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FULL PAPER

Phosphorus-Chalcogen Chemistry

Reactivity of Woollins' Reagent Toward 2-En-1-imines (Schiff Bases): A Facile Approach to Synthesize New Selenium-Phosphorus-Nitrogen Heterocycles

Guoxiong Hua^[a], David B. Cordes^[a], Alexandra M. Z. Slawin^[a] and J. Derek Woollins^{*[a][b]}

Abstract: Woollins' Reagent serves as a reductive cycloaddition reagent, reacting with 2-en-1-imines containing a conjugated C=C bond group (Schiff bases) leading to a series of four-, five-, six-membered 1,2-azaphospholidines incorporating one or two N-P=Se linkages. Ten single crystal X-ray structures confirming the formation of these small N-P-Se heterocycles are reported.

Introduction

Phosphorus-containing heterocycles have attracted considerable attention particularly due to their roles as supporting ligands in homogeneous catalysis¹⁻³ and in pharmaceutical and biological applications such as anticancer, cytotoxicity or antitumor effects.⁴⁻⁷ Nevertheless, their straightforward synthesis remains challenging, largely because the chemical transformations available for the preparation of organic heterocycles are not available to phosphorus-containing species. The synthesis of new phosphorus-carbon heterocycles has seen the use of the 2-phosphaethynolate anion (PCO⁻) for the synthesis of novel four- to six-membered ring systems.⁸⁻¹⁴ In addition, ring closure metathesis (RCM) has emerged as a convenient tool for the preparation of dihydro-phosphinine oxides involving a further functionalization or reduction step as advanced precursors in sequences leading to 1,2-azaphospholidine targets.¹⁵⁻¹⁷ To the best of our knowledge, organic heterocyclic studies on the direct reaction between Schiff bases and chalcogen reagents have remained unexplored. We have developed and exploited the chemistry of 2,4-bis(phenyl)-1,3-diselenadiphosphetane-2,4-diselenide (Woollins' Reagent, **WR**) as a versatile selenation reagent in synthetic chemistry in recent years.¹⁸⁻³¹ We have also successfully applied Woollins' Reagent to efficiently synthesize a series of eight-, nine-, and ten-membered selenophosphorus heterocycles with P-Se-Se-P linkages,³² and a unique octaselenocyclododecane with four carbon

atoms and eight selenium atoms in a twelve-membered macrocycle³³. To continue our interest in the chemistry of Woollins' Reagent towards various organic substrates, in this context, we report a comprehensive study on the outcome of the reaction between Schiff bases (2-en-1-imines) and Woollins' Reagent and ten related single crystal X-ray structures. This is the first reported synthesis and single crystal structures of such four- to six-membered ring heterocycles incorporating one or two N-P=Se linkages.

Results and Discussion

Synthesis and Spectroscopic Characterization

Schiff bases (imines) are one of the most widely used precursors in organic synthesis and are important ligands in coordination chemistry.³⁴ Schiff bases can be prepared from aliphatic or aromatic amines and carbonyl-containing compounds by nucleophilic addition, following by a dehydration to give imines. In this study, we particularly focused on conjugated Schiff bases, thus a series of conjugated Schiff bases (2-en-1-imines) **1a-n** was synthesized by means of literature procedures.³⁵⁻⁴⁰ First, we investigated the reaction of typical simple Schiff bases with Woollins' Reagent. The precursor **1a** reacts with Woollins' Reagent upon refluxing for 7 h in toluene *via* a [3+2] cycloaddition reaction leading to the formation of a five-membered selenazadiphospholidine-2,5-diselenide **2a** in 43% isolated yield after workup in open air, as shown in Scheme 1. In solution, compound **2a** shows four typical phosphorus ³¹P NMR signals at 69.3, 65.1, 60.2 and 55.4 ppm, accompanied by the corresponding coupling constants of 343-385 Hz for P-Se single bonds and 817-822 Hz for P=Se double bonds, respectively, revealing the formation of two diastereomers in *ca.* 3:1 intensity ratio.

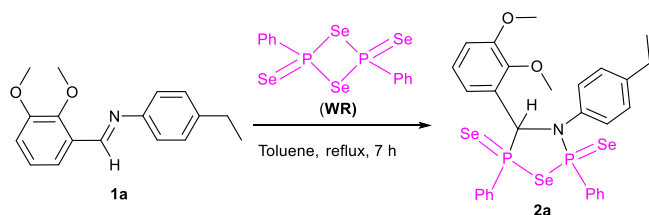
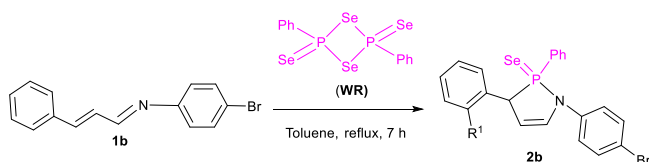
We speculated that the Schiff bases with a conjugated C=C bond might be especially reactive, thus, **1b** was prepared as starting material. Reacting **1b** and Woollins' Reagent in refluxing toluene for 7 h gave five-membered 1,2-azaphosphole 2-selenide **2b** in 89% yield (Scheme 2) *via* a [1+4] cycloaddition reaction. The ³¹P NMR signals of two typical phosphorus centres at 59.9 and 59.8 ppm were observed, accompanied by the corresponding coupling constants of 825 and 823 Hz for P=Se double bonds, revealing the formation of two diastereomers (in *ca.* 1:1 intensity ratio) in compound **2b**.

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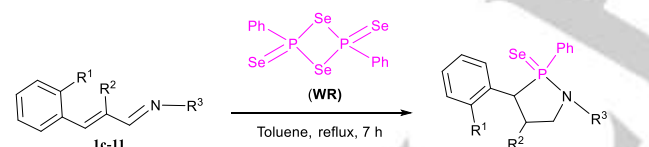
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Scheme 1. Cycloaddition derivative **2a** of Schiff base **1a**Scheme 2. Cycloaddition derivative **2b** of Schiff base **1b**

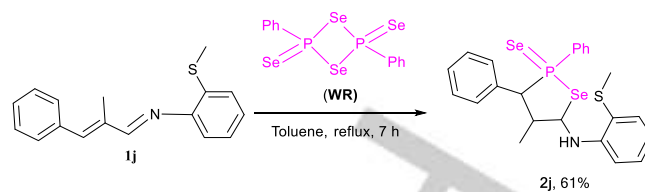
A series of saturated five-membered ring products **2c-i** were obtained in moderate to good yields (34-67%) when substituted Schiff bases **1c-i** with a conjugated C=C link were reacted with Woollins' Reagent *via* both cycloaddition reaction and further reduction reaction as shown in Scheme 3. The solution ^{31}P NMR spectra of compounds **2c-g** and **2i**, only one typical phosphorus signal (68.8-79.0 ppm) was observed, accompanied by the corresponding coupling constants of 758-788 Hz for P=Se double bonds, respectively, indicating the absence of any diastereomers. However, for **2h**, three phosphorus signals at 74.4, 76.7 and 78.4 ppm were observed, suggesting the presence of three diastereomers. It is worth noting that the ^{31}P shifts at 68.8-79.0 for these saturated five-membered rings **2c-i** are significantly greater than those in the unsaturated five-membered ring **2b** (59.9 and 59.8 ppm).



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|--|--|
| 1c. R ¹ = OCH ₃ , R ² = H, R ³ = 4-C ₂ H ₅ C ₆ H ₄ | 2c. R ¹ = OCH ₃ , R ² = H, R ³ = 4-C ₂ H ₅ C ₆ H ₄ , 66% |
| 1d. R ¹ = OCH ₃ , R ² = H, R ³ = C ₆ H ₄ CH(CH ₃) | 2d. R ¹ = OCH ₃ , R ² = H, R ³ = C ₆ H ₄ CH(CH ₃), 66% |
| 1e. R ¹ = OCH ₃ , R ² = H, R ³ = 2-CH ₃ C ₆ H ₄ CH ₂ | 2e. R ¹ = OCH ₃ , R ² = H, R ³ = 2-CH ₃ C ₆ H ₄ CH ₂ , 67% |
| 1f. R ¹ = OCH ₃ , R ² = H, R ³ = 4-C ₁₀ H ₂₃ C ₆ H ₄ | 2f. R ¹ = OCH ₃ , R ² = H, R ³ = 4-C ₁₀ H ₂₃ C ₆ H ₄ , 48% |
| 1g. R ¹ = OCH ₃ , R ² = H, R ³ = C(CH ₃) ₃ | 2g. R ¹ = OCH ₃ , R ² = H, R ³ = C(CH ₃) ₃ , 37% |
| 1h. R ¹ = H, R ² = CH ₃ , R ³ = <i>o</i> -Hex | 2h. R ¹ = H, R ² = CH ₃ , R ³ = <i>o</i> -Hex, 34% |
| 1i. R ¹ = OCH ₃ , R ² = H, R ³ = <i>o</i> -Hex | 2i. R ¹ = OCH ₃ , R ² = H, R ³ = <i>o</i> -Hex, 44% |

Scheme 3. Cycloaddition derivatives **2c-i** of Schiff bases **1c-i**

Interestingly, Schiff base **1j**, with a CH₃S group attached to an aminophenyl ring, when treated with Woollins' Reagent under the same conditions via a [2+3] cycloaddition reaction to afford an unexpected five-membered heterocycle **2j** in 61% yield rather than an analogue of five-membered heterocycles **2c-i** (Scheme 4). NMR spectra show that two isomers were found in **2j** in *ca.* 1:1 intensity ratio. The ^{31}P chemical shifts are 53.6 and 54.8 ppm, which are significantly smaller than the values in these saturated phosphorus-nitrogen five-membered rings **2c-i** (68.8-79.0 ppm).

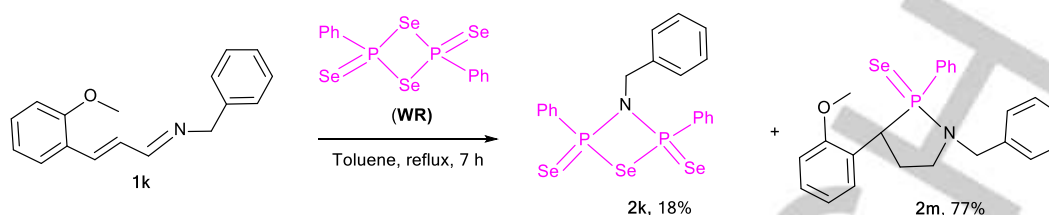
Scheme 4. Cycloaddition derivatives **2j** of Schiff base **1j**

The suggested reaction mechanisms for the formation of compounds **2a-2j** can be explained as follows. As we can observe, in all cases, PhP(Se) or PhP(Se)Se or PhP(Se)-Se-P(Se)Ph moieties from the monomic part of Woollins' Reagent were engaged in the final products **2a-2j**. The formation of the five-membered **2a** is made up of a PhP(Se)-Se-P(Se)Ph unit, resulted from the replacement of an Se atom in four-membered ring P(μ -Se)(μ -Se)P from Woollins' Reagent by an C=N group from Schiff base **1a**. The five-membered heterocycle **2b** consists of a PhP(Se) fragment, which is the result of the reaction of PhP(Se)Se species with Schiff base **1b** *via* a typical cycloaddition of a P=Se bond across the C=C-C=N bond leading to a six-membered intermediate, the latter finally loses a Se atom. The 1,2-azaphospholidine 2-selenides **2c-i** also comprise a PhP(Se) fragment, the same mechanism as **2b** was applied, accompanied with further reduction of C=N double bond in the newly formed five-membered ring by Woollins' Reagent. The similar reduction mechanism has been reported previously, Woollins' Reagent is acted as an efficient chemoselective reductant of the double bond of diketones⁴¹ and 2- α,β -unsaturated thioazo and selenazolidinones.⁴² The five-membered heterocycle **2j** is also the consequence of reaction PhP(Se)Se with Schiff base **1j** *via* a cycloaddition reaction as well as further reduction reaction by Woollins' Reagent.

The expected heterocycle **2m** along with a four-membered heterocycle **2k** were obtained in 77% and 18% isolated yields respectively when Schiff base **1k** was reacted with Woollins' Reagent (Scheme 5). It appears likely that the minor product **2k**, which includes a PhP(Se)-Se-P(Se)Ph fragment, arises from the cleavage of the C=N bond in starting material **1k**, with one of two Se atoms within the four-membered ring in Woollins' Reagent being replaced by a PhCH₂N group from the conjugated Schiff base **1k**. The analogues of four-membered heterocycle **2k** can be also prepared from other starting material or other approach, for instance, Woollins' Reagent reacts with azobenzene to give PhP(Se)(μ -Se)(μ -NPh)P(Se),⁴³ whilst PhP(Se)(μ -Se)(μ -NMe)P(Se) was obtained from the oxidative ring contraction of [-PhP-NMe-PPh-Se-]₂ with selenium.⁴⁴ The formation mechanism of **2m** is the same as that in **2c-i** as described as above. The ^{31}P NMR spectrum of compound **2m** (81.2 ppm) is similar to the saturated phosphorus-nitrogen five-membered rings **2c-i** (68.8-79.0 ppm). However, the ^{31}P chemical shift of the four-membered heterocycle **2k** (44.4 ppm) is similar to its analogues [43.4 ppm for PhP(Se)(μ -Se)(μ -NPh)P(Se) and 44.7 for PhP(Se)(μ -Se)(μ -NMe)P(Se)],^{43,44} which are significantly smaller than the values in these saturated

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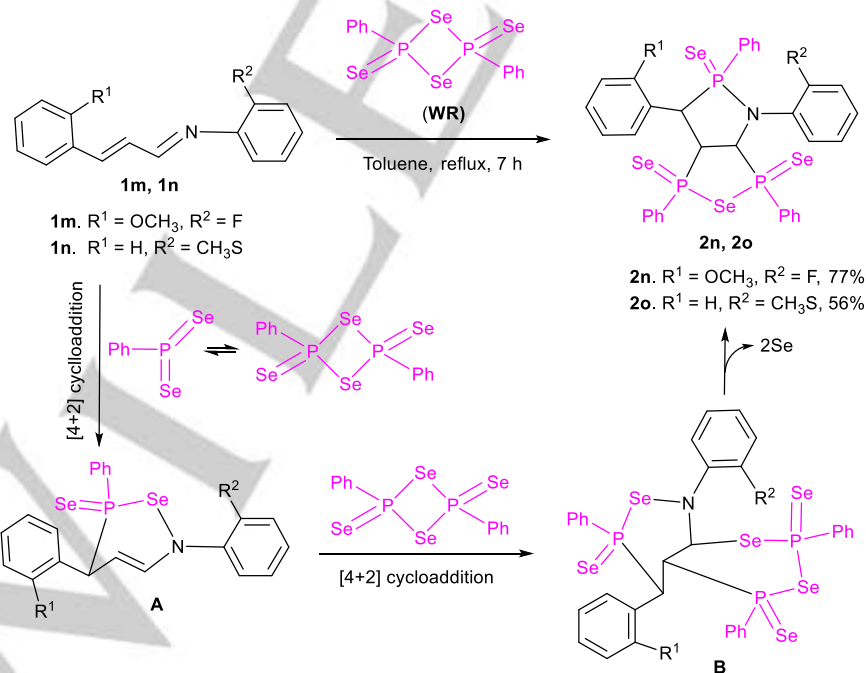
phosphorus-nitrogen five-membered rings **2c-i**, **2k** (68.8-81.2 ppm).



Scheme 5. Cycloaddition derivatives **2k** and **2m** of Schiff base **1k**

The *ortho*-fused heterocycles **2n** and **2o** were formed by the reaction of Schiff bases **1m** and **1n** with Woollins' Reagent (Scheme 6). In contrast to the above reactions, both PhP(Se) and PhP(Se)-Se-P(Se)Ph moieties from the monomic part of Woollins' reagent were inserted into the final products. Schiff bases **1m** and **1n** react with Woollins' Reagent leading to the intermediate A via a [4+2] cycloaddition reaction (in an analogous manner to that seen in the formation of **2b-i**), then a further [4+2] cycloaddition reaction gives the intermediate B by the reaction of intermediate A with another molecule of Woollins' Reagent.

Finally, the unstable intermediate B is converted into the *ortho*-fused heterocycles **2n** and **2o** via a ring contraction with loss of two Se atoms. The *ortho*-fused heterocycles **2n** and **2o** can be described as the composite of the single five-membered ring **2a** and the saturated phosphorus-nitrogen five-membered rings **2c-i**, **2k**. However, the ^{31}P NMR spectra of the fused rings in **2n** and **2o** are not simply combined, the chemical shifts of C_3NP rings (97.3 ppm in **2n** and 92.7 ppm in **2o**) are much greater than those in the single phosphorus-nitrogen five-membered rings **2c-i**, **2k** (68.8-81.2 ppm), and the chemical shifts of $\text{C}_2\text{P}(\text{Se})\text{SeP}(\text{Se})$ (59.6/42.4 ppm in **2n**, and 60.9/41.6 ppm in **2o**) are significantly smaller than those in the single five-membered heterocycle **2a** (69.3/60.2 and 65.1/55.4 ppm).



Scheme 6. Cycloaddition *ortho*-fused derivatives **2n** and **2o** of Schiff bases **1m** and **1n**

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Single Crystal X-ray Structures

To further characterize these new heterocycles, single crystals of **2a**, **2c**, **2d**, **2g**, **2h**, **2i**, **2j**, **2k**, **2n** and **2o** suitable for X-ray crystallographic analysis were obtained from the slow evaporation of dichloromethane or chloroform solution of the compound in air at room temperature. The crystallographic data and structure refinement are listed in Tables S1 and S2 and the resulting molecular structures are illustrated in Figures 1-10. The asymmetric units of the structures of **2a**, **2c**, **2g**, **2j** and **2k** contain a single molecule of the compound, while for **2d**, **2i**, **2n** and **2o** the asymmetric unit contains two independent molecules, or three for **2h**. The only structures with co-crystallised solvent are **2n** and **2o**, with one equivalent of chloroform, and half an equivalent of dichloromethane, respectively.

It can be seen from Figure 1, the framework of **2a** contains a saturated five-membered P₂SeCN ring bearing a P(Se)-Se-P(Se) linkage with the exocyclic P=Se groups orientated trans to each other. Two phenyl rings attached on the two phosphorus atoms also positioned in trans to each other with the dihedral angles of 72.04° and 84.91°, respectively, to the mean-plane of the new P₂SeCN ring. The other two aryl rings are also *trans* to each other with dihedral angles of 80.26° and 81.57°, respectively, to the mean-plane of the new P₂SeCN ring. The P-Se and P=Se bond lengths are typical and comparable with those found in the literature for unsaturated five-membered P₂SeCN rings; however, the P-Se-P angle [92.01(3)°] is larger than those [89.97(7)-91.44(3)°] found in unsaturated five-membered P₂SeCN rings.^{45,46} The geometries around P(1) [Se(1)-P(1)-Se(2): 115.06(3) Å] and P(3) [Se(3)-P(3)-Se(2): 111.39(3) Å] are distorted tetrahedral due to the effects of the steric hindrance of the attached phenyl rings.⁴⁷ The transannular P...P distance is 3.236 Å, similar to those in related P₂SeCN ring systems [3.21-3.24 Å].⁴⁵ However, this distance is marginally longer than those observed in a four-membered P₂Se₂ ring systems [3.1 Å] and considerably shorter than those measured in a six-membered P₂Se₄ ring system [4.3 Å].⁴⁹

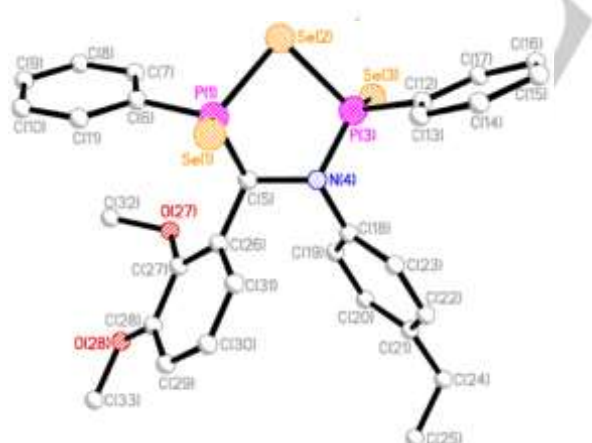


Figure 1. X-ray structure of compound **2a** (Hydrogen atoms omitted for clarity). Selected bond lengths (Å) and angles (°) (esds in parentheses): Se(1)-P(1) 2.0870(8), P(1)-Se(2) 2.2407(7), P(1)-C(5) 1.866(2), Se(3)-P(3) 2.0798(8), P(3)-Se(2) 2.2574(7), P(3)-N(4) 1.709(2), C(5)-N(4) 1.479(3); P(1)-Se(2)-P(3) 92.01(3), Se(1)-P(1)-Se(2) 115.06(3), Se(1)-

P(1)-C(5) 118.54(9), Se(2)-P(1)-C(5) 96.33(8), Se(3)-P(3)-Se(2) 111.39(3), Se(3)-P(3)-N(4) 118.80(8), Se(2)-P(3)-N(4) 100.18(7), P(1)-C(5)-N(4) 106.81(16), P(3)-N(4)-C(5) 115.79(16)

The X-ray analyses of **2c**, **2d**, **2g**, **2h** and **2i** confirm that these 1,2-azaaphospholidine 2-selenides contain newly formed five-membered PNC₃ ring in the solid state as shown in Figures 2-6. The crystal structures contain multiple independent molecules in **2d**, **2h** and **2i**, the principal difference between these being the orientation of the attached phenyl rings. The newly formed PNC₃ rings are distinctly folded in all of **2c**, **2d**, **2g**, **2h** and **2i**. The dihedral angles between exocyclic phenyl rings and the newly formed PNC₃ rings are 67.76, 15.20 and 74.46° for **2c**, 44.71[39.69], 82.31[84.63] and 86.76[86.49]° for **2d**, 68.06 and 81.27° for **2g**, 84.68[83.47, 87.08], 88.79 [77.35, 79.56] (the dihedral angle between the newly ring and exocyclic hexyl ring) and 85.02[86.88, 85.00]° for **2h**, and 41.55[40.36], 76.95[83.20] (the dihedral angle between the newly ring and exocyclic hexyl ring) and 72.30[78.38]° for **2i**. The geometry at endocyclic nitrogen atom is closer to planarity in **2c** ($\Sigma\langle N = 359.84^\circ$), **2d** ($\Sigma\langle N = 358.30/359.60^\circ$), **2h** ($\Sigma\langle N = 359.74/358.97/359.22^\circ$) and **2i** ($\Sigma\langle N = 359.85/359.62^\circ$) than in **2g** ($\Sigma\langle N = 357.6^\circ$) because of the different substituents on the nitrogen atom. The P=Se bond distances ranging from 2.0986(9) to 2.1126(14) Å are slightly longer than P=Se bond lengths previously observed in other related compounds containing the P(Se)(μ -Se) unit.^{43,47,49,50} The elongated bonds are likely the result of ring strain in the five-membered rings, which are all puckered.

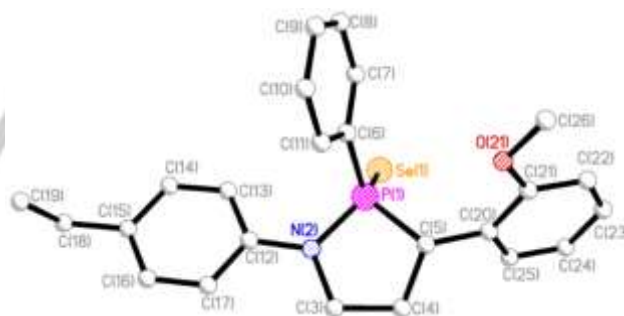


Figure 2. X-ray structure of compound **2c** (Hydrogen atoms omitted for clarity). Selected bond lengths (Å) and angles (°) (esds in parentheses): P(1)-Se(1) 2.0986(9), P(1)-N(2) 1.690(3), P(1)-C(5) 1.837(3), N(2)-C(3) 1.472(4), C(3)-C(4) 1.515(4), C(4)-C(5) 1.531(4); Se(1)-P(1)-N(2) 118.45(9), Se(1)-P(1)-C(5) 115.86(10), N(2)-P(1)-C(5) 93.02(12), P(1)-N(2)-C(3) 113.56(19), P(1)-C(5)-C(4) 101.84(19), N(2)-C(3)-C(4) 106.1(2), C(3)-C(4)-C(5) 105.8(3)

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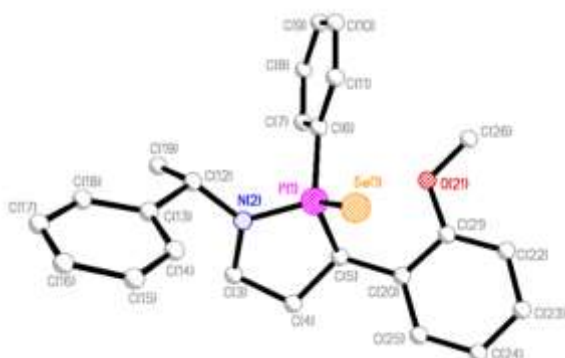


Figure 3. X-ray structure of compound **2d** (Only one independent molecule shown, hydrogen atoms omitted for clarity). Selected bond lengths (Å) and angles (°) (esds in parentheses): Se(1)-P(1) 2.1060(11) [2.1040(11)], P(1)-N(2) 1.661(3) [1.660(3)], P(1)-C(5) 1.847(4) [1.851(4)], N(2)-C(3) 1.466(4) [1.464(5)], C(3)-C(4) 1.514(5) [1.519(5)], C(4)-C(5) 1.534(5) [1.537(5)]; Se(1)-P(1)-N(2) 117.08(12) [114.51(11)], Se(1)-P(1)-C(5) 115.22(13) [117.14(13)], N(2)-P(1)-C(5) 93.37(16) [93.95(16)], P(1)-N(2)-C(3) 115.1(2) [114.3(2)], P(1)-C(5)-C(4) 100.8(2) [102.6(2)], N(2)-C(3)-C(4) 105.7(3) [104.7(3)], C(3)-C(4)-C(5) 107.5(3) [106.6(3)].

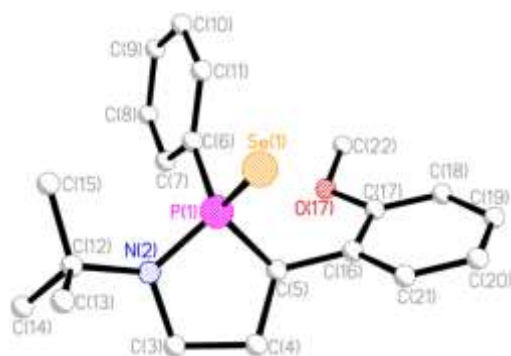


Figure 4. X-ray structure of compound **2g** (Hydrogen atoms omitted for clarity). Selected bond lengths (Å) and angles (°) (esds in parentheses): P(1)-Se(1) 2.1126(14), P(1)-N(2) 1.6630(12), P(1)-C(5) 1.8443(14), N(2)-C(3) 1.4836(18), C(3)-C(4) 1.520(2), C(4)-C(5) 1.533(2); Se(1)-P(1)-N(2) 119.29(5), Se(1)-P(1)-C(5) 115.51(5), N(2)-P(1)-C(5) 93.17(6), P(1)-N(2)-C(3) 113.01(9), P(1)-C(5)-C(4) 100.43(10), N(2)-C(3)-C(4) 107.60(12), C(3)-C(4)-C(5) 106.00(12).

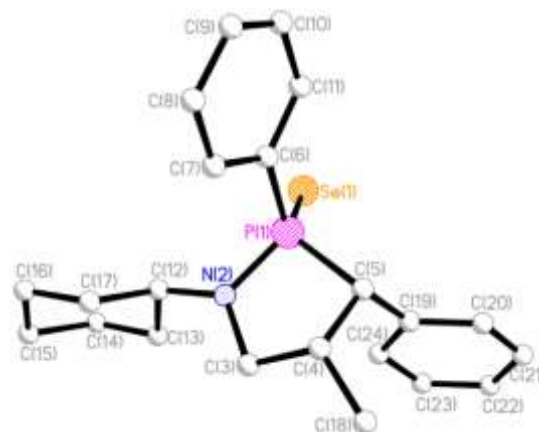


Figure 5. X-ray structure of compound **2h** (Only one independent molecule shown, hydrogen atoms omitted for clarity). Selected bond lengths (Å) and angles (°) (esds in parentheses): P(1)-Se(1) 2.102(3) [2.099(3), 2.104(3)], P(1)-N(2) 1.656(9) [1.657(9), 1.652(9)], P(1)-C(5) 1.857(11) [1.820(10), 1.821(11)], N(2)-C(3) 1.4651,459(14) [1.478(13), 1.442(13)], C(3)-C(4) 1.550(16) [1.536(15), 1.516(14)], C(4)-C(5) 1.549(16) [1.562(15), 1.561(14)]; Se(1)-P(1)-N(2) 117.7(3) [117.5(3), 116.8(3)], Se(1)-P(1)-C(5) 118.5(4) [118.4(4), 119.4(4)], N(2)-P(1)-C(5) 94.7(5) [94.7(5), 93.9(5)], P(1)-N(2)-C(3) 114.5(7) [114.6(7), 114.6(7)], P(1)-C(5)-C(4) 102.2(7) [101.4(7), 101.8(7)], N(2)-C(3)-C(4) 107.2(9) [106.2(8), 107.9(8)], C(3)-C(4)-C(5) 105.8(9) [106.3(8), 104.9(8)].

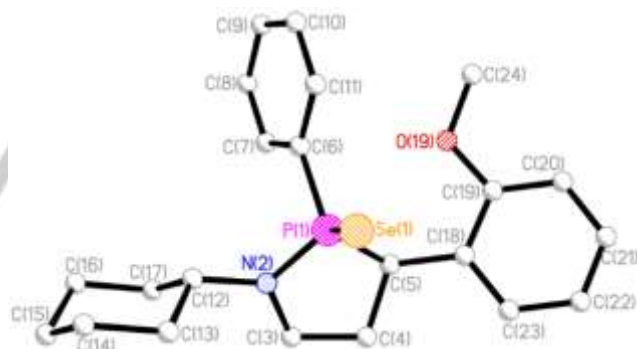


Figure 6. X-ray structure of compound **2i** (Only one independent molecule shown, hydrogen atoms omitted for clarity). Selected bond lengths (Å) and angles (°) (esds in parentheses): P(1)-Se(1) 2.1083(12) [2.1096(12)], P(1)-N(2) 1.657(4) [1.657(4)], P(1)-C(5) 1.848(4) [1.854(4)], N(2)-C(3) 1.465(4) [1.465(6)], C(3)-C(4) 1.516(6) [1.516(6)], C(4)-C(5) 1.525(6) [1.527(6)]; Se(1)-P(1)-N(2) 118.58(14) [118.76(14)], Se(1)-P(1)-C(5) 116.59(15) [115.98(15)], N(2)-P(1)-C(5) 92.88(18) [92.46(19)], P(1)-N(2)-C(3) 115.5(3) [115.6(3)], P(1)-C(5)-C(4) 100.8(3) [100.8(3)], N(2)-C(3)-C(4) 105.9(3) [106.1(4)], C(3)-C(4)-C(5) 108.0(3) [107.8(3)].

The X-ray structure of **2j** reveals a five-membered ring PSeC₃ motif with two exocyclic phenyl rings adopting a *cis*-orientation to the newly formed ring (Figure 7). The dihedral angles between three exocyclic phenyl rings and the mean

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plane of the newly formed PSeC₃ ring are 60.07°, 65.34° and 82.99°, respectively. The relative short P(1)-C(6) bond length of 1.814(4) Å, compared to P(1)-C(5) 1.852(4) Å, indicates partial double bond character. The bond distances of P(1)-Se(1) [2.0974(11) Å] and P(1)-Se(2) [2.2163(11) Å] are similar to the P-Se and P=Se bond lengths previously observed in other related compounds containing the P(Se)(μ-Se) unit.^{43,47,49,50} The molecular structure of **2k** (Figure 8) displays comparable structural parameters to those reported for other analogues containing the P₂SeN ring motif, which were obtained previously, thus, we abstain from a detailed discussion here.^{43,51}

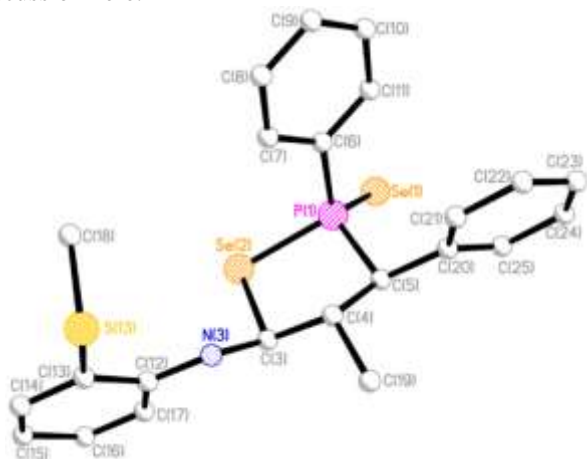


Figure 7. X-ray structure of compound **2j** (Hydrogen atoms omitted for clarity). Selected bond lengths (Å) and angles (°) (esds in parentheses): P(1)-Se(1) 2.0974(11), P(1)-Se(2) 2.2163(11), P(1)-C(5) 1.852(4), P(1)-C(6) 1.814(4), Se(2)-C(3) 2.070(4), C(3)-C(4) 1.516(5), C(4)-C(5) 1.533(5), C(3)-N(3) 1.421(5); Se(1)-P(1)-Se(2) 117.05(5), Se(1)-P(1)-C(5) 113.54(12), Se(2)-P(1)-C(5) 97.23(13), P(1)-Se(2)-C(3) 90.72(10), P(1)-C(5)-C(4) 108.9(3), Se(2)-C(3)-C(4) 110.1(2), C(3)-C(4)-C(5) 118.3(3).

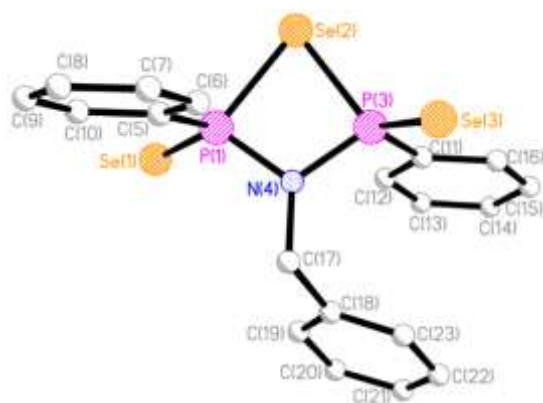


Figure 8. X-ray structure of compound **2k** (Hydrogen atoms omitted for clarity). Selected bond lengths (Å) and angles (°) (esds in parentheses): P(1)-Se(1) 2.0829(6), P(1)-Se(2) 2.2706(7), P(3)-Se(3) 2.0873(7), P(3)-Se(2) 2.2670(7), P(1)-N(4) 1.686(2), P(3)-N(4) 1.692(2); P(1)-Se(2)-P(3) 74.92(2), Se(1)-P(1)-Se(2) 119.20(3), Se(1)-P(1)-N(4) 117.51(7), Se(3)-P(3)-Se(2) 118.41(3), Se(3)-P(3)-N(4) 114.74(7), P(1)-N(4)-P(3) 109.60(11).

The molecular structures of the fused heterocycles **2n** and **2o** are displayed in Figures 9 and 10. The configurations of two structures appear similar to each other, with two exocyclic phenyl rings and two P=Se bonds displaying a *trans*-orientation to the newly formed P₂SeC₂ ring. The conformations for **2n** and **2o** can be described as twisted-chair configurations. The newly formed fused rings are also distorted as reflected by the bond angles of N(2)-C(3)-P(4) and C(8)-C(7)-P(6) [115.1(3)° and 116.1(3)° in **2n**, and 116.90(18)° and 115.17(18)° in **2o**]. The P=Se and P-Se bond lengths [P(1)-Se(1) 2.0885(13) Å, P(4)-Se(4) 2.0890(13) Å, P(6)-Se(6) 2.0847(13) Å, P(4)-Se(5) 2.2789(12) Å and P(6)-Se(5) 2.2858(12) Å in **2n**, and P(1)-Se(1) 2.0872(8) Å, P(4)-Se(4) 2.0807(8) Å, P(6)-Se(6) 2.0814(8) Å, P(4)-Se(5) 2.2832(8) Å and P(6)-Se(5) 2.2800(8) Å in **2o**] are comparable with those in **2a**, also typical of P-Se and P=Se bond lengths in related compounds incorporating the P(Se)(μ-Se) unit.^{43,47,49,50}

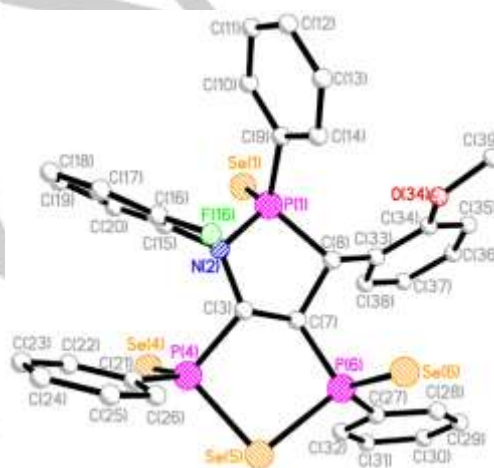


Figure 9. X-ray structure of compound **2n** (Solvent and hydrogen atoms omitted for clarity). Selected bond lengths (Å) and angles (°) (esds in parentheses): P(1)-Se(1) 2.0885(13), P(1)-N(2) 1.684(3), P(1)-C(8) 1.853(4), N(2)-C(3) 1.451(5), P(4)-C(3) 1.859(4), P(4)-Se(4) 2.0890(13), P(4)-Se(5) 2.2789(12), P(6)-Se(5) 2.2858(12), P(6)-Se(6) 2.0847(13), P(6)-C(7) 1.837(4), C(7)-C(8) 1.532(5), C(3)-C(7) 1.528(6); Se(1)-P(1)-N(2) 116.67(13), Se(1)-P(1)-C(8) 116.06(15), N(2)-P(1)-C(8) 93.09(17), Se(4)-P(4)-Se(5) 114.60(6), Se(4)-P(4)-C(3) 113.16(14), Se(5)-P(4)-C(3) 95.54(13), Se(6)-P(6)-Se(5) 115.78(6), Se(6)-P(6)-C(7) 113.10(14), Se(5)-P(6)-C(7) 97.85(13), P(1)-N(2)-C(3) 114.9(3), P(1)-C(8)-C(7) 100.9(3), P(4)-C(3)-N(2) 115.1(3), P(4)-C(3)-C(7) 107.2(3), P(4)-Se(5)-P(6) 93.34(4), P(6)-C(7)-C(8) 116.1(3), P(6)-C(7)-C(3) 107.2(3), N(2)-C(3)-C(7) 105.5(3), C(3)-C(7)-C(8) 107.0(3).

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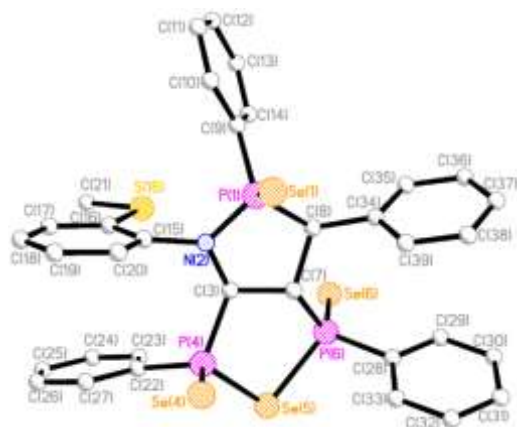


Figure 10. X-ray structure of compound **2o** (Solvent and hydrogen atoms omitted for clarity). Selected bond lengths (Å) and angles (°) (esds in parentheses): P(1)-Se(1) 2.0872(8), P(1)-N(2) 1.682(2), P(1)-C(8) 1.853(3), N(2)-C(3) 1.462(3), P(4)-C(3) 1.857(3), P(4)-Se(4) 2.0807(8), P(4)-Se(5) 2.2832(8), P(6)-Se(5) 2.2800(8), P(6)-Se(6) 2.0814(8), P(6)-C(7) 1.829(3), C(7)-C(8) 1.534(4), C(3)-C(7) 1.526(3); Se(1)-P(1)-N(2) 117.30(8), Se(1)-P(1)-C(8) 116.54(9), N(2)-P(1)-C(8) 92.32(11), Se(4)-P(4)-Se(5) 114.61(3), Se(4)-P(4)-C(3) 115.66(9), Se(5)-P(4)-C(3) 95.50(8), Se(6)-P(6)-Se(5) 114.52(4), Se(6)-P(6)-C(7) 115.36(9), Se(5)-P(6)-C(7) 97.56(9), P(1)-N(2)-C(3) 114.98(16), P(1)-C(8)-C(7) 99.76(16), P(4)-C(3)-N(2) 116.90(18), P(4)-C(3)-C(7) 106.77(16), P(4)-Se(5)-P(6) 93.51(3), P(6)-C(7)-C(8) 115.17(18), P(6)-C(7)-C(3) 108.37(18), N(2)-C(3)-C(7) 105.2(2), C(3)-C(7)-C(8) 106.7(2).

Conclusions

a series of new four-, five- and six-membered heterocycles has been prepared from the reaction of Woollins' Reagent and 2-en-1-imines (Schiff bases) with a conjugated C=C bond. Woollins' Reagent in these reactions acts as a very efficiently reductive cycloaddition reagent to Schiff bases. Ten single crystal X-ray structures, further confirming the formation of these small N-P-Se heterocycles, reveal different structural profiles. In all cases, the newly formed 1,3-selenazole ring is not completely planar, and none of the mean planes of the newly formed five-membered ring are co-planar with the exocyclic aryl rings, displaying a range of dihedral angles. It is anticipated that this route would be a very useful approach for the synthesis of small P(Se)-N heterocycles, which will be easily available for further investigations into their chemistry and biological applications.

Experimental Section

Unless otherwise stated, all reactions were carried out under on oxygen free nitrogen atmosphere using pre-dried solvents and standard Schlenk techniques, subsequent chromatographic and work up procedures were performed in air. ^1H (400.1 MHz), ^{13}C (100.6 MHz) and ^{31}P - $\{^1\text{H}\}$ (162.0 MHz) were recorded at 25 °C on a Noah Bruker Advance II 400s and ^{77}Se - $\{^1\text{H}\}$ (51.4 MHz referenced to external Me_2Se)

NMR spectra was recorded at 25 °C on a JEOL GSX 270. IR spectra were recorded as KBr pellets in the range of 4000-250 cm^{-1} on a Perkin-Elmer 2000 FTIR/Raman spectrometer. The University of St-Andrews microanalysis service performed microanalysis. Mass spectrometry was performed by the EPSRC National Mass Spectrometry Service Centre, Swansea and the University of St Andrews Mass Spectrometry Service. Unless otherwise stated, all reactions were carried out under on oxygen free nitrogen atmosphere using pre-dried solvents and standard Schlenk techniques, subsequent chromatographic and work up procedures were performed in air. ^1H (400.1 MHz), ^{13}C (100.6 MHz) and ^{31}P - $\{^1\text{H}\}$ (162.0 MHz) NMR spectra were recorded at 25 °C (unless stated otherwise) on Bruker Advance II 400. IR spectra were recorded as KBr pellets in the range of 4000-250 cm^{-1} on a Perkin-Elmer 2000 FTIR/Raman spectrometer. Mass spectrometry was performed by the EPSRC National Mass Spectrometry Service Centre, Swansea. X-ray diffraction data for all compounds were collected at 173 K by using a Rigaku FR-X Ultrahigh Brilliance Microfocus RA generator/confocal optics and XtaLAB P200 diffractometer system, with Mo K α radiation ($\lambda = 0.71075$ Å). Intensity data were collected using ω steps accumulating area detector images spanning at least a hemisphere of reciprocal space. All data were corrected for Lorentz polarization effects. A multi-scan absorption correction was applied by using CrystalClear.⁵² Structures were solved by either Patterson (PATTY)⁵³ or charge-flipping (SUPERFLIP),⁵⁴ methods and refined by full-matrix least-squares against F^2 (SHELXL-2017/1).⁵⁵ Non-hydrogen atoms were refined anisotropically, and hydrogen atoms were refined using a riding model, except for the NH hydrogen in **2j** which was located from the difference Fourier map and refined isotropically subject to a distance restraint. All calculations were performed using the CrystalStructure interface.⁵⁶ CCDC 1937139-1937148 contains the supplementary crystallographic data for this paper. The data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/structures.

General procedure for Synthesis of compounds 2a-o. A solution of Schiff base (1.0 mmol) and Woollins' Reagent (0.54 g, 1.0 mmol) in 20 mL of dry toluene was stirred at 130°C for 7 h. Following cooling to room temperature and removing solvent in vacuo, the organic residue was purified by silica gel column (eluted by 1:1 hexane/dichloromethane) to give the targeted products **2a-o**. The detailed characterization of new compounds can be seen in SI.

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Keywords: Woollins' Reagent • Schiff bases • 2-En-1-imines • Selenium-phosphorus-nitrogen heterocycles • Single crystal X-ray structures

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