Tetrahedron Letters 50 (2009) 1914–1916

Contents lists available at ScienceDirect

Tetrahedron Letters

journal homepage: www.elsevier.com/locate/tetlet

Extending Pummerer reaction chemistry. Examination of the prospects for forming vicinal quaternary carbon centers

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ARTICLE INFO

Article history:
Received 9 January 2009
Revised 3 February 2009
Accepted 4 February 2009
Available online 8 February 2009

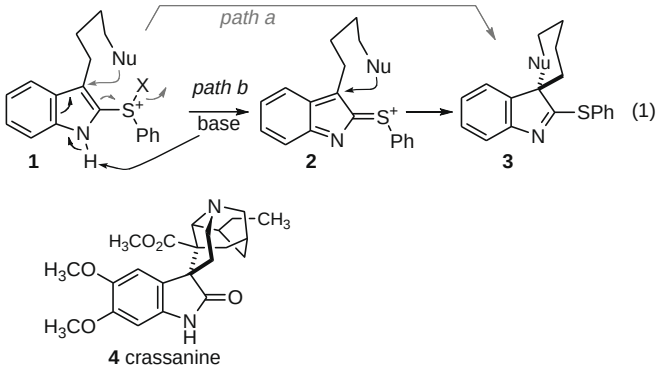
ABSTRACT

Pummerer chemistry applied to 2-sulfinyl indoles promotes oxidative cyclization of pendant nucleophiles to furnish C(3) spirocyclic indolenine products. Use of tetrasubstituted silyl enol ether nucleophiles in this transform yields spirocycles featuring vicinal all-carbon quaternary centers in two cases, but fails when a nearby amine can intervene.

The application of Pummerer reaction chemistry to the problem of controlled oxidative cyclization of indole and imidazole rings has led to the efficient syntheses of indolenine and imidazoline products, respectively (Scheme 1).[1,2] The ready acquisition of spirocyclic constructs of the general type **3** can impact on synthesis studies of cognate natural products, and in fact the imidazole variant of this chemistry is at the core of recent syntheses of the oroidin-derived sponge alkaloids dibromophakelstatin, dibromophakellin, and dibromoagelaspongin.[3] One question left unanswered by all of these studies focuses on a very demanding C–C bond formation; the construction of a bond between two quaternary carbon centers. Numerous indole-derived alkaloids contain this structural feature (e.g., crassanine (**4**)[4]), and so the extension of the Pummerer methodology toward this challenge in C–C bond formation might prove enabling for that class of targets. In this Letter, the feasibility of accomplishing this goal is established, and some significant limitations are exposed.

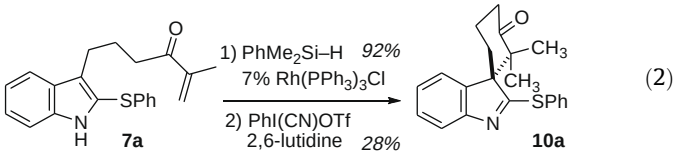
The extension of this oxidative cyclization chemistry to vicinal quaternary C–C bond formation is illustrated in Scheme 2. The tetrasubstituted silyl enol ethers **9a** and **9b** were assembled via standard functional group manipulation chemistry as shown. Silyl enol ether **9b** was formed as the strictly *E*-alkene (NOE, Scheme 2) in accord with precedent.[5] Exposure of either of the enol ethers **9a** or **9b** to typical Pummerer initiation conditions (Tf_2O, hindered base) rapidly furnished spirocyclic products in moderate yields. The structural assignments of **10a** and **10b** rested on the striking similarity between the ^1H and ^{13}C NMR data for these species and those of the related but less substituted spirocycles prepared earlier,[1a,d] and on a single crystal X-ray analysis of **10b** (see Scheme 3).[6]

Spirocycle **10b** was formed as a single diastereomer featuring an equatorial Ph substituent and an axially disposed aryl ring from the indolenine core. Mechanistic speculation about the basis for this selectivity might cite competing cyclization transition states **11a** and **11b** (assuming a vinylogous Pummerer mechanism (path b, Scheme 1) rather than an additive one (path a, Scheme 1) for simplicity). The acquisition of **10b** rather than **12** then suggests that the gauche-type interaction illustrated in **11a** is more energetically penalizing than any of the other steric interactions that might arise.



Scheme 1. Illustrative example of a Pummerer reaction-mediated oxidative spirocyclization.

A variant of the Pummerer initiator methodology was explored briefly, Eq. 2. Stang's reagent-mediated initiation of the Pummerer sequence[1b] on the corresponding sulfide formed by hydrosilylation of **7a** did afford the desired spirocyclic material **10a**, but in inferior yield compared to the sulfoxide/Tf_2O initiated process.



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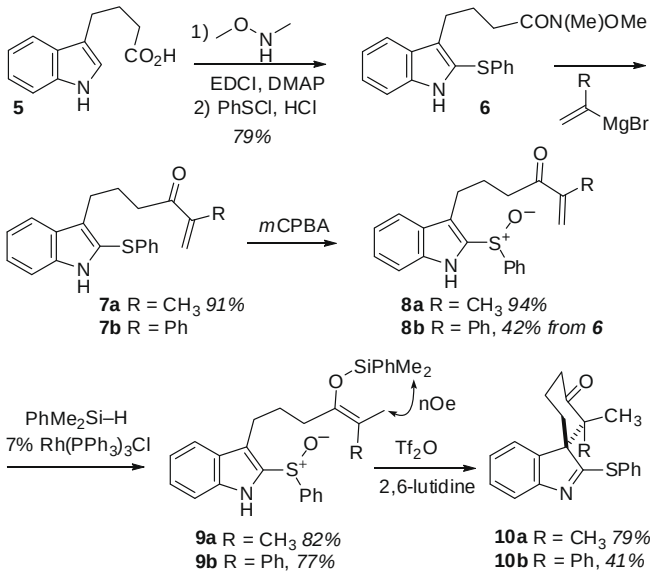
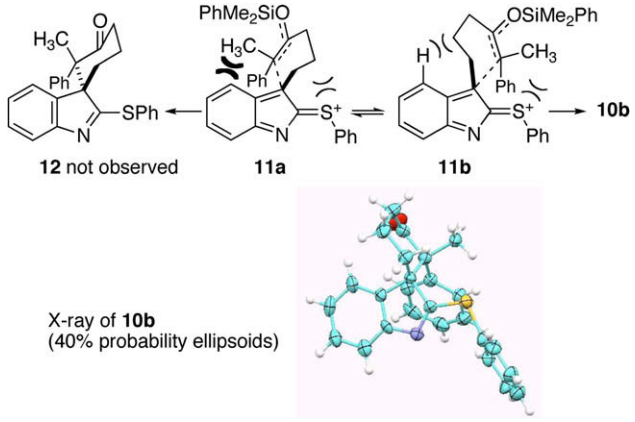
doi:10.1016/j.tetlet.2009.02.024



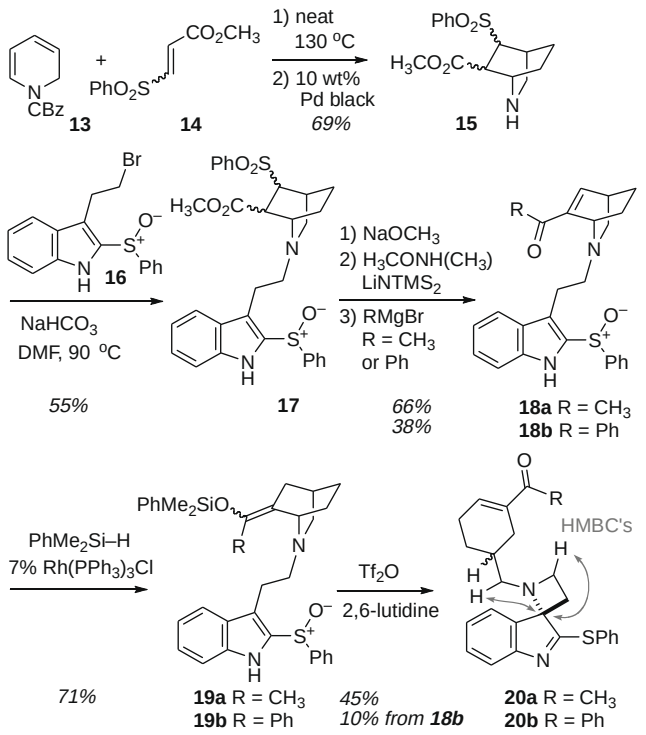
Scheme 2. Synthesis and oxidative cyclization chemistry of tetrasubstituted silyl enol ethers to form vicinal quaternary centers.[10]



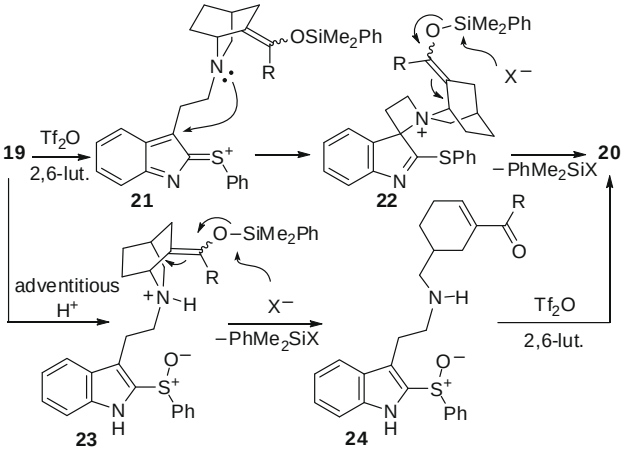
Scheme 3. Cyclization transition state analysis; X-ray structure of **10b**.

Finally, a more complicated substrate relevant to a projected synthesis of crassanine was investigated, Scheme 4. Both methyl- and phenyl-substituted silyl enol ethers **19a** and **19b** (unassigned geometry), respectively, were prepared from the known Diels–Alder precursors **13**[7] and **14**[8] and the sulfoxide **16**, which was synthesized from 3-(2-bromoethyl)indole (PhSCl, HCl (94%); mCPBA (96%)). Submission of either substrate to the optimized Pummerer initiation conditions led to modest amounts of spirocyclic material in both cases as apparent 1:1 mixtures of diastereomers, but the ^{1}H NMR and ^{13}C NMR data of these products were clearly inconsistent with formation of the desired C–C bonded spirocycle. An unsaturated ketone function was evident, and the spirocyclic carbons in **20a** (diastereomers) appeared at δ 82.2 and 82.4 compared to this same carbon in **10a** at δ 68.8. The former observation indicated that the azabicyclo[2.2.2]octane moiety had ruptured, whereas the latter one suggested that a heteroatom and not a carbon atom had bonded to the spirocyclic carbon. Further NMR spectroscopic analysis (HMQC, HMBC, DEPT) provided evidence consistent with the azetidine structures **20a** and **20b**; key HMBC correlations are indicated.

The formation of **20** from **19** requires two distinct mechanistic operations (Scheme 5): (1) addition of the nitrogen nucleophile



Scheme 4. Synthesis and Pummerer-mediated oxidative cyclization chemistry of a crassanine model.[10]



Scheme 5. Mechanistic speculation regarding the conversion of **19** into **20**.

within the azabicyclo[2.2.2]octane to the transiently electrophilic C(3) of the Pummerer intermediate (cf. **21**→**22** or **24**→**20**), and (2) β-elimination of the amine function to generate the product's enone (cf. **22**→**20** or **23**→**24**). The sequence of these events is not known. Circumstantial evidence tends to favor the pathway proceeding through initial Pummerer reaction via **21** and **22**: (a) treatment of **19a** with aqueous HCl led to formation of a ketone product with the azabicyclo[2.2.2]octane system intact, suggesting that protonation of the nitrogen per se (cf. **23**) is not sufficient to promote ring cleavage, and (b) a secondary amine intermediate like **24** might be expected to undergo N-triflation under the reaction conditions, but that product was not detected. Nevertheless, the

failure of the silyl enol ether nucleophile to out-compete the tertiary amine (or secondary amine after β-elimination) eliminates this chemistry from use in crassanine-type alkaloid synthesis. Curiously, however, this C(3)-azetidine spirocyclic indolenine structure is found in the core of members of the chartelline alkaloids.[9]

Acknowledgment

Support from the National Science Foundation via CHE 0808983 and CHE 0131112 (X-Ray Crystallography facility) is gratefully acknowledged.

References and notes

1. (a) Feldman, K. S.; Vidulova, D. B. *Org. Lett.* **2004**, *6*, 1869–1871; (b) Feldman, K. S.; Boneva, V. D. *Tetrahedron Lett.* **2004**, *45*, 5035–5037; (c) Feldman, K. S.; Karatjas, A. G. *Org. Lett.* **2004**, *6*, 2849–2852; (d) Feldman, K. S.; Vidulova, D. B.; Karatjas, A. G. *J. Org. Chem.* **2005**, *70*, 6429–6440.
2. Feldman, K. S. *Tetrahedron* **2006**, *62*, 5003–5034.
3. (a) Feldman, K. S.; Skoumbourdis, A. P. *Org. Lett.* **2005**, *7*, 929–931; (b) Feldman, K. S.; Skoumbourdis, A. P.; Fodor, M. D. *J. Org. Chem.* **2007**, *72*, 8076–8086; (c) Feldman, K. S.; Fodor, M. D. *J. Am. Chem. Soc.* **2008**, *130*, 14964–14965.
4. Cava, M. P.; Watanabe, Y.; Bessho, K.; Weisbach, J. A.; Douglas, B. *J. Org. Chem.* **1968**, *33*, 3350–3352.
5. (a) Ojima, I.; Kogure, T. *Organometallics* **1982**, *1*, 1390–1399; (b) Evans, D. A.; Fu, G. C. *J. Org. Chem.* **1990**, *55*, 5680–5683.
6. Cambridge crysallographic data base access for **10b**: CCDC 651553.
7. Sundberg, R. J.; Bloom, J. D. *J. Org. Chem.* **1981**, *46*, 4836–4842.
8. Buss, A. D.; Hirst, G. C.; Parsons, P. J. *J. Chem. Soc., Chem. Commun.* **1987**, 1836–1837.
9. (a) Chevolot, L.; Chevolot, A.-M.; Ghajhede, M.; Larsen, C.; Anthoni, U.; Christophersen, C. *J. Am. Chem. Soc.* **1985**, *107*, 4542–4543; (b) Anthoni, U.; Chevolot, L.; Larsen, C.; Neilsen, P. H.; Christophersen, C. *J. Org. Chem.* **1987**, *52*, 4709–4715.
10. Spectral data for **7a**, **8a**, **8b**, **9b**, **10a**, **10b**, **15**, **16**, **17**, **18a**, **18b**, **20a**, and **20b**.
Compound **7a**: mp 70–71 °C: IR (thin film) 3338, 1668 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 8.14 (s, 1H), 7.64–7.61 (m, 1H), 7.24–6.95 (m, 9H), 5.69 (t, J = 0.8 Hz, 1H), 5.58 (m, 1H), 2.87 (t, J = 7.4 Hz, 2H), 2.62 (t, J = 7.4 Hz, 2H), 1.94 (quintet, J = 7.4 Hz, 2H), 1.77 (dd, J = 0.6, 0.9 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 202.0, 144.2, 137.2, 137.0, 129.0, 127.6, 126.3, 125.6, 124.4, 123.4, 121.5, 119.6, 119.5, 111.0, 36.9, 24.9, 24.2, 17.5; LRMS (ESI+) m/z (relative intensity) 336.1 (100% M+H$^+$); HRMS (ESI) m/z calcd for $[C_{21}H_{22}NOS]^+$, 336.1409; found, 336.1422.
Compound **8a**: mp = 124–125 °C; IR (thin film) 3215, 1673 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 9.95 (s, 1H), 7.68–7.64 (m, 3H), 7.43–7.38 (m, 3H), 7.34–7.31 (m, 1H), 7.25–7.19 (m, 1H), 7.13–7.07 (m, 1H), 5.89 (br s, 1H), 5.73 (m, 1H), 3.12–2.99 (m, 2H), 2.86–2.77 (m, 2H), 2.09–2.02 (m, 2H), 1.88 (m, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 201.4, 144.3, 143.3, 137.8, 131.8, 130.9, 129.3, 126.8, 124.9, 124.8, 124.6, 121.8, 120.2, 120.0, 112.3, 36.7, 25.3, 23.7, 17.6; LRMS (ESI+) m/z (relative intensity) 352.1 (100% M+H$^+$); HRMS (ESI) m/z calcd for $[C_{21}H_{22}NO_2S]^+$, 352.1369; found, 352.1371.
Compound **8b**: mp 138–139 °C; IR (thin film) 3205, 1681, 1615 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 10.0 (s, 1H), 7.70–7.61 (m, 3H), 7.43–7.30 (m, 9H), 7.23 (ddd, J = 7.0, 1.2, 1.1 Hz, 1H), 7.11 (ddd, J = 7.7, 1.0, 1.0 Hz, 1H), 6.09 (s, 1H), 5.89 (s, 1H), 3.17–3.00 (m, 2H), 2.88 (td, J = 6.9, 2.6 Hz, 2H), 2.20–2.03 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 201.3, 149.1, 143.3, 137.8, 137.1, 131.8, 130.9, 129.3, 128.3, 128.1, 128.0, 126.8, 124.9, 124.8, 124.7, 121.5, 120.2, 120.0, 112.3, 38.7, 25.3, 23.6; LRMS (ESI) m/z (relative intensity) 414.2 (100% M+H$^+$); HRMS (ESI) m/z calcd for $[C_{26}H_{24}NO_2S]^+$, 413.1526; found 414.1528.
Compound **9a**: IR (thin film) 3211, 1679 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 10.9 (br s, 1H), 7.68–7.43 (m, 6H), 7.23–7.00 (m, 5H), 6.9–6.82 (m, 3H), 2.93–2.82 (m, 2H), 2.20–2.02 (m, 2H), 2.02–1.88 (m, 2H), 1.85 (s, 3H), 1.50 (s, 3H), 0.36–0.35 (app d, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 145.0, 144.2, 138.7, 138.6, 133.7, 132.5, 130.7, 129.9, 129.4, 125.4, 125.0, 122.0, 120.5, 120.2, 113.1, 32.1, 29.0, 24.1, 18.8, 18.3, 0.690, −.072.
Compound **10a**: IR (thin film) 1709, 1510 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.66–7.62 (m, 2H), 7.40–7.39 (m, 1H), 7.11–7.6.97 (m, 5H), 6.86 (dt, J = 7.6 Hz, 1H), 2.46–2.24 (m, 2H), 1.94–1.85 (m, 2H), 1.83–1.73 (m, 1H), 1.46–1.39 (m, 1H), 1.22 (s, 3H), 0.86 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 213.1, 182.5, 154.3, 140.9, 134.4, 129.3, 129.0, 128.2, 124.0, 123.5, 119.9, 68.8, 49.0, 36.7, 29.7, 21.8, 21.7, 21.2; LRMS (ESI+) m/z (relative intensity) 336.1 (100% M+H$^+$); HRMS (ESI) m/z calcd for $[C_{21}H_{22}NOS]^+$, 336.1445; found, 336.1422.
Compound **10b**: mp 116–117 °C; IR (thin film) 1707, 1509 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.61–7.57 (m, 2H), 7.44–7.39 (m, 3H), 7.17–6.96 (m, 8H), 6.85 (d, J = 7.3 Hz, 1H), 3.17 (quintet, J = 9.0 Hz, 1H), 2.95–2.86 (m, 1H), 2.60–2.37 (m, 3H), 2.04 (s, 3H), 1.89–1.78 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 210.2, 181.5, 154.1, 140.6, 137.5, 133.5, 129.3, 129.2, 128.8, 128.7, 128.2, 126.9, 126.7, 124.0, 123.6, 119.7, 68.6, 56.9, 37.0, 29.1, 21.7, 19.7; LRMS (ESI+) m/z (relative intensity) 398.0 (100% M+H$^+$); HRMS (ESI) m/z calcd for $[C_{26}H_{24}NOS]^+$, 398.1597; found, 398.1579.
Compound **15**: mp 107–108 °C; IR (thin film) 3350, 1732, 1148; ^1H NMR (300 MHz, $CDCl_3$) δ 7.89–7.86 (m, 2H), 7.67–7.61 (m, 1H), 7.56–7.51 (m, 2H), 3.86 (dt, J = 7.2, 1.7 Hz, 1H), 3.45 (s, 3H), 3.19–3.17 (m, 1H), 3.14 (d, J = 8.1 Hz, 1H), 3.00–2.91 (m, 2H), 2.48–2.25 (m, 2H), 2.00–1.80 (m, 2H), 1.65–1.58 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 172.9, 138.2, 133.8, 129.1, 128.6, 62.6, 52.3, 47.8 (two carbons), 45.0, 26.8, 24.8, 19.5; LRMS (ESI+) m/z (relative intensity) 310.1 (100% M+H$^+$); HRMS (ESI) m/z calcd for $[C_{15}H_{20}NO_4S]^+$, 311.1109; found, 311.1113.
Compound **16**: mp 107–108 °C; IR (thin film) 3203 cm^{-1}: ^1H NMR (300 MHz, $CDCl_3$) δ 9.52 (s, 1H), 7.49–7.46 (m, 2H), 7.36 (d, J = 8.0 Hz, 1H), 7.24 (t, J = 3.1 Hz, 3H), 7.12 (d, J = 8.3 Hz, 1H), 7.05–7.01 (m, 1H), 6.91 (t, J = 7.5 Hz, 1H), 3.47–3.38 (m, 1H), 3.34–3.15 (m, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 143.6, 138.0, 133.5, 131.7, 129.9, 126.9, 125.6, 125.5, 121.0, 120.0, 118.8, 113.0, 32.3, 28.7; LRMS (ESI+) m/z (relative intensity) 348.0 (100% M+H$^+$); HRMS (ESI) m/z calcd for $[C_{16}H_{15}BrNOS]^+$, 348.0053; found, 348.0058.
Compound **17**: mp 91–92 °C; IR (thin film) 3207, 1737; ^1H NMR (300 MHz, $CDCl_3$, ~1:1 mixture of diastereomers) δ 9.41 (s, 1H), 9.40 (s, 1H), 7.92–7.91 (m, 2H), 7.89–7.88 (m, 2H), 7.66–7.57 (m, 8H), 7.54–7.50 (m, 4H), 7.44–7.41 (m, 6H), 7.30–7. 29 (m, 2H), 7.23–7.18 (m, 2H), 7.10–7.05 (m, 2H), 4.47 (dd, J = 8.4, 7.0 Hz, 2H), 3.40 (s, 3H), 3.34 (s, 3H), 3.26–3.23 (m, 2H), 3.15–3.07 (m, 4H), 3.00–2.92 (m, 4H), 2.81–2.60 (m, 4H), 2.55–2.48 (m, 2H), 2.43 (br s, 2H), 2.40–2.30 (m, 2H), 2.07–1.87 (m, 2H), 1.82–1.66 (m, 2H), 1.62–1.48 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 172.6, 172.5, 144.0, 143.9, 139.3, 138.0, 137.9, 134.0, 132.7, 132.6, 131.4 (two carbons), 129.8 (two carbons), 129.5, 128.9, 127.4, 127.3, 125.4, 125.3, 120.6, 120.4, 120.3 (two carbons), 120.1, 112.7, 62.4, 62.3, 57.0 (two carbons), 56.7 (two carbons), 55.0, 54.9, 52.6, 52.5, 46.5, 46.4, 27.4, 24.3, 22.2 (three carbons), 20.7 (two carbons); LRMS (ESI+) m/z (relative intensity) 599.2 (100% M+Na$^+$); HRMS (ESI) m/z calcd for $[C_{31}H_{33}N_2O_5S_2]^+$, 577.1876; found, 577.1831.
Compound **18a**: mp 96–97 °C; IR (thin film) 3212, 1660 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$, ~1:1 mixture of diastereomers) δ 9.12 (s, 1H), 9.02 (s, 1H), 7.68–7.64 (m, 4H), 7.60 (dd, J = 7.7, 3.4 Hz, 2H), 7.47–7.42 (m, 6H), 7.32–7.29 (m, 2H), 7.29–7. 26 (m, 2H), 7.22 (t, J = 14.9 Hz, 2H), 7.12–7.08 (m, 2H), 4.22 (s, 1H), 4.18 (s, 1H), 3.22–3.14 (m, 4H), 3.09–3.02 (m, 2H), 2.76–2.68 (m, 4H), 2.36–2.31 (m, 1H), 2.29 (s, 3H), 2.28 (s, 3H), 2.25–2.17 (m, 1H), 2.04 (br s, 4H), 1.67–1.59 (m, 2H), 1.26 (t, J = 7.2 Hz, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 195.4, 195.3, 144.2, 144.1, 143.7, 143.6, 143.4, 137.6, 137.4, 132.5, 132.4, 130.9, 130.8, 129.3 (two carbons), 127.1, 126.9, 125.0 (two carbons), 124.9 (two carbons), 120.7, 120.3, 120.2 (two carbons), 120.1, 112.1, 59.0 (two carbons), 54.7, 54.6, 50.1, 49.5, 31.9, 31.8, 26.3, 26.0, 24.3 (two carbons), 23.5, 21.9, 21.7; LRMS (ESI+) m/z (relative intensity) 419.1 (100% M+H$^+$); HRMS (ESI) m/z calcd for $[C_{26}H_{30}N_3O_3S]^+$, 419.1781; found, 419.1793.
Compound **18b**: mp 64–65 °C; IR (thin film) 3230, 1637 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 9.27 (s, 1H), 9.18 (s, 1H), 7.73–7.65 (m, 10H), 7.55–7.51 (m, 2H), 7.45–7.39 (m, 10H), 7.29–7.27 (m, 2H), 7.22 (t, J = 7.6 Hz, 2H), 7.10 (d, J = 7.8 Hz, 2H), 7.06 (d, J = 7.7 Hz, 2H), 4.28 (s, 1H), 4.25 (s, 1H), 3.29–3.10 (m, 4H), 3.17–3.10 (m, 2H), 2.94–2.88 (m, 2H), 2.80–2.74 (m, 2H), 2.50–2.47 (m, 1H), 2.38–2.30 (m, 1H), 2.16–2.04 (m, 4H), 1.75–1.64 (m, 2H), 1.46–1.36 (m, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 193.4, 193.3, 145.8 (two carbons), 143.7, 143.6, 142.9, 142.8, 137.7, 137.6, 137.4, 132.4, 132.2, 131.9 (two carbons), 130.7 (two carbons), 129.3 (two carbons), 129.2, 129.1, 128.1, 127.0, 126.8, 125.0, 124.9, 124.8, 120.7, 120.3, 120.2, 120.0, 112.2, 59.2 (two carbons), 55.0, 54.9, 52.0, 51.7, 31.8 (two carbons), 26.6, 26.3, 23.6, 21.9, 21.7; LRMS (ESI+) m/z (relative intensity) 481.2 (100% M+H$^+$); HRMS (ESI) m/z calcd for $[C_{30}H_{29}N_2O_2S]^+$, 481.1932; found, 481.1950.
Compound **20a**: IR (thin film) 1665, 1516 cm^{-1}; ^1H NMR (300 MHz, C_6D_6, mixture of diastereomers) δ 7.83–7.80 (m, 4H), 7.39–7.31 (m, 4H), 7.15–7.07 (m, 4H), 7.03–6.98 (m, 4H), 6.96–6.89 (m, 2H), 6.09 (br s, 2H), 3.50–3.36 (m, 2H), 3.24 (quit, J = 6.9 Hz, 2H), 2.74–2.67 (m, 4H), 2.46–2.36 (m, 2H), 2.27–2.17 (m, 2H), 2.08–1.96 (m, 2H), 1.91 (s, 3H), 1.88 (s, 3H), 1.86–1.76 (m, 4H), 1.76–1.64 (m, 2H), 1.64–153 (m, 2H), 1.40–1.05 (m, 2H), 0.97–0.90 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 200.4 (two carbons), 185.9, 155.1 (two carbons), 142.1, 142.0, 140.0, 139.3, 138.8, 135.4 (two carbons), 130.4, 130.2 (two carbons), 130.1, 129.9, 125.4, 125.3, 124.6, 124.5, 120.8 (two carbons), 82.4, 82.2, 59.5, 59.4, 52.5, 52.4, 32.5 (two carbons), 31.2 (two carbons), 29.0, 28.8, 27.0, 26.9, 26.7, 26.6, 26.5 (two carbons); LRMS (ESI+) m/z (relative intensity) 403.1 (100% M+H$^+$); HRMS (ESI) m/z calcd for $[C_{25}H_{27}N_2OS]^+$, 403.1847; found, 403.1844.
Compound **20b**: IR (thin film) 1643, 1515 cm^{-1}; ^1H NMR (300 MHz, C_6D_6, mixture of diastereomers) δ 7.82–7.78 (m, 4H), 7.61–7.54 (m, 4H), 7.39 (d, J = 7.2 Hz, 2H), 7.35 (d, J = 7.4 Hz, 2H), 7.11–7.00 (m, 14H), 6,96–6.90 (m, 2H), 6.18 (br s, 2H), 3.49–3.40 (m, 2H), 3.31–3.22 (m, 2H), 2.97–2.89 (m, 1H), 2.75–2.66 (m, 2H), 2.65–2.58 (m, 1H), 2.49 (dd, J = 12.2, 6.1 Hz, 1H), 2.42 (dd, J = 12.2, 6.6 Hz, 1H), 2.32–2.23 (m, 2H), 2.09–1.99 (m, 4H), 1.91–1.58 (m, 6H), 1.36–1.27 (m, 2H), 1.04–0.92 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 198.0 (two carbons), 184.7 (two carbons), 153.9, 143.9 (two carbons), 138.7 (two carbons), 138.1, 137.9, 137.6, 137.3, 134.3, 134.2, 133.0, 131.2, 129.2, 129.1, 129.0 (three carbons), 128.7, 128.6, 127.9 (two carbons), 124.2 (two carbons), 123.4, 123.3, 119.7, 119.6, 81.2, 81.1, 58.3 (two carbons), 51.3, 51.2, 31.5 (two carbons), 30.1, 30.0, 28.7, 28.5, 26.0, 25.7 (two carbons), 25.5; LRMS (ESI+) m/z (relative intensity) 465.2 (100% M+H$^+$); HRMS (ESI) m/z calcd for $[C_{30}H_{29}N_2OS]^+$, 465.2019; found, 465.2001.