpha'b) = 8.4$, $J(3endo,\alpha'a) = 6.6$, $J(2exo,3endo) = 4.7$, $J(3endo,7^{C(5)}) \approx 1.7$, H_{endo}–C(3)). ^{13}C-NMR (75 MHz): 157.48, 157.39 (2*q*, J(C,F) = 43.1 and 42.8, resp., 2 C=O); 138.26, 133.96 (2*d*, C(5), C(6)); 114.60 (*q*, J(C,F) = 285.7, 2 CF_3); 70.70, 70.48 (2*t*, C(α), C(α′)); 46.36 (*t*, C(7)); 44.32, 44.02, 42.60, 42.16 (4*d*, C(1), C(2), C(3), C(4)). MS: 346 (0.1, M^+), 119 (8), 91 (15), 79 (9), 69 (21), 66 (100). Anal. calc. for $C_{13}H_{12}F_6O_4$ (346.21): C 45.10, H 3.49; found: C 45.37, H 3.67.

Transesterification of **26** *with MeOH.* $MeSO_3H$ (0.8 g, 8.38 mmol) was added to a soln. of **26** (1.9 g, 4.19 mmol) in MeOH (60 ml) and the mixture stirred for 2 weeks at 60°. The solvent was removed, the resulting oil dissolved in Et_2O (100 ml), and the mixture washed with sat. Na_2CO_3 soln. and H_2O. The crude product was separated by FC (pentane/Et_2O 10:1, silica gel (90 g)) to give 73 mg (5%) of a 85:15 mixture (by ^{1}H-NMR) of endo-*[(1′R,2′S,5′R)-menthyl]* exo-*methyl (2S,3S)-bicyclo[2.2.1]hept-5-ene-2-*endo,*3-*exo-*dicarboxylate* (**34**) *and* endo-*methyl exo-[(1′R,2′S,5′R)-menthyl] (2S,3S)-bicyclo[2.2.1]hept-5-ene-2-*endo,*3-*exo-*dicarboxylate* (**35**) as well as 583 mg (66%) of *dimethyl (2S,3S)-bicyclo[2.2.1]hept-5-ene-2-*endo,*3-*exo-*dicarboxylate* (**31**).

Data of **34**/**35** 85:15 (see also [38b]): ^{1}H-NMR (400 MHz): among others 6.00, 6.07 (2*dd*, $J(5,6) = 5.6$, $J(1,6) = 2.8$, H–C(6) of **34** and **35**, resp.); 4.58, 4.70 (2*ddd*, $J(1'ax,2'ax) = J(1'ax,6'ax) = 10.8$, $J(1'ax,6'eq) = 4.3$, H_{ax}–C(1′)OOC$_{endo}$–C(2) of **34** and H_{ax}–C(1′)OOC$_{exo}$–C(3) of **35**, resp.); 3.71 (*s*, MeOOC$_{exo}$–C(3) of **34**); 3.64 (*s*, MeOOC$_{endo}$–C(2) of **35**); 3.33, 3.37 (2*dd*, $J(2exo,3endo) = 4.5$, $J(1,2exo) = 4.0$, H_{exo}–C(2) of **34** and **35**, resp.); 2.71, 2.67 (*dd*, $J(2exo,3endo) = 4.5$, $J(3endo,7^{C(5)}) = 1.6$, H_{endo}–C(3) of **34** and **35**, resp.).

Data of **31**: CSP GC (after $LiAlH_4$ reduction and trifluoroacetylation (→ **29**)): > 99% ee. B.p. 58–59°/0.005 Torr. $[\alpha]_D^{r.t.} = +136.6$ ($c = 0.48$, $CHCl_3$). IR ($CHCl_3$): 3520*w*, 2940*m*, 2868*w*, 1715*s*, 1568*w*, 1432*m*, 1354*w*, 1308*m*, 1260*s* (br.), 1170*s* (br.), 1110*m*, 1064*w*, 1016*m*, 945*w*, 905*m*, 858*w*, 824*w*. ^{1}H-NMR (400 MHz): 6.28 (*dd*, $J(5,6) = 5.6$, $J(4,5) = 3.1$, H–C(5)); 6.07 (*dd*, $J(5,6) = 5.6$, $J(1,6) = 2.8$, H–C(6)); 3.72 (*s*, MeOOC$_{exo}$–C(3)); 3.65 (*s*, MeOOC$_{endo}$–C(2)); 3.38 (*dd*, $J(2exo,3endo) = 4.5$, $J(1,2exo) = 3.9$, H_{exo}–C(2)); 3.27 (*m*, $w_{1/2} \approx 8$, among others $J(1,2exo) = 3.9$, $J(1,6) = 2.7$, H–C(1)); 3.13 (*m*, $w_{1/2} \approx 5$, among others $J(4,5) = 3.1$, $J(4,7^{C(2)}) = 0.8$, H–C(4)); 2.69 (*dd*, $J(2exo,3endo) = 4.5$, $J(3endo,7^{C(5)}) = 1.8$, H_{endo}–C(3)); 1.62 (*dm*, $J_{gem} = 8.8$, $w_{1/2} \approx 3$ each, among others $J(4,7^{C(2)}) = 0.8$, $H^{C(2)}$–C(7)); 1.45 (*dddd*, $J_{gem} = 8.8$, $J(1,7^{C(5)}) = J(3endo,7^{C(5)}) = J(4,7^{C(5)}) \approx 1.8$, $H^{C(5)}$–C(7)). ^{13}C-NMR (75 MHz): 174.90, 173.71, (2*s*, 2 C=O); 137.58, 135.19 (2*d*, C(5), C(6)); 52.09, 51.81 (2*q*, 2 MeO); 47.91, 47.65, 47.16, 45.67 (4*d*, C(1), C(2), C(3), C(4)); 47.36 (*t*, C(7)). MS: 210 (3, M^+), 179 (12), 151 (12), 145 (43), 119 (19), 113 (58), 91 (27), 66 (100), 65 (12) 59 (10), 39 (21). Anal. calc. for $C_{11}H_{14}O_4$ (210.23): C 62.85, H 6.71; found: C 62.67, H 6.60.

Transesterification of **26** *with EtOH.* According to [54], a mixture of **26** (6.0, 13 mmol), EtOH (125 ml), and tetraethyl orthotitanate (4.1 g, 18.5 mmol) was refluxed with stirring for 2 weeks under Ar. The solvent was removed and the resulting oil dissolved in Et_2O (100 ml). After addition of H_2O (4 ml), the pale mixture was vigorously stirred for 10 min. The flaky suspension was filtered and the Et_2O soln. evaporated. The residue was separated by FC (pentane/Et_2O 3:1, silica gel (550 g)) to give 1.19 g (26%) of a 75:25 mixture (by ^{1}H-NMR) of endo-*[(1′R,2′S,5′R)-menthyl]* exo-*ethyl (2S,3S)-bicyclo[2.2.1]hept-5-ene-2-*endo,*3-*exo-*dicarboxylate* (**36**) and endo-*ethyl* exo-*[(1′R,2′S,5′R)-menthyl] (2S,3S)-bicyclo[2.2.1]hept-5-ene-2-*endo,*3-*exo-*dicarboxylate* (**37**) as well as 1.63 g (51%) of *diethyl (2S,3S)-bicyclo[2.2.1]hept-5-ene-2-*endo,*3-*exo-*dicarboxylate* (**32**).

Data of **36**/**37** 75:25: CSP-GC (after $LiAlH_4$ reduction and trifluoroacetylation (→ **29**)): > 99% ee. ^{1}H-NMR (500 MHz): among others 6.01, 6.07 (2*dd*, $J(5,6) = 5.6$, $J(1,6) = 2.8$, H–C(6) of **36** and **37**, resp.); 4.58, 4.69 (2*ddd*, $J(1'ax,2'ax) = J(1'ax,6'ax) = 10.9$, $J(1'ax,6'eq) = 4.3$, H_{ax}–C(1′)OOC$_{endo}$–C(2) of **36** and H_{ax}–C(1′)OOC$_{exo}$–C(3) of **37**, resp.); 3.34, 3.39 (2*dd*, $J(2exo,3endo) = 4.5$, $J(1,2exo) = 3.8$, H_{exo}–C(2) of **36** and **37**, resp.); 2.69, 2.66 (2*dd*, $J(2exo,3endo) = 4.5$, $J(3endo,7^{C(5)}) = 1.7$, H_{endo}–C(3) of **36** and **37**, resp.).

Data of **32**: CSP-GC (after $LiAlH_4$ reduction and trifluoroacetylation (→ **29**)): > 99% ee. B.p. 60–61°/0.005 Torr. $[\alpha]_D^{r.t.} = +107.2$ ($c = 1.0$, $CHCl_3$). IR ($CHCl_3$): 2960*m*, 1718*s*, 1442*w*, 1365*m*, 1305*m*, 1260*m* (br.), 1173*m* (br.), 1109*m*, 1024*m*. ^{1}H-NMR (500 MHz): 6.28 (*dd*, $J(5,6) = 5.6$, $J(4,5) = 3.1$, H–C(5)); 6.07 (*dd*, $J(5,6) = 5.6$,

$J(1,6) = 2.8$, H–C(6)); 4.17, 4.17, 4.11, 4.08 (4*q*, $J(1',2') = 7.1$, 2 MeCH_2OOC); 3.37 (*dd*, $J(2exo,3endo) = 4.4$, $J(1,2exo) = 3.8$, H_{exo}–C(2)); 3.26 (*m*, $w_{1/2} \approx 9$, among others $J(1,2exo) = 3.8$, $J(1,6) = 2.8$, $J(1,7^{C(5)}) = 1.6$, H–C(1)); 3.12 (*m*, $w_{1/2} \approx 6$, among others $J(4,5) = 3.2$, $J(4,7^{C(2)}) = 0.9$, H–C(4)); 2.68 (*ddd*, $J(2exo,3endo) = 4.4$, $J(3endo,7^{C(5)}) = 1.8$, $J(3endo,4) = 0.4$, H_{endo}–C(3)); 1.62 (*dm*, $J_{gem} = 8.8$, $w_{1/2} \approx 4$ each, among others $J(4,7^{C(2)}) = 0.9$, $H^{C(2)}$–C(7)); 1.45 (*dddd*, $J_{gem} = 8.8$, $J(1,7^{C(5)}) = J(3endo,7^{C(5)}) = J(4,7^{C(5)}) \approx 1.8$, $H^{C(5)}$–C(7)); 1.28, 1.24 (2*t*, $J(1',2') = 7.1$, 2 *Me*CH_2OOC). ^{13}C-NMR (75 MHz): 174.50, 173.31 (2*s*, 2 C=O); 137.61, 135.12 (2*d*, C(5), C(6)); 60.84, 60.53 (2*t*, 2 CH_2CO); 47.94, 47.81, 47.28, 45.74 (4*d*, C(1), C(2), C(3), C(4)); 47.28 (*t*, C(7)); 14.28, 14.28 (2*q*, 2 Me). MS: 238 (4, M^+), 193 (18), 173 (55), 165 (28), 145 (15), 127 (72), 119 (27), 99 (25), 91 (21), 66 (100), 65 (10), 29 (11). Anal. calc. for $C_{13}H_{18}O_4$ (238.28): C 65.53, H 7.61; found: C 65.70, H 7.45.

General Procedure for **8b** *and* **8a**. According to [17], 1 equiv. of **31** or **32** in Et_2O or THF was added dropwise at 0–5° under Ar to a soln. of 6 equiv. of *Grignard* reagent in Et_2O or THF, resp., cooled with an ice/H_2O bath. After addition, the mixture was stirred for 2 h at 0–5° and then for 4 h under reflux. After cooling to r.t., NH_4Cl was added and the mixture vigorously stirred for 10 min. The suspension was filtered, the filtrate washed with Et_2O, the org. phase dried ($MgSO_4$) and evaporated, and the residue purified by FC.

*(2S,3S)-α,α,α′,α′-Tetraphenylbicyclo[2.2.1]hept-5-ene-2-*endo,*3-*exo*-dimethanol* (**8a**). From **32** (3.1 g, 13 mmol) in THF (30 ml) with PhMgCl in THF (42 g, 78 mmol of a 25% soln.). FC (pentane/Et_2O 3:1, silica gel (550 g)) gave 4.6 g (77.5%) of **8a**. CSP-HPLC: > 99% ee. M.p. 162–163°. $[\alpha]_D^{r.t.} = +171.2$ ($c = 1.0$, $CHCl_3$). IR ($CHCl_3$): 3540*s*, 3349*s* (br.), 3048*m*, 2983*s*, 2875*w*, 1950*w*, 1820*w*, 1596*w*, 1558*w*, 1487*m*, 1442*s*, 1328*m*, 1283*w*, 1156*m*, 1124*m*, 1083*w*, 1030*w*, 1015*w*, 1000*m*, 908*w*. ^{1}H-NMR (500 MHz): 7.59–7.56 (*m*, 2 arom. H); 7.46–7.44 (*m*, 2 arom. H); 7.38–7.35 (*m*, 2 arom. H); 7.33–7.18 (*m*, 14 arom. H); 6.29 (*dd*, $J(5,6) = 5.5$, $J(4,5) = 3.3$, H–C(5)); 5.24 (*dd*, $J(5,6) = 5.5$, $J(1,6) = 2.7$, H–C(6)); 3.90 (*s*, OH); 3.51 (*dd*, $J(2exo,3endo) = 5.8$, $J(1,2exo) = 3.0$, H_{exo}–C(2)); 3.04 (*dd*, $J(2exo,3endo) = 5.8$, $J(3endo,7^{C(5)}) = 1.6$, H_{endo}–C(3)); 2.75 (*m*, $w_{1/2} \approx 7$, H–C(4)); 2.72 (*m*, $w_{1/2} \approx 8$, H–C(1)); 2.58 (*s*, OH); 0.76 (*dddd*, $J_{gem} = 8.6$, $J(1,7^{C(5)}) = J(3endo,7^{C(5)}) = J(4,7^{C(5)}) \approx 1.5$, $H^{C(5)}$–C(7)); 0.18 (*dm*, $J_{gem} = 8.6$, $w_{1/2} \approx 4$ each, $H^{C(2)}$–C(7)). ^{13}C-NMR (75 MHz): 148.87, 148.81, 147.16, 145.02 (4*s*, 4 C_{ipso}); 137.48, 136.15 (2*d*, C(5), C(6)); 128.58, 128.29, 128.09, 127.79, 127.67, 127.48, 127.34, 126.93, 126.67, 126.50 (10*d*, 20 arom. C); 79.73, 78.76 (2*s*, C(α), C(α′)); 49.97, 48.81, 46.60, 46.04 (4*d*, C(1), C(2), C(3), C(4)); 47.91 (*t*, C(7)). MS: 458 (< 0.1, M^+), 422 (20), 269 (13), 259 (21), 258 (100), 217 (16), 192 (16), 190 (22), 183 (24), 167 (49), 165 (22), 105 (37), 77 (19), 28 (30). Anal. calc. for $C_{33}H_{30}O_2$ (458.60): C 86.43, H 6.59; found: C 86.40, H 6.65.

*(2S,3S)-α,α,α′,α′-Tetramethylbicyclo[2.2.1]hept-5-ene-2-*endo,*3-*exo*-dimethanol* (**8b**). From **31** (578 mg, 2.75 mmol) in Et_2O (15 ml) with MeMgI (16.5 mmol, prepared from 401 mg of Mg and 2.342 g of MeI in 10 ml of Et_2O). FC (Et_2O/pentane 2:1, silica gel (80 g)) gave 366 mg (63%) of **8b**. CSP GC: > 99% ee. M.p. 153–154°. $[\alpha]_D^{r.t.} = +3.5$ ($c = 0.48$, $CHCl_3$). IR ($CHCl_3$): 3585*w*, 3360*s* (br.), 2960*s*, 1567*w*, 1469*m*, 1403*w*, 1378*m*, 1368*m*, 1335*w*, 1287*w*, 1154*m*, 1138*w*, 1107*m*, 976*w*, 953*w*, 937*m*, 897*m*, 857*w*. ^{1}H-NMR (300 MHz): 6.25 (*dd*, $J(5,6) = 5.6$, $J(4,5) = 3.2$, H–C(5)); 6.00 (*dd*, $J(5,6) = 5.6$, $J(1,6) = 2.8$, H–C(6)); 3.91 (*s*, 2 OH); 2.84 (*m*, $w_{1/2} \approx 7$, among others $J(1,7^{C(5)}) = 1.6$, $J(1,5) < 0.5$, H–C(1)); 2.53 (*m*, $w_{1/2} \approx 6$, among others $J(4,5) = 3.2$, $J(4,7^{C(5)}) = 1.5$, $J(4,6) < 0.5$, H–C(4)); 2.17 (*dd*, $J(2exo,3endo) = 6.3$, $J(1,2exo) = 3.0$, H_{exo}–C(2)); 1.56 (*dd*, $J(2exo,3endo) = 6.3$, $J(3endo,7^{C(5)}) = 1.5$, H_{endo}–C(3)); 1.53 (*dm*, $J_{gem} = 8.3$, $w_{1/2} \approx 4$ each, $H^{C(2)}$–C(7)); 1.37, 1.33 (2*s*, 2 Me); 1.29 (*dddd*, $J_{gem} = 8.3$, $J(1,7^{C(5)}) = J(3endo,7^{C(5)}) = J(4,7^{C(5)}) \approx 1.7$, $H^{C(5)}$–C(7)); 1.20, 0.96 (2*s*, 2 Me). ^{13}C-NMR (75 MHz): 138.00, 134.30 (2*d*, C(5), C(6)); 71.91 (*s*, C(α), C(α′)); 52.64, 51.89, 46.74, 45.38 (4*d*, C(1), C(2), C(3), C(4)); 48.36 (*t*, C(7)); 31.98, 31.43, 26.48, 26.08 (4*q*, 4 Me). MS: 211 (0.1, $[M + 1]^+$), 191 (1), 178 (3), 177 (22), 135 (15), 134 (100), 133 (11), 127 (30), 119 (89), 117 (19), 111 (25), 109 (13), 105 (17), 93 (16), 92 (25), 91 (45), 83 (16), 69 (26), 66 (76), 59 (34), 43 (38), 41 (13). Anal. calc. for $C_{13}H_{22}O_2$ (210.32): C 74.24, H 10.54; found: C 74.25, H 10.77.

7. *Bicyclo[2.2.1]heptane- and 7-Oxabicyclo[2.2.1]heptane-2-*endo,*3-*exo*-dimethanols* **9a** *and* **9b**, *resp. (2S,3S)-α,α,α′,α′-Tetraphenylbicyclo[2.2.1]heptane-2-* endo,*3-*exo*-dimethanol* (**9a**). A mixture of **8a** (1.83 g, 4 mmol) and 10% Pd/C (120 mg) in Et_2O (200 ml), was stirred under H_2. After 2 h at r.t., the suspension was filtered through *Celite*. The solvent was removed and the crude product recrystallized from pentane/Et_2O: 1.7 g (94%) of **9a**. CSP-HPLC: > 99% ee. M.p. 192–193°. $[\alpha]_D^{r.t.} = +122.2$ ($c = 1.0$, $CHCl_3$). IR ($CHCl_3$): 3545*m*, 3335*s* (br.), 3050*w*, 2940*s* (br.), 2860*m*, 1953*w*, 1810*w*, 1595*m*, 1558*w*, 1487*m*, 1442*s*, 1315*w*, 1299*w*, 1154*w*, 1027*m*, 995*m*, 946*w*, 907*w*, 894*w*. ^{1}H-NMR (500 MHz): 7.58–7.52 (*m*, 4 arom. H); 7.37–7.15 (*m*, 16 arom. H); 4.06 (*s*, OH); 3.24 (*ddd*, $J(2exo,3endo) = 6.8$, $J(1,2exo) = 3.5$, $J(2exo,6exo) = 1.5$, H_{exo}–C(2)); 3.06 (*dm*, $J(2exo,3endo) = 6.8$, $w_{1/2} \approx 3$ each, H_{endo}–C(3)); 2.55 (*s*, OH); 2.28 (*m*, $w_{1/2} \approx 8$, among others $J(4,5exo) = 4.3$, H–C(4)); 2.18 (*m*, $w_{1/2} \approx 9$, H–C(1)); 1.47 (*dddd*, $J_{gem} = 12.2$, $J(5exo,6exo) = 12.2$, $J(4,5exo) = J(5exo,6endo) = 4.3$, H_{exo}–C(5)); 1.39 (*m*, $w_{1/2} \approx 18$, H_{endo}–C(5)); 1.07 (*m*, $w_{1/2} \approx 23$, H_{endo}–C(6)); 0.89 (*ddddd*, $J_{gem} = 12.2$, $J(5exo,6exo) = 12.2$, $J(1,6exo) = J(5endo,6exo) = 5.0$, $J(2exo,6exo) = 1.5$, H_{exo}–C(6)); 0.62 (*dm*, $J_{gem} = 9.8$, $w_{1/2} \approx 4$ each, among others $J(3endo,7^{C(5)}) = 1.5$, $H^{C(5)}$–C(7)); 0.25 (*dm*, $J_{gem} = 9.8$, $w_{1/2} \approx 6$ each, among others $J(5endo,7^{C(2)}) = J(6endo,7^{C(2)}) \approx 1.5$, $H^{C(2)}$–C(7)). ^{13}C-NMR (75 MHz): 149.97, 148.75, 147.00, 145.09 (4*s*, 4

C_{ipso}); 128.68, 128.16, 127.77, 127.56, 127.35, 127.19, 126.89, 126.80, 126.46, 126.38 (10*d*, 20 arom. C); 80.73, 78.50 (2*s*, C(α), C(α')); 53.12, 49.88, 42.67, 41.06 (4*d*, C(1), C(2), C(3), C(4)); 37.36, 30.34, 24.68 (3*t*, C(5), C(6), C(7)). MS: 425 (18), 424 (50), 356 (10), 261 (22), 260 (100), 259 (132), 231 (22), 206 (18), 183 (61), 167 (17), 165 (14), 105 (51), 91 (18), 77 (21), 28 (15), Anal. calc. for $C_{33}H_{32}O_2$ (460.62): C 86.05, H 7.00; found: C 85.90, H 6.88.

*Di[(1'R,2'S,5'R)-menthyl] (2R,3R)- and (2S,3S)-7-Oxabicyclo[2.2.1]hept-5-ene-2-*endo*,3-*exo*-dicarboxylate* (**41** and **42**, resp.). As described in [55], a soln. of *rac*-7-oxabicyclo[2.2.1]hept-5-ene-2-*endo*,3-*exo*-bis(carbonyl chloride) [41] (**40**/*ent*-**40**; 9.6 g, 43.4 mmol) in abs. Et_2O (40 ml) was added dropwise at 0° under Ar to a mixture of (−)-(1*R*,2*S*,5*R*)-menthol (17 g, 108.8 mmol, 2.5 equiv.), pyridine[31]) (8.6 g, 108.8 mmol, 2.5 equiv.; freshly distilled from CaH_2) and abs. Et_2O (150 ml). The mixture was stirred at 0° for 3.5 h (→violet suspension) and then filtered under pressure, the filter cake washed with Et_2O, the solvent evaporated and the excess of pyridine removed under high vacuum at 0°. The crude product (21.5 g) was purified by FC (pentane/Et_2O 5:1) to yield 14.7 g (74%) of clear oily **41**/**42** 1:1. A part (1.5 g) of **41**/**42** was separated by FC (Et_2O/pentane 5:1, silica gel *60* (330 g), ΔR_f (**41**–**42**) 0.04): 0.52 g (35%) of each diastereoisomer. Both decomposed (*retro-Diels-Alder* reaction) in soln. already at r.t., however, slower at +5°.

Data of **41**: ^{1}H-NMR and CSP GC (after hydrogenation, $LiAlH_4$ reduction, and trifluoroacetylation (→ **49**)): > 99% de. M.p. 90.5–92.0° (MeOH). $[\alpha]_D^{r.t.} = +12.1$ (*c* = 0.16, $CHCl_3$). IR ($CHCl_3$): 2940*s*, 2920*s*, 2860*m*, 1718*s*, 1448*m*, 1380*w*, 1368*m*, 1310*m*, 1288*s*, 1173*s*, 1150*w*, 1095*w*, 1030*w*, 1005*w*, 983*s*, 963*m*, 900*m*, 863*m*. ^{1}H-NMR (500 MHz): 6.54 (*dd*, *J*(5,6) = 5.8, *J*(4,5) = 1.8, H–C(5)); 6.30 (*dd*, *J*(5,6) = 5.8, *J*(1,6) = 1.5, H–C(6)); 5.23 (*ddd*, *J*(1,2*exo*) = 4.8, *J*(1,6) = 1.5, *J*(1,4) = 0.9, H–C(1)); 5.21 (*dd*, *J*(4,5) = 1.8, *J*(1,4) = 0.9, H–C(4)); 4.74, 4.59 (2*ddd*, *J*(1'ax,2'ax) = *J*(1'ax,6'ax) = 10.9, *J*(1'ax,6'eq) = 4.2, H_{ax}–C(1')OOC$_{exo}$–(3) and H_{ax}–C(1')OOC$_{endo}$–(2), resp.); 3.57 (*dd*, *J*(1,2*exo*) = 4.8, *J*(2*exo*,3*endo*) = 4.1, H_{exo}–C(2)); 2.83 (*d*, *J*(2*exo*,3*endo*) = 4.1, H_{endo}–C(3)); 2.02, 1.95 (2*dddd*, J_{gem} = 12.0, *J*(1'ax,6'eq) ≈ 4.2, *J*(5'ax,6'eq) ≈ 3.6, *J*(4'eq,6'eq) = 1.8, 2 H_{eq}–C(6')); 1.90, 1.86 (2*qqd*, 2*J* = 7.0 each, *J*(2'ax,CH–C(2')) ≈ 3.0, 2 CH–C(2')); 1.72–1.65 (*m*, 2 H–C(4')); 1.71–1.64 (*m*, 2 H–C(3')); 1.56–1.42 (*m*, 2 H_{ax}–C(5')); 1.46–1.37 (*m*, among others *J*(2'ax,CH–C(2')) ≈ 3.0, 2 H_{ax}–C(2')); 1.12–0.98 (*m*, 2 H–C(3')); 0.99, 0.95 (2*ddd*, J_{gem} = *J*(5'ax,6'ax) ≈ 11.7, *J*(1'ax,6'ax) = 10.9, 2 H_{ax}–C(6')); 0.96–0.87 (*m*, 2 H–C(4')); 0.92–0.91 (*d*, *J* = 7.0, 2 *Me*CH–C(2')); 0.905, 0.899 (2*d*, *J* ≈ 6.6, 2 Me–C(5')); 0.77–0.75 (*d*, *J* = 7.0, 2 *Me*CH–C(2')). ^{13}C-NMR (125 MHz): 171.72, 170.49 (2*s*, 2 C=O); 136.93 (*d*, C(5)); 134.70 (*d*, C(6)); 82.57 (*d*, C(4)); 79.42 (*d*, C(1)); 75.23, 75.20 (2*d*, 2 C(1')); 47.81 (*d*, C(2)); 47.63 (*d*, C(3)); 47.08, 46.85 (2*d*, 2 C(2')); 40.86, 40.76 (2*t*, 2 C(6')); 34.25, 34.19 (2*t*, 2 C(4')); 31.40, 31.37 (2*d*, 2 C(5')); 26.35, 26.21 (2*d*, 2 *C*H–C(2')); 23.33, 23.20 (2*t*, 2 C(3')); 22.00, 21.98 (2*q*, 2 *Me*–C(5')); 20.86, 20.81, 16.19, 16.05 (4*q*, 4 *Me*CH–C(2')). MS ($C_{28}H_{44}O_5$, 462.66): 254 (7), 155 (7), 139 (59), 138 (100), 137 (14), 123 (32), 109 (7), 100 (14), 99 (31), 96 (19), 95 (75), 83 (38), 82 (28), 81 (48), 69 (18), 68 (12), 55 (19), 41 (10).

Data of **42**: ^{1}H-NMR and CSP GC (after hydrogenation, $LiAlH_4$ reduction, and trifluoroacetylation (→ **49**)): > 99% de. Thermally unstable oil. $[\alpha]_D^{r.t.} = -150$ (*c* = 0.46, $CHCl_3$). IR ($CHCl_3$): 2940*s*, 2920*s*, 2860*s*, 1720*s*, 1450*m*, 1383*w*, 1368*m*, 1327*w*, 1312*m*, 1287*s*, 1174*s*, 1150*m*, 1093*m*, 1077*w*, 1033*w*, 1004*m*, 982*s*, 963*m*, 903*s*, 878*w*, 862*m*, 840*w*. ^{1}H-NMR (500 MHz): 6.52 (*dd*, *J*(5,6) = 5.8, *J*(4,5) = 1.8, H–C(5)); 6.36 (*dd*, *J*(5,6) = 5.8, *J*(1,6) = 1.5, H–C(6)); 5.22 (*ddd*, *J*(1,2*exo*) = 4.9, *J*(1,6) = 1.5, *J*(1,4) = 0.9, H–C(1)); 5.18 (*dd*, *J*(4,5) = 1.8, *J*(1,4) = 0.9, H–C(4)); 4.79, 4.64 (2*ddd*, *J*(1'ax,2'ax) = *J*(1'ax,6'ax) = 10.9, *J*(1'ax,6'eq) = 4.4, H_{ax}–C(1')OOC$_{exo}$–C(3) and H_{ax}–C(1')OOC$_{endo}$–C(2), resp.); 3.57 (*dd*, *J*(1,2*exo*) = 4.9, *J*(2*exo*,3'*endo*) = 3.9, H_{exo}–C(2)); 2.82 (*d*, *J* = 2*exo*,3*endo*) = 3.9, H_{endo}–C(3)); 2.06–2.01 (*m*, 2 H_{eq}–C(6')); 1.93–1.79 (*m*, 2 CH–C(2')); 1.73–1.64 (*m*, 2 H–C(4'), 2 H–C(3')); 1.57–1.35 (*m*, 2 H_{ax}–C(5'), 2 H_{ax}–C(2')); 1.12–0.82 (*m*, sequence 2 H–C(3'), 2 H_{ax}–C(6'), 2 H–C(4')); 0.898, 0.902 (2*d*, *J* = 7.0, 2 *Me*CH–C(2')); 0.92 (*d*, *J* = 6.7, 2 Me–C(5')); 0.77, 0.74 (2*d*, *J* = 7.0, 2 *Me*CH–C(2')). ^{13}C-NMR (125 MHz): 171.82, 170.46 (2*s*, 2 C=O); 136.78 (*d*, C(5)); 134.98 (*d*, C(6)); 82.63 (*d*, C(4)); 79.29 (*d*, C(1)); 75.21, 74.94 (2*d*, 2 C(1')); 47.82 (*d*, C(2)); 47.56 (*d*, C(3)); 47.04, 46.96 (2*d*, 2 C(2')); 40.81, 40.72 (2*t*, 2 C(6')); 34.27, 34.19 (2*t*, 2 C(4')); 31.38, 31.37 (2*d*, 2 C(5')); 26.30, 26.27 (2*d*, 2 *C*H–C(2')); 23.45, 23.40 (2*t*, 2 C(3')); 22.00, 21.99 (2*q*, 2 *Me*–C(5')); 20.82, 20.74, 16.34, 16.29 (4*q*, 4 *Me*CH–C(2')).

*Di[(1'R,2'S,5'R)-menthyl] (2R,3R)- and (2S,3S)-7-Oxabicyclo[2.2.1]heptane-2-*endo*,3-*exo*-dicarboxylate* (**43** and **44**, resp.). At 0°, **41**/**42** 1:1 (2.20 g, 4.78 mmol) and 10% Pd/C (95 mg) in Et_2O (200 ml) was stirred under H_2. The temp. was slowly raised to r.t. overnight. The mixture was filtered throught *Celite*, the solvent removed, and the crude product purified by FC (pentane/Et_2O 5:1, silica gel *60*) to yield 2.15 g (97%) of **43**/**44**. A part (1.5 g) of **43**/**44** was separated by FC (Et_2O/pentane 5:1, silica gel *60* (330 g), ΔR_f (**43**–**44**) 0.04): 0.63 g (42%) of each diastereoisomer[32]).

---

[31]) Et_3N is not suitable because of the formation of a by-product that is difficult to separate.

[32]) Each of the diastereoisomers **41** and **42** was also reduced separately to **43** and **44**, resp.

Data of **43**: ^{1}H-NMR and CSP-GC (after $LiAlH_4$ reduction and trifluoroacetylation (→ **49**)): > 99% de. M.p. 90.5–91.5° (MeOH). $[\alpha]_D^{r.t.} = -19.1$ ($c = 0.17$, $CHCl_3$). IR ($CHCl_3$): 2915*s*, 2860*m*, 1716*s*, 1500*m*, 1383*w*, 1368*m*, 1330*m*, 1295*s*, 1170*s*, 1090*w*, 1075*w*, 1048*w*, 1030*w*, 1005*w*, 978*m*, 960*m*, 920*w*, 908*w*, 855*m*, 843*w*. ^{1}H-NMR (400 MHz): 4.84 (*d*, $J(4,5exo) = 5.3$, H–C(4)); 4.80 (*dd*, $J(1,2exo) = J(1,6exo) = 5.1$, H–C(1)); 4.69, 4.66 (2*ddd*, $J(1'ax,6'ax) = 10.9$, $J(1'ax,2'ax) = 8.8$, $J(1'ax,6'eq) = 4.3$, H_{ax}–C(1′)OOC_{exo}–C(3) and H_{ax}–C(1′)OOC_{endo}–C(2), resp.); 3.48 (*ddd*, $J(1,2exo) = J(2exo,3endo) = 5.1$, $J(2exo,6exo) = 1.6$, H_{exo}–C(2)); 3.05 (*d*, $J(2exo,3endo) = 5.1$, H_{endo}–C(3)); 2.02, 1.99 (2*dddd*, $J_{gem} \approx 12.0$, $J(1'ax,6'eq) = 4.3$, $J(5'ax,6'eq) \approx 3.0$, $J(4'eq,6'eq) \approx 1.8$, 2 H_{eq}–C(6′)); 1.89 (*qqd*, $2J \approx 7.0$ each, $J(2'ax,CH–C(2')) \approx 2.8$, 2 CH–C(2′)); 1.85–1.77 (*m*, H–C(5)); 1.73–1.60 (*m*, sequence H–C(4′), 2 H–C(3′), H–C(4′), H–C(6), H–C(5)); 1.59–1.35 (*m*, sequence H–C(6), 2 H_{ax}–C(5′), 2 H_{ax}–C(2′)); 1.12–0.99 (*m*, 2 H–C(3′)); 0.99 (*ddd*, $J_{gem} = J(5'ax,6'ax) \approx 11.8$, $J(1'ax,6'ax) = 10.9$, 2 H_{ax}–C(6′)); 0.91, 0.89 (2*d*, $J = 6.4$, 2 Me–C(5′)); 0.90 (*d*, $J = 7.0$, 2 *Me*CH–C(2′)); 0.93–0.80 (*m*, 2 H–C(4′)); 0.76, 0.75 (*d*, $J = 7.0$, 2 *Me*CH–C(2′)). ^{13}C-NMR (100 MHz): 171.98, 170.85 (2*s*, 2 C=O); 80.63 (*d*, C(4)); 77.93 (*d*, C(1)); 75.32, 75.07 (2*d*, 2 C(1′)); 51.81 (*d*, C(2)); 51.20 (*d*, C(3)); 47.04, 46.78 (2*d*, 2 C(2′)); 40.83 (*t*, 2 C(6′)); 34.23, 34.19 (2*t*, 2 C(4′)); 31.40, 31.37 (2*d*, 2 C(5′)); 29.40 (*t*, C(5)); 26.28, 26.12 (2*d*, 2 CH–C(2′)); 25.57 (*t*, C(6)); 23.30, 23.19 (2*t*, 2 C(3′)); 21.99 (2*q*, 2 *Me*–C(5′)); 20.85, 20.78, 16.17, 16.01 (4*q*, 4 *Me*CH–C(2′)). MS: 462 (0.03, M^+), 187 (53), 186 (97), 169 (21), 168 (26), 158 (19), 141 (24), 140 (14), 139 (70), 138 (93), 124 (14), 123 (29), 118 (33), 117 (10), 97 (21), 96 (12), 95 (44), 83 (100), 82 (12), 81 (40), 69 (41), 68 (16), 67 (18), 57 (27), 55 (44), 43 (18), 41 (23). Anal. calc. for $C_{28}H_{46}O_5$ (462.67): C 72.69, H 10.02; found: C 72.59, H 9.76.

Data of **44**: ^{1}H-NMR und CSP-GC (after $LiAlH_4$ reduction and trifluoroacetylation (→ **49**)): > 99% de. B.p. 135–139°/0.01 Torr. $[\alpha]_D^{r.t.} = -116.5$ ($c = 1.4$, $CHCl_3$). IR ($CHCl_3$): 2940*s*, 2920*s*, 2860*m*, 1720*s*, 1450*m*, 1382*w*, 1368*m*, 1330*m*, 1293*s*, 1173*s*, 1150*w*, 1095*w*, 1078*w*, 1050*w*, 1032*w*, 1005*w*, 978*m*, 960*m*, 905*s*, 855*m*. ^{1}H-NMR (500 MHz): 4.83 (*d*, $J(4,5exo) = 5.4$, H–C(4)); 4.79 (*dd*, $J(1,2exo) = J(1,6exo) = 5.2$, H–C(1)); 4.71, 4.68 (2*ddd*, $J(1'ax,2'ax) = J(1'ax,6'ax) = 10.9$, $J(1'ax,6'eq) = 4.5$, H_{ax}–C(1′)OOC_{exo}–C(3) and H_{ax}–C(1′)OOC_{endo}–C(2), resp.); 3.46 (*ddd*, $J(1,2exo) = J(2exo,3endo) = 5.1$, $J(2exo,6exo) = 1.7$, H_{exo}–C(2)); 3.03 (*d*, $J(2exo,3endo) = 5.1$, H_{endo}–C(3)); 2.08–1.33 (*m*, sequence 2 H_{eq}–C(6′), 2 CH–C(2′), H–C(5), H–C(4′), 2 H–C(3′), H–C(4′), H–C(6), H–C(5), H–C(6), 2 H_{ax}–C(5′), 2 H_{ax}–C(2′)); 1.12–1.02 (*m*, 2 H–C(3′)); 0.99 (*ddd*, $J_{gem} = J(5'ax,6'ax) \approx 11.7$, $J(1'ax,6'ax) = 10.9$, 2 H_{ax}–C(6′)); 0.91, 0.90 (2*d*, $J = 6.6$, 2 Me–C(5′)); 0.94–0.82 (*m*, 2 H–C(4′)); 0.90, 0.89, 0.77, 0.75 (4*d*, $J = 7.1$, 4 *Me*CH–C(2′)). ^{13}C-NMR (125 MHz): 172.06, 170.88 (2*s*, 2 C=O); 80.65 (*d*, C(4)); 77.88 (*d*, C(1)); 75.03, 74.98 (2*d*, 2 C(1′)); 51.44 (*d*, C(2)); 51.03 (*d*, C(3)); 47.00, 46.93 (2*d*, 2 C(2′)); 40.82, 40.78 (2*t*, 2 C(6′)); 34.26, 34.20 (2*t*, 2 C(4′)); 31.40, 31.36 (2*d*, 2 C(5′)); 29.25 (2*t*, C(5)); 26.34, 26.24 (2*d*, 2 CH–C(2′)); 25.61 (*t*, C(6)); 23.49, 23.38 (2*t*, 2 C(3′)); 22.02, 22.00 (2*q*, Me–C(5′)); 20.82, 20.75, 16.39, 16.28 (4*q*, 4 *Me*CH–C(2′)). MS: 462 (0.04, M^+), 187 (57), 186 (98), 169 (24), 168 (28), 158 (19), 141 (23), 140 (13), 139 (75), 138 (100), 124 (13), 123 (27), 118 (32), 117 (11), 97 (19), 96 (10), 95 (39), 83 (96), 82 (10), 81 (33), 69 (35), 68 (12), 67 (13), 57 (20), 55 (31), 43 (12), 41 (14). Anal. calc. for $C_{28}H_{46}O_5$ (462.67): C 72.69, H 10.02; found: C 72.57, H 9.72.

Transesterification of **43** *with MeOH*. A mixture of **43** (7.59 g, 16.4 mmol), dry MeOH (200 ml, 158.2 g, 4.94 mol, 150 equiv.), and $MeSO_3H$ (3.16 g, 2.1 ml, 32.9 mmol) was vigorously refluxed (oil bath 83°) for 6.5 d[33]. The solvent was removed and the resulting oil dissolved in Et_2O (180 ml) and washed with $NaHCO_3$ soln. (3.3 g (39.3 mmol) of $NaHCO_3$ in 50 ml of H_2O) and with H_2O (2 × 25 ml). The crude product (8.2 g) was separated by FC (pentane/AcOEt 10:2) to yield 2.1 g (38%) of endo-*[(1′R,2′S,5′R)-menthyl]* exo-*methyl (2R,3R)-7-oxabicyclo[2.2.1]heptane-2*-endo,*3*-exo-*dicarboxylate* (**45**) and 1.9 g (54%) of *dimethyl (2R,3R)-7-oxabicyclo[2.2.1]-heptane-2*-endo,*3*-exo-*dicarboxylate* (**46**)[34]).

Data of **45**: ^{1}H-NMR and CSP-GC (after $LiAlH_4$ reduction and trifluoroacetylation (→ **49**)): > 99% de. M.p. 74.0–74.5° (MeOH). $[\alpha]_D^{r.t.} = +2.9$ ($c = 0.77$, $CHCl_3$). IR ($CHCl_3$): 2920*m*, 2860*m*, 1719*s*, 1445*m*, 1433*m*, 1365*m*, 1330*m*, 1295*s*, 1170*s*, 978*m*, 950*w*, 921*w*, 908*w*, 850*m*. ^{1}H-NMR (500 MHz): 4.86 (*d*, $J(4,5exo) = 5.4$, H–C(4)); 4.81 (*dd*, $J(1,2exo) = J(1,6exo) = 5.1$, H–C(1)); 4.65 (*ddd*, $J(1'ax,2'ax) = J(1'ax,6'ax) = 10.9$, $J(1'ax,6'eq) = 4.4$, H_{ax}–C(1′)OOC_{endo}–C(2)); 3.72 (*s*, $MeOOC_{exo}$–C(3)); 3.48 (*ddd*, $J(1,2exo) = J(2exo,3endo) = 5.3$, $J(2exo,6exo) = 1.8$, H_{exo}–C(2)); 3.09 (*d*, $J(2exo,3endo) = 5.1$, H_{endo}–C(3)); 2.04 (*dddd*, $J_{gem} = 12.0$, $J(1'ax,6'eq) = 4.4$, $J(5'ax,6'eq) \approx 3.4$, $J(4'eq,6'eq) = 1.8$, H_{eq}–C(6′)); 1.85–1.77 (*m*, H–C(5)); 1.84 (*qqd*, $2J = 7.0$ each, $J(2'ax,CH–C(2')) = 2.8$, CH–C(2′)); 1.73–1.45 (*m*, sequence H–C(4′), H–C(3′), H–C(6), H–C(5), H–C(6), H_{ax}–C(5′)); 1.42 (*dddd*, $J(2'ax,3'ax) \approx 12.4$, $J(1'ax,2'ax) = 10.9$, $J(2'ax,CH–C(2')) = 2.8$, $J(2'ax,3'eq) = 3.4$, H_{ax}–C(2′)); 1.10–0.98 (*m*, H–C(3′)); 0.99 (*ddd*, $J_{gem} = J(5'ax,6'ax) \approx 11.7$, $J(1'ax,6'ax) = 10.9$, H_{ax}–C(6′)); 0.91

---

[33]) The transesterification was much fast at 118° in a sealed tube.

[34]) TLC: detection of **46** in I_2 vapors only at higher concentrations; no detection with UV and phosphomolybdic acid.

(*d*, *J* = 6.8, Me–C(5'), *Me*CH–C(2')); 0.90–0.83 (*m*, H–C(4')); 0.75 (*d*, *J* = 7.0, *Me*CH–C(2')). ^{13}C-NMR (125 MHz): 172.95, 170.74 (2*s*, 2 C=O); 80.59 (*d*, C(4)); 77.90 (*d*, C(1)); 75.47 (*d*, C(1')); 52.31 (*q*, *Me*OOC$_{exo}$–C(3)); 51.96 (*d*, C(2)); 50.72 (*d*, C(3)); 46.81 (*d*, C(2')); 40.86 (*t*, C(6')); 34.19 (*t*, C(4')); 31.42 (*d*, C(5')); 29.30 (*t*, C(5)); 26.09 (*d*, *C*H–C(2')); 25.59 (*t*, C(6)); 23.16 (*t*, C(3')); 21.98 (*q*, *Me*–C(5')); 20.78, 15.95 (2*q*, 2 *Me*CH–C(2')). MS: 338 (0.05, M^+), 201 (26), 200 (42), 183 (27), 182 (26), 172 (45), 168 (23), 155 (43), 154 (11), 141 (30), 140 (12), 139 (44), 138 (96), 132 (84), 131 (42), 127 (29), 124 (13), 123 (100), 114 (42), 113 (28), 97 (19), 96 (14), 95 (61), 83 (78), 82 (12), 81 (43), 69 (37), 68 (17), 67 (26), 57 (15), 55 (36), 43 (14), 41 (23). Anal. calc. for $C_{19}H_{30}O_5$ (338.44): C 67.43, H 8.93; found: C 67.19, H 8.65.

Data of **46**: CSP-GC (after $LiAlH_4$ reduction and trifluoroacetylation (→ **49**)): > 99% ee. M.p. 44.0–45.0° (pentane/Et_2O). $[\alpha]_D^{r.t.}$ = +75.5 (*c* = 0.55, $CHCl_3$). IR ($CHCl_3$): 2990*w*, 2942*m*, 2870*w*, 2840*w*, 1725*s*, 1460*w*, 1433*s*, 1368*m*, 1330*m*, 1298*s*, 1170*s*, 1050*w*, 1030*w*, 990*m*, 980*m*, 920*m*, 903*w*, 880*w*, 850*m*. ^{1}H-NMR (500 MHz): 4.87 (*d*, *J*(4,5*exo*) = 5.4, H–C(4)); 4.81 (*dd*, *J*(1,2*exo*) = *J*(1,6*exo*) = 5.2, H–C(1)); 3.73, 3.72 (2*s*, 2 MeO); 3.51 (*ddd*, *J*(1,2*exo*) = *J*(2*exo*,3*endo*) = 5.2, *J*(2*exo*,6*exo*) = 1.8, H_{exo}–C(2)); 3.08 (*d*, *J*(2*exo*,3*endo*) = 5.2, H_{endo}–C(3)); 1.86–1.76 (*m*, $J_{gem} \approx 11.1$, *J*(4,5*exo*) ≈ 5.4, among other *J*(5*exo*,6*exo*) ≈ 13.0, *J*(5*exo*,6*endo*) ≈ 3.1, H_{exo}–C(5)); 1.72–1.64 (*m*, $J_{gem} \approx 11.6$, *J*(1,6*exo*) ≈ 5.2, *J*(2*exo*,6*exo*) ≈ 1.8, among others *J*(5*exo*,6*exo*) ≈ 11.0, *J*(5*endo*, 6*exo*) ≈ 5.0, H_{exo}–C(6)); 1.62 (*ddd*, $J_{gem} \approx 11.4$, *J*(5*endo*,6*endo*) ≈ 7.8, *J*(5*endo*,6*exo*) = 5.0, H_{endo}–C(5)); 1.52 (*ddd*, $J_{gem} \approx 11.4$, *J*(5*endo*,6*endo*) ≈ 7.4, *J*(5*exo*,6*endo*) ≈ 3.1, H_{endo}–C(6)). ^{13}C-NMR (125 MHz): 172.78, 171.67 (2*s*, 2 C=O); 80.57 (*d*, C(4)); 77.84 (*d*, C(1)); 52.33 , 52.20 (2*q*, 2 MeO); 51.32 (*d*, C(2)); 50.93 (*d*, C(3)); 29.22 (*t*, C(5)); 25.81 (*t*, C(6)). MS: 214 (0.15, M^+), 183 (40), 182 (15), 155 (100), 154 (12), 153 (10), 150 (11), 146 (18), 145 (38), 127 (66), 126 (26), 123 (69), 122 (10), 115 (14), 114 (29), 113 (47), 111 (21), 95 (40), 81 (20), 69 (14), 68 (15), 67 (24), 59 (25), 41 (14). Anal. calc. for $C_{10}H_{14}O_5$ (214.22): C 56.07, H 6.59; found: C 56.11, H 6.52.

Treatment of **46** *with PhMgCl*. As described in [17], a soln. of **46** (1.5 g, 7.0 mmol) in abs. THF (8 ml) was added dropwise at 0° under Ar to a soln. of PhMgCl (23.9 ml, 42 mmol; 6 equiv. of a 25% soln. in THF). Further abs. THF (25 ml) was added and the mixture stirred 15 min in an ice bath, 1 h at r.t., and 2 h under weak reflux (64°, oil bath)[35]. The mixture was cooled to 0°, and Et_2O (20 ml) and 10 g of ice were added. The Et_2O layer was separated, the solid residue washed with THF (2 × 20 ml)[36], and the combined org. layer dried ($MgSO_4$) and filtered. Silica gel (5 g) was added and the solvent evaporated. The solid mixture was separated by FC (pentane/AcOEt 10:4, silica gel (250 g)) to give 0.36 g (11.1%) of (*2R,3R*)-α,α,α',α'-*tetraphenyl-7-oxabicyclo[2.2.1]heptane-2*-endo,*3*-exo-*dimethanol* (**9b**)[37] and 1.6 g (67.5%) of *methyl (2R,3R)-3*-exo-*[hydroxy(diphenyl)methyl]-7-oxabicyclo[2.2.1]heptane-2*-endo-*carboxylate* (**50**).

Data of **9b**: M.p. 249.5–250.0° (MeOH). $[\alpha]_D^{r.t.}$ = +54.6 (*c* = 0.43, THF). IR (nujol): 3540*m*, 3280*m* (br.), 1590*w*, 1480*w*, 1310*w*, 1245*m*, 1220*m*, 1205*w*, 1190*w*, 1170*w*, 1140*m*, 1058*m*, 1025*m*, 995*s*, 970*w*, 955*m*, 925*m*, 910*w*, 895*m*, 870*m*, 838*w*, 805*m*, 765*m*, 748*m*, 733*s*, 722*w*, 700*s*, 685*s*, 650*m*, 630*m*, 615*m*. ^{1}H-NMR (400 MHz): 7.56–7.46, 7.27–7.20, 7.17–7.07, 6.87–6.78, 6.78–6.71 (5*m*, 4, 4, 6, 3, and 3 arom. H); 4.52 (*dd*, *J*(1,2*exo*) = *J*(1,6*exo*) ≈ 5.0, H–C(1)); 4.46 (*s*, OH); 4.47 (*d*, *J*(4,5*exo*) ≈ 5.6, H–C(4)); 3.98 (*ddd*, *J*(1,2*exo*) ≈ 5.0, *J*(2*exo*,3*endo*) ≈ 4.3, *J*(2*exo*,6*exo*) = 1.4, H_{exo}–C(2)); 3.37 (*d*, *J*(2*exo*,3*endo*) = 4.3, H_{endo}–C(3)); 2.63 (*s*, OH); 2.02 (*ddd*, J_{gem} = 12.3, *J*(5*endo*,6*endo*) = 8.7, *J*(5*endo*,6*exo*) = 3.6, H_{endo}–C(5)); 1.87–1.62 (*m*, H_{exo}–C(5), H_{endo}–C(6)); 1.23 (*m*, $w_{1/2} \approx 34$, among others *J* = 11.6, *J*(1,6*exo*) ≈ 5.0, *J*(5*endo*,6*exo*) ≈ 3.6, *J*(2*exo*,6*exo*) = 1.4, H_{exo}–C(6)). ^{13}C-NMR (100 MHz): 149.43, 147.23, 146.86, 145.22 (4*s*, 4 C_{ipso}); 128.21, 128.16 (2*d*, 4 C_o, 2 C_m); 127.61 (*d*, 2 C_m); 126.33, 126.30, 126.19, 126.14 (4*d*, 4 C_p); 125.78 (*d*, 2 C_o); 125.28 (*d*, 2 C_m); 125.05 (*d*, 2 C_o); 123.99 (*d*, 2 C_m); 83.14 (*d*, C(4)); 80.81 (*d*, C(1)); 79.76, 77.10 (2*s*, C(α), C(α')); 51.81 (*d*, C(3)); 50.98 (*d*, C(2)); 28.77 (*t*, C(5)); 26.89 (*t*, C(6)). MS: 444 (0.01, $[M - 18]^+$), 206 (7), 184 (14), 183 (100), 105 (95), 104 (26), 91 (9), 77 (48), 72 (12), 28 (22). Anal. calc. for $C_{32}H_{30}O_3$ (462.59): C 83.09, H 6.54; found: C 82.83, H 6.73.

Data of **50**: M.p. 186.5–187.5° (MeOH). $[\alpha]_D^{r.t.}$ = +20.7 (*c* = 0.16, $CHCl_3$). IR ($CHCl_3$): 3445*m* (br.), 3080*w*, 3030*w*, 2990*m*, 2945*m*, 2870*w*, 1950*w*, 1810*w*, 1725*s*, 1595*m*, 1485*m*, 1460*w*, 1443*s*, 1433*s*, 1380*w*, 1350*m*, 1308*w*, 1293*s*, 1170*s*, 1065*m*, 1018*m*, 1000*m*, 980*w*, 968*m*, 918*m*, 905*w*. ^{1}H-NMR (400 MHz): 7.60–7.55, 7.50–7.45, 7.35–7.28, 7.26–7.17, 7.14–7.08 (5*m*, 2, 2, 2, 3, and 1 arom. H); 4.76 (*dd*, *J*(1,2*exo*) = *J*(1,6*exo*) = 4.9, H–C(1)); 4.52 (*d*, *J*(4,5*exo*) = 5.4, H–C(4)); 4.07 (*s*, OH–C(α')); 3.51 (*s*, MeOOC$_{exo}$–C(3)); 3.51 (*d*, *J*(2*exo*,3*endo*) ≈ 4.5, H_{endo}–C(3)); 3.13 (*ddd*, *J*(1,2*exo*) = *J*(2*exo*,3*endo*) = 4.5, *J*(2*exo*,6*exo*) ≈ 1.2, H_{exo}–C(2)); 1.85–1.74 (*m*, among others J_{gem} = 11.3, *J*(4,5*exo*) ≈ 5.5, H_{exo}–C(5)); 1.74–1.57 (*m*, H_{endo}–C(5), 2 H–C(6)). ^{13}C-NMR (100 MHz): 172.37 (*s*, C=O); 147.39, 145.36 (2*s*, 2 C_{ipso}); 128.35, 127.94 (2*d*, 4 C_m); 126.66, 126.46 (2*d*, 2 C_p); 125.89, 125.66 (2*d*,

---

[35]) At higher temperatures, further by-products were formed.

[36]) Required due to the low solubility of **9b** in Et_2O.

[37]) Longer reaction times did not raise the yield of **9b**, however, the amount of by-products were increased.

4 C_o); 80.49 (*d*, C(4)); 79.16 (*s*, C(α)); 78.48 (*d*, C(1)); 53.88 (*d*, C(3)); 51.92 (*q*, MeO); 50.11 (*d*, C(2)); 28.82 (*t*, C(5)); 26.30 (*t*, C(6)). MS: 338 (0.4, M^+), 184 (31), 183 (100), 182 (13), 155 (8), 138 (7), 105 (67), 77 (33). Anal. calc. for $C_{21}H_{22}O_4$ (338.40): C 74.54, H 6.55; found: C 74.62, H 6.56.

*(2R,3R)-7-Oxabicyclo[2.2.1]heptane-2-*endo*,3-*exo*-dimethanol* (**48**). A soln. of **46** (3.0 g, 14 mmol) in abs. THF (33 ml) was added dropwise to $LiAlH_4$ (1.06, 28 mmol) in abs. THF (20 ml) at 0°. The mixture was stirred overnight at r.t. Et_2O (35 ml) was added, the mixture cooled to 0° and treated with NH_4Cl soln., the Et_2O layer separated, and the solid washed with Et_2O (2 × 15 ml). The combined org. layers were dried ($MgSO_4$) and evaporated. The residual oil was dried 2 h under h.v. and distilled (105°/0.05 Torr): 1.3 g (59%) of viscous, colorless oily **48**. CSP-GC (after trifluoroacetylation (→ **49**)): > 99% ee. B.p. 103–105°/0.01 Torr. $[\alpha]_D^{r.t.} = +43.7$ ($c = 0.50$, EtOH). IR ($CHCl_3$): 3600*w*, 3365*s* (br.), 2940*s*, 2915*s*, 2865*s*, 1460*m*, 1140*w*, 1080*m*, 1030*m*, 993*m*, 970*m*, 920*m*, 895*w*, 880*w*, 860*m*, 810*w*. ^{1}H-NMR (300 MHz): 4.50 (*dd*, $J(1,2exo) = J(1,6exo) = 4.7$, H–C(1)); 4.29 (*d*, $J(4,5exo) = 5.3$, H–C(4)); 3.68 (*s*, 2 OH); 3.60 (*dd*, $J_{gem} = 10.2$, $J(2exo,\alpha a) = 6.5$, H_a–C(α)$_{endo}$); 3.59 (*dd*, $J_{gem} = 9.9$, $J(3endo,\alpha' a) = 6.6$, H_a–C(α′)$_{exo}$); 3.49 (*dd*, $J_{gem} = 10.2$, $J(2exo,\alpha b) = 8.7$, H_b–C(α)$_{endo}$); 3.32 (*dd*, $J_{gem} = 9.9$, $J(3endo,\alpha' b) = 8.6$, H_b–C(α′)$_{exo}$); 1.93 (*dddd*, $J(2exo,\alpha b) = 8.7$, $J(2exo,\alpha a) = 6.5$, $J(2exo,3endo) = 4.9$, $J(1,2exo) = 4.7$, H_{exo}–C(2)); 1.82–1.68 (*m*, among others $J_{gem} = 11.0$, $J(4,5exo) = 5.3$, H_{exo}–C(5)); 1.67–1.56 (*m*, H_{endo}–C(6), H_{exo}–C(6)); 1.51 (*ddd*, $J(3endo,\alpha' b) = 8.6$, $J(3endo,\alpha' a) = 6.6$, $J(2exo,3endo) = 4.9$, H_{endo}–C(3)); 1.41 (*ddd*, $J_{gem} = 11.1$, $J(5endo,6endo) = 8.6$, $J(5endo,6exo) = 4.6$, H_{endo}–C(5)). ^{13}C-NMR (75 MHz): 78.60 (*d*, C(4)); 78.06 (*d*, C(1)); 64.49 (*t*, C(α)); 62.55 (*t*, C(α′)); 50.99 (*d*, C(3)); 49.58 (*d*, C(2)); 29.84 (*t*, C(5)); 24.08 (*t*, C(6)). MS: 159 (1.2, $[M + 1]^+$), 127 (32), 110 (14), 109 (40), 97 (29), 96 (18), 95 (34), 93 (19), 91 (14), 87 (74), 85 (100), 84 (18), 83 (47), 82 (23), 81 (88), 80 (17), 79 (72), 77 (22), 71 (14), 70 (23), 69 (44), 68 (48), 67 (56), 66 (13), 65 (12), 57 (25), 56 (10), 55 (52), 54 (24), 53 (26), 43 (17), 42 (10), 41 (46), 39 (36), 31 (31), 29 (18). Anal. calc. for $C_8H_{14}O_3$ (158.20): C 60.74, H 8.92; found: C 60.61, H 8.80.

*(2R,3R)-7-Oxabicyclo[2.2.1]heptane-2-*endo*,3-*exo*-dimethyl Bis(trifluoroacetate)* (**49**). According to [53], $(CF_3CO)_2O$ (6.0 g, 28.4 mmol, 2.5 equiv.) was added to **48** (0.9 g, 5.69 mmol) under Ar. The mixture was stirred overnight, the excess of $(CF_3CO)_2O$ evaporated, and the residue dried under h.v. and distilled (75°/0.02 Torr): 1.85 g (93%) of **49**. CSP-GC: > 99% ee. B.p. 75°/0.02 Torr. $[\alpha]_D^{r.t.} = +32.8$ ($c = 0.56$, $CHCl_3$). IR ($CHCl_3$): 2980*m*, 2950*m*, 1780*s*, 1460*m*, 1398*m*, 1352*s*, 1235*m*, 1140*s*, 1025*w*, 988*m*, 932*m*, 890*w*, 870*w*, 838*w*, 815*w*. ^{1}H-NMR (300 MHz): 4.62 (*dd*, $J(1,2exo) = J(1,6exo) \approx 4.0$, H–C(1)); 4.46 (*dd*, $J_{gem} = 11.3$, $J(2exo,\alpha a) = 7.2$, H_a–C(α)$_{endo}$); 4.44 (*d*, $J(4,5exo) \approx 5.3$, H–C(4)); 4.31 (*dd*, $J_{gem} = 11.3$, $J(2exo,\alpha b) = 8.7$, H_b–C(α)$_{endo}$); 4.26 (*dd*, $J_{gem} = 10.8$, $J(3endo,\alpha' b) = 8.8$, H_b–C(α′)$_{exo}$); 4.19 (*dd*, $J_{gem} = 10.8$, $J(3endo,\alpha' a) = 6.8$, H_a–C(α′)$_{exo}$); 2.17 (*m*, $w_{1/2} \approx 25$, among others $J(2exo,\alpha b) = 8.7$, $J(1,2exo) \approx 4.0$, $J(2exo,6exo) \approx 1.3$, H_{exo}–C(2)); 1.96–1.80 (*m*, H_{endo}–C(3), H_{exo}–C(5)); 1.80–1.00 (*m*, 2 H–C(6)); 1.49 (*ddd*, $J_{gem} = 11.6$, $J(5endo,6endo) = 7.7$, $J(5endo,6exo) = 5.9$, H_{endo}–C(5)). ^{13}C-NMR (100 MHz): 157.51 (*q*, J(C,CF) = 42.6, C=O); 157.40 (*q*, J(C,CF) = 42.8, C=O); 114.70 (*q*, J(C,F) = 286.1, 2 CF_3); 78.47 (*d*, C(4)); 78.01 (*d*, C(1)); 69.14 (*t*, C(α′)); 67.72 (*t*, C(α)); 46.71 (*d*, C(3)); 44.57 (*d*, C(2)); 29.36 (*t*, C(5)); 24.44 (*t*, C(6)). ^{19}F-NMR (282 MHz): –75.47, –75.48 (2*s*, 2 CF_3). MS: 350 (5, M^+), 122 (20), 109 (14), 105 (12), 95 (49), 94 (12), 93 (25), 81 (39), 80 (12), 79 (68), 78 (15), 77 (13), 69 (100), 68 (16), 67 (27), 66 (10), 55 (22), 53 (14), 41 (23), 39 (11). Anal. calc. for $C_{12}H_{12}F_6O_5$ (350.20): C 41.16, H 3.45, F 32.55; found C 40.91, H 3.48, F 32.78.

$LiAlH_4$ Reduction of **45**. $LiAlH_4$ (10.1 mg, 0.27 mmol, 0.53 equiv.) was added at once to a soln. of **45** (180 mg, 0.53 mmol) in abs. Et_2O (2 ml) at –50° under Ar. The suspension was stirred and the temp. allowed to rise slowly to r.t. overnight. Wet Et_2O (10 ml) and a few drops of sat. NH_4Cl soln. were added. The org. layer was separated, the residue washed with Et_2O (2 × 5 ml), and the combined org. layer dried ($MgSO_4$) evaporated: 35 mg (19.5%) of unreacted **45**, 52 mg (32%) of *(1′R,2′S,5′R)-menthyl (2R,3R)-3-*exo*-(hydroxymethyl)-7-oxabicyclo[2.2.1]heptane-2-*endo*-carboxylate* (**47**) and a small amount of diol **48**.

Data of **47**: CSP-GC (after $LiAlH_4$ reduction and trifluoroacetylation (→ **49**)): de > 99%. M.p. 79.0–81.0° (Et_2O). $[\alpha]_D^{r.t.} = -18.3$ ($c = 0.53$, $CHCl_3$). IR ($CHCl_3$): 3630*w*, 3460*m* (br.), 2960*s*, 2925*m*, 2875*m*, 1720*s*, 1464*m*, 1455*m*, 1387*m*, 1370*m*, 1340*w*, 1308*m*, 1297*m*, 1260*s*, 1179*w*, 1132*w*, 1123*w*, 1089*m*, 1075*w*, 1048*w*, 1030*w*, 1005*m*, 978*m*, 912*m*, 895*m*. ^{1}H-NMR (500 MHz): 4.72 (*dd*, $J(1,2exo) = J(1,6exo) = 5.0$, H–C(1)); 4.66 (*ddd*, J(1′ax, 2′ax) = J(1′ax,6′ax) = 10.9, J(1′ax,6′eq) = 4.4, H_{ax}–C(1′)OOC$_{endo}$–C(2)); 4.48 (*d*, $J(4,5exo) = 5.4$, H–C(4)); 3.53 (*dd*, $J_{gem} = 10.5$, $J(3endo,\alpha' b) = 7.4$, H_b–C(α′)$_{exo}$); 3.50 (*dd*, $J_{gem} = 10.5$, $J(3endo,\alpha' a) = 6.1$, H_a–C(α′)$_{exo}$); 2.68 (*ddd*, $J(1,2exo) = J(2exo,3endo) = 5.0$, $J(2exo,6exo) = 1.8$, H_{exo}–C(2)); 2.36 (*ddd*, $J(3endo,\alpha' b) = 7.4$, $J(3endo,\alpha' a) = 6.1$, $J(2exo,3endo) = 5.0$, H_{endo}–C(3)); 2.02 (*dddd*, $J_{gem} = 12.0$, J(1′ax,6′eq) = 4.4, J(5′ax, 6′eq) ≈ 3.4, J(4′eq,6′eq) = 1.8, H_{eq}–C(6′)); 1.85 (*qqd*, 2J = 7.0 each, J(2′ax,CH–C(2′)) = 2.8, CH–C(2′)); 1.82–1.75 (*m*, H–C(5)); 1.74–1.63 (*m*, H–C(4′), H–C(3′), H–C(6)); 1.66–1.54 (*m*, H–C(5), H–C(6)); 1.55–1.44 (*m*, H_{ax}–C(5′)); 1.40 (*dddd*, J(2′ax,3′ax) = 12.2, J(1′ax,2′ax) = 10.9, J(2′ax,3′eq) ≈ 3.4, J(2′ax,CH–C(2′)) = 2.8, H_{ax}–C(2′)); 1.10–0.99 (*m*, H–C(3′)); 0.97 (*ddd*, J_{gem} = J(1′ax,6′ax) = J(5′ax,6′ax) = 11.5, H_{ax}–C(6′)); 0.93–0.81

(*m*, H–C(4′)); 0.91 (*d*, *J* = 6.9, Me–C(5′), *Me*CH–C(2′)); 0.75 (*d*, *J* = 7.0, *Me*CH–C(2′)). ^{13}C-NMR (125 MHz): 171.50 (*s*, C=O); 79.83 (*d*, C(4)); 77.76 (*d*, C(1)); 75.09 (*d*, C(1′)); 64.87 (*t*, C(α′)); 51.92, 48.24 (2*d*, C(2), C(3)); 46.87 (*d*, C(2′)); 40.90 (*t*, C(6′)); 34.20 (*t*, C(4′)); 31.40 (*d*, C(5′)); 29.30 (*t*, C(5)); 26.12 (*d*, *C*H–C(2′)); 25.95 (*t*, C(6)); 23.16 (*t*, C(3′)); 21.99 (*q*, Me–C(5′)); 20.80, 15.98 (2*q*, 2 *Me*CH–C(2′)). MS: 311 (0.3, $[M+1]^+$), 173 (11), 172 (26), 155 (20), 154 (21), 142 (14), 141 (100), 139 (66), 138 (39), 137 (12), 126 (11), 124 (29), 123 (18), 110 (11), 109 (12), 104 (24), 97 (18), 95 (34), 87 (53), 86 (24), 83 (66), 82 (12), 81 (46), 79 (14), 69 (26), 68 (13), 67 (17), 57 (12), 55 (33), 43 (14), 41 (19). Anal. calc. for $C_{18}H_{30}O_4$ (310.43): C 69.64, H 9.74; found: C 69.73, H 9.74.

8. *Bicyclo[2.2.2]oct-5-ene-2$^{C(6)}$,3$^{C(8)}$-dimethanols* **10a–c** *and Bicyclo[2.2.2]octan-2$^{C(6)}$,3$^{C(8)}$-dimethanol* (**11**). *Di[(1′R,2′S,5′R)-menthyl] (2S,3S)-Bicyclo[2.2.2]oct-5-ene-2$^{C(6)}$,3$^{C(8)}$-dicarboxylate* (**27**). A soln. of di[(1′*R*, 2′*S*,5′*R*)-mentyl] fumarate (1.37 g, 3.49 mmol) in toluene (20 ml) was treated with $AlCl_3$ (0.93 g, 6.98 mmol) at −78° under Ar. After 15 min of stirring, cyclohexadiene (0.56 g, 6.98 mmol) was added dropwise and stirring continued for 2 h. The mixture was slowly warmed up to r.t. overnight, hydrolyzed with sat. $KHCO_3$ soln. (15 ml), and extracted with Et_2O. The org. phase was separated, filtered through *Celite*, and evaporated and the crude product (94% de) recrystallized from EtOH: 1.15 g (70%) of **27**. ^{1}H-NMR and CSP-HPLC: > 99% de. M.p. 118–119°. $[\alpha]_D^{r.t.} = -38.5$ (*c* = 0.56, $CHCl_3$). IR ($CHCl_3$): 2940*s*, 2860*m*, 1708*s*, 1450*m*, 1382*w*, 1368*m*, 1302*w*, 1284*m*, 1175*s*, 1092*w*, 1074*w*, 1018*m*, 978*m*, 958*m*, 893*w*, 839*w*. ^{1}H-NMR (500 MHz): 6.37 (*ddd*, *J*(5,6) = 7.5, *J*(4,5) = 6.9, *J*(1,5) = 1.1, H–C(5)); 6.15 (*ddd*, *J*(5,6) = 7.5, *J*(1,6) = 7.0, *J*(4,6) = 1.0, H–C(6)); 4.69, 4.60 (2*ddd*, *J*(1′ax,2′ax) = *J*(1′ax,6′ax) = 10.9, *J*(1′ax,6′ax) = 4.4, H_{ax}–C(1′)OOC$^{C(8)}$–C(3) and H_{ax}–C(1′)OOC$^{C(6)}$–C(2), resp.); 3.15 (*dd*, *J*(2$^{C(7)}$,3$^{C(5)}$ = 5.5, *J*(1,2$^{C(7)}$) = 2.2, H$^{C(7)}$–C(2)); 3.03 (*m*, $w_{1/2} \approx 13$, among others *J*(1,6) = 7.0, *J*(1,2$^{C(7)}$) = 2.2, *J*(1,5) = 1.1, H–C(1)); 2.94 (*m*, $w_{1,2} \approx 12$, among others *J*(3$^{C(5)}$,4) = 2.9, *J*(4,6) = 1.0, H–C(4)); 2.88 (*ddd*, *J*(2$^{C(7)}$,3$^{C(5)}$) = 5.5, *J*(3$^{C(5)}$,4) = 2.9, *J*(3$^{C(5)}$,8$^{C(5)}$) = 2.0, H$^{C(5)}$–C(3)); 2.05–1.87 (*m*, 2 H_{eq}–C(6′), 2 CH–C(2′)); 1.72–1.64 (*m*, 4 menth. H, H$^{C(2)}$–C(7)); 1.57–1.35 (*m*, 4 menth. H, H$^{C(3)}$–C(8)); 1.31 (*dddd*, J_{gem} = 12.3, *J*(7$^{C(6)}$,8$^{C(5)}$) = 12.2, *J*(1,7$^{C(6)}$) = *J*(7$^{C(6)}$,8$^{C(3)}$) = 3.8, H$^{C(6)}$–C(7)); 1.13 (*ddddd*, J_{gem} = 12.1, *J*(7$^{C(6)}$,8$^{C(5)}$) = 12.2, *J*(7$^{C(2)}$,8$^{C(5)}$) = 4.1, *J*(4,8$^{C(5)}$) = 3.1, *J*(3$^{C(5)}$,8$^{C(5)}$) = 2.0, H$^{C(5)}$–C(8)); 1.08–0.78 (6 menth. H)); 0.92, 0.91 (2*d*, *J* = 7.0 each, 2 *Me*CH–C(2′)); 0.89, 0.88 (2*d*, *J* = 6.2 each, 2 Me–C(5′)); 0.76, 0.74 (2*d*, *J* = 7.0 each, 2 *Me*CH–C(2′)). ^{13}C-NMR (125 MHz): 173.74, 173.47 (2*s*, 2 C=O); 134.69, 132.29 (2*d*, C(5), C(6)); 74.74, 74.51 (2*d*, 2 C(1′)); 47.10, 47.01 (2*d*, 2 C(2′)); 46.36, 45.49 (2*d*, C(2), C(3)); 40.92, 40.87 (2*t*, 2 C(6′)); 34.31 (*t*, 2 C(4′)); 32.79, 32.55 (2*d*, C(1), C(4)); 31.42, 31.39 (2*d*, 2 C(5′)); 26.12, 26.10 (2*d*, 2 CH–C(2′)); 24.64, 20.28 (2*t*, C(7), C(8)); 23.18, 23.12 (2*t*, 2 C(3′)); 22.01 (*q*, 2 Me–C(5′)); 20.88 (*q*, 2 *Me*CH–C(2′)); 16.01, 15.93 (2*q*, 2 *Me*CH–C(2′)). MS: (1, M^+), 198 (11), 197 (100), 196 (46), 179 (47), 178 (30), 151 (18), 139 (39), 138 (91), 123 (15), 95 (27), 83 (46), 81 (21), 80 (10), 79 (13), 69 (15), 55 (14). Anal. calc. for $C_{30}H_{48}O_4$ (472.71): C 76.23, H 10.23; found: C 76.68, H 9.56.

Transesterification of **27** *with MeOH*. As described for the transesterification of **26**, with **27** (6.6 g, 14 mmol): 1.93 g (40%) of a 1:9 mixture (by ^{1}H-NMR) of *(1′R,2′S,5′R)-menthyl$^{C(6)}$ methyl$^{C(8)}$ (2S,3S)-bicyclo[2.2.2]oct-5-ene-2$^{C(6)}$,3$^{C(8)}$-dicarboxylate* (**38**) and *methyl$^{C(6)}$ (1′R,2′S,5′R)-menthyl$^{C(8)}$ (2S,3S)-bicyclo[2.2.2]oct-5-ene-2$^{C(6)}$,3$^{C(8)}$-dicarboxylate* (**39**) as well as 857 mg (27%) of *dimethyl (2S,3S)-bicyclo[2.2.2]oct-5-ene-2$^{C(6)}$,3$^{C(8)}$-dicarboxylate* (**33**).

Data of **38**/**39** 1:9. ^{1}H-NMR (500 MHz): among others 6.13, 6.20 (2*ddd*, *J*(5,6) = *J*(1,6) = 7.6, *J*(4,6) = 0.8, H–C(6) of **38** and **39**, resp.); 4.60, 4.68 (2*ddd*, *J*(1′ax,2′ax) = *J*(1′ax,6′ax) = 10.9, *J*(1′ax,6′eq) = 4.3, H_{ax}–C(1′)OOC$^{C(6)}$–C(2) of **38** and H_{ax}–C(1′)OOC$^{C(8)}$–C(3) of **39**, resp.); 3.71, 3.63 (2*s*, MeOOC$^{C(8)}$–C(3) of **38** and MeOOC$^{C(6)}$–C(2) of **39**, resp.); 3.12, 3.19 (2*dd*, *J*(2$^{C(7)}$,3$^{C(5)}$) = 5.1 and 5.6, resp., *J*(1,2$^{C(7)}$) = 2.2, H$^{C(7)}$–C(2) of **38** and **39**, resp.).

Data of **33**: CSP GC (after $LiAlH_4$ reduction and trifluoroacetylation (→ **30**)): > 99% ee. B.p. 58–59°/0.01 Torr. $[\alpha]_D^{r.t.} = +58.4$ (*c* = 0.45, $CHCl_3$). IR ($CHCl_3$): 2940*s*, 2860*w*, 1720*s*, 1432*m*, 1367*w*, 1307*m*, 1280*s*, 1170*s*, 1110*w*, 1070*w*, 1024*m*, 894*w*, 857*w*. ^{1}H-NMR (300 MHz): 6.37 (*ddd*, *J*(5,6) = 8.0, *J*(4,5) = 6.7, *J*(1,5) = 1.3, H–C(5)); 6.20 (*ddd*, *J*(5,6) = 8.0, *J*(1,6) = 6.5, *J*(4,6) = 1.0, H–C(6)); 3.73 (*s*, MeOOC$^{C(8)}$–C(3)); 3.65 (*s*, MeOOC$^{C(6)}$–C(2)); 3.17 (*dd*, *J*(2$^{C(7)}$,3$^{C(5)}$) = 5.5, *J*(1,2$^{C(7)}$) ≈ 2.4, H$^{C(7)}$–C(2)); 3.03 (*ddddd*, *J*(1,6) = 6.5, *J*(1,7$^{C(6)}$) = 3.6, *J*(1,2$^{C(7)}$) = *J*(1,7$^{C(2)}$) ≈ 2.4, *J*(1,5) = 1.3, H–C(1)); 2.96 (*ddddd*, *J*(4,5) = 6.7, *J*(4,8$^{C(5)}$) = 3.0, *J*(3$^{C(5)}$,4) = 2.8, *J*(4,8$^{C(3)}$) = 2.4, *J*(4,6) = 1.0, H–C(4)); 2.86 (*ddd*, *J*(2$^{C(7)}$,3$^{C(5)}$ = 5.5, *J*(3$^{C(5)}$,4) = 2.8, *J*(3$^{C(5)}$,8$^{C(5)}$) = 2.0, H$^{C(5)}$–C(3)); 1.65 (*dddd*, J_{gem} = 12.2, *J*(7$^{C(2)}$,8$^{C(3)}$) ≈ 9.5, *J*(7$^{C(2)}$,8$^{C(5)}$) = 4.1, *J*(1,7$^{C(2)}$) ≈ 2.4, H$^{C(2)}$–C(7)); 1.49 (*dddd*, J_{gem} = 12.2, *J*(7$^{C(2)}$,8$^{C(3)}$) ≈ 9.5, *J*(7$^{C(6)}$,8$^{C(3)}$) = 3.6, *J*(4,8$^{C(3)}$) = 2.4, H$^{C(3)}$–C(8)); 1.30 (*dddd*, J_{gem} = *J*(7$^{C(6)}$,8$^{C(5)}$) = 12.2, *J*(1,7$^{C(6)}$) = *J*(7$^{C(6)}$,8$^{C(3)}$) = 3.6, H$^{C(6)}$–C(7)); 1.16 (*ddddd*, J_{gem} = *J*(7$^{C(6)}$,8$^{C(5)}$) = 12.2, *J*(7$^{C(2)}$,8$^{C(5)}$) = 4.1, *J*(4,8$^{C(5)}$) = 3.0, *J*(3$^{C(5)}$,8$^{C(5)}$) = 2.0, H$^{C(5)}$–C(8)). ^{13}C-NMR (75 MHz): 174.68, 174.38 (2*s*, 2 C=O); 134.57, 132.53 (2*d*, C(5), C(6)); 52.05, 51.95 (2*q*, 2 MeO); 46.06, 45.27 (2*d*, C(2), C(3)); 32.57, 32.43 (2*d*, C(1), C(4)); 24.54, 20.36 (2*t*, C(7), C(8)). MS: 224 (2, M^+), 193 (15), 192 (30), 165 (26), 164

(29), 145 (32), 137 (20), 133 (10), 114 (34), 113 (27), 105 (64), 104 (12), 91 (24), 87 (14), 80 (100), 79 (64), 78 (47), 77 (54), 59 (57), 52 (10), 51 (18), 39 (20). Anal. calc. for $C_{12}H_{16}O_4$ (224.26): C 64.27, H 7.19; found: C 64.17, H 6.97.

General Procedure for **10a** *and* **10b**. As described for **8a** and **8b**, with 6 equiv. of *Grignard* reagent and 1 equiv. of **33**.

(2S,3S)-α,α,α′,α′-Tetraphenylbicyclo[2.2.2]oct-5-ene-2 $^{C(6)}$*,3* $^{C(8)}$*-dimethanol* (**10a**). From **33** (673 mg, 3.0 mmol) in THF (15 ml) and PhMgCl in THF (9.8 g, 18 mmol of a 25% soln.), FC (pentane/Et_2O 3:1, silica gel (80 g)) led to 1.18 g (83%) of **10a**, which was sublimed (220–225°/0.005 Torr). M.p. 241–242° (evacuated sealed capillary tube). $[\alpha]_D^{r.t.} = +201.5$ ($c = 0.46$, $CHCl_3$). IR ($CHCl_3$): 3575*m*, 3350*s* (br.), 3045*m*, 2980*m*, 2935*s*, 2853*w*, 1950*w*, 1810*w*, 1595*m*, 1577*w*, 1488*m*, 1440*s*, 1363*w*, 1315*m*, 1165*m*, 1082*w*, 1056*w*, 1027*m*, 998*m*, 968*w*, 942*w*, 908*m*. ^{1}H-NMR (300 MHz): 7.49–7.16 (*m*, 20 arom. H); 6.11 (*ddd*, $J(5,6) = 8.0$, $J(4,5) = 6.7$, $J(1,5) \approx 1.0$, H–C(5)); 4.91 (*ddm*, $J(5,6) = 8.0$, $J(1,6) = 6.2$, $w_{1/2} \approx 2$ each, H–C(6)); 4.23, 3.69 (2*s*, 2 OH); 3.48 (*dm*, $J(2^{C(7)},3^{C(5)}) = 7.2$, $w_{1/2} \approx 3$ each, $H^{C(7)}$–C(2)); 3.28 (*dm*, $J(2^{C(7)},3^{C(5)}) = 7.2$, $w_{1/2} \approx 4$ each, $H^{C(5)}$–C(3)); 2.57 (*m*, $w_{1/2} \approx 13$, H–C(1)); 2.48 (*m*, $w_{1/2} \approx 13$, H–C(4)); 1.35 (*dddd*, $J_{gem} = 12.2$, $J(7^{C(2)},8^{C(3)}) = 9.3$, $J(7^{C(2)},8^{C(5)}) = 5.4$, $J(1,7^{C(2)}) = 2.2$, $H^{C(2)}$–C(7)); 1.00 (*dddd*, $J_{gem} = J(7^{C(6)},8^{C(5)}) = 12.2$, $J(1,7^{C(6)}) = J(7^{C(6)},8^{C(3)}) = 3.7$, $H^{C(6)}$–C(7)); 0.34 (*ddddd*, $J_{gem} = 12.5$, $J(7^{C(6)},8^{C(5)}) = 12.2$, $J(7^{C(2)},8^{C(5)}) = 5.4$, $J(4,8^{C(5)}) = 3.2$, $J(3^{C(5)},8^{C(5)}) \approx 1.5$, $H^{C(5)}$–C(8)); 0.22 (*dddd*, $J_{gem} = 12.5$, $J(7^{C(2)},8^{C(3)}) = 9.3$, $J(7^{C(6)},8^{C(3)}) = 3.7$, $J(4,8^{C(3)}) = 2.6$, $H^{C(3)}$–C(8)). ^{13}C-NMR (125 MHz): 149.82, 148.42, 146.83, 146.19 (4*s*, 4 C_{ipso}); 134.89, 131.42 (2*d*, C(5), C(6)); 128.87, 128.25, 128.12, 127.92, 127.51, 127.17, 126.98, 126.83, 126.70, 126.02 (10*d*, 20 arom. C); 80.65, 78.86 (2*s*, C(α), C(α′)); 47.20, 46.42 (2*d*, C(2), C(3)); 34.95, 34.29 (2*d*, C(1), C(4)); 25.80, 20.05 (2*t*, C(7), C(8)). MS: 272 (15), 244 (17), 192 (12), 183 (42), 167 (11), 165 (12), 105 (100), 91 (13), 78 (21), 77 (69), 51 (12), 28 (14). Anal. calc. for $C_{34}H_{32}O_2$ (472.63): C 86.41, H 6.82; found: C 85.91, H 6.84.

(2S,3S)-α,α,α′,α′-Tetramethylbicyclo[2.2.2]oct-5-ene-2 $^{C(6)}$*,3* $^{C(8)}$*-dimethanol* (**10b**). From **33** (673 mg, 3.0 mmol) in Et_2O (15 ml) with MeMgI (18 mmol, prepared from 437 mg of Mg and 2.555 g of MeI in 10 ml of Et_2O), FC (Et_2O/pentane 2:1, silica gel (80 g)) gave 387 mg (58%) of **10b**. M.p. 170–171°. $[\alpha]_D^{r.t.} = -46.4$ ($c = 0.55$, $CHCl_3$). IR ($CHCl_3$): 3585*w*, 3340*s* (br.), 3024*w*, 2950*s*, 2860*w*, 1720*w*, 1640*w*, 1463*m*, 1408*m*, 1368*s*, 1320*w*, 1155*s*, 1138*w*, 1075*w*, 967*w*, 944*m*, 913*s*, 877*w*, 860*w*. ^{1}H-NMR (500 MHz): 6.31 (*ddd*, $J(5,6) = 8.0$, $J(4,5) = 7.0$, $J(1,5) = 1.3$, H–C(5)); 6.04 (*ddd*, $J(5,6) = 8.0$, $J(1,6) = 5.7$, $J(4,6) \approx 1.0$, H–C(6)); 4.22–3.46 (*s*, 2 OH); 2.62 (*ddddd*, $J(4,5) = 7.0$, $J(3^{C(5)},4) = J(4,8^{C(3)}) = J(4,8^{C(5)}) \approx 2.6$, $J(4,6) \approx 1.0$, H–C(4)); 2.55 (*m*, $w_{1/2} \approx 13$, among others $J(1,6) = 5.7$, $J(1,7^{C(2)}) = 2.3$, $J(1,2^{C(7)}) = 1.6$, H–C(1)); 1.88 (*dd*, $J(2^{C(7)},3^{C(5)}) = 6.6$, $J(1,2^{C(7)}) = 1.6$, $H^{C(7)}$–C(2)); 1.69 (*dddd*, $J_{gem} = 12.8$, $J(7^{C(2)},8^{C(3)}) = 9.7$, $J(7^{C(6)},8^{C(3)}) = 3.6$, $J(4,8^{C(3)}) = 2.6$, $H^{C(3)}$–C(8)); 1.66 (*m*, $w_{1/2} \approx 8$, $H^{C(5)}$–C(3)); 1.44 (*dddd*, $J_{gem} = 12.5$, $J(7^{C(2)},8^{C(3)}) = 9.7$, $J(7^{C(2)},8^{C(5)}) = 5.5$, $J(1,7^{C(2)}) = 2.3$, $H^{C(2)}$–C(7)); 1.33 (*s*, 3 Me); 1.31 (*dddd*, $J_{gem} = 12.5$, $J(7^{C(6)},8^{C(5)} = 12.3$, $J(1,7^{C(6)}) = J(7^{C(6)},8^{C(3)}) = 3.6$, $H^{C(6)}$–C(7)); 0.97 (*ddddd*, $J_{gem} = 12.8$, $J(7^{C(6)},8^{C(5)}) = 12.3$, $J(7^{C(2)},8^{C(5)}) = 5.5$, $J(4,8^{C(5)}) = 2.6$, $J(3^{C(5)},8^{C(5)}) = 1.7$, $H^{C(5)}$–C(8)); 0.98 (*s*, Me). ^{13}C-NMR (125 MHz): 135.64, 131.92 (2*d*, C(5), C(6)); 73.21, 71.93 (2*s*, C(α), C(α′)); 50.94, 50.15 (2*d*, C(2), C(3)); 32.96, 32.88 (2*d*, C(1), C(4)); 31.64, 30.93, 27.11, 26.99 (4*q*, 4 Me); 26.04, 20.50 (2*t*, C(7), C(8)). MS: 191 (12), 149 (10), 148 (65), 145 (10), 133 (65), 121 (10), 120 (83), 119 (14), 117 (13), 109 (10), 108 (18), 107 (11), 106 (15), 105 (100), 93 (25), 92 (27), 91 (31), 80 (70), 79 (44), 78 (16), 77 (19), 59 (48), 43 (28), 41 (13). Anal. calc. for $C_{14}H_{24}O_2$ (224.34): C 74.95, H 10.78; found: C 74.80, H 11.14.

(2S,3S)-Bicyclo[2.2.2]oct-5-ene-2 $^{C(6)}$*,3* $^{C(8)}$*-dimethanol* (**10c**). As described for **28**, with **27** (581 mg, 1.23 mmol): 162 mg (78.5%) of **10c**. CSP-GC (after trifluoroacetlyation (→ **30**)): > 99% ee. M.p. 97–98°. $[\alpha]_D^{r.t.} = -93.8$ ($c = 0.56$, $CHCl_3$). IR ($CHCl_3$): 3609*w*, 3360*m* (br.), 2922*s*, 2861*m*, 1637*w*, 1610*w*, 1462*m*, 1370*w*, 1308*w*, 1164*w*, 1068*w*, 1050*m*, 1024*s*, 988*s*, 855*w*, 834*w*. ^{1}H-NMR (300 NMR): 6.36 (*ddd*, $J(5,6) = 8.0$, $J(4,5) = 6.7$, $J(1,5) = 1.2$, H–C(5)); 6.12 (*ddd*, $J(5,6) = 8.0$, $J(1,6) = 5.6$, $J(4,6) \approx 1.0$, H–C(6)); 3.65 (*dd*, $J_{gem} = 9.8$, $J(3^{C(5)},\alpha'a) = 5.3$, H_a–C(α′)$^{C(8)}$); 3.55 (*dd*, $J_{gem} = 9.7$, $J(2^{C(7)},\alpha a) = 5.2$, H_a–C(α)$^{C(6)}$); 3.54 (*dd*, $J_{gem} = 9.8$, $J(3^{C(5)},\alpha'b) = 9.5$, H_b–C(α′)$^{C(8)}$); 3.13 (*dd*, $J_{gem} = 9.7$, $J(2^{C(7)},\alpha b) = 9.6$, H_b–C(α)$^{C(6)}$); 2.84 (*s*, $w_{1/2} \approx 10$, OH); 2.47 (*m*, $w_{1/2} \approx 12$, H–C(4)); 2.43 (*m*, $w_{1/2} \approx 13$, H–C(1)); 1.71 (*s*, $w_{1/2} \approx 4$, OH); 1.57 (*dddd*, $J_{gem} = 11.6$, $J(7^{C(2)},8^{C(3)}) = 9.7$, $J(7^{C(6)},8^{C(3)}) = 3.9$, $J(4,8^{C(3)}) = 2.4$, $H^{C(3)}$–C(8)); 1.56 (*m*, $w_{1/2} \approx 19$, $H^{C(7)}$–C(2)); 1.48 (*dddd*, $J_{gem} = 12.1$, $J(7^{C(2)},8^{C(3)}) = 9.7$, $J(7^{C(2)},8^{C(5)}) = 3.8$, $J(1,7^{C(2)}) = 2.4$, $H^{C(2)}$–C(7)); 1.38 (*ddddd*, $J(3^{C(5)},\alpha'b) = 9.5$, $J(3^{C(5)},\alpha'a) = 5.3$, $J(2^{C(7)},3^{C(5)}) = 5.3$, $J(3^{C(5)},4) = 2.3$, $J(3^{C(5)},8^{C(5)}) = 1.7$, $H^{C(5)}$–C(3)); 1.30 (*dddd*, $J_{gem} = 12.1$, $J(7^{C(6)},8^{C(5)}) = 11.6$, $J(1,7^{C(6)}) = J(7^{C(6)},8^{C(3)}) = 3.9$, $H^{C(6)}$–C(7)); 1.10 (*ddddd*, $J_{gem} = 11.6$, $J(7^{C(6)},8^{C(5)}) = 11.6$, $J(4,8^{C(5)}) = 3.1$, $J(7^{C(2)},8^{C(5)}) = 3.8$, $J(3^{C(5)},8^{C(5)}) = 1.7$, $H^{C(5)}$–C(8)). ^{13}C-NMR (125 MHz): 135.70, 131.97 (2*d*, C(5), C(6)); 67.85, 66.49 (2*t*, C(α), C(α′)); 46.90, 44.51 (2*d*, C(2), C(3)); 32.34, 32.02 (2*d*, C(1), C(4)); 25.82, 19.37 (2*t*, C(7), C(8)). MS: 168 (5, M^+), 150 (8), 132 (5), 92 (12), 91 (21), 81 (11), 80 (100), 79 (51), 78 (16), 77 (17). Anal. calc. for $C_{10}H_{16}O_2$ (168.24): C 71.39, H 9.59; found: C 71.40, H 9.38.

(2S,3S)-Bicyclo[2.2.2]oct-5-ene-2 $^{C(6)}$*,3* $^{C(8)}$*-dimethyl Bis(trifluoroacetate)* (**30**). In analogy to [53], **10c** (0.02 mmol) was added to a soln. of $(CF_3CO)_2O$ (100 µl) in CH_2Cl_2 (250 µl) under Ar. The mixture was stirred

overnight at r.t., the solvent removed, the residue dissolved in CH_2Cl_2 (1 ml), and the soln. analyzed by CSP-GC: > 99% ee. B.p. 80–82°/0.01 Torr. $[\alpha]_D^{r.t.} = +8.6$ ($c = 0.54$, $CHCl_3$). IR ($CHCl_3$): 2935*m*, 2865*w*, 1780*s*, 1457*w*, 1396*m*, 1340*m*, 1150*s* (br.), 937*m*. ^{1}H-NMR (500 MHz): 6.43 (*ddd*, $J(5,6) = 8.0$, $J(4,5) = 6.8$, $J(1,5) = 1.2$, H–C(5)); 6.10 (*ddd*, $J(5,6) = 8.0$, $J(1,6) = 6.6$, $J(4,6) = 1.0$, H–C(6)); 4.42 (*dd*, $J_{gem} = 10.9$, $J(3^{C(5)},\alpha' a) = 6.5$, H_a–$C(\alpha')^{C(8)}$); 4.30 (*dd*, $J_{gem} = 10.9$, $J(3^{C(5)},\alpha' b) = 9.1$, H_b–$C(\alpha')^{C(8)}$); 4.08–4.01 (*m*, 2 H–$C(\alpha)^{C(6)}$); 2.57 (*m*, $w_{1/2} \approx 25$, H–C(1), H–C(4)); 1.68 (*dddd*, $J_{gem} = 12.0$, $J(7^{C(2)},8^{C(3)}) = 9.6$, $J(7^{C(6)},8^{C(3)}) = 4.0$, $J(4,8^{C(3)}) = 2.5$, $H^{C(3)}$–C(8)); 1.66 (*m*, $w_{1/2} = 24$, among others $J(1,2^{C(7)}) = 1.7$, $H^{C(7)}$–C(2)); 1.49 (*m*, $w_{1/2} \approx 30$, $H^{C(5)}$–C(3), $H^{C(2)}$–C(7)); 1.39 (*dddd*, $J_{gem} = 12.1$, $J(7^{C(6)},8^{C(5)}) = 12.1$, $J(1,7^{C(6)}) = J(7^{C(6)},8^{C(3)}) = 4.0$, $H^{C(6)}$–C(7)); 1.21 (*ddddd*, $J_{gem} = 12.0$, $J(7^{C(6)},8^{C(5)}) = 12.1$, $J(7^{C(2)},8^{C(5)}) = 4.8$, $J(4,8^{C(5)}) = 3.0$, $J(3^{C(5)},8^{C(5)}) = 1.7$, $H^{C(5)}$–C(8)). ^{13}C-NMR: 157.39 (*q*, $J(C,CF) = 45$, 2 C=O); 135.68, 131.71 (2*d*, C(5), C(6)); 114.50 (*q*, $J(C,F) = 285.6$, 2 CF_3); 70.80, 69.27 (2*t*, C(α), C(α')); 41.06, 39.15 (2*d*, C(2), C(3)); 31.13, 30.36 (2*d*, C(1), C(4)); 24.93, 18.61 (2*t*, C(7), C(8)). MS: 360 (4, M^+, $[C_{14}H_{14}F_6O_4]^+$), 105 (10), 104 (16), 91 (32), 80 (100), 79 (23), 69 (16).

(2S,3S)-α,α,α',α'-Tetraphenylbicyclo[2.2.2]octan-2$^{C(6)}$,3$^{C(8)}$-dimethanol (**11**). As described for **9a**, with **10a** (256 mg, 0.54 mmol), Et_2O (20 ml), and 10% Pd/C (20 mg) under H_2: 230 mg (90%) of **11**, which was sublimed (205–210°/0.005 Torr). M.p. 222–223° (evacuated sealed capillary tube). $[\alpha]_D^{r.t.} = +143.5$ ($c = 0.50$, $CHCl_3$). IR ($CHCl_3$): 3580*w*, 3340*s* (br.), 3050*w*, 2985*w*, 2915*s*, 2850*m*, 1950*w*, 1810*w*, 1670*w*, 1594*w*, 1576*w*, 1487*m*, 1440*s*, 1290*w*, 1020*w*, 967*w*, 905*w*, 892*w*. ^{1}H-NMR (400 MHz): 7.49–7.46 (*m*, 4 arom. H); 7.36–7.22 (*m*, 16 arom. H); 4.17 (*s*, 2 OH); 3.46 (*m*, $w_{1/2} \approx 3$, $H^{C(5)}$–C(3), $H^{C(7)}$–C(2)); 1.70 (*m*, $w_{1/2} \approx 8$, H–C(1), H–C(4)); 1.36 (*dddd*, $J_{gem} = 11.6$, $J(7^{C(2)},8^{C(3)}) = 10.7$, $J(7^{C(2)},8^{C(5)}) = 6.0$, $J(1,7^{C(2)}) = 3.2$, $H^{C(2)}$–C(7), $H^{C(3)}$–C(5)); 1.25 (*dddd*, $J_{gem} = 11.6$, $J(7^{C(6)},8^{C(5)}) = 11.5$, $J(1,7^{C(6)}) = J(7^{C(6)},8^{C(3)}) = 3.5$, $H^{C(6)}$–C(7), $H^{C(8)}$–C(5)); 0.70 (*ddddd*, $J_{gem} = 14.0$, $J(7^{C(6)},8^{C(5)}) = 11.5$, $J(7^{C(2)},8^{C(5)}) = 6.0$, $J(4,8^{C(5)}) = 2.3$, $J(3^{C(5)},8^{C(5)}) \approx 1.5$, $H^{C(5)}$–C(8), $H^{C(7)}$–C(6)); 0.16 (*dddd*, $J_{gem} = 14.0$, $J(7^{C(2)},8^{C(3)}) = 10.7$, $J(4,8^{C(3)}) = J(7^{C(6)},8^{C(3)}) = 3.5$, $H^{C(3)}$–C(8), $H^{C(2)}$–C(6)). ^{13}C-NMR (75 MHz): 149.52, 146.47 (2*s*, 4 C_{ipso}); 128.36, 128.20, 127.28, 127.23, 127.10, 126.94 (6*d*, 20 arom. C); 79.95 (*s*, C(α), C(α')); 45.82 (*d*, C(2), C(3)); 29.18 (*d*, C(1), C(4)); 29.64, 20.78, (2*t*, C(5), C(6), C(7), C(8)). MS: 275 (12), 274 (53), 183 (48), 167 (15), 165 (10), 105 (100), 91 (18), 77 (50). Anal. calc. for $C_{34}H_{34}O_2$ (474.64): C 86.04, H 7.22; found: C 85.68, H 7.51.

9. *1,3-Dioxolane-4,5-dimethanols* **12a–d**. *(4R,5R)-4,5-Dibenzoyl-2,2-dimethyl-1,3-dioxolane* (**25**). According to [34a], Me_2NH (22.6 g, 0.5 mol) was bubbled through a soln. of dimethyl (4*R*,5*R*)-2,2-dimethyl-1,3-dioxolane-4,5-dicarboxylate (24.0 g, 0.11 mol) in MeOH (26 ml). After stirring at r.t. for 4 d, the mixture was evaporated and recrystallized from AcOEt/hexane: *(4R,5R)-N,N,N',N',2,2-hexamethyl-1,3-dioxolane-4,5-dicarboxamide* (24.4 g, 91%). Colorless crystals. M.p. 83–85. $[\alpha]_D^{r.t.} = +52.3$ ($c = 3.0$, benzene) ([34a]: M.p. 83–85°, $[\alpha]_D^{r.t.} = +53$. ($c = 3.0$, benzene)).

To a soln. of the obtained (4*R*,5*R*)-*N,N,N',N'*,2,2-hexamethyl-1,3-dioxolane-4,5-dicarboxamide in THF (350 ml) at 0° was added a soln. of PhMgBr prepared from Mg (9.72 g, 0.40 mol) and bromobenzene (42 ml, 0.40 mol) in THF (120 ml). After stirring at r.t. overnight, the mixture was poured into a mixture of ice and sat. aq. NH_4Cl soln. (500 ml). The aq. layer was extracted with Et_2O and the combined org. layer washed with sat. NaCl soln., dried ($MgSO_4$), and evaporated. Purification by FC (hexane/AcOEt 9:1) gave **25** (24.1 g, 77%). Crystalline solid. M.p. 57–58°. $[\alpha]_D^{r.t.} = -75.5$ ($c = 1.0$, $CHCl_3$). CSP HPLC (hexane/i-PrOH 98:2) after 4 recrystallizations (hexane/AcOEt 9:1): only 1 peak, t_R 6.28 min[38]). $[\alpha]_D^{r.t.} = -78.4$ ($c = 1.0$, $CHCl_3$). IR (KBr): 2990, 2938, 1682, 1597, 1579, 1449, 1380, 1339, 1282, 1209, 1152, 1090, 1054, 1015, 972, 882, 856, 770, 725, 700, 686, 663. ^{1}H-NMR (200 MHz): 8.14–8.09 (*m*, 4 arom. H); 7.64–7.44 (*m*, 6 arom. H); 5.85 (*s*, H–C(4), H–C(5)); 1.43 (*s*, 2 Me). ^{13}C-NMR (75 MHz): 196.18 (C=O); 134.73, 133.72, 129.45, 128.56 (arom. C); 113.20 (C(2)); 78.95 (C(4), C(5)); 26.63 (2 Me). MS: 311 (100, $[M + 1]^+$), 293 (86), 253 (17), 235 (37), 205 (54). Anal. calc. for $C_{19}H_{18}O_4$ (310.4): C 73.53, H 5.85; found: C 74.10, H 6.07. The unrecrystallized product was used without further purification in the following reaction.

A small amount of a side product, tentatively identified as *(4R,5R)-4-benzoyl-5-[hydroxy(diphenyl)methyl]-2,2-dimethyl-1,3-dioxolane* on the basis of its spectral properties was isolated (0.579 g, 3%) during the chromatography (more polar fraction). Colorless crystals. M.p. 186–187.5°. $[\alpha]_D^{r.t.} = +60.6$ ($c = 1.0$, $CHCl_3$). IR (KBr): 3546, 3057, 3025, 2983, 2930, 1684, 1596, 1580, 1493, 1449, 1387, 1373, 1262, 1222, 1157, 1070, 1042, 1004, 974, 950, 901, 878, 845, 756, 696, 636. ^{1}H-NMR (200 MHz): 7.81–7.76 (*m*, 2 arom. H); 7.66–7.62 (*m*, 2 arom. H); 7.52–7.22 (*m*, 8 arom. H); 5.87 (*d*, $J = 6.4$, H–C(4) or H–C(5)); 5.15 (*d*, $J = 6.4$, H–C(4) or H–C(5)); 3.30 (br. *s*, OH); 1.52, 1.43 (2 Me). ^{13}C-NMR (50 MHz): 196.74 (C=O); 145.20, 142.33, 135.45, 133.22, 129.03, 128.16, 128.00, 127.30, 127.15, 127.02, 125.75 (arom. C); 112.13 (C(2)); 80.61 (C(4) or C(5)); 76.88 (COH); 76.13 (C(4) or C(5)); 26.90, 26.00 (Me).

---

[38]) The enantiomer prepared from (*S,S*)-*N,N,N',N'*,2,2-hexamethyl-1,3-dioxolane-4,5-dicarboxamide using the same procedure as above appeared at 6.92 min under the same conditions.

Preparation of **12a–c** *with No Racemization. Using 'Methylcerium'*: MeLi (1.2M in Et_2O; 13.6 ml, 16 mmol) was added to a suspension of $CeCl_3$ (4.00 g, 16 mmol; dried at 130°/0.05 Torr, > 3 h) in THF (66 ml) at 0°. After stirring for 1 h, the mixture was cooled to −78°. To this yellow suspension, a soln. of **25** (1.24 g, 4.0 mmol) in THF (10 ml) was added. After stirring for 3 h at the same temp., the mixture was poured into a mixture of sat aq. NH_4Cl soln. and ice and extracted with Et_2O. The org. layer was washed with aq. NaCl soln., dried ($MgSO_4$), and evaporated: crude mixture of **12a–c**. FC (hexane/toluene/AcOEt 18:1:1→8:1:1) gave **12a/12c** 98:2 (0.705 g, 51%; less polar) and **12b** (0.214 g, 16%; more polar). Recrystallization from hexane/AcOEt gave pure **12a** and **12b**.

Using Methylmagnesium Chloride: A THF soln. of MeMgCl (3M; 8.04 ml, 24 mmol) was concentrated *in vacuo* and diluted with Et_2O (60 ml). To this suspension, a soln. of **25** (1.87 g, 6.0 mmol) in Et_2O (20 ml) was added at 0°. After stirring for 3 h, the mixture was poured into a mixture of sat. aq. NH_4Cl soln. and ice. Extraction with Et_2O, washing with aq. NaCl soln., drying ($MgSO_4$), and evaporation gave a crude mixture of **12a–c**. FC (hexane/toluene/AcOEt 18:1:1→8:1:1) gave **12a/12c** 2:98 (1.31 g, 63%; less polar) and **12b** (0.621 g, 30%; more polar). Recrystallizations from hexane/AcOEt gave pure **12b** and **12c**.

(αR,α'R,4R,5R)-2,2,α,α,α',α'-Tetramethyl-α,α'-diphenyl-1,3-dioxolane-4,5-dimethanol (**12a**). M.p. 192–193°. $[\alpha]_D^{r.t.} = +46.4$ ($c = 0.627$, $CHCl_3$). CSP-HPLC (hexane/i-PrOH 98:2): > 98% ee; no (αS,α'S,4S,5S)-enantiomer detected. IR (KBr): 3246, 2989, 2885, 1602, 1495, 1446, 1372, 1335, 1254, 1214, 1168, 1148, 1070, 879, 778, 724, 699, 657, 622. ^{1}H-NMR (200 MHz): 7.60–7.54 (*m*, 4 arom. H); 7.40–7.23 (*m*, 6 arom. H); 4.25 (br. *s*, 2 OH); 3.50 (*s*, H–C(4), H–C(5)); 1.59 (*s*, 2 Me); 1.03 (*s*, 2 Me). ^{13}C-NMR (75 MHz): 143.34, 127.57, 127.01, 126.83 (arom. C); 108.29 (C(2)); 83.60 (C(4), C(5)); 74.19 (C(α), C(α')); 29.21, 27.06 (Me). MS: 325 (5, $[M - OH]^+$), 307 (5), 268 (96), 206 (90), 176 (100). Anal. calc. for $C_{21}H_{26}O_4$ (342.44): C 73.66, H 7.65; found: C 73.84, H 7.67.

(αR,α'S,4R,5R)-2,2,α,α,α',α'-Tetramethyl-α,α'-diphenyl-1,3-dioxolane-4,5-dimethanol (**12b**). M.p. 113–114°. $[\alpha]_D^{r.t.} = +1.8$ ($c = 0.88$, $CHCl_3$). CSP-HPLC (hexane/i-PrOH 98:2): > 98% ee; no (αS,α'R,4S,5S)-enantiomer detected. IR (KBr): 3226, 2984, 2933, 2898, 1494, 1446, 1377, 1222, 1173, 1134, 1067, 1030, 965, 931, 912, 874, 772, 750, 733, 699, 650. ^{1}H-NMR (200 MHz): 7.50–7.20 (*m*, 10 arom. H); 4.29 (*d*, $J = 7.8$, H–C(4) or H–C(5)); 3.9 (br. *s*, OH); 3.64 (*d*, $J = 7.8$, H–C(4) or H–C(5)); 3.1 (br. *s*, OH); 1.71, 1.41, 1.42, 1.10 (*s*, 4 Me). ^{13}C-NMR (75 MHz): 145.92, 144.30, 128.11, 127.57, 127.34, 126.83, 126.34, 125.82 (arom. C); 108.69 (C(2)); 83.65, 83.08 (C(4), C(5)); 74.04, 73.85 (C(α), C(α')); 28.39, 27.54, 27.32, 24.27 (Me). MS: 325 (3, $[M - OH]^+$), 307 (4), 268 (97), 249 (12), 206 (97), 176 (100). Anal. calc. for $C_{21}H_{26}O_4$ (342.44): C 73.66, H 7.65; found: C 73.84, H 7.62.

(αS,α'S,4R,5R)-2,2α,α'-Tetramethyl-α,α'-diphenyl-1,3-dioxolane-4,5-dimethanol (**12c**). M.p. 131–133°. $[\alpha]_D^{r.t.} = -24.6$ ($c = 0.618$, $CHCl_3$). CSP-HPLC (hexane/i-PrOH 98:2): > 98% ee; no (αR,α'R,4S,5S)-enantiomer detected. IR (KBr): 3215, 2986, 2905, 1603, 1495, 1449, 1377, 1239, 1170, 1131, 1066, 960, 911, 874, 772, 747, 699, 652. ^{1}H-NMR (200 MHz): 7.45–7.20 (*m*, 10 arom. H); 4.25 (*s*, 4 H–C(4), H–C(5)); 2.90 (*s*, 2 OH); 1.52 (*s*, 2 Me); 1.36 (*s*, 2 Me). ^{13}C-NMR (75 MHz): 145.85, 128.06, 127.12, 125.72 (arom. C); 109.9 (C(2)); 83.54 (C(4), C(5)); 74.29 (C(α), C(α')); 27.87, 24.91 (Me). MS: 325 (2, $[M - OH]^+$), 307 (2), 268 (100), 249 (9), 247 (8), 205 (67), 175 (66). Anal. calc. for $C_{21}H_{26}O_4$ (342.44): C 73.66, H 7.65; found: C 73.73, H 7.60.

Preparation of **12a–c**, *with Some Racemization. Using Methyllithium*: A soln. of **25** (6.21 g, 20 mmol) in Et_2O (60 ml) was added to 0.6M MeLi in Et_2O (100 ml, 60 mmol) at 0°. The mixture was allowed to warm up to r.t., stirred for 12 h, and then poured into a mixture of ice and sat. aq. NH_4Cl soln. (500 ml). The aq. layer was extracted with Et_2O (2 × 100 ml), the combined org. layer dried ($MgSO_4$), and evaporated, and the residue purified by FC (hexane/AcOEt 85:15→4:1): less polar fraction containing **12a/12c** and more polar fraction **12b** (2.57 g, 37%). A further FC (hexane/Et_2O 13:7) separated **12a/12c**: less polar **12c** (colorless crystals; 1.76 g, 25%) and more polar **12a** (colorless crystals; 0.923 g, 13%). CSP-HPLC (hexane/i-PrOH 98:2): only 65% ee for all. During the first FC, in front of **12a/12c**, the by-product *(4R,5R)-4-benzoyl-5-(1-hydroxy-1-phenylethyl)-2,2-dimethyl-1,3-dioxolane* (0.95 g, 15%) was eluted. IR (KBr): 3539, 3060, 2986, 2940, 1686, 1599, 1580, 1496, 1448, 1384, 1370, 1322, 1264, 1211, 1193, 1172, 1115, 1070, 1048, 1028, 876, 838, 761, 722, 701, 685, 640. ^{1}H-NMR (200 MHz): 7.79–7.75 (*m*, 2 arom. H); 7.51–7.00 (*m*, 8 arom. H); 5.07 (*d*, $J = 6.3$, H–C(4) or H–C(5)); 4.96 (*d*, $J = 6.3$, H–C(4) or H–C(5)); 1.69, 1.57, 1.35 (*s*, 3 Me); the relative configuration was not determined though the ^{1}H-NMR showed only a set of peaks corresponding to one single diastereoisomer. ^{13}C-NMR (75 MHz): 197.09 (C=O); 142.65, 135.45, 133.16, 129.05, 128.16, 128.10, 127.15, 125.02 (arom. C); 111.72 (C(2)); 83.11, 76.33 (C(4), C(5)); 73.15 (COH); 28.46, 27.00, 25.91 (3 Me).

Preparation of rac-**12a,c**. Using the methyllithium procedure above, starting with *rac*-diethyl tartrate, *rac*-**12a,c** were obtained. *rac*-**12a**: m.p. 210–211°. *rac*-**12c**: m.p. 137–139°. Spectral data: identical to those of the corresponding enantiomers.

(αR,α'S,4R,5R)-2,2-Dimethyl-α,α'-di(naphthalen-1-yl)-α,α'-diphenyl-1,3-dioxolane-4,5-dimethanol (**12d**). A soln. of 1-bromonaphthalene (1.24 g, 6.0 mmol) in THF (2 ml) was added to a suspension of Mg (0.146 g, 6.0 mmol) in THF (1 ml). Then THF (17 ml) was added, the mixture cooled to 0°, and a soln. of **25** (0.620 g, 20 mmol)

in THF (10 ml) added. After stirring for 1 h at r.t., the mixture was poured into sat. aq. NH_4Cl soln. and extracted twice with Et_2O. The extract was dried ($MgSO_4$) and evaporated. FC of the residue (hexane/AcOEt 9:1→4:1) gave **12d** (0.552 g, 49%). Colorless crystals. M.p. 281–282°. $[\alpha]_D^{r.t.} = -96.8$ ($c = 0.91$, $CHCl_3$). IR ($CHCl_3$): 3572*s* (br.), 3354*s* (br.), 3059*m*, 3007*s*, 1730*m*, 1601*m*, 1508*w*, 1492*w*, 1448*w*, 1371*w*, 1165*w*, 1080*w*. ^{1}H-NMR (300 MHz, 80°, (D_6)DMSO): 8.20–6.96 (*m*, 24 arom. H); 4.97 (*d*, $J = 7.9$, H–C(2) or H–C(3)); 4.81 (*d*, $J = 7.9$, H–C(2) or H–C(3)); 0.67 (*s*, Me); 0.53 (*s*, Me). MS: 531 (13), 317 (28), 316 (10), 287 (30), 274 (11), 258 (45), 233 (100). Anal. calc. for $C_{39}H_{34}O_4$ (566.70): C 82.66, H 6.05; found: C 82.66, H 5.77.

10. *Addition of [TiMe(i-PrO)$_3$] to Benzaldehyde in the Presence of Chiral Titanium Complexes of Diols* **1a**, **4**–**7**, *or* **12a**–**e**,**h**. A stock soln. of 1.0M [TiMe(i-PrO)$_3$] (0.30 ml, 0.30 mmol) in toluene was added to a soln. of diol (0.1 mmol) in toluene (1 ml) at −78°. After stirring at r.t. for 30 min, the mixture was recooled to −78°. To this soln., benzaldehyde (11 µl, 0.11 mmol) was added and the mixture warmed gradually to −10° (*ca.* 15 h). After stirring for 4 h, sat. aq. NH_4Cl soln. was added. Stirring was continued for several h (*ca.* 24 h). Then the mixture was extracted with Et_2O, the org. layer washed with sat. aq. NaCl soln., dried ($MgSO_4$), and evaporated, and the residue, a mixture of diol and 1-phenylethanol, purified by bulb-to-bulb distillation (bath temp. 120°/15 Torr). The residue was almost pure diol. The isolated yields and selectivities (determined by GC) of 1-phenylethanol are shown in *Table 2*.

11. *Titanium Complexes of* **4** *and* **7**–**12h** *and Their Use as Catalyst in the Addition of ZnEt$_2$ to Aldehydes*. This procedure has been reported [15] [21]. For chemical yields and selectivities, see *Table 3*.

*[Ti(i-PrO)$_2$(***4** *− 2H$^+$)]*: ^{1}H-NMR (200 MHz): 7.70–6.65 (*m*, 20 arom. H); 4.60–4.45 (*m*, 2 Me_2CH); 3.90–3.60 (br. *m*, H–C(1), H–C(2)); 1.40–1.00 (*m*, CH_2(3), CH_2(4), 2 Me_2CH).

*[Ti(i-PrO)$_2$(***7** *− 2H$^+$)]*: ^{1}H-NMR (200 MHz): 7.90–6.95 (*m*, 20 arom. H); 4.55–4.30 (*m*, 2 Me_2CH); 3.90–3.70 (*m*, H–C(1), H–C(2)); 2.00–1.65 (*m*, CH_2(3), CH_2(6)); 1.65–0.50 (*m*, CH_2(4), CH_2(5), 2 Me_2CH).

*[Ti(i-PrO)$_2$(***8a**–*2H$^+$)]*: ^{1}H-NMR (200 MHz): 7.65–7.00 (*m*, 20 arom. H); 5.84 (*dd*, $J = 3, 5$, H–C(5)); 4.34 (*dd*, $J = 2, 5$, H–C(6)); 4.15–3.98 (*m*, 2 Me_2CH); 3.66 (*dd*, $J = 3, 6$, H–C(2)); 3.08 (*d*, $J = 6$, H–C(3)); 2.82–2.70 (*m*, H–C(1), H–C(4)); 1.25–1.05 (*m*, 2 Me_2CH); 0.69 (*d*, $J = 8$, $H^{C(5)}$–C(7)); 0.02 (*d*, $J = 8$, $H^{C(2)}$–C(7)); also signals of the free ligand (20%).

*[Ti(i-PrO)$_2$(***8b**–*2H$^+$)]*: ^{1}H-NMR (200 MHz): 6.31 (*dd*, $J = 3, 6$, H–C(5)); 6.10 (*dd*, $J = 3, 6$, H–C(6)); 4.80–4.60 (*m*, 2 Me_2CH); 3.00–2.90 (br. *m*, H–C(1)); 2.65–2.55 (br. *m*, H–C(4)); 2.49 (*dd*, $J = 3, 7$, H–C(2)); 1.89 (*d*, $J = 8$, $H^{C(2)}$–C(7)); 1.70 (*d*, $J = 8$, $H^{C(5)}$–C(7)); 1.49 (*s*, Me); 1.42 (*s*, Me); 1.38 (*d*, $J = 6$, 2 Me_2CH, H–C(3)); 1.33 (*s*, Me); 1.10 (*s*, Me).

*[Ti(i-PrO)$_2$(***9a**–*2H$^+$)]*: ^{1}H-NMR (200 MHz): 7.75–7.10 (*m*, 20 arom. H); 4.50–4.15 (br. *m*, 2 Me_2CH); 3.63 (*dd*, $J = 3, 6$, H–C(2)); 3.17 (*d*, $J = 6$, H–C(3)); 2.41–2.30 (*m*, H–C(4)); 2.30–2.24 (*m*, H–C(1)); 1.50–0.95 (*m*, CH_2(5), CH_2(6)); 0.62 (*d*, $J = 9$, $H^{C(5)}$–C(7)); 0.10 (*d*, $J = 9$, $H^{C(2)}$–C(7)). ^{13}C-NMR (75 MHz): 150.62, 149.62, 147.47, 145.45 (arom. C); 128.72, 128.34, 128.11, 127.96, 127.38, 126.92, 126.64, 126.52, 126.37, 125.07 (arom. C); 92.52, 91.05 (Ph_2COTi); 76.05 (Me_2CHOTi); 52.72, 49.98, 42.97, 41.10 (C(1), C(2), C(3), C(4)); 37.19, 29.45, 24.01 (C(5), C(6), C(7)); 26.08 (Me).

*[Ti(i-PrO)$_2$(***10a**–*2H$^+$)]*: ^{1}H-NMR (200 MHz): 7.40–7.28 (*m*, 20 arom. H); 6.18 (*dd*, $J = 7$, H–C(5)); 4.96 (*dd*, $J = 7$, H–C(6)); 4.54–4.20 (br. *m*, 2 Me_2CH); 3.85 (*d*, $J = 7$, H–C(2)); 3.75 (*d*, $J = 7$, H–C(3)); 3.02–2.90 (br. *m*, H–C(1)); 2.80–2.66 (br. *m*, H–C(4)); 1.60–1.42 (*m*, $H^{C(2)}$–C(7)); 1.42–1.00 (br. *m*, $H^{C(6)}$–C(7), 4 Me); 0.62–0.40 (*m*, $H^{C(5)}$–C(8)); 0.24–0.05 (*m*, $H^{C(3)}$–C(8)).

*[Ti(i-PrO)$_2$(***10b**–*2H$^+$)]*: ^{1}H-NMR (200 MHz): 6.39 (*dd*, $J = 7, 8$, H–C(5)); 6.10 (*dd*, $J = 7$, H–C(6)); 4.75–4.55 (*m*, 2 Me_2CH); 2.72–2.58 (*m*, H–C(4), H–C(1)); 2.25 (*d*, $J = 6$, H–C(2)); 2.09 (*d*, $J = 6$, H–C(3)); 1.72–1.80 (*m*, $H^{C(3)}$–C(8)); 1.65–1.20 (*m*, $H^{C(2)}$–C(7), $H^{C(6)}$–C(7)); 1.49 (*s*, Me); 1.42 (*s*, Me); 1.38 (*s*, Me); 1.34 (*d*, $J = 6$, 2 Me_2CH); 1.15–0.90 (*m*, $H^{C(5)}$–C(8)); 1.09 (*s*, Me).

*[Ti(i-PrO)$_2$(***10c**–*2H$^+$)]*: ^{1}H-NMR (200 MHz): 6.40–6.20 (br. *m*, H–C(5)); 6.15–5.95 (br. *m*, H–C(6)); 5.20–3.20 (br. *m*, $CH_2(\alpha)$, $CH_2(\alpha')$, 2 Me_2CH); 2.40–2.10 (br. *m*, H–C(1), H–C(4)); 1.60–0.60 (br. *m*, H–C(2), H–C(3), CH_2(7), CH_2(8), 2 Me_2CH).

*[Ti(i-PrO)$_2$(***11**–*2H$^+$)]*: ^{1}H-NMR (200 MHz): 7.80–7.15 (*m*, 20 arom. H); 4.50–4.20 (*m*, 2 Me_2CH); 3.79 (*s*, H–C(2), H–C(3)); 1.85–1.70 (*m*, H–C(1), H–C(4)); 1.55–0.90 (*m*, CH_2(7), CH_2(5), 2 Me_2CH); 1.80–0.55 (*m*, $H^{C(5)}$–C(8), $H^{C(7)}$–C(6)); 0.15–0.10 (*m*, $H^{C(3)}$–C(8), $H^{C(2)}$–C(6)).

*[Ti(i-PrO)$_2$(***12a**–*2H$^+$)]*: ^{1}H-NMR (200 MHz): 7.90–7.10 (*m*, 10 arom. H); 5.10–4.85 (*m*, 2 Me_2CH); 4.10 (*s*, H–C(4), H–C(5)); 1.84 (*s*, Me–C(α), Me–C(α')); 1.51 (*d*, $J = 6$, 2 Me_2CH); 0.80 (*s*, 2Me–C(2)).

*[Ti(i-PrO)$_2$(***12b**–*2H$^+$)]*: ^{1}H-NMR (200 MHz): 7.75–7.60 (*m*, 4 arom. H); 7.40–7.18 (*m*, 6 arom. H); 4.90–4.70 (*m*, 2 Me_2CH); 4.45 (*d*, $J = 7$, H–C(4) or H–C(5)); 3.98 (*d*, $J = 7$, H–C(4) or H–C(5)); 1.92 (*s*, Me–C(α)); 1.82 (*s*, Me–C(α')); 1.48 (*s*, Me–C(2)); 1.37 (*d*, $J = 6$, 2 Me_2CH); 0.83 (*s*, Me–C(2)). ^{13}C-NMR

(75 MHz): 148.70, 143.51, 128.41, 128.08, 127.52, 127.12, 127.05, 126.16, 108.88, 89.89, 89.65, 85.01, 83.15, 78.00, 77.91, 30.81, 28.32, 27.62, 26.27, 26.17, 24.20.

*[Ti(i-PrO)$_2$(***12c**$-2H^+$*)]*: ^{1}H-NMR (200 MHz): 7.81–7.20 (*m*, 10 arom. H); 4.75–4.55 (*m*, 2 Me_2CH); 4.46 (*s*, H–C(4), H–C(5)); 1.80 (*s*, Me–C(α), Me–C(α′)); 1.51 (*s*, 2 Me–C(2)); 1.33 (*dd*, J = 2, 2 Me_2CH). ^{13}C-NMR (75 MHz): 149.01, 128.09, 127.14, 126.44, 108.43, 89.19, 83.91, 77.40, 28.27, 26.25, 24.21.

*[Ti(i-PrO)$_2$(***12e**$-2H^+$*)] and [Ti(i-PrO)$_2$(***12f**$-2H^+$*)]*: see [21].

*Ti(i-PrO)$_2$(***12g**$-2H^+$*)]*: ^{1}H-NMR (200 MHz): 4.58 (*s*, H–C(4), H–C(5)); 4.65–4.45 (*m*, 2 Me_2CH); 2.25–1.10 (*m*, 44 cyclohexyl H); 1.40 (*s*, 2 Me–C(2)); 1.28 (*d*, J = 6, 2 Me_2CH). ^{13}C-NMR (75 MHz): 106.93, 93.71, 80.45, 76.22, 45.36, 43.45, 28.94, 28.16, 27.94, 27.51, 27.32, 27.11, 27.00, 26.67.

*Ti(i-PrO)$_2$(***12h**$-2H^+$*)]*: ^{1}H-NMR (200 MHz): 8.10–7.00 (*m*, 10 arom. H); 5.40–3.80 (*m*, 4 CH, CH_2); 1.80–0.50 (*m*, 6 Me).

12. *Catalyst Competition in the [TiMe(i-PrO)$_3$] Addition to Benzaldehyde.* A 1:1 mixture of **1a** (46.7 mg, 0.1 mmol) and either **12e** (21.8 mg, 0.1 mmol), **12a** or **12c** (34.2 mg, 0.1 mmol) was dissolved in toluene (1 ml) and evaporated under h.v. to remove traces of H_2O. After repeating this azeotropic drying, the residue was dissolved in toluene (1 ml). To this soln., 0.55 ml (0.5 mmol) of 1M [TiMe(i-PrO)$_3$] in toluene was added at −60° and then allowed to warm to −15° over 30 min. After cooling to −78°, benzaldehyde (10 µl, 0.1 mmol) was added and the mixture allowed to warm to −10° overnight (15 h). The mixture was hydrolyzed with sat. NH_4Cl soln. (1 ml) and filtered. The filtrate was extracted with Et_2O (1 ml). The conversion and e.r. were determined by GC (see *Scheme 8, Pathway a*).

13. *Catalyst Competition in the $ZnEt_2$ Addition to Benzaldehyde.* A 1:1 mixture of **1a** (46.7 mg, 0.1 mmol) and either **12e** (21.8 mg, 0.1 mmol), **12a** or **12c** (34.2 mg, 0.1 mmol) was dried as described in *Exper. 12*. To the residue in toluene (5 ml) was added 0.2 ml (0.2 mmol) of 1M [Ti(i-PrO)$_4$] at r.t., and the soln. was stirred for 1–2 h before it was evaporated under h.v. The residue was dissolved in toluene (5 ml), and at r.t. additional 1M [Ti(i-PrO)$_4$] (0.6 ml, 0.6 mmol) was added along with benzaldehyde (50 µl, 0.5 mmol). The mixture was cooled in a −25° bath and stirred for 30 min, whereupon 2M $ZnEt_2$ in toluene (0.55 ml, 1.1 mmol) was added. The mixture was stirred at −25° overnight (15 h), and then hydrolyzed with sat. NH_4Cl soln. (1 ml) and filtered. The filtrate was extracted with Et_2O (1 ml). The conversion and e.r. were determined by CSP GC (see *Scheme 8, Pathway b*).

14. *Crystal Structure Analyses.* 14.1. *α,α,α′,α′-Tetraphenylcyclobutane-1,2-dimethanol* (*rac*-**4**; $C_{30}H_{28}O_2$)[13]). Determination of the cell parameters and collection of the reflection intensities were performed on an *Enraf-Nonius-CAD4* four-circle diffractometer (graphite monochromatized MoK_α radiation, λ = 0.7107 Å). Monoclinic, space group $P2_1/n$, a = 9.772(2) Å, b = 15.296(3) Å, c = 15.694(3) Å, β = 101.97(3)°, V = 2294.8(8) Å^3, Z = 4, $\rho_{calc.}$ = 1.22 gcm^{-3}, μ = 0.075 mm^{-1}, F(000) = 896. Nummber of reflections measured 3732 (ω scan, 2 < 2θ < 50°); 3732 unique reflections, of which 3008 with $I > 3\sigma(I)$ were used for the determination (direct methods, SHELXS-86 [56]). SHELXL-93 [57] was used for structure refinement. The non-H-atoms were refined anisotropically. The H-atoms bound to O- and to the ring C-atoms were located from differential *Fourier* syntheses and refined isotropically. H-Atoms bound to the C-atoms of the Ph rings were added to the molecule with constant isotropic temperature factors on idealized positions and refined according to the riding model with variable distance to the C-atom (afix 4). Extinction but no absorption correction was applied. The refinement converged at R = 0.045 ($wR2$ = 0.129, number of variables 342).

14.2. *(1R,2R)-α,α,α′,α′-Tetraphenylcyclohexane-1,2-dimethanol* (**7**; $C_{32}H_{32}O_2$)[13]). As described in *14.1* (graphite monochromatized CuK_α radiation, λ = 1.5418 Å). Monoclinic, space group $P2_1$, a = 8.879(8) Å, b = 16.791(2) Å, c = 8.878(12) Å, β = 111.87(9)°, V = 1228.4(4) Å^3, Z = 2, $\rho_{calc.}$ = 1.21 gcm^{-3}, μ = 0.571 mm^{-1}, F(000) = 480. Number of reflections measured 3832 (ω scan, 6 < 2θ < 130°); 2144 unique reflections, of which 2017 with $I > 3\sigma(I)$ were used for the determination (direct methods, SHELXS-86). SHELXL-93 was used for structure refinement, as described in *14.1*. The refinement converged at R = 0.035 ($wR2$ = 0.096, number of variables 376).

14.3. *(1R,2R)-α,α,α′,α′-Tetraphenylcyclohexane-1,2-dimethanol-Piperidine* (**7**·$C_5H_{11}N$; $C_{32}H_{32}O_2$·$C_5H_{11}N$)[13]). As described in *14.1* (graphite monochromatized CuK_α radiation, λ = 1.5418 Å). Monoclinic, space group $P2_1$, a = 8.784(3) Å, b = 20.820(2) Å, c = 9.0758(14) Å, β = 113.21(2)°, V = 1525(6) Å^3, Z = 2, $\rho_{calc.}$ = 1.16 gcm^{-3}, μ = 0.542 mm^{-1}, F(000) = 576. Number of reflections measured 2626 (ω scan, 6 < 2θ < 130°); 2626 unique reflections, of which 1472 with $I > 3\sigma(I)$ were used for the determination (direct methods, SHELXS-86). SHELXL-93 was used for structure refinement. The non-H-atoms were refined anisotropically. The H-atoms bound to O- or N- and to the ring C-atoms were located from differential *Fourier* syntheses and refined with constant-temperature factors. H-Atoms bound to the C-atoms of the Ph rings were added to the molecule with constant isotropic temp. factors on idealized positions and refined according to the riding model (afix 3). Neither

extinction nor absorption correction were applied. The refinement converged at $R = 0.065$ ($wR2 = 0.143$, number of variables 361).

14.4. *(αR,α'R,4R,5R)-2,2,α,α'-Tetramethyl-α,α'-diphenyl-1,3-dioxolane-3,4-dimethanol* (**12a**; $C_{21}H_{26}O_4$)[13]). As described in *14.1* (graphite monochromatized CuK_α radiation, $\lambda = 1.5418$ Å). Monoclinic, space group $P2_1$, $a = 10.863(2)$ Å, $b = 7.500(2)$ Å, $c = 12.602(2)$ Å, $\beta = 110.63(12)°$, $V = 961.0(3)$ Å^3, $Z = 2$, $\rho_{calc.} = 1.18$ gcm^{-3}, $\mu = 0.650$ mm^{-1}, $F(000) = 368$. Number of reflections measured 1767 (ω scan, $6 < 2\theta < 130°$); 1767 unique reflections, of which 1728 with $I > 3\sigma(I)$ were used for the determination (direct methods, SHELXS-86). SHELXL-93 was used for structure refinement. The non-H-atoms were refined anisotropically. The H-atoms were located from differential *Fourier* syntheses and refined isotropically. Extinction but no absorption correction was applied. The refinement converged at $R = 0.025$ ($wR2 = 0.068$, number of variables 368).

REFERENCES

[1] D. Y. Curtin, E. E. Harris, E. K. Meislich, *J. Am. Chem. Soc.* **1952,** *74,* 2901.
[2] D. J. Cram, F. A. Abd Elhafez, *J. Am. Chem. Soc.* **1952,** *74,* 5828.
[3] V. Prelog, *Helv. Chim. Acta* **1953,** *36,* 308.
[4] G. J. Karabatsos, *J. Am. Chem. Soc.* **1967,** *89,* 1367.
[5] M. Cherest, H. Felkin, N. Prudent, *Tetrahedron Lett.* **1968,** 2199.
[6] H. B. Bürgi, J. D. Dunitz, E. Schefter, *J. Am. Chem. Soc.* **1973,** *95,* 5065.
[7] N. T. Anh. O. Eisenstein, *Nouv. J. Chim.* **1977,** *1,* 61.
[8] E. P. Lodge, C. H. Heathcock, *J. Am. Chem. Soc.* **1987,** *109,* 3353.
[9] R. O. Duthaler, A. Hafner, *Chem. Rev.* **1992,** *92,* 807.
[10] K. Soai, S. Niwa, *Chem. Rev.* **1992,** *92,* 833.
[11] R. Noyori, 'Asymmetric Catalysis in Organic Synthesis', J. Wiley and Sons, New York, 1994.
[12] D. Seebach, A. K. Beck, M. Schiess, L. Widler, A. Wonnacott, *Pure Appl. Chem.* **1983,** *55,* 1807.
[13] D. Seebach, B. Weidmann, L. Widler, 'Modern Synthetic Methods 1983', Ed. R. Scheffold, Salle + Sauerländer, Aarau, and J. Wiley and Sons, New York, 1983, Vol. 3, p. 217–353.
[14] D. Seebach, A. K. Beck, Imwinkelried, S. Roggo, A. Wonnacott, *Helv. Chim. Acta* **1987,** *70,* 954.
[15] D. Seebach, A. K. Beck, B. Schmidt, Y. M. Wang, *Tetrahedron* **1994,** *50,* 4363.
[16] B. Weber, D. Seebach, *Tetrahedron* **1994,** *50,* 7473.
[17] A. K. Beck, B. Bastani, D. A. Plattner, W. Petter, D. Seebach, H. Braunschweiger, P. Gysi, L. La Vecchia, *Chimia* **1991,** *45,* 238.
[18] B. Schmidt, D. Seebach, *Angew. Chem.* **1991,** *103,* 1383; *ibid. Int. Ed.* **1991,** *30,* 1321.
[19] B. Schmidt, D. Seebach, *Angew. Chem.* **1991,** *103,* 100; *ibid. Int. Ed.* **1991,** *30,* 99.
[20] a) D. Seebach, L. Behrendt, D. Felix, *Angew. Chem.* **1991,** *103,* 991; *ibid. Int. Ed.* **1991,** *30,* 1008; b) J. L. v.d. Bussche-Hünnefeld, D. Seebach, *Tetrahedron* **1992,** *48,* 5719.
[21] D. Seebach, D. A. Plattner, A. K. Beck, Y. M. Wang, D. Hunziker, W. Petter, *Helv. Chim. Acta* **1992,** *75,* 2171.
[22] W. Klyne, V. Prelog, *Experientia* **1960,** *16,* 521.
[23] D. Seebach, M. Hayakawa, J.-i. Sakaki, W. B. Schweizer, *Tetrahedron* **1993,** *49,* 1711.
[24] J.-i. Sakaki, W. B. Schweizer, D. Seebach, *Helv. Chim. Acta* **1993,** 76, 2654.
[25] E. Juaristi, A. K. Beck, J. Hansen, T. Matt, T. Mukhopadhyay, M. Simson, D. Seebach, *Synthesis* **1993,** 1271.
[26] M. Hayakawa, Ph. D. Thesis No. 10352, ETH, 1993; B. T. Weber, Ph. D. Thesis No. 10663, ETH, 1994; H. Schäfer, Ph. D. Thesis No. 10822, ETH, 1994.
[27] D. Seebach, R. Dahinden, R. Marti, A. K. Beck, D. A. Plattner, F. N. M. Kühnle, *J. Org. Chem.*, submitted.
[28] a) R. Dahinden, A. K. Beck, D. Seebach, in 'Encyclopedia of Reagents for Organic Synthesis', Ed.-in-Chief L. A. Paquette, John Wiley and Sons, Chichester, expected publication date in early 1995 (a copy of the manuscript may be requested from the correspondence author of the present paper); b) K. Narasaka, N. Iwasawa, in 'Organic Synthesis: Theory and Application', Ed. T. Hudlicky, JAI, Greenwich, CT, 1993, Vol. 2, Chapt. 4.
[29] F. B. Kipping, J. J. Wren, *J. Chem. Soc.* **1957,** 3246.
[30] a) G. Sabbioni, M. L. Shea, J. B. Jones, *J. Chem. Soc., Chem. Commun.* **1984,** 236; b) G. Sabbioni, J. B. Jones, *J. Org. Chem.* **1987,** *52,* 4565; c) S. Kobayashi, K. Kamiyama, M. Ohno, *Chem. Pharm. Bull.* **1990,** *38,* 350; d) H.-J. Gais, K. L. Lukas, W. A. Ball, S. Braun and H. J. Lindner, *Liebigs Ann. Chem.* **1986,** 687; e) W. R. Rausch, H. R. Gillis, A. I. Ko, *J. Am. Chem. Soc.* **1982,** *104,* 2269.
[31] D. H. Crout, M. Christen, 'Modern Synthetic Methods 1989', Ed. R. Scheffold, Springer-Verlag, Berlin, 1989, Vol. 5, p. 1–114.

[32] A. Studer, unpublished results, ETH Zürich, 1994.
[33] a) N.A. Porter, Q.J.J. Harp, I.J. Rosenstein, A.T. McPhail, *Tetrahedron Lett.* **1993,** *34,* 4457; b) R. Quermann, R. Maletz, H.J. Schäfer, *Liebigs Ann. Chem.* **1993,** 1219; c) G.S. Miracle, S.M. Cannizzaro, N.A. Porter, *Chemtracts Org. Chem.* **1993,** *6,* 147; d) J.L. Belletire, E.G. Spletzer, A.R. Pinhas, *Tetrahedron Lett.* **1984,** *25,* 5969; e) B. Teichmann, *Acta Chim. Hung. Tomus* **1965,** *46,* 241; f) B. Teichmann, *ibid.* **1964,** *42,* 275.
[34] a) D. Seebach, H.O. Kalinowski, B. Bastani, G. Crass, H. Daum, H. Dörr, N.P. DuPreez, V. Ehrig, W. Langer, C. Nüssler, H. Oei, M. Schmidt, *Helv. Chim. Acta* **1977,** *60,* 302; b) M.A. Briggs, A.H. Haines, *J. Chem. Soc., Perkin Trans. 1* **1985,** 795.
[35] T. Imamoto, *Pure Appl. Chem.* **1990,** *62,* 747.
[36] P. Rothe-Streit, R.O. Duthaler, A. Hafner, unpublished results.
[37] D. Seebach, E. Devaquet, A. Ernst, M. Hayakawa, F.N.M. Kühnle, W.B. Schweizer, B. Weber, in preparation.
[38] a) K. Furuta, K. Iwanaga, H. Yamamoto, *Tetrahedron Lett.* **1986,** *27,* 4507; b) K. Maruoka, S. Saito, H. Yamamoto, *J. Am. Chem. Soc.* **1992,** *114,* 1089.
[39] H. Hartmann, A.F.A. Hady, K. Sartor, J. Weetman, G. Helmchen, *Angew. Chem.* **1987,** *99,* 1188; *ibid. Int. Ed.* **1987,** *26,* 1143.
[40] D. Horton, T. Machinami, *J. Chem. Soc., Chem. Commun.* **1981,** *88;* C. Döbler, H.-J. Kreuzfeld, *J. Prakt. Chem.* **1981,** *323,* 667.
[41] L.A. Paquette, T.M. Kravetz, P. Charumilind, *Tetrahedron* **1986,** *42,* 1789.
[42] H.-J. Kreuzfeld, C. Döbler, *Z. Chem.* **1984,** *24,* 405.
[43] A.W. Clauss, S.R. Wilson, R.M. Buchanan, C.G. Pierpont, D.N. Hendrickson, *Inorg. Chem.* **1983,** *22,* 628; J.M. Townsend, J.F. Blount, *Inorg. Chem.* **1981,** *20,* 269; E. Benedetti, P. Corradini, C. Pedone, *Acta Crystallogr., Sect. B* **1970,** *26,* 493.
[44] J. Irrure, C. Alonso-Alija, J.F. Piniella, A. Alvarez-Larena, *Tetrahedron: Asymmetry* **1992,** *3,* 1591.
[45] D. Seebach, P.B. Rheiner, A.K. Beck, F.N.M. Kühnle, B. Jaun, *Polish J. Chem.* **1994,** in press.
[46] G. Chang, W. Guida, W.C. Still, *J. Am. Chem. Soc.* **1989,** *111,* 4379.
[47] C. Dreisbach, U. Kragel, C. Wandrey, *Synthesis* **1994,** 911.
[48] H. Waldmann, M. Weigerding, C. Dreisbach, C. Wandrey, *Helv. Chim. Acta* **1994,** *77,* 2111.
[49] A. Hafner, R.O. Duthaler, R. Marti, G. Rihs, P. Rothe-Streit, F. Schwarzenbach, *J. Am. Chem. Soc.* **1992,** *114,* 2321.
[50] S.C. Watson, J.F. Eastham, *J. Organomet. Chem.* **1967,** *9,* 165.
[51] H.-P. Nowotny, D. Schmalzing, D. Wistuba, V. Schurig, *J. High Resolut. Chromatogr.* **1989,** *12,* 383; V. Schuring, H.-P. Nowotny, *J. Chromatogr.* **1988,** *441,* 155; K. Grob, 'Making and Manipulating Capillary Columns for Gas Chromatography', Huethig, Heidelberg, 1986.
[52] F.B. Kipping, J.J. Wren, *J. Chem. Soc.* **1957,** 3246.
[53] W.A. König, S. Lutz, G. Wenz, E. von der Bey, *J. High Resolut. Chromatogr., Chromatogr. Commun. HR & CC* **1988,** *11,* 506.
[54] D. Seebach, E. Hungerbühler, R. Naef, P. Schnurrenberger, B. Weidmann, M. Züger, *Synthesis* **1982,** 138.
[55] S. Inokuma, A. Sugie, K. Moriguchi, J. Katsube, *Heterocycles* **1983,** *20,* 1109.
[56] 'SHELXS-86, Progam for the Solution of Crystal Stuctures', University of Göttingen, 1986.
[57] 'SHELXL-93', G.M. Sheldrick, *Current Contents* (Physical Chemical and Earth Sciences) **1989,** *29,* 14.