Development of the Juliá asymmetric epoxidation reaction. Part 2. Application of the oxidation to alkyl enones, enediones and unsaturated keto esters

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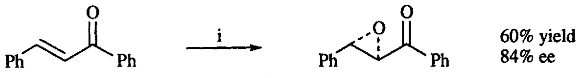
Polyleucine-based systems have been used to catalyse the asymmetric oxidation of a variety of alkyl enones 1–4, 9–14, an enynone 16 and a dienone 17 to afford the corresponding epoxides 5–8, 18–26 in good to excellent yield and optical purity. A range of enediones 30–32, 34 and one unsaturated keto ester 33 have also been epoxidised stereoselectively to afford optically active epoxides 35–39. The epoxidations were carried out with basic peroxide as the oxidant; the polyleucine catalyst was prepared from leucine *N*-carboxyanhydride using 1,3-diaminopropane, water (employing a humidity cabinet) or a polystyrene immobilised amine as the initiator. Preliminary mass spectral data on material derived from L-leucine and 1,3-diaminopropane (DAP-PLL) suggest that the catalyst consists of material that contains 22 ± 10 leucine residues.

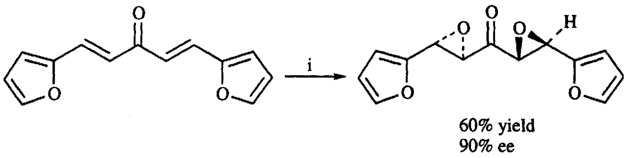
Introduction and background information

The use of polyamino acids as catalysts in the asymmetric epoxidation of chalcones was discovered by Juliá. The reaction involves a triphasic system consisting of aqueous basic peroxide, an organic solvent and an insoluble polyamino acid such as poly-L-leucine[1] (Scheme 1). Further investigations into this reaction showed that a range of chalcone-type substrates could be converted into the epoxides in high yield and with excellent stereoselectivity.[2,3]


60% yield
84% ee

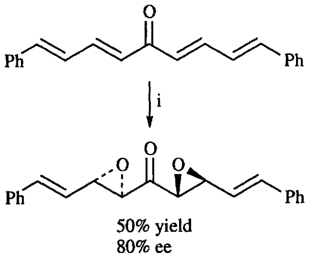
Scheme 1 *Conditions:* i, NaOH, H_2O_2, H_2O, poly-L-leucine, CCl_4

From the earlier papers, highly stereoselective reactions appeared to be limited to *trans*-chalcone derivatives; however, we felt that polyamino acids had a greater synthetic potential and we set up a programme to investigate the full versatility of the reaction. In our previous papers[4,5] we demonstrated that the substrate range is more extensive and includes dienes (Scheme 2) and tetraenes (Scheme 3). Moreover, it was shown that other oxidants such as perborate and percarbonate were also effective at giving the desired oxiranes in good enantiomeric excess.[5] In addition, we found a reliable method for the preparation of good quality catalyst (DAP-PLL) from L-leucine *N*-carboxyanhydride using a homogeneous method and employing 1,3-diaminopropane as the polymerisation initiator.


60% yield
90% ee

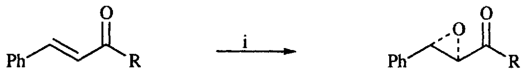
Scheme 2 *Conditions:* i, NaOH, H_2O_2, H_2O, poly-L-leucine, CH_2Cl_2

Given the improved access to reliable catalyst we wanted to explore further the range of asymmetric epoxidations catalysed by polyleucine derivatives. We report some of our more recent results in this paper.[6]


50% yield
80% ee

Scheme 3 *Conditions:* i, NaOH, H_2O_2, H_2O, poly-L-leucine, CH_2Cl_2

Table 1



i, PLL, NaOH, H_2O_2, H_2O, CH_2Cl_2

Entry	Enone	R	Time (h)	Product	Yield (%)	ee (%)
1	**1**	Bu^t	18	**5**	92	89
2	**2**	$C(Me_2)OMe$	84	**6**	70	63
3	**3**	Pr^i	168	**7**	60	62
4	**4**	Cyclopropyl	18	**8**	85	77

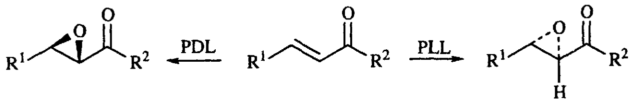
Results and discussion

(a) Oxidation of some enones, an enynone and a dienone

The scope of the asymmetric epoxidation has been broadened by removal of unsaturated moieties bonded to C-1 and/or C-3 on the enone unit. Table 1 shows the results obtained for a range of alkyl enones.

Oxidation in the three-phase system comprising aqueous basic peroxide, organic solvent and poly-L-leucine afforded the corresponding optically active epoxides in good yield and

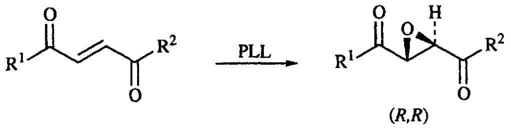
Table 2



Entry	Enone	R^1	R^2	Reaction conditions	Product	Time (h)	Yield (%)	ee (%)
1	**9**	2-Naphthyl	Cyclopropyl	*a*	**18**	38	56	90
2	**9**	2-Naphthyl	Cyclopropyl	*b*	**19**	29	61	90
3	**10**	2-Quinolyl	Cyclopropyl	*a*	**20**	18	94	79
4	**11**	PhCH=CH	Cyclopropyl	*a*	**21**	42	73	74
5	**11**	PhCH=CH	Cyclopropyl	*c*	**21**	19	52	98
6	**12**	4-Pyridyl	Bu^t	*d*	**22**	30	70	72
7	**13**	Bu^t	Ph	*d*	**23**	18	85	90
8	**14**	Cyclopropyl	2-Naphthyl	*a*	**24**	28	73	>98
9	**15**	Pr^i	Ph	*d*	—	—	—	—
10	**16**	Ph	PhC≡C	*e*	**25**	96	57	90
11	**17**	Ph	$CH{=}CS(CH_2)_2S$	*a*	**26**	115	51	>94

[a] PLL (hc), NaOH, H_2O_2, H_2O, CH_2Cl_2. [b] PDL (hc), NaOH, H_2O_2, H_2O, CH_2Cl_2. [c] PLL (hc), NaOH, $NaBO_3$, H_2O, CH_2Cl_2. [d] PLL–DAP, NaOH, H_2O_2, H_2O, CH_2Cl_2. [e] Immobilised PLL, NaOH, H_2O_2, H_2O, toluene.

Table 3



Entry	Substrate	R^1	R^2	Reaction conditions	Product	Yield (%)	ee (%)
1	**30**	Ph	Ph	*a*	**35**	76	76
2	**31**	*p*-ClC_6H_4	Ph	*b*	**36**	60	89
3	**31**	*p*-ClC_6H_4	Ph	*c*	**36**	57	>98
4	**32**	Ph	Bu^t	*a*	**37**	79	82
5	**32**	Ph	Bu^t	*c*	**37**	75	>95
6	**33**	Ph	OBu^t	*c*	**38**	66	>95
7	**34**	Bu^t	Bu^t	*c*	**39**	100	>95

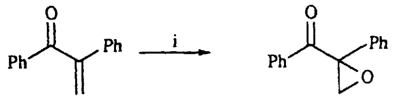
[a] PLL–DAP, NaOH, H_2O_2, H_2O, CH_2Cl_2. [b] PLL (hc), NaOH, $NaBO_3$, H_2O, CH_2Cl_2. [c] Immobilised PLL, NaOH, H_2O_2, H_2O, toluene.

moderate to good enantiomeric excess. Entry 1 shows that a *tert*-butyl group can be accommodated adjacent to the ketone moiety with excellent results in terms of yield and enantiomeric excess. Replacement of one of the methyl groups of the *tert*-butyl group by a proton or a methoxy group (entries 2 and 3) resulted in prolonged reaction times and a decrease in enantiomeric excess. In contrast, a cyclopropyl group is well tolerated (entry 4) and the epoxide **8** is obtained in good yield and good enantiomeric excess.

It was proposed that the different rates of reaction of the *tert*-butyl compound (entry 1) and the isopropyl compound (entry 3) could be due to a longer residence time of the isopropyl enone or epoxide in the 'active site' of the catalyst. This was studied by running the epoxidation catalysed by poly-L-leucine on a mixture of the two enones. The *tert*-butyl compound was converted into the epoxide at the usual rate demonstrating that the presence of the isopropyl compound had no detrimental effect on the activity and selectivity of the catalyst.

The oxidation of a range of cyclopropyl-substituted enones is shown in Table 2 (entries 1, 2, 3, 4, 5 and 8). The epoxidations were carried out using poly-L-leucine prepared in a humidity cabinet[3] with basic peroxide or perborate as the oxidant. All reactions gave rise, after 1 or 2 days, to the corresponding optically active epoxides with a good to excellent degree of enantioselectivity. *tert*-Butyl and cyclopropyl substituents are tolerated, both adjacent to the carbonyl group or at the β-position of the enone (entries 6, 7 and 8). In contrast, an isopropyl group is tolerated adjacent to the carbonyl group (entry 3, Table 1) but when placed at the β-position of the enone no epoxidation is observed (entry 9, Table 2). An enynone has been successfully converted into the corresponding epoxide (entry 10) in excellent enantiomeric excess when using immobilised poly-L-leucine. The immobilised PLL was prepared by a modification of Itsuno's procedure.[7] This polymer has the advantage of being very easily recycled and reused without decrease in yield and enantiomeric excess. Last but not least, the dienone **17** has been oxidised to the corresponding monoepoxide **26** (entry 11) in good yield and enantiomeric excess.

The enone **27** was oxidised with moderate stereoselectivity using immobilised PLL (Scheme 4). The absolute configuration



27 **28**

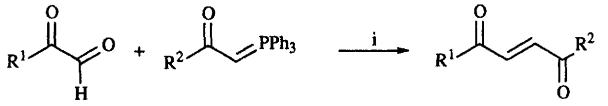
78% yield
59% ee

Scheme 4 *Conditions:* i, NaOH, H_2O_2, H_2O, immobilised PLL, toluene

of the product **28** has not been established. This is the first example of an α-substituted β-unsubstituted enone undergoing asymmetric oxidation with any degree of efficiency using this methodology.

(b) Oxidation of selected enediones and an unsaturated keto ester

The enedione **30** is commercially available while enediones **31**, **32**, **34** and the unsaturated keto ester **33** were prepared by reaction of a glyoxaldehyde with the required stabilised Wittig reagent in the presence of molecular sieves (Scheme 5). The predominant product was the *trans*-alkene accompanied by a



30 $R^1 = Ph$ $R^2 = Ph$
31 $R^1 = p\text{-}ClC_6H_4$ $R^2 = Ph$ 82%
32 $R^1 = Ph$ $R^2 = Bu^t$ 82%
33 $R^1 = Ph$ $R^2 = OBu^t$ 77%
34 $R^1 = Bu^t$ $R^2 = Bu^t$ 61%

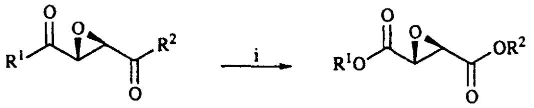
Scheme 5 *Conditions:* i, Bu^{t}OH, toluene

small amount of the *cis*-isomer. The *cis*-isomer could be either separated by flash chromatography or very easily isomerised to the *trans*-isomer by brief exposure to acid. This treatment was always carried out prior to epoxidation to ensure that no *cis*-isomer was present, as the *cis*-enediones afforded racemic epoxides under the PLL-catalysed epoxidation conditions.

The best system for these epoxidations consisted of immobilised PLL as the catalyst, basic peroxide as the oxidant and toluene as the organic solvent (Table 3, entries 3, 5, 6 and 7). Under these conditions, epoxides were obtained in good to excellent yield and with enantiomeric excesses >95%.

Note that the absolute configuration of the epoxides prepared with any of the poly-L-leucine based catalysts was invariably (2*R*) as established by circular dichroism measurements.[8]

Baeyer–Villiger oxidation of the keto epoxides **36–39** was carried out using *meta*-chloroperoxybenzoic acid (MCPBA) (Scheme 6). The diketo epoxide **37** and the keto ester epoxide **38** were both converted into the diester **41** confirming that the epoxides **37** and **38** possess the same absolute configuration. The diketo epoxide **39** was readily oxidised to the di-*tert*-butyl ester **42**.



36 $R^1 = p\text{-}ClC_6H_4$, $R^2 = Ph$ **40** 77%
37 $R^1 = Ph$, $R^2 = Bu^t$ **41** 53%
38 $R^1 = Ph$, $R^2 = OBu^t$ **41** 73%
39 $R^1 = Bu^t$, $R^2 = Bu^t$ **42** 76%

Scheme 6 *Conditions:* i, MCPBA, CH_2Cl_2

(c) Structure of 1,3-DAP-PLL

1,3-DAP-PLL is insoluble in water and in all common organic solvents. However, it does dissolve in trifluoroacetic acid (TFA) or 1,1,1,3,3,3-hexafluoropropan-2-ol containing dichloromethane (30%) and mass spectra of material from these solutions were obtained using the MALDI-TOF technique (see Fig. 1). The peaks (each separated, one from the other, by 113 mass units corresponding to a leucine residue) are due to polymer associated with sodium ions (M + 23). This was deduced because treatment of the matrix with lithium chloride so as to provide lithium ions instead of sodium ions gave an identical pattern corresponding to M + 7. One of the major peaks in the spectrum (labelled * in Fig. 1) gave M + 23 = 2248.0 indicating a composition of 1 diaminopropane residue (72.0), 19 leucine residues (2151.0), hydrogen atoms on the terminal leucine units (2.0) and a sodium ion (23.0). Whether the catalytic activity is due to all of the material across the molecular weight range exhibited in the spectrum remains to be determined.

Conclusions

We have shown that the Juliá asymmetric epoxidation protocol may be applied to a wide range of α,β-unsaturated carbonyl and dicarbonyl compounds. We have used three methods for the preparation of catalyst: the material prepared using a humidity cabinet and DAP-PLL are effective catalysts but in some cases they are inferior, in terms of substrate range and the stereoselectivity of oxidation, to the immobilised system (introduced by Itsuno).

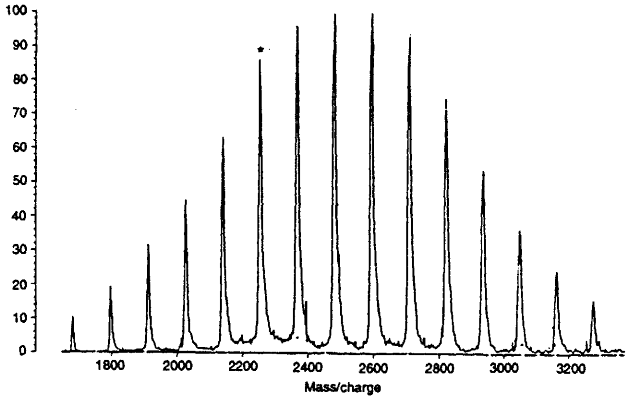


Fig. 1

Experimental

General

Flash column chromatography was carried out using silica gel (Merck 60, 40–63 mm). Thin layer chromatography was carried out on commercially available pre-coated plates (Merck silica gel 60 F254). Chiral HPLC was performed using a Chiralpak AD column. Mps were recorded with a Gallenkamp apparatus and are uncorrected. IR spectra were determined with a Nicolet Magna-IR 550 IR spectrometer. ^{1}H and ^{13}C NMR spectra were recorded on Bruker AM 300 or Bruker DRX 400 spectrometers. Chemical shifts are quoted in ppm. *J* Values are given in Hz. High- and low-resolution mass spectra were recorded with a Kratos Profile HV 3000 spectrometer. Optical rotations were measured with a AA-1000 polarimeter and are recorded in units of 10^{-1} deg cm^2 g^{-1}. Microanalyses were carried out at Butterworths.

General procedure A: preparation of racemic epoxides

To a solution of NaOH (12 equiv.) in distilled water (0.5 cm^3 mmol^{-1} substrate), cooled in an ice-bath, were added toluene (4.7 cm^3 mmol^{-1} substrate), EDTA (0.0025 equiv.), the enone (1 equiv.) and Aliquat 336 (0.1 equiv.). A solution of 30% aqueous H_2O_2 (21 equiv.) was added dropwise to the mixture which was then stirred at room temperature until the reaction was complete. The resulting mixture was diluted with diethyl ether and the aqueous phase was separated and extracted with diethyl ether. The combined organic extracts were washed with water and brine, dried ($MgSO_4$) and evaporated under reduced pressure to afford the racemic epoxide which was further purified by recrystallisation or column chromatography and analysed using chiral HPLC.

General procedure B: asymmetric epoxidation using hydrogen peroxide and PLL or DAP-PLL

To a solution of NaOH (206 mg, 5.15 mmol) in distilled water (0.5 cm^3), cooled in an ice-bath, were added dichloromethane or hexane (1.8 cm^3), poly-L-leucine or poly-D-leucine (111 mg) and 30% aqueous H_2O_2 (1 cm^3, 9 mmol). The mixture was allowed to warm to room temperature after which it was stirred for 6 h to allow the polymer to swell; the substrate (0.43 mmol) was then added to it. If after 18 h the reaction was incomplete, a solution of NaOH (30 mg) in 30% aqueous H_2O_2 (0.3 cm^3) was added to the reaction mixture and stirring was continued until the reaction was finished. After dilution of the reaction mixture with ethyl acetate the catalyst was filtered off and the filtrate was washed with water and brine, dried ($MgSO_4$) and evaporated under reduced pressure to afford the crude product. The enantiomeric excess of the epoxide was determined either using chiral HPLC, after filtration of the crude product (dissolved in dichloromethane) through silica, or by chiral shift ^{1}H NMR spectroscopy using Eu(hfc)$_3$.

General procedure C: asymmetric epoxidation using hydrogen peroxide and immobilised PLL

To a 4.37 M solution of NaOH (0.4 cm^3, 1.8 mmol) were added toluene (1.6 cm^3), immobilised poly-L-leucine (200 mg) and 30% aqueous H_2O_2 (0.4 cm^3, 3.5 mmol). The mixture was stirred at room temperature for 6 h after which the substrate (0.43 mmol) was added to it. If after 18 h the reaction was incomplete, a solution of NaOH (30 mg) in 30% aqueous H_2O_2 (0.3 cm^3) was added to the reaction mixture and stirring was continued until the reaction was finished. After dilution of the reaction mixture with ethyl acetate the catalyst was filtered off and the filtrate was washed with water and brine, dried ($MgSO_4$) and evaporated under reduced pressure to afford the crude product. The enantiomeric excess of the epoxide was determined either using chiral HPLC, after filtration of the crude product (dissolved in dichloromethane) through silica, or by chiral shift ^{1}H NMR spectroscopy using Eu(hfc)$_3$.

General procedure D: asymmetric epoxidation using perborate and PLL or DAP-PLL

To a 0.43 M solution of NaOH (1 cm^3, 0.43 mmol) were sequentially added distilled water (1 cm^3), $NaBO_3{\cdot}4H_2O$ (132 mg, 0.86 mmol), dichloromethane (2 cm^3), poly-L-leucine or poly-D-leucine (111 mg) and Aliquat 336 (1 drop). The mixture was stirred at room temperature for 6 h after which the substrate (0.43 mmol) was added to it. The reaction was followed by thin layer chromatography and stirring was continued until the reaction was complete. After dilution of the reaction mixture with ethyl acetate the catalyst was filtered off and the filtrate was washed with water and brine, dried ($MgSO_4$) and evaporated under reduced pressure to afford the crude product. The enantiomeric excess of the epoxide was determined either using chiral HPLC, after filtration of the crude product (dissolved in dichloromethane) through silica, or by chiral shift ^{1}H NMR spectroscopy using Eu(hfc)$_3$.

***trans*-(±)-2,3-Epoxy-3-phenyl-1-*tert*-butylpropan-1-one 5.** Obtained from enone **1** according to general procedure A (75%); mp 68–70 °C (from diethyl ether–hexane); ν_{max}(KBr)/cm^{-1} 1706 (C=O), 1240 and 881 (C–O); δ_H(300 MHz; $CDCl_3$) 1.24 (9 H, s, CCH_3), 3.86 [2 H, d, J 1.9, CH(O)CHC=O and CH(O)CHC=O] and 7.29–7.38 (5 H, m, PhH); δ_C(100.6 MHz; $CDCl_3$) 25.7 (CCH_3), 43.6 (CCH_3), 59.1 and 59.3 (C epoxide), 125.6 (CH × 2), 128.7 (CH × 2), 128.9 (CH), 135.7 (C) and 208.1 (C=O); m/z 204 (M$^+$, 31) and 57 (100%) (Found: M$^+$, 204.1150. $C_{13}H_{16}O_2$ requires 204.1160); chiral HPLC (5:95, ethanol–hexane, 254 nm, 1 cm^3 min^{-1}) 9.5 and 14.1 min.

***trans*-(−)-2,3-Epoxy-3-phenyl-1-*tert*-butylpropan-1-one 5.** Obtained from enone **1** according to general procedure B (92%); $[\alpha]_D^{28}$ −162 (c 0.6 in $CHCl_3$); chiral HPLC (5:95, ethanol–hexane, 254 nm, 1 cm^3 min^{-1}) 9.5 min.

***trans*-(±)-2,3-Epoxy-1-(1′-methyl-1′-methoxyethyl)-3-phenylpropan-1-one 6.** Obtained from enone **2** according to general procedure A (73%); ν_{max}(neat)/cm^{-1} 1717 (C=O), 1203 and 1069 (C–O); δ_H(300 MHz; $CDCl_3$) 1.38 [6 H, s, $C(CH_3)_2$], 3.25 (3 H, s, CH_3O), 3.89 [1 H, d, J 1.8, CH(O)CHC=O], 4.18 [1 H, d, J 1.8 CH(O)CHC=O] and 7.25–7.50 (5 H, m, PhH); δ_C(100.6 MHz; $CDCl_3$) 22.7 (CCH_3), 52.2 (OCH_3), 43.9 and 74.5 (C epoxide), 126.0 (CH × 2), 128.4, 128.5 (CH × 2), 130.2 (CH), 133.7 (C) and 202.9 (C=O); m/z 220 (M$^+$, 2.9) and 73 (100%) (Found: M$^+$, 220.1099. $C_{13}H_{16}O_3$ requires 220.1105); chiral HPLC (2:98 isopropyl alcohol–hexane, 232 nm, 0.5 cm^3 min^{-1}) 22.4 and 25.6 min.

***trans*-(−)-2,3-Epoxy-1-(1′-methyl-1′-methoxyethyl)-3-phenylpropan-1-one 6.** Obtained from enone **2** according to general procedure B (70%); $[\alpha]_D^{19}$ −10 (c 0.6 in $CHCl_3$); chiral HPLC (2:98, isopropyl alcohol–hexane, 232 nm, 0.5 cm^3 min^{-1}) 25.6 min.

***trans*-(±)-2,3-Epoxy-1-isopropyl-3-phenylpropan-1-one 7.** Obtained from enone **3** according to general procedure A (68%); ν_{max}(neat)/cm^{-1} 1703 (C=O) and 1062 (C–O); δ_H(300 MHz; $CDCl_3$) 1.19 [6 H, d, $(CH_3)_2$CH] 2.93 [1 H, m, C$H(CH_3)_2$], 3.61 [1 H, d, CH(O)CHC=O], 3.93 [1 H, d, CH(O)CHC=O] and 7.30–7.61 (5 H, m, PhH); m/z 190 (M$^+$, 10.3) and 131 (100%) (Found: M$^+$, 190.0994. $C_{12}H_{14}O_2$ requires 190.0989); chiral HPLC (5:95, ethanol–hexane, 240 nm, 1 cm^3 min^{-1}) 9.6 and 17.7 min.

***trans*-(−)-2,3-Epoxy-1-isopropyl-3-phenylpropan-1-one 7.** Obtained from enone **3** according to general procedure B (70%); $[\alpha]_D^{19}$ −48 (c 0.85 in $CHCl_3$); chiral HPLC (5:95, ethanol–hexane, 240 nm, 0.5 cm^3 min^{-1}) 9.6 min.

***trans*-(±)-1-Cyclopropyl-2,3-epoxy-3-phenylpropan-1-one 8.** Obtained from enone **4** according to general procedure A (91%); mp 55 °C (from dichloromethane–hexane); ν_{max}(KBr)/cm^{-1} 1692 (C=O), 1237, 902 and 802 (C–O); δ_H(300 MHz; $CDCl_3$) 1.01 (2 H, m, CH_2), 1.16 (2 H, m, CH_2), 2.18 (1 H, tt, J 8 and 4, CH), 3.59 [1 H, d, J 2, CH(O)CHC=O], 4.08 [1 H, d, J 2, CH(O)CHC=O] and 7.28–7.40 (5 H, m, PhH); δ_C(75.5 MHz; $CDCl_3$) 11.8 and 12.3 (CH_2), 15.6 (CH cyclopropyl), 57.7 and 63.4 (C epoxide), 125.8 (CH × 2), 128.7 (CH × 2), 129.9 (CH), 135.3 (C) and 205.7 (C=O); m/z 188 (M$^+$, 4.4) and 69 (100%) (Found: M$^+$, 188.0841. $C_{12}H_{12}O_2$ requires 188.0837) (Found: C, 76.76; H, 6.4. $C_{12}H_{12}O_2$ requires C, 76.57; H, 6.42%); chiral HPLC (30:70, isopropyl alcohol–hexane, 254 nm, 0.2 cm^3 min^{-1}) 27.3 and 30.9 min.

***trans*-(−)-1-Cyclopropyl-2,3-epoxy-3-phenylpropan-1-one 8.** Obtained from enone **4** according to general procedure B (85%) as an oil; ee 77%; $[\alpha]_D$ −702 (c 2.4 in $CHCl_3$); chiral HPLC (30:70, isopropyl alcohol–hexane, 254 nm, 0.2 cm^3 min^{-1}) 30.9 min.

***trans*-(±)-1-Cyclopropyl-2,3-epoxy-3-(2-naphthyl)propan-1-one 18.** Obtained from enone **9** according to general procedure A (65%); mp 97–98 °C (from diethyl ether–hexane); ν_{max}(KBr)/cm^{-1} 1696 (C=O), 1174, 901 and 834 (C–O); δ_H(400 MHz; $CDCl_3$) 1.04 (2 H, m, CH_2), 1.19 (2 H, m, CH_2), 2.23 (1 H, tt, J 8 and 4.5, CH cyclopropyl), 3.71 [1 H, d, J 2, CH(O)CHC=O], 4.26 [1 H, d, J 2, CH(O)CHC=O], 7.35 (1 H, dd, J 8.5 and 2, H-3 naphthyl) and 7.51 (2 H, m, H-6 and H-7 naphthyl), 7.82–7.87 (3 H, m, H-4, H-5 and H-8 naphthyl), 7.84 (1 H, s, H-1 naphthyl); δ_C(100.6 MHz; $CDCl_3$) 11.8 and 12.4 (CH_2), 15.7 (CH cyclopropyl), 58.0 and 63.5 (C epoxide), 122.5 (CH), 125.9 (CH), 126.5 (CH), 126.6 (CH), 127.8 (CH), 127.9 (CH), 128.7 (CH), 132.6 (C), 133.1 (C), 133.6 (C), 205.8 (C=O); m/z 238 (M$^+$, 29) and 154 (100%) (Found: M$^+$, 238.099 81. $C_{16}H_{14}O_2$ requires 238.099 38) (Found: C, 80.59; H, 5.96. $C_{16}H_{14}O_2$ requires C, 80.65; H, 5.92); chiral HPLC (20:80, isopropyl alcohol–hexane, 254 nm, 1 cm^3 min^{-1}) 7.1 and 9.2 min.

***trans*-(−)-1-Cyclopropyl-2,3-epoxy-3-(2-naphthyl)propan-1-one 18.** Obtained from enone **9** according to general procedure B (56%); mp 97–99 °C; $[\alpha]_D$ −97 (c 0.5 in $CHCl_3$); chiral HPLC (20:80, isopropyl alcohol–hexane, 254 nm, 1 cm^3 min^{-1}) 9.2 min.

***trans*-(+)-1-Cyclopropyl-2,3-epoxy-3-(2-naphthyl)propan-1-one 19.** Obtained from enone **9** according to general procedure B (PDL) (61%); mp 95–96 °C; $[\alpha]_D$ +93 (c 0.3 in $CHCl_3$); chiral HPLC (20:80, isopropyl alcohol–hexane, 254 nm, 1 cm^3 min^{-1}) 7.1 min.

***trans*-(±)-1-Cyclopropyl-2,3-epoxy-3-(2-quinolyl)propan-1-one 20.** Obtained from enone **10** according to general procedure A (91%); ν_{max}(KBr)/cm^{-1} 1694 (C=O), 912 and 829 (C–O); δ_H(300 MHz; $CDCl_3$) 0.95–1.01 (2 H, m, CH_2), 1.10–1.20 (2 H, m, CH_2), 2.17 (1 H, tt, J 8 and 4, CH), 3.77 [1 H, d, J

2, C*H*(O)CHC=O], 4.43 [1 H, d, *J* 2, CH(O)C*H*C=O], 7.26 (1 H, d, *J* 8, H-4 quinolyl), 7.51 (1 H, ddd *J* 9, 8 and 1, H-7 or H-6 quinolyl), 7.69 (1 H, ddd, *J* 9, 7 and 1, H-6 or H-7 quinolyl), 7.76 (1 H, dd, *J* 9 and 1, H-5 quinolyl), 8.03 (1 H, dd, *J* 8 and 1, H-8 quinolyl), 8.12 (1 H, *J* 9, H-3 quinolyl); δ_C(75.5 MHz; $CDCl_3$) 11.8 and 12.6 (CH_2), 15.5 (CH cyclopropyl), 58.4 and 62.3 (C epoxide), 116.6 (CH), 127.0 (CH), 127.7 (CH), 128.0 (C), 129.0 (CH), 130.1 (CH), 137.5 (CH), 147.6 (C), 151.1 (C) and 205.1 (C=O); chiral HPLC (5:95, isopropyl alcohol–hexane, 254 nm, 1 cm^3 min^{-1}) 17.0 and 22.2 min.

***trans*-(−)-1-Cyclopropyl-2,3-epoxy-3-(2-quinolyl)propan-1-one 20.** Obtained from enone **10** according to general procedure B (94%) as a crystalline solid; mp 74–76 °C; ee 79%; $[\alpha]_D$ 0 (*c* 1 in $CHCl_3$); chiral HPLC (5:95, isopropyl alcohol–hexane, 254 nm, 1 cm^3 min^{-1}) 22.2 min.

***trans*(±)-2,3-Epoxy-5-phenyl-1-cyclopropylpent-4-en-1-one 21.** Obtained from enone **11** according to general procedure A (57%); mp 67–70 °C; ν_{max}(KBr)/cm^{-1} 1696 (C=O) and 1626 (C=C); δ_H(400 MHz; $CDCl_3$) 0.91–1.00 (2 H, m, CH_2), 1.11–1.50 (2 H, m, CH_2), 2.12–2.17 (1 H, m, CH cyclopropyl), 3.56 [1 H, d, *J* 2, CH=CHCH(O)C*H*], 3.76 [1 H, m, CH=CHC*H*(O)CH], 5.91 [1 H, dd, *J* 16 and 8, CH=C*H*CH(O)CH], 6.95 [1 H, m, C*H*=CHCH(O]CH] and 7.25–7.50 (5 H, m, PhH); δ_C(100.6 MHz; $CDCl_3$) 11.7 (CH_2), 12.3 (CH_2), 15.5 (CH cyclopropyl), 58.1 and 61.6 (CH epoxide), 124.3 (CH), 126.6 (CH), 128.5 (CH), 135.6 (C), 141.1 (CH), 142.0 (CH) and 206.2 (C=O); *m/z* 250 (M^+, 0.5) and 69 (100%) (Found: M^+, 250.0995. $C_{17}H_{14}O_2$ requires 250.0994); chiral HPLC (20:80, isopropyl alcohol–hexane, 261 nm, 1 cm^3 min^{-1}) 7.0 and 7.9 min.

***trans*-(−)-2,3-Epoxy-5-phenyl-1-cyclopropylpent-4-en-1-one 21.** Obtained from enone **11** according to general procedure D (62%); ee 98%; $[\alpha]_D$ −31 (*c* 0.4 in $CHCl_3$); chiral HPLC (20:80, isopropyl alcohol–hexane, 261 nm, 1 cm^3 min^{-1}) 7.9 min.

***trans*-(±)-2,3-Epoxy-1-*tert*-butyl-3-(4-pyridyl)propan-1-one 22.** Obtained from enone **12** according to general procedure A (60%) as an oil; ν_{max}(neat)/cm^{-1} 1717 (C=O) and 1080 (C–O); δ_H(400 MHz; $CDCl_3$) 1.21 [9 H, s, C(CH_3)$_3$], 3.78 [1 H, d, *J* 1.8, C*H*(O)CHC=O], 3.84 [1 H, d, *J* 1.8, CH(O)C*H*C=O], 7.20 (2 H, d, *J* 5.3, pyridyl) and 8.60 (2 H, d, *J* 5.3, pyridyl); δ_C(100.6 MHz; $CDCl_3$) 25.6 [C(CH$_3$)$_3$], 43.7 [C(CH$_3$)$_3$], 57.4 and 58.7 (C epoxide), 120.4 (CH), 144.9 (CH), 150.0 (CH) and 207.2 (C=O); *m/z* 205 (M^+, 15.2) and 57 (100%) (Found: M^+, 205.1103. $C_{12}H_{15}O_2$ requires 205.1107); chiral HPLC (10:90, isopropyl alcohol–hexane, 260 nm, 1 cm^3 min^{-1}) 11.1 and 12.5 min.

***trans*-(−)-2,3-Epoxy-1-*tert*-butyl-3-(4-pyridyl)propan-1-one 22.** Obtained from enone **12** according to general procedure B (70%); $[\alpha]_D$ −19 (*c* 0.4 in $CHCl_3$); chiral HPLC (10:90, isopropyl alcohol–hexane, 260 nm, 1 cm^3 min^{-1}) 11.1 min.

***trans*-(±)-2,3-Epoxy-3-*tert*-butyl-1-phenylpropan-1-one 23.** Obtained from enone **13** according to general procedure A (70%); ν_{max}(KBr)/cm^{-1} 1692 (C=O), 1231 and 881 (C–O); δ_H(300 MHz; $CDCl_3$) 1.02 [9 H, s, C(CH_3)$_3$], 2.94 [1 H, d, *J* 2.2, C*H*(O)CHC=O], 4.09 [1 H, d, *J* 2.2, CH(O)C*H*C=O], 7.45–7.60 (3 H, m, PhH) and 7.97–8.01 (2 H, m, PhH); δ_C(100.6 MHz; $CDCl_3$) *inter alia* 54.9 and 67.6 (C epoxide), 128.2 (CH × 2), 128.8 (CH × 2), 133.7 (CH), 135.6 (C) and 195.0 (C=O); *m/z* 204 (M^+, 0.1) and 105 (100%) (Found: M^+, 204.1150. $C_{13}H_{16}O_2$ requires 204.1149); chiral HPLC (5:95, isopropyl alcohol–hexane, 254 nm, 0.5 cm^3 min^{-1}) 16.0 and 19.2 min.

***trans*-(−)-2,3-Epoxy-3-*tert*-butyl-1-phenylpropan-1-one 23.** Obtained from enone **13** according to general procedure B (85%); $[\alpha]_D$ −14 (*c* 0.2 in $CHCl_3$); chiral HPLC (5:95, isopropyl alcohol–hexane, 254 nm, 0.5 cm^3 min^{-1}) 16.0 min.

***trans*-(±)-3-Cyclopropyl-2,3-epoxy-1-(2-naphthyl)propan-1-one 24.** Obtained from enone **14** according to general procedure A (21%); mp 132–134 °C; ν_{max}(KBr)/cm^{-1} 1686 (C=O), 1288 and 1234 (C–O); δ_H(400 MHz; $CDCl_3$) 0.53 (2 H, m, CH_2), 0.62–0.73 (2 H, m, CH_2), 1.10 (1 H, m, CH cyclopropyl), 3.01 [1 H, dd, *J* 5.6 and 2, C*H*(O)CHC=O], 4.22 [1 H, d, *J* 2, CH(O)C*H*C=O], 7.55–7.65 (2 H, m, H-6 and H-7 naphthyl), 7.89 (1 H, d, *J* 8, H-5 or H-8 naphthyl), 7.92 (1 H, d, *J* 8.5, H-5 or H-8 naphthyl), 7.99 (1 H, d, *J* 8, H-4 naphthyl), 8.04 (1 H, dd, *J* 8.5 and 1.5, H-3 naphthyl) and 8.59 (1 H, s, H-1 naphthyl); δ_C(100.6 MHz; $CDCl_3$) 2.5 and 2.4 (CH_2), 11.4 (CH cyclopropyl), 57.5 and 61.9 (CH epoxide), 123.7 (CH), 127.0 (CH), 127.9 (CH), 128.7 (CH), 128.9 (CH), 129.7 (CH), 130.3 (CH), 132.4 (C), 133.0 (C), 135.9 (C) and 194.3 (C=O); *m/z* 238 (M^+, 34) and 155 (100%) (Found: M^+, 238.099 99. $C_{16}H_{14}O_2$ requires 238.099 38); chiral HPLC (1:99, ethanol–hexane, 254 nm, 1 cm^3 min^{-1}) 56 and 63 min.

***trans*-(+)-3-Cyclopropyl-2,3-epoxy-1-(2-naphthyl)propan-1-one 24.** Obtained from enone **14** according to general procedure B (73%); $[\alpha]_D$ +37 (*c* 0.5 in $CHCl_3$); chiral HPLC (1:99, ethanol–hexane, 254 nm, 1 cm^3 min^{-1}) 56 min.

***trans*-(±)-4,5-Epoxy-1,5-diphenylpent-1-yn-3-one 25.** To a solution of NaOH (106 mg, 2.64 mmol) in distilled water (0.25 cm^3) were added toluene (0.9 cm^3), poly-L-leucine (26 mg), poly-D-leucine (30 mg) and 30% aqueous H_2O_2 (0.25 cm^3, 2.2 mmol). The mixture was stirred at room temperature for 6 h, after which enynone **16** was added to it and stirring was continued for 18 h. After addition of a solution of NaOH (30 mg) in 30% aqueous H_2O_2 (0.3 cm^3) to the mixture it was stirred for a further 24 h and worked up by dilution with ethyl acetate, washing with water and brine and drying ($MgSO_4$). Column chromatography (hexane–dichloromethane, 1:9) afforded the racemic epoxide **25** as an oil (10 mg, 22%); ν_{max}(neat)/cm^{-1} 2208 (C≡C), 1664 (C=O), 1290 and 1165 (C–O); δ_H(400 MHz; $CDCl_3$) 3.73 [1 H, d, *J* 1.8, C*H*(O)CHC=O], 4.27 [1 H, d, *J* 1.8, CH(O)C*H*C=O], 7.30–7.55 (7 H, m, PhH) and 7.60–7.7 (3 H, m, PhH); δ_C(100.6 MHz; $CDCl_3$) 58.8 and 63.8 (CH epoxide), 85.4 and 94.9 (C≡C), 119.4 (C), 125.8 (CH × 2), 128.7 (CH × 2), 129.1 (CH), 131.3 (CH), 133.4 (CH × 2), 134.8 (C) and 182.4 (C=O); *m/z* 248 (M^+, 32) and 129 (100%) (Found: M^+, 248.083 31. $C_{17}H_{12}O_2$ requires 248.083 73); chiral HPLC (20:80, isopropyl alcohol–hexane, 254 nm, 0.7 cm^3 min^{-1}) 10 and 11.5 min.

***trans*-(−)-4,5-Epoxy-1,5-diphenylpent-1-yn-3-one 25.** Obtained from enynone **16** according to general procedure C (57%); $[\alpha]_D$ −208 (*c* 1.2 in $CHCl_3$); chiral HPLC (20:80, isopropyl alcohol–hexane, 254 nm, 0.7 cm^3 min^{-1}) 11.5 min.

***trans*-(±)-2-(3,4-Epoxy-2-oxo-4-phenylbutylidene)-1,3-dithietane 26.** Obtained from dienone **17** according to general procedure A (55%); mp 123–125 °C; ν_{max}(KBr)/cm^{-1} 1610 (C=O) and 1499 (C=C); δ_H(400 MHz; $CDCl_3$) 3.36–3.52 (4 H, m, SCH_2CH_2S), 3.55 [1 H, d, *J* 1.8, C*H*(O)CHC=O], 3.96 [1 H, d, *J* 1.8, CH(O)C*H*C=O], 6.78 (1 H, s, CH=CS) and 7.2–7.4 (5 H, m, PhH); δ_C(100.6 MHz; $CDCl_3$) 35.6 and 39.2 (SCH_2CH_2S), 58.6 and 63.0 (CH epoxide), 106.1 (*C*H=CS), 125.7 (CH × 2), 128.6 (CH × 2), 128.7 (CH), 135.7 (C_{ipso}), 170.2 (CH=*C*S) and 189.7 (C=O); *m/z* 264 (M^+, 22) and 145 (100%) (Found: M^+, 264.028 31. $C_{13}H_{12}O_2S_2$ requires 264.027 87); chiral HPLC (20:80, isopropyl alcohol–hexane, 332 nm, 1 cm^3 min^{-1}) 27 and 36 min.

***trans*-(−)-2-(3,4-Epoxy-2-oxo-4-phenylbutylidene)-1,3-dithietane 26.** Obtained from dienone **17** according to general procedure B (51%); mp 152–153 °C; $[\alpha]_D$ −186 (*c* 0.3 in $CHCl_3$); chiral HPLC (20:80, isopropyl alcohol–hexane, 332 nm, 1 cm^3 min^{-1}) 27 min.

(±)-2,3-Epoxy-1,2-diphenylpropan-1-one 28. Obtained from enone **27** according to general procedure A (50%) as an oil; ν_{max}(neat)/cm^{-1} 1682 (C=O); δ_H(400 MHz; $CDCl_3$) 3.08 (1 H, d, *J* 5.4, CH_2), 3.40 (1 H, d, *J* 5.4, CH_2), 7.23–7.48 (8 H, m, PhH) and 8.03–8.05 (2 H, m, PhH); δ_C(100.6 MHz; $CDCl_3$) 55.0 (CH_2), 63.2 (C epoxide), 125.4 (CH × 2), 128.5 (CH × 2), 128.6 (CH), 128.8 (CH × 2), 130.0 (CH × 2), 133.7 (CH), 134.3 (C), 135.6 (C) and 194.7 (C=O); *m/z* 224 (M^+, 3.3) and 105 (100%) (Found: M^+, 224.0841. $C_{15}H_{12}O_2$ requires 224.0837); chiral HPLC (2:98, isopropyl alcohol–hexane, 254 nm, 1 cm^3 min^{-1}) 8.7 and 9.6 min.

(−)-2,3-Epoxy-1,2-diphenylpropan-1-one 28. Obtained from enone **27** according to general procedure C (78%); $[\alpha]_D$ −69 (*c* 0.9 in $CHCl_3$); chiral HPLC (2:98, isopropyl alcohol–hexane, 254 nm, 1 cm^3 min^{-1}) 9.6 min.

***trans*-1-(4-Chlorophenyl)-4-phenylbut-2-ene-1,4-dione 31.** 2-Bromo-4-chloroacetophenone (1 g, 4.28 mmol) and diethylhydroxylamine (0.66 cm^3, 6.4 mmol) were heated under reflux in methanol (20 cm^3) for 15 h. After cooling and removal of the solvent *in vacuo* the crude mixture was dissolved in diethyl ether (20 cm^3) to precipitate the diethylamine hydrochloride, which was filtered off; the filtrate was evaporated to yield the crude aldehyde. To phenacyl(triphenyl)phosphonium bromide (2 g, 4.28 mmol) in toluene (20 cm^3) under an atmosphere of nitrogen was added potassium *tert*-butoxide (0.48 g, 4.28 mmol) in one portion, and the mixture was stirred at room temperature for 1 h. The crude aldehyde was dissolved in anhydrous THF (20 cm^3) and added to the solution containing the stabilised Wittig reagent and stirred at room temperature for 15 h. After being filtered and evaporated *in vacuo* the crude mixture was subjected to flash chromatography (diethyl ether–light petroleum, 1:8). The mixture of *cis*/*trans* compounds was dissolved in dichloromethane (5 cm^3) and two drops of HCl (conc.) were added to the solution which was then swirled and treated with sodium hydrogen carbonate to neutralise the acid. Drying ($MgSO_4$), filtration and evaporation of the mixture *in vacuo* gave the enedione **31** as a red solid (0.94 g, 82%); mp 95–96 °C; ν_{max}(film)/cm^{-1} 1687 (C=O), 1648 (C=O) and 1597 (C=C); δ_H(400 MHz; $CDCl_3$) 7.2–7.6 (6 H, m) and 7.9–8.2 (5 H, m); δ_C(100.6 MHz; $CDCl_3$) 128.8 (CH × 2), 128.9 (CH × 2), 129.3 (CH × 2), 130.2 (CH × 2), 133.9 (CH), 134.5 (CH), 135.2 (C), 135.5 (CH), 136.8 (C), 140.5 (C), 188.5 (C=O) and 189.6 (C=O); *m*/*z* 270 (M^+, 20) and 105 (100%) (Found: M^+, 270.044 02. $C_{16}H_{11}O_2Cl$ requires 270.044 75).

***trans*-1-Phenyl-4-*tert*-butylbut-2-ene-1,4-dione 32.** To a stirred solution of pivaloylmethylene(triphenyl)phosphonium chloride (2.76 g, 6.73 mmol) and powdered molecular sieves (*ca.* 0.5 g) in toluene (50 cm^3) under nitrogen was added potassium *tert*-butoxide (0.755 g, 6.73 mmol) in one portion. The mixture was stirred at room temperature for 1 h after which it was treated with phenylglyoxal monohydrate (1.02 g, 6.73 mmol) in one portion and stirring continued for 15 h. After filtration and evaporation *in vacuo* the crude mixture was subjected to flash chromatography (diethyl ether–light petroleum, 1:4). The mixture of *cis*/*trans* compounds was dissolved in dichloromethane (20 cm^3) and 2 drops of HCl (conc.) were added to the solution which was then swirled and neutralised with sodium hydrogen carbonate. Drying ($MgSO_4$), filtration and evaporation *in vacuo* of the mixture gave the enedione (1.19 g, 82%) as a yellow oil; ν_{max}(film)/cm^{-1} 1698 (C=O), 1670 (C=O) and 1604 (C=C); δ_H(400 MHz; $CDCl_3$) 1.23 (9 H, s, 3 × CH_3), 7.56 (2 H, m, PhH), 7.57 (1 H, d, *J* 15, CH), 7.60 (1 H, m, PhH), 7.87 (1 H, d, *J* 15, CH) and 8.02 (2 H, m, PhH); δ_C(100.6 MHz; $CDCl_3$) *inter alia* 25.8 (CH_3), 43.7 (C), 128.8 (CH), 133.8 (CH), 134.0 (CH), 134.3 (CH), 137.0 (C), 189.9 (C=O) and 204.28 (C=O); *m*/*z* (EI) 216 (M^+, 0.1) and 57 (71%) (Found: M^+, 216.115 27. $C_{14}H_{16}O_2$ requires 216.115 03).

***tert*-Butyl *trans*-4-oxo-4-phenylbut-2-enoate 33.** To a stirred solution of pivaloylmethylene(triphenyl)phosphonium chloride (2.71 g, 6.57 mmol) and powdered molecular sieves (*ca.* 0.5 g) in tetrahydrofuran (50 cm^3) under an atmosphere of nitrogen was added potassium *tert*-butoxide (0.737 g, 6.57 mmol) in one portion. The mixture was stirred at room temperature for 1 h after which it was treated with phenylglyoxal monohydrate (1.00 g, 6.57 mmol) in one portion. The mixture was then stirred for 15 h, after which it was filtered and evaporated *in vacuo* to give the crude mixture which was subjected to flash chromatography (diethyl ether–light petroleum, 1:6). The mixture of *cis*/*trans* compounds was dissolved in dichloromethane (20 cm^3) and 2 drops of HCl (conc.) were added to the solution which was then swirled and neutralised with sodium hydrogen carbonate. Drying ($MgSO_4$), filtration and evaporation of the mixture *in vacuo* gave the ester (1.18 g, 77%) as a yellow oil; ν_{max}(film)/cm^{-1} 1723 (C=O), 1670 (C=O) and 1637 (C=C); δ_H(400 MHz; $CDCl_3$) 1.54 (9 H, s, 3 × CH_3), 6.79 (1 H, d, *J* 15.6 (CH), 7.50 (2 H, m, PhH), 7.61 (1 H, m, PhH), 7.79 (1 H, d, *J* 15.6, CH) and 7.98 (2 H, m, PhH); δ_C(100.6 MHz; $CDCl_3$) *inter alia* 28.0 (CH_3), 81.9 (C), 128.8 (CH), 134.6 (CH), 135.6 (CH), 136.8 (C), 164.8 (C=O) and 190.0 (C=O); *m*/*z* (EI) 232 (M^+, 5) and 57 (100%) (Found: M^+, 232.1105. $C_{14}H_{16}O_3$ requires 232.1099).

***trans*-Dipivaloyl ethylene 34.** Bromopinacolone (3.90 g, 3 cm^3, 21.8 mmol) and diethylhydroxylamine (2.3 g, 2.7 ml, 26 mmol) were heated under reflux in methanol (50 cm^3) for 15 h. After cooling and evaporation *in vacuo* of the crude mixture, the residue was dissolved in diethyl ether to precipitate the diethylamine hydrochloride; this was filtered off. The filtrate was evaporated to yield the crude glyoxaldehyde. To pivaloylmethylene(triphenyl)phosphonium chloride (6.0 g, 13.6 mmol) in toluene (50 cm^3) under nitrogen was added potassium *tert*-butoxide (1.53 g, 13.6 mmol) in one portion, and the mixture was stirred at room temperature for 1 h. The crude glyoxaldehyde was added to the solution containing the stabilised Wittig reagent and the mixture was stirred at room temperature for 15 h. After filtration and evaporation *in vacuo* of the mixture the crude product was subjected to flash chromatography (diethyl ether–light petroleum, 1:8). The mixture of *cis*/*trans* compounds was dissolved in dichloromethane (20 cm^3) and 2 drops of HCl (conc.) were added to the solution which was then swirled and neutralised with sodium hydrogen carbonate. Drying ($MgSO_4$), filtration and evaporation of the mixture *in vacuo* gave the enedione (1.62 g, 61%) as a colourless crystalline solid; mp 106–108 °C; ν_{max}(film)/cm^{-1} 1690 (C=O) and 1657 (C=C); δ_H(400 MHz; $CDCl_3$) 1.17 (18 H, s, 6 × CH_3) and 7.45 (2 H, s, CH × 2); δ_C(100.6 MHz; $CDCl_3$) 25.7 (CH_3), 43.6 (C), 133.1 (CH) and 204.4 (C=O).

***trans*-(−)-1,4-Diphenyl-2,3-epoxybutane-1,4-dione 35.** PLL-DAP (110 mg) was added to a stirred mixture of sodium hydroxide (0.18 g, 4.5 mmol), water (0.5 cm^3), dichloromethane (1.8 cm^3) and aqueous hydrogen peroxide (30% w/v, 1.0 cm^3) at 0 °C; the mixture was then allowed to warm to ambient temperature. After 6 h *trans*-1,2-dibenzoylethylene **30** (102 mg, 0.43 mmol) was added to the mixture which was then stirred at room temperature for 15 h. After being filtered and washed, the mixture was extracted with dichloromethane, and the extract was dried ($MgSO_4$) and evaporated *in vacuo* to afford the epoxide (82 mg, 76%) as a colourless crystalline solid (which turned yellow with time; *NB* on scaling up the reaction it was found that the PLL needed to be washed with methanol to remove the product from the catalyst), mp 96–100 °C; $[\alpha]_D$ −88 (*c* 0.55 in $CHCl_3$); chiral shift ^1H NMR spectroscopy using $Eu(hfc)_3$ indicated the enantiomeric excess to be 76%; ν_{max}($CHCl_3$)/cm^{-1} 1683 and 1602 (C=O); δ_H(400 MHz; $CDCl_3$) 4.91 (2 H, s, CH × 2), 7.52 (4 H, m, PhH), 7.64 (2 H, m, PhH) and 8.07 (4 H, m, PhH); δ_C(100.6 MHz; $CDCl_3$) 56.4 (CH), 128.6 (CH), 129.1 (CH), 134.5 (CH), 135.1 (C) and 192.2 (CO); *m*/*z* (EI) 252 (M^+, 0.4) and 105 (100%) (Found: M^+, 252.0786. $C_{16}H_{12}O_3$ requires 252.0786) (Found: C, 76.47; H, 4.83. $C_{16}H_{12}O_3$ requires C, 76.18; H, 4.79%).

***trans*-(±)-1-(4-Chlorophenyl)-4-phenyl-2,3-epoxybutane-1,4-dione 36.** 1-(4-Chlorophenyl)-4-phenylbut-2-ene-1,4-dione **31** (0.2 g, 0.74 mmol) was added to a stirred mixture of sodium hydroxide (30 mg, 0.74 mmol), water (4 cm^3), dichloromethane (3.6 cm^3), Aliquat 336 (1 drop) and sodium perborate (0.23 g, 1.5 mmol). After 16 h, the reaction mixture was evaporated to dryness to give the crude epoxide **36** purification of which by flash chromatography (ethyl acetate–light petroleum, 1:3) afforded a white solid (0.12 g, 56%), mp 105–107 °C; ν_{max}($CHCl_3$)/cm^{-1} 1689 and 1591 (C=O); δ_H(300 MHz; $CDCl_3$) 4.43 (1 H, d, *J* 2, CH), 4.47 (1 H, d, *J* 2, CH), 7.46–7.53 (4 H, m, PhH), 7.64–7.69 (1 H, m, PhH) and 7.98–8.04 (4 H, m, C_6H_4Cl); δ_C(72.5 MHz; $CDCl_3$) 56.3 and 56.4 (CH epoxide), 128.6, 129.0, 129.4, 130.0 and 134.5 (CH, C_6H_4Cl and C_6H_5), 133.3, 135.0 and 141.1 (C, C_6H_4Cl and C_6H_5), 191.2 and 191.9 (C=O); *m/z* (EI) 181 ($M^+ - PhCO$, 33%), 139 (58, $ClC_6H_4CO^+$) and 105 (100, $C_6H_5CO^+$) (Found: M^+, 286.039 33. $C_{16}H_{11}ClO_3$ requires 286.039 67).

***trans*-(−)-1-(4-Chlorophenyl)-4-phenyl-2,3-epoxybutane-1,4-dione 36.** Immobilised PLL (0.1 g) was added to a stirred mixture of sodium hydroxide (0.177 g, 4.4 mmol), water (0.5 cm^3), toluene (1.8 cm^3) and hydrogen peroxide (30% w/v; 0.88 cm^3, 7.8 mmol) at 0 °C; the mixture was then allowed to warm to ambient temperature. After 6 h, the dione **31** (0.1 g, 0.37 mmol) was added to the mixture. After 16 h, the reaction mixture was filtered and evaporated to dryness to give the crude epoxide **36**, purification of which by flash chromatography (ethyl acetate–light petroleum, 1:4) afforded a white solid (60 mg, 57%), $[\alpha]_D^{20}$ −102 (*c* 1.0 in $CHCl_3$); chiral shift ^1H NMR spectroscopy indicated the enantiomeric excess to be >98%.

***trans*-(−)-4-*tert*-Butyl-1-phenyl-2,3-epoxybutane-1,4-dione 37.** Immobilised-PLL (1.44 g) was added to a stirred mixture of sodium hydroxide (480 mg), water (2.8 cm^3), toluene (10 cm^3) and hydrogen peroxide (30% w/v, 2.8 cm^3) at 0 °C; the mixture was then allowed to warm to ambient temperature. After 6 h 1-*tert*-butyl-4-phenylbut-2-ene **32** (372 mg, 1.72 mmol) was added to the mixture which was then stirred at room temperature for 15 h. After being filtered and washed, the mixture was extracted with dichloromethane and the extract was dried ($MgSO_4$) and evaporated *in vacuo* to afford the epoxide **37** (299 mg, 75%) as a colourless crystalline solid; mp 79–81 °C; $[\alpha]_D$ −161.6 (*c* 0.625 in $CHCl_3$); chiral shift ^1H NMR spectroscopy using Eu(hfc)$_3$ indicated the enantiomeric excess to be >95%; $\nu_{max}(CHCl_3)/cm^{-1}$ 1723 (C=O) and 1697 (C=O); δ_H(400 MHz; $CDCl_3$) 1.24 (9 H, s, 3 × CH_3), 4.05 (1 H, d, *J* 2, CH), 4.30 (1 H, d, *J* 2, CH), 7.50 (2 H, m, PhH), 7.64 (1 H, m, PhH) and 8.02 (2 H, m, PhH); δ_C(100.6 MHz; $CDCl_3$) 25.5 (CH_3), 44.0 (C), 54.5 (CH), 56.5 (CH), 128.5 (CH), 129.0 (CH), 134.4 (CH), 135.0 (C), 192.3 (C=O) and 207.3 (C=O); *m/z* (EI) 232 (M^+, 0.6) and 147 (42%) (Found: M^+, 232.1119. $C_{14}H_{16}O_3$ requires 232.1100) (Found: C, 72.26; H, 7.06. $C_{14}H_{19}O_3$ requires C, 72.39; H, 6.94%).

***tert*-Butyl *trans*-(−)-2,3-epoxy-4-oxo-4-phenylbut-2-enoate 38.** Immobilised-PLL (360 mg) was added to a stirred mixture of sodium hydroxide (120 mg), water (0.7 cm^3), toluene (2.5 cm^3) and hydrogen peroxide (30% w/v, 0.7 cm^3) at 0 °C; the mixture was then allowed to warm to ambient temperature. After 6 h the ester **33** (102 mg, 0.43 mmol) was added to the mixture which was then stirred at room temperature for 15 h. After being filtered and washed, the mixture was extracted with dichloromethane and the extract was dried ($MgSO_4$) and evaporated *in vacuo* to afford the epoxide (70 mg, 0.28 mmol, 66%) as a colourless oil; $[\alpha]_D$ −73.3 (*c* 0.79 in $CHCl_3$); chiral shift ^1H NMR spectroscopy using Eu(hfc)$_3$ indicated the enantiomeric excess to be >95%; $\nu_{max}(film)/cm^{-1}$ 1749 (C=O) and 1703 (C=O); δ_H(400 MHz; $CDCl_3$) 1.53 (9 H, s, 3 × CH_3), 3.58 (1 H, d, *J* 1.8, CH), 4.37 (1 H, d, *J* 1.8, CH), 7.52 (2 H, m, PhH), 7.65 (1 H, m, PhH) and 8.03 (2 H, m, PhH); δ_C(100 MHz; $CDCl_3$) 27.9 (CH_3), 53.7 (CH), 55.3 (CH), 83.5 (C), 128.6 (CH), 128.9 (CH), 134.3 (CH), 135.1 (C), 166.1 (C=O) and 192.2 (C=O); *m/z* (EI) 147 (21, $M^+ - PhCO$) and 105 (100%).

***trans*-(−)-1,4-Di-*tert*-butyl-2,3-epoxybutane-1,4-dione 39.** PLL-immobilised (360 mg) was added to a stirred mixture of sodium hydroxide (120 mg), water (0.7 cm^3), toluene (2.5 cm^3) and hydrogen peroxide (30% w/v; 0.7 cm^3) at 0 °C; the mixture was then allowed to warm to ambient temperature. After 6 h compound **34** (84 mg, 0.43 mmol) was added to the mixture which was then stirred at room temperature for 15 h. After being filtered and washed, the mixture was extracted with dichloromethane, and the extract was dried ($MgSO_4$) and evaporated *in vacuo* to afford the epoxide **39** (91 mg, 0.43 mmol, 100%) as a colourless crystalline solid; mp 118–119 °C; $[\alpha]_D$ −201 (*c* 0.24 in $CHCl_3$). Chiral shift ^1H NMR spectroscopy using Eu(hfc)$_3$ indicated the enantiomeric excess to be >94%; $\nu_{max}(film)/cm^{-1}$ 1703 (C=O); δ_H(400 MHz; $CDCl_3$) 1.23 (18 H, s, 6 × CH_3) and 3.86 (2 H, s, CH × 2); δ_C(100.6 MHz; $CDCl_3$) 25.5 (CH_3), 43.9 (C), 54.5 (CH) and 207.3 (C=O); *m/z* (EI) 212 (M^+, 0.2) and 57 (100%) (Found: M^+, 212.1403. $C_{12}H_{12}O_3$ requires 212.1412).

***trans*-(±)-4-Chlorophenyl-1-phenyl-2,3-epoxybutane-1,4-dioate 40.** The dione **36** (0.30 g, 1.1 mmol) was added to *m*-chloroperoxybenzoic acid (MCPBA) (72%, 1.02 g, 4.2 mmol) in dichloromethane (30 cm^3) with stirring under a nitrogen atmosphere and the reaction mixture was heated to reflux. After 16 h, the reaction mixture was washed with a saturated aqueous sodium hydrogen carbonate (3 × 25 cm^3) and brine (25 cm^3), dried ($MgSO_4$), filtered through Celite and evaporated to dryness to give the crude diester. Purification of this by flash chromatography (ethyl acetate–light petroleum, 1:3) afforded the diester **40** (0.20 g, 60%) as a white solid; mp 155–156 °C; $\nu_{max}(KBr)/cm^{-1}$ 1758 (C=O); δ_H(300 MHz; DMSO) 4.28–4.30 (2 H, m, CH × 2) and 7.26–7.55 (9 H, m, C_6H_4Cl and C_6H_5); δ_C(72.5 MHz; DMSO) 52.0 and 52.1 (CH × 2), 121.5, 123.5, 129.6 and 129.7 (CH, C_6H_4Cl and C_6H_5), 148.6 and 149.9 (C, C_6H_4Cl and C_6H_5) and 165.2 and 163.3 (C=O); *m/z* (EI) 318 (M^+, 43) and 139 (100%) (Found: M^+, 318.030 14. $C_{16}H_{11}ClO_5$ requires 318.029 50).

1-Phenyl 4-*tert*-butyl *threo*-2,3-epoxysuccinate 41. The epoxide **37** (ee >95%) (102 mg, 0.44 mmol) and MCPBA (379 mg, 2.20 mmol) in dichloromethane (2 cm^3) were heated under reflux for 24 h after which a further portion of MCPBA (379 mg, 2.20 mmol) was added to the mixture and the heating under reflux continued. After cooling and evaporation the mixture was diluted with diethyl ether and treated with 2 M aqueous sodium hydroxide. The organic phase was separated, dried ($MgSO_4$) and evaporated *in vacuo* to afford the crude product. This was filtered through a column of Florisil (eluent diethyl ether–light petroleum, 1:3) to yield the epoxide (61 mg, 53%) as a colourless crystalline solid; mp 60–61 °C; $[\alpha]_D$ −65.3 (*c* 0.38 in $CHCl_3$; chiral shift ^1H NMR spectroscopy using Eu(hfc)$_3$ indicated the enantiomeric excess to be >95%; $\nu_{max}(film)/cm^{-1}$ 1782 (C=O) and 1756 (C=O); δ_H(400 MHz; $CDCl_3$) 1.53 (9 H, s, 3 × CH_3), 3.72 (1 H, d, *J* 1.6, CH), 3.84 (1 H, d, *J* 1.6, CH), 7.13 (2 H, m, PhH), 7.27 (1 H, m, PhH) and 7.40 (2 H, m, PhH); δ_C(100.6 MHz; $CDCl_3$) 27.9 (CH_3), 51.8 (CH), 53.0 (CH), 83.78 (C), 121.0 (CH), 129.5 (CH), 129.6 (CH), 150.0 (C), 165.5 (C=O) and 165.7 (C=O); *m/z* (EI) 264 (M^+, 26) and 57 (100%) (Found: M^+, 264.0997. $C_{14}H_{16}O_5$ requires 264.0997).

The epoxide **38** (ee >95%) (37 mg, 0.15 mmol) and MCPBA (130 mg, 0.75 mmol) in dichloromethane (10 cm^3) were heated to reflux for 24 h. After cooling and evaporation, the mixture was diluted with diethyl ether and treated with 2 M aqueous sodium hydroxide. The organic phase was separated, dried ($MgSO_4$) and evaporated *in vacuo* to afford the crude product which was filtered through a column of Florisil (eluent diethyl ether–light petroleum, 1:3) to yield the epoxide (29 g, 73%) as a colourless crystalline solid, mp 60–61 °C; $[\alpha]_D$ −50.6 (*c* 0.53 in $CHCl_3$).

Di-*tert*-butyl *threo*-2,3-epoxysuccinate 42. The epoxide **39** (ee >95%; 40 mg, 0.19 mmol) and MCPBA (65 mg, 0.38 mmol) in dichloromethane (2 cm^3) were stirred together at room temperature for 15 h. After evaporation, the reaction mixture was diluted with 2 M aqueous sodium hydroxide and diethyl ether. The organic phase was separated, dried ($MgSO_4$) and evaporated *in vacuo* to afford the crude product which was filtered through a column of Florisil (eluent diethyl ether) to yield the epoxide (35 mg, 76%) as a colourless oil; $[\alpha]_D$ −107.3 (*c* 1.64 in Et_2O); chiral shift ^1H NMR spectroscopy using Eu(hfc)$_3$ indicated the enantiomeric excess to be >95%; $\nu_{max}(film)/cm^{-1}$ 1736 (C=O); δ_H(400 MHz; $CDCl_3$) 1.49 (18 H, s, 6 × CH_3) and 3.45 (2 H, s, CH × 2); δ_C(100.6 MHz; $CDCl_3$) 27.9 (CH_3), 52.5 (CH), 83.3 (C) and 166.0 (C=O); *m/z* (EI) 244 (M^+, 3) and 57 (100%) (Found: M^+, 244.1308. $C_{12}H_{20}O_5$ requires 244.1311).

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8 Full details of this work will be described in a separate paper.

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