Vanadium-catalyzed selenide oxidation with *in situ* [2,3] sigmatropic rearrangement (SOS reaction): Scope and asymmetric applications.[†]

T. Campbell Bourland, Rich G. Carter* and Alexandre F. T. Yokochi[¶]

Department of Chemistry, Oregon State University, Corvallis, OR 97331, USA. Fax: 541 737-9496; Tel: 541 737-9486; E-mail: rich.carter@oregonstate.edu

---

Electronic Supplementary Information

[†] A portion of the this work was conducted in the Department of Chemistry and Biochemistry, University of Mississippi, Oxford, MS 38677.

[¶] Director of X-ray Crystallographic Facility, Department of Chemistry, Oregon State University, Corvallis, OR 97331; E-mail: Alexandre.Yokochi@oregonstate.edu.

General experimental procedure for synthesis of selenides 9

To a stirred solution of the allylic alcohol (0.3 M in THF) was added *o*-nitrophenyl selenocyanate (1.2 equiv.) followed by PBu_3 (1.1 equiv.) dropwise over 5 minutes. After 4-12 h, the reaction was quenched with aqueous NaOH (1 M) and extracted with EtOAc (3 X). The dried ($MgSO_4$) extract was concentrated *in vacuo* and purified by chromatography over silica gel, eluting with 2-20% ethyl-acetate/hexane

9a:[1] Purified by column chromatography over silica gel, eluting with 5-20% EtOAc / hexanes, to give **9a** (86%): IR (neat) 2924, 1504, 1130, 728 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 8.29 (dd, J = 1.1, 7.6 Hz, 1H), 7.50-7.56 (m, 2H), 7.27-7.34 (m, 1H), 5.78 (dt, J = 7.2, 15.1 Hz, 1 H), 5.57 (dt, J = 7.6, 15.1 Hz, 1 H), 3.58 (d, J = 7.2 Hz, 2H), 1.99-2.06 (m, 2H), 1.24-1.35 (m, 8H), 0.87 (t, J = 6.9 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 146.9, 136.5, 134.4, 133.7, 129.6, 126.5, 125.6, 123.5, 32.6, 31.9, 29.3, 29.0, 28.9, 22.8, 14.3.

9b:[1] Purified by column chromatography over silica gel, eluting with 5-20% EtOAc / hexanes, to give **9b** (75%): IR (neat) 2922, 2849, 1590, 1565, 1504 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 8.29 (dd, J = 1.1, 8.5 Hz, 1H), 7.49-7.55 (m, 2H), 7.28-7.33 (m, 1H), 5.70 (dd, J = 6.8, 15.2 Hz, 1 H), 5.52 (dt, J = 7.3, 15.2 Hz, 1 H), 3.57 (d, J = 7.3 Hz, 2H), 1.94-1.97 (m, 1H), 1.58-1.73 (m, 4H), 1.01-1.27 (m, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 146.9, 142.2, 134.3, 133.6, 129.8, 126.5, 125.6, 121.0, 40.8, 32.9, 29.1, 26.3, 26.1.

9c:[1] Purified by column chromatography over silica gel, eluting with 5-20% EtOAc / hexanes, to give **9c** (92%): IR (neat) 2900, 2845, 1513, 1330, 729 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 8.29 (dd, J = 1.1, 6.9 Hz, 1H), 7.49-7.54 (m, 2H), 7.33 (dd, J = 6.9, 8.0 Hz, 1H), 5.62 (d, J = 15.5 Hz, 1 H), 5.41 (dt, J = 7.2, 15.5 Hz, 1 H), 3.59 (d, J = 7.2 Hz, 2H), 1.97 (bs, 3H), 1.54-1.73 (m, 12H); ^{13} C NMR (75 MHz, $CDCl_3$) δ 147.7, 146.9, 134.3, 133.6, 129.8, 126.4, 125.6, 118.4, 42.2, 36.9, 35.2, 29.4, 28.5.

9d:[1] Purified by chromatography over silica gel, eluting with 5-30 % EtOAc / petroleum ether, to give **9d** (85%): IR (neat) 2940, 1596, 1506 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 8.28 (dd, J = 0.9, 8.3 Hz, 1H), 7.50-7.61 (m, 2H), 7.27-7.35 (m, 3H) 6.87 (d, J = 7.4 Hz, 2H), 6.61 (d, J = 15.7 Hz, 1H), 6.20 (dt, J = 7.5, 15.7 Hz, 1H), 3.81 (s, 3H), 3.79 (d, J = 7.5 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 159.6, 146.9, 134.2, 134.0, 133.9, 129.6, 129.4, 127.8, 126.6, 125.8, 121.1, 114.2, 55.5, 29.4.

9e:[2] Purified by chromatography over silica gel, eluting with 2-20 % EtOAc / petroleum ether, to give **9e** (70%): IR (neat) 3079, 3056, 2927, 1589, 1565, 1513 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 8.30 (dd, J = 1.6, 8.1 Hz, 1H), 7.24-7.41 (m, 8H), 6.64 (d, J = 11.5 Hz, 1H), 6.20 (dt, J = 8.0, 11.5 Hz, 1H), 3.86 (d, J = 8.0 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 146.7, 136.5, 133.9, 133.8, 133.3, 129.6, 129.0, 128.8, 127.7, 126.6, 125.8, 125.7, 25.0.

9f:[1] Purified by chromatography over silica gel, eluting with 5-10 % EtOAc / petroleum ether, to give **9f** (66%): IR (neat) 2982, 1562, 1507 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 8.28 (dd, J = 1.0, 8.1 Hz, 1H), 7.64 (d, 8.1 Hz, 1H), 7.53 (ddd, J = 1.0, 7.3, 7.9 Hz, 1H), 7.21-7.37 (m, 6H), 6.64 (s, 1H), 3.82 (s, 2H), 2.07 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 147.2, 137.5, 134.3, 133.7, 132.9, 129.9, 129.8, 129.0, 128.4, 126.9, 126.5, 125.8, 37.8, 18.3.

9g:[1] Purified by column chromatography over silica gel, eluting with 5-20% EtOAc / hexanes, to give **12** (86%): IR 2924, 1504, 1130, 728, cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 8.29 (d, J = 8.1 Hz, 1H), 7.50-7.56 (m, 2H), 7.27-7.34 (m, 1H), 5.57-5.69 (m, 2H), 3.64 (d, J = 6.8 Hz, 2H), 2.13-2.20 (m, 1H), 1.29-1.45 (m, 10H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 146.7, 135.9, 135.0, 133.8, 129.5, 126.5, 125.5, 122.5, 36.7, 33.4, 26.1, 25.9, 24.0.

9h:[2] Purified by chromatography over silica gel, eluting with 2-20 % EtOAc / petroleum ether, to give **9h** (70%): IR (neat) 3079, 3056, 2927, 1589, 1565, 1513 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 8.30 (dd, J = 1.6, 8.1 Hz, 1H), 7.24-7.41 (m, 8H), 6.64 (d, J = 11.5 Hz, 1H), 6.20 (dt, J = 8.0, 11.5 Hz, 1H), 3.86 (d, J = 8.0 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 146.7, 136.5, 133.9, 133.8, 133.3, 129.6, 129.0, 128.8, 127.7, 126.6, 125.8, 125.7, 25.0.

12:[1] Purified by chromatography over silica gel, eluting with 10 -20 % EtOAc / hexanes, to give **12** (81%): IR (neat) 2919, 1560, 1503 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 8.28 (dd, J = 1.0, 8.1 Hz, 1H), 7.48-7.51 (m, 2H), 7.09-7.35 (m, 6H), 5.71 (dd, J = 6.7, 15.1 Hz, 1H), 5.49 (dt, J = 7.3 Hz, 15.1 Hz), 3.55 (d, J = 7.3 Hz), 2.42-2.65 (m, 3H), 0.97 (d, J = 6.2 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 141.1, 140.5, 134.3, 133.6, 129.6, 129.4, 128.3, 126.5, 126.1, 125.6, 122.3, 43.5, 38.6, 28.7, 20.0.

14:[1] Purified by column chromatography over silica gel, eluting with 2-20% EtOAc / hexanes, to give **14** (60%): IR (neat) 3024, 2957, 2923, 1589, 1565, 1512 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 8.29 (d, J = 8.1Hz, 1H), 7.48 (dd, J = 6.8, 7.8 Hz, 1H), 7.15-7.40 (m, 7 H), 5.43-5.57 (m, 2H), 3.41 (dd, J = 7.3, 10.8 Hz, 1H), 3.26 (dd, J = 6.2, 10.8 Hz, 1H), 2.79-2.87 (m, 1H), 2.54-2.74 (m, 2H), 1.07 (d, J = 6.7 Hz, 3Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 146.2, 140.6, 134.9, 133.8, 129.5, 129.4, 128.6, 128.4, 126.6, 126.3, 125.5, 121.8, 43.8, 24.7, 23.7, 21.1.

General experimental for synthesis of rearranged alcohols 10

To a stirred solution of the selenide **9** in CH_2Cl_2 (0.3 M) with powdered 4Å molecular sieves (1g per mmol) was added $VO(acac)_2$ (10 mol %). After 10 -15 min, the green solution was cooled to -10°C in an ice / acetone bath and cumene hydrogen peroxide (1.8 equiv.) was added. After 30 min, the deep red solution was quenched with PBu_3 (1.2 equiv.). After an additional 5 min, saturated aqueous NH_4Cl was added and extracted with Et_2O (3 X). The dried ($MgSO_4$) extract was concentrated *in vacuo* and purified.

10a:[3] Purified by column chromatography over silica gel, eluting with 0.5%-1% MeOH / CH_2Cl_2 , to give **10a** (70% from **9a**, 89% from **9g**): IR (neat) 3351, 2928, 2857, 1644 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.87 (ddd, J = 6.3, 10.5, 17.2 Hz, 1H), 5.21 (dd, J =, 1.4, 17.2 Hz, 1H), 5.10 (dd, J =, 1.4, 10.5 Hz, 1H), 4.08-4.10 (m, 1H),1.25-1.63 (m, 10H), 0.88 (t, J = 6.8 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 141.5, 114.7, 73.5, 37.2, 31.9, 29.4, 25.4, 22.8, 14.2.

10b:[4] Purified by column chromatography over silica gel, eluting with 0.5%-1% MeOH / CH_2Cl_2, to give **10b** (75%): IR (neat) 3398, 2924, 2852, 1643 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.85 (ddd, J = 6.4, 10.4, 17.1 Hz, 1H), 5.20 (dd, J = 1.6, 17.1 Hz, 1H), 5.14 (dd, J =

1.6, 10.4 Hz, 1H), 3.80 (dd, J = 6.3, 6.4 Hz, 1H), 1.60-1.95 (m, 5H), 0.96-1.50 (m, 6H); ^{13} C NMR (75 MHz, $CDCl_3$) δ 139.9, 115.7, 78.0, 43.6, 28.9, 28.5, 26.7, 26.2.

10c:[1] Purified by column chromatography over silica gel, eluting with 2-20% EtOAc / hexanes, to give **10c** (84%): IR (neat) 3368, 2902, 2847 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.94 (ddd, J = 6.9, 10.9, 17.4 Hz, 1H), 5.17-5.23 (m, 2H), 3.57 (d, J = 6.9 Hz, 1H), 1.98 (bs, 3H), 1.40-1.90 (m, 12H); ^{13} C NMR (75 MHz, $CDCl_3$) δ 139.1, 116.7, 81.7, 38.2, 37.3, 37.0, 28.5.

10d:[5] Purified by chromatography over silica gel, eluting with 2-25 % Et_2O / pentane, to give **10d** (66%): IR (neat) 3400, 3076, 3003, 2956, 1610, 1513 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.29 (d, J = 6.8 Hz, 2H), 6.89 (d, J = 6.8 Hz, 2H), 6.04 (ddd, J = 5.6, 10.3, 17.0 Hz, 1H), 5.33 (dd, J = 1.1, 17.0 Hz, 1H), 5.15-5.21 (m, 2H), 3.80 (s, 3H), 2.16 (bs, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 159.4, 140.6, 135.1, 127.9, 115.0, 114.1, 75.1, 55.5.

10e:[6] Purified by chromatography over silica gel, eluting with 2-15 % Et_2O / petroleum ether, to give **10e** (65% for **9e**, 86% for **9h**): IR (neat) 3364, 3071, 2862, 1501 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.26-7.43 (m, 5H), 6.06 (ddd, J = 6.0, 10.3, 17.0 Hz, 1H), 5.36 (d, J = 17.0 Hz, 1H), 5.19-5.23 (m, 2H), 2.16 (bs, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 142.8, 140.4, 128.7, 128.0, 126.5, 115.3, 75.6.

10f:[7] Purified by chromatography over silica gel, eluting with 2-15 % Et_2O / petroleum ether, to give **10f** (70%): IR (neat) 3383, 2972, 1651, 1492, 1450 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.26-7.40 (m, 5H), 5.22 (s, 1H), 5.13 (s, 1H), 4.97 (s, 1H), 2.15-2.25 (bs, 1H) 1.62 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 147.0, 142.2, 128.6, 127.9, 126.7, 111.4, 78.0, 18.5.

13:[1] Purified by chromatography over silica gel, eluting with 2-20 % Et_2O / pentane, to give **13** (60% from **12**, 71% from **14**): IR (neat) 3386, 3082, 3025, 2962, 2927, 1602; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.17-7.31 (m, 5H), 5.86-5.93 (m, 1H), 5.17-5.30 (m, 2H), 4.06 (bs, 1H of a diastereomer), 3.99 (bs, 1H of a diastereomer), 2.84-2.92 (m, 1H), 2.33-2.44 (m, 1H), 1.91-1.94 (m, 1H), 1.75 (bs, 1H), 0.87 (d, J = 6.9 Hz, 3H of a diastereomer), 0.84 (d, J = 6.9 Hz, 3H of a diastereomer); ^{13} C NMR (75 MHz, $CDCl_3$) δ 141.2, 141.0, 139.9, 139.2, 129.5, 129.4, 128.5, 128.4, 126.1, 116.5, 115.5, 77.6, 75.7, 40.84, 40.80, 39.4, 38.9, 29.9, 15.0, 14.0.

X-Ray analysis

Crystals of both compounds were grown from a solution in hexane/ethyl acetate (1:1) by cooling to -20°C. For the crystal structure determination, data collection was carried out on a Rigaku/MSC R-Axis Rapid diffractometer (Cu-Kα radiation, λ = 1.5418 Å) equipped with an Oxford Cryosystems HT low temperature device. Data collection occurred as a series of five scan sequences consisting of 40 images of 5° rotation about omega each (θ = 0 – 200°), at different settings of chi and phi (χ = 0, ϕ = 0; χ = 50, ϕ = 0, χ = 50, ϕ = 90, χ = 50 ϕ = 180; χ = 50, ϕ = 270°). The program TwinSolve as included in CrystalClear was used to search the images for strong reflections, autoindexing, unit cell refinement, reflection integration, absorption correction (multiscans or analytical face indexed method) and final merging/scaling of the reflections to a SHELX style data file. The structure of **55** was

determined at a temperature of 100(2)K, whereas that for **66**, due to complications including a temperature induced order/disorder phase transition, was determined at room temperature.

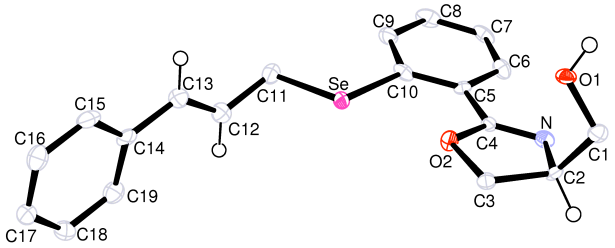

Figure 2. Molecular structure of compound **55** showing the numbering system and the conformation of the molecule. Displacement ellipsoids drawn at the 50% probability level.

Crystal data for **55**: $C_{19}H_{19}NO_2Se$, M = 372.31, a = 9.0550(9), b = 4.8997(6), c = 18.0554(19) Å, β = 100.842(3)°, V = 786.76(15) Å^3, $P2_1$ (#5), Z = 2, μ = 3.305 mm^{-1} (multiscans absorption correction), 8096 reflections were recorded in the range θ = 2.49 to 68.46°, of which 2157 were independent [R(int) = 0.072] and all of which were strongly observed [2σ(I)]. The structure was solved by direct methods using the program SHELXS-97 and refined using SHEXL-97. All hydrogen atoms were placed in geometrically idealized positions. Full-matrix least-squares methods on F^2 converged to R1 = 0.0319 and wR2 = 0.0914 with a goodness of fit of 1.098. The refined value of the absolute structure parameter (Flack parameter)[8] of -0.03(3) indicates that the model obtained accurately depicts the absolute structure of the molecule.

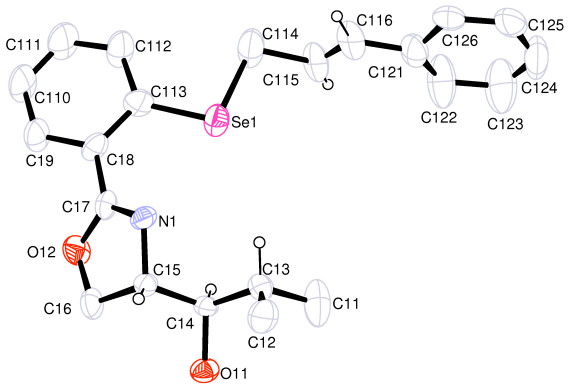

Figure 3. Molecular structure of compound **66** showing one of the independent conformers in the asymmetric unit, the numbering system and the conformation of the molecule. The numbering scheme for the second independent conformer is identical to that shown with the exception that atom numbers start with 2 (e.g., C21, C22, etc.). Displacement ellipsoids are drawn at the 30% probability level.

Crystal data for **66**: $C_{22}H_{25}NO_2Se$, M = 414.39, a = 5.2672(14), b = 12.0311(14), c = 17.196(2) Å, α = 104.049(9), β = 98.288(15), γ = 99.018(15), V = 1025.0(3) Å^3, $P1$ (#1), Z = 2, μ = 2.590 mm^{-1} (multiscans absorption correction), 10804 reflections were recorded in the range μ = 2.69 to 71.59°, of which 4859 were independent [R(int) = 0.044] and of which

4512 were considered observed [$2\alpha(I)$]. The structure was solved by direct methods using the program SHELXS-97 and refined using SHEXL-97. All hydrogen atoms were placed in geometrically idealized positions. Full-matrix least-squares methods on F^2 converged to R1 = 0.0362, wR2 = 0.0735 (all data) with a goodness of fit of 1.097. The refined value of the absolute structure parameter (Flack parameter) of 0.00(2) indicates that the model obtained accurately depicts the absolute structure of the molecule. Refinement of the structure in space group P-1 (#2) was attempted but resulted in a severely disordered oxazole fragment. That, coupled with the fact that the compound under examination is known to be enantiomerically pure indicates that the best space group in which to refine the present structure is P1 (#1).

Table 9. Selected intramolecular parameters about the Se atoms (distances in Å, angles in °) from the X-ray diffraction data.

55		**66** (Conformer #1)		**66** (Conformer #2)	
Se-C(10)	1.912(4)	Se(1)-C(113)	1.864(7)	Se(2)-C(213)	1.950(5)
Se-C(11)	1.955(5)	Se(1)-C(114)	1.941(9)	Se(2)-C(214)	1.974(8)
Se…O(2)	2.709(4)	N(1)…Se(1)	2.990(7)	N(2)…Se(2)	2.764(6)
C(10)-Se-C(11)	101.6(2)	C(113)-Se(1)-C(114)	99.5(3)	C(213)-Se(2)-C(214)	100.7(3)
C(10)-Se…O(2)	73.7(2)	C(113)-Se(1)…N(1)	72.9(2)	C(213)-Se(1)…N(1)	74.3(2)
C(11)-Se…O(2)	174.2(2)	C(114)-Se(1)…N(1)	166.6(3)	C(214)-Se(1)…N(1)	174.4(3)

1 R. G. Carter, T. C. Bourland, *Chem. Commun.,* 2000, 2031.
2 N. Komatsu, Y. Nishibayashi, S. Uemura, *Tetrahedron Lett.,* 1993, **34**, 2339.
3 F. Bohlmann, H. G. Viehe, *Chem. Ber.*, 1955, **88**, 1245-51.
4 P. A. Aristoff, P. D. Johnson, A. W. Harrison, *J. Amer. Chem. Soc.*, 1985, **107**, 7967-74.
5 W. N. White, W. K. Fife, *J. Am. Chem. Soc.,* 1961**, 83**, 3846-53.
6 F. A. Davis, R. T. Reddy, *J. Org. Chem.,* 1992, **57**, 2599.
7 P. G. Stevens, O. C. W. Allenby, A. S. DuBois, *J. Am. Chem. Soc.,* 1940, **62**, 1424-28.
8 Flack, H. D. *Acta Crystallogr.* 1983, **A39**, 876.