Supporting Information, Section C

Practical and Highly Selective Sulfur Ylide-Mediated Asymmetric Epoxidations and Aziridinations Using a Cheap and Readily Available Chiral Sulfide. Extensive studies to map out scope and limitations, and rationalization of diastereo- and enantioselectivities.

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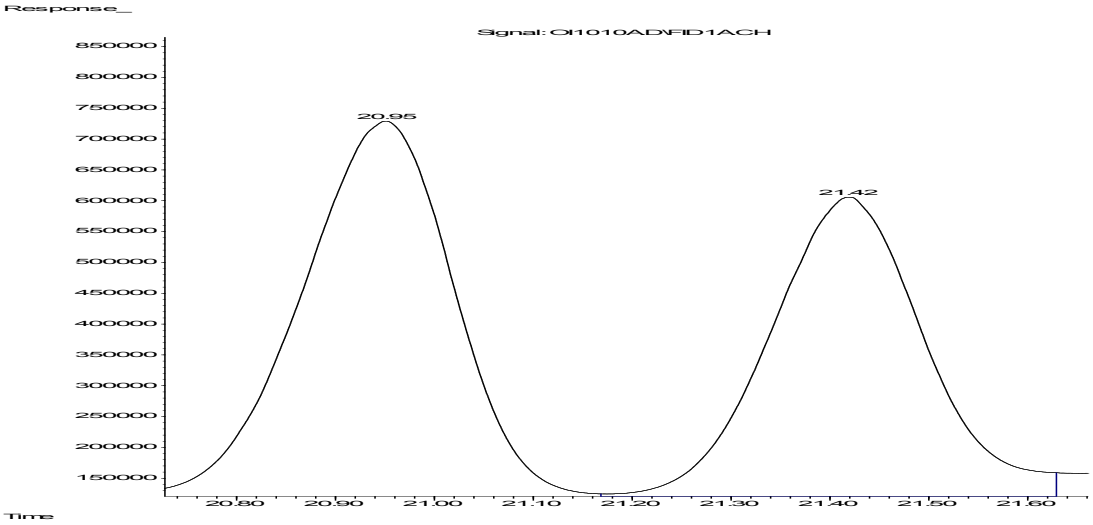
A, B and C represent three separate files

Gas Chromatograms for Isothiocineole 2

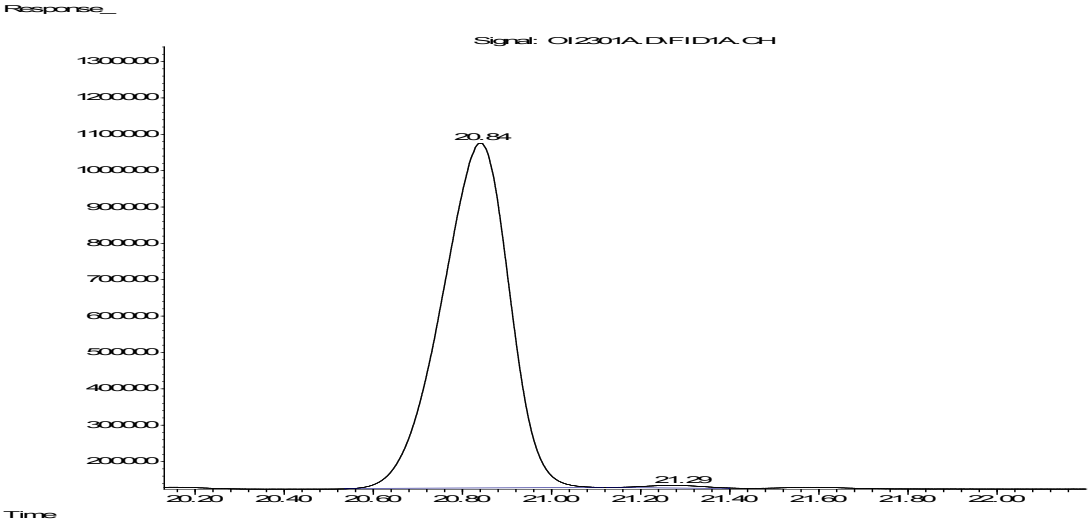
Isothiocineole (2)

Chiral-phase GC conditions: α-Dex column, oven temperature: 110 °C; R_t 20.85 min (*R*), 21.39 min (*S*); Injection/detector temperatures: 250 °C;

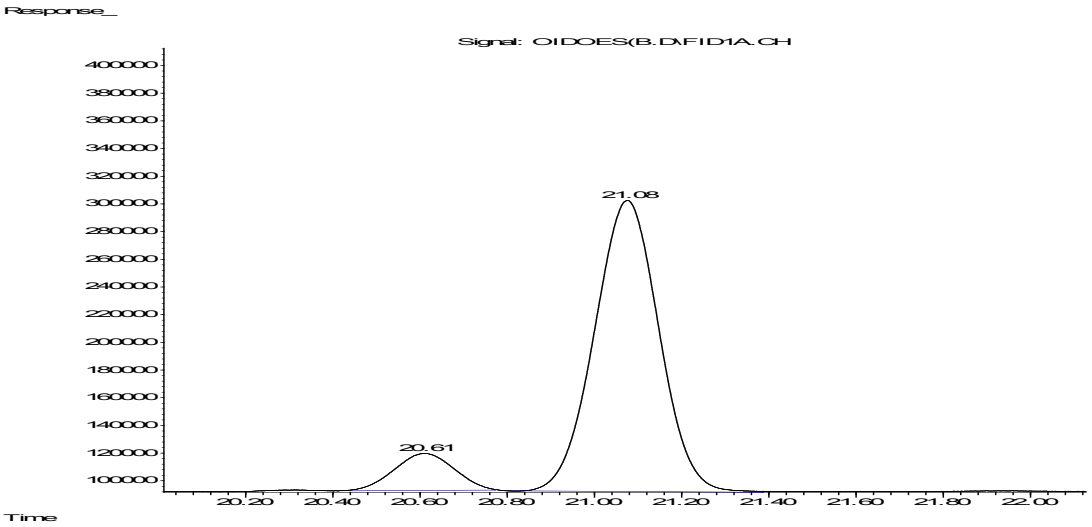
Racemic Isothiocineole (±-2)



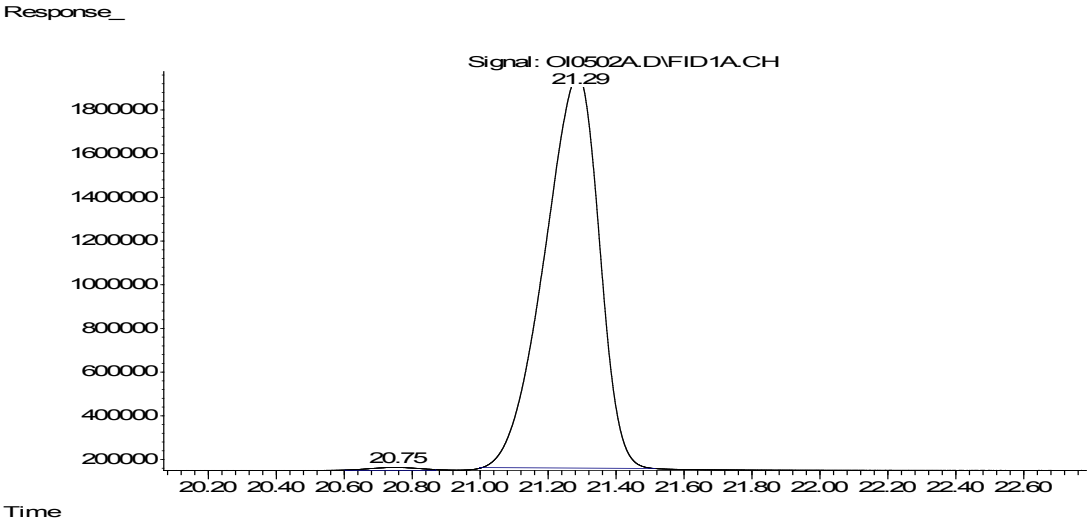
(*1R*,*4R*,*5R*)-Isothiocineole 2 derived from (*R*)-Limonene



(*1S*,*4S*,*5S*)-Isothiocineole 2 derived from (*S*)-Limonene before crystallization

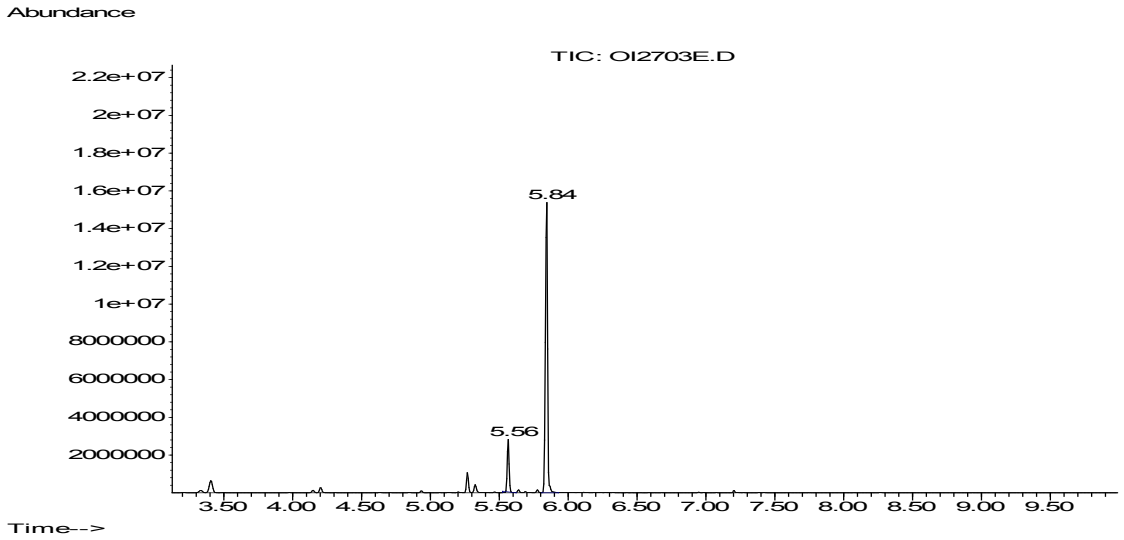


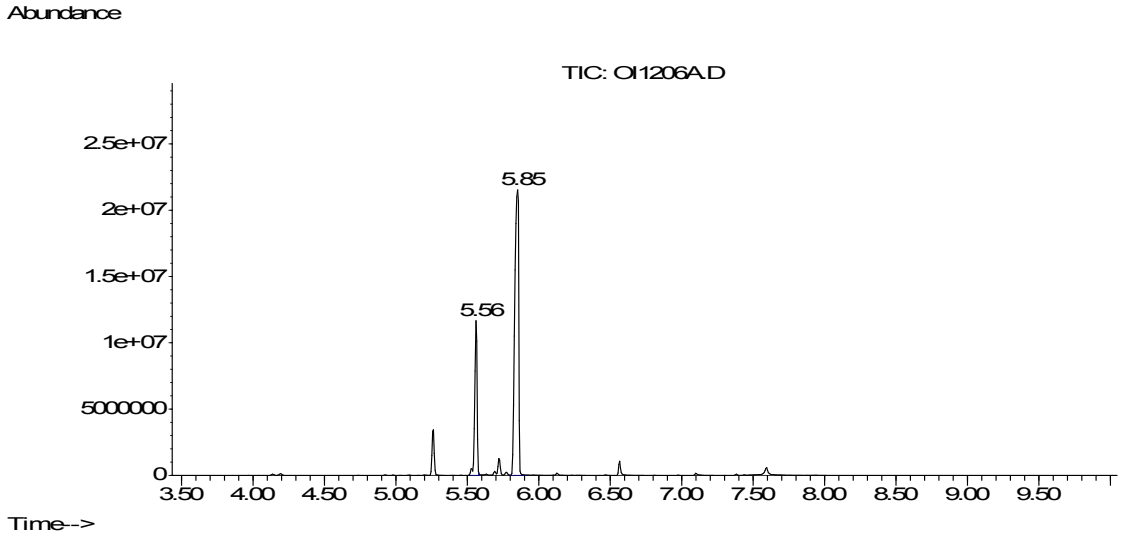
(*1S*,*4S*,*5S*)-Isothiocineole 2 derived from (*S*)-Limonene after crystallization



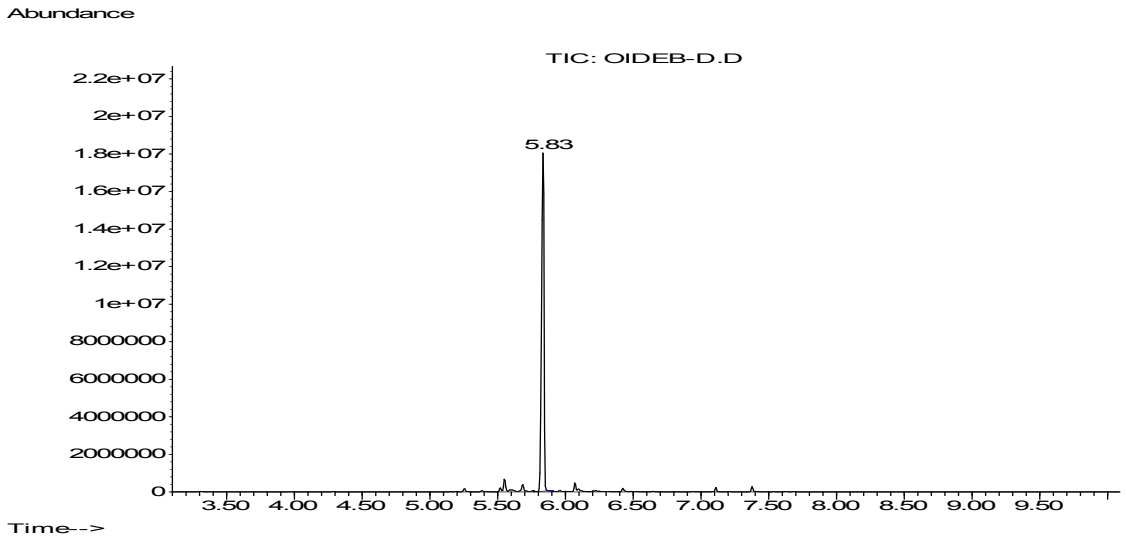
GC Chromatogram of Distillate from Initial Method for synthesis of isothiocineole (reaction carried out in the absence of γ-terpinene/1,4-cyclohexadiene)

GC conditions, supelco-SLB5MS, 15 m × 0.25 mm i.d., Injection 250 °C; detector temperature 280 °C; oven temperature: 70 °C (3 min), increase by 25 °C/min to 200 °C, followed by temperature ramp to 300 °C, R_t isothiocineole (**2**) 5.8 min, (1*R*,5*R*)-4,7,7-trimethyl-6-thiabicyclo[3.2.1]oct-3-ene (**13**) 5.5 min.



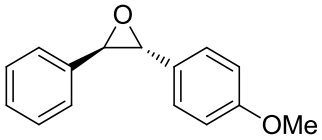


GC Chromatogram of Distillate from Improved Method for synthesis of isothiocineole (carried out in the presence of γ-terpinene)



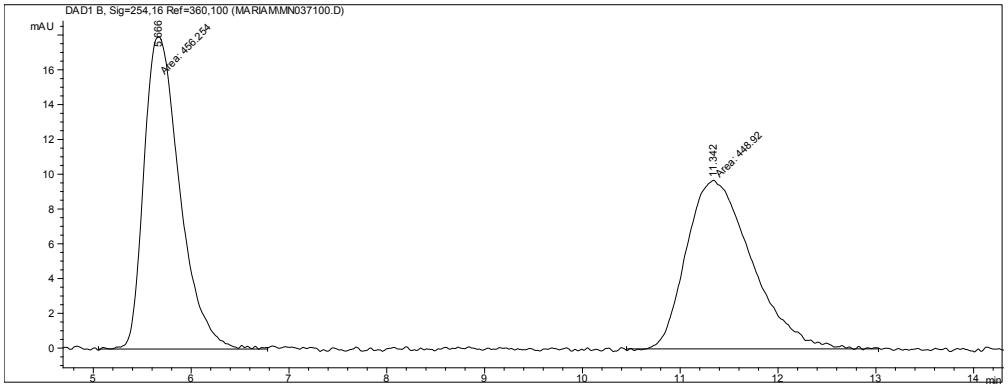
Chiral HPLC data for Epoxides

(2*R*,3*R*)-2-(4-Methoxyphenyl)-3-phenyloxirane, (*R*,*R*)-25ab from 23a

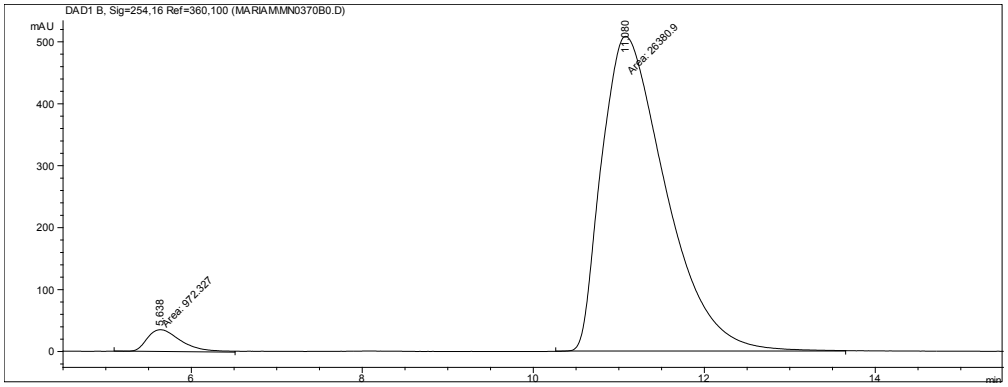


Short OD chiralcel, 1.0% *i*PrOH/Hexane, 0.5 mL/min, 20 °C.

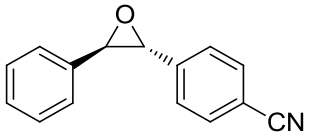
Racemic



Asymmetric, 98:2 er

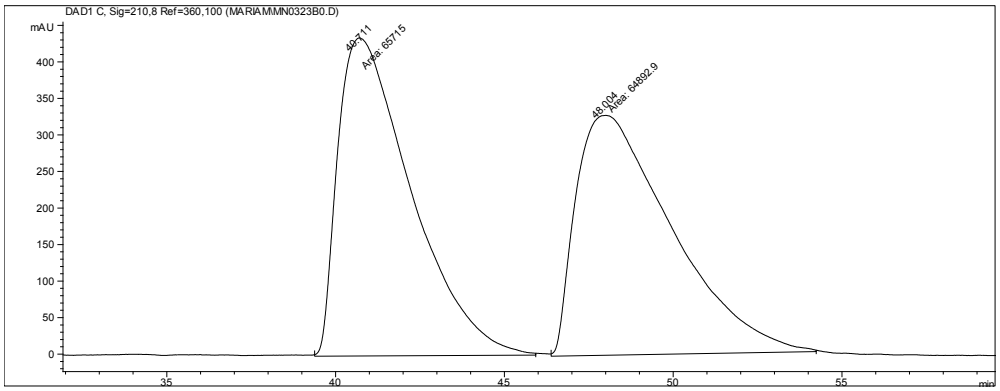


4-((2*R*,3*R*)-3-Phenyloxiran-2-yl)benzonitrile, (*R*,*R*)-25ac from 23a

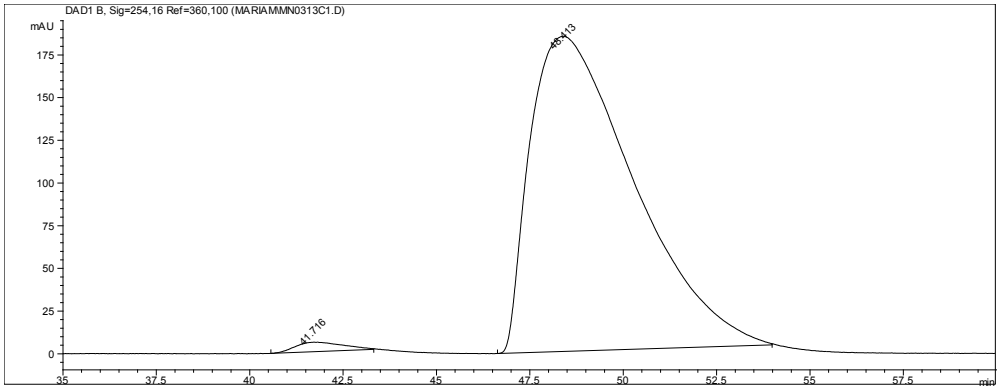


OD chiralcel, 2% *i*PrOH/Hexane, 1.0 mL/min, 20 °C.

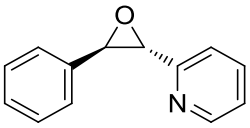
Racemic



Asymmetric, >99:1 er

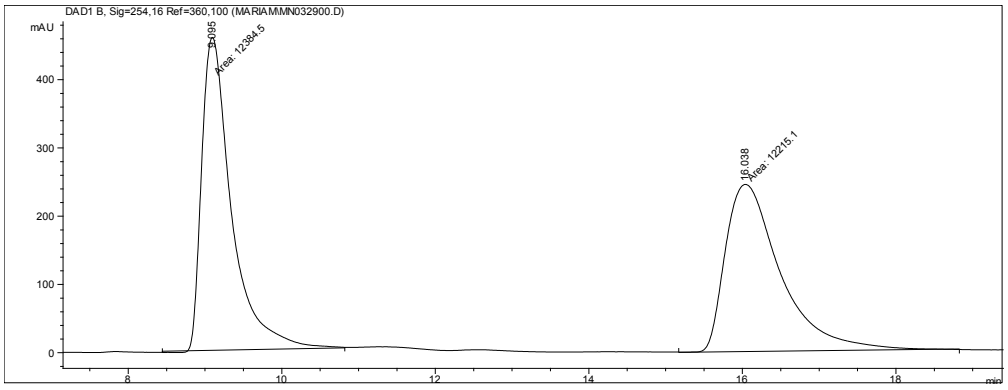


2-((2*R*,3*R*)-3-Phenyloxiran-2-yl)pyridine, (*R*,*R*)-25ag from 23a

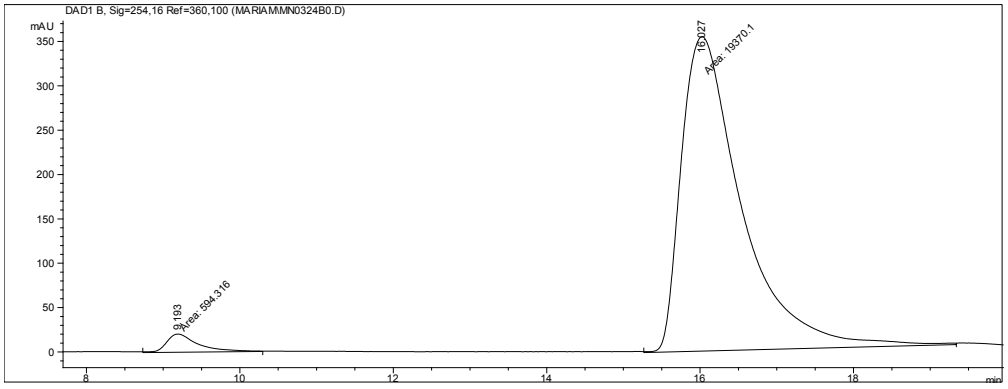


ODH chiralcel, 10.0% *i*PrOH/Hexane, 1 mL/min, 20 °C.

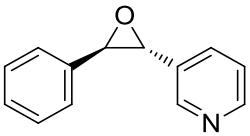
Racemic



Asymmetric, 98:2 er

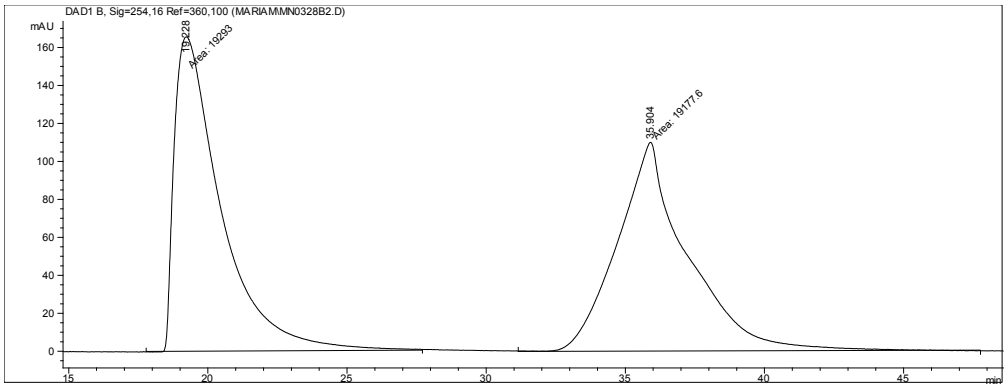


3-((2*R*,3*R*)-3-phenyloxiran-2-yl)pyridine, (*R*,*R*)-25ah from 23a

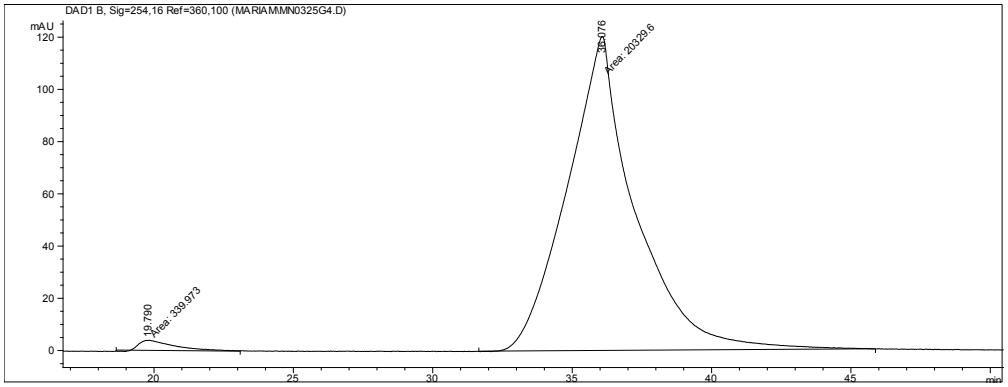


OJ chiralcel, 10.0% *i*PrOH/Hexane, 1 mL/min, 20 °C.

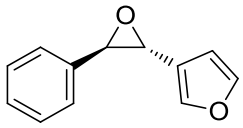
Racemic



Asymmetric, 98:2 er

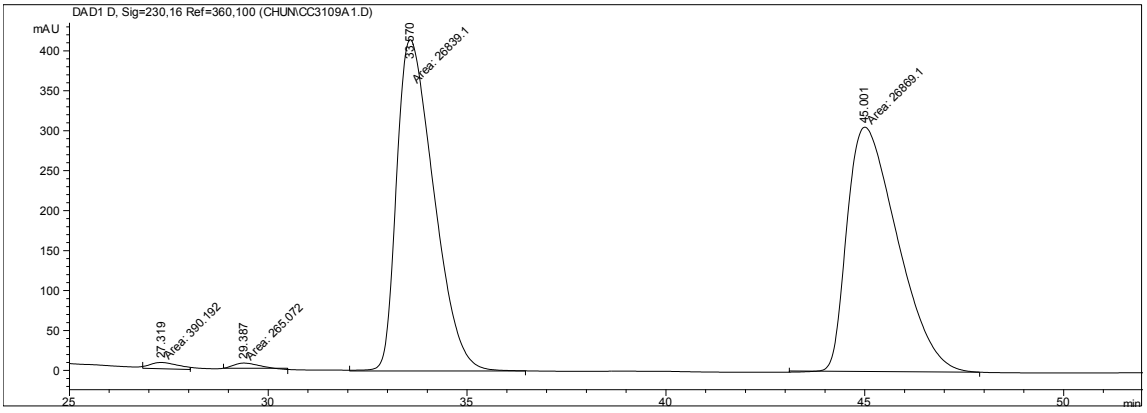


3-((2*R*,3*R*)-3-Phenyloxiran-2-yl)furan, (*R*,*R*)-25ai from 23a

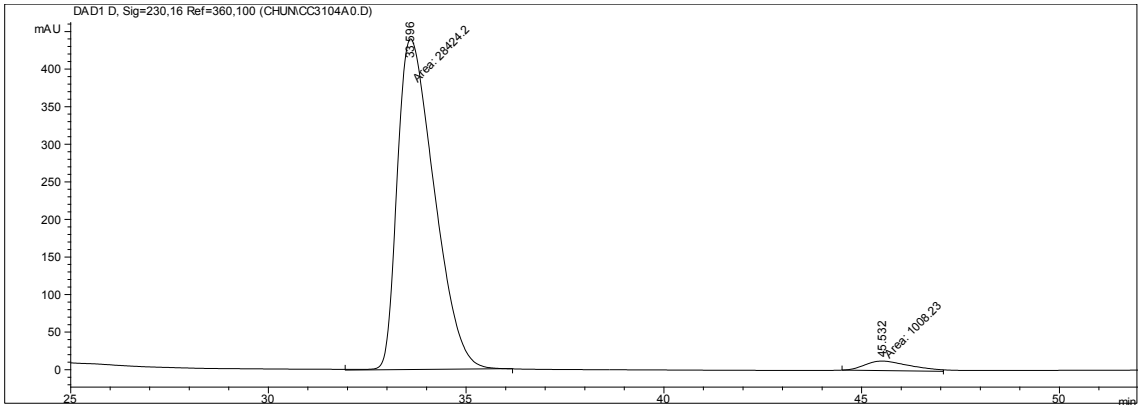


OJH column, 5% *i*PrOH/Hexane, 0.5 mL/min, 20 °C, t_R 33.6 min (*R,R*) major) and 45.5 min ((*S,S*) minor)

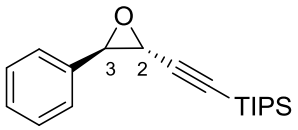
Racemic



Asymmetric: major 33.6 min; minor 45.5 min; e.r. 97:3

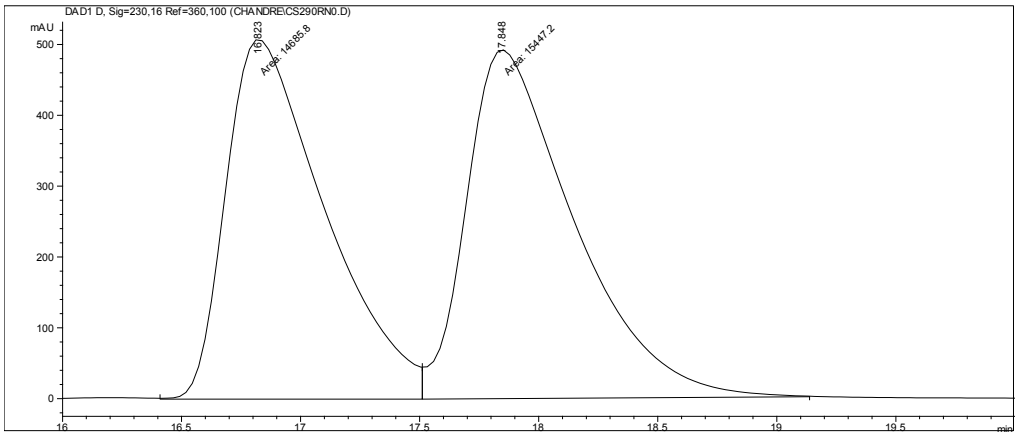


Triisopropyl(((2*R*,3*R*)-3-phenyloxiran-2-yl)ethynyl)silane (*R*,*R*)-25am from 23a

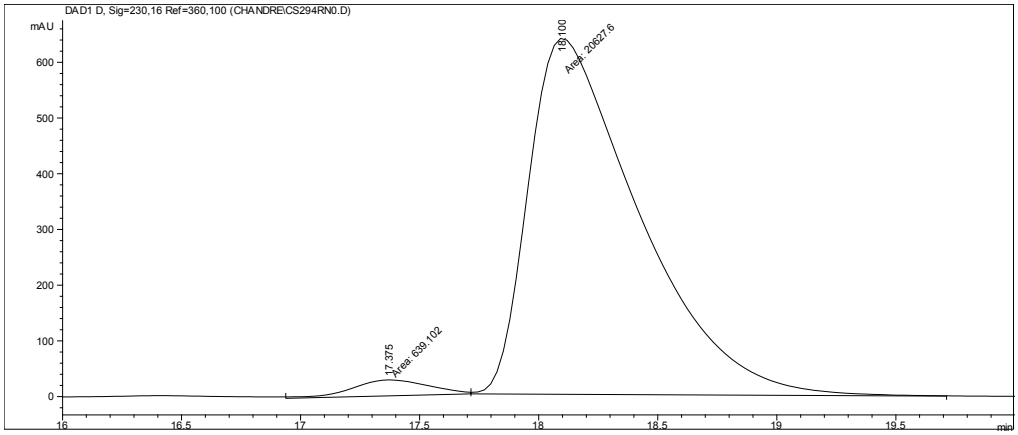


IB column with guard, 0.1% *i*PrOH/Hexane, flow rate: 0.5 mL/min, 10 ºC,

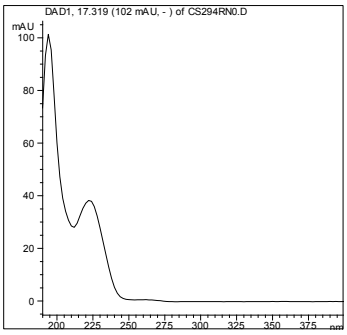
Racemic epoxide.

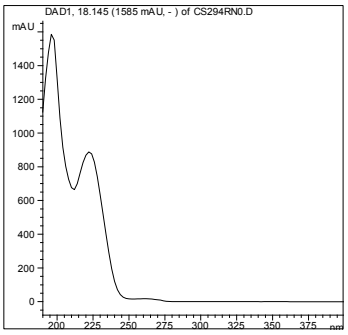


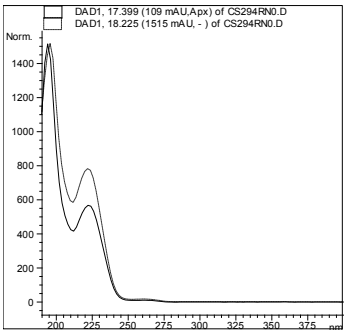
Neat MeCN: (*e.r.* = 97:3), t_R 17.3 min ((*S,S*) minor) and 18.1 min ((*R,R*) major).



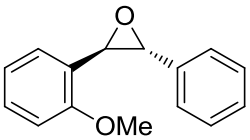
UV spectra of the peaks at 17.3 min and 18.1 min.





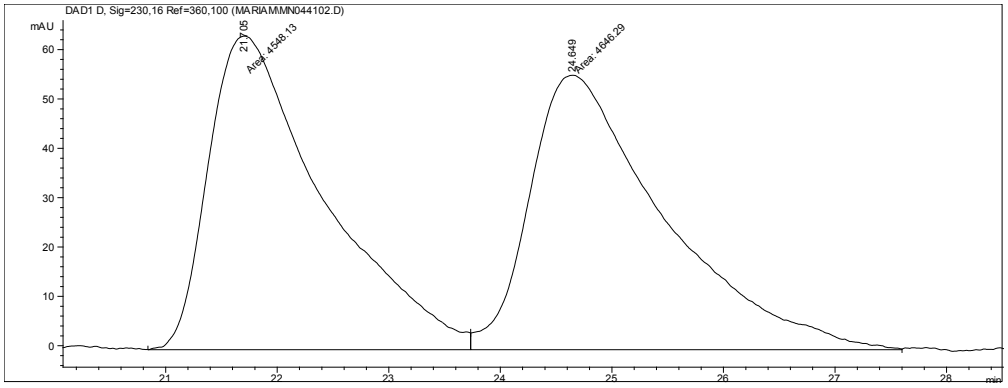


(2*R*,3*R*)-2-(2-Methoxyphenyl)-3-phenyloxirane, (*R*,*R*)-25ba from 23b

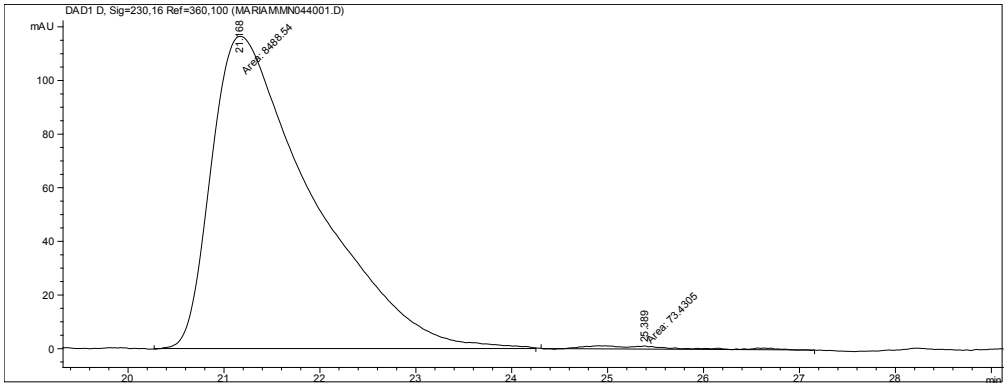


OD chiralcel, 1% *i*PrOH/Hexane, 1 mL/min, 0 °C.

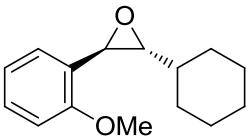
Racemic



Asymmetric, >99:1 er

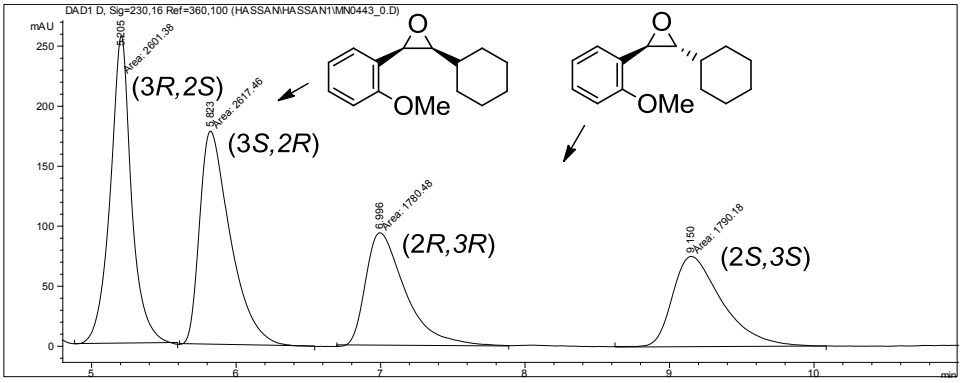


(2*R*,3*R*)-2-Cyclohexyl-3-(2-methoxyphenyl)oxirane, (*R*,*R*)-25bj from 23b

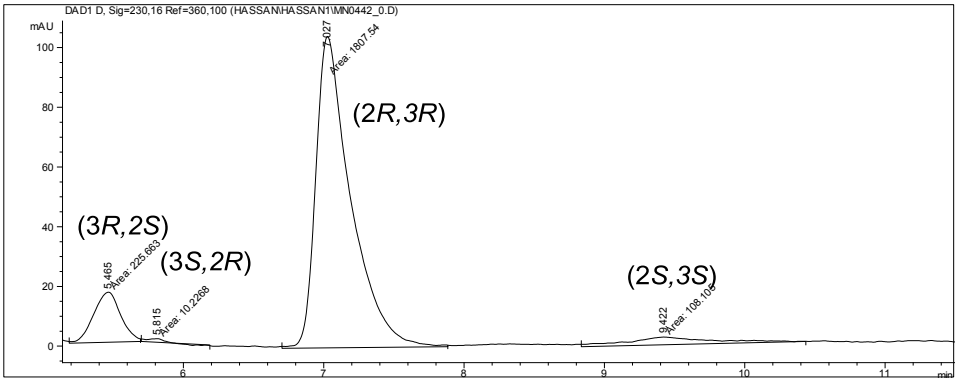


AD chiralcel, 0.5% *i*PrOH/Hexane, 1 mL/min, 0 °C.

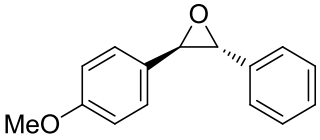
Racemic



Asymmetric, >98:2 er

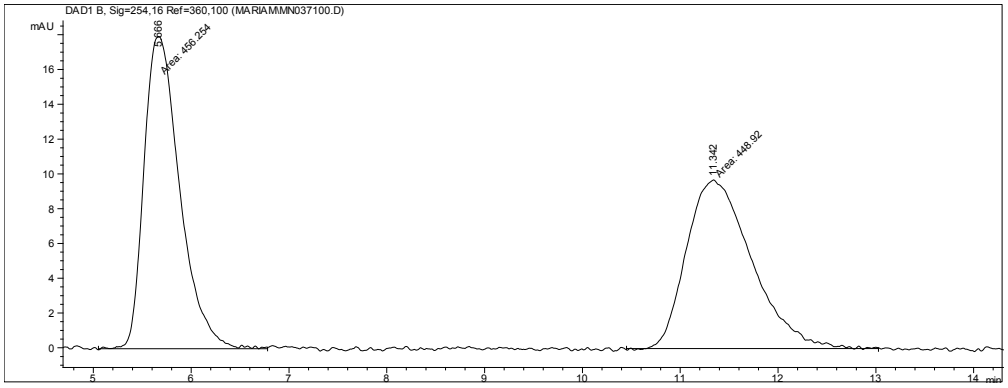


(2*R*,3*R*)-2-(4-Methoxyphenyl)-3-phenyloxirane, (*R*,*R*)-25ca from 23c

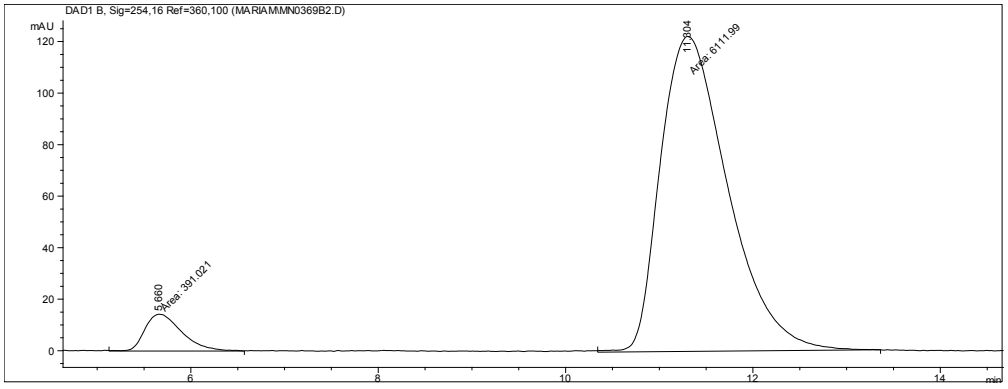


Short OD chiralcel, 1.0% *i*PrOH/Hexane, 0.5 mL/min, 20 °C.

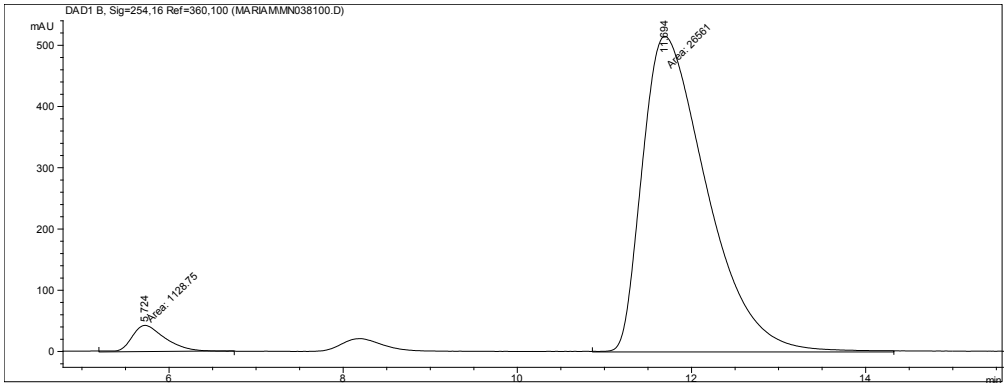
Racemic



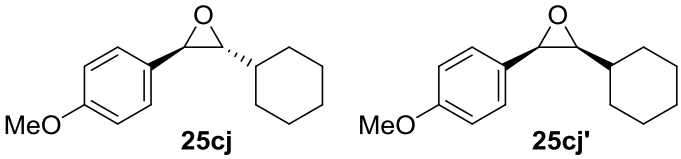
Asymmetric, 94:6 er (Reaction conditions A: MeCN:H_2O 9:1)



Asymmetric, 96:4 er (Reaction conditions: neat MeCN)

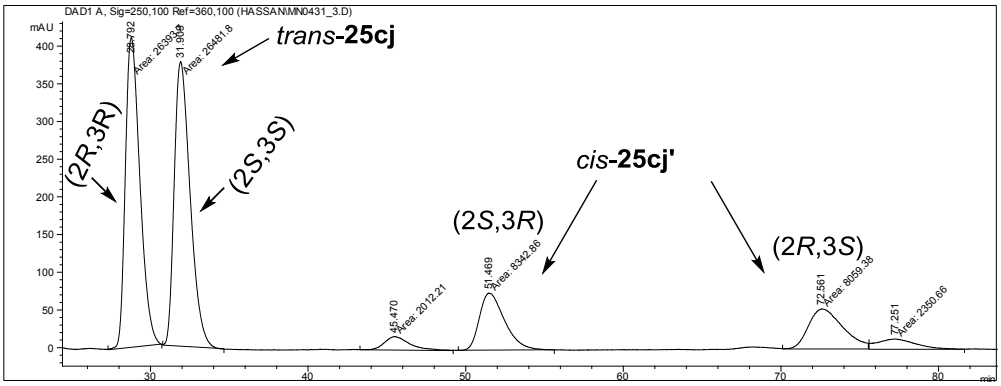


(2*R*,3*R*)-2-Cyclohexyl-3-(4-methoxyphenyl)oxirane, (2*R*,3*R*)-25cj and (2*S*,3*R*)-2-Cyclohexyl-3-(4-methoxyphenyl)oxirane, (2*S*,3*R*)-25cj′ from 23c

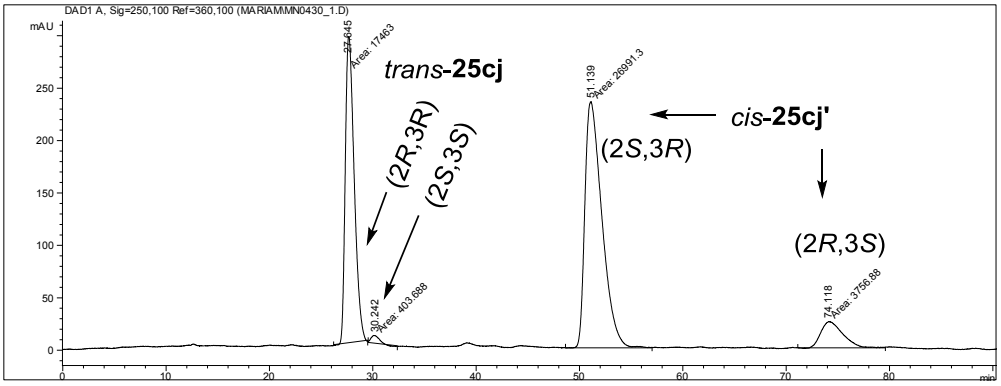


AD chiralcel, 1% *i*PrOH/Hexane, 0.25 mL/min, 20 °C.

Racemic

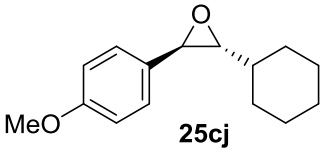


Asymmetric (2*R*,3*R*)-**25cj**: 98:2 er and (2*S*,3*R*)-**25cj′**: 88:12 er



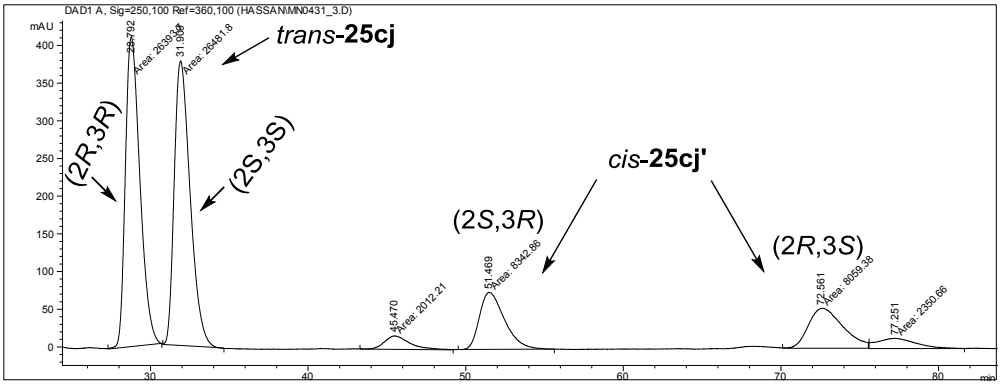
Note: Please see zoomed in regions of **25cj** and **25cj′**

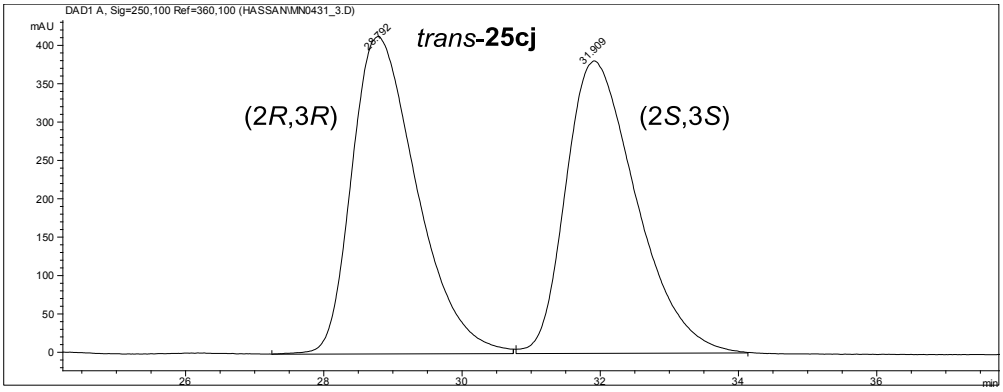
Zoomed in region of (2*R*,3*R*)-2-cyclohexyl-3-(4-methoxyphenyl)oxirane, (2*R*,3*R*)-25cj from 23c



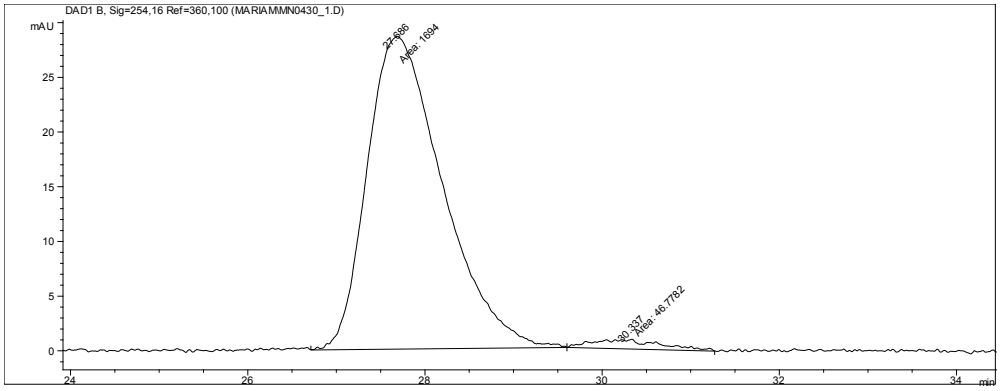
AD chiralcel, 1% *i*PrOH/Hexane, 0.25 mL/min, 20 °C.

Racemic

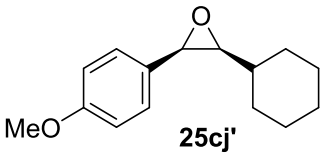




Asymmetric (2*R*,3*R*)-**25cj**, 98:2 e.r.

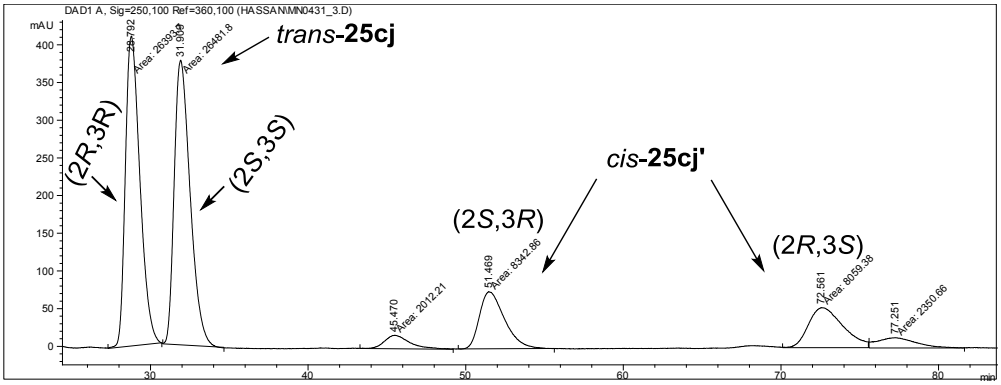


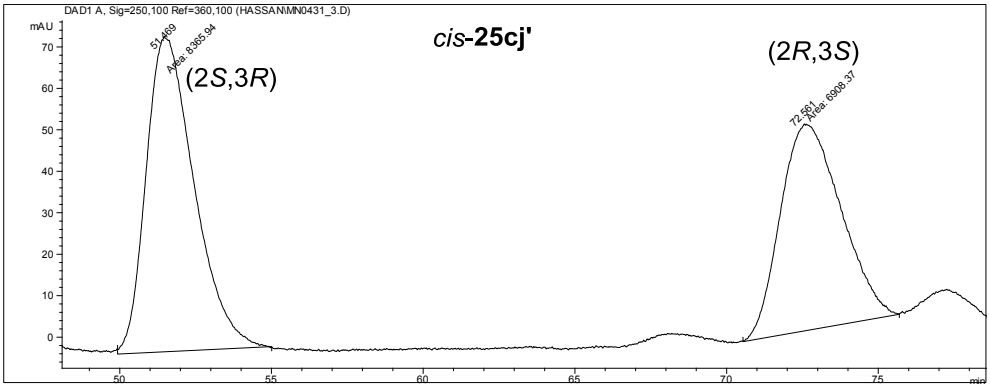
Zoomed in region of (2*S*,3*R*)-2-cyclohexyl-3-(4-methoxyphenyl)oxirane, (2*S*,3*R*)-25cj' from 23c



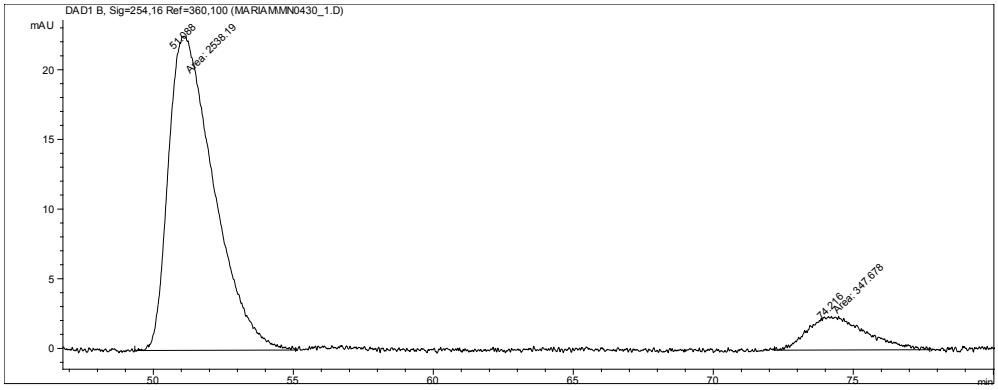
AD chiralcel, 1% *i*PrOH/Hexane, 0.25 mL/min, 20 °C.

Racemic

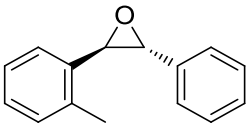




Asymmetric (2*S*,3*R*)-**25cj'**, 88:12 er

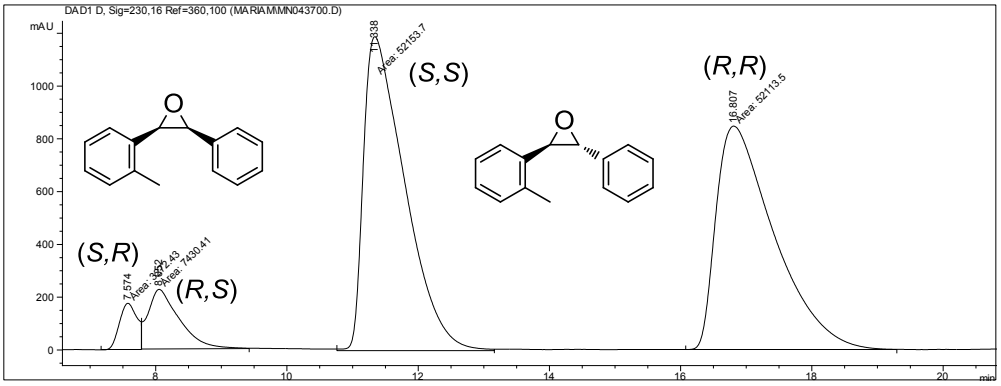


(2*R*,3*R*)-2-Phenyl-3-(o-tolyl)oxirane, (*R*,*R*)-25da from 23d

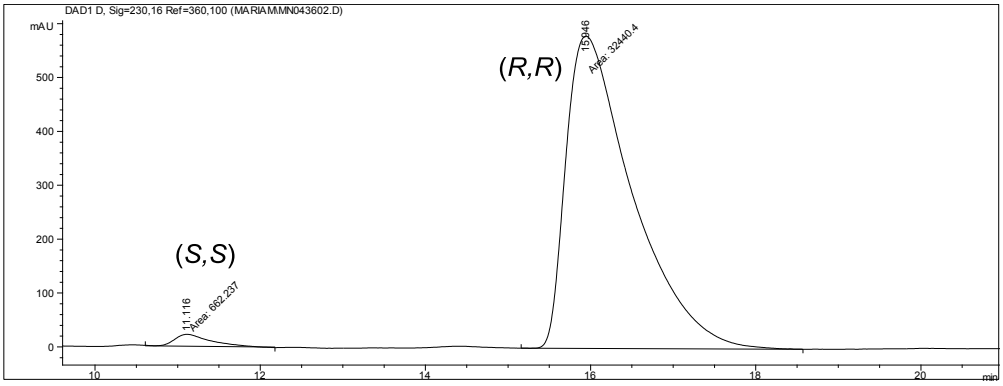


OD chiralcel, 1% *i*PrOH/Hexane, 1 mL/min, 0 °C.

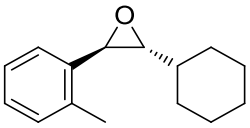
Racemic



Asymmetric, 98:2 ee

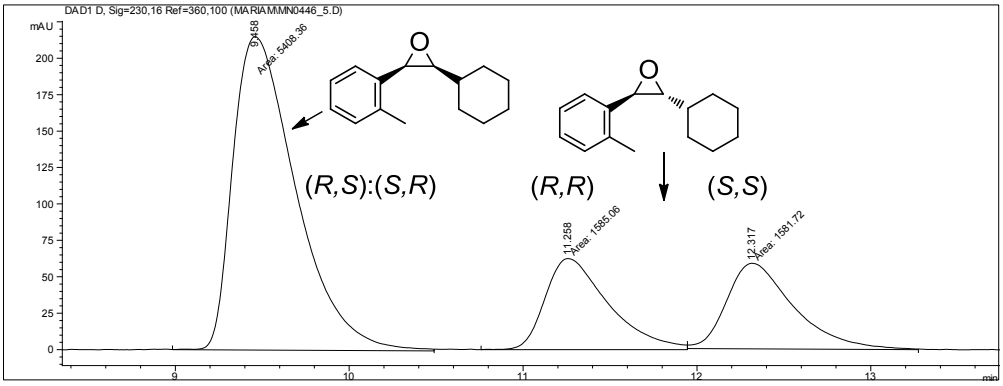


(2*R*,3*R*)-2-Cyclohexyl-3-(o-tolyl)oxirane, (*R*,*R*)-25dj from 23d

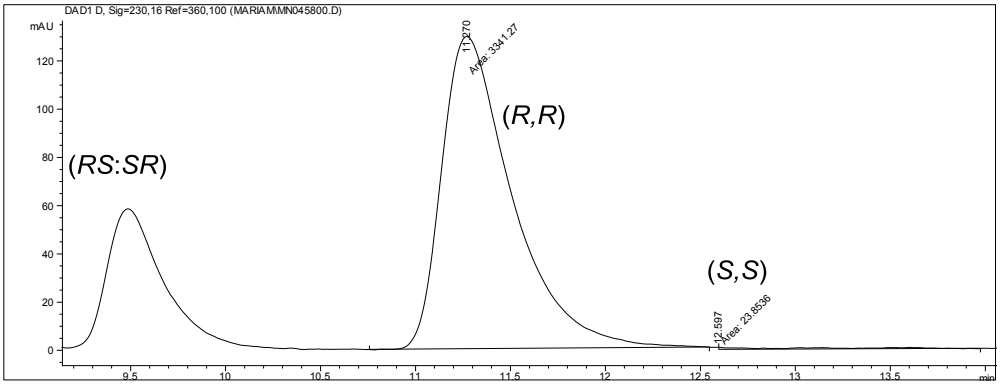


AD chiralcel, 1% *i*PrOH/Hexane, 0.5 mL/min, 0 °C.

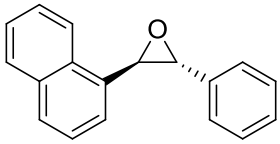
Racemic



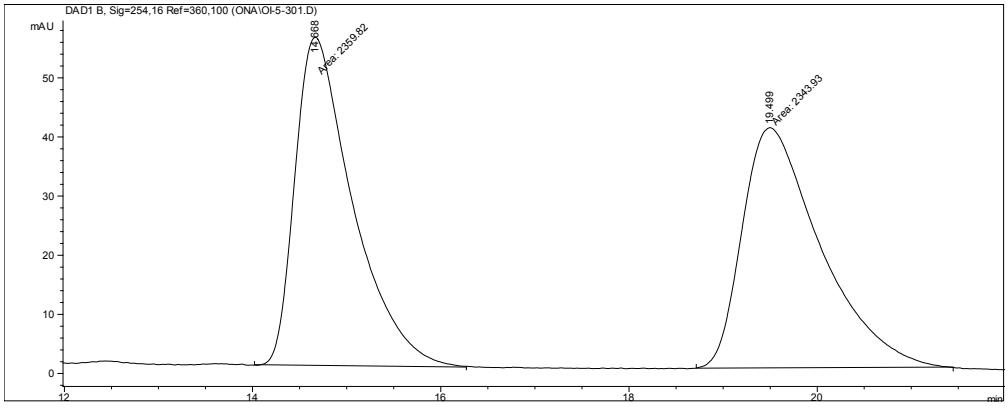
Asymmetric, 99:1 er, (*R*,*R*)-**25dj**



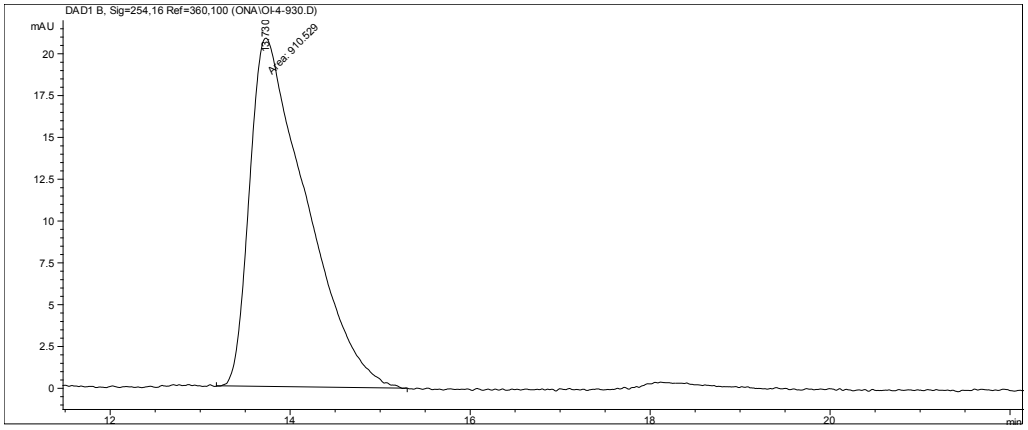
(2*R*,3*R*)-2-(Naphthalen-1-yl)-3-phenyloxirane 25ea from 23e



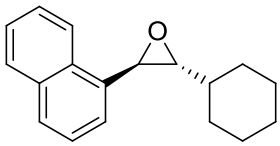
Racemic



Enantioenriched, OD column, 5% *i*PrOH/Hexane, 1 ml/min, 13.73 min ((*R,R*), major), 18.20 min ((*S,S*), minor), 98:2 er

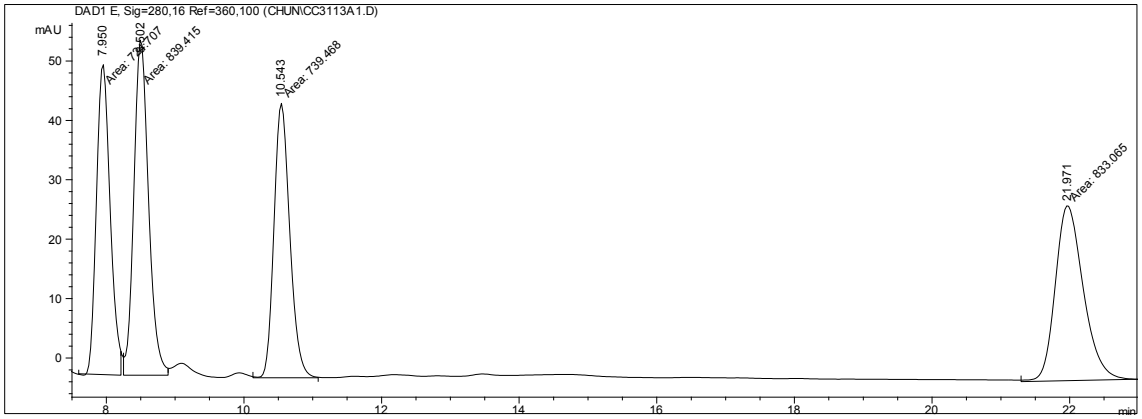


(2*R*,3*R*)-2-Cyclohexyl-3-(naphthalen-1-yl)oxirane 25ej from 23e



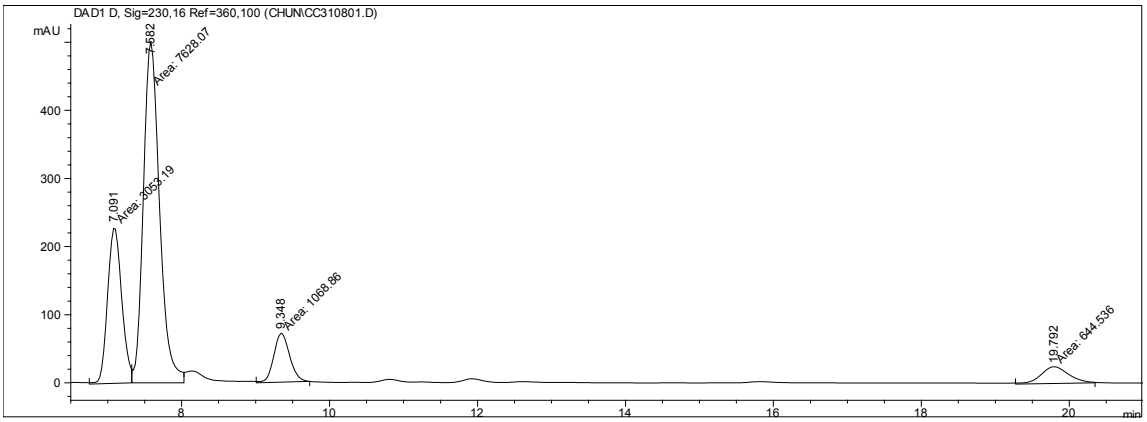
IB column, 0.7 ml/min, 5% iPrOH/hexane; *trans*: major 7.58 min and minor 19.8 min. *cis*: major 7.09 min and minor 9.34 min.

Racemic

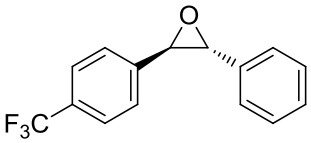


e.r. 92:8

Enantioenriched

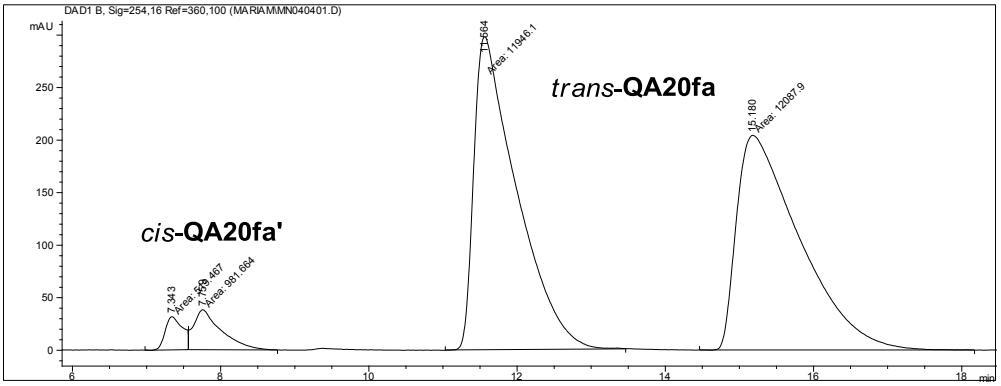


(2*R*,3*R*)-2-Phenyl-3-(4-(trifluoromethyl)phenyl)oxirane, (2*R*,3*R*)-25fa from 23f

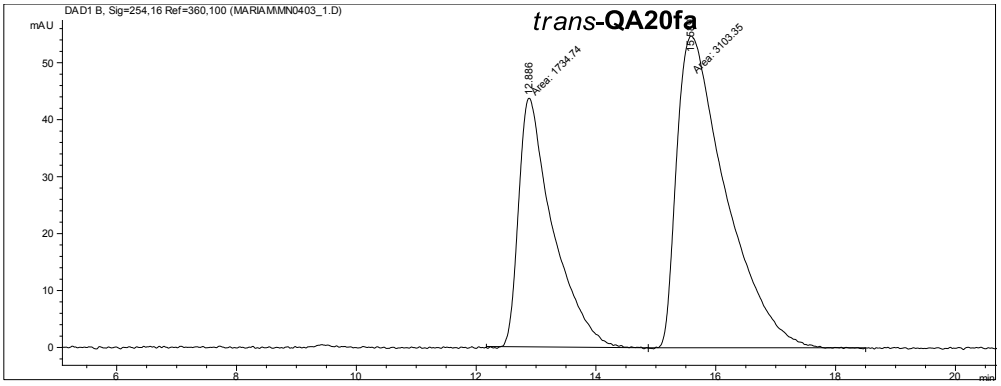


OD chiralcel, 10% *i*PrOH/Hexane, 1.0 mL/min, 20 °C.

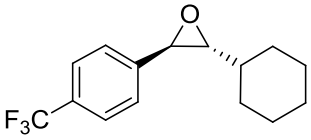
Racemic



Asymmetric, 64:36 er

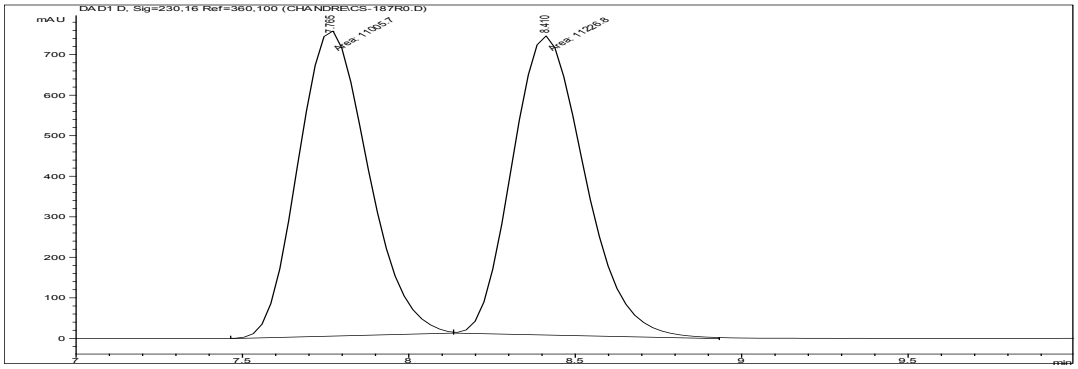


(2*R*,3*R*)-2-Cyclohexyl-3-(4-(trifluoromethyl)phenyl)oxirane 25fj from 23f

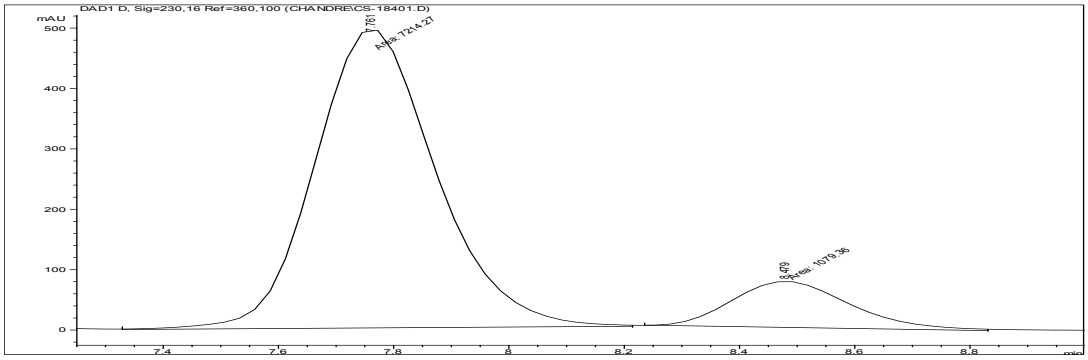


IC column with guard, 5% *i*PrOH/Hexane, flow rate: 0.50 mL/min, 20 ºC

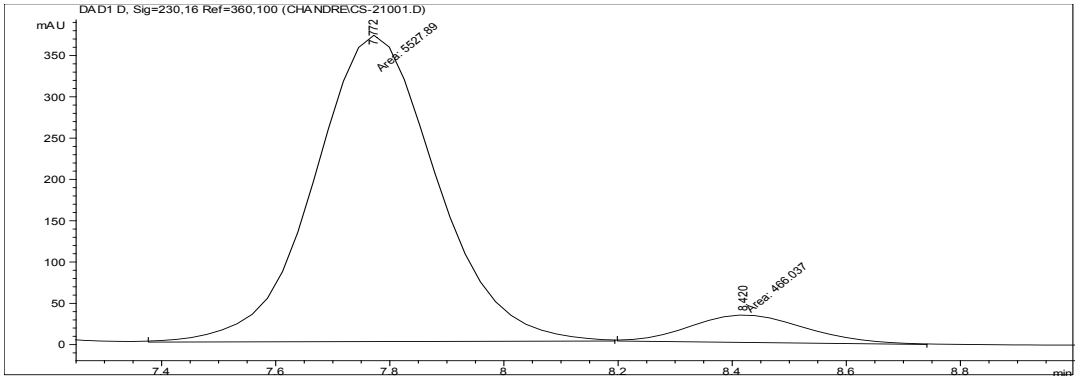
Racemic Epoxide.



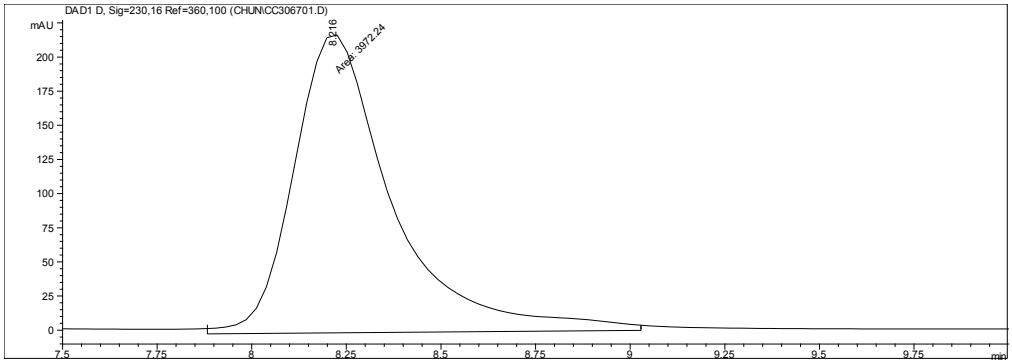
Method B: KOH, MeCN:t-BuOH (15:1); (*e.r.* = 87:13), t_R 7.8 min ((*R,R*) major) and 8.5 min ((*S,S*) minor).



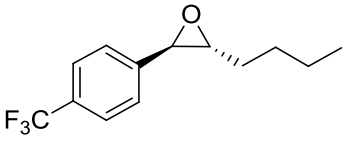
Method C: KOH, MeCN:t-BuOH (1:5), (*e.r.* = 92:8), t_R 7.8 min ((*R,R*) major) and 8.4 min ((*S,S*) minor).



Method D: LiHMDS, THF, - 78 ^{o}C, (*e.r*: >99:1), R_t <u>*trans*</u>: 8.21 min ((2*R,3R*), major);

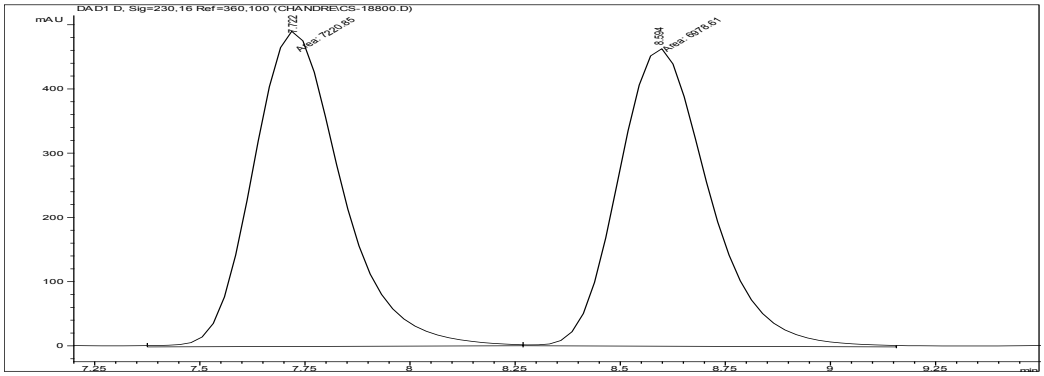


(2*R*,3*R*)-2-butyl-3-(4-(trifluoromethyl)phenyl)oxirane 25fk from 23f

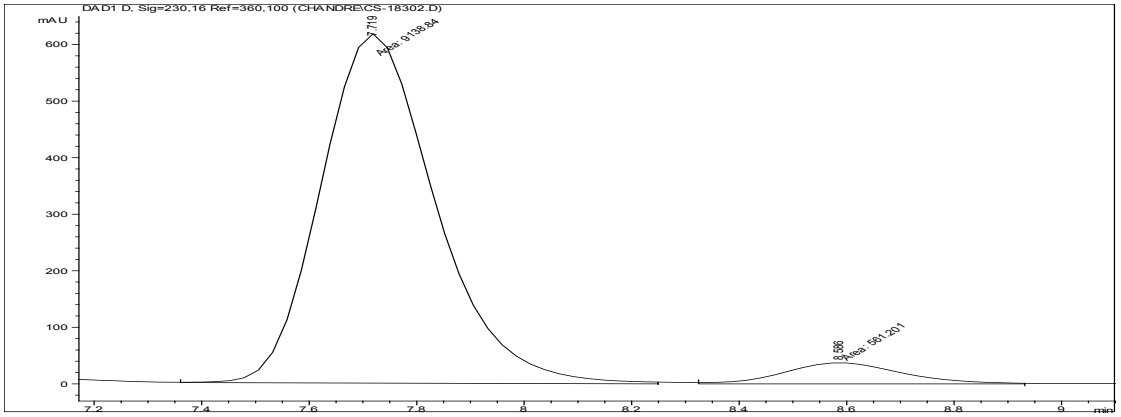


IC column with guard, 5% *i*PrOH/Hexane, flow rate: 0.5 mL/min, 20 ºC

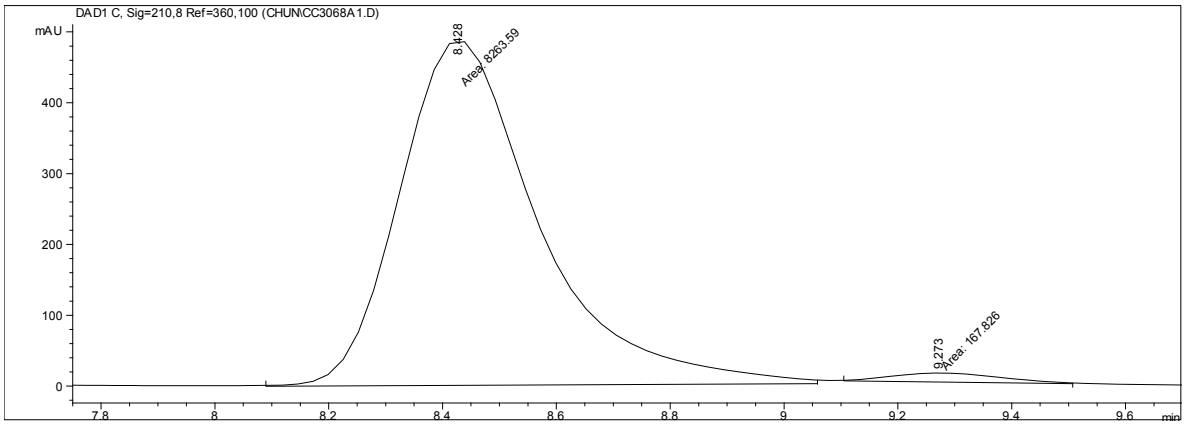
Racemic Epoxide



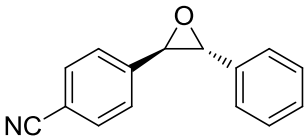
Method C; KOH, MeCN:t-BuOH (1:5), (*e.r.* = 94:6), t_R 7.7 min ((*R,R*) major) and 8.6 min ((*S,S*) minor).



Method D: LiHMDS, THF, –78 °C, (*e.r*: 98:2), R_t <u>*trans*</u>: 8.42 min ((2*R,3R*), major); 9.27 min ((2*S,3S*), minor).

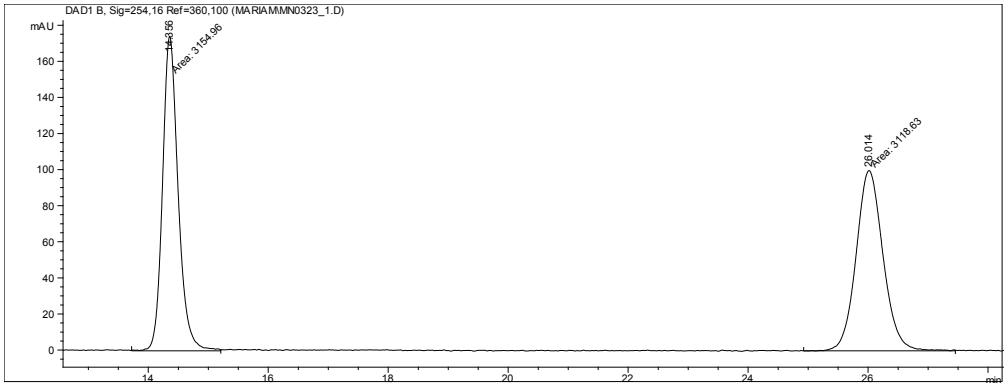


4-((2*R*,3*R*)-3-Phenyloxiran-2-yl)benzonitrile, (*R*,*R*)-25ga from 23g

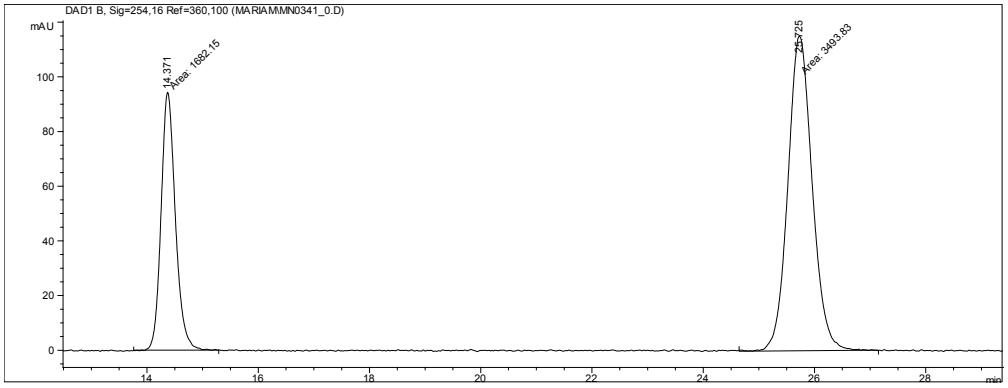


IA chiralcel with guard, 10.0% *i*PrOH/Hexane, 0.7 mL/min, 20 °C.

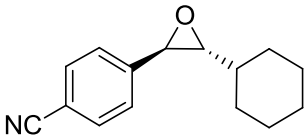
Racemic



Asymmetric, 67:33 er, (Reaction conditions A: MeOH:H_2O 9:1)

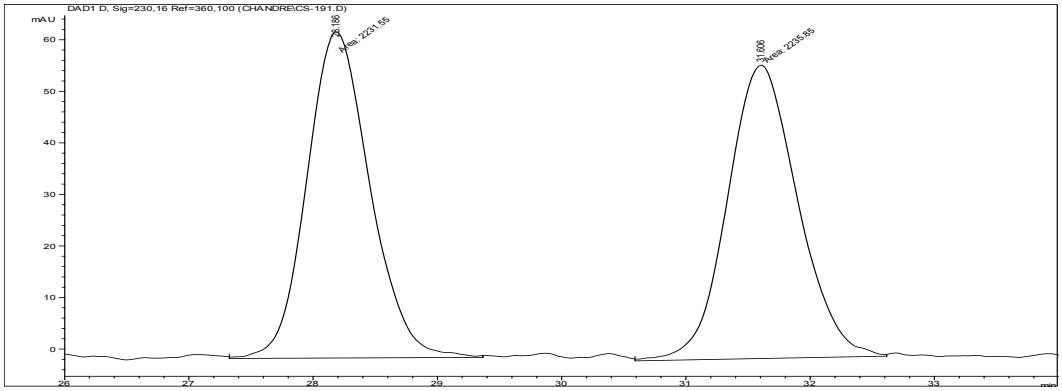


4-((2*R*,3*R*)-3-cyclohexyloxiran-2-yl)benzonitrile 25gj from 23g

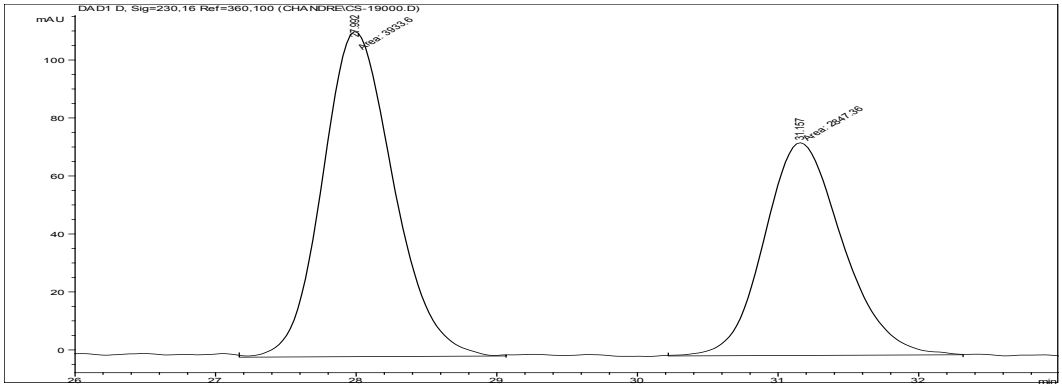


IC column with guard, 0.5% *i*PrOH/Hexane, flow rate: 0.7 mL/min, 20 °C

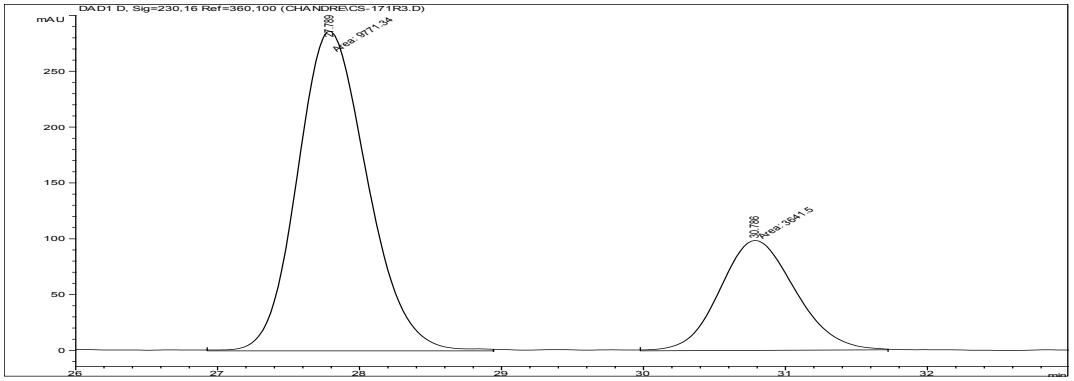
Racemic Epoxide.



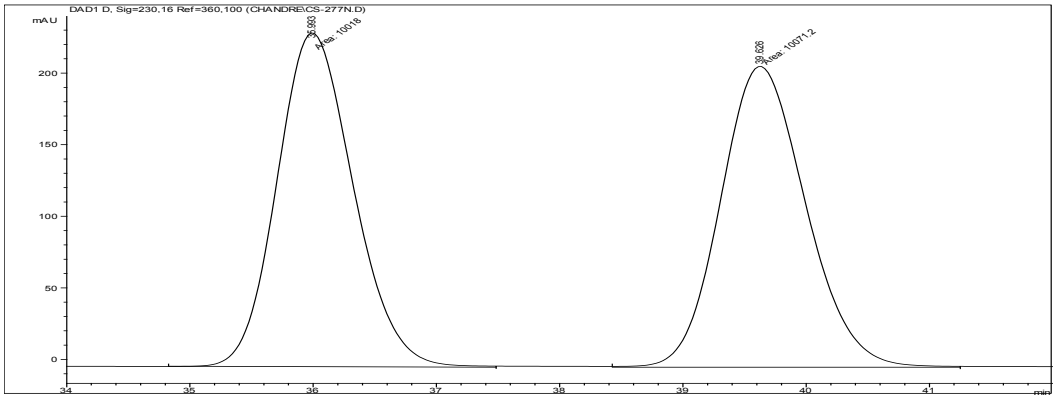
Method B: KOH, MeCN:*t*-BuOH (15:1), (*e.r.* = 58:42), t_R 27.9 min ((*R,R*) major) and 31.2 min ((*S,S*) minor).



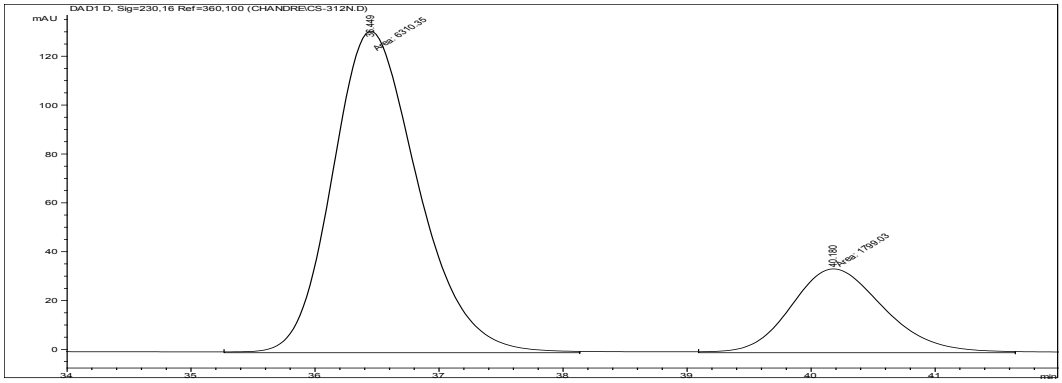
Method C: KOH, MeCN:t-BuOH (1:5), (*e.r.* = 73:27), t_R 27.8 min ((*R,R*) major) and 30.8 min ((*S,S*) minor).



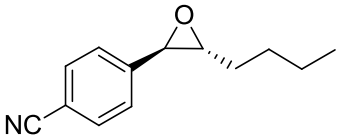
Method D: Racemic Epoxide (IC column with guard, 0.5% *i*PrOH/Hexane, 0.5 mL/min, 20 °C). t_R 36.4 min (*R,R*) and 40.2 min (*S,S*).



Method D: LiHMDS, THF, -78 °C, (*e.r.* = 78:22), t_R 36.4 min ((*R,R*) major) and 40.2 min ((*S,S*) minor).

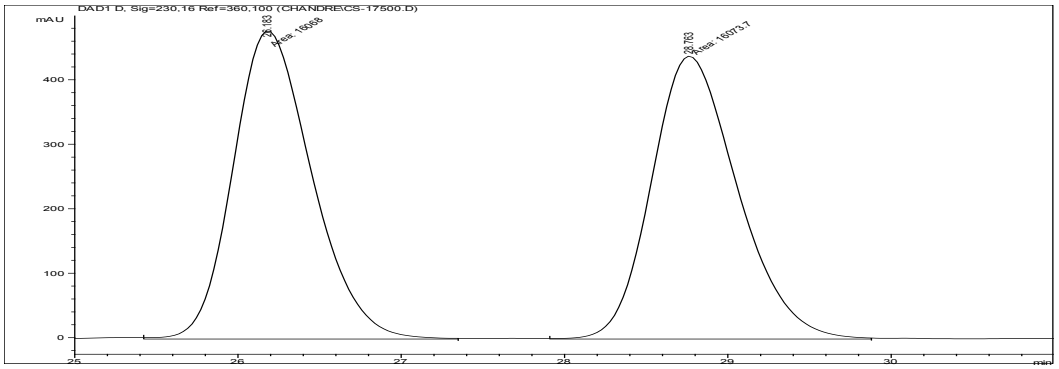


4-((2*R*,3*R*)-3-butyloxiran-2-yl)benzonitrile 25gk from 23g

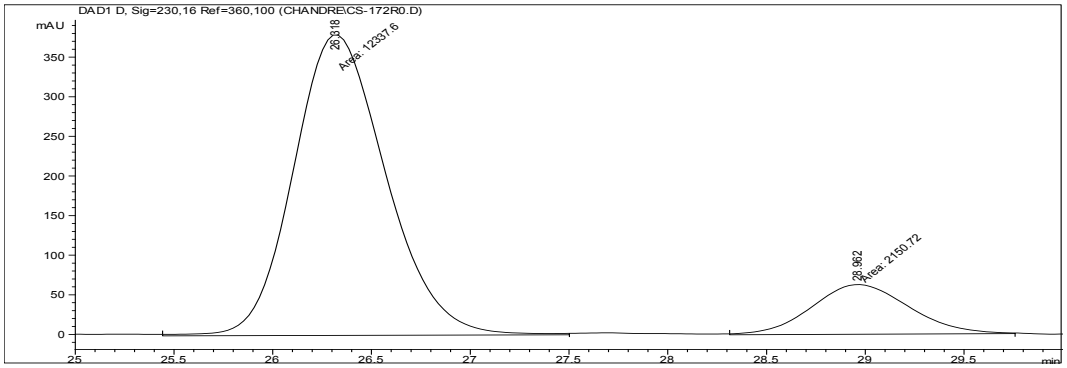


IC column with guard, 0.5% *i*PrOH/Hexane, flow rate: 0.7 mL/min, 20 ºC

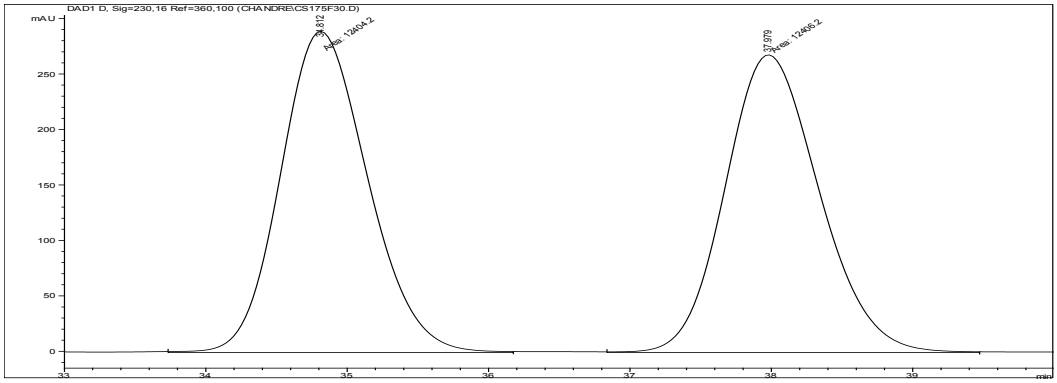
Method C: Racemic Epoxide.



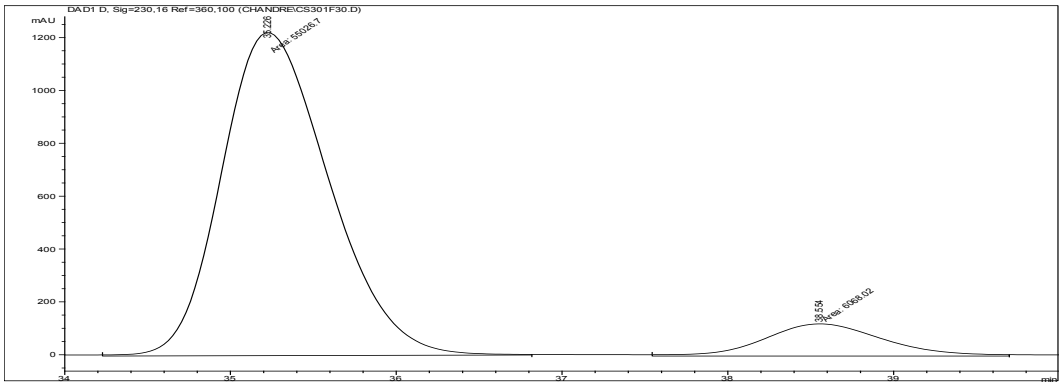
Method C: KOH, MeCN:t-BuOH (1:5), (*e.r.* = 85:15), t_R 26.3 min ((*R,R*) major) and 28.9 min ((*S,S*) minor).



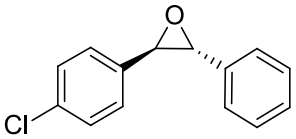
Method D: Racemic Epoxide, IC column with guard, 0.5% *i*PrOH/Hexane, flow rate: 0.5 mL/min, 20 ºC



Method D: LiHMDS, THF, –78 °C, (*e.r.* = 90:10), t_R 35.2 min ((*R,R*) major) and 38.5 min ((*S,S*) minor).

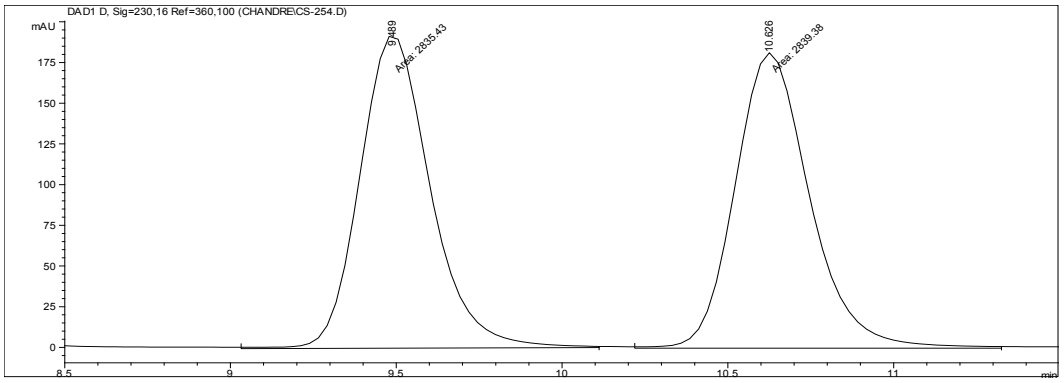


(2*R*,3*R*)-2-(4-chlorophenyl)-3-phenyloxirane 25ha from 23h

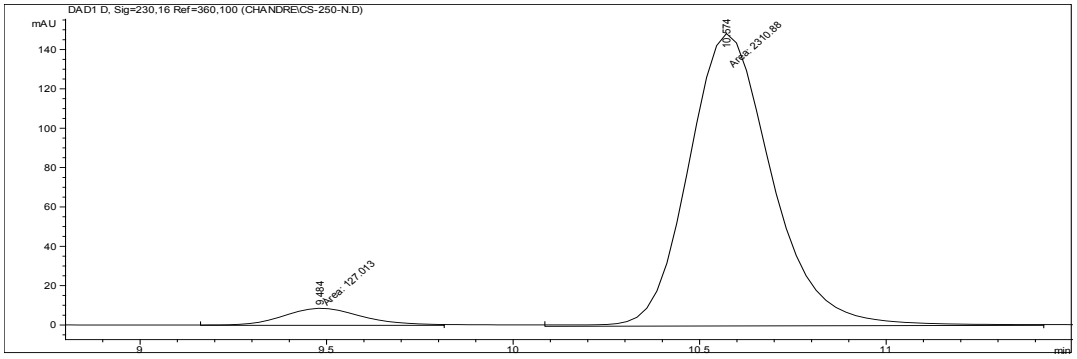


IB column with guard, 2.0% *i*PrOH/Hexane, flow rate: 0.7 mL/min, 20 ºC

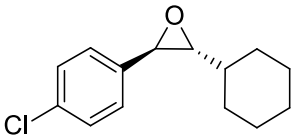
Racemic epoxide:



Method A: (MeOH:H_2O 9:1), (*e.r.* = 95:5), t_R 9.5 min ((*S,S*) minor) and 10.6 min ((*R,R*) major).

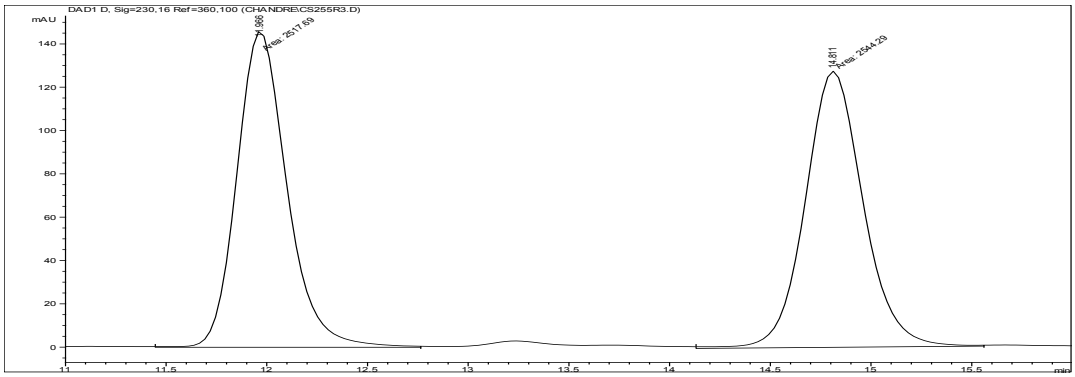


(2*R*,3*R*)-2-(4-chlorophenyl)-3-cyclohexyloxirane 25hj from 23h

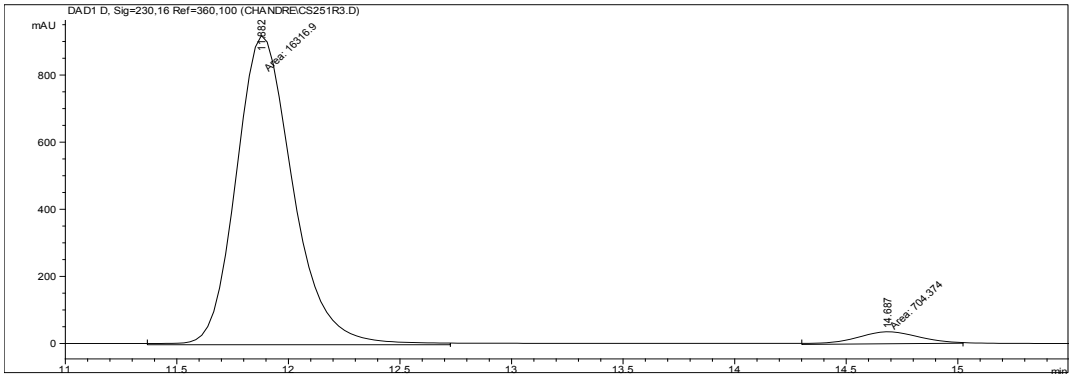


IA column with guard, 0.1% *i*PrOH/Hexane, flow rate: 0.5 mL/min, 20 ºC

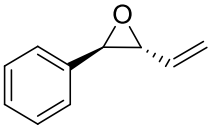
Racemic Epoxide



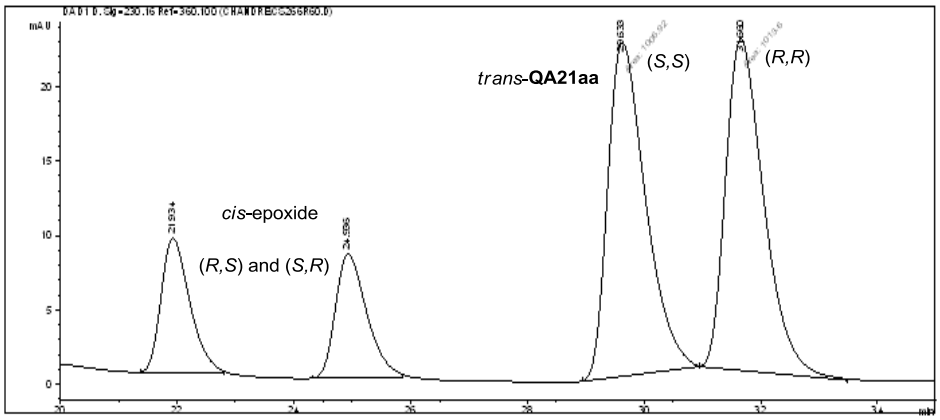
Method B: KOH, MeCN:t-BuOH (15:1), (*e.r.* = 95:5), t_R 11.8 min ((*R,R*) major) and 14.7 min ((*S,S*) minor).



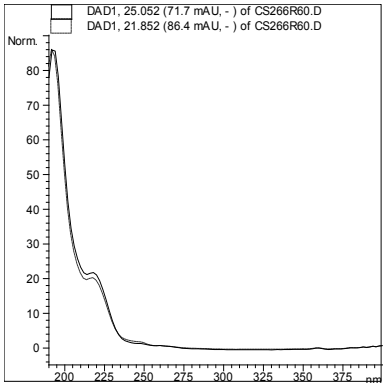
(2*R*,3*R*)-2-Phenyl-3-vinyl-oxirane 27aa from 26a

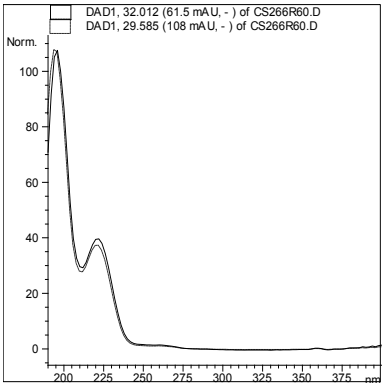


IB column with guard, 0.1% *i*PrOH/Hexane, flow rate: 0.5 mL/min, 20 ºC,
Racemic Epoxide (mixture of two diastereomers)

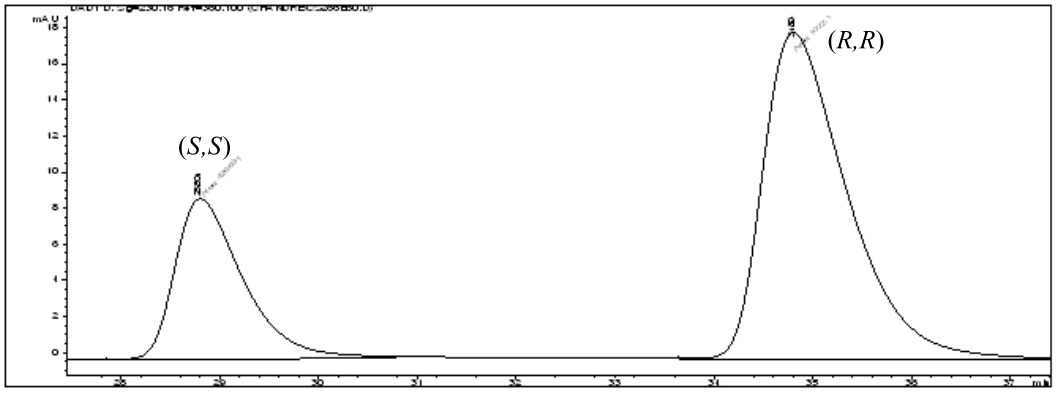


UV traces of the racemic peaks:



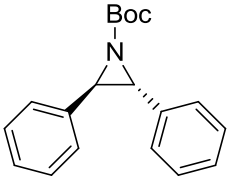


Method A: (MeOH:H_2O 9:1), (*e.r.* = 30:70), t_R 28.9 min ((*S*,*S*) minor) and 34.8 min ((*R*,*R*) major).

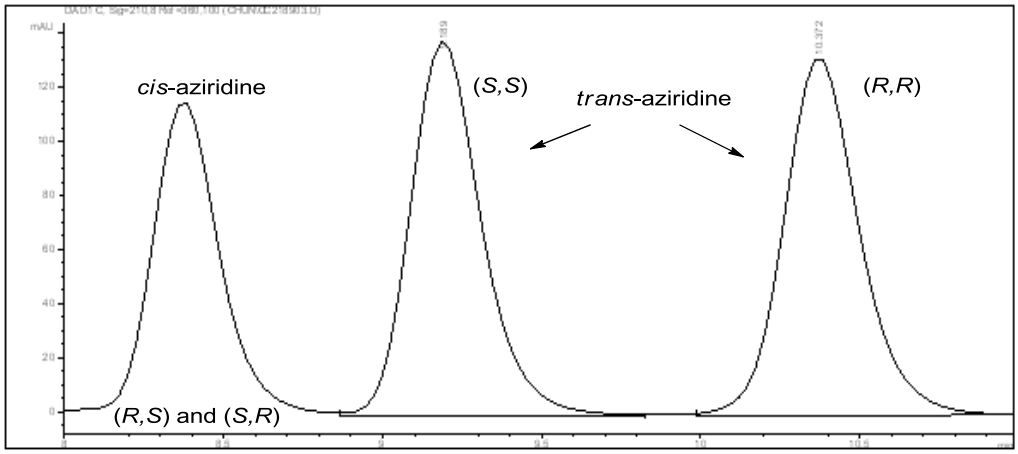


Chiral HPLC data for Aziridines

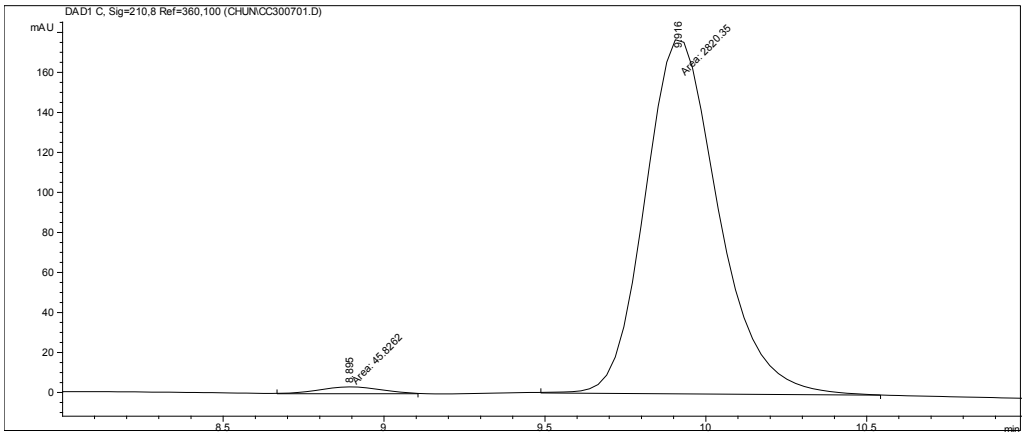
(2*R*,3*R*)-*N*-(*tert*-Butoxycarbonyl)-2,3-diphenylaziridine 29aa from 23a



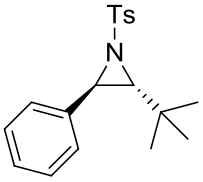
Racemic mixture



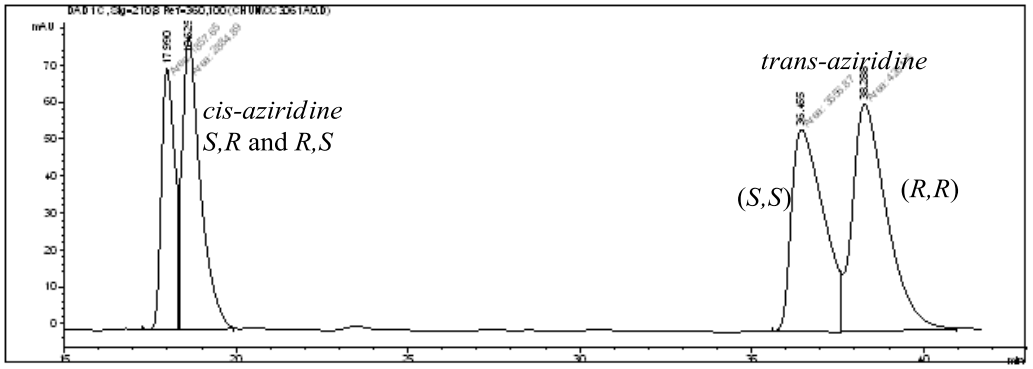
trans-Aziridine: IB column, 1% *i*PrOH/Hexane, 0.7 ml/min, R_t <u>*trans*</u>: 9.91 min ((2*R,3R*), major), 8.89 min ((2*S,3S*), minor), e.r: 98:2



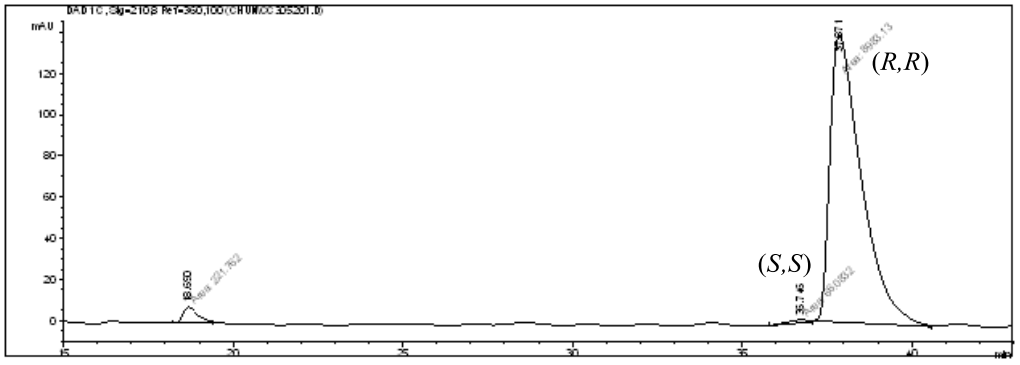
(2*R*,3*R*)-2-(tert-Butyl)-3-phenyl-1-tosylaziridine 28ag from 23a



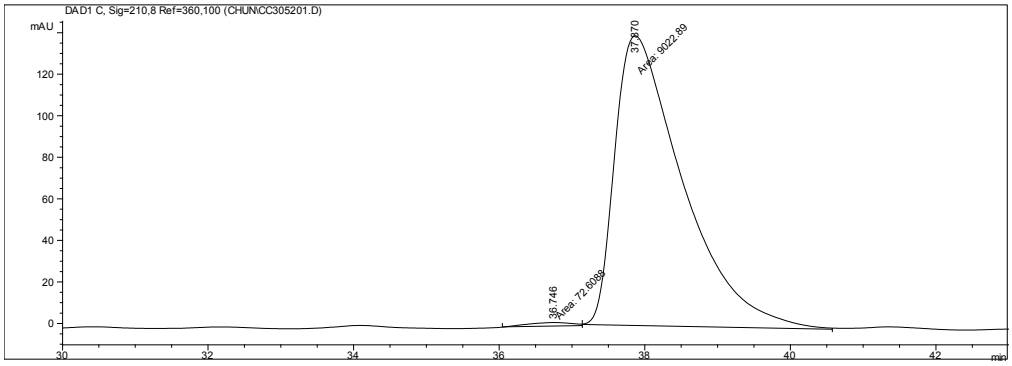
Racemic mixture:



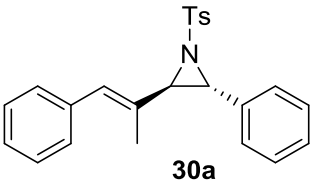
HPLC conditions for *trans*-isomer: IB column, 0.3% *i*PrOH/Hexane, 0.5 ml/min, R_t <u>*trans*</u>: 38.28 min ((2*R,3R*), major), 36.71 min ((2*S,3S*), minor), e.r: >99:1.



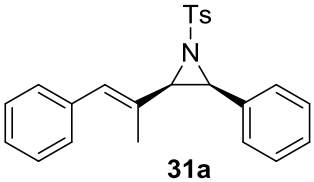
Expanded HPLC for *trans* isomer



(2*R*,3*R*)-(*E*)-2-Phenyl-3-(1-phenylprop-1-en-2-yl)-1-tosylaziridine 30a and (2*S*,3*R*)- (*E*)-2-phenyl-3-(1-phenylprop-1-en-2-yl)-1-tosylaziridine 31a

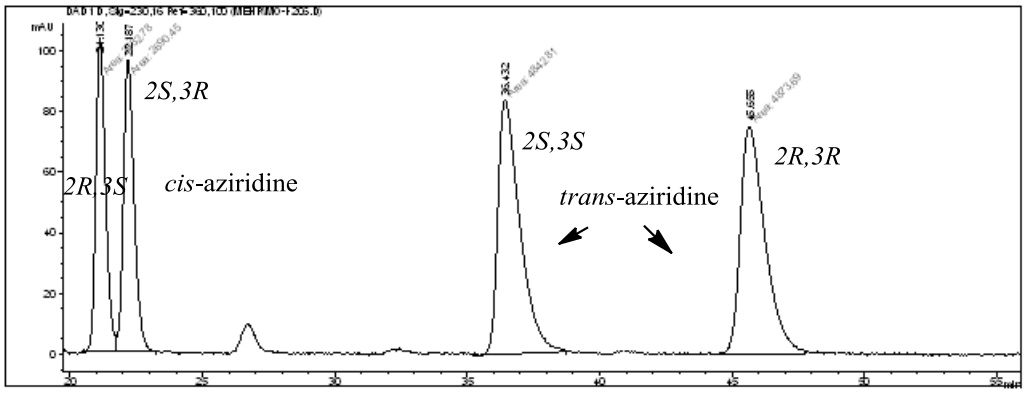


30a

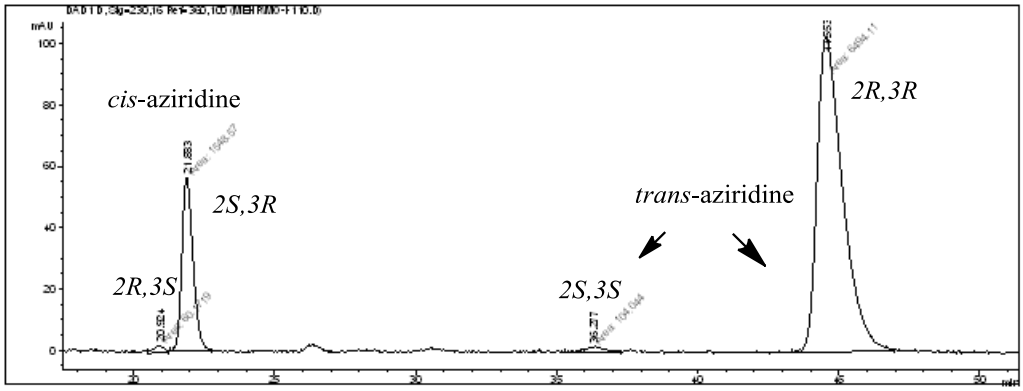


31a

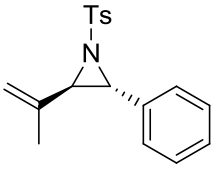
Chiral HPLC-Chromatogram of the crude racemic mixture (separation for *trans* and *cis* isomers); IB column, 1% *i*PrOH/Hexane, 0.7 ml/min.



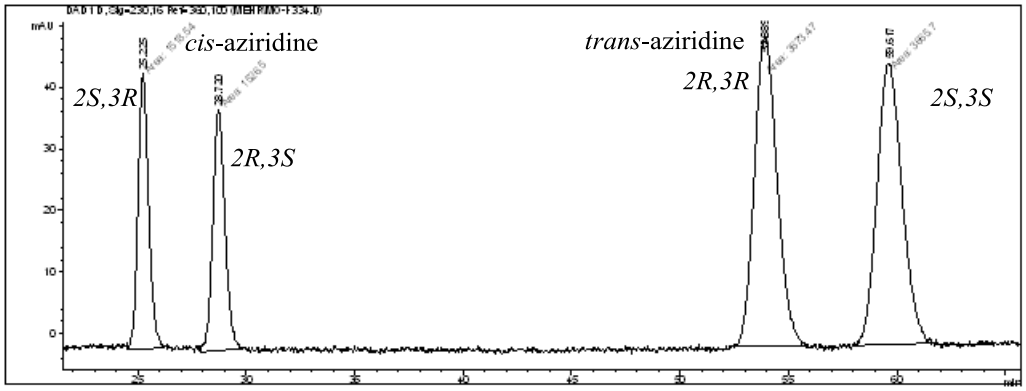
Chiral HPLC-Chromatogram of the crude enantioenriched mixture (*trans* and *cis*), R_t <u>*trans*</u>: 36.42 min ((2*S,3S*), minor), 44.53 min ((2*R,3R*), major), e.r: 99:1. R_t <u>*cis*</u>: 20.88 min ((*2R*,3*S*), minor), 21.89 min ((*2S,3R*), major), e.r: 97:3. (dr 78:22, *trans:cis*)



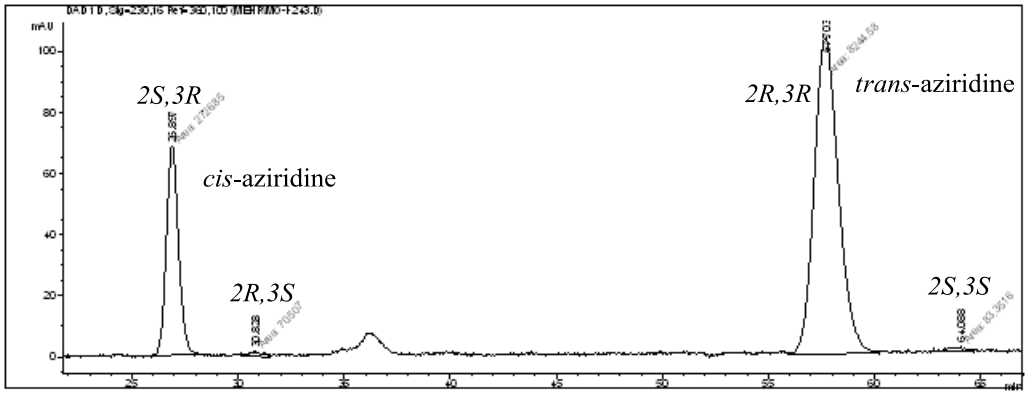
(*2R,3R*)-2-Phenyl-3-(prop-1-en-2-yl)-1-tosyl-aziridine 30b



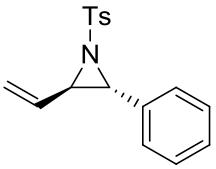
Chiral HPLC- Chromatogram of the crude racemic mixture (Separation for *cis* and *trans* isomers); IC column, 10% *i*PrOH/Hexane, 0.7 ml/min.



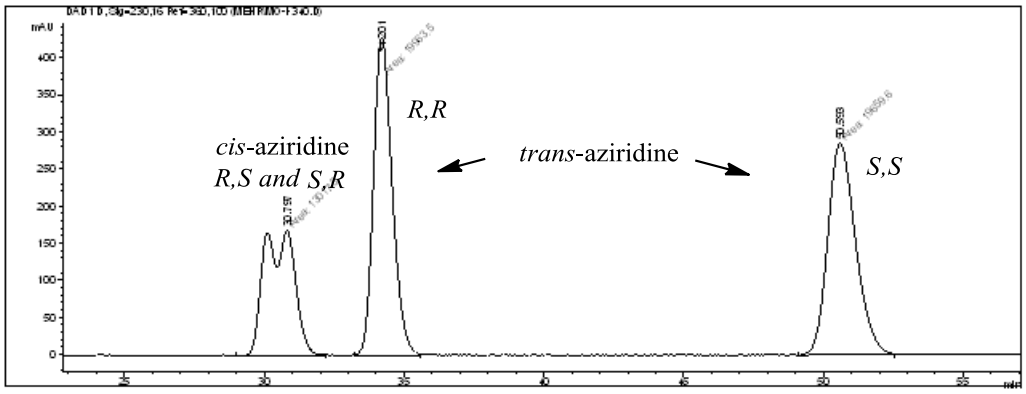
Chiral HPLC- Chromatogram of the crude enantioenriched mixture (*trans* and *cis*), R_t <u>*trans*</u>: 57.70 min ((2*R,3R*), major), 64.08 min ((2*S,3S*), minor), e.r: 99:1. R_t <u>*cis*</u>: 26.89 min ((*2S,*3*R*), major), 30.82 min ((*2R*,3*S*), minor), e.r: >99:1. (dr 83:17, *trans*:*cis*)



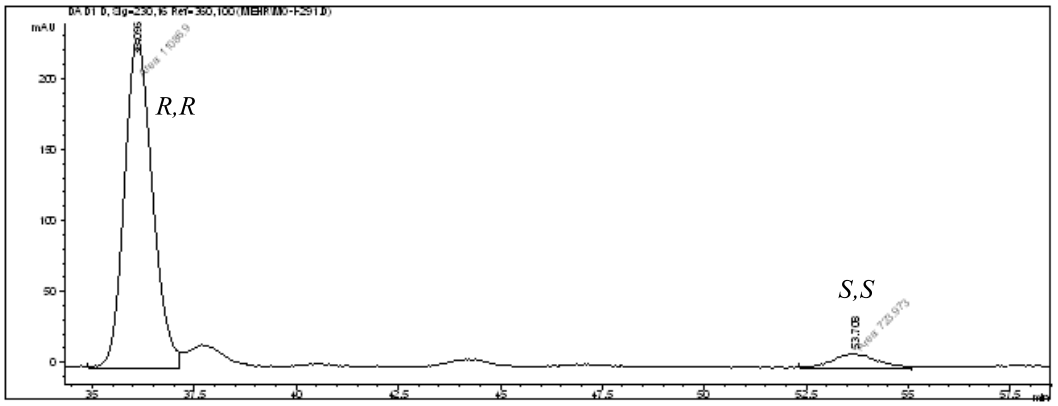
(2*R*,3*R*)-2-Phenyl-1-tosyl-3-vinyl-aziridine 30c



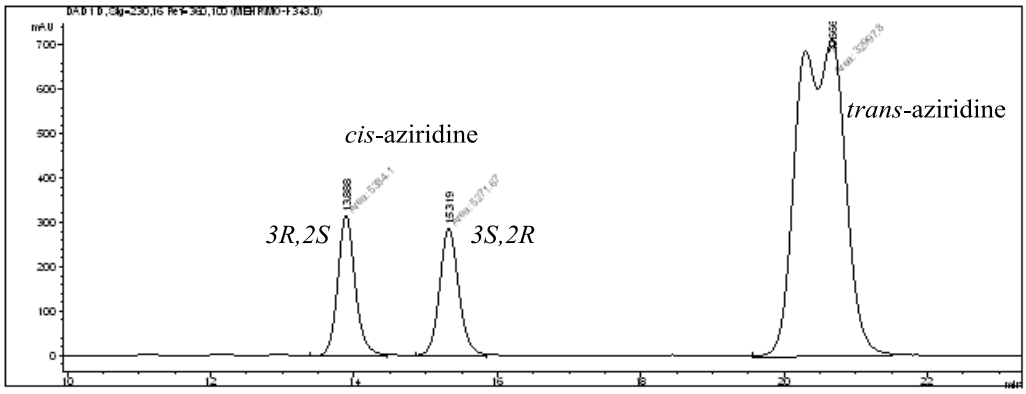
Chiral HPLC-Chromatogram of the crude racemic mixture (Separation for *trans*-isomer); IC column, 10% *i*PrOH/Hexane, 0.7 ml/min.



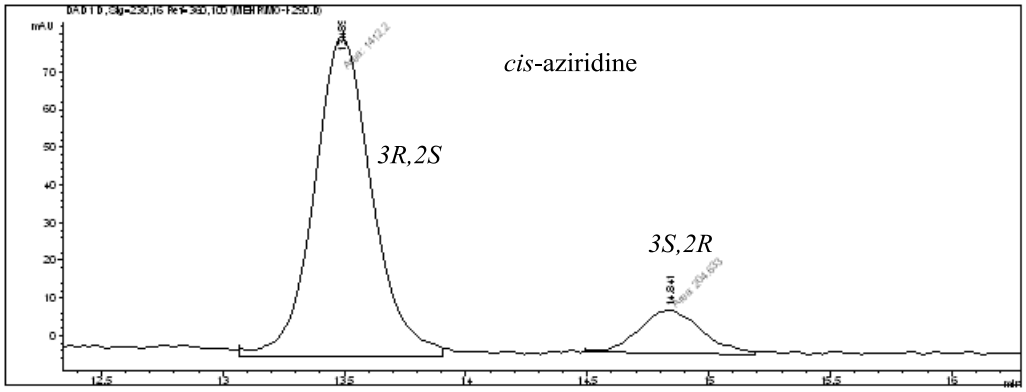
Chiral HPLC-Chromatogram of the crude enantioenriched mixture (separation for *trans* isomer), R_t <u>*trans*</u>: 36.09 min ((2*R,3R*), major), 53.70 min ((2*S,3S*), minor), e.r: 94:6.



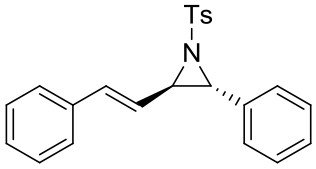
Chiral HPLC-Chromatogram of the crude racemic mixture (Separation for *cis* isomer). IA column, 10% *i*PrOH/Hexane, 0.7 ml/min,



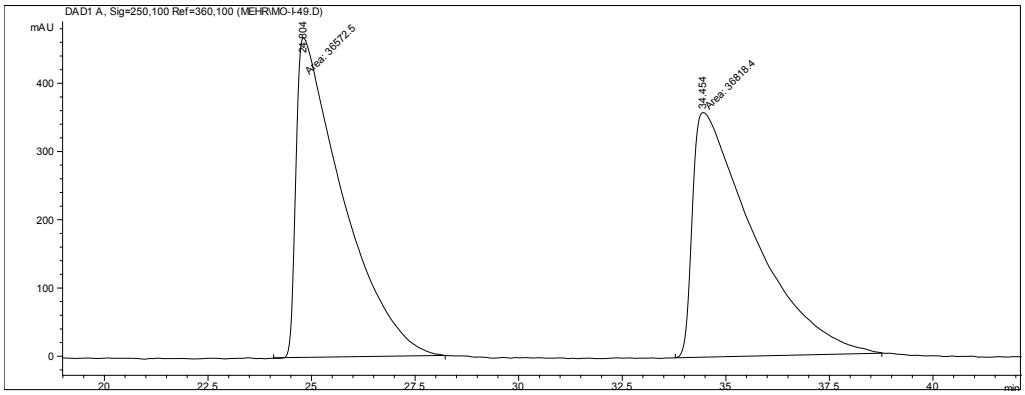
Chiral HPLC-Chromatogram of the crude enantioenriched mixture (separation for *cis* isomer), R_t <u>*cis*</u>: 13.48 min ((3*R,2S*), major), 14.84 min ((*3S,*2*R*), minor), e.r: 85:15.



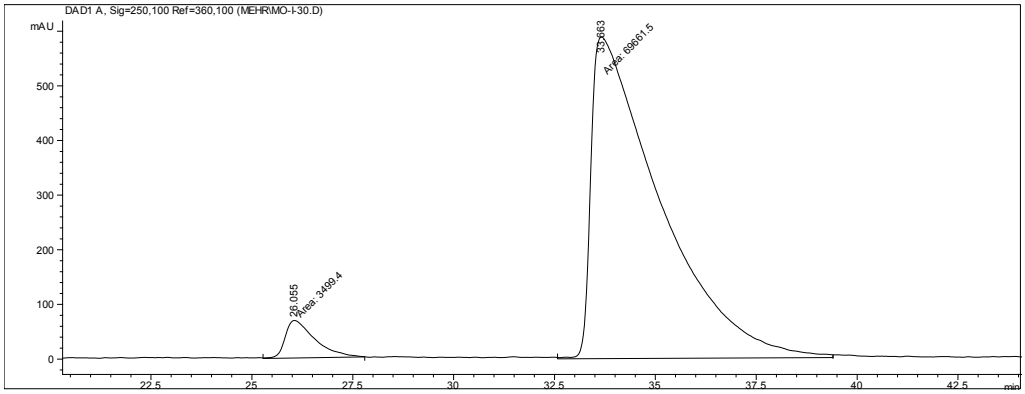
(*2R,3R*)-(*E*)-2-Phenyl-3-styryl-1-tosylaziridine 30d



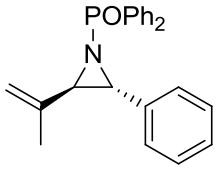
Chiral HPLC-Chromatogram of the pure racemic mixture (*trans* isomer); IB column, 4% *i*PrOH/Hexane, 0.7 ml/min.



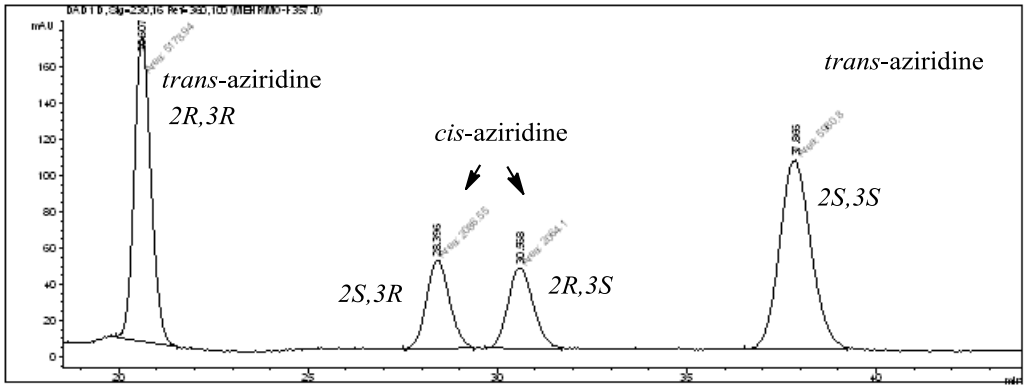
Chiral HPLC-Chromatogram of the pure enantioenriched *trans* isomer, R_t <u>*trans*</u>: 26.05 min ((2*S,3S*), minor), 33.66 min ((2*R,3R*), major), e.r*:* 95:5.



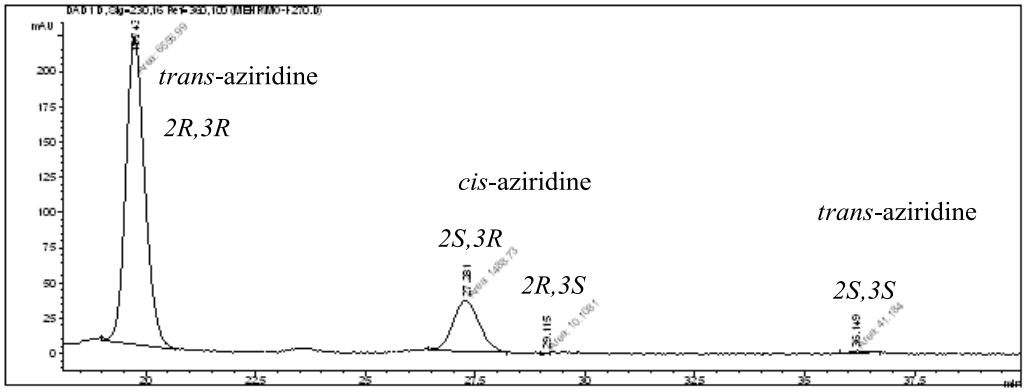
(*2R,3R*)-1-(Diphenyl-phosphinoyl)-2-phenyl-3-(prop-1-en-2-yl)aziridine 32b



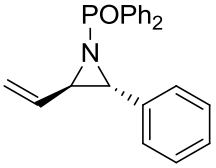
Chiral HPLC-Chromatogram of the crude racemic mixture (separation for *trans* and *cis* isomers). IC column, 10% *i*PrOH/Hexane, 0.7 ml/min.



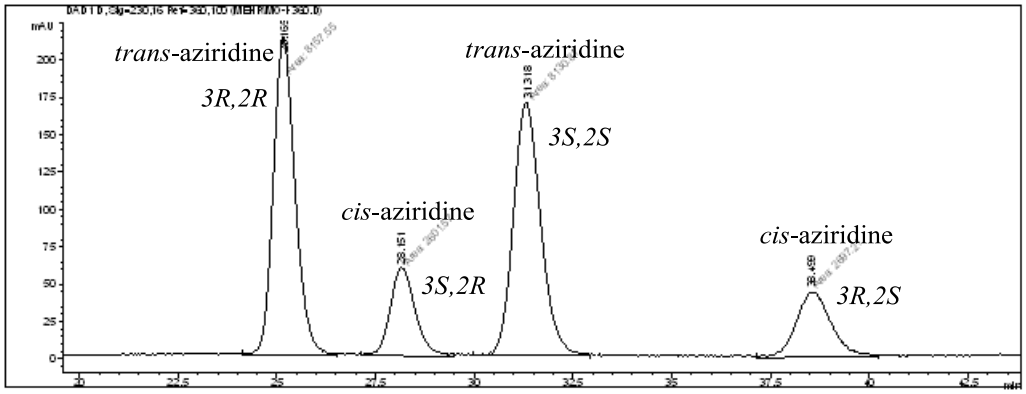
Chiral HPLC-Chromatogram of the crude enantioenriched mixture (*trans* and *cis*), R_t <u>*trans*</u>: 36.14 min ((2*S,3S*), minor), 19.74 min ((2*R,3R*), major), e.r: 99:1. R_t <u>*cis*</u>: 29.11 min ((*2R,3S*), minor), 27.28 min ((*2S*,3*R*), major), e.r: >99:1. (dr 84:16, *trans:cis*)



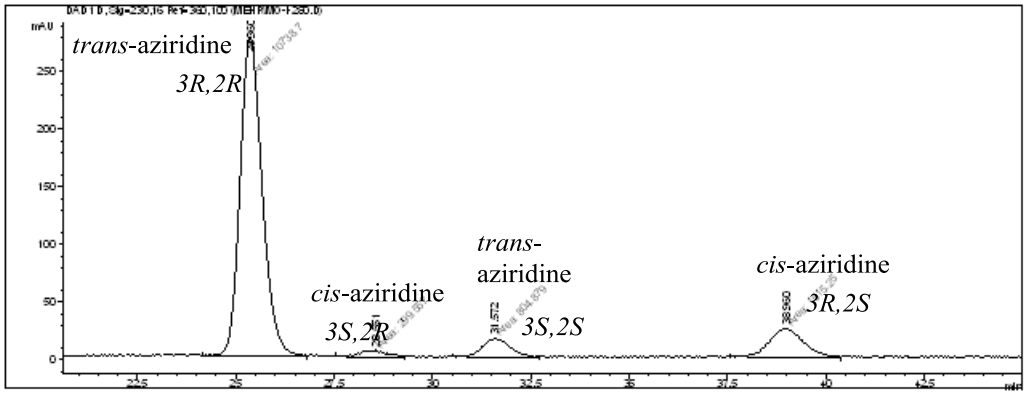
(*2R,3R*)-1-(Diphenyl-phosphinoyl)-2-phenyl-3-vinyl-aziridine 32c



Chiral HPLC-Chromatogram of the crude racemic mixture (separation for *trans* and *cis* isomers). IC column, 10% *i*PrOH/Hexane, 0.7 ml/min.

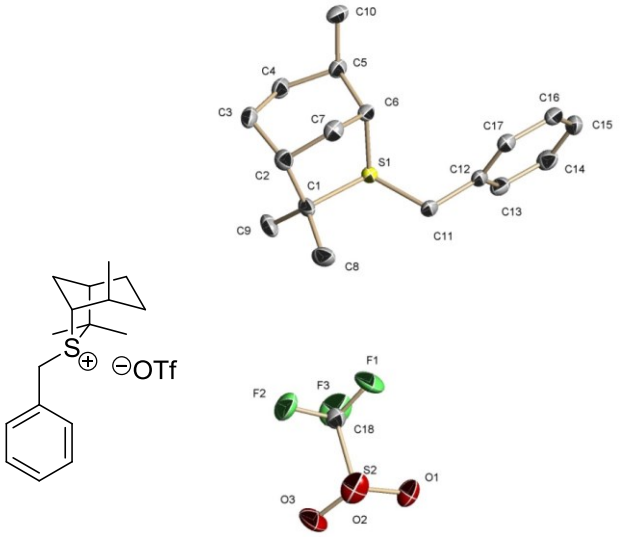


Chiral HPLC-Chromatogram of the crude enantioenriched mixture (*trans* and *cis*), R_t <u>*trans*</u>: 25.36 min ((2*R,3R*), major), 31.57 min ((2*S,3S*), minor), e.r: 91:9. R_t <u>*cis*</u>: 28.55 min ((*3S,* 2*R*), minor), 38.96 min ((*3R,* 2*S*), major), e.r: 90:10. (dr 86:14, *trans:cis*)

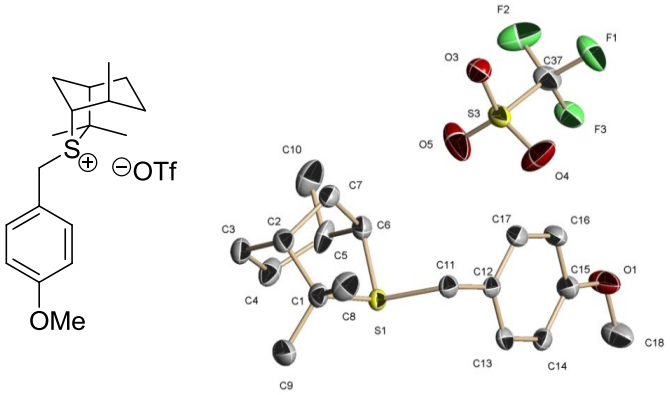


Summary of Crystal Structure data for sulfonium salts

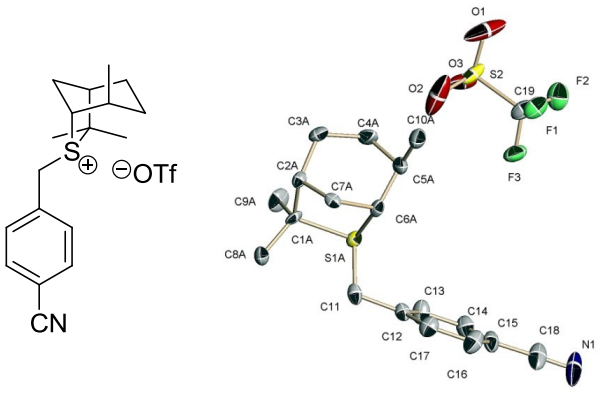
Crystal Structure of Sulfonium Salts 23a, 23c, 23g and Elimination Product 48



23a



23c

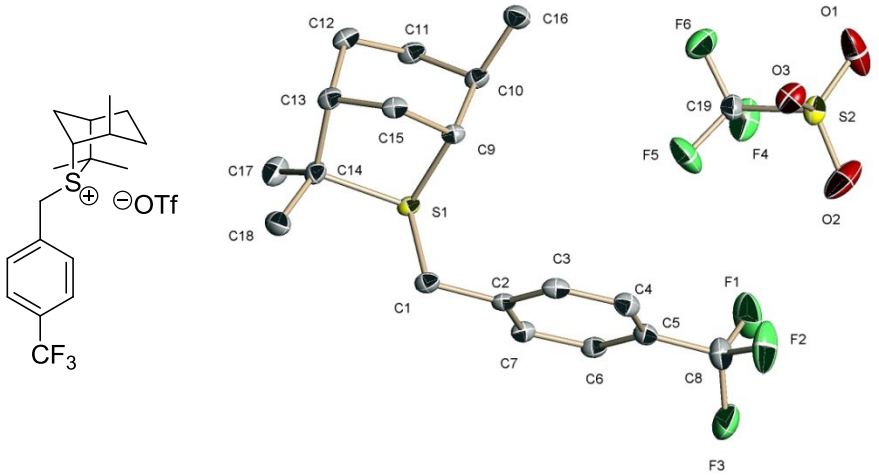


23g

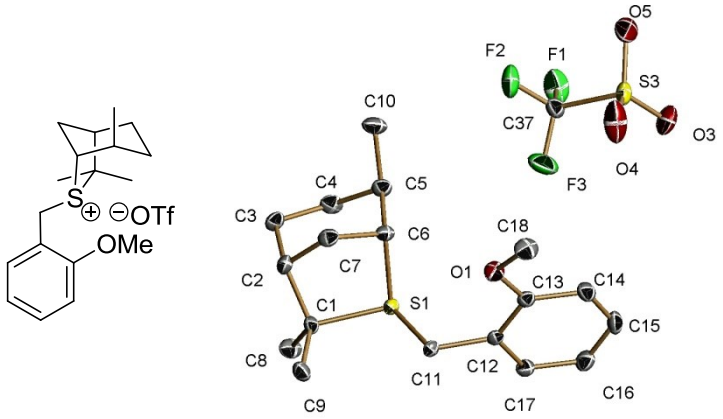
Table 8: X-Ray Structural Data for Sulfonium Salts 23a, 23c, 23g

Compound	**23a**	**23c**	**23g**
Colour, habit	colourless block	colourless plate	colourless rod
Size/mm	0.35×0.35×0.20	0.15×0.15×0.01	0.30×0.12×0.12
Empirical Formula	$C_{18}H_{25}F_3O_3S_2$	$C_{19}H_{27}F_3O_4S_2$	$C_{19}H_{24}F_3NO_3S_2$
M	410.50	440.53	435.51
Crystal system	tetragonal	monoclinic	orthorhombic
Space group	$P4_12_12$	$P2_1$	$P2_12_12_1$
a/Å	8.5336(2)	8.7194(8)	8.1940(14)
b/Å	8.5336(2)	11.8139(10)	10.6676(19)
c/Å	53.044(2)	20.6534(19)	23.526(4)
α/°	90.00	90.00	90.00
β/°	90.00	93.628(6)	90.00
γ/°	90.00	90.00	90.00
V/Å^3	3862.8(2)	2123.2(3)	2056.4(6)
Z	8	4	4
μ/mm^{-1}	0.319	2.708	0.305
T/K	100	100	100
$\theta_{min,max}$	3.32,27.48	4.29,65.22	2.10,27.51
Completeness	0.996 to θ= 27.48°	0.927 to θ= 65.22°	0.999 to θ= 27.51°
Reflections: total/independent	33795/4423	22352/6388	18032/4732
R_{int}	0.0388	0.0556	0.0374
Final $R1$ and $wR2$	0.0360, 0.0967	0.0429, 0.1101	0.0526, 0.1462
Largest peak, hole/eÅ^{-3}	0.292, -0.286	0.367, -0.266	0.914, -0.441
ρ_{calc}/g cm^{-3}	1.412	1.378	1.407
Flack parameter	0.02(7)	0.000(15)	0.08(10)

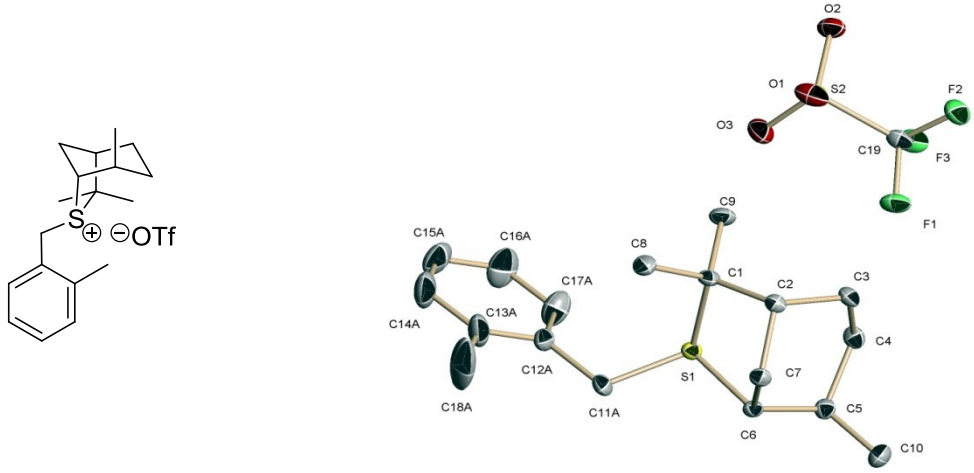
Crystal Structure of Sulfonium Salts 23f, 23b and 23d



23f



23b



23d

Table 9: X-Ray Structural Data for Sulfonium Salts 23f, 23b and 23d

Compound	**23f**	**23b**	**23d**
Colour, habit	colourless block	colourless plate	colourless block
Size/mm	0.51×0.48×0.24	0.35×0.26×0.08	0.48×0.36×0.25
Empirical Formula	$C_{19}H_{24}F_6O_3S_2$	$C_{19}H_{27}F_3O_4S_2$	$C_{19}H_{27}F_3O_3S_2$
M	478.50	440.53	424.53
Crystal system	monoclinic	monoclinic	monoclinic
Space group	$P2_1$	$P2_1$	$P2_1$
a/Å	8.7869(6)	11.1827(5)	6.45560(10)
b/Å	11.7532(9)	11.9964(5)	8.7614(2)
c/Å	11.0410(7)	16.4547(7)	17.6419(4)
α/°	90.00	90.00	90.00
β/°	112.029(4)	107.059(2)	91.0270(10)
γ/°	90.00	90.00	90.00
V/Å^3	1057.01(13)	2110.31(16)	997.67(4)
Z	2	4	2
μ/mm^{-1}	0.322	0.300	0.311
T/K	100	100	100
$\theta_{min,max}$	2.55,27.52	2.55,27.51	3.16,27.58
Completeness	0.996 to θ= 27.52°	0.997 to θ= 27.51°	0.997 to θ= 27.58°
Reflections: total/independent	9691/3855	36279/9587	17625/4620
R_{int}	0.0211	0.0285	0.0274
Final $R1$ and $wR2$	0.0267, 0.0676	0.0266, 0.0664	0.0257, 0.0688
Largest peak, hole/eÅ^{-3}	0.325, -0.231	0.334, -0.274	0.306, -0.270
ρ_{calc}/g cm^{-3}	1.503	1.387	1.413
Flack parameter	0.07(6)	-0.01(3)	-0.05(4)

X-ray diffraction experiments on all compounds except **23c** were carried out at 100K on a Bruker APEX II diffractometer using Mo-K$_\alpha$ radiation (λ = 0.71073 Å). Data collections for **23c** were carried out on a Bruker Microstar rotating anode diffractometer using Cu radiation (λ = 1.54178 Å). All data collections were performed using a CCD area detector from a single crystal mounted on a glass fibre. Intensities were integrated[i] from several series of exposures measuring 0.5° in ω or ϕ. Absorption corrections were based on equivalent reflections using SADABS or TWINABS.[ii] The structures were solved using SHELXS and refined against all F_o^2 data with hydrogen atoms riding in calculated positions using SHELXL.[iii] Crystal structure and refinement data are given in Tables 8 and 9.

[i] (a) Bruker-AXS SAINT V7.68A, Madison, Wisconsin.
[ii] G. M. Sheldrick, SADABS V2008/1 or 2007/2, University of Göttingen, Germany.
[iii] G. M. Sheldrick, *Acta Cryst.* **A64**, 2008, 112-122