Diels–Alder reactions of three fused nitrogen-containing bicyclic enones: an efficient method toward novel nitrogen-containing angular tricyclic skeletons†

Chi-Min Chau* and Kuan-Miao Liu*

Received 21st April 2008, Accepted 4th June 2008
First published as an Advance Article on the web 1st July 2008
DOI: 10.1039/b806773m

The syntheses of three fused bicyclic enones, including 1,2,6,6*a*-tetrahydro-1-tosyl-cyclopenta[*b*]pyrrol-3(5*H*)-one, 1,2,3,6,7,7*a*-hexahydro-4*H*-1-tosyl-cyclopenta[*b*]pyridin-4-one and 1,2,5,6,7,7*a*-hexahydro-3*H*-1-tosyl-indol-3-one, *via* anionic cyclization and Diels–Alder reactions with various dienes to construct novel nitrogen-containing angular tricyclic skeletons are described.

Introduction

1,2,6,6*a*-Tetrahydro-1-tosyl-cyclopenta[*b*]pyrrol-3(5*H*)-one (**7**), 1,2,3,6,7,7*a*-hexahydro-4*H*-1-tosyl-cyclopenta[*b*]pyridin-4-one (**8**) and 1,2,5,6,7,7*a*-hexahydro-3*H*-1-tosyl-indol-3-one (**9**) have unique structures, as shown below, and are suggested synthetically versatile and potential intermediates. They can be further functionalized *via* different organic methods and subsequently used in the construction of core skeletons or total syntheses of some natural products (Fig. 1). The synthetic utility of 1,2,5,6,7,7*a*-hexahydro-3*H*-indol-3-one had been demonstrated in the total synthesis of (−)-brunsvigine[1] and (±)-lentiginosine,[2] wherein S_N2 alkylation and oxidative cleavage were used as the key steps, respectively. Here, we continued to exploit their potential synthetic applications, and have found that the enone moieties of these three compounds undergo Diels–Alder cycloadditions with various dienes to afford novel nitrogen-containing angular tricyclic skeletons in high yields.

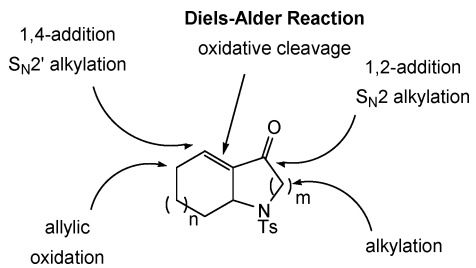
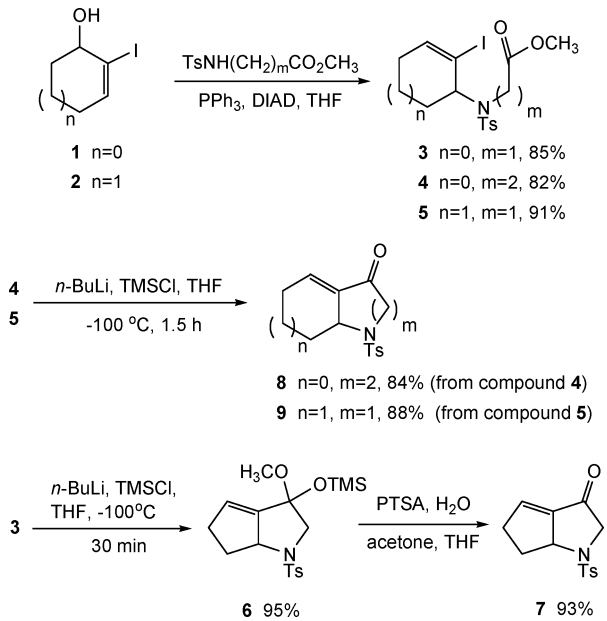


Fig. 1 The structures and synthetic versatility of enones **7**, **8** and **9**.

These three compounds, which have a common and unique enone moiety across two adjacent rings, were prepared according to a modified approach, shown in Scheme 1.[3] In general, the vinyl iodides with ester functionalities were treated with *n*-BuLi, and the resulting vinyl lithium initiated the intramolecular anionic cyclization reaction to furnish the desired enone compounds. In the preparation of 1,2,6,6*a*-tetrahydro-1-tosyl-cyclopenta[*b*]pyrrol-3(5*H*)-one **7**, the acetal **6** was isolated as a stable compound, and compound **7** could later be obtained when treated with an acidic solution.



Scheme 1 Synthetic process of enones **7**, **8** and **9**.

Because of their special fused cyclic enone structures, we examined their dienophilicity by treating them with various dienes. The Diels–Alder cycloadducts possess novel nitrogen-containing angular tricyclic skeletons, which could be important intermediates toward some natural products, are not easy to obtain by other methods. Several efforts, including Michael addition and the subsequent direct alkylation of the resulting enolate or alkylation of the corresponding silyl enone ether, had been carried out to introduce an alkyl chain at the bridgehead position of compound **9**; however, all these methods were unsuccessful. Thus the development of an efficient method or stategy to construct the desired tricyclic structures or to introduce an alkyl chain at the bridgehead position is the target of this work.

School of Applied Chemistry, Chung Shan Medical University, Taichung, 40201, Taiwan, ROC. E-mail: cmchau@csmu.edu.tw, lkm@csmu.edu.tw

† Electronic supplementary information (ESI) available: ^1H and ^{13}C NMR spectroscopic and analytical data of all the compounds in Table 1 and Schemes 1 and 2. CCDC reference numbers 678651–678653. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/b806773m

Results and discussion

To study the Diels–Alder reactions of these three fused cyclic enones, the treatment of 1,2,5,6,7,7*a*-hexahydro-3*H*-1-tosyl-indol-3-one **9** with 2,3-dimethyl-1,3-butadiene **15** in xylene in a sealed tube at 180 °C was carried out as a model reaction. The cycloadduct was obtained successfully in 75% yield, but this method became inconvenient and dangerous when the dienes had low boiling points. In order to perform the reaction under milder conditions, we opted for the Lewis acid catalysed method, which had been used in many other Diels–Alder reactions.[4] First, we used $SnCl_4$ as the catalyst and carried out the Diels–Alder reaction of compound **9** with 2,3-dimethyl-1,3-butadiene in CH_2Cl_2 at 0 °C. The reaction was completed within 30 min, and the yield of the adduct was 86%, which is better than that of the thermal adduct. However, in the cases of 2-methyl-1,3-pentadiene and 1,3-pentadiene, the yields of the products were very poor, and almost all the starting enone was recovered. The substitution of $SnCl_4$ with $BF_3{\cdot}OEt_2$ improved the yields dramatically and also yielded favourable results in the other cases. The results are summarized in Table 1. In addition, nonsubstituted furan and *N*-methyl pyrrole, which were not considered to be good dienes as compared with cyclopentadiene,[5] but were good nucleophiles towards enone systems,[6] were also subjected to the Diels–Alder reaction in the presence of $BF_3{\cdot}OEt_2$. The reaction results were consistent with our expectations in that the 1,4-addition products were predominantly formed. However, the reaction of **7** with furan furnished the Diels–Alder adduct **39** as the sole compound. In addition, the stereochemistry of **39**, which was identified as *endo* by nuclear overhauser effect experiments,[7] differed from that of **36**, which was the product of the reaction of compound **7** with cyclopentadiene, and its stereostructure was confirmed as *exo* by X-ray analysis, as shown in the ESI.† The exact reason for the difference in the diastereoselectivity was not entirely clear. We attempted to illustrate the *exo*-diastereoselectivity of the reaction of enone **7** with cyclopentadiene, as shown in Fig. 2. The diene approached from the less-hindered face, the convex face, of the fused bicyclic enone; thus, the relative stereochemistry of H_1 and the newly formed bonds in the cycloadduct must be *cis*.

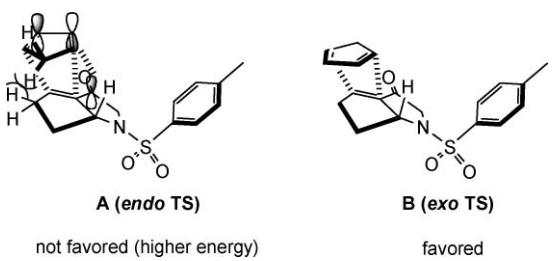
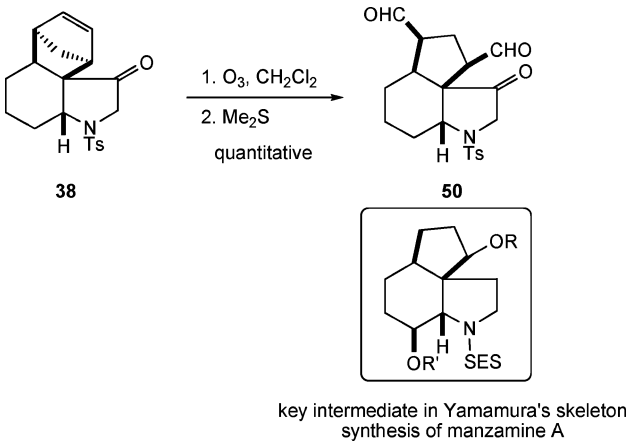


Fig. 2 Proposed transition state illustration of *exo*-diastereoselectivity of the Diels–Alder reaction of enone **7** with cyclopentadiene.

Furthermore, the *exo* preference may be attributed to a secondary orbital interaction between the carbonyl group of the fused bicyclic enone and the approached diene, which was not strong enough because the π orbital alignments were not good for competing with the repulsive interaction between the methylene of the diene with the other parts of the enone in the *endo* transition state. Consequently, the repulsive steric effect was the dominant feature that determined the conformation of the cycloadduct, and the *exo* product was obtained due to its lower energy transition state as compared with that of the *endo* product.

In order to illustrate the synthetic utility of this reaction, we further cleaved the double bond of compound **38** to obtain another tricyclic skeleton **50**, which is similar to the key intermediate in Yamamura *et al.*'s skeleton synthesis of manzamine A[8] (Scheme 2). Furthermore, we believed that compounds **36** and **37** could also be converted into two new structures. In addition to the carbon-based Diels–Alder reaction, the aza-Diels–Alder reaction, where nitrogen-containing dienes are used, will be our future subject of study.



Scheme 2 One of the synthetic potentials of the Diels–Alder reaction methodology presented in this study.

Conclusions

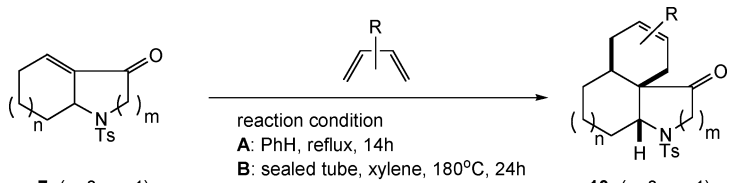
In conclusion, we have used the well known Lewis acid-catalysed Diels–Alder reaction to achieve novel nitrogen-containing angular tricyclic skeletons, which are not easily obtained by other methods. It is a synthetically valuable method to establish a third 6- or 5-membered ring from the structurally unique fused bicyclic enones. The application of this strategy to construct core skeletons of natural products, for example, the tricyclic core skeleton of manzamine A, is currently in progress.

Experimental

General experimental

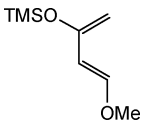
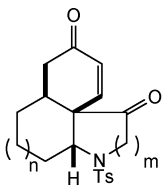
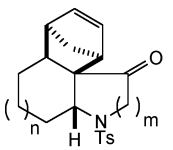
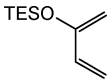
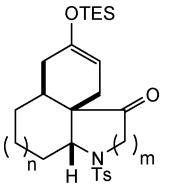
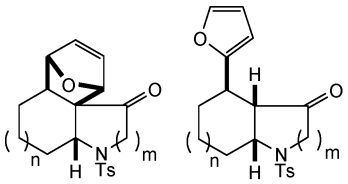
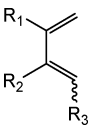
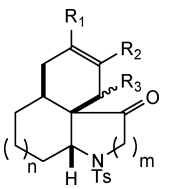
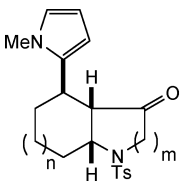
Reactions were carried out in oven and flame-dried glassware under a positive pressure of argon. THF was distilled over sodium–benzophenone. Dichloromethane and xylene were distilled over calcium hydride. Cyclopentadiene was distilled before use. All reagents were purchased commercially and used without further purification. TLC was performed on Merck 5735 DC-plastikfolien Kieselgel 60 F254 precoated plates. Flash column chromatography was performed with silica gel Merck 7736 Kieselgel 60H. ^{1}H-NMR (7.24 ppm for $CDCl_3$ as internal standard) and ^{13}C-NMR (77.0 ppm for $CDCl_3$ as internal standard) spectra were recorded on Varian Unity-400 MHz instrument. Coupling constants are measured in Hertz. IR spectra were recorded from a Bomen

Table 1 Diels–Alder reactions of enones **7**, **8** and **9** with various dienes



7 (n=0, m=1)
8 (n=0, m=2)
9 (n=1, m=1)

10 (n=0, m=1)
11 (n=0, m=2)
12 (n=1, m=1)

Diene	Reaction conditions	Product[a]/yield	Diene	Reaction conditions	Product[a]/yield
 **13**	A	 **22** (n=1, m=1, 70%)	 **19**	C	 **36** (n=0, m=1, 93%) **37** (n=0, m=2, 91%) **38** (n=1, m=1, 95%)
 **14**	B	 **23** (n=1, m=1, 72%)	 **20**	C	 **39** (n=0, m=1, 88%) **40** (n=0, m=2, 40%) **41** (n=1, m=1, 85%)
 **15** $R_1 = R_2 = CH_3$, $R_3 = H$ **16** $R_1 = CH_3$, $R_2 = R_3 = H$ **17** $R_1 = R_3 = CH_3$, $R_2 = H$ **18** $R_3 = CH_3$, $R_1 = R_2$ H	C	 **24** $R_1 = R_2 = CH_3$, $R_3 = H$ ($n = 0$, $m = 1$, 89%) **25** ($n = 0$, $m = 2$, 86%) **26** ($n = 1$, $m = 1$, 90%) **27** $R_1 = CH_3$, $R_2 = R_3 = H$ ($n = 0$, $m = 1$, 90%) **28** ($n = 0$, $m = 2$, 88%) **29** ($n = 1$, $m = 1$, 86%) **30a**[b] + **30b**[c] $R_1 = R_3 = CH_3$, $R_2 = H$ ($n = 0$, $m = 1$, 67% + 8%) **31a**[b] + **31b**[c] ($n = 0$, $m = 2$, 62% + 8%) **32a**[b] + **32b**[c] ($n = 1$, $m = 1$, 70%[e]) **33a**[b] + **33b**[c] $R_3 = CH_3$, $R_1 = R_2 = H$ ($n = 0$, $m = 1$, 66% + 8%) **34a**[b] + **34b**[c] ($n = 0$, $m = 2$, 66%[d]) **35a**[b] + **35b**[c] ($n = 1$, $m = 1$, 68%[d])	 **21**	C	 **42** (n=0, m=1, 88%) **43** (n=0, m=2, 89%) **44** (n=1, m=1, 90%)

[a] All the products are racemates. [b] R_3 is *trans* to the hydrogen at the bridgehead. [c] R_3 is *cis* to the hydrogen at the bridgehead. [d] Total yield of the inseparable mixture.

MB-100FT spectrometer. Melting points were recorded on a Buchi 530 melting point apparatus and are not corrected. HRMS data were obtained from a FOEL JMS-HX110 spectrometer. Single crystal X-ray analysis was performed on a Siemens Smart CCD diffractometer.

Methyl 3-(*N*-(2-iodocyclopent-2-enyl)-*N*-tosylamino) propanoate (4). To a solution of compound **1** (55.0 mg, 0.26 mmol) in THF (8 mL) was added triphenyl phosphine (89.4 mg, 0.34 mmol) and methyl 3-(tosylamino) propanoate (87.6 mg, 0.34 mmol). After all solid was dissolved completely, DIAD (67 μL, 0.34 mmol)

was added slowly to the mixture at 0 °C. The reaction mixture was stirred for an additional 1 hour at room temperature (25 °C) followed by removal of the solvent. Purification by flash column chromatography (ethyl acetate–hexane 1 : 15) afforded compound **4** as a pale yellow solid (96.5 mg, 82%).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.70 (d, $J = 8.6$ Hz, 2H), 7.27 (d, $J = 8.6$ Hz, 2H), 6.30 (brs, 1H), 4.93–4.87 (m, 1H), 3.62 (s, 3H), 3.35–3.25 (m, 1H), 2.99–2.75 (m, 3H), 2.38 (s, 3H), 2.36–2.29 (m, 1H), 2.26–2.16 (m, 1H), 2.09–1.97 (m, 1H), 1.45–1.35 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.0 (C), 145.0 (CH), 143.5 (C), 136.6 (C), 129.6 (CH), 127.5 (CH), 95.4 (C), 71.1 (CH), 51.6 (CH_3), 39.5 (CH_2), 36.1 (CH_2), 33.5 (CH_2), 26.1 (CH_2), 21.5 (CH_3); IR (neat) 2977, 2938, 1755, 1739, 1343 cm^{-1}; MS (EI) m/z 449 (M^+, 21), 322 (65), 263 (48), 108 (100), 51 (40); HRMS (EI) m/z calcd for $C_{16}H_{20}INO_4S$ 449.0158, found 449.0157; mp 159.1–160.5 °C.

1,2,3,5,6,6*a*-Hexahydro-3-methoxy-1-tosyl-3-(trimethylsilyloxy)-cyclopenta[*b*]pyrrole (6). To a stirred solution of substrate **3** (655 mg, 1.51 mmol) in dry THF (10 mL) at −100 °C was added TMSCl (0.38 mL, 3.01 mmol). A solution of *n*-BuLi in *n*-hexane (2.0 M, 1.51 mL, 3.01 mmol) was slowly added at −100 °C, and the reaction mixture was maintained at −100 °C for 30 min. The cooling bath was removed and the reaction mixture was quenched at 0 °C with a solution of NH_4Cl (saturated, 5 mL) and ether (10 mL) and HCl (2 N, 5 mL). The mixture was extracted with ether (10 mL × 4). The organic layer was washed with brine (10 mL) and dried over $MgSO_4$. Removal of solvent followed by flash column chromatography (ethyl acetate–hexane 1 : 25) afforded pure compound **6** as a pale yellow solid (545 mg, 95%).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.71 (d, $J = 8.0$ Hz, 2H), 7.27 (d, $J = 8.0$ Hz, 2H), 5.78 (dd, $J = 5.2$, 2.0 Hz, 1H), 4.36–4.29 (m, 1H), 3.65 (AB, $J = 10.4$ Hz, 1H), 3.59 (AB, $J = 10.4$ Hz, 1H), 3.24 (s, 3H), 2.54–2.42 (m, 3H), 2.38 (s, 3H), 2.06–1.93 (m, 1H), −0.21 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 146.1 (C), 143.2 (C), 134.6 (C), 129.4 (CH), 127.9 (CH), 125.8 (CH), 98.4 (C), 68.3 (CH), 63.1 (CH_2), 51.0 (CH_3), 35.6 (CH_2), 34.9 (CH_2), 21.4 (CH_3), 0.56 (CH_3); IR (neat) 2981, 2936, 1349, 1163 cm^{-1}; MS (EI) m/z 381 (M^+, 6), 226 (100), 195 (45), 122 (21); HRMS (EI) m/z calcd for $C_{18}H_{27}NO_4SSi$ 381.1430, found 381.1427; mp 157.5–158.3 °C.

1,2,6,6*a*-Tetrahydro-1-tosyl-cyclopenta[*b*]pyrrol-3(5*H*)-one (7). To a solution of compound **6** (292 mg, 0.77 mmol) in THF (10 mL) was added a solution of acetone (5 mL) and water (5 mL) at 0 °C. *p*TSA (39.5 mg, 0.23 mmol) was then added and the reaction mixture was stirred for 1 hour. The reaction mixture was quenched with water (3 mL) and extracted with ether (10 mL × 4). The organic layer was washed with brine (10 mL) and dried over $MgSO_4$. Concentration and silica gel column chromatography (ethyl acetate–hexane 1 : 5) gave compound **7** as a white solid (197 mg, 93%).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.70 (d, $J = 8.4$ Hz, 2H), 7.36 (d, $J = 8.4$ Hz, 2H), 6.70 (dd, $J = 6.0$, 2.8 Hz, 1H), 4.40–4.33 (m, 1H), 4.03 (AB, $J = 16.8$ Hz, 1H), 3.52 (AB, $J = 16.8$ Hz, 1H), 2.85–2.78 (m, 2H), 2.70–2.62 (m, 1H), 2.43 (s, 3H), 2.41–2.25 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 191.1 (C), 144.5 (C), 143.1 (C), 139.6 (CH), 131.4 (C), 129.9 (CH), 128.3 (CH), 68.0 (CH), 61.0 (CH_2), 37.4 (CH_2), 36.7 (CH_2), 21.5 (CH_3); IR (neat) 2975, 2880, 1705, 1661 cm^{-1}; MS (EI) m/z 277 (M^+, 2), 122 (89), 65 (100); HRMS (EI) m/z calcd for $C_{14}H_{15}NO_3S$ 277.0773, found 277.0770; mp 165.3–166.2 °C.

1,2,3,6,7,7*a*-Hexahydro-4*H*-1-tosyl-cyclopenta[*b*]pyridin-4-one (8). To a stirred solution of substrate **4** (801 mg, 1.78 mol) in dry THF (15 mL) at −100 °C was added TMSCl (0.57 mL, 4.46 mmol). A solution of *n*-BuLi in *n*-hexane (2.0 M, 1.80 mL, 3.57 mmol) was slowly added at −100 °C, and the reaction mixture was maintained at −100 °C for 30 min. The cooling bath was removed and the reaction mixture was quenched at 0 °C with a solution of NH_4Cl (saturated, 8 mL) and ether (10 mL) and HCl (2 N, 5 mL). The mixture was extracted with ether (15 mL × 4). The organic layer was washed with brine (20 mL) and dried over $MgSO_4$. Removal of solvent followed by flash column chromatography (ethyl acetate–hexane 1 : 3) afforded pure compound **8** as a pale yellow solid (436 mg, 84%).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.70 (d, $J = 8.0$ Hz, 2H), 7.31 (d, $J = 8.0$ Hz, 2H), 6.82 (dd, $J = 5.4$, 2.4 Hz, 1H), 4.39–4.32 (m, 1H), 3.59–3.53 (m, 2H), 2.69 (dt, $J = 13.2$, 6.4 Hz, 1H), 2.56–2.44 (m, 1H), 2.40 (s, 3H), 2.39–2.28 (m, 2H), 2.20–2.02 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 194.2 (C), 143.7 (C), 142.7 (CH), 139.0 (C), 134.8 (C), 129.8 (CH), 127.1 (CH), 62.0 (CH), 43.0 (CH_2), 38.8 (CH_2), 35.9 (CH_2), 30.2 (CH_2), 21.2 (CH_3); IR (neat) 2977, 2880, 1707, 1664 cm^{-1}; MS (EI) m/z 291 (M^+, 36), 136 (65), 122 (54), 79 (100); HRMS (EI) m/z calcd for $C_{15}H_{17}NO_3S$ 291.0929, found 291.0925; mp 164.3–164.9 °C.

3-Tosyl-2,3,3*a*,4,5,6,6*a*,7-octahydro-3-aza-cyclopenta[*d*]naphthalene-1,8-dione (22). To a solution of compound **9** (65.0 mg, 0.42 mmol) in toluene (8 mL) was added Danishefsky diene (290 mg, 1.69 mmol). The mixture was refluxed under Ar for 14 hours. After cooling to room temperature, 6 N HCl (1 mL) was added, and the mixture was stirred for an additional 1 hour. Addition of water (2 mL) and ether (2 mL) were followed by extraction with ether (5 mL × 4). The combined organic layer was washed with saturated $NaHCO_3$ (5 mL) and brine (5 mL) and dried over $MgSO_4$. After filtration and concentration, purification by flash column chromatography (ethyl acetate–hexane 1 : 2) afforded compound **22** as a white solid (106 mg, 70%).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.69 (d, $J = 8.0$ Hz, 2H), 7.38 (d, $J = 8.0$ Hz, 2H), 6.12 (d, $J = 10.2$ Hz, 1H), 6.04 (dd, $J = 10.2$, 1.6 Hz, 1H), 4.12 (AB, $J = 18.2$ Hz, 1H), 3.51 (AB, $J = 18.2$ Hz, 1H), 3.37 (brs, 1H), 2.59 (dd, $J = 17.0$, 5.6 Hz, 1H), 2.53–2.45 (m, 2H), 2.44 (s, 3H), 2.17 (dd, $J = 16.8$, 4.4 Hz, 1H), 1.94–1.82 (m, 1H), 1.74–1.50 (m, 3H), 1.44–1.31 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 203.7 (C), 197.4 (C), 144.8 (C), 141.9 (CH), 132.7 (CH), 131.6 (C), 130.1 (CH), 127.9 (CH), 63.4 (CH), 56.3 (C), 54.5 (CH_2), 39.6 (CH_2), 33.5 (CH), 27.7 (CH_2), 25.4 (CH_2), 21.6 (CH_3), 18.6 (CH_2); IR (neat) 1711, 1693, 1672, 1344, 966 cm^{-1}; MS (EI) m/z 359 (M^+, 7), 155 (37), 148 (79), 106 (41), 91 (100), 65 (44); HRMS (EI) m/z calcd for $C_{19}H_{21}NO_4S$ 359.1191, found 359.1189.

3-Tosyl-8-triethylsilyloxy-3,3*a*,4,5,6,6*a*,7,10-octahydro-2*H*-3-aza-cyclopenta[*d*]naphthalen-1-one (23). Compound **9** (61.4 mg, 0.21 mmol) and (buta-1,3-dien-2-yloxy)triethylsilane **14** (117 mg, 0.63 mmol) were dissolved in xylene (2 mL). The mixture was transferred into a sealed tube and degassed three times under vacuum. The sealed tube was put into an oven, which was set at 180 °C, for 24 hours. The crude mixture was purified by flash column chromatography (ethyl acetate–hexane 1 : 10) to afford compound **23** as a liquid (52.3 mg, 72%).

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.66 (d, $J = 8.0$ Hz, 2H), 7.33 (d, $J = 8.0$ Hz, 2H), 4.60 (brs, 1H), 3.93 (AB, $J = 18.2$ Hz, 1H),

3.37 (AB, J = 18.2 Hz, 1H), 3.10 (t, J = 4.0 Hz, 1H), 2.42 (s, 3H), 2.31–2.22 (m, 1H), 2.20–2.15 (m, 2H), 1.93–1.30 (m, 8H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 209.5 (C), 148.4 (C), 144.1 (C), 132.5 (C), 129.8 (CH), 127.6 (CH), 98.3 (CH), 61.8 (CH), 53.3 (CH_2), 50.8 (C), 32.2 (CH_2), 30.3 (CH), 27.7 (CH_2), 25.6 (CH_2), 25.3 (CH_2), 21.5 (CH_3), 19.4 (CH_2), 6.6 (CH_3), 4.8 (CH_2); IR (neat) 1715, 1343, 1216, 841 cm^{-1}; MS (EI) m/z 475 (M^+, 1), 321 (75), 292 (34), 263 (96), 155 (49), 91 (100), 86 (62); HRMS (EI) m/z calcd for $C_{25}H_{37}NO_4SSi$ 475.2213, found 475.2217.

General procedure for $BF_3{\cdot}OEt_2$ catalysed Diels–Alder cycloadditions. The enone (1 equiv.) was dissolved in dichloromethane (0.3 M) and cooled to 0 °C. $BF_3{\cdot}OEt_2$ (0.3 equiv.) was slowly added to the solution and it was allowed to stir for 10 min, followed by the slow addition of diene (2 equiv.). The mixture was stirred for an additional 30 min. The solution was quenched with water and ether, and was extracted with diethyl ether (× 4) and then washed with brine. The combined organic layers were dried over anhydrous sodium sulfate. After filtration and concentration, purification by flash column chromatography afforded the desired product.

5,6-Dimethyl-1-tosyl-2,3,4,7,7*a*,8,9,9*a*-octahydro-1*H*-indeno[1,7*a*-*b*]pyrrol-3-one (24). The reaction of enone **7** with 2,3-dimethyl-1,3-butadiene **15** gave the cycloadduct **24** in 89% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.70 (d, J = 8.4 Hz, 2H), 7.32 (d, J = 8.4 Hz, 2H), 3.87 (dd, J = 6.0, 5.2 Hz, 1H), 3.80 (AB, J = 18.4 Hz, 1H), 3.73 (AB, J = 18.4 Hz, 1H), 2.41 (s, 3H), 2.39–2.32 (m, 1H), 2.11–1.94 (m, 3H), 1.86–1.63 (m, 4H), 1.62 (s, 3H), 1.54 (s, 3H), 1.32–1.21 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 214.2 (C), 144.0 (C), 134.8 (C), 129.9 (CH), 127.5 (CH), 127.0 (C), 123.0 (C), 69.5 (CH), 61.3 (C), 53.4 (CH_2), 39.9 (CH), 34.7 (CH_2), 33.9 (CH_2), 31.7 (CH_2), 31.1 (CH_2), 21.5 (CH_3), 19.6 (CH_3), 19.3 (CH_3); IR (neat) 1714, 1374, 1370, 1345 cm^{-1}; MS (EI) m/z 359 (M^+, 5), 204 (23), 161 (54), 119 (78), 91 (100); HRMS (EI) m/z calcd for $C_{20}H_{25}NO_3S$ 359.1555, found 359.1553.

6,7-Dimethyl-1-tosyl-1,2,3,4,5,8,8*a*,9,10,10*a*-decahydroindeno-[1,7*a*-*b*]pyridin-4-one (25). The reaction of enone **8** with 2,3-dimethyl-1,3-butadiene **15** gave the cycloadduct **25** in 86% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.66 (d, J = 8.6 Hz, 2H), 7.27 (d, J = 8.6 Hz, 2H), 4.14 (t, J = 8.4 Hz, 1H), 4.10–4.03 (m, 1H), 3.13 (td, J = 12.8, 2.8 Hz, 1H), 2.79–2.62 (m, 2H), 2.39 (s, 3H), 2.31–2.21 (m, 2H), 2.05–1.96 (m, 1H), 1.74 (brd, 1H), 1.63 (s, 6H), 1.50–1.41 (m, 1H), 1.20–0.99 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 211.1 (C), 143.5 (C), 137.0 (C), 129.8 (CH), 127.1 (CH), 126.2 (C), 123.4 (C), 61.6 (CH), 58.0 (C), 40.3 (CH_2), 38.6 (CH_2), 36.4 (CH_2), 35.0 (CH), 34.6 (CH_2), 28.6 (CH_2), 23.6 (CH_2), 21.5 (CH_3), 19.6 (CH_3), 19.2 (CH_3); IR (neat) 1715, 1375, 1371, 1343 cm^{-1}; MS (EI) m/z 373 (M^+, 4), 218 (53), 161 (33), 119 (63), 91 (100); HRMS (EI) m/z calcd for $C_{21}H_{27}NO_3S$ 373.1712, found 373.1714.

5,6-Dimethyl-1-tosyl-1,2,3,4,7,7*a*,8,9,10,10*a*-decahydrobenzo-[*d*]indol-3-one (26). The reaction of enone **9** with 2,3-dimethyl-1,3-butadiene **15** gave the cycloadduct **26** in 90% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.66 (d, J = 8.4 Hz, 2H), 7.33 (d, J = 8.4 Hz, 2H), 3.93 (AB, J = 18.0 Hz, 1H), 3.38 (AB, J = 18.0 Hz, 1H), 3.09 (t, J = 8.4 Hz, 1H), 2.42 (s, 3H), 2.31–2.22 (m, 1H), 2.08–1.98 (m, 3H), 1.82–1.22 (m, 13H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 210.3 (C), 144.1 (C), 133.0 (C), 129.9 (CH), 127.6 (CH), 123.9 (C), 120.4 (C), 62.1 (CH), 53.3 (CH_2), 52.3 (C), 34.3 (CH_2), 32.8 (CH_2), 29.8 (CH), 27.5 (CH_2), 25.6 (CH_2), 21.5 (CH_3), 19.4 (CH_2), 19.1 (CH_3), 18.6 (CH_3); IR (neat) 1715, 1374, 1371, 1344 cm^{-1}; MS (EI) m/z 373 (M^+, 5), 218 (14), 161 (75), 119 (34), 91 (100); HRMS (EI) m/z calcd for $C_{21}H_{27}NO_3S$ 373.1712, found 373.1711.

6-Methyl-1-tosyl-2,3,4,7,7*a*,8,9,9*a*-octahydro-1*H*-indeno[1,7*a*-*b*]pyrrol-3-one (27). The reaction of enone **7** with 2-methyl-1,3-butadiene **16** gave the cycloadduct **27** in 90% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.70 (d, J = 8.2 Hz, 2H), 7.32 (d, J = 8.2 Hz, 2H), 5.29 (brs, 1H), 3.93 (dd, J = 7.2, 4.4 Hz, 1H), 3.75 (s, 2H), 2.42 (s, 3H), 2.10–2.00 (m, 2H), 1.88–1.71 (m, 4H), 1.67 (s, 3H), 1.64–1.56 (m, 2H), 1.38–1.28 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 214.0 (C), 144.1 (C), 135.3 (C), 134.5 (C), 129.9 (CH), 127.6 (CH), 117.2 (CH), 69.5 (CH), 59.9 (C), 53.5 (CH_2), 39.4 (CH), 31.9 (CH_2), 31.7 (CH_2), 30.7 (CH_2), 28.2 (CH_2), 23.8 (CH_3), 21.5 (CH_3); IR (neat) 1714, 1665, 1376, 1345, 965 cm^{-1}; MS (EI) m/z 345 (M^+, 11), 190 (63), 134 (100), 133 (61), 91 (45); HRMS (EI) m/z calcd for $C_{19}H_{23}NO_3S$ 345.1399, found 345.1396.

7-Methyl-1-tosyl-1,2,3,4,5,8,8*a*,9,10,10*a*-decahydroindeno[1,7*a*-*b*]pyridin-4-one (28). The reaction of perhydropyridinone **8** with 2-methyl-1,3-butadiene **16** gave the cycloadduct **28** in 88% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.66 (d, J = 8.6 Hz, 2H), 7.27 (d, J = 8.6 Hz, 2H), 5.29 (brs, 1H), 4.26 (t, J = 8.0 Hz, 1H), 4.08–4.01 (m, 1H), 3.15 (td, J = 12.4, 2.8 Hz, 1H), 2.76–2.62 (m, 2H), 2.39 (s, 3H), 2.33–2.22 (m, 2H), 1.98 (dd, J = 17.2, 7.6 Hz, 1H), 1.80–1.71 (m, 1H), 1.66 (s, 1H), 1.65–1.52 (m, 3H), 1.23–1.07 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 211.0 (C), 143.5 (C), 136.9 (C), 134.1 (C), 129.7 (CH), 127.1 (CH), 117.5 (CH), 61.3 (CH), 56.6 (C), 40.3 (CH_2), 38.4 (CH_2), 34.5 (CH), 32.5 (CH_2), 30.0 (CH_2), 28.9 (CH_2), 23.7 (CH_3), 23.2 (CH_2), 21.5 (CH_3); IR (neat) 1715, 1666, 1376, 1343, 969 cm^{-1}; MS (EI) m/z 359 (M^+, 5), 204 (55), 148 (100), 147 (57), 91 (68); HRMS (EI) m/z calcd for $C_{20}H_{25}NO_3S$ 359.1555, found 359.1558.

6-Methyl-1-tosyl-1,2,3,4,7,7*a*,8,9,10,10*a*-decahydrobenzo[*d*]-indol-3-one (29). The reaction of enone **9** with 2-methyl-1,3-butadiene **16** gave the cycloadduct **29** in 86% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.65 (d, J = 8.0 Hz, 2H), 7.33 (d, J = 8.0 Hz, 2H), 5.19 (brs, 1H), 3.95 (AB, J = 17.8 Hz, 1H), 3.35 (AB, J = 17.8 Hz, 1H), 3.04 (brs, 1H), 2.42 (s, 3H), 2.39–2.31 (m, 1H), 2.14–2.00 (m, 2H), 1.91–1.21 (m, 8H), 1.62 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 210.2 (C), 144.1 (C), 132.7 (C), 132.2 (C), 129.9 (CH), 127.7 (CH), 115.8 (CH), 62.3 (CH), 53.5 (CH_2), 51.0 (C), 32.7 (CH_2), 29.8 (CH), 27.7 (CH_2), 26.6 (CH_2), 25.3 (CH_2), 23.6 (CH_3), 21.5 (CH_3), 19.5 (CH_2); IR (neat) 1715, 1664, 1377, 1345, 966 cm^{-1}; MS (EI) m/z 359 (M^+, 11), 204 (17), 148 (100), 147 (68), 91 (45); HRMS (EI) m/z calcd for $C_{20}H_{25}NO_3S$ 359.1555, found 359.1553.

4,6-Dimethyl-1-tosyl-2,3,4,7,7*a*,8,9,9*a*-octahydro-1*H*-indeno[1,7*a*-*b*]pyrrol-3-one (30a, 30b). The reaction of enone **7** with 2-methyl-1,3-pentadiene **17** gave the cycloadducts **30a** and **30b** in 67% and 8% yields, respectively.

30a. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.71 (d, J = 8.0 Hz, 2H), 7.34 (d, J = 8.0 Hz, 2H), 5.16 (brs, 1H), 3.90 (dd, J = 6.4, 3.8 Hz, 1H), 3.82 (AB, J = 17.8 Hz, 1H), 3.50 (AB, J = 17.8 Hz, 1H), 2.43 (s, 3H), 2.42–2.35 (m, 1H), 2.15–2.09 (m, 3H), 1.98–1.86 (m, 2H), 1.76–1.71 (m, 1H), 1.66 (s, 3H), 1.52–1.45 (m,1H), 0.67 (d, J = 7.2 Hz, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 210.9 (C), 144.2 (C), 133.3 (C), 132.9 (C), 129.8 (CH), 127.8 (CH), 123.6 (CH), 69.6

(CH), 63.2 (C), 56.1 (CH_2), 40.3 (CH), 32.5 (CH_2), 32.1 (CH), 31.7 (CH_2), 31.0 (CH_2), 23.4 (CH_3), 21.6 (CH_3), 16.0 (CH_3); IR (neat) 1715, 1666, 1374, 1373, 1345, 966 cm^{-1}; MS (EI) *m/z* 359 (M^+, 8), 204 (40), 147 (36), 91 (100); HRMS (EI) *m/z* calcd for $C_{20}H_{25}NO_3S$ 359.1555, found 359.1552.

30b. ^1H NMR (600 MHz, $CDCl_3$) δ 7.71 (d, $J = 8.2$ Hz, 2H), 7.31 (d, $J = 8.2$ Hz, 2H), 5.09 (d, $J = 1.5$ Hz, 1H), 4.13 (dd, $J =$ 7.0, 3.8 Hz, 1H), 3.72 (s, 2H), 2.52–2.49 (m, 1H), 2.41 (s, 3H), 2.34–2.31 (m, 1H), 2.17–2.12 (m, 1H), 1.84–1.79 (m, 1H), 1.67 (s, 3H), 1.66–1.55 (m, 3H), 1.29–1.20 (m, 1H), 0.65 (d, $J = 7.3$ Hz, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 216.9 (C), 143.9 (C), 136.9 (C), 135.4 (C), 129.8 (CH), 127.4 (CH), 125.2 (CH), 66.2 (C), 64.6 (CH), 54.6 (CH_2), 43.1 (CH), 34.7 (CH), 33.8 (CH_2), 32.5 (CH_2), 32.1 (CH_2), 23.4 (CH_3), 21.6 (CH_3), 16.0 (CH_3); IR (neat) 1715, 1665, 1376, 1371, 1343, 966 cm^{-1}; MS (EI) *m/z* 359 (M^+, 5), 204 (55), 147 (28), 91 (100); HRMS (EI) *m/z* calcd for $C_{20}H_{25}NO_3S$ 359.1555, found 359.1554.

5,7-Dimethyl-1-tosyl-1,2,3,4,5,8,8*a*,9,10,10*a*-decahydroindeno-[1,7*a*-*b*]pyridin-4-one (31a, 31b). The reaction of enone **8** with 2-methyl-1,3-pentadiene **17** gave the cycloadducts **31a** and **31b** in 62% and 8% yields, respectively.

31a. ^1H NMR (600 MHz, $CDCl_3$) δ 7.66 (d, $J = 8.2$ Hz, 2H), 7.27 (d, $J = 8.2$ Hz, 2H), 5.34–5.31 (brs, 1H), 4.39 (t, $J = 9.0$ Hz, 1H), 4.11–4.06 (m, 1H), 3.10 (td, $J = 12.7$, 2.9 Hz, 1H), 2.69–2.64 (m, 2H), 2.56–2.53 (m, 1H), 2.27 (d, $J = 14.0$ Hz, 1H), 2.09 (dd, $J = 18.0$, 8.4 Hz, 1H), 1.66–1.52 (m, 2H), 1.63 (s, 1H), 1.47 (dd, $J = 18.0$, 8.2 Hz, 1H), 1.19–1.08 (m, 2H), 0.68 (d, $J = 7.1$ Hz, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 210.7 (C), 143.5 (C), 136.8 (C), 130.7 (C), 129.7 (CH), 127.1 (CH), 124.0 (CH), 61.4 (CH), 60.7 (C), 41.0 (CH_2), 39.8 (CH_2), 32.7 (CH_2), 31.9 (CH), 30.6 (CH), 29.2 (CH_2), 23.5 (CH_3), 21.9 (CH_2), 21.5 (CH_3), 18.5 (CH_3); IR (neat) 1715, 1665, 1377, 1375, 1345, 966 cm^{-1}; MS (EI) *m/z* 373 (M^+, 6), 218 (50), 161 (100), 147 (36), 91 (77); HRMS (EI) *m/z* calcd for $C_{21}H_{27}NO_3S$ 373.1712, found 373.1712.

31b. ^1H NMR (600 MHz, $CDCl_3$) δ 7.67 (d, $J = 8.2$ Hz, 2H), 7.28 (d, $J = 8.2$ Hz, 2H), 5.22–5.20 (brs, 1H), 4.34 (td, $J = 8.2$, 1.4 Hz, 1H), 4.01–3.95 (m, 1H), 3.12 (td, $J = 12.3$, 4.0 Hz, 1H), 2.75–2.64 (m, 1H), 2.63–2.58 (m, 1H), 2.52 (dd, $J = 16.8$, 2.4 Hz, 1H), 2.41 (s, 3H), 2.32–2.28 (m, 1H), 2.05 (dd, $J = 16.2$, 7.3 Hz, 1H), 1.70 (s, 3H), 1.63 (dd, $J = 16.2$, 5.7 Hz, 1H), 1.48–1.39 (m, 2H), 1.24 (d, $J = 7.5$ Hz, 3H), 1.12–0.99 (m, 2H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 213.9 (C), 143.6 (C), 136.3 (C), 135.4 (C), 129.7 (CH), 127.3 (CH), 125.9 (CH), 61.4 (C), 57.9 (CH), 41.7 (CH), 41.0 (CH_2), 38.8 (CH_2), 37.9 (CH), 32.9 (CH_2), 29.5 (CH_2), 24.4 (CH_2), 23.7 (CH_3), 21.5 (CH_3), 17.5 (CH_3); IR (neat) 1715, 1664, 1374, 1372, 1345, 967 cm^{-1}; MS (EI) *m/z* 373 (M^+, 3), 218 (34), 161 (100), 147 (33), 91 (45); HRMS (EI) *m/z* calcd for $C_{21}H_{27}NO_3S$ 373.1712, found 373.1715.

4,6-Dimethyl-1-tosyl-1,2,3,4,7,7*a*,8,9,10,10*a*-decahydrobenzo-[*d*]indol-3-one (32a, 32b). The reaction of enone **9** with 2-methyl-1,3-pentadiene **17** gave a cycloadduct mixture of **32a** and **32b** in a total yield of 70%. After careful purification, a trace amount of pure **32a** was obtained.

32a. ^1H NMR (400 MHz, $CDCl_3$) δ 7.67 (d, $J = 8.0$ Hz, 2H), 7.33 (d, $J = 8.0$ Hz, 2H), 5.09 (brs, 1H), 3.83 (AB, $J = 18.0$ Hz, 1H), 3.43 (brs, 1H), 3.33 (AB, $J = 18.0$ Hz, 1H), 2.43 (s, 3H), 2.20–2.04 (m, 4H), 1.70–1.04 (m, 5H), 1.63 (s, 3H), 0.67 (d, $J =$ 7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 208.6 (C), 144.1 (C), 133.3 (C), 131.2 (C), 129.9 (CH), 127.7 (CH), 122.8 (CH), 60.8 (CH), 54.9 (C), 54.1 (CH_2), 32.6 (CH_2), 30.0 (CH), 29.2 (CH), 27.5 (CH_2), 25.9 (CH_2), 23.4 (CH_3), 21.6 (CH_3), 19.3 (CH_2), 16.1 (CH_3); IR (neat) 1716, 1664, 1376, 1372, 1343, 965 cm^{-1}; MS (EI) *m/z* 373 (M^+, 4), 218 (57), 161 (100), 147 (28), 91 (75); HRMS (EI) *m/z* calcd for $C_{21}H_{27}NO_3S$ 373.1712, found 373.1712.

4-Methyl-1-tosyl-2,3,4,7,7*a*,8,9,9*a*-octahydro-1*H*-indeno[1,7*a*-*b*]pyrrol-3-one (33a, 33b). The reaction of enone **7** with 1,3-pentadiene **18** gave the cycloadducts **33a** and **33b** in 66% and 8% yields, respectively.

33a. ^1H NMR (600 MHz, $CDCl_3$) δ 7.71 (d, $J = 8.0$ Hz, 2H), 7.34 (d, $J = 8.0$ Hz, 2H), 5.73–5.69 (m, 1H), 5.50–5.46 (m, 1H), 3.93 (dd, $J = 6.5$, 3.8 Hz, 1H), 3.83 (AB, $J = 17.8$ Hz, 1H), 3.51 (AB, $J = 17.8$ Hz, 1H), 2.43 (s, 3H), 2.40–0.81 (m, 8H), 0.67 (d, $J = 7.3$ Hz, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 210.7 (C), 144.2 (C), 133.0 (C), 129.7 (CH), 127.7 (CH), 127.6 (CH), 125.8 (CH), 69.6 (CH), 63.2 (C), 56.1 (CH_2), 39.8 (CH), 31.7 (CH_2), 31.6 (CH_2), 31.0 (CH), 25.9 (CH_2), 21.7 (CH_3), 15.6 (CH_3); IR (neat) 1716, 1645, 1376, 1345, 966 cm^{-1}; MS (EI) *m/z* 345 (M^+, 5), 190 (54), 133 (55), 91 (100); HRMS (EI) *m/z* calcd for $C_{19}H_{23}NO_3S$ 345.1399, found 345.1396.

33b. ^1H NMR (600 MHz, $CDCl_3$) δ 7.70 (d, $J = 8.2$ Hz, 2H), 7.30 (d, $J = 8.2$ Hz, 2H), 5.82–5.78 (m, 1H), 5.42 (brd, $J = 9.6$ Hz, 1H), 4.16 (dd, $J = 7.1$, 3.5 Hz, 1H), 3.72 (s, 2H), 2.53–2.48 (m, 1H), 2.42 (s, 3H), 2.38–2.32 (m, 1H), 2.20–2.13 (m, 1H), 1.91–1.83 (m, 1H), 1.80–1.56 (m, 3H), 1.34–1.29 (m, 1H), 0.68 (d, $J = 7.3$ Hz, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 216.6 (C), 143.9 (C), 135.4 (C), 131.6 (CH), 129.8 (CH), 128.6 (CH), 127.3 (CH), 66.2 (C), 64.4 (CH), 54.4 (CH_2), 42.2 (CH), 34.1 (CH), 32.5 (CH_2), 31.7 (CH_2), 28.5 (CH_2), 21.6 (CH_3), 15.9 (CH_3); IR (neat) 1715, 1647, 1376, 1343, 968 cm^{-1}; MS (EI) *m/z* 345 (M^+, 9), 190 (36), 133 (65), 91 (100); HRMS (EI) *m/z* calcd for $C_{19}H_{23}NO_3S$ 345.1399, found 345.1398.

5-Methyl-1-tosyl-1,2,3,4,5,8,8*a*,9,10,10*a*-decahydroindeno[1,7*a*-*b*]pyridin-4-one (34a, 34b). The reaction of enone **8** with 1,3-pentadiene **18** gave an inseparable cycloadduct mixture of **34a** and **34b** in a total yield of 66%.

^1H NMR (600 MHz, $CDCl_3$) δ 7.68–7.65 (m, 4H), 7.32–7.23 (m, 4H), 5.79–5.76 (m, 1H), 5.64–5.53 (m, 1H), 5.54–5.51 (m, 1H), 5.48–5.45 (m, 1H), 4.43–4.41 (m, 1H), 4.13–4.09 (m, 1H), 4.02–3.97 (m, 1H), 3.11 (td, $J = 12.0$, 4.1 Hz, 1H), 3.05–2.99 (m, 1H), 2.78–2.58 (m, 4H), 2.55–2.45 (m, 2H), 2.44–2.34 (m, 2H), 2.42 (s, 3H), 2.41 (s, 3H), 2.13–2.06 (m, 2H), 2.00–1.94 (m, 1H), 1.89–1.84 (m, 1H), 1.76–1.64 (m, 2H), 1.54–1.37 (m, 2H), 1.27 (s, 3H), 1.17–1.06 (m, 2H), 1.13 (s, 3H), 1.12 (s, 3H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 143.8 (C), 143.6 (C), 136.3 (C), 134.7 (C), 132.2 (CH), 131.5 (CH), 129.8 (CH), 129.8 (CH), 127.6 (CH), 127.5 (CH), 127.0 (CH), 124.2 (CH), 66.5 (CH), 61.6 (C), 58.5 (C), 57.6 (CH), 48.0 (CH_2), 40.9 (CH_2), 40.5 (CH), 39.7 (CH_2), 38.8 (CH_2), 37.0 (CH), 35.0 (CH), 29.9 (CH_2), 28.2 (CH), 27.7 (CH_2), 27.1 (CH_2), 27.0 (CH_2), 25.3 (CH_2), 24.3 (CH_2), 21.5 (CH_3), 20.5 (CH_3), 17.5 (CH_3); IR (neat) 1715, 1649, 1377, 1342, 968 cm^{-1}; MS (EI) *m/z* 359 (M^+, 3), 204 (36), 155 (24), 147 (76), 91 (100); HRMS (EI) *m/z* calcd for $C_{20}H_{25}NO_3S$ 359.1555, found 359.1552.

4-Methyl-1-tosyl-1,2,3,4,7,7*a*,8,9,10,10*a*-decahydrobenzo[*d*]-indol-3-one (35a, 35b). The reaction of enone **9** with

1,3-pentadiene **18** gave an inseparable cycloadduct mixture of **35a** and **35b** in a total yield of 68%.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.72–7.64 (m, 3.6H), 7.36–7.28 (m, 3.6H), 5.69–5.56 (m, 1.8H), 5.42–5.32 (m, 1.8H), 3.99 (t, J = 4.0 Hz, 1H), 3.87 (AB, J = 17.4 Hz, 0.8H), 3.86 (AB, J = 18.4 Hz, 1H), 3.65 (AB, J = 18.4 Hz, 1H), 3.40 (t, J = 4.4 Hz, 0.8H), 3.32 (AB, J = 17.4 Hz, 0.8H), 2.42 (s, 2.4H), 2.41 (s, 3H), 2.32–1.20 (m, 18H), 0.78 (d, J = 7.6 Hz, 3H), 0.70 (d, J = 7.2 Hz, 2.4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 213.9 (C), 208.3 (C), 144.1 (C), 143.8 (C), 135.5 (C), 133.0 (C), 130.6 (CH), 129.9 (CH), 129.8 (CH), 128.6 (CH), 127.7 (CH), 127.3 (CH), 126.1 (CH), 124.0 (CH), 60.7 (CH), 59.3 (CH), 55.0 (C), 54.9 (C), 54.5 (CH_2), 54.3 (CH_2), 36.5 (CH), 31.6 (CH), 30.3 (CH_2), 29.3 (CH), 28.9 (CH), 27.7 (CH_2), 27.5 (CH_2), 26.6 (CH_2), 25.6 (CH_2), 25.4 (CH_2), 21.5 (CH_3), 19.4 (CH_2), 16.6 (CH_3), 16.5 (CH_2), 15.7 (CH_3); IR (neat) 1717, 1649, 1375, 1343, 969 cm^{-1}; MS (EI) m/z 359 (M^+, 5), 204 (26), 155 (24), 147 (76), 91 (100); HRMS (EI) m/z calcd for $C_{20}H_{25}NO_3S$ 359.1555, found 359.1553.

5-Tosyl-5-azatetracyclo[8.2.1.0^{2,6}.0^{2,9}]tridec-11-en-3-one (36). The reaction of enone **7** with cyclopentadiene **19** gave the cycloadduct **36** in 93% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.70 (d, J = 8.0 Hz, 2H), 7.33 (d, J = 8.0 Hz, 2H), 6.30 (dd, J = 5.6, 2.8 Hz, 1H), 6.03 (dd, J = 5.6, 2.8 Hz, 1H), 3.88 (AB, J = 18.2 Hz, 1H), 3.83 (t, J = 6.6 Hz, 1H), 3.79 (AB, J = 18.2 Hz, 1H), 2.80–2.73 (m, 2H), 2.42 (s, 3H), 2.26 (brs, 1H), 2.11–1.96 (m, 2H), 1.83–1.68 (m, 2H), 1.44–1.40 (m, 1H), 1.11–1.01 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 214.1 (C), 144.0 (C), 139.8 (CH), 136.0 (CH), 134.5 (C), 129.8 (CH), 127.4 (CH), 69.1 (C), 66.3 (CH), 55.0 (CH), 54.1 (CH_2), 50.6 (CH_2), 49.3 (CH), 46.0 (CH), 36.8 (CH_2), 27.6 (CH_2), 21.5 (CH_3); IR (neat) 1716, 1666, 1647, 1345, 970 cm^{-1}; MS (EI) m/z 343 (M^+, 3), 188 (42), 131 (69), 91 (100), 66 (58); HRMS (EI) m/z calcd for $C_{19}H_{21}NO_3S$ 343.1242, found 343.1240.

6-Tosyl-6-azatetracyclo[9.2.1.0^{2,7}.0^{2,10}]tetradec-12-en-3-one (37). The reaction of enone **8** with cyclopentadiene **19** gave the cycloadduct **37** in 91% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.69 (d, J = 8.4 Hz, 2H), 7.30 (d, J = 8.4 Hz, 2H), 6.28 (dd, J = 5.4, 3.0 Hz, 1H), 6.15 (dd, J = 5.4, 3.0 Hz, 1H), 4.07–4.00 (m, 1H), 3.88 (dd, J = 12.4, 5.2 Hz, 1H), 3.33–3.19 (m, 2H), 2.78–2.68 (m, 2H), 2.62 (brs, 1H), 2.41 (s, 3H), 2.40–2.38 (m, 1H), 1.76 (AB, J = 8.0 Hz, 1H), 1.69–1.39 (m, 3H), 1.48 (AB, J = 8.0 Hz, 1H), 0.78–0.68 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 209.3 (C), 143.6 (C), 139.2 (C), 136.9 (C), 136.7 (CH), 129.7 (CH), 127.1 (CH), 66.9 (C), 60.4 (CH), 50.5 (CH_2), 49.1 (CH), 47.3 (CH), 45.3 (CH), 41.0 (CH_2), 39.9 (CH_2), 32.3 (CH_2), 25.1 (CH_2), 21.5 (CH_3); IR (neat) 1715, 1665, 1647, 1344, 969 cm^{-1}; MS (EI) m/z 357 (M^+, 6), 290 (53), 263 (71), 155 (42), 136 (51), 91 (100), 66 (49), 65 (42); HRMS (EI) m/z calcd for $C_{20}H_{23}NO_3S$ 357.1399, found 357.1402.

5-Tosyl-5-azatetracyclo[9.2.1.0^{2,6}.0^{2,10}]tetradec-12-en-3-one (38). The reaction of enone **9** with cyclopentadiene **19** gave the cycloadduct **38** in 95% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.75 (d, J = 8.0 Hz, 2H), 7.33 (d, J = 8.0 Hz, 2H), 6.34 (dd, J = 6.0, 3.2 Hz, 1H), 5.98 (dd, J = 6.0, 3.2 Hz, 1H), 3.97 (AB, J = 18.2 Hz, 1H), 3.68 (dd, J = 11.0, 6.0 Hz, 1H), 3.67 (AB, J = 18.2 Hz, 1H), 2.79 (brs, 1H), 2.59–2.54 (m, 1H), 2.42 (s, 3H), 2.06 (brs, 1H), 2.02–1.93 (m, 1H), 1.61 (brs, 1H), 1.54 (AB, J = 8.6 Hz, 1H), 1.52–1.43 (m, 1H), 1.34–1.25 (m, 1H), 1.23–1.12 (m, 1H), 1.09 (AB, J = 8.6 Hz, 1H), 1.07–0.94 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 212.3 (C), 143.9 (C), 139.8 (CH), 136.2 (CH), 136.0 (C), 129.8 (CH), 127.2 (CH), 62.0 (CH), 60.5 (C), 51.4 (CH), 51.1 (CH_2), 49.4 (CH), 45.2 (CH_2), 42.0 (CH), 29.9 (CH_2), 25.4 (CH_2), 21.5 (CH_3), 19.9 (CH_2); IR (neat) 1715, 1666, 1649, 1343, 969 cm^{-1}; MS (EI) m/z 357 (M^+, 3), 290 (64), 263 (69), 155 (53), 136 (51), 91 (100), 66 (58), 65 (44); HRMS (EI) m/z calcd for $C_{20}H_{23}NO_3S$ 357.1399, found 357.1398.

4-(2-Furyl)-1-tosyl-perhydrocyclopenta[*b*]pyrrol-3-one (39). The reaction of enone **7** with furan **20** gave the cycloadduct **39** in 88% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.74 (d, J = 8.2 Hz, 2H), 7.35 (d, J = 8.2 Hz, 2H), 6.49 (dd, J = 5.8, 1.6 Hz, 1H), 6.26 (dd, J = 5.8, 1.6 Hz, 1H), 4.67 (brs, 1H), 4.36 (brs, 1H), 4.14 (t, J = 5.4 Hz, 1H), 3.84 (AB, J = 18.2 Hz, 1H), 3.74 (AB, J = 18.2 Hz, 1H), 2.43 (s, 3H), 2.28–2.18 (m, 2H), 2.10–1.98 (m, 2H), 1.64–1.54 (m, 1H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 209.9 (C), 144.4 (C), 137.4 (CH), 133.9 (CH), 133.8 (C), 130.0 (CH), 127.8 (CH), 85.4 (CH), 82.5 (CH), 69.5 (C), 67.9 (CH), 55.5 (CH), 55.5 (CH_2), 35.3 (CH_2), 28.6 (CH_2), 21.6 (CH_3); IR (neat) 1715, 1667, 1346, 1172, 968 cm^{-1}; MS (EI) m/z 345 (M^+, 21), 190 (41), 133 (71), 91 (100); HRMS (EI) m/z calcd for $C_{18}H_{19}NO_4S$ 345.1035, found 345.1034.

5-(2-Furyl)-1-tosyl-perhydrocyclopenta[*b*]pyridin-4-one (40). The reaction of enone **8** with furan **20** gave the product **40** in 40% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.72 (d, J = 8.0 Hz, 2H), 7.31 (d, J = 8.0 Hz, 3H), 6.25 (brs, 1H), 6.02 (brd, J = 3.2 Hz, 1H), 4.76–4.64 (m, 1H), 4.08–4.00 (m, 1H), 3.91 (ddd, J = 8.9, 6.4, 2.4 Hz, 1H), 3.31 (ddd, J = 13.5, 10.4, 3.2 Hz, 1H), 2.79 (d, J = 7.2 Hz, 1H), 2.52–2.32 (m, 2H), 2.41 (s, 3H), 2.11–2.00 (m, 1H), 1.82–1.74 (m, 1H), 1.70–1.58 (m, 1H), 1.40–1.28 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.6 (C), 156.9 (C), 143.9 (C), 141.3 (CH), 136.1 (C), 129.9 (CH), 127.1 (CH), 110.3 (CH), 105.2 (CH), 59.0 (CH), 57.5 (CH), 41.6 (CH_2), 40.2 (CH_2), 31.5 (CH), 28.4 (CH_2), 27.1 (CH_2), 21.5 (CH_3); IR (neat) 3018, 2952, 1715, 1344, 1220 cm^{-1}; MS (EI) m/z 359 (M^+, 65), 204 (55), 147 (71), 91 (100), 65 (20); HRMS (EI) m/z calcd for $C_{19}H_{21}NO_4S$ 359.1191, found 359.1189.

4-(2-Furyl)-1-tosyl-perhydro-3-indolone (41). The reaction of perhydroindolone **9** with furan **20** gave the product **41** in 85% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.74 (d, J = 8.0 Hz, 2H), 7.31 (d, J = 8.0 Hz, 3H), 6.30–6.28 (m, 1H), 5.95 (brd, J = 3.2 Hz, 1H), 4.51–4.43 (m, 1H), 3.87 (AB, J = 18.4 Hz, 1H), 3.65 (AB, J = 18.4 Hz, 1H), 3.56 (brs, 1H), 2.56 (brd, 1H), 2.41 (s, 3H), 2.12–2.02 (m, 1H), 1.85–1.75 (m, 1H), 1.54–1.04 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 208.6 (C), 156.3 (C), 144.2 (C), 141.3 (CH), 135.7 (C), 130.1 (CH), 127.2 (CH), 110.2 (CH), 105.3 (CH), 56.7 (CH), 51.4 (CH_2), 51.2 (CH), 31.5 (CH), 29.4 (CH_2), 26.3 (CH_2), 21.5 (CH_3), 18.9 (CH_2); IR (neat) 3018, 2952, 1716, 1345, 1218 cm^{-1}; MS (EI) m/z 359 (M^+, 12), 204 (41), 147 (78), 91 (100), 65 (38); HRMS (EI) m/z calcd for $C_{19}H_{21}NO_4S$ 359.1191, found 359.1190.

1-Tosyl-4-(1-methyl-1*H*-2-pyrrolyl)perhydrocyclopenta[*b*]pyrrol-3-one (42). The reaction of perhydropyrrolone **7** with *N*-methyl pyrrole **21** gave the product **42** in 88% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.76 (d, J = 8.0 Hz, 2H), 7.37 (d, J = 8.0 Hz, 2H), 6.54 (brs, 1H), 6.02 (dd, J = 3.6, 2.4 Hz, 1H), 5.79 (brd, J = 3.6 Hz, 1H), 4.59–4.53 (m, 1H), 3.82 (AB, J = 18.0 Hz, 1H), 3.69 (AB, J = 18.0 Hz, 1H), 3.59 (s, 3H), 3.51–3.46 (m, 1H), 2.89 (dd, J = 8.8, 2.8 Hz, 1H), 2.46 (s, 3H), 2.34–2.23 (m, 1H), 2.19–2.08 (m, 1H), 2.07–1.96 (m, 1H), 1.89–1.80 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 210.5 (C), 144.3 (C), 134.1 (C), 133.6 (C), 130.0 (CH), 127.7 (CH), 122.1 (CH), 106.6 (CH), 104.7 (CH), 63.3 (CH), 58.7 (CH), 54.7 (CH_2), 39.9 (CH), 33.8 (CH_3), 33.4 (CH_2), 31.4 (CH_2), 21.5 (CH_3); IR (neat) 3021, 2955, 1714, 1345 cm^{-1}; MS (EI) m/z 358 (M^+, 100), 203 (87), 146 (100), 91 (31); HRMS (EI) m/z calcd for $C_{19}H_{22}N_2O_3S$ 358.1351, found 358.1350.

1-Tosyl-5-(1-methyl-1*H*-2-pyrrolyl)perhydrocyclopenta[*b*]pyridin-4-one (43). The reaction of enone **8** with *N*-methyl pyrrole **21** gave the product **43** in 89% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.72 (d, J = 8.0 Hz, 2H), 7.30 (d, J = 8.0 Hz, 2H), 6.50 (brs, 1H), 6.02 (dd, J = 3.4, 2.4 Hz, 1H), 5.85 (brd, J = 3.4 Hz, 1H), 4.75–4.66 (m, 1H), 4.09–4.01 (m, 1H), 3.90 (ddd, J = 8.9, 6.5, 2.2 Hz, 1H), 3.32 (ddd, J = 13.5, 10.5, 3.2 Hz, 1H), 3.50 (s, 3H), 2.66 (d, J = 7.2 Hz, 1H), 2.52–2.34 (m, 2H), 2.41 (s, 3H), 2.11–2.01 (m, 1H), 1.83–1.74 (m, 1H), 1.70–1.59 (m, 1H), 1.40–1.27 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.6 (C), 143.9 (C), 136.4 (C), 136.1 (C), 129.9 (CH), 127.1 (CH), 121.7 (CH), 106.7 (CH), 104.1 (CH), 59.0 (CH), 57.3 (CH), 41.5 (CH_2), 40.3 (CH_2), 33.7 (CH_3), 31.4 (CH), 28.4 (CH_2), 27.0 (CH_2), 21.5 (CH_3); IR (neat) 3020, 2956, 1715, 1345 cm^{-1}; MS (EI) m/z 372 (M^+, 100), 217 (81), 161 (54), 120 (45), 107 (63), 91 (55); HRMS (EI) m/z calcd for $C_{20}H_{24}N_2O_3S$ 372.1508, found 372.1511.

1-Tosyl-4-(1-methyl-1*H*-2-pyrrolyl)perhydro-3-indolone (44). The reaction of enone **9** with *N*-methyl pyrrole **21** gave the product **44** in 90% yield.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.77 (d, J = 8.0 Hz, 2H), 7.31 (d, J = 8.0 Hz, 2H), 6.52 (brs, 1H), 6.04 (dd, J = 3.6, 2.6 Hz, 1H), 5.85 (brd, J = 3.6 Hz, 1H), 4.67–4.58 (m, 1H), 3.87 (AB, J = 18.2 Hz, 1H), 3.66 (AB, J = 18.2 Hz, 1H), 3.58 (brs, 1H), 3.49 (s, 3H), 2.43 (brd, 1H), 2.38 (s, 3H), 2.05–2.01 (m, 1H), 1.65–1.04 (m, 5H); ^{13}C NMR (100 MHz, d_6-DMSO) δ 208.9 (C), 143.9 (C), 135.1 (C), 133.3 (C), 130.2 (CH), 127.1 (CH), 121.7 (CH), 106.0 (CH), 106.0 (CH), 56.5 (CH), 51.5 (CH), 51.3 (CH_2), 33.1 (CH_3), 28.9 (CH), 28.8 (CH_2), 26.8 (CH_2), 21.0 (CH_3), 17.7 (CH_2); IR (neat) 3020, 2957, 1715, 1346 cm^{-1}; MS (EI) m/z 372 (M^+, 100), 217 (87), 189 (40), 161 (48), 120 (53), 107 (51), 91 (31); HRMS (EI) m/z calcd for $C_{20}H_{24}N_2O_3S$ 372.1508, found 372.1505.

Decahydro-1-oxo-3-tosyl-1*H*-cyclopenta[*d*]indole-7,9-dicarbaldehyde (50). O_3 gas was introduced into a solution of compound **38** (15 mg, 0.042 mmol) in CH_2Cl_2 (3 mL) at 0 °C. After 20 min, the ozone was stopped and the excess ozone was removed by introducing Ar gas into the solution. Finally, Me_2S (6 µl, 0.084 mmol) was added into the reaction solution, which was then stirred for 20 min. The reaction solvent was removed directly by rotary evaporator to give the crude compound. Purification by flash column chromatography (ethyl acetate–hexane 1 : 3) afforded compound **50** (16 mg, 98%).

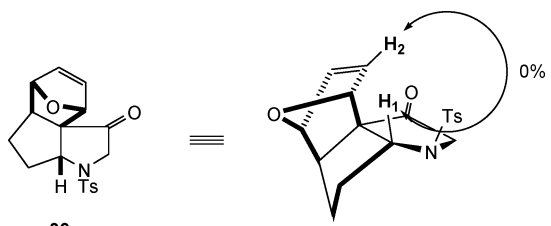
^{1}H NMR (400 MHz, $CDCl_3$) δ 9.78 (d, J = 1.2 Hz, 1H), 9.62 (d, J = 2.4 Hz, 1H), 7.66 (d, J = 8.0 Hz, 2H), 7.36 (d, J = 8.4 Hz, 2H), 4.03 (AB, J = 18.4 Hz, 1H), 3.65 (dd, J = 4.2, 4.2 Hz, 1H), 3.45 (AB, J = 18.4 Hz, 1H), 3.02 (dd, J = 18.2, 7.8 Hz, 1H), 2.83–2.65 (m, 2H), 2.44 (s, 3H), 2.38–2.27 (m, 1H), 2.06–1.96 (m, 1H), 1.80–1.68 (m, 1H), 1.62–1.53 (m, 1H), 1.48–1.32 (m, 2H), 1.30–1.10 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 208.2 (C), 201.5 (CH), 200.7 (CH), 144.8 (C), 132.1 (C), 130.1 (CH), 127.8 (CH), 62.5 (C), 57.6 (CH), 53.2 (CH_2), 52.5 (CH), 51.8 (CH), 40.9 (CH), 24.8 (CH_2), 23.7 (CH_2), 23.3 (CH_2), 21.6 (CH_3), 17.7 (CH_2); IR (neat) 1725, 1720, 1715, 1343, 1230, 969 cm^{-1}; MS (EI) m/z 389 (M^+, 3), 360 (60), 331 (62), 176 (100); HRMS (EI) m/z calcd for $C_{20}H_{23}NO_5S$ 389.4653, found 389.1297.

Acknowledgements

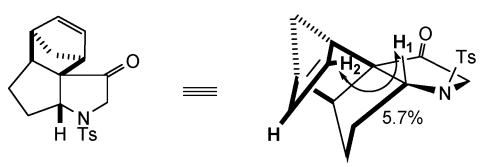
We thank the National Science Council of the Republic of China for financial support.

Notes and references

1 C. K. Sha, A. W. Hong and C. M. Huang, *Org. Lett.*, 2001, **3**, 2177.
2 C. K. Sha and C. M. Chau, *Tetrahedron Lett.*, 2003, **44**, 499.
3 The experimental procedures are in the ESI.
4 For recent reviews, see: (*a*) E. J. Corey, *Angew. Chem., Int. Ed.*, 2002, **41**, 1650; (*b*) D. A. Evans and J. S. Johnson, in *Comprehensive Asymmetric Catalysis*, ed. E. N. Jacobsen, A. Pfaltz and H. Yamamoto, Springer Press, Berlin, 1999, vol. 3, p. 1177; (*c*) K. Ishihara and H. Yamamoto, *Eur. J. Org. Chem.*, 1999, **7**, 527.
5 (*a*) A. P. Kozikowski, W. C. Floyd and M. P. Kuniak, *J. Chem. Soc., Chem. Commun.*, 1977, 582–583; (*b*) H. Takayama, A. Iyobe and T. Koizumi, *J. Chem. Soc., Chem. Commun.*, 1986, 771–772; (*c*) B. L. Feringa, O. J. Gelling and L. Meesters, *Tetrahedron Lett.*, 1990, **31**, 7201–7204.
6 (*a*) H. Suga, T. Kitamura, A. Kakehi and T. Baba, *Chem. Commun.*, 2004, **12**, 1414–1415; (*b*) L. T. An, J. P. Zou, L. L. Zhang and Y. Zhang, *Tetrahedron Lett.*, 2007, **48**, 4297.
7 The NOE experiments of compound **39** and **36** are shown below:



39



8 (*a*) S. Li, S. Ohba, S. Kosemura and S. Yamamura, *Tetrahedron Lett.*, 1996, **37**, 7365; (*b*) S. Li, S. Kosemura and S. Yamamura, *Tetrahedron*, 1998, **54**, 6661