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Phase-Transfer Catalysed Asymmetric Epoxidation of Enones using *N*-Anthracenylmethyl-Substituted Cinchona Alkaloids

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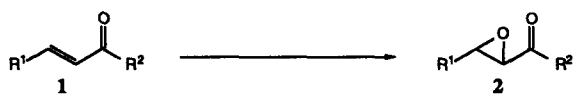
Abstract: A study into the enantioselective epoxidation of α, β-unsaturated ketones utilising *Cinchona* alkaloid-derived quaternary ammonium phase-transfer catalysts bearing an *N*-anthracenylmethyl function is presented. It has been found that the *O*-benzyl derivatives of these catalysts in conjunction with sodium hypochlorite give high enantio- and diastereoselectivities in the epoxidation of a range of substrates $R^1CH{=}CHCOR^2$, where R^1=alkyl or aryl and R^2=aryl. In the cases where R^2=alkyl high enantioselectivity has also been observed, however the rate of reaction is substantially reduced. Application of this process to the enantioselective synthesis of a range of *trans*-α, β-epoxy ketones (e.e. 71-90%) is presented.

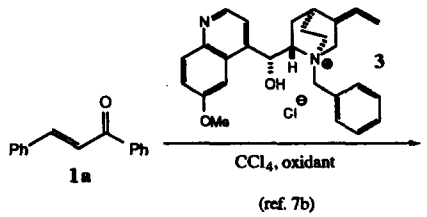
Keywords: Asymmetric phase-transfer catalysis, quaternary ammonium salts, epoxidation, enones, cinchona alkaloids

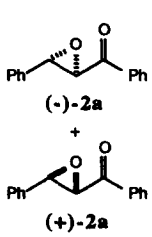
The enantioselective epoxidation of acyclic α, β-unsaturated ketones of type 1 employing chiral catalysts has received considerable attention in recent years.[1,2]



Scheme 1

As a consequence a variety of methods have been reported to effect this transformation, including the use of polyphasic systems involving hydrogen peroxide in the presence of polyamino acids,[3] alkylperoxides in conjunction with lanthanoid-binaphthol complexes,[4] tartrate-modified metal *tert*-butyl peroxides,[5] and hydrogen peroxide in the presence of chiral platinum (II) complexes.[6] Asymmetric phase-transfer catalysis has also been utilised for transformations of this type.[7,8,9,10]





Oxidant	$[\alpha]_D$ (578nm)	% e.e.[a]
30% H_2O_2 / 10% NaOH	-72.2	34
t-BuOOH	+24	11
28% NaOCl	+53	25

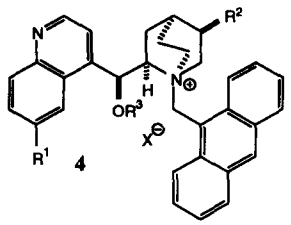
a - based on rotation value

Scheme 2

PII: S0040-4020(99)00205-7

In this latter context, early studies by Wynberg demonstrated that chiral quaternary ammonium salts derived from cinchona alkaloids (e.g. *N*-benzylquininium chloride **3**) could effect epoxidation of simple acyclic α, β-unsaturated ketones with moderate enantioselectivities (≥54% e.e.). Intriguingly, during the course of this work it was noted that the sense of selectivity in the asymmetric epoxidation of chalcone **1a** changed depending upon the nature of the stochiometric oxidant[7b] (scheme 1). These studies also suggested that the reaction was subject to strong solvent effects,[7c] with non-polar solvents generally leading to higher enantioselectivity. The asymmetric phase-transfer catalysed epoxidations have been applied to a range of alternative enone substrates and a number of modified reaction conditions developed,[7] however until recently[9,10] no catalysts that gave high enantioselectivities over a wide range of substrates of type **1** had been identified.

The recent observation that phase-transfer catalysts of the type **4a-e, 5a-e** were superior to previously reported quaternary ammonium salts for the asymmetric alkylation of glycine-imines[11] prompted us to examine their utility in the phase-transfer mediated oxidation of α, β-unsaturated ketones.



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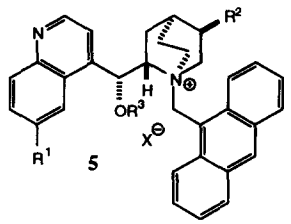

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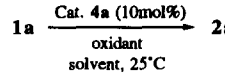
a, R^1 = H, R^2 = $CH{=}CH_2$, R^3 = H
b, R^1 = H, R^2 = $CH_2{-}CH_3$, R^3 = H
c, R^1 = OCH_3, R^2 = $CH{=}CH_2$, R^3 = H
d, R^1 = H, R^2 = $CH{=}CH_2$, R^3 = Bn
e, R^1 = H, R^2 = $CH_2{-}CH_3$, R^3 = Bn

Preliminary studies,[9] carried out using catalyst *N*-anthracenylmethylcinchoninium chloride **4a, X=Cl** (10mol. %) and chalcone **1a** as the substrate, indicated that successful epoxidation could be achieved using either hydrogen peroxide or sodium hypochlorite as the stochiometric oxidant, however in both cases the enantioselectivities obtained were low (table 1).



Solvent	Oxidant	Time (h)	% e.e.[b] (sign of rotation)	% Yield[c]
toluene	11% aq. NaOCl	48	39 (-)	65
toluene	30% aq. H_2O_2[a]	48	0	<10[d]
dichloromethane	11% aq. NaOCl	48	23 (-)	71
dichloromethane	30% aq. H_2O_2[a]	4	11 (+)	75

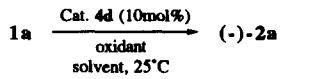
a - 1 drop of 50% aq. KOH also added. b - e.e. values reproducible to ±2%, determined by HPLC on Chiralcel OD-H column. c - After purification by chromatography. d - remainder starting material.

Table 1

In line with previous reports,[7b,c] we found that the opposite sense of enantioselectivity was obtained on switching from sodium hypochlorite to hydrogen peroxide (table 1, entries 3-4) and that strong solvent effects were evident (table 1, compare entries 1, 3 and 2, 4). This would tend to suggest that two (or more) competing reaction pathways may be operating. This is also reflected in the surprising rate changes observed on changing oxidant and solvent (table 1, compare entries 2, 4).

Control studies demonstrated that both the hydroxyl group and the anthracene ring in catalyst **4a** were stable towards oxidation under the reaction conditions (sodiun hypochlorite) and that the uncatalysed rate of epoxidation was extremely slow (no reaction observed after 48h at 25°C with either oxidant). It was therefore considered that these effects may be associated with interaction of the oxidant or the substrate (*via* hydrogen bonding) with the hydroxy group in the catalyst. In order to test this hypothesis we decided to prepare the corresponding *O*-benzyl derivative **4d**. This was readily achieved *via* treatment of **4a** with benzylbromide

under two-phase conditions,[12] giving the product **4d** in good yield (72%). Investigation of catalyst **4d** in the epoxidation of chalcone was then examined (table 2).



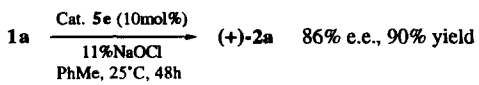
Solvent	Oxidant	Time (h)	% e.e.[b]	% Yield[c]
toluene	11% aq. NaOCl	48	81	90
toluene	30% aq. H_2O_2[a]	48	10	69
dichloromethane	11% aq. NaOCl	48	66	60
dichloromethane	30% aq. H_2O_2[a]	48	2	<10

a - 1 drop of 50% aq. KOH also added. b - e.e. values reproducible to ±2%, determined by HPLC on Chiralcel OD-H column. c - After purification by chromatography.

Table 2

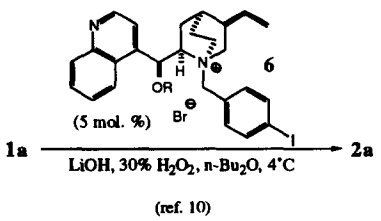
As can be seen from the results, the *O*-benzyl catalyst **4d** shows a remarkable improvement in enantioselectivity when sodium hypochlorite is used as the oxidant. In addition, although low, the enantioselectivity obtained using hydrogen peroxide is now in the same direction, giving epoxide **(-)-2a** in excess. A substantial decrease in reaction rate was also observed when using hydrogen peroxide in conjunction with dichloromethane (table 2, compare entries 2, 4). These results show that derivatisation of the hydroxyl function in the catalyst strongly influences the reaction outcome and appears critical to obtaining high enantioselectivities when using sodium hypochlorite. It is perhaps significant that the oxygen function in catalyst **4d** cannot participate directly in hydrogen bonding interactions with either the substrate or sodium hypochlorite, whereas this possibility still remains for the peroxide ion. It also appears from these results that toluene is the preferred reaction solvent when using sodium hypochlorite.

In order to establish that the reaction systems could be modified to provide an excess of either enantiomer of epoxide **2a** we next investigated the reaction using the cinchonidine-derived catalyst **5e**. Generally it would be expected that phase-transfer catalysts derived from cinchonidine (e.g. **5a-e**) would give similar but opposite enantioselectivities to those derived from cinchonine (e.g. **4a-e**),[7] and this indeed proved to be the case (scheme 3), demonstrating the flexibility of this approach towards epoxides of type **2**.



Scheme 3

It is interesting to compare these results with those described by Arai, Shioiri and co-workers in a recent study on the epoxidation of α, β-unsaturated ketones using of *N*-[(4-substituted)benzyl]cinchoninium bromides in conjunction with hydrogen peroxide.[10] In this work it was found that *N*-[(4-iodo)benzyl]cinchoninium bromide **6a** gave high enantioselectivity in the epoxidation of chalcone **1a**, whereas the corresponding *O*-substituted catalyst **6b** did not (scheme 4). In addition, the major isomer obtained in this case was **(+)-2a**, *the opposite enantiomer from that obtained with catalyst 4d and sodium hypochlorite* (table 2, entry 1).

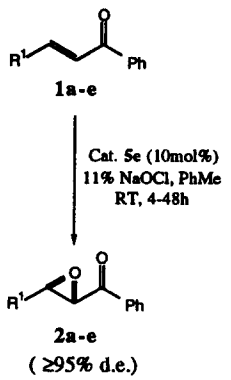


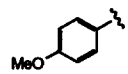
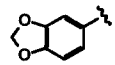
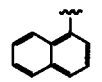
Catalyst	% e.e.	% Yield
6a, R = H	84	97
6b, R = $CH_2CH{=}CH_2$	2	72

Scheme 4

Although the mechanistic detail of these two reaction systems remains to be clearly defined, taken together, these results indicate that chiral phase-transfer catalysts derived from the same cinchona alkaloid (cinchonine) can give high selectivity for either enantiomer of epoxide **2a**. This shows that both the choice of oxidation conditions and the precise nature of the *O*- and *N*-substituents in the catalyst can have a profound effect on the enantioselectivity of the epoxidation reaction. Given this it seems appropriate to report the effects of the substrate structure on reaction selectivity and some of our studies using the *N*-anthracenylmethyl catalyst **5e** are described below.[9]

The results outlined in table 3[13] illustrate the selectivity obtained for a series of phenylketones **1a-e**. We chose a simple series of β-substituents (R^1) in order to determine if there were any obvious limitations to the nature of substituents that could be incorporated in this position of the enone.



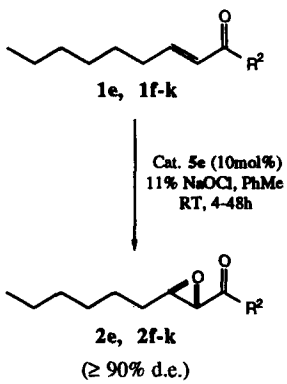
Epoxide	R^1	% e.e.[a]	% Yield[b]
2a		86	90
2b		82	87
2c		83	97
2d		82	86
2e		77	92

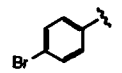
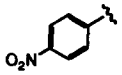
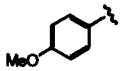
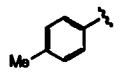
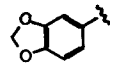
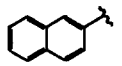
a - e.e. values reproducible to ±2%, determined by HPLC on Chiralcel OD-H column. b - After purification by chromatography.

Table 3

Within the series of aryl R^1-substituents tested (enones **1a-d**), there appears to be relatively little variation in enantioselectivity. Since this series includes a range of different substitution patterns, and aromatic ring-systems with significantly differing electronic properties, it would appear to suggest that the catalyst will tolerate a variety of aromatic substituents in position R^1. In the case where $R^1 = n\text{-}C_6H_{11}$, the enantioselectivity is slightly diminished. In all these examples the *trans*-epoxides were obtained with high diastereoselectivity.[14] Since the asymmetric epoxidation of β-alkyl substituted enones would allow access to a wide range of useful chiral materials we investigated the consequences of varying the aryl group (R^2) in substrates of this type (table 4).[13]

It appears from these results that the precise nature of the aryl group R^2 can have a small but significant influence on the enantioselectivity of the reaction. Thus with R^2 = phenyl, the corresponding epoxide **2e** is obtained in 77% e.e., whereas with R^2 = 4-nitrophenyl, the product **2g** is obtained with 90% e.e., demonstrating that it is possible to obtain high enantiomeric excesses with β-alkyl groups simply by varying the R^1 substituent. Although this points to a potential limitation in the application of these catalysts to the synthesis of chiral epoxides, there are a number of cases when the nature of the substituent at position R^1 is unimportant. For example the Baeyer-Villiger reaction has been applied to substrates of type **2**, giving high yields of the corresponding α, β-epoxyesters.[3g,h] In this context, the aryl group is usually removed by subsequent hydrolysis which means that the enantioselectivity of the ultimate target material can be optimised by choosing the most appropriate R^2 substituent.

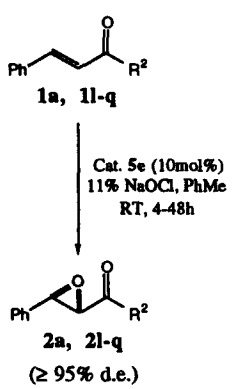


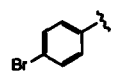
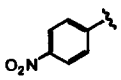
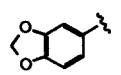
Epoxide	R^2	% e.e.[a]	% Yield[b]
2e		77	92
2f		84	89
2g		90	79
2h		84	94
2i		81	93
2j		86	87
2k		78	83

a - e.e. values reproducible to ±2%, determined by HPLC on Chiralcel OD-H column. b - After purification by chromatography.

Table 4

We also examined the influence of R^2 in substrates that contained a β-phenyl substituent (table 5).[13]



Epoxide	R^2	% e.e.[a]	% Yield[b]
2a		86	90
2l		88	99
2m		83	85
2n		85	82
2o		89	95
2p		71	77
2q		85	40 (74)[c]

a - e.e. values reproducible to ±2%, determined by HPLC on Chiralcel OD-H column. b - After purification by chromatography. c - yield in parentheses based on unrecovered enone

Table 5

Here again we see some variation in enantioselectivity, but the majority of examples fall into a narrow range (83-89% e.e.). It is also of note that enone **1q** (R^2=*t*-Bu) falls into this selectivity range. This would tend to suggest that a range of different groups can be tolerated at position R^2 in the enone substrates.

The rates of epoxidation of the enones **1a-p** are generally comparable, typically taking 4-48h to reach completion.[15] One exception to this is enone **1q** where the reaction is substantially slower and is only *ca.* 50% complete after 5 days. This is the only example shown above in which R^2≠aryl, however we have also observed that with other alkyl substituents in this position (R^2=*i*-Pr, Me), the rate of epoxidation is also slow, making the desired transformation impractical in these instances. This would seem to suggest a general limitation for substrates of this type.

In conclusion, we have shown that phase-transfer catalysts of type **4d** and **5e** in conjunction with sodium hypochlorite give high enantio- (71-90% e.e.) and diastereoselectivities (90-95% d.e.) in the epoxidation of a range of enone substrates of type **1**. This study suggests that the catalyst system is tolerant of a variety of different substituents in position R^1, but may be limited on grounds of practicality, to aryl substituents in position R^2. Further studies into the mode of action and utility of these catalysts is currently underway and will be reported in due course.

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Experimental

Infra-red absorption spectra were recorded on Perkin-Elmer 1600 and 1710 Fourier-transform spectrometers. All the spectra were recorded neat. ^{1}H nuclear magnetic resonance (nmr) spectra were recorded at 300MHz and ^{13}C nuclear magnetic resonance spectra at 75MHz on a Bruker AC300 spectrometer. All chemical shifts (δ) were referenced to the deuterium lock and are reported in parts per million (ppm). The following abbreviations have been used to describe the signal multiplicity: br (broad), s (singlet), d (doublet), dd (doublet of doublets), t (triplet), dt (doublet of triplets), q (quartet), m (multiplet), and J (coupling constant in Hz). Mass spectra (MS) were recorded at low resolution on a Finnigan 4500 instrument with chemical ionisation (CI) using ammonia. Accurate mass measurement (high resolution) and fast atom bombardment (FAB) mass spectra were recorded on a Kratos Concept 1-S instrument. Optical rotations ($[\alpha]_D$) are quoted to ±4 and were measured on an AA-10 monochromatic 589nm (Optical Activity Ltd.) polarimeter at room temperature. Melting points (mp) were determined using an electrothermal apparatus and are uncorrected. Thin layer chromatography (TLC) was performed on plates pre-coated (0.25mm) with CAMLAB DC-Fertigplatten SIL G-25 UV254 (silica). The plates were visualised by the use of a combination of ultraviolet light, iodine, ethanolic vanillin, or aqueous potassium permanganate. Silica gel 60 (particle sizes 40-63 m), supplied by Merck, was employed for flash chromatography. HPLC analysis was performed using a Gilson apparatus in conjunction with a 0.46x25cm Chiralcel OD-H column (Diacel Chemical Ind., Ltd.) and UV detection. All non-racemic materials were compared with racemic material generated using tetra-*n*-butylammonium bromide as the phase-transfer catalyst. Where necessary, solvents and reagents were dried and purified according to recommended procedures.[16] Enones **1a-d**, **1n**, and **1p** were prepared *via* aldol condensation using standard conditions.[17] Enones **1e-k**, **1l-m**, and **1q** were prepared *via* Wittig reaction again using standard conditions.[18]

Preparation of (2R, 5R, 1'S)-1-(9-anthracenyl)methyl-5-ethylene-2-[1-hydroxy-1-(quinol-4-yl)]methyl-1-azoniabicyclo[2.2.2]octane chloride (4a)

A mixture of cinchonine (500mg, 1.70mmol) and 9-chloromethylanthracene (390mg, 1.72mmol) was heated at reflux in toluene (20ml) under argon for 4h. The solution was then cooled to room temperature and the resulting precipitate filtered. The residue was recrystallised from chloroform/petroleum ether to give the

product **4a** (521mg, 59%) as a yellow solid. R_f (silica gel) 0.3(93:7, dichloromethane:methanol). $[\alpha]_D$ +240 (c=1.0, $CHCl_3$). mp 166-167°C. ν_{max} (neat) 3050(OH) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$)[19] 9.25(1H, d, J=9.0Hz), 8.96(1H, d, J=8.5Hz), 8.85(1H, d, J=4.0Hz), 8.39(1H, d, J=9.0Hz), 8.07(1H, d, J=4.5Hz), 7.85(1H, s), 7.61(1H, d, J=8.5Hz), 7.54(1H, d, J=8.0Hz), 7.44(1H, d, 8.5Hz), 7.30-6.91(8H, m, Ar-H, C$H_a$$H_b$Anth), 6.46(1H, d, J=13.5Hz, CH_aH_bAnth), 5.62-5.51(1H, m, CH=CH_2), 5.01(1H, d, J=10.5Hz, C=C$H_a$$H_b$), 4.79(1H, d, J=12.0Hz, C=CH_aH_b), 4.77-4.52(1H, m, H-2), 4.45-4.35(1H, m, H-6a), 4.32-4.18(1H, m, H-7a), 2.53-2.39(1H, m, H-6b), 2.37-2.25(1H, m, H-7b), 1.90-1.85(1H, m, H-3a), 1.79-1.60(3H, m, H-5, H-8a, OH), 1.57-1.45(1H, m, H-4), 1.41-1.30(1H, m, H-8b), 0.70-0.55(1H, m, H-3b). ^{13}C nmr δ (75MHz, $CDCl_3$) 148.9, 146.3, 146.1, 135.4, 132.9, 132.6, 130.9, 130.2, 129.9, 128.6, 128.4, 128.1, 127.5, 127.2, 126.8, 124.8, 124.5, 124.1, 120.0, 117.9, 117.4, 67.6, 66.6, 57.5, 54.1, 53.8, 38.0, 26.2, 24.0, 22.6. m/z (FAB) 191(80%), 398(45%), 404(100%), 485(M^+-Cl, 30%). Found $[M-Cl]^+$ 485.2603, $C_{34}H_{33}N_2O$ requires 485.2593.

Preparation of (2S, 5R, 1'R) 1-(1-anthracenyl)methyl-5-ethyl-2-[1-hydroxy-1-(quinol-4-yl)]methyl-1-azoniabicyclo[2.2.2]octane chloride (5b)

A mixture of dihydrocinchonidine (230mg, 0.78mmol) and 9-chloromethylanthracene in toluene (10ml) was heated at reflux under argon for 24h. The solution was then cooled to room temperature and the resulting precipitate filtered to give the product **5b** (270mg, 66%) as a yellow solid. R_f (silica gel) 0.3(93:7, dichloromethane:methanol). $[\alpha]_D$ -250 (c=0.8, $CHCl_3$). mp 155-156°C. ν_{max} (neat) 3054(OH) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$)[19] 8.96(1H, d, J=8.5Hz), 8.85-8.76(2H, m), 8.66(1H, d, J=9.0Hz), 8.12(1H, d, J=5.0Hz), 8.01(1H, d, J=4.5Hz), 7.98(1H, s), 7.72-7.60(2H, m), 7.56(1H, d, J=8.0Hz), 7.38-6.96(7H, m), 6.66(1H, d, J=13.5Hz, C$H_a$$H_b$Anth), 6.56(1H, d, J=13.5Hz, CH_aH_bAnth), 4.77-4.56(2H, m, H-2, H-7a), 3.62-3.49(1H, m, H-6a), 2.65-2.50(1H, m, H-6b), 2.38-2.25(1H, m, H-7b), 1.98-1.70(2H, m, H-3a, H-8a), 1.65-1.57(1H, m, H-4), 1.30-0.88(5H, m, H-3b, H-5, H-8b, CH_2Me), 0.52(3H, t, J=7.0Hz, CH_3). ^{13}C nmr δ (75MHz, $CDCl_3$) 149.5, 147.1, 145.8, 133.0, 132.7, 131.0, 130.4, 130.2, 129.3, 128.4, 127.6, 127.1, 127.0, 126.1, 125.4, 124.8, 124.3, 123.8, 120.2, 118.2, 67.4, 66.9, 63.8, 54.9, 50.7, 37.0(C-5), 26.6, 26.1, 23.2, 22.9, 11.4. m/z (FAB) 191(100%), 487(M^+-Cl, 30%). Found $[M-Cl]^+$ 487.2755, $C_{34}H_{35}N_2O$ requires 487.2749.

Preparation of (2R, 5R, 1'S)-1-(1-anthracenyl)methyl-5-ethylene-2-[1-benzyloxy-1-(quinol-4-yl)]methyl-1-azoniabicyclo[2.2.2]octane bromide (4d)

50% Aqueous sodium hydroxide (0.1ml, 0.13mmol) was added to a solution of salt **4a** (0.20g, 0.38mmol) and benzyl bromide (0.13ml, 1.10mmol) in dichloromethane (3ml) and the mixture stirred vigorously for 1.5h. Water (2ml) was then added and the aqueous layer extracted with dichloromethane (2ml). The combined organics were dried over magnesium sulfate, filtered, and concentrated under reduced pressure. The residue was purified by chromatography on silica gel (19:1, dichloromethane:methanol) to give the product **4d** (0.16g, 72%) as a yellow solid. R_f (silica gel) 0.6(95:5, dichloromethane:methanol). $[\alpha]_D$ +220 (c=0.90, $CHCl_3$). mp 124-125°C. ν_{max} (neat) 3406 cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$)[19] 9.91-9.61(2H, m), 9.50-9.31(1H, m), 9.17-8.90(2H, m), 8.60(1H, s), 8.35-8.21(1H, m), 8.20-8.06(1H, m), 8.05-7.97(2H, m), 7.95-7.66(4H, m), 7.64-7.46(4H, m), 7.42-7.21(2H, m), 6.95-6.50(2H, m, H-1', C$H_a$$H_b$Anth), 5.95-5.47(4H, m, CH_aH_bAnth, CH=CH_2, H-2, H-6a), 5.31-5.18(1H, m, C=C$H_a$$H_b$), 5.10-4.76(3H, m, C=$CH_aH_b$, C$H_2$Ph), 4.41-4.15(1H, m, H-7a), 3.05-2.89(1H, m, H-7b), 2.70-2.25(2H, m), 2.20-2.1.69(3H, m), 1.65-1.45(1H, m, H-5), 1.32-1.11(1H, m, H-3b). ^{13}C nmr δ (75MHz, $CDCl_3$) 149.0, 148.4, 139.9, 136.3, 135.7, 133.9, 133.3, 132.3, 131.4, 130.8, 129.9, 129.2, 128.9, 128.7, 128.6, 128.3, 127.5, 127.2, 127.0, 126.8, 126.0, 125.4, 124.9, 123.2, 118.9, 117.9, 117.5, 75.6, 71.2, 65.9, 57.1, 55.0, 54.8, 37.6, 26.3, 24.4, 23.8. m/z (FAB) 191(100%), 575(M^+-Br, 45%). Found $[M-Br]^+$ 575.3045, $C_{41}H_{39}N_2O$ requires 575.3062.

Preparation of (2S, 5R, 1'R)-1-(1-anthracenyl)methyl-5-ethyl-2-[1-benzyloxy-1-(quinol-4-yl)]methyl-1-azoniabicyclo[2.2.2]octane bromide (5e)

50% Aqueous sodium hydroxide (0.35ml, 0.44mmol) was added to a solution of salt **5b** (0.70g, 1.34mmol) and benzyl bromide (0.46ml, 3.89mmol) in dichloromethane (10ml) and the mixture stirred vigorously for 1.5h. Water (5ml) was then added and the aqueous layer was extracted with dichloromethane (5ml). The combined organics were dried over magnesium sulfate, filtered, and concentrated under reduced pressure. The residue was purified by chromatography on silica gel (19:1, dichloromethane:methanol) to give the product **5e** (0.46g, 58%) as a yellow solid. R_f (silica gel) 0.6 (19:1, dichloromethane:methanol). $[\alpha]_D$ -215 (c=1.1, $CHCl_3$). mp 137-138°C. ν_{max} (neat) 3382 cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$)[19] 9.62(1H, d, J=9.0 Hz), 9.32-9.08(1H, m), 9.00(1H, d, J=4.0Hz), 8.49(1H, s), 8.15(1H, d, J=8.5Hz), 8.03-7.85(3H, m), 7.84-7.65(4H, m), 7.61-7.48(6H, m), 7.38-7.26(1H, m), 6.95-6.57(2H, m, C*H*$_a$H$_b$Anth, H-1'), 5.95-5.60(1H, m, CH$_a$*H*$_b$Anth), 5.49-5.18(1H, m, H-2), 4.95-4.78(2H, m, CH_2Ph), 4.65-4.29(2H, m, H-6a, H-7a), 2.96-2.70(1H, m, H-7b), 2.62-2.41(1H, m, H-6b), 2.39-2.11(2H, m, H-3a, H-8a), 2.04-1.90(1H, m, H-8b), 1.89-1.79(1H, m, H-4), 1.59-1.47(2H, m, H-5, C*H*$_a$H$_b$Me), 1.46-1.13(2H, m, H-3b, CH$_a$*H*$_b$Me), 0.72-0.59(3H, m, CH_3). ^{13}C nmr δ (75MHz, $CDCl_3$) 148.5, 148.4, 136.3, 134.0, 133.2, 132.1, 131.4, 130.8, 129.9, 129.2, 128.8, 128.6, 127.4, 127.1, 125.9, 125.6, 124.8, 123.3, 118.1, 75.5, 71.5, 66.0, 62.8, 55.0, 51.1, 37.0, 26.4, 26.3, 23.5, 23.4, 11.6. m/z (FAB) 191(100%), 387(25%), 577(M^+-Br, 40%). Found $[M-Br]^+$ 577.3198, $C_{41}H_{41}N_2O$ requires 577.3219.

General procedure for the epoxidation of enones

A solution of the enone (0.34mmol) and the appropriate catalyst (0.034mmol) in toluene (2ml) was treated with 11% aqueous sodium hypochlorite (0.4ml, 0.74mmol) and the mixture was stirred (*ca.* 1000rpm) at room temperature for 4-48 hours.[16] Water (2ml) was then added and the aqueous layer was extracted with ethyl acetate (2x3ml). The combined organics were dried over sodium sulfate, filtered, and concentrated under reduced pressure. The residue was then purified by passing through a pad of silica gel (1:1, ethyl acetate:petroleum ether).

Preparation of *trans*-2,3-epoxy-1,3-diphenylpropan-1-one (2a)

R_f (silica gel) 0.7(9:1, petroleum ether:ethyl acetate). +179 (c=1.0, THF, 86% e.e.), lit $[\alpha]_D$ +195 (c=2.73 THF).[3g] mp 76-77°C. ν_{max} (neat) 1689(C=O) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$) 8.04-7.93(2H, m, Ar-H), 7.67-7.32(8H, m, Ar-H), 4.29(1H, d, J=1.5Hz, H-2), 4.06(1H, d, J=1.5Hz, H-3). m/z (NH_3, Cl) 225($M+H^+$, 55%), 242($M+NH_4^+$, 100%). Found $(M+H)^+$ 225.0913, $C_{15}H_{13}O_2$ requires 225.0915. R_t HPLC (95:5, hexane:dioxane, 254nm, 0.5ml/min) 35.9min, (+)-isomer; 39.4min, (-)-isomer.

Preparation of *trans*-2,3-epoxy-3-(4-methoxyphenyl)-1-phenylpropan-1-one (2b)

R_f (silica gel) 0.3(9:1, petroleum ether:ethyl acetate). $[\alpha]_D$ +131 (c=0.70, $CHCl_3$, 82% e.e.). ν_{max} (neat) 1688(C=O) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$) 8.03-7.95(2H, m, H-2', H-6'), 7.63-7.41(3H, m, H-3', H-4', H-5'), 7.32-7.23(2H, m, H-2", H-6"), 6.95-6.87(2H, m, H-3", H-5"), 4.28(1H, d, J=2.0Hz, H-2), 4.00(1H, d, J=2.0Hz, H-3), 3.80(3H, s, CH_3). m/z (NH_3, Cl) 105(100%), 255($M+H^+$, 40%). Found $(M+H)^+$ 255.1022, $C_{16}H_{15}O_3$ requires 255.1021. R_t HPLC (95:5, hexane:dioxane, 254nm, 0.5ml/min) 49.3min, (+)-isomer; 53.0min, (-)-isomer.

Preparation of *trans*-2,3-epoxy-3-[3,4-(methylenedioxy)phenyl]-1-phenylpropan-1-one (2c)

R_f (silica gel) 0.3(9:1, petroleum ether:ethyl acetate). $[\alpha]_D$ -229 (c=1.0, $CHCl_3$, 83% e.e.). mp 83-84°C. ν_{max} (neat) 1689(C=O) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$) 8.01-7.93(2H, m, H-2', H-6'), 7.53-7.41(1H, m, H-4'), 7.52-7.42(2H, m, H-3', H-5'), 6.86(1H, dd, J=1.5, 8.0Hz, H-6"), 6.81-6.71(2H, m, H-2", H-5"), 5.96(2H, apparent s, CH_2), 4.23(1H, d, J=2.0Hz, H-2), 3.97(1H, d, J=2.0Hz, H-3). m/z (NH_3, Cl) 105(45%), 168(100%), 269($M+H^+$, 5%), 286($M+NH_4^+$, 65%). Found $(M+H)^+$ 269.0815, $C_{16}H_{13}NO_4$

requires 269.0814. R_t HPLC (95:5, hexane:dioxane, 254nm, 0.5ml/min) 61.9min, (-)-isomer; 65.1min, (+)-isomer.

Preparation of *trans*-2,3-epoxy-3-(naphth-1-yl)-1-phenylpropan-1-one (2d)

R_f (silica gel) 0.6(4:1, petroleum ether:ethyl acetate). $[\alpha]_D$ -69 (c=1.0, $CHCl_3$, 82% e.e.). ν_{max} (neat) 1689 (C=O) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$) 8.11-8.01(2H, m, Ar-H), 8.0-7.93(1H, m, Ar-H), 7.92-7.82(2H, m, Ar-H), 7.68-7.40(7H, m, Ar-H), 4.72(1H, d, J=1.5Hz, H-2), 4.30(1H, d, J=1.5Hz, H-3). m/z (NH_3, Cl) 105(100%), 275($M+H^+$, 30%). Found $(M+H)^+$ 275.1066, $C_{19}H_{15}O_2$ requires 275.1072. R_t HPLC (95:5, hexane:dioxane, 254nm, 0.5ml/min) 39.4min, (-)-isomer; 49.5min, (+)-isomer.

Preparation of *trans*-2,3-epoxy-1-phenylnonan-1-one (2e)

R_f (silica gel) 0.5(9:1, petroleum ether:ethyl acetate). $[\alpha]_D$ +7 (c=0.6, $CHCl_3$, 77% e.e.). ν_{max} (neat) 1690(C=O) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$) 8.03-7.92(2H, m, H-2', H-6'), 7.75-7.54(1H, m, H-4'), 7.53-7.40(2H, H-3', H-5'), 4.00(1H, d, J=2.0Hz, H-2), 3.16-3.05(1H, m, H-3), 1.84-1.60(2H, m, H-4a, H-4b), 1.59-1.15(8H, m, H-5a, H-5b, H-6a, H-6b, H-7a, H-7b, H-8a, H-8b), 0.95-0.73(3H, m, CH_3). m/z (NH_3, Cl) 233($M+H^+$, 15%), 250($M+NH_4^+$, 100%). Found $(M+H)^+$ 233.1547, $C_{15}H_{21}O_2$ requires 233.1541. R_t HPLC (95:5, hexane:dioxane, 254nm, 0.5ml/min) 15.8min, (+)-isomer; 17.1min, .

Preparation of *trans*-2,3-epoxy-1-(4-bromophenyl)nonan-1-one (2f)

R_f 0.5(silica gel) (90:10, petroleum ether:ethyl acetate). mp 59-60°C. $[\alpha]_D$ +6 (c=2, $CHCl_3$, 84% e.e.). ν_{max} (neat) 1682(C=O) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$) 7.89-7.85(2H, m, Ar-H), 7.64-7.60(2H, m, Ar-H), 3.92(1H, d, J=2.0Hz, H-2), 3.14-3.09(1H, m, H-3), 1.79-1.23(10H, m), 0.89-0.84(3H, m, H_3-9). m/z (NH_3, Cl) 311/313($M+H^+$, 5%), 328/330($M+NH_4^+$, 100%). Found $(M+H)^+$ 311.0650, $C_{15}H_{20}BrO_2$ requires 311.0647. R_t HPLC (95:5, hexane:IPA, 254nm, 0.5ml/min) 13.3min, (+)-isomer; 14.3min, (-)-isomer.

Preparation of *trans*-2,3-epoxy-1-(4-nitrophenyl)nonan-1-one (2g)

R_f 0.4(silica gel) (90:10, petroleum ether:ethyl acetate). mp 45-46°C. $[\alpha]_D$ +36 (c=2, $CHCl_3$, 90% e.e.). ν_{max} (neat) 1673(C=O) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$) 8.34-8.30(2H, m, Ar-H), 8.19-8.14(2H, m, Ar-H), 3.94(1H, d, J=2.0Hz, H-2), 3.16-3.12(1H, m, H-3), 1.81-1.23(10H, m), 0.89-0.85(3H, m, H_3-9). m/z (NH_3, Cl) 174(60%), 248(52%), 278($M+H^+$, 8%), 295($M+NH_4^+$, 100%). Found $(M+H)^+$ 278.1392, $C_{15}H_{20}NO_4$ requires 278.1392. R_t HPLC (99:1, hexane:IPA, 254nm, 0.5ml/min) 55.1min, (-)-isomer; 58.5min, (+)-isomer.

Preparation of *trans*-2,3-epoxy-1-(4-methoxyphenyl)nonan-1-one (2h)

R_f 0.3(silica gel) (90:10, petroleum ether:ethyl acetate). $[\alpha]_D$ -4 (c=2, $CHCl_3$, 84% e.e.). ν_{max} (neat) 1678(C=O) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$) 8.02-7.98(2H, m, Ar-H), 6.97-6.92(2H, m, Ar-H), 3.96(1H, d, J=2.0Hz, H-2), 3.87(3H, s, OCH_3), 3.13-3.09(1H, m, H-3), 1.78-1.17(10H, m), 0.88-0.84(3H, m, H_3-9). m/z (NH_3, Cl) 263($M+H^+$, 100%), 280($M+NH_4^+$, 88%). Found $(M+H)^+$ 263.1647, $C_{16}H_{23}O_3$ requires 263.1647. R_t HPLC (95:5, hexane:IPA, 254nm, 0.5ml/min) 16.6min, (-)-isomer; 17.5min, (+)-isomer.

Preparation of *trans*-2,3-epoxy-1-(4-methylphenyl)nonan-1-one (2i)

R_f 0.6(silica gel) (90:10, petroleum ether:ethyl acetate). $[\alpha]_D$ -3 (c=2.5, $CHCl_3$, 81% e.e.). ν_{max} (neat) 1689(C=O) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$) 7.91-7.89(2H, m, Ar-H), 7.29-7.26(2H, m, Ar-H), 3.99(1H, d, J=2.0Hz, H-2), 3.13-3.09(1H, m, H-3), 2.41(3H, s, $ArCH_3$), 1.79-1.17(10H, m), 0.89-0.84(3H, m, H_3-9). m/z (NH_3, Cl) 247($M+H^+$, 31%), 264($M+NH_4^+$, 100%). Found $(M+H)^+$ 247.1697, $C_{16}H_{23}O_2$ requires 247.1698. R_t HPLC (99:1, hexane:IPA, 254nm, 0.5ml/min) 21.7min, (-)-isomer; 23.7min, (+)-isomer.

Preparation of *trans*-2,3-epoxy-1-[(3,4-methylenedioxy)phenyl]nonan-1-one (2j)
R_f 0.4(silica gel) (90:10, petroleum ether:ethyl acetate). $[\alpha]_D$ +1 (c=2, $CHCl_3$, 86% e.e.). ν_{max} (neat) 1678(C=O) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$) 7.64(1H, dd, J=1.0, 8.5Hz, H-6'), 7.46(1H, br. s, H-2'), 6.86(1H, d, J=8.5Hz, H-5'), 3.92(1H, d, J=2.0Hz, H-2), 3.12-3.08(1H, m, H-3), 1.78-1.21(10H, m), 0.88-0.84(3H, m, H_3-9). m/z (NH_3, Cl) 264(82%), 277($M+H^+$, 61%), 294($M+NH_4^+$, 100%). Found $(M+H)^+$ 277.1437, $C_{16}H_{21}O_4$ requires 277.1440. R_t HPLC (98:2, hexane:IPA, 234nm, 0.5ml/min) 30.9min, (-)-isomer; 33.3min, (+)-isomer.

Preparation of *trans*-2,3-epoxy-1-(naphth-2-yl)nonan-1-one (2k)
R_f 0.5(silica gel) (90:10, petroleum ether:ethyl acetate). $[\alpha]_D$ -16 (c=2, $CHCl_3$, 78% e.e.). ν_{max} (neat) 1682(C=O) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$) 8.57(1H, br. s, H-1'), 8.04-7.87(4H, m, Ar-H), 7.65-7.54(2H, m, Ar-H), 4.15(1H, d, J=2.0Hz, H-2), 3.22-3.18(1H, m, H-3), 1.85-1.23(10H, m), 0.89-0.87(3H, m, H_3-9). m/z (NH_3, Cl) 283($M+H^+$, 39%), 300($M+NH_4^+$, 100%). Found $(M+H)^+$ 283.1702, $C_{19}H_{23}O_2$ requires 283.1698. R_t HPLC (95:5, hexane:IPA, 254nm, 0.6ml/min) 17.2min, (-)-isomer; 23.2min, (+)-isomer.

Preparation of *trans*-2,3-epoxy-3-phenyl-1-(4-bromophenyl)propan-1-one (2l)
R_f 0.4(silica gel) (90:10, petroleum ether:ethyl acetate). mp 90-91°C. $[\alpha]_D$ +194 (c=1.5, $CHCl_3$, 88% e.e.). ν_{max} (neat) 1674(C=O) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$) 7.89-7.85(2H, m, Ar-H), 7.64-7.60(2H, m, Ar-H), 7.42-7.32(5H, m, Ar-H), 4.21(1H, d, J=2.0Hz, H-2), 4.05(1H, d, J=2.0Hz, H-3). m/z (NH_3, Cl) 303/305($M+H^+$, 12%), 320/322($M+NH_4^+$, 100%). Found $(M+H)^+$ 303.0022, $C_{15}H_{12}BrO_2$ requires 303.0021. R_t HPLC (95:5, hexane:IPA, 234nm, 0.5ml/min) 30.3min, (-)-isomer; 32.4min, (+)-isomer.

Preparation of *trans*-2,3-epoxy-3-phenyl-1-(4-nitrophenyl)propan-1-one (2m)
R_f 0.2(silica gel) (90:10, petroleum ether:ethyl acetate). $[\alpha]_D$ +222 (c=2, $CHCl_3$, 83% e.e.). ν_{max} (neat) 1681(C=O) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$) 8.34-8.30(2H, m, Ar-H), 8.20-8.15(2H, m, Ar-H), 7.43-7.33(5H, m, Ar-H), 4.24(1H, d, J=2.0Hz, H-2), 4.09(1H, d, J=2.0Hz, H-3). m/z (NH_3, Cl) 270($M+H^+$, 5%), 287($M+NH_4^+$, 100%). Found $(M+H)^+$ 270.0764, $C_{15}H_{12}NO_4$ requires 270.0766. R_t HPLC (80:20, hexane:IPA, 254nm, 0.6ml/min) 59.6min, ()-isomer; 70.0min, ()-isomer.

Preparation of *trans*-2,3-epoxy-3-phenyl-1-(thien-2-yl)propan-1-one (2n)
R_f 0.3(silica gel) (80:20, petroleum ether:ethyl acetate). mp 85-86°C, lit. mp 88-90°C.[3b] $[\alpha]_D$ +198 (c=2, $CHCl_3$, 85% e.e.). ν_{max} (neat) 1659(C=O) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$) 7.99(1H, dd, J=1.0, 4.0Hz, H-3'), 7.73(1H, dd, J=1.0, 5.0Hz, H-5'), 7.42-7.31(5H, m, Ar-H), 7.16(1H, dd, J=4.0, 5.0Hz, H-4'), 4.15(1H, d, J=2.0Hz, H-2), 4.06(1H, d, J=2.0Hz, H-3). m/z (NH_3, Cl) 231($M+H^+$, 69%), 248($M+NH_4^+$, 100%). Found $(M+H)^+$ 231.0489, $C_{13}H_{10}SO_2$ requires 231.0480. R_t HPLC (95:5, hexane:IPA, 254nm, 0.5ml/min) 30.4min, (-)-isomer; 35.3min, (+)-isomer.

Preparation of *trans*-2,3-epoxy-1-[3,4-(methylenedioxy)phenyl]-3-phenylpropan-1-one (2o)
R_f (silica gel) 0.3(9:1, petroleum ether:ethyl acetate). $[\alpha]_D$ +172 (c=1.0, $CHCl_3$, 89% e.e.). mp 83-84°C. ν_{max} (neat) 1678(C=O) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$) 7.61(1H, dd, J=1.5, 8.0Hz, H-6'), 7.46(1H, d, J=1.5Hz, H-2'), 7.42-7.30(5H, m, H-2'', H-3'', H-4'', H-5'', H-6''), 6.84(1H, d, J=8.0Hz, H-5'), 6.04(2H, apparent s, CH_2), 4.20(1H, d, J=2.0Hz, H-2), 4.03(1H, d, J=2.0Hz, H-3). m/z (NH_3, Cl) 149(100%), 269($M+H^+$, 5%), 286($M+NH_4^+$, 10%). Found $(M+H)^+$ 269.0815, $C_{16}H_{13}O_4$ requires 269.0814. R_t HPLC (95:5, hexane:dioxane, 254nm, 0.5ml/min) 72.0min, (+)-isomer; 84.3min, (-)-isomer.

Preparation of *trans*-2,3-epoxy-1-(naphth-1-yl)-3-phenylpropan-1-one (2p)
R_f (silica gel) 0.4(9:1, petroleum ether:ethyl acetate). $[\alpha]_D$ -188 (c=1.0, $CHCl_3$, 71% e.e.). ν_{max} (neat) 1686(C=O) cm^{-1}. ^1H nmr δ (300MHz, $CDCl_3$) 8.68(1H, d, J=7.5Hz, Ar-H), 8.08-7.81(3H, m, Ar-H), 7.68-7.28(8H, m, Ar-H), 4.25(1H, d, J=2.0Hz, H-2), 4.14(1H, d, J=2.0Hz, H-3). m/z (NH_3, Cl)

155(100%), 275(M+H$^+$, 5%), 292(M+NH$_4^+$, 15%). Found (M+H)$^+$ 275.1083 $C_{19}H_{15}O_2$ requires 275.1072. R_t HPLC (95:5, hexane:dioxane, 254nm, 0.5ml/min) 52.5min, (+)-isomer; 60.0min, (-)-isomer.

Preparation of *trans*-1,2-epoxy-4,4-dimethyl-1-phenylpentan-3-one (2q)

R_f (silica gel) 0.5(97:3, petroleum ether:ethyl acetate). mp 58-59°C, lit. mp 68-70°C.[31] $[\alpha]_D$ +183 (c=1.0, $CHCl_3$, 85% e.e.), lit. $[\alpha]_D$ +162 (c=0.6, $CHCl_3$).[31] ν_{max} (neat) 1704(C=O) cm^{-1}. ^{1}H nmr δ (300MHz, $CDCl_3$) 7.42-7.25(5H, m, Ar-H), 3.86-3.82(2H, m, H-1, H-2), 1.22(9H, s, $C(CH_3)_3$). m/z (NH_3, Cl) 85(50%), 205(M+H$^+$, 20%), 222(M+NH$_4^+$, 100%). Found (M+H)$^+$ 205.1237, $C_{13}H_{17}O_2$ requires 205.1228. R_t HPLC (98.5:1.5, hexane:dioxane, 232nm, 0.5ml/min) 32.8min, (-)-isomer; 34.8min, (+)-isomer.

References

1. Fruh, T. *Agro. Food Indust. Hi-Tech.*, **1996**, *7*, 31; Ebrahim, S; Wills, M. *Tetrahedron Asymm.*, **1997**, *8*, 3163.
2. Good enantioselectivities have also been achieved using non-catalytic systems involving molecular oxygen in the presence of diethylzinc/chiral amino alcohols, see: Enders, D; Zhu, J; Raabe, G. *Angew. Chem. Int. Ed. Engl.*, **1996**, *35*, 1725; Enders, D; Zhu, J. Kramps, L. *Ann.*, **1997**, 1101.
3. (a) Juliá, S; Masana, J.; Vega, J.C. *Angew. Chem. Int. Ed. Engl.*, **1980**, *19*, 929; (b) Juliá, S; Guixer, J; Masana, J; Rocas, J; Colonna, S; Annunziata, R; Molinari, H. *J. Chem. Soc., Perkin Trans I*, **1982**, 1317; (c) Colonna, S; Molinari, H; Banfi, S; Juliá, S; Masana, J; Alverez, A. *Tetrahedron*, **1983**, *39*, 1635; (d) Banfi, S; Colonna, S; Molinari, H; Juliá, S; Guixer, J. *Tetrahedron*, **1984**, *40*, 5207; (e) Bezuidenhoudt, B.C.B; Swanepoel, A; Augustyn, J.A.N; Ferreira, D. *Tetrahedron Lett.*, **1987**, *28*, 4857; (f) Itsuno, S; Sakakura, M; Ito, K. *J. Org. Chem.*, **1990**, *55*, 6047; (g) Baures, P.W; Eggleston, D.S; Flisak, J.R; Gombatz, K.J; Lantos, I; Mendelson, W; Remich, J.J. *Tetrahedron Lett.*, **1990**, *31*, 6501; (h) Flisak, J.R; Gombatz, K.J; Holmes, M.M; Jarmas, A.A; Lantos, I; Mendelson, W.L; Novack, V.J; Remich, J.J; Snyder, L. *J. Org. Chem.*, **1993**, *58*, 6247; (i) Lasterra-Sánchez, M.E; Roberts, S.M. *J. Chem. Soc., Perkin Trans I*, **1995**, 1467; (j) Kroutil, W; Mayon, P; Lasterra-Sánchez, M.E; Maddrell, S.J; Roberts, S.M; Thornton, S.R; Todd, C.J; Tüter, M. *Chem. Commun.*, **1996**, 845, 2495; (k) Lasterra-Sánchez, M.E; Felfer, U; Mayon, P; Roberts, S.M; Thornton, S.R; Todd, C.J. *J. Chem. Soc., Perkin Trans I*, **1996**, 343; (l) Kroutil, W; Lasterra-Sánchez, M.E; Maddrell, S.J; Mayon, P; Morgan, P; Roberts, S.M; Thornton, S.R; Todd, C.J; Tüter, M. *J. Chem. Soc., Perkin Trans. I*, **1996**, 2837; (m) Bentley, P.A; Bergeron, S; Cappi, M.W; Hibbs, D.E; Hursthouse, M.B; Nugent, T.C; Pulido, R; Roberts, S.M; Wu. L.E. *Chem. Commun.*, **1997**, 739; (n) Allen, J.V; Cappi, M.W; Kary, P.D; Roberts, S.M; Williamson, N.M; Wu, L.E. *J. Chem. Soc., Perkin Trans. I*, **1997**, 3297; (o) Adger, B.M; Barkley, J.V; Bergeron, S; Cappi, M.W; Flowerdew, B.E; Jackson, M.P; McCague, R; Nugent, T.C; Roberts, S.M. *J. Chem. Soc., Perkin Trans. I*, **1997**, 3501; (p) Cappi, M.W; Chen, W.-P; Flood, R.W; Liao, Y.-W; Roberts, S.M; Skidmore, J; Smith, J. A; Williamson, N.M. *Chem. Commun.*, **1998**, 1159.
4. Bougauchi, M; Watanabe, S; Arai, T; Sasai, H; Shibasaki, M. *J. Am. Chem. Soc.*, **1997**, *119*, 2329; Daikai, K; Kamaura, M; Inanaga, J. *Tetrahedron Lett.*, **1998**, *39*, 7321; Watanabe, S; Kobayashi, Y; Arai, T; Sasai, H; Bougauchi, M; Shibasaki, *Tetrahedron Lett.*, **1998**, *39*, 7353.
5. Elston, C.L; Jackson, R.W.F; MacDonald, S.J.F; Murray, P.J. *Angew. Chem. Int. Ed. Engl.*, **1997**, *36*, 410.
6. Baccin, C; Gusso, A; Pinna, F; Strukul, G. *Organomet.*, **1995**, *14*, 1161.
7. See for example: (a) Helder, R; Hummelen, J.C; Laane, R.W.P.M; Wiering, J.S; Wynberg, H. *Tetrahedron Lett.*, **1976**, 1831; (b) Hummelen, J.C; Wynberg, H. *Tetrahedron Lett.*, **1978**, 1089; (c) Wynberg, H; Greijdanus, B. *J. Chem. Soc., Chem. Commun.*, **1978**, 427; (d) Wynberg, H;

Marsman, B. *J. Org. Chem.*, **1980**, *45*, 158; (e) Pluim, H; Wynberg, H. *J. Org. Chem.*, **1980**, *45*, 2498; (f) Harigaya, Y; Yamaguchi, H; Onda, M. *Heterocycles*, **1981**, *15*, 183; (g) Mazaleyrat, J.P. *Tetrahedron Lett.*, **1983**, *24*, 1243; (h) Baba, N; Oda, J; Kawaguchi, M; *Agric. Biol. Chem.*, **1986**, *50*, 3113; (i) Baba, N; Oda, J; Kawahara, S; Hamada, M. *Bull. Inst. Chem. Res., Kyoto Univ.*, **1989**, *67*, 121; (j) Shi, M; Masaki, Y. *J. Chem. Res. (S)*, **1994**, 250; (k) Shi, M; Kazuta, K; Satoh, Y; Masaki, Y. *Chem. Pharm. Bull.*, **1994**, *42*, 2625; (l) Macdonald G; Alcaraz L; Lewis N.J; Taylor R.J.K. *Tetrahedron Lett.*, **1998**, *39*, 5433; (m) Arai, S; Oku, M; Miura, M; Shioiri, T. *Synlett*, **1998**, 1201; (n) Watanabe, S; Arai, T; Sasai, H; Bougauchi, M; Shibasaki, M. *J. Org. Chem.*, **1998**, *63*, 8090.

8. For the enantioselective preparation of epoxides of type **2** *via* asymmetric phase-transfer catalysed Darzens reaction see Arai, S; Ishida, T; Shioiri, T. *Tetrahedron Lett.*, **1998**, *39*, 8299 and references therein.

9. For preliminary communication on the use of *N*-anthracenylmethyl substituted cinchona alkaloids in the highly enantioselective epoxidation of α, β-unsaturated ketones see: Lygo, B; Wainwright, P.G. *Tetrahedron Lett.*, **1998**, *39*, 1599.

10. For the use of *N*-[4-(iodo)benzyl]cinchoninium bromide in the highly enantioselective epoxidation of α, β-unsaturated ketones see: Arai, S; Tsuge, H; Shioiri, T. *Tetrahedron Lett.*, **1998**, *39*, 7563.

11. Lygo, B; Wainwright, P.G. *Tetrahedron Lett.*, **1997**, *38*, 8595; Corey, E.J; Xu, F; Noe, M.C. *J. Am. Chem. Soc.*, **1997**, *119*, 12414; Corey, E.J; Noe, M.C; Xu, F. *Tetrahedron Lett.*, **1998**, *39*, 5347; O'Donnel, M.J; Delgado, F; Hostettler, C; Schwesinger, R. *Tetrahedron Lett.*, **1998**, *39*, 8775.

12. O'Donnell, M.J; Wu, S; Huffman, J.C. *Tetrahedron*, **1994**, *50*, 4507.

13. The absolute stereochemistry depicted for the epoxide products **2** is based on the known stereochemistry of compound **2a**. In these schemes it is assumed that the same sense of selectivity applies to the other substrates.

14. If the reactions are terminated before complete consumption of the starting *E*-enones **1**, significant amounts of the corresponding *Z*-alkene isomers can be detected. This suggests that isomerisation of the alkene geometry in the enone substrates occurs readily under the epoxidation conditions.

15. The rate of epoxidation is dependant on the rate of stirring, and the efficiency of mixing of the two phase system, however rate of reaction does not appear to affect the enantioselectivity.

16. Perrin, D.D; Armarego, W.L.F. *"Purification of Laboratory Chemicals"*, 3rd Ed., Pergamon Press, Oxford, **1988**.

17. Kohler, E.P; Chadwell, H.M. *Org. Synth. Col. Vol. I*, **1932**, 78.

18. Chaffee, A.L; Cooke, R.G; Dagley, I.J; Perlmutter, P; Thomas, R.L. *Aust. J. Chem.*, **1981**, *34*, 587.

19. ^{1}H nmr spectra of the quaternary ammonium salts are concentration dependent, these data were recorded on solutions containing 40mg/ml.