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Discovery of a Dual SENP1 and SENP2 Inhibitor

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Abstract: SUMOylation is a reversible post–translational modification (PTM) involving covalent attachment of small ubiquitin-related modifier (SUMO) proteins to substrate proteins. Dysregulation of SUMOylation and deSUMOylation results in cellular malfunction and is linked to various diseases, such as cancer. Sentrin-specific proteases (SENPs) were identified for the maturation of SUMOs and the deconjugation of SUMOs from their substrate proteins. Hence, this is a promising target tackling the dysregulation of the SUMOylation process. Herein, we report the discovery of a novel protein-protein interaction (PPI) inhibitor for SENP1-SUMO1 by virtual screening and subsequent medicinal chemistry optimization of the hit molecule. The optimized inhibitor ZHAWOC8697 showed IC50 values of 8.6 µM against SENP1 and 2.3 µM against SENP2. With a photo affinity probe the SENP target was validated. This novel SENP inhibitor represents a new valuable tool for the study of SUMOylation processes and the SENP-associated development of small molecule-based treatment options.

Keywords: medicinal chemistry; SENP; deubiquitinating enzymes; structure activity relationship; inhibitors; cancer; small molecules; drug discovery

1. Introduction

SUMOylation is a reversible post-translational modification that targets a variety of proteins by attachment of small ubiquitin-like modifiers (SUMOs) [1,2]. SUMO proteins are similar to ubiquitin and are considered members of the ubiquitin-like protein family. It has been shown that SUMOylation and deSUMOylation has a major influence on cellular processes such as transcription, DNA damage response or cell division [3–6]. SUMOylation is regulated by a cascade of reactions catalyzed by SUMO-specific activating enzyme E1, conjugation enzyme E2, and ligase enzyme E3, whereas deSUMOylation is regulated by the family of Sentrin-specific proteases (SENPs) [7]. SENPs are cysteine proteases, which are responsible for the activation of proSUMOs to SUMOs and removal of small ubiquitin-like modifiers (SUMOs) from the post-translational modified proteins.

All SUMOs are expressed as proSUMOs. At the C-terminus, during the maturation of proSUMOs to SUMOs, two to eleven amino acids are proteolytically cleaved by SENP endopeptidases. In total, there are six different human SENPs (1, 2, 3, 5, 6, and 7), which have a sequence similarity between 20 and 60%.

SUMOylation is of great importance for the regulated cell cycle and genome stability. If SENP1 expression is incorrectly regulated, serious diseases, such as prostate [8,9], bladder [10], multiple myeloma [11], pancreatic [12] or neuroblastoma cancer [13] can occur. SENP1 is therefore a clinically highly relevant antitumor target and of growing interest for developing novel treatment options for cancer patients [14,15]. Other research showed that SENP1 deSUMOylates and stabilizes hypoxia-inducible factor 1α (HIF-1α) during hypoxia [16].

Early research on SENP1 inhibitors focused on peptide-based probes derived from SUMO1 protein, which covalently bind to cysteine in the catalytic site of the protease [17,18]. The first small molecule inhibitors reported in 2011 were also covalent inhibitors targeting...
the catalytic site resulting in two-digit micromolar inhibitors (1–3) (Figure 1) [19,20]. Later, non-covalent inhibitors (4–10) for SENP1 were developed [21–26], with the most potent compounds 7 and 9 having IC_{50} values of 1.08 [21] and 0.99 µM [25], respectively (Figure 1). Herein, we report the identification and biological evaluation of novel, non-covalent, small molecule SENP1 inhibitors, resulting, to the best of our knowledge, in one of the most potent non-covalent SENP1 inhibitors currently known.

![Chemical structures of reported small molecule SENP1 inhibitors (1-10).](image)

Figure 1. Selection of reported small molecule SENP1 inhibitors (1–10).

2. Results

2.1. Virtual Screening

We envisaged a virtual screening on the interface between SENP1 and SUMO1 (PDB code: 2G4D) proteins to identify new structural elements for the development of novel SENP1 inhibitors (Figure 2A). An in-house diversity library containing 10,240 compounds was screened against the SENP1-SUMO1 interface using AutoDock Vina [27] and resulted in 598 virtual hits with a binding score of <−7.3 kcal/mol (Figure 2B). After visual inspection of the compounds in the hypothesized binding mode to SENP1, 50 promising compounds were shortlisted for screening at 50 µM by a fluorescence-based assay against the catalytic domain of SENP1, using SUMO1-AMC as substrate. At this concentration, five compounds showed a SENP1 activity decrease of >50% (Figure 2C,D). Two of the hit molecules had solubility issues at the tested concentration and were not further investigated. IC_{50} values were determined of the remaining three hit molecules with the most promising compound 11 (ZHAWOC8697) showing an IC_{50} of 5.1 µM (Figure 2D).
Figure 2. (A) X-ray crystal structure of SUMO1 (cartoon: magenta)-SENPI (PDB code: 2G4D); (B) Virtual screening process against the protein-protein interaction between SENPI and SUMO1; (D) The hit structures 11 (ZHAWOCS8697), 12 and 13 are shown with the corresponding in vitro measured IC₅₀ value and the proposed binding mode (C).

To confirm the activity of the spiro dihydroquinoxalinone (DHQ), compound 11 was resynthesized to validate the activity and the structural identity. Additionally, the importance of the spirocyclic dihydroquinoxalinone was investigated through the synthesis of gem-dimethyl and non-substituted dihydroquinoxalinone analogues. The synthesis of the spiro dihydroquinoxalinone (15) and gem-dimethyl (16) building block was performed according to Lai et al. [28] with a Bargellini reaction of 1,2-diaminobenzene (14) and cyclopentanone or acetone, chloroform and NaOH to obtain the compounds 15 and 16 in 71% and 73% yield, respectively (Scheme 1).

Scheme 1. Synthetic scheme for hit compound 11 and the analogues 23 and 24. Reagents and conditions: (i) cyclopentanone or acetone, 14 (diamine), CHCl₃, BnEt₃NCl, CH₂Cl₂, 33% NaOH (aq.), 0 °C—rt, overnight, 73% for 15; 71% for 16; (ii) NaN₃, NH₃Cl, 120 °C, overnight, 87%; (iii) methyl chloroacetate, Et₃N, MeCN, 70 °C, 2 h, 9:1 mixture of the 2H- (19, 81%) and 1H- substituted tetrazole (20, 9%); (iv) LiOH, THF/H₂O, rt, 16 h, 100%; (v) 1: 19 (carboxylic acid), oxalyl chloride, DMF (cat.), CH₂Cl₂, rt, 15 min, 2: DHQ (15, 16 or 25), Et₃N, rt, 3 h, 13% (11), 7% (23), 17% (24).
The synthesis of the phenyl tetrazole building block 21 commenced with a [2 + 3] dipolar cycloaddition of benzonitrile 17 with sodium azide to generate tetrazole 18. Subsequently the phenyl tetrazole 18 was N-alkylated with methyl chloroacetate to the desired 1H-(19) and 2H-regiosomer (20), followed by ester hydrolysis to obtain compounds 21 and 22. The 2H-tetrazole 21 was converted to an acid chloride with oxalyl chloride and directly coupled to either the spirocyclic (15), gem-dimethyl (16) or non-substituted (25) DHQ derivative to isolate the hit molecule 11 and its close analogues 23 and 24 (Scheme 1).

The resynthesized hit molecule 11 and its derivatives 23 and 24 were tested for the inhibition of the catalytic activity of SENP1 (Table 1). Pleasingly, the inhibition of the resynthesized hit compound 11 was confirmed with an IC₅₀ of 8.6 µM. Interestingly, the gem-dimethyl (23) and non-substituted (24) DHQ derivatives showed reduced inhibition by a factor of 1.5 and 10, respectively (Table 1). This raises the question, as to whether this is due to the reduced compound lipophilicity or the steric restriction of the amide bond [29] between the DHQ amine and the bulky carboxylic amide phenyl tetrazole substituent. MD calculations for the rotational barrier of this amide bond were performed by umbrella sampling using Amber 17. The results indicate that with the gem-dimethyl and non-substituted dihydroquinoxalinone derivatives two preferred orientations of the amide linker with an angle of 44° and 136° or 22° and 158° are possible, whereas the spirocyclic compound has just one energy minimum at 120° due to steric clash with the bulky spirocyclopentane DHQ scaffold (Figure S1).

Table 1. IC₅₀ values of hit compound 11 and the corresponding modifications of the spiro DHQ scaffold 23 and 24; (a) n = 5; (b) n = 2.

| Compound | Structure | IC₅₀ SENP1 (µM) |
|----------|-----------|----------------|
| 11       | ![Structure](image1) | 8.6 (6.3–12) (a) |
| 23       | ![Structure](image2) | 12.3 (9.2–16.5) (b) |
| 24       | ![Structure](image3) | 77.6 (57.8–104) (b) |

2.2. Fragments

To investigate this theory, structurally relevant fragments were tested in the SENP1 inhibition assay at concentrations of up to 1 mM. The spirocyclic compound 15 had an IC₅₀ of 116 µM, whereas the gem-dimethyl DHQ derivative 16 showed only around 50% inhibition at 500 µM (Table 2). The sterically hindered amide bond is not present in those fragments, allowing us to conclude that the different orientations of the amide bond do not result in different ligand binding affinities.
Table 2. List of the synthesized fragments (15, 16, 25–41). LE = ligand efficiency (calculated: 1.4(-logIC_{50})/N) [30]. (a) n = 4, (b) n = 2. * Compound is fluorescent at c > 10 µM; NA = not applicable.

| Compound | Structure | IC_{50} SENP1 [µM] | LE  | Compound | Structure | IC_{50} SENP1 [µM] | LE  |
|----------|-----------|---------------------|-----|----------|-----------|---------------------|-----|
| 15       | ![Structure](image1.png) | 116 (79–170) [a]     | 0.37| 33       | ![Structure](image3.png) | >500 [b]         | NA |
| 16       | ![Structure](image2.png) | >500 [b]           | NA  | 34       | ![Structure](image4.png) | >500 [b]         | NA |
| 25       | ![Structure](image5.png) | >500 [b]           | NA  | 35       | ![Structure](image6.png) | 37 [b] (23–61)   | 0.44|
| 26       | ![Structure](image7.png) | 78 [b] (47–130)     | 0.38| 36       | ![Structure](image8.png) | 61 [b] (38–98)   | 0.39|
| 27       | ![Structure](image9.png) | 261 [b] (199–344)   | 0.31| 37       | ![Structure](image10.png) | 110 [b] (92–133) | 0.34|
| 28       | ![Structure](image11.png) | 51 [b] (32–79)      | 0.33| 38       | ![Structure](image12.png) | 61 [b] (47–79)   | 0.33|
| 29       | ![Structure](image13.png) | 66 [b] (57–77)      | 0.42| 39       | ![Structure](image14.png) | 198 [b] (141–288)| 0.32|
| 30       | ![Structure](image15.png) | 81 [b] (66–99)      | 0.41| 40       | ![Structure](image16.png) | 202 [b] (110–373)| 0.28|
| 31       | ![Structure](image17.png) | 233 [b] (182–298)   | 0.32| 41       | ![Structure](image18.png) | 67 [b] (48–94)   | 0.34|
| 32       | ![Structure](image19.png) | NA * [b]           | NA  |          |           |                     |     |

Various modifications of fragment 15 were synthesized to gain a better understanding of the important features and aiding inhibitor optimization. Compound 26 indicates that the secondary amine is not crucial and can be replaced by an ether resulting in comparable activity (Table 2). Increasing the spirocyclic ring size to increase the lipophilic character was beneficial for the cyclooctane derivative 28 (IC_{50}: 51 µM), whereas a slightly reduced activity of the cyclohexyl analogue 27 (IC_{50}: 261 µM) was measured. The spirocyclobutyl compound 29 had a slightly increased potency compared to 15 (Table 2). This is a surprising observation, that the spirocyclic ring size is equally important to the lipophilicity. Incorporation of an oxetane (30) or tetrahydropryan (31) into the spirocyclic compound resulted in a comparable inhibition profile similar to the aliphatic 4- (29) or 6-membered (27) derivatives (Table 2). In addition, with the heterospirocyclic compounds, the 6-membered spirocyclic compound 31 is less active compared to the 4-membered analogue 30. The inverse amide 32 was self-fluorescent at concentrations of up to 10 µM and hence no IC_{50} could be determined. Reduction of the amide bond of 15 to the amine 33 resulted in a loss of activity indicating that this hydrogen bond acceptor is crucial (Table 2). Modifications of the aromatic part by introducing a pyridine (34) resulted in a complete loss of activity up to 500 µM. Meanwhile, replacing the benzene moiety to a thiophene (35 and 36) gave a three-fold affinity increase, which is also a solid improvement in terms of ligand efficiency.
from 0.37 to 0.44 (Table 2). The attachment of substituents to the aromatic core of the dihydroquinolxinone, either with an electron-donating methoxy group (37, 39) or an electron-withdrawing group such as methyl ester (38, 40) or nitro (41), was well tolerated overall but showed a remarkable dependence on the point of attachment, suggesting defined interactions. Thus, the best affinities in this series were measured with electron-withdrawing groups in the 7- and 8-position (38, 41).

2.3. Modifications

Subsequently, the influence of modifications of the phenyl substituent on the heteroaromatic moiety was investigated with respect to the inhibitory effect. For easier synthetic accessibility, the tetrazole was replaced by a 1,2,3 triazole. The synthesis for those derivatives commenced by an N-acylation of DHQ fragment 15 with 2-chloroacetic chloride to obtain intermediate 42 (Scheme 2). Substitution of the chlorine with azide by an S_N2 reaction yielded the azide derivative 43, which was used to react with different alkyne substrates by copper catalyzed azide-alkyne coupling to obtain the desired triazole derivatives 44–53 in moderate yields.

![Scheme 2](image)

Scheme 2. Synthetic scheme of 1,2,3-triazole derivatives (44–53). Reagents and conditions: (i) 2-chloro acetic chloride, Et_3N, DMF, 0 °C, 30 min, 98%; (ii) NaN_3, DMF, 80 °C, 30 min, 78%; (iii) R-alkyne, CuSO_4, sodium ascorbate, t-BuOH, H_2O, DMSO, rt, 14–20 h, 15–47%.

In the fluorescence-based assay, the triazole derivative 44 showed a three-fold activity decrease compared to tetrazole 11 with an IC_{50} of 23 µM (Table 3). Despite the reduced activity, the structure activity relationship (SAR) can be well compared to the tetrazole derivatives within this compound series. In general, a flat SAR was observed. Exchanging the phenyl ring (44) by a saturated cyclohexyl (45) maintained the inhibition profile. A subtle activity decrease was measured with a benzyl (46) or 3-benzoic acid (47) substituent (Table 3). Having a substituent on the para position of the phenyl ring, such as the electron-deficient methyl ester (48) or electron-rich methoxy (49), resulted in a slightly increased inhibition of SENP1 with an IC_{50} of 7.5 and 13 µM, respectively (Table 3). Replacement of the phenyl ring with a basic 2-pyridine analogue (50) showed only slight inhibition at 200 µM (Table 3). This is not surprising as SENP1 is a lysine rich protein, hence, electronic repulsion of the ligand with the protein may explain this activity decrease. Replacement of the phenyl group with a cyclopropyl (51), carboxylic acid (52) or ethyl methyl ether (53) diminished the SENP1 activity. In addition, other phenyl tetrazole replacements (Supplementary compounds S1–S7) such as phenols, anilines and indolines were tested, however, all of them had drastically reduced inhibition (Table S1). Additionally, the 1H-phenyl tetrazole DHQ derivative (54) was synthesized by coupling 15 with 22 in an analogous manner to the procedure described in Scheme 1 and tested, which resulted in a five-fold activity reduction compared to the 2H derivative (11). Compound 55 was synthesized by an amide coupling of thieno[3,4-b]pyrazine (35) with the 2H-tetrazole (21) and is equipotent to the DHQ derivative (11).
Table 3. IC<sub>50</sub> values of 11 and its analogues; (a) n = 5.

| Compound | X     | R                | IC<sub>50</sub> SENP1 (µM) n = 2 |
|----------|-------|------------------|----------------------------------|
| 11       | N     | Ph               | 8.6<sup>(a)</sup> (6.3–12)       |
| 44       | CH    | Ph               | 23 (19–27)                       |
| 45       | CH    | cyclohexyl       | 19 (17–21)                       |
| 46       | CH    | benzyl           | 38 (28–52)                       |
| 47       | CH    | 3-benzoic acid   | 29 (24–36)                       |
| 48       | CH    | 4-benzoic acid methyl ester | 7.5 (6.3–8.9)       |
| 49       | CH    | 4-methoxyphenyl  | 13 (9–18)                        |
| 50       | CH    | 2-pyridine       | >200                             |
| 51       | CH    | cyclopropyl      | >200                             |
| 52       | CH    | CH<sub>2</sub>CO<sub>2</sub>H | >100                             |
| 53       | CH    | (CH<sub>2</sub>)<sub>2</sub>OCH<sub>3</sub> | >100                             |
| 54       |       |                  | 50 (43–57)                       |
| 55       |       |                  | 10 (8–13)                        |
| 56       |       |                  | 24 (20–29)                       |
| 57       |       |                  | 6.6 (5.7–7.7)                    |

2.4. Mode of Action and Target Verification

To confirm 11 is active on the native substrates and not just on the SUMO1-AMC test substrate in the fluorogenic assay, a protocol for gel-based assay for the recombinant human proSUMO substrate was adopted from Mikolajczyk et al. [31]. For proSUMO1, the terminal four amino acids are cleaved by SENP1 in the maturation process of the protein, whereas for proSUMO3 there are 12 amino acids. In the case of proSUMO1, the protein bands on the SDS gel could not be separated. However, with proSUMO3 a good separation of the matured protein with a 15% SDS polyacrylamide gel was achieved. For this reason, the inhibitory endopeptidase activity of 11 on SENP1 was determined with the proSUMO3 substrate. It could be clearly demonstrated that a full inhibition of SENP1 was observed at an inhibitor concentration of 200 µM, whereas at lower concentrations a dose-dependent
response was observed (Figure 3A). This confirms that the inhibitor does not only show activity on the SUMO-AMC test substrate, but also on native substrates, which underlines its biological significance and makes it a useful tool for further biological studies.

The photo affinity probe 56 consisting of the spiro DHQ scaffold coupled to a minimalist terminal alkyne-containing diazirine photo crosslinker [32] was synthesized to confirm the inhibitor-protein interaction (Scheme S1). With the fluorescent SENP1-SUMO1-AMC bioassay this compound showed an IC$_{50}$ value of 24 µM (Table 3). In comparison, the n-octyl derivative 57, which does not include the photo labile group, showed similar IC$_{50}$ data, indicating the diazirine group did not interfere in the fluorescent assay. To assess the interaction of SENP1 with the photo affinity probe, 56 was incubated with purified SENP1 and crosslinked via UV irradiation at 350 nM. The protein ligand mixture was coupled by CuAAC with the fluorescent TAMRA-azide dye and separated by SDS page electrophoresis. A fluorescent band was visible indicating the covalent binding of the probe to SENP1, confirming its interaction (Figure 3B,C). A competition experiment with the photo probe 56 and 11 under the same conditions showed that the fluorescently labelled band of SENP1 was significantly decreased, indicating a selective binding to the protein (Figure 3D,E).

![Figure 3](image-url)

**Figure 3.** SDS page gels of the maturation of proSUMO3 (A) and photo crosslinking experiments with 56 on SENP1 (B–E). (A) Endopeptidase inhibition of 11 against the maturation of proSUMO3 (c = 5 µM) with SENP1 (200 nM) incubated at 37 °C for 1 h: 1: no SENP1 added; 2–7: 3-fold dilution of 11 starting at 200 µM and final concentration of 0.8 µM; 8: no 11 added; (B,C) crosslinking experiments of 56 (200 µM) with SENP1 (10 µM) followed by CuAAC of the crosslinked probe to azide-fluor 545. 1: no UV irradiation 2–4: UV irradiation for 30 min; (D,E) crosslinking competition experiment of 56 (200 µM) with SENP1 (10 µM) followed by CuAAC of the crosslinked probe to azide-fluor 545. 1–2: no competitor inhibitor, 3–4: 11 (400 µM) was added. SDS gels were visualized by Coomassie blue stain (B,D) and fluorescence (Ex. 520 nm; Em. 575 nm) (C,E).

A mode of inhibition study with 11 was performed by kinetic measurement with SENP1 and SUMO1-AMC employing five different substrate concentrations (Figure 4). The IC$_{50}$ values decreased slightly by lowering the SUMO1-AMC substrate concentration from 1000 nM to 62.5 nM, indicating a slight binding preference to the SUMO1-SENP1 complex (Figure 4A). On analysis of the mixed inhibition model using GraphPad Prism on the global Michaelis-Menten plot, a K$_i$ of 10.6 µM and alpha of 0.23 was observed (Figure 4B). The alpha value indicates that a slight preference for the SUMO1-SENP1 complex is demonstrated.
Figure 4. (A) Mode of inhibition study: IC50 curves for compound 11 (ZHAVOC8697) against SENP1 at different substrate (SUMO1-AMC) concentrations; (B) global fit of Michaelis-Menten plots (GraphPad Prism).

2.5. Target Selectivity

The selectivity of the most promising compounds 11, 55 and the most potent published SENP1 inhibitor 7 was evaluated against SUMO2 and SUMO3 as well as SENP2 and the two DUB proteins, UCHL1 and Ataxin 3 (Table 4). The compounds 11 and 55 showed a moderate selectivity for the SUMO1 substrate over the SUMO2 and SUMO3 substrates, whereas 7 resulted in no significant differences. Surprisingly, this compound series had a slightly increased activity on the SENP2 protein. SENP2 has been identified by others to modulate atherosclerosis [33], neurodegenerative diseases [34], fatty acid metabolism [35] and adipogenesis [36]. With this wide range of functions, our discovered inhibitors could also be used to explore further the understudied SENP2 biology.

Table 4. IC50 values of 11 (ZHAVOC8697), 55 and published compound 7 [21]; n = 2.

| Compound | SENP1-SUMO1-AMC (µM) | SENP1-SUMO2-AMC (µM) | SENP1-SUMO3-AMC (µM) | SENP2-SUMO1-AMC (µM) | SENP2-SUMO2-AMC (µM) | SENP2-SUMO3-AMC (µM) | UCHL1 (µM) | Ataxin 3 (µM) |
|----------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-------------|--------------|
| 11       | 8.6 (6.3–12)          | 43 (31–59)            | 59 (41–86)            | 2.3 (1.6–3.5)         | 77 (57–105)           | 68 (53–89)            |             |              |
| 55       | 10 (8–13)             | 18 (15–22)            | 23 (15–38)            | 5.8 (3.2–10)          | 132 (107–162)         | >100                  |             |              |
| 7        | 9 (8–11)              | 4.3 (3.8–5.0)         | 8.5 (6.4–11)          | 9.3 (7.2–12)          | 64 (51–81)            | >100                  |             |              |

3. Materials and Methods
3.1. Computational Studies

3.1.1. Virtual Screening

All docking experiments were performed using AutoDock Vina [27] and PyMol 2.3.5 (The PyMOL Molecular Graphics System, Version 2.0 Schrödinger, LLC) for visualization.
SENP1 from co-crystal structure (PDB-code: 2G4D [37]) was used as receptor. The receptor was first prepared by deleting the solvent molecules and SUMO1 protein. In a second step, AutoDockTools package (version 1.5.6) was employed to add the hydrogen atoms and the corresponding charges to the atoms and generate the necessary receptor.pdbqt. The structure preparation of our in-house diversity library was performed with OpenBabel [38] (version 3.1.1) and the python script “prepare_ligand4.py” from the AutodockTools [39,40] package and included 3D structure generation, the addition of hydrogens and partial charges using Gasteiger charges. With AutodockTools, the search space (x = −35.8, y = −25.6, z = 22.4) and grid size (40, 40, 40) were defined and the “exhaustiveness” of the search parameter was set to 9. For the number of binding modes, the default setting of 9 was used.

3.1.2. Molecular Dynamics Simulations

To validate the conformational preferences of the DHQ tetrazole amide bond, umbrella sampling simulations were carried out for compounds 11, 23 and 24 calculating the potential of mean force (PMF) as a function of the torsion angles. Prior to umbrella sampling, each small molecule was solvated (TIP3P) and equilibrated at 300 K for 100 ps. The C-N bond was varied from 0 to 180° using umbrella windows spaced 3° apart. Each window was then subjected to a 50 ps incrementally restrained equilibration prior to a 100 ps restrained simulation at constant temperature (25°C) and pressure (1 atm). The torsions of the central residue were restrained using a harmonic penalty function with a force constant of 200 kcal/mol rad² for each window with 3° intervals about each torsion angle. From each set, the unbiased potential of mean force was reconstructed using the weighted histogram analysis method (WHAM) [41,42].

3.2. Chemistry

3.2.1. General Information

All reagents and solvents were purchased from Sigma-Aldrich, Alfa Aesar, Enamine, or Fluorochem and used as received. All NMR spectra were recorded on a Bruker AVANCE III HD 500 One Bay spectrometer with a magnetic field of 11.75 T and a 5 mm SmartProbe BB(F)-H-D. For 1H-NMR spectra, a frequency of 500 MHz resulted. Chemical shifts are reported in ppm from tetramethylsilane as internal standard in CDCl₃ or from [D₆]DMSO as an internal standard (δ = 2.50). Data are reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, quint = quintet, br = broad, m = multiplet), coupling constants (Hz), integration. For 13C-NMR spectra, a frequency of 126 MHz resulted. Chemical shifts are reported in ppm from tetramethylsilane as internal standard in CDCl₃ or from DMSO-d₆ (δ = 39.52). Purity was assayed by HPLC (Interchim Strategy C-18 column, 4.6 mm × 250 mm) with a gradient of 5-100% methanol in 0.2% aqueous acetic acid with UV detection at λ = 254 nm. All final compounds were obtained with ≥95% purity.

3.2.2. General Procedure A for the Bargellini Reaction

To an ice-cooled suspension of diamine 14 (1 eq.), ketone (2.5 eq.), chloroform (2 eq.) and benzyltriethylammonium chloride (0.05 eq.) in dichloromethane (V_DCM = n_Diam + n_Ketone) 2 mol/L was added an aq. 33% NaOH solution (5 eq.) over 45 min. The reaction mixture was allowed to warm to ambient temperature and stirred overnight. EtOAc (100 mL) was added to the reddish suspension and the organic layer was washed with brine (2 × 50 mL), dried (Na₂SO₄), filtered and concentrated in vacuo.

3.2.3. General Procedure B for CuAAc

To a solution of azide 43 (50 mg, 0.175 mmol, 1.0 eq) and alkyne (0.175 mmol, 1.0 eq) dissolved in 1BuOH/H₂O/DMSO (1:1:1; 8 mL) was added a 0.05 M aq. CuSO₄ solution (700 µL, 0.035 mmol, 0.2 eq) and 0.05 M aq. sodium ascorbate solution (1.75 mL, 0.088 mmol, 0.5 eq). The reaction mixture was stirred at ambient temperature overnight.
was taken up with EtOAc (80 mL), extracted with brine (40 mL), 0.2 M aq. EDTA solution (2 × 40 mL), brine (2 × 40 mL), dried (Na₂SO₄), filtered and concentrated in vacuo.

3.2.4. 3′,4′-Dihydro-1′H-spiro[cyclopentane-1,2′-quinoxalin]-3′-one (15)

The reaction with 1,2-diaminobenzene (14) (2.16 g, 20.0 mmol, 1.0 eq) and cyclopetanone was performed analogous to the general procedure A. The residue was purified by a silica column eluting with a gradient of 0 to 50% EtOAc in cyclohexane to afford a brownish solid of 15 (2.96 g, 14.6 mmol, 73%). Mp 174 °C [Lit [28]: 176–179 °C]. ¹H-NMR (500 MHz, (CD₃)₂SO): δ 10.51 (s, 1H), 6.78–6.68 (m, 3H), 6.62–6.57 (m, 1H), 6.03 (s, 1H), 2.03–1.95 (m, 2H), 1.78–1.71 (m, 2H), 1.65–1.51 (m, 4H). ¹³C-NMR (126 MHz, (CD₃)₂SO): δ 171.0, 134.7, 127.1, 122.9, 118.3, 114.3, 65.2, 36.9, 24.8. LRMS (ESI) m/z [M+H]^+ 203; RP-HPLC: RT 11.11 min; purity: 94.1%.

3.2.5. 3,3-Dimethyl-1,2,3,4-tetrahydroquinoxalin-2-one (16)

The reaction with 1,2-diaminobenzene (14) (2.16 g, 20.0 mmol) and acetone was performed analogous to the general procedure A. The residue was purified by a silica column eluting with a gradient of 10 to 70% EtOAc in cyclohexane to afford a yellowish solid of 16 (2.51 g, 14.3 mmol, 71%). Mp 178 °C [Lit [43]: 178 °C]. ¹H-NMR (500 MHz, (CD₃)₂SO): δ 10.13 (s, 1H), 6.76 (ddd, J = 7.6, 6.2, 1.2 Hz, 2H), 6.73 (dd, J = 7.6, 1.2 Hz, 1H), 6.67 (dd, J = 7.6, 1.2, 1H), 5.94 (s, 1H), 1.21 (s, 6H). ¹³C-NMR (126 MHz, (CD₃)₂SO): δ 155.4, 131.7, 129.6, 128.8, 123.5, 53.5, 53.4. LRMS (ESI) m/z [M+H]^+ 177; RP-HPLC: RT 9.97 min; purity: 98.2%.

3.2.6. 5-Phenyl-2H-1,2,3,4-tetrazole (18)

A suspension of NaN₃ (3.00 g, 46.2 mmol, 2.3 eq), NH₄Cl (2.50 g, 46.7 mmol, 2.3 eq) and benzonitrile (17) (2.1 mL, 20.4 mmol, 1 eq) in DMF (40 mL) was stirred at 120 °C overnight. The white suspension was cooled with an ice bath and water (20 mL) was added. The resulting colorless solution was acidified with 1 M HCl (35 mL) leading to precipitation of a white solid. The phenyltetrazole was filtered off and dried in a vacuum-drying cabinet (40 °C overnight) to afford a white solid of 18 (2.65 g, 18.1 mmol, 91%). ¹H-NMR (500 MHz, (CD₃)₂SO): δ 8.08–8.03 (m, 2H), 7.64–7.57 (m, 3H). ¹³C-NMR (126 MHz, (CD₃)₂SO): δ 155.9 (HMBC), 131.2, 129.4, 127.0, 124.1. LRMS (ESI) m/z [M+H]^+ 147.

3.2.7. Methyl 2-(5-phenyl-2H-1,2,3,4-tetrazol-2-yl)acetate (19) and methyl 2-(5-phenyl-1H-1,2,3,4-tetrazol-2-yl)acetate (20)

A solution of 18 (2.31 g, 15.8 mmol, 1 eq) and Et₃N (8.8 mL, 63.5 mmol, 4.0 eq) in MeCN (100 mL) was added to a refluxing solution of methyl chloroacetate (2.8 mL, 31.9 mmol, 2.0 eq) and stirred at reflux for 2 h. The reaction was left to cool to ambient temperature and was then concentrated in vacuo. The residue was separated by a silica column eluting with a gradient of 0 to 20% TBME in toluene to afford 19 as a colorless solid (2.66 g, 12.2 mmol, 77%) and 20 as a yellowish oil (0.44 g, 2.02 mmol, 13%). ¹H-NMR (500 MHz, CDCl₃): δ 8.19–8.14 (m, 2H), 7.53–7.45 (m, 3H), 5.47 (s, 2H), 3.83 (s, 3H). ¹³C-NMR (126 MHz, CDCl₃): δ 165.8, 165.7, 130.7, 129.1, 127.2, 127.1, 53.4, 53.4. LRMS (ESI) m/z [M+H]^+ 219. 20: ¹H-NMR (500 MHz, CDCl₃): δ 7.66–7.62 (m, 2H), 7.62–7.57 (m, 1H), 7.57–7.53 (m, 2H), 5.20 (s, 2H), 3.80 (s, 3H). ¹³C-NMR (126 MHz, CDCl₃): δ 166.1, 155.4, 131.7, 129.6, 128.8, 123.5, 53.5, 48.7. LRMS (ESI) m/z [M+H]^+ 219.

3.2.8. 2-(5-Phenyl-2H-1,2,3,4-tetrazol-2-yl)acetic acid (21)

LiOH × H₂O (1.04 g, 24.7 mmol, 2 eq) was added to a solution of 19 (2.66 g, 12.2 mmol, 1 eq) in THF (30 mL) and water (20 mL). The reaction was stirred at ambient temperature overnight. The reaction mixture was acidified with 32% HCl to pH = 1 and brine (100 mL) was added and the resulting mixture was extracted with EtOAc (3 × 100 mL). The combined org. layers were dried (Na₂SO₄), filtered and concentrated in vacuo to obtain a white solid of 21 (2.45 g, 12.0 mmol, 98%) which was used without further purification. Mp 179-184 °C.
2.2.9. 2-(5-Phenyl-1H-1,2,3,4-tetrazol-1-yl)acetic acid (22)

LiOH × H₂O (0.17 g, 4.05 mmol, 2 eq) was added to a solution of 20 (0.44 g, 2.02 mmol, 1 eq) in THF (4.9 mL) and water (3.2 mL). The reaction was stirred at ambient temperature overnight. The reaction mixture was acidified with 32% HCl to pH = 1 and brine (20 mL) were added and the resulting mixture was extracted with EtOAc (3 × 20 mL). The combined org. layers were dried (Na₂SO₄), filtered and concentrated in vacuo to obtain a yellowish solid of 22 (0.37 g, 1.81 mmol, 90%) which was used without further purification. Mp 171–178 °C decomp. [Lit [45]: 180–182 °C]; ¹H-NMR (500 MHz, (CD₃)₂SO): δ 13.76 (br s, 1H), 7.61–7.53 (m, 3H), 5.76 (s, 2H). ¹³C-NMR (126 MHz, (CD₃)₂SO): δ 167.5, 164.2, 130.7, 129.3, 126.7, 126.4 53.6. LRMS (ESI) m/z [M+H]+ 205.

3.2.10. 1′-[2-(5-Phenyl-2H-1,2,3,4-tetrazol-2-yl)acetyl]-3′,4′-dihydro-1′H-spirocyclopentane-1,2′-’quinoxalin-3′-one (11)

To a suspension of 2-(5-phenyl 2H-1,2,3,4 tetrazol-yl acetic acid) (21) (46.0 mg, 0.225 mmol, 1.0 eq) in dichloromethane (3 mL) was added oxalyl chloride (28.6 mg, 0.225 mmol, 1.1 eq) followed by a drop of DMF and stirred for 15 min at ambient temperature. To this solution, 15 (50 mg, 0.205 mmol, 1.0 eq) and Et₃N (47 µL, 0.308 mmol, 1.5 eq) were added and stirred for 3 h. This solution was diluted with dichloromethane (20 mL), washed with brine (3 × 20 mL), dried (Na₂SO₄), filtered and concentrated in vacuo. The residue was purified by a SiO₂ column eluting with a gradient of 10 to 60% EtOAc in cyclohexane to afford an off-white solid, which still contains some carboxylic acid. A second chromatographic purification on SiO₂ eluting with a gradient of 10 to 50% EtOAc in cyclohexane resulted in a colorless solid of 11 (9.3 mg, 0.027 mmol, 13%). Mp 237–239 °C decomp.; ¹H-NMR (500 MHz, (CD₃)₂CO): δ 9.60 (s, 1H), 8.12–8.07 (m, 2H), 7.86–7.83 (m, 1H), 7.56–7.50 (m, 3H), 7.43 (ddd, J = 7.8, 7.8, 1.3, 1H), 7.27–7.22 (m, 2H), 5.67 (br s, 2H), 2.25–1.89 (br m, 4H), 1.82–1.60 (br m, 4H). ¹³C-NMR (126 MHz, (CD₃)₂SO): δ 171.7, 166.7, 164.7, 134.9, 130.3, 129.0, 129.7, 128.0, 127.6, 126.5, 123.3, 122.8 116.2, 70.2, 55.4, 34.5, 23.5. LRMS (ESI) m/z [M+H]+ 389. RP-HPLC: RT 12.78 min; purity: 99.7%. 3.2.11. 3,3-Dimethyl-4-[2-(5-phenyl-2H-1,2,3,4-tetrazol-2-yl)acetyl]-1,2,3,4-tetrahydroquinoxalin-2-one (23)

The 2-(5-Phenyl 2H-1,2,3,4 tetrazol-yl acetic acid) (21) (128 mg, 0.625 mmol, 1.1 eq) was suspended in dichloromethane (3 mL). Oxalyl chloride (52.5 µL, 78.8 mg, 0.625 mmol, 1.1 eq) and a drop of DMF were added and stirred for 15 min. Then, 6 (100 mg, 0.568 mmol, 1.0 eq) and Et₃N (158 µL, 115 mg, 1.141 mmol, 2.0 eq) dissolved in dichloromethane (3 mL) were added over 5 min and stirred at ambient temperature and monitored by UPLC-MS. After 30 min, the reaction was completed. The reaction mixture was diluted with EtOAc (30 mL) and extracted with sat. NaHCO₃ (2 × 30 mL) and brine (2 × 30 mL), dried (Na₂SO₄), filtered and concentrated in vacuo. The residue was purified by a SiO₂ column eluting with a gradient of 10 to 80% EtOAc in cyclohexane to afford an off-white solid, which still had some impurities. A second purification on a reversed phase C₁₈ column eluting with a gradient of 10 to 100% MeCN in H₂O containing 0.1% AcOH to afford a colorless solid of 23 (14.8 mg, 0.041 mmol, 7%). Mp 252–254 °C decomp.; ¹H-NMR (500 MHz, (CD₃)₂SO): δ 10.76 (s, 1H), 8.07–8.01 (m, 2H), 7.66–7.62 (m, 1H), 7.61–7.53 (m, 3H), 7.28 (ddd, J = 7.7, 7.7, 1.0 Hz, 1H), 7.13 (ddd, J = 7.7, 7.7, 1.0 Hz, 1H), 7.03 (dd, J = 7.7, 1.0 Hz, 1H), 5.80 (s, br, 2H), 1.49 (s, 6H). ¹³C-NMR (126 MHz, (CD₃)₂SO): δ 171.5, 166.5, 164.5, 132.0, 131.1, 129.8, 127.9, 127.2, 126.8, 125.4, 125.2, 123.4, 116.2, 61.8, 56.7, 23.5 ppm. LRMS (ESI) m/z [M+H]+ 363. RP-HPLC: rt 12.39 min; purity: 99.4%. 
3.2.12. 4-[2-(5-Phenyl-2H-1,2,3,4-tetrazol-2-yl)acetyl]-1,2,3,4-tetrahydroquinoxalin-2-one (24)

2-(5-Phenyl 2H-1,2,3,4 tetrazol-yl acetic acid) (21) (60.3 mg, 0.295 mmol, 1.1 eq) was suspended in dichloromethane (3 mL). Oxalyl chloride (31.8 µL, 0.477 mmol, 1.4 eq) and a drop of DMF were added and stirred for 15 min at ambient temperature. The 1,2,3,4-tetrahydroquinoxalin-2-one (40 mg, 0.270 mmol, 1.0 eq) and Et3N (75 µL, 0.541 mmol, 2.0 eq) were added and stirred at ambient temperature and monitored by UPLC-MS. After 30 min, the reaction was completed. The reaction mixture was diluted with EtOAc (30 mL) and extracted with sat. NaHCO3 (2 × 30 mL), brine (2 × 30 mL), dried (Na2SO4), filtered and concentrated in vacuo. The residue was purified by a SiO2 column chromatography eluting with a gradient of 30 to 100% EtOAc in cyclohexane to afford an off-white solid, which still had some impurities. A second purification on the reversed phase C18 column eluting with a gradient of 10 to 100% MeCN in H2O containing 0.1% AcOH afforded a white solid of 24 (15.6 mg, 0.047 mmol, 17%). Mp 231 ºC decompr.; 1H-NMR (500 MHz; 375K; (CD3)2SO; δ 10.61 (s, 1H), 8.08–8.04 (m, 2H), 7.78–7.73 (m, 1H), 7.61–7.52 (m, 3H), 7.29–7.22 (m, 1H), 7.12–7.05 (m, 2H), 6.06 (s, 2H), 4.44 (dd, J = 0.9 Hz, 2H); 13C-NMR (126 MHz, (CD3)2SO; δ 167.1 (HMBC), 164.7, 164.6, 132.6 (HMBC), 131.1, 129.8, 127.8 (HMBC), 127.2, 126.8, 125.6, 124.2, 122.9 (HSQC), 117.0 (HSQC), 54.7 (HSQC), 47.3 (HSQC). LRMS (ESI) m/z [M+H]+ 335. RP-HPLC: RT 11.46 min; purity: 99.4%.

3.2.13. 3,4-Dihydropyrrolo [1,4-benzoxazine-2,1′-cyclopentan]-3-one (26)

To an ice-cooled solution of methyl 1-hydroxyxycyclopentan-1-carboxylate (0.55 g, 3.62 mmol, 1 eq) in dry THF (7.5 mL) was added sodium hydride (60% suspension in paraffin oil, 0.185 g, 4.35 mmol, 1.2 eq) in two portions (caution: vigorous gas production). Then, 10 min after the completed addition, 2-fluoronitrobenzene (0.46 mL, 4.39 mmol, 1.2 eq) was added and stirred at 0 ºC for another 20 min. The reaction mixture was stirred at ambient temperature overnight. The reaction mixture was quenched with sat. aq. NH4Cl solution (25 mL), diluted with water (5 mL) and the organic components of the aq. layer were extracted with EtOAc (3 × 30 mL). The combined organic layers were dried (MgSO4), filtered and concentrated in vacuo. The residue was purified by silica column chromatography eluting with a gradient of 0 to 20% EtOAc in cyclohexane to afford an off-white solid of 26 (0.13 g, 0.64 mmol, 18% over 2 steps). Mp 157–162 ºC; 1H-NMR (500 MHz, CDCl3; δ 7.83 (s, 1H), 6.99–6.92 (m, 3H), 6.79–6.73 (m, 1H), 2.23–2.13 (m, 2H), 2.05–1.97 (m, 2H), 1.95–1.75 (m, 4H); 13C-NMR (126 MHz, CDCl3; δ 170.1, 143.0, 127.3, 124.0, 122.5, 117.9, 115.2, 88.6, 35.7, 24.7. LRMS (ESI) m/z [M+H]+ 204. RP-HPLC: RT 12.99 min; purity: 99.7%.

3.2.14. 3′,4′-Dihydro-1′H-spiro[cyclohexane-1,2′-quinoxalin]-3′-one (27)

The reaction with 1,2-diaminobenzene (14) (1.08 g, 10.0 mmol) and cyclohexanone was performed analogous to the general procedure A. The residue was purified by a silica column eluting with a gradient of 0 to 30% EtOAc in cyclohexane to afford a greenish solid of 27 (0.89 g, 4.12 mmol, 41%). Mp 230–234 ºC decompr. [Lit [8]: 239–240 ºC]; 1H-NMR (500 MHz, (CD3)2SO; δ 10.80 (br s, 1H), 6.89 (dd, J = 7.8, 1.1 Hz, 1H), 6.75 (td, J = 7.6, 1.5 Hz, 1H), 6.70 (dd, J = 7.8, 1.4 Hz, 1H), 6.59 (dd, J = 7.6, 1.3 Hz, 1H), 5.92 (br s, 1H), 1.71–1.42 (m, 9H), 1.29–1.16 (m, 1H); 13C-NMR (126 MHz, (CD3)2SO; δ 170.1, 133.3, 132.2, 122.5, 117.8, 114.2, 55.7, 31.4, 25.02, 19.9. LRMS (ESI) m/z [M+H]+ 217. RP-HPLC: RT 11.97 min; purity: >99.9%.

3.2.15. 3,4-Dihydropyrrolo [1,4-benzoxazine-2′,1′-cyclopentan]-3′-one (26)

The reaction with 1,2-diaminobenzene (14) (1.08 g, 10.0 mmol) and cyclohexanone was performed analogous to the general procedure A. The residue was purified by a silica column eluting with a gradient of 0 to 30% EtOAc in cyclohexane to afford a greenish solid of 26 (0.89 g, 4.12 mmol, 41%). Mp 230–234 ºC decompr. [Lit [8]: 239–240 ºC]; 1H-NMR (500 MHz, (CD3)2SO; δ 10.80 (br s, 1H), 6.89 (dd, J = 7.8, 1.1 Hz, 1H), 6.75 (td, J = 7.6, 1.5 Hz, 1H), 6.70 (dd, J = 7.8, 1.4 Hz, 1H), 6.59 (dd, J = 7.6, 1.3 Hz, 1H), 5.92 (br s, 1H), 1.71–1.42 (m, 9H), 1.29–1.16 (m, 1H); 13C-NMR (126 MHz, (CD3)2SO; δ 170.1, 133.3, 132.2, 122.5, 117.8, 114.2, 55.7, 31.4, 25.02, 19.9. LRMS (ESI) m/z [M+H]+ 217. RP-HPLC: RT 11.97 min; purity: >99.9%.
3.2.15. 3′,4′-Dihydro-1′H-spiro[cyclooctane-1,2′-quinoxalin]-3′-one (28)

The reaction with 1,2-diaminobenzene (14) (1.08 g, 10.0 mmol) and cyclooctanone was performed analogous to the general procedure A. The residue was purified by a silica column eluting with a gradient of 0 to 40% EtOAc in cyclohexane to afford a reddish/brown solid of 28 (0.07 g, 0.29 mmol, 3%). 1H-NMR (500 MHz, CDCl3): δ 7.90 (br s, 1H), 6.88 (td, J = 7.6, 1.1 Hz, 1H), 6.75 (td, J = 7.6, 1.2 Hz, 2H), 6.70–6.65 (m, 2H), 3.93 (br s, 1H), 2.28–2.17 (m, 2H), 1.71–1.52 (m, 12H). LRMS (ESI) m/z [M+H]+ 245. RP-HPLC: RT 11.74 min; purity: 96.1%.

3.2.16. 3′,4′-Dihydro-1′H-spiro[cyclobutane-1,2′-quinoxalin]-3′-one (29)

The reaction with 1,2-diaminobenzene (14) (0.546 g, 5.05 mmol) and cyclobutanone was performed analogous to the general procedure A. The residue was purified by a silica column eluting with a gradient of 0 to 20% EtOAc in cyclohexane followed by a RP column eluting with 10 to 100% B in A (A: 95/5 water/MeCN + 0.2% AcOH, B: 5/95 water/MeCN + 0.2% AcOH) to afford a yellowish solid of 29 (0.07 g, 0.29 mmol, 3%). Mp 189–194 °C decomp.; 1H-NMR (500 MHz, CD3OD): δ 6.82 (ddd, J = 7.8, 7.3, 1.5 Hz, 1H), 6.76–6.72 (m, 2H), 6.68 (ddd, J = 7.7, 7.3, 1.3 Hz, 1H), 2.62–2.54 (m, 2H), 2.14–2.06 (m, 2H), 1.98–1.91 (m, 2H). LRMS (ESI) m/z 114.7, 114.5, 60.1, 31.7, 28.4, 25.1, 22.1. LRMS (ESI) m/z 114.7, 114.5, 60.1, 31.7, 28.4, 25.1, 22.1. LRMS (ESI) m/z 114.7, 114.5, 60.1, 31.7, 28.4, 25.1, 22.1. LRMS (ESI) m/z [M+H]+ 245. RP-HPLC: RT 11.74 min; purity: 96.1%.

3.2.17. 3′,4′-Dihydro-1′H-spiro[oxetane-3,2′-quinoxalin]-3′-one (30)

The reaction with 1,2-diaminobenzene (14) (1.08 g, 10.0 mmol) and cyclooctanone was performed analogous to the general procedure A. The residue was purified over a silica gel column eluting with a gradient of 0 to 70% EtOAc in cyclohexane. A total of 100 mg of the still impure product was separated by a semi-prep RP chromatography (C18 column) eluting with a gradient of 14 to 95% MeCN in water, which afforded a red solid of 30 (0.017 g, 0.089 mmol, 1%). Mp 165–170 °C decomp.; 1H-NMR (500 MHz, CD3OD): δ 10.46 (br s, 1H), 7.18 (br s, 1H), 6.81–6.71 (m, 3H), 6.62 (dd, J = 7.0, 7.0 Hz, 1H), 4.87 (d, J = 6.0 Hz, 2H), 4.47 (d, J = 6.0 Hz, 1H). LRMS (ESI) m/z [M+H]+ 219. RP-HPLC: RT 9.04 min; purity: 95.2%.

3.2.18. 3′,4′-Dihydro-1′H-spiro[oxane-4,2′-quinoxalin]-3′-one (31)

The reaction with 1,2-diaminobenzene (14) (1.08 g, 10.0 mmol) and tetrahydro-4H-pyran-4-one was performed analogous to the general procedure A. The residue was purified over a silica gel column eluting with a gradient of 0 to 40% EtOAc in cyclohexane. The impurity could be separated by RP chromatography (C18 column) eluting with a gradient of 14 to 50% MeCN in water with 0.2% AcOH, which afforded 31 as a brownish-yellow solid (0.185 g, 0.85 mmol, 8%). Mp 211–226 °C decomp.; 1H-NMR (500 MHz, CDCl3): δ 8.06 (br s, 1H), 6.92 (ddd, J = 7.7, 7.7, 1.2 Hz, 1H), 6.81 (ddd, J = 7.7, 7.7, 1.2 Hz, 1H), 6.77 (dd, J = 7.7, 1.2 Hz, 1H), 6.73 (dd, J = 7.7, 1.2 Hz, 1H), 4.06 (br s, 1H), 4.00–3.88 (m, 2H), 3.82–3.67 (m, 2H), 2.28–2.15 (m, 2H), 1.65–1.55 (m, 2H). LRMS (ESI) m/z [M+H]+ 33.0. RP-HPLC: RT 9.69 min; purity: 99.1%.

3.2.19. 3′,4′-Dihydro-1′H-spiro[cyclopentane-1,2′-quinazolin]-4′-one (32)

To a solution of 2-aminoazemidam (0.255 g, 1.87 mmol, 1 eq) and cyclopentanone (0.17 mL, 1.92 mmol, 1 eq) in EtOH (5.5 mL) was added NH4Cl (8.5 mg, 0.159 mmol, 0.08 eq). The reaction was stirred for 24 h at ambient temperature. Water (5 mL) was added and the precipitate was filtered off. The dry crystals were recrystallized in acetone (2 mL) to afford the clean product of 32 (0.15 g, 0.742 mmol, 40%). Mp 233–238 °C decomp. [Lit. 254–256 °C [46]]. 1H-NMR (500 MHz, CD32SO): δ 8.07 (br s, 1H), 7.57 (d, J = 7.7, 1H), 7.24–7.18 (m, 1H), 6.73 (br s, 1H), 6.69 (d, J = 7.8 Hz, 1H), 6.65–6.60 (m, 1H), 1.85–1.73 (m,
3.2.20. 3′,4′-Dihydro-1′H-spiro[cyclopentane-1,2′-quinoxaline] (33)

To an ice cooled solution of 15 (0.20 g, 0.494 mmol, 1.0 eq.) in THF (1 mL) a flame-dried flask was added a solution of LiAlH₄ (2 M in THF, 0.99 mL, 0.494 mmol, 1 eq.) dropwise. The reaction was heated at reflux overnight. The mixture was cooled with an ice bath, quenched with EtOAc (4 mL) and water (4 mL), filtered over celite and rinsed with EtOAc (3 × 30 mL) and water (3 × 10 mL). The pH of the aqueous phase was set to alkaline with NaOH (2 M, ca. 5 mL), the phase was separated, and the aq. phase was extracted with EtOAc (3 × 50 mL). The combined organ. layers were dried (Na₂SO₄), filtered, and evaporated in vacuo to give a dark oil. The residue was purified by a silica column eluting with a gradient of 0 to 25% EtOAc in cyclohexane to afford a reddish-brown solid of 33 (0.13 g, 0.690 mmol, 70%). Mp 80–82 °C; ¹H-NMR (500 MHz, CDCl₃): δ 6.62–6.56 (m, 2H), 6.55–6.51 (m, 1H), 6.50–6.46 (m, 1H), 3.68 (br s, 2H), 3.12 (s, 2H), 1.83–1.64 (m, 6H, 1H), 1.62–1.54 (m, 2H). ¹³C-NMR (126 MHz, CDCl₃): δ 133.3, 133.1, 118.8, 118.7, 115.1, 114.5, 59.6, 50.7, 38.3, 24.3. LRMS (ESI) m/z [M+H]+ 203. RP-HPLC: RT 10.64 min; purity: > 99.9%.

3.2.21. 3′,4′-Dihydro-1′H-spiro[cyclopentane-1,2′-pyrido [2,3-b]pyrazin]-3′-one (34)

The reaction with 6-bromopyridine-2,3-diamine (0.25 g, 2.19 mmol) and cyclopentanone was performed analogous to the general procedure A. The residue was purified by a silica column eluting with a gradient of 0 to 30% EtOAc in cyclohexane to afford a yellowish solid (0.33 g, 1.17 mmol, 31%). Mp 220–226 °C decomp.; ¹H-NMR (500 MHz, CDCl₃): δ 10.91 (br s, 1H), 6.99–6.94 (m, 2H), 6.52 (br s, 1H), 2.05–1.97 (m, 2H), 1.79–1.70 (m, 2H), 1.66–1.52 (m, 4H). ¹³C-NMR (126 MHz, CDCl₃): δ 170.8, 141.0, 129.3, 125.0, 122.5, 121.4, 64.8, 36.9, 24.4. LRMS (ESI) m/z [M+H]+ 282. RP-HPLC: rt 11.73 min; purity: 96.2%. A suspension of Pd/C (30 mg, 0.014 mmol, 0.06 eq) and (68 mg, 0.23 mmol, 1 eq) in MeOH (3 mL) was degassed with Argon and then H₂ and stirred for 5 h. The reaction was filtered over celite and the filter cake was rinsed with EtOAc (3 × 10 mL). The solvent was evaporated in vacuo and the crude product was purified by silica column eluting with 0 to 50% EtOAc in cyclohexane to afford an off-white solid 34 (6 mg, 0.030 mmol, 13%). Mp 226–233 °C decomp.; ¹H-NMR (500 MHz, CDCl₃): δ 9.80 (br s, 1H), 7.85 (dd, J = 5.0, 1.4 Hz, 1H), 6.92 (dd, J = 7.7, 1.4 Hz, 1H), 6.83 (dd, J = 7.7, 5.0 Hz, 1H), 3.87 (br s, 1H), 2.37–2.26 (m, 2H), 1.88–1.62 (m, 6H). ¹³C-NMR (126 MHz, CDCl₃): δ 171.4, 140.9, 138.2, 128.9, 120.5, 119.1, 66.4, 37.9, 24.8. LRMS (ESI) m/z [M+H]+ 204. RP-HPLC: RT 10.09 min; purity: 98.0%.

3.2.22. 3′,4′-Dihydro-1′H-spiro[cyclopentane-1,2′-thieno [3,4-b]pyrazin]-3′-one (35)

The reaction with thiophene-3,4-diamine (0.25 g, 2.19 mmol) and cyclopentanone was performed analogous to the general procedure A. The residue was purified by a silica column eluting with a gradient of 0 to 50% EtOAc in cyclohexane to afford a yellow solid 35 (0.23 g, 1.10 mmol, 50%). Mp 126–130 °C decomp.; ¹H-NMR (500 MHz, CDCl₃): δ 8.84 (br s, 1H), 6.38 (d, J = 3.1 Hz, 1H), 6.09 (d, J = 3.1 Hz, 1H), 3.91 (br s, 1H), 2.26–2.19 (m, 2H), 1.81–1.68 (m, 6H). ¹³C-NMR (126 MHz, CDCl₃): δ 171.7, 134.5, 129.2, 102.0, 99.0, 66.8, 37.5, 24.7. LRMS (ESI) m/z [M+H]+ 209, RP-HPLC: RT 10.89 min; purity: 99.1%.

3.2.23. 3′,4′-Dihydro-1′H-spiro[cyclohexane-1,2′-thieno [3,4-b]pyrazin]-3′-one (36)

The reaction with thiophene-3,4-diamine (0.25 g, 2.19 mmol) and cyclohexanone was performed analogous to the general procedure A. The residue was purified by a silica column eluting with a gradient of 0 to 30% EtOAc in cyclohexane to afford a yellowish solid 36 (0.055 g, 0.25 mmol, 11%). Mp 170–174 °C decomp.; ¹H-NMR (500 MHz, CDCl₃): δ 8.28 (br s, 1H), 6.36 (d, J = 3.1 Hz, 1H), 6.12 (d, J = 3.1 Hz, 1H), 4.27 (br s, 1H), 1.90–1.84 (m, 2H), 1.72–1.67 (m, 5H), 1.46–1.30 (m, 3H). ¹³C-NMR (126 MHz, CDCl₃): δ 171.4, 133.7,
3.2.24. 5′-Methoxy-3′,4′-dihydro-1′H-spiro[cyclopentane-1,2′-quinoxalin]-3′-one (37)

A suspension of 3-fluoro-2-nitroanisol (182 mg, 1.06 mmol, 1.0 eq), methyl 1-aminocyclopentane-1-carboxylate (191 mg, 1.06 mmol, 1.00 eq) and potassium carbonate (305 mg, 2.55 mmol, 2.40 eq) in DMF (1.8 mL) was heated to 80 °C for 11 d. The dark brown reaction mixture was diluted with EtOAc (50 mL), water (5 mL) and brine (30 mL). The organic phase was washed with brine (25 mL), 0.5 M LiCl solution (20 mL) and brine (15 mL), dried (Na₂SO₄), filtered and concentrated in vacuo. The residue was purified by silica column (40 g) chromatography (0 to 15% EtOAc in cyclohexane). The impure product fractions were pooled, evaporated and purified again over RP column (C₁₈, 250/21 mm HPLC) eluting with 10 to 100% B in A (A: 95/5 water/MeCN, B: 5/95 water/MeCN) to afford a yellow solid (65 mg). A suspension of the intermediate (0.060 g, 0.186 mmol, 1 eq), NH₄Cl (0.270 g, 5.05 mmol, 27 eq) and Zn (0.304 g, 4.65 mmol, 25 eq) in DMF (2 mL) was stirred overnight. The reaction mixture was diluted with EtOAc (50 mL), water (5 mL) and brine (30 mL). The organic mixture was diluted with EtOAc (50 mL), water (5 mL) and brine (30 mL), dried (Na₂SO₄), filtered and concentrated in vacuo. The residue was purified by silica column (40 g) eluting with 10–100% B in A (A: 95/5 water/MeCN, B: 5/95 water/MeCN) to afford an ochre solid of 38 (13 mg, 0.0499 mmol, 7% over 2 steps). Mp 176–180 °C. H NMR (500 MHz, CDCl₃): δ 171.0, 147.2, 135.5, 123.8, 116.0, 108.4, 102.5, 66.4, 56.4, 37.4, 25.3. LRMS (ESI) m/z [M+H]⁺ 233. RP-HPLC: RT 11.52 min; purity: 98.9%.

3.2.25. Methyl 3′-oxo-3′,4′-dihydro-1′H-spiro[cyclopentane-1,2′-quinoxaline]-5′-carboxylate (38)

A suspension of methyl 3-fluoro-2-nitrobenzoate (205 mg g, 1.03 mmol, 1.03 eq), methyl 1-aminocyclopentane-1-carboxylate (180 mg, 1.00 mmol, 1.00 eq) and potassium carbonate (300 mg, 2.51 mmol, 2.51 eq) in DMF (1.8 mL) was heated to 80 °C for 6 d. The dark brown reaction mixture was diluted with EtOAc (50 mL), water (5 mL) and brine (30 mL). The organic phase was washed with brine (25 mL), 0.5 M LiCl solution (20 mL) and brine (15 mL), dried (Na₂SO₄), filtered and concentrated in vacuo. The residue was purified by silica column (40 g) eluting with 0–15% EtOAc in cyclohexane. The impure product fractions were pooled, evaporated and purified again over RP column (C₁₈, 250/21 mm HPLC) eluting with a gradient of 10 to 100% B in A (A: 95/5 water/MeCN, B: 5/95 water/MeCN) to afford an orange solid of 38 (13 mg, 0.0499 mmol, 5% over two steps). Mp 147–149 °C. H NMR (500 MHz, CDCl₃): δ 172.0, 169.0, 135.5, 129.7, 122.9, 121.1, 119.5, 113.8, 66.0, 56.4, 37.4, 25.3, 20.8. LRMS (ESI) m/z [M+H]⁺ 261. RP-HPLC: RT 11.03 min; purity: 99.9%.

3.2.26. 7′-Methoxy-3′,4′-dihydro-1′H-spiro[cyclopentane-1,2′-quinoxalin]-3′-one (39)

A suspension of 3-fluoro-4-nitroanisole (185 mg, 1.08 mmol, 1.0 eq), methyl 1-aminocyclopentane-1-carboxylate hydrochloride (186 mg, 1.04 mmol, 1.0 eq) and potassium carbonate (300 mg, 2.51 mmol, 2.4 eq) in DMF (1.8 mL) was heated to 80 °C for 5 d. The dark
brown reaction mixture was diluted with EtOAc (75 mL), water (5 mL) and brine (25 mL). The organic phase was washed with brine (20, 15 mL), 0.5 M LiCl (15 mL) solution and brine (15 mL), dried (Na₂SO₄), filtered and concentrated in vacuo. The residue was purified by silica column (80 g) chromatography eluting with 0 to 15% EtOAc in cyclohexane. The impure product fractions were pooled, evaporated and purified over RP column (C₁₈, 250/21 mm HPLC) eluting with 10–100 B in A (A: 95/5 water/McCN, B: 5/95 water/McCN) to afford a yellow solid (0.127 g). This intermediate (0.127 g, 0.432 mmol, 1.0 eq), NH₄Cl (0.577 g, 10.8 mmol, 25 eq) and Zn (0.705, 10.8 mmol, 25 eq) in DMF (2 mL) was stirred overnight. The reaction mixture was diluted with EtOAc (50 mL), filtered and the filter cake was rinsed with EtOAc (2 × 10 mL). The organic layer was washed with water (2 × 20 mL), 0.5 M LiCl solution (10 mL) and brine (10 mL), dried (Na₂SO₄), filtered and evaporated in vacuo. The residue was purified by a RP column (21 × 150, C₁₈) eluting with a gradient 10–100% B in A (A: 95/5 H₂O/McCN, B: 5/95 H₂O/McCN). The yellowish solid was suspended in MeCN, filtered, the yellow filtrate was discarded, and an off-white solid of 39 was collected (27 mg, 0.116 mmol, 11%). Mp 224–227 °C decomp.; ¹H-NMR (500 MHz, (CD₃)₂SO): δ 9.99 (br s, 1H), 6.62 (d, J = 8.5 Hz, 1H), 6.31 (d, J = 2.7 Hz, 1H), 6.18 (dd, J = 8.5, 2.7 Hz, 1H), 6.05 (br s, 1H), 3.63 (s, 3H), 2.01–1.93 (m, 2H), 1.77–1.68 (m, 2H), 1.64–1.48 (m, 4H). 

3.2.27. Methyl 3′-oxo-3′,4′-dihydro-1′H-spiro[cyclopentane-1,2′-quinoxaline]-6′-carboxylate (40)

A suspension of methyl 3-fluoro-2-nitrobenzoate (205 mg, 1.03 mmol, 1.0 eq), methyl 1-aminocyclopentane-1-carboxylate (187 mg, 1.01 mmol, 1.0 eq) and potassium carbonate (302 mg, 2.53 mmol, 2.5 eq) in DMF (1.8 mL) was heated to 80 °C for 4 d. The dark brown reaction mixture was diluted with EtOAc (75 mL), water (5 mL) and brine (25 mL). The organic phase was washed with brine (20 and 15 mL), 0.5 M LiCl solution (15 mL) and brine (15 mL), dried (Na₂SO₄), filtered and concentrated in vacuo. The residue was purified by silica column (40 g) chromatography eluting with 5 to 20% EtOAc in cyclohexane to afford the desired compound as a yellow solid (198 mg, 0.614 mmol, 61%). Mp 246–250 °C dec.; ¹H NMR (500 MHz, (CD₃)₂SO): δ 10.38 (br s, 1H), 7.41 (dd, J = 8.3, 1.8 Hz, 1H), 7.36 (d, J = 1.8 Hz, 1H), 6.88 (br s, 1H), 6.72 (d, J = 8.3 Hz 1H), 3.75 (s, 3H), 2.09–2.01 (m, 2H), 1.71–1.68 (m, 2H), 1.57–1.49 (m, 6H). 

3.2.28. 6′-Nitro-3′,4′-dihydro-1′H-spiro[cyclopentane-1,2′-quinoxalin]-3′-one (41)

A mixture of 1,2-diamino-4-nitrobenzene (0.92 g, 6.00 mmol, 1.0 eq), cyclopentanone (1.35 mL, 15.2 mmol, 2.6 eq), chloroform (1.5 mL, 18.6 mmol, 3.1 eq) benzyltriethylammonium chloride (71 mg, 0.312 mmol, 0.05 eq) in dichloromethane (4 mL) was cooled to 0 °C. A 50% aqueous NaOH solution (1.8 mL, 30.4 mmol, 5.1 eq) was carefully added over 20 min to the red suspension. The reaction was stirred at 0°C for 45 min and then left to warm to ambient temperature and stirred overnight. EtOAc (100 mL) was added to the reddish suspension and the organic layer was washed with brine (3 × 50 mL), dried (Na₂SO₄), filtered and concentrated in vacuo. The residue was purified by a silica column (24 g) eluting with a gradient of 0 to 30% EtOAc in cyclohexane to afford 41 as an orange solid (710 mg, 48%). Mp 275–278 °C; ¹H NMR (500 MHz, (CD₃)₂SO): δ 10.84 (br s, 1H), 7.59 (d, J = 2.5 Hz, 1H), 7.56 (dd, J = 8.5, 2.5 Hz, 1H), 6.88 (d, J = 8.5 Hz, 1H), 6.73 (br s, 1H), 7.59 (d, J = 2.5 Hz, 1H), 7.56 (dd, J = 8.5, 2.5 Hz, 1H), 6.88 (d, J = 8.5 Hz, 1H), 6.73 (br s, 1H), 7.59 (d, J =
2.07–1.99 (m, 2H), 1.81–1.72 (m, 2H), 1.68–1.55 (m, 4H). 13C-NMR (126 MHz, (CD3)2SO): δ 170.4, 142.4, 134.3, 132.7, 114.3, 114.1, 108.0, 64.5, 36.8, 24.3. LRMS (ESI) m/z [M+H]+ 248. RP-HPLC: RT 11.62 min; purity: 99.9%.

3.2.29. 1′-(2-Chloroacetyl)-3′,4′-dihydro-1′H-spiro[cyclopentane-1,2′-quinoxalin]-3′-one (42)

A solution of 15 (500 mg, 2.48 mmol, 1.0 eq) in DMF (20 mL) was cooled to 0 °C. The 2-chloroacetyl chloride (422 μL, 5.84 mg, 3.71 mmol, 1.5 eq) was added over 15 min. The reaction mixture was stirred at 0 °C for 30 min, at which point the TLC indicated complete consumption of the starting material. To the reaction mixture was added EtOAc (100 mL) and the organic layer was washed with brine (3 × 100 mL), 0.5 M aq LiCl (3 × 50 mL), brine (100 mL), dried (Na2SO4), filtered and concentrated in vacuo. The residue was purified on a SiO2 column eluting with a gradient of 10 to 70% EtOAc in cyclohexane to afford a colorless solid 42 (679 mg, 2.44 mmol, 98%). 1H-NMR (500 MHz, (CDCl3): δ 8.96 (s, 1H), 7.40 (dd, J = 7.8, 1.3 Hz, 1H), 7.33 (ddd, J = 7.8, 1.3 Hz, 1H), 7.15 (ddd, J = 7.8, 1.3 Hz, 1H), 7.00 (dd, J = 7.8, 1.3 Hz, 1H), 4.04 (s, 2H), 2.46–2.03 (m, 4H), 1.88–1.72 (m, 4H). 13C-NMR (126 MHz, (CDCl3): δ 173.7, 168.9, 133.8, 128.9, 128.6, 125.5, 123.5, 116.5, 70.6, 43.5 35.1, 24.3. LRMS (ESI) m/z [M+H]+ 279.

3.2.30. 1′-(2-Azidoacetyl)-3′,4′-dihydro-1′H-spiro[cyclopentane-1,2′-quinoxalin]-3′-one (43)

A suspension of 42 (490 mg, 1.76 mmol, 1.0 eq) in DMF (10 mL) was stirred at 80 °C for 30 min, at which point the TLC indicated complete consumption of the starting material. To the reaction mixture was added EtOAc (100 mL) and the organic layer was washed with brine (3 × 100 mL), 0.5 M aq LiCl (3 × 50 mL), brine (100 mL), dried (Na2SO4), filtered and concentrated in vacuo. The residue was purified on a SiO2 column eluting with a gradient of 10 to 70% EtOAc in cyclohexane to afford a colorless solid 43 (390 mg, 1.37 mmol, 78%). 1H-NMR (500 MHz, (CDCl3): δ 9.28 (s, 1H), 7.32 (ddd, J = 7.9, 7.9, 1.1 Hz, 1H), 7.25 (dd, J = 7.9, 1.1 Hz, 1H), 7.10 (ddd, J = 7.9, 7.9, 1.1 Hz, 1H), 7.04 (dd, J = 7.9, 1.1 Hz, 1H) 3.79 (s, 2H), 2.49–2.03 (m, 4H), 1.86–1.49 (m, 4H). 13C-NMR (126 MHz, (CDCl3): δ 173.9, 170.3, 133.7, 128.5, 128.2, 125.6, 123.2, 116.5, 70.3, 70.3, 52.1, 35.1, 24.1. LRMS (ESI) m/z [M+H]+ 286.

3.2.31. 1′-[2-(4-Phenyl-1H-1,2,3-triazol-1-yl)acetyl]-3′,4′-dihydro-1′H-spiro[cyclopentane-1,2′-quinoxalin]-3′-one (44)

The reaction was performed analogous to the general procedure B. The product was purified on a SiO2 column eluting with a gradient of 30 to 100% EtOAc in cyclohexane to afford a colorless solid of 44 (15.3 mg, 0.039 mmol, 23%). Mp 256 °C. 1H-NMR (500 MHz, (CDCl3): δ 10.54 (s, 1H), 8.41 (s, 1H), 7.84–7.80 (m, 2H), 7.76 (dd, J = 7.9, 1.1 Hz, 1H), 7.46–7.41 (m, 2H), 7.37 (ddd, J = 7.6, 7.6, 1.1 Hz, 1H), 7.33 (tt, J = 7.3, 0.9 Hz, 1H), 7.15 (ddd, J = 7.6, 7.6 Hz, 1.1, 1H), 7.08 (dd, J = 8.1, 1.1 Hz, 1H), 5.32 (br s, 2H), 2.28–1.85 (br m, 4H), 1.75–1.51 (br m, 4H). 13C-NMR (126 MHz, (CDCl3): δ 172.2, 168.5, 146.5, 134.8, 131.2, 129.4, 128.9, 128.3, 128.1, 126.7, 125.5, 123.6, 123.0, 116.5, 69.6, 52.7, 35.4, 24.1. LRMS (ESI) m/z [M+H]+ 388. RP-HPLC: RT 12.10 min; purity: 97.7%.

3.2.32. 1′-[2-(4-Cyclohexyl-1H-1,2,3-triazol-1-yl)acetyl]-3′,4′-dihydro-1′H-spiro[cyclopentane-1,2′-quinoxalin]-3′-one (45)

The reaction was performed analogous to the general procedure B. The product was purified on a SiO2 column eluting with a gradient of 20 to 80% EtOAc in cyclohexane to afford a colorless solid of 45 (60.7 mg, 0.154 mmol, 63%). Mp 205 °C. 1H-NMR (500 MHz, (CDCl3): δ 10.54 (s, 1H), 7.69 (dd, J = 8.0, 1.0 Hz, 1H), 7.65 (s, 1H), 7.34 (ddd, J = 8.0, 8.0, 1.0 Hz, 1H), 7.12 (ddd, J = 7.9, 7.9, 1.1 Hz, 1H), 7.06 (dd, J = 7.9, 1.1 Hz, 1H), 5.18 (br s, 2H), 2.64 (m, 1H), 2.26–1.80 (br m, 6H), 1.74–1.49 (br m, 8H), 1.40–1.26 (m, 4H).
13C-NMR (126 MHz, (CD3)2SO): δ 172.2, 168.7, 152.1, 134.8, 128.8 128.2, 126.8, 122.9, 122.7, 116.4, 69.6, 52.4, 42.1, 35.0, 33.0, 26.1, 26.0, 24.0. LRMS (ESI) m/z [M+H]+ 394. RP-HPLC: RT 12.76 min; purity: 98.9%.

3.2.33. 1-[2-(4-Benzyl-1H-1,2,3-triazol-1-yl)acetyl]-3',4'-dihydro-1'H-spiro[cyclopentane-1,2'-quinoxalin]-3'-one (46)

The reaction was performed analogous to the general procedure B. The product was purified on a semi-prep reversed-phase HPLC eluting with a gradient of 10 to 100% MeCN in H2O, but there were still some minor impurities. A second purification on a SiO2 column eluting with a gradient of 20 to 80% EtOAc in cyclohexane afforded a colorless solid of 46 (38.0 mg, 0.095 mmol, 39%). Mp 203 °C decom.; 1H-NMR (500 MHz, (CD3)2SO): δ 10.53 (s, 1H), 7.70–7.64 (m, 2H), 7.33 (dd, J = 7.8, 7.8, 1.4 Hz, 1H), 7.31–7.26 (m, 2H), 7.25–7.17 (m, 3H), 7.11 (dd, J = 7.9, 7.9, 1.1 Hz, 1H), 7.07 (dd, J = 7.9, 1.1 Hz, 1H), 7.02 (br s, 2H), 3.97 (s, 2H), 2.26–1.80 (br m, 4H), 1.74–1.49 (br m, 4H). 13C-NMR (126 MHz, (CD3)2SO): δ 172.2, 168.7, 146.1, 140.0, 134.8, 129.0, 128.84, 128.77, 128.2, 124.7, 122.9, 116.4, 69.6, 52.4, 31.7, 24.0. LRMS (ESI) m/z [M+H]+ 402. RP-HPLC: RT 12.23 min; purity: 95.3%.

3.2.34. 3-[1-(2-Oxo-2-[3'-oxo-3',4'-dihydro-1'H-spiro[cyclopentane-1,2'-quinoxalin]-1'-yl]ethyl)-1H,1,2,3-triazol-4-yl]benzoic acid (47)

The reaction was performed analogous to the general procedure B. The product was purified on a C18 column eluting with a gradient of 10 to 100% MeCN in H2O containing 0.2% AcOH to afford the colorless solid of 47 (24.3 mg, 0.056 mmol, 23%). Mp 272 °C decom.; 1H-NMR (500 MHz, (CD3)2SO): δ 12.16 (br s, 1H), 10.58 (s, 1H), 8.54 (s, 1H), 8.40 (dd, J = 1.6, 1.6 Hz, 1H), 8.04 (dd, J = 7.8, 1.6, 1.6 Hz, 1H), 7.92 (dd, J = 7.8, 1.6, 1.6 Hz, 1H), 7.76 (dd, J = 8.0, 1.1, 1H), 7.57 (dd, J = 7.8, 7.8 Hz, 1H), 7.37 (dd, J = 8.0, 1.1 Hz, 1H), 7.16 (dd, J = 8.0, 1.1 Hz, 1H), 7.08 (dd, J = 8.0, 1.1 Hz, 1H), 5.25 (br s, 2H), 2.16–1.84 (br m, 4H), 1.74–1.52 (br m, 4H). 13C-NMR (126 MHz, (CD3)2SO): δ 172.2, 168.4, 167.6, 145.7, 134.8, 131.5, 129.7, 129.0, 128.9, 128.1, 126.6, 126.2, 124.1, 123.0, 116.5, 69.7, 52.8, 43.4, 24.1. LRMS (ESI) m/z [M+H]+ 432. RP-HPLC: RT 11.80 min; purity: 99.2%.

3.2.35. Methyl 4-[1-(2-oxo-2-[3'-oxo-3',4'-dihydro-1'H-spiro[cyclopentane-1,2'-quinoxalin]-1'-yl]ethyl)-1H,1,2,3-triazol-4-yl]benzoate (48)

The reaction was performed analogous to the general procedure B. The product was purified on a SiO2 column eluting with a gradient of 20 to 90% EtOAc in cyclohexane to afford a colorless solid of 48 (60.7 mg, 0.136 mmol, 56%). Mp 263 °C decom.; 1H-NMR (500 MHz, (CD3)2SO): δ 10.59 (s, 1H), 8.57 (s, 1H), 8.05–8.01 (m, 2H), 8.01–7.96 (m, 2H) 7.77 (dd, J = 8.0, 1.0 Hz, 1H), 7.37 (dd, J = 8.0, 1.0 Hz, 1H), 7.15 (dd, J = 8.0, 1.0 Hz, 1H), 7.08 (dd, J = 8.0, 1.0 Hz, 1H), 5.36 (br s, 2H), 3.87 (s, 3H), 2.26–1.80 (br m, 4H), 1.74–1.49 (br m, 4H). 13C-NMR (126 MHz, (CD3)2SO): δ 172.2, 168.4, 166.4, 145.4, 135.7, 134.8, 130.4, 129.1, 128.9, 128.1, 126.5, 125.6, 124.9, 123.0, 116.5, 69.7, 52.9, 52.6, 44.0, 23.8. LRMS (ESI) m/z [M+H]+ 446. RP-HPLC: RT 12.22 min; purity: 95.2%.

3.2.36. 1',2-[2-(4-Methoxyphenyl)-1H-1,2,3-triazol-1-yl]acetyl]-3',4'-dihydro-1'H-spiro[cyclopentane-1,2'-quinoxalin]-3'-one (49)

The reaction was performed analogous to the general procedure B. The product was purified on a SiO2 column eluting with a gradient of 30 to 100% EtOAc in cyclohexane to afford a colorless solid of 49 (34.0 mg, 0.082 mmol, 47%). Mp 249 °C decom.; 1H-NMR (500 MHz, (CD3)2SO): δ 10.58 (s, 1H), 8.29 (s, 1H), 7.78–7.72 (m, 3H), 7.37 (dd, J = 7.9, 7.9, 1.1 Hz, 1H), 7.15 (dd, J = 7.9, 7.9, 1.1 Hz, 1H), 7.08 (dd, J = 7.9, 1.1 Hz, 1H), 7.03–6.98 (m, 2H), 5.31 (br s, 2H), 3.79 (s, 3H), 2.28–1.86 (br m, 4H), 1.75–1.52 (br m, 4H). 13C-NMR (126 MHz, (CD3)2SO): δ 172.2, 168.6, 159.4, 146.4, 134.8, 128.9, 128.1, 126.9, 126.7, 123.8, 123.0,
122.6, 116.5, 114.8, 69.6, 55.6, 52.7. LRMS (ESI) m/z [M+H]+ 418. RP-HPLC: RT 12.09 min; purity: 98.0%.

3.2.37. 1′-[4-(Pyridin-2-yl)-1H-1,2,3-triazol-1-yl]acetyl]-3′,4′-dihydro-1′H-spiro[cyclopentane-1,2′-quinoxalin]-3′-one (50)

The reaction was performed analogous to the general procedure B. The residue was purified on a reversed phase C18 column eluting with a gradient of 10 to 100% MeCN in H2O to afford a colorless solid of 50 (10.2 mg, 0.026 mmol, 15%). Mp 218 °C decomp.; 1H-NMR (500 MHz, (CD3)2CO): δ 9.53 (s, 1H), 8.58-8.55 (m, 1H), 8.35 (s, 1H), 8.10 (dt, J = 7.6, 1.1, 1 Hz, 1H), 7.86 (dd, J = 7.6, 1.8 Hz, 1H) 7.78 (dd, J = 7.8, 1.2 Hz, 1H), 7.41 (dd, J = 7.9, 1.1 Hz, 1H), 7.29 (dd, J = 7.7, 4.7, 1.2 Hz, 1H), 7.26–7.20 (m, 2H), 5.40 (br s, 2H), 3.65–3.34 (br m, 4H), 1.81–1.60 (br m, 4H). 13C-NMR (126 MHz, (CD3)2CO): δ 171.9, 167.9, 150.8, 147.9, 136.7, 135.2, 128.5, 128.2, 126.4, 124.5, 122.6, 122.5, 119.3, 116.1, 69.9, 52.5, 34.8, 23.7. LRMS (ESI) m/z [M+H]+ 389. RP-HPLC: RT 11.49 min; purity: 99.3%.

3.2.38. 1′-[4-Cyclopropyl-1H-1,2,3-triazol-1-yl]acetyl]-3′,4′-dihydro-1′H-spiro[cyclopentane-1,2′-quinoxalin]-3′-one (51)

The reaction was performed analogous to the general procedure B. The residue was purified on a reversed phase C18 column eluting with a gradient of 10 to 100% MeCN in H2O to afford a colorless oil of 51 (14.2 mg, 0.040 mmol, 23%). 1H-NMR (500 MHz, (CD3)2CO): δ 9.49 (s, 1H), 7.72 (dd, J = 7.8, 1.2 Hz, 1H), 7.53 (s, 1H), 7.40 (dd, J = 7.9, 1.1 Hz, 1H), 7.23–7.16 (m, 2H), 5.20 (br s, 2H), 2.24–1.95 (br m, 4H), 1.96–1.85 (m, 1H), 1.79–1.60 (br m, 4H), 0.91–0.85 (m, 2H), 0.77–0.73 (m, 2H). 13C-NMR (126 MHz, (CD3)2CO): δ 171.8, 168.2, 149.0, 134.9, 128.4, 126.4, 122.6, 121.9, 116.0, 69.8, 52.2, 34.6, 23.7, 7.0, 6.4. LRMS (ESI) m/z [M+H]+ 352. RP-HPLC: RT 11.45 min; purity: 97.1%.

3.2.39. 2-[1-(2-Oxo-2-oxo-3′,4′-dihydro-1′H-spiro[cyclopentane-1,2′-quinoxalin]-1′-yl)ethyl]-1H-1,2,3-triazol-4-yl]acetic acid (52)

The reaction was performed analogous to the general procedure B. The product was purified on a semi-prep reversed phase HPLC eluting with a gradient of 10 to 100% MeCN in H2O to afford a colorless solid of 52 (13.6 mg, 0.035 mmol, 20%). Mp 230 °C decomp.; 1H-NMR (500 MHz, (CD3)2SO): δ 10.58 (s, 1H), 8.62 (s, 1H), 7.73 (dd, J = 7.9, 1.1 Hz, 1H), 7.36 (ddd, J = 7.9, 7.9, 1.1 Hz, 1H), 7.14 (ddd, J = 7.9, 7.9, 1.1 Hz, 1H), 7.07 (ddd, J = 7.9, 1.1 Hz, 1H), 5.35 (br s, 2H), 3.82 (s, 2H), 2.26–1.80 (br m, 4H), 1.74–1.50 (br m, 4H). 13C-NMR (126 MHz, (CD3)2SO): δ 172.1, 168.0, 161.1, 138.7, 134.9, 131.4, 128.9, 127.9, 126.5, 123.0, 116.5, 69.7, 53.0, 52.3, 35.1, 23.7. LRMS (ESI) m/z [M+H]+ 370. RP-HPLC: RT 10.98 min; purity: 94.1%.

3.2.40. 1′-[4-(2-Methoxyethyl)-1H-1,2,3-triazol-1-yl]acetyl]-3′,4′-dihydro-1′H-spiro[cyclopentane-1,2′-quinoxalin]-3′-one (53)

The reaction was performed analogous to the general procedure B. The residue was purified on a reversed phase C18 column eluting with a gradient of 10 to 100% MeCN in H2O to afford a colorless solid of 53 (24.3 mg, 0.066 mmol, 38%). Mp 153 °C decomp.; 1H-NMR (500 MHz, (CD3)2CO): δ 9.50 (s, 1H), 7.80 (s, 1H), 7.76–7.72 (m, 1H), 7.41 (dd, J = 7.9, 7.9, 1.1 Hz, 1H), 7.23–7.17 (m, 2H), 5.29 (br s, 2H), 4.48–4.46 (m, 2H), 3.30 (s, 3H), 2.81–2.77 (m, 2H), 2.20–1.90 (br m, 4H), 1.78–1.61 (br m, 4H). 13C-NMR (126 MHz, (CD3)2CO): δ 171.8, 168.1, 144.2, 134.9, 128.5, 128.2, 126.4, 124.9, 122.6, 116.1, 116.0, 69.8, 65.4, 56.9, 52.2, 34.9, 23.6. LRMS (ESI) m/z [M+H]+. RP-HPLC: RT 10.88 min; purity: 99.1%.
3.2.41. 1′-[2-(5-Phenyl-1H-1,2,3,4-tetrazol-1-yl)acetyl]-3′,4′-dihydro-1′H-spiro[cyclopentane-1,2′-quinoxalin]-3′-one (54)

22 (74.4 mg, 0.364 mmol, 1.2 eq) was dissolved in dichloromethane (0.1 mL) and excess SOCl2 (1 mL) was added. The SOCl2 solution was stirred at 45 °C for 1 h before the solvent and the SOCl2 was evaporated in vacuo. The residue was dissolved in dichloromethane (1 mL), 5 (61.7 mg, 0.304 mmol, 1.0 eq), and Et3N (0.05 mL, 0.361 mmol, 1.2 eq) was added and the reaction was stirred at ambient temperature for 2 h. MeOH (0.5 mL) was added and the reaction mixture was evaporated. The residue was purified by a silica column eluting with a gradient of 0 to 50% EtOAc in cyclohexane to afford a colorless solid of 54 (16.5 mg, 0.042 mmol, 14%). Mp 197–202 °C dec. 1H-NMR (500 MHz, CDCl3): δ 8.92 (br s, 1H), 7.48–7.42 (m, 2H), 7.31–7.28 (m, 2H), 7.05 (ddd, J = 7.8, 7.8, 1.2 Hz, 1H), 6.97 (dd, J = 7.8, 1.2 Hz, 1H), 5.03 (br s, 2H), 2.05 (m, 2H), 1.70 (m, 4H), 1.31–1.15 (m, 2H). 13C-NMR (126 MHz, CDCl3): δ 173.4, 166.9, 155.3, 134.0, 131.6, 129.34, 129.32, 128.7, 127.8, 125.9, 123.7, 123.6, 116.8, 70.9, 50.5, 29.7, 24.1. RP-HPLC: RT 11.58 min; purity: 99.9%.

3.2.42. 1′-[2-(5-Phenyl-2H-1,2,3,4-tetrazol-2-yl)acetyl]-3′,4′-dihydro-1′H-spiro[cyclopentane-1,2′-thieno[3,4-b]pyrazin]-3′-one (55)

To a solution of 21 (125 mg, 0.623 mmol, 1.0 eq) in dichloromethane (1.5 mL) was added oxalyl chloride (0.06 mL, 0.699 mmol, 1.1 eq) followed by a drop of DMF. When the gas evolution stopped, the acid chloride solution was added to a solution of 35 (152 mg, 0.735 mmol, 1.2 eq) in dichloromethane (1.5 mL) and the reaction stirred at ambient temperature overnight. The reaction mixture was diluted with EtOAc (100 mL) and sat. aq. NaHCO3 solution (40 mL). The layers were separated, and the org. layer was washed with and brine (20 mL), dried (Na2SO4), filtered and evaporated in vacuo. The residue was purified by silica column eluting with 10 to 35% EtOAc in cyclohexane followed by semi-prep RP chromatography (C18 column) eluting with a gradient of 10 to 100% B in A (A: 95/5 water/McCN, B: 5/95 water/McCN) to afford 55 as an off-white solid (16 mg, 0.041 mmol, 7%). Mp 231–233 °C dec; 1H-NMR (500 MHz, CDCl3): δ 9.63 (br s, 1H), 8.13–8.07 (m, 2H), 7.82 (d, J = 3.2 Hz, 1H), 7.58–7.49 (m, 3H), 6.85 (d, J = 3.2 Hz, 1H), 5.88 (s, 2H, 6), 2.29–2.14 (m, 4H), 1.81–1.63 (m, 4H). 13C-NMR (126 MHz, CDCl3): δ 170.4, 166.8, 165.6, 134.1, 131.2, 130.3, 129.9, 128.5, 127.4, 118.2, 103.8, 72.7, 56.4, 36.0, 24.4. LRMS (ESI) m/z [M+H]+ 395. RP-HPLC: RT 12.49 min; purity: 99.5%.

3.2.43. 1′-([3-[3-(But-3-yn-1-yl)-3-hydrazinyl]propanoyl]-3′,4′-dihydro-1′H-spiro[cyclopentane-1,2′-quinoxalin]-3′-one (56)

S15 (40 mg, 0.241 mmol, 1.0 eq) was dissolved in thionyl chloride (2 mL) and stirred for 15 min at 40 °C. Thionyl chloride was removed in vacuo. The residue was taken up with dichloromethane (2 mL) and added dropwise to a solution of 5 (58.4 mg, 0.289 mmol, 1.2 eq), Et3N (73 mg, 0.722 mmol, 3.0 eq) and dichloromethane (2 mL) and stirred for 1 h. The reaction mixture was concentrated in vacuo and purified by semi-prep HPLC on a C18 column eluting with a gradient of 10 to 100% MeCN in H2O containing 0.2% AcOH to afford a pale yellow oil of 56 (20.7 mg, 0.059 mmol, 25%). 1H-NMR (500 MHz, CDCl3): δ 8.81 (s, 1H), 7.31–7.25 (m, 2H), 7.12–7.08 (m, 1H), 6.99–6.95 (m, 1H), 2.20–1.81 (m, 8H), 1.79–1.65 (m, 7H), 1.59–1.53 (m, 2H). 13C-NMR (126 MHz, CDCl3): δ 174.5, 174.2, 133.9, 129.8, 128.0, 126.6, 123.0, 116.1, 82.7, 69.5, 69.1, 34.9, 32.4, 29.8, 27.9, 27.7, 23.7, 13.2. LRMS (ESI) m/z [M+H]+ 351. RP-HPLC: RT 13.34 min; purity: 92.6%.

3.2.44. 1′-Octanoyl-3′,4′-dihydro-1′H-spiro[cyclopentane-1,2′-quinoxalin]-3′-one (57)

To a solution of octanoic acid (0.09 mL, 0.566 mmol, 1.2 eq) and oxalyl chloride (0.05 mL, 0.582 mmol, 1.2 eq) in dichloromethane (2 mL) was added one drop of DMF (approximately 5 μL, 0.130 mmol, 0.13 eq), resulting in a strong gas evolution. After 5 min, gas formation was complete and 5 (97 mg, 0.480 mmol, 1 eq) and Et3N (0.1 mL, 0.717 mmol, 1.5 eq) were added. The reaction was stirred at ambient temperature for 10
min and then quenched with brine (5 mL). The layers were separated, and the aq. layer was extracted with dichloromethane (2 × 5 mL). The org. layers were dried (Na₂SO₄), filtered and evaporated in vacuo. The crude product was purified by silica column eluting with a gradient of 0 to 10% MeOH in dichloromethane and semi-prep RP chromatography (C₁₈ column) eluting with a gradient of 40 to 100% B in A (A: 95/5 water/MeCN + 0.2% AcOH, B: 5/95 water/MeCN + 0.2% AcOH) to afford an off-white solid of 57 (24 mg, 0.073 mmol, 15%). Mp 67–70 °C; ¹H-NMR (500 MHz, CDCl₃): δ 9.23 (br s, 1H), 7.29 (d, J = 7.8 Hz, 1H), 7.23 (ddd, J = 7.8, 7.8, 1.3 Hz, 1H), 7.05 (ddd, J = 7.8, 7.8, 1.3 Hz, 1H), 6.97 (d, J = 7.8 Hz, 1H) 2.72–1.79 (m, 6H), 1.79–1.61 (m, 4H), 1.49–1.39 (m, 2H), 1.27–1.08 (m, 8H), 0.82 (t, J = 7.1 Hz, 3H). ¹³C–NMR (126 MHz, CDCl₃): δ 176.9, 174.9, 134.1, 130.4, 127.7, 126.7, 122.8, 116.2, 69.4, 36.0, 35.4, 31.7, 29.2, 29.1, 25.2, 24.4, 22.7, 14.2. LRMS (ESI) m/z [M+H]⁺ 329. RP-HPLC: RT 14.46 min; purity: 99.9%.

3.3. Biological Assays

3.3.1. Fluorogenic SENP1 Assay

IC₅₀ measurements were performed with at least two replications using eight concentrations starting at 200 µM and for the fragments at 500 µM with three-fold dilution. Human recombinant, His₆-SENP1 Catalytic Domain (Boston Biochem Cat# E-700, Bio-Techne AG, Zug, Switzerland) was prepared in reaction buffer (50 mM HEPES, 150 mM NaCl, 0.5 mM EDTA, 1 mM DTT, pH 7.5, 0.01% CHAPS). To this solution, a 20 mM or 50 mM inhibitor stock solution in DMSO was added and the mixture was incubated for 15 min at ambient temperature. The substrate SUMO1/2 or 3-AMC (SUMO1-AMC; Boston Biochem Cat# UL-551; SUMO2-AMC; Boston Biochem Cat# UL-758; SUMO3-AMC; Boston Biochem Cat# UL-768; Bio-Techne AG, Zug, Switzerland) was delivered to a 96 well-plate to initiate the reaction. The enzyme activities were monitored (Ex/Em = 355/460 nm) as a time-course measurement of the increase in fluorescence signal from SUMO1/2 or 3-AMC for 60 min at 25 °C. The data were analyzed by taking the slope (signal/time) of the linear portion of measurement. The slope was calculated using Excel and the curve fits were performed using GraphPad Prism7 with a four-parameter least-squares fit. The final reaction conditions contained 0.02 nM SENP1 and 300 nM SUMO1/2 or 3-AMC.

3.3.2. Fluorogenic SENP2 Assay

The IC₅₀ measurements were conducted at Reaction Biology Corporation, Malvern, PA, USA, with two replications using 10 concentrations starting at 200 µM with a three-fold dilution. Curve fits were performed where the enzyme activities at the highest concentration of compounds were less than 65%. UCH-L3 I was used as a control inhibitor. To SENP2 (Enzo Cat# BML-UW9765, Human recombinant catalytic domain expressed in E. coli.) in reaction buffer (50 mM HEPES, 150 mM NaCl, 0.5 mM EDTA, 1 mM DTT, pH 7.5, 0.01% CHAPS) was delivered the compound stock solution by acoustic technology (Echo550; nanoliter range) and subsequently incubated for 15 min at ambient temperature. The substrate SUMO1-AMC (R&D Systems Cat# UL-551-050, Lot# 07613314A, Fluorescence labeled full-length SUMO1 protein) was delivered to the well-plate to initiate the reaction. The enzyme activities were monitored (Ex/Em = 355/460 nm) as a time-course measurement of the increase in fluorescence signal from SUMO1/2 or 3-AMC for 60 min at 25 °C. The data were analyzed by taking the slope (signal/time) of the linear portion of measurement. The slope was calculated using Excel and the curve fits were performed using GraphPad Prism7 with a four-parameter least-squares fit. The final reaction conditions contained 0.015 nM SENP2 and 300 nM SUMO1/2 or 3-AMC.

3.3.3. UCHL1 Activity Assay

IC₅₀ measurements were conducted at Reaction Biology Corporation, Malvern, PA, USA, with two replications using 10 concentrations starting at 200 µM with three-fold dilution. Curve fits were performed where the enzyme activities at the highest concentration of compounds were less than 65%. UCHL1 II was used as a control inhibitor. The procedure
was performed analogous to the fluorogenic SENP2 assay described in 3.3.2. using the UCHL1 enzyme (SignalChem Cat# U22-30H) and Ubiquitin-AMC substrate (Enzo Cat# BML-SE211-0025). The final reaction conditions contained 0.2 nM UCHL1 and 100 nM Ubiquitin-AMC.

3.3.4. Ataxin-3 Activity Assay

IC50 measurements were conducted at Reaction Biology Corporation, Malvern, PA, USA, with two replications using 10 concentrations starting at 200 µM with three-fold dilution. Curve fits were performed where the enzyme activities at the highest concentration of compounds were less than 65%. UCHL1 II was used as a control inhibitor. The procedure was performed analogous to the fluorogenic SENP2 assay described in 3.3.2. using the Ataxin-3 enzyme (BPS Cat# 80399) and Ubiquitin-AMC substrate (Enzo Cat# BML-SE211-0025). The final reaction conditions contained 500 nM Ataxin-3 and 100 nM Ubiquitin-AMC.

3.3.5. SENP1 Endopeptidase Activity with proSUMO3

Measurements were performed using six different inhibitor concentrations starting at 200 µM of 11 with three-fold dilution. Human recombinant, His6-SENP1 Catalytic Domain (Boston Biochem Cat# E-700, Bio-Techne AG, Zug, Switzerland) was prepared in reaction buffer (50 mM HEPES, 150 mM NaCl 0.5 mM EDTA, 1 mM DTT, pH 7.5, 0.01% CHAPS) as 555 nM solution. A 20 mM compound DMSO stock-solution (1.1 µL) was added to the freshly prepared 555 nM enzyme solution (98.9 µL). Five sequential three-fold dilutions resulted in a final inhibitor concentration of 0.8 µM and the enzyme inhibitor complex was incubated for 15 min at 0 °C. Then, 50 µM proSUMO3 (5 µL) was added to the freshly prepared enzyme inhibitor solution (45 µL) and incubated for 60 min at 37 °C and subsequently the reaction was stopped by adding 4× Laemmli-Buffer (16.7 µL) and denaturing the protein at 100 °C for 30 min. Those solutions (10 µL) were loaded on a casted 15% sodium dodecyl sulfate polyacrylamide gel and separated on a Mini-PROTEAN Tetra Cell (Bio-Rad, Hercules, CA, USA). After SDS-PAGE gel electrophoresis separation, the gels were stained with staining solution Bio-Safe Coomassie Brilliant Blue G-250 (BioRad) for 60 min. De-staining was performed with 40% (v/v) methanol, 10% (v/v) glacial acetic acid, 50% (v/v) Milli-Q water until protein bands became visible.

3.3.6. Crosslinking Experiments

A buffer exchange of the commercially available 6 × His-SENP1 Protein (Boston Biochem Cat# E-700) to a 50 mM HEPES, 150 mM NaCl; 0.5 mM EDTA, 1 mM DTT, pH 7.5 was performed. A total of 200 µM of the photo affinity probe 56 with or without competitor molecule 11 (400 µM) was incubated in 10 µM SENP1 for 30 min at 0 °C. Subsequently, the mixtures were irradiated in a Proma UV exposure unit equipped with four 8 Watt lamps (Hitachi FL8BL-8, ~350 nm) for 30 min at 0 °C. Then, 50 µL of the crosslinked proteins were mixed with freshly prepared click mix solution (50 µL; 1 mM CuSO4, 1 mM TCEP, 100 uM THPTA from a 5 mM DMSO stock, dissolved in Milli-Q Water) and a 10 mM stock solution of azide fluor 545 (1 µL) and incubated at 0 °C for 14 h. A pre-casted gradient sodium dodecyl sulfate polyacrylamide gel (4–20% Mini-PROTEAN® TGX™ Precast Protein Gel, 10-well, 50 µL #4561094) was used. Sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE) was performed using Mini-PROTEAN Tetra Cell (Bio-Rad) using a Tris-Glycine discontinuous buffer system. Protein samples for SDS-PAGE were first prepared in 1× Laemmli sample buffer (diluted from 4× Laemmli sample buffer (ROTI® Load), and subsequently denatured at 100 °C for 15 min. After SDS-PAGE gel electrophoresis separation, the fluorescence was visualized (Ex. 520 nm, Em. 575 nm) on the SDS PAGE gel using ImageQuant™ 4000 LAS (GE Healthcare, Chicago, IL, USA). Secondly, the gels were stained with Bio-Safe Coomassie Brilliant Blue G-250 (BioRad) for 60 min. De-staining was performed with 40% (v/v) methanol, 10% (v/v) glacial acetic acid, 50% (v/v) Milli-Q water until protein bands became visible.
4. Conclusions

Building on a virtual screening campaign, a series of novel SENP inhibitors could be established by fragment-based and synthetic modifications of the screening hit. It was also shown that our inhibitor 11 (ZHAWOC8697) is not only able to inhibit the cleavage of the SUMO1-AMC test substrate, but more importantly the maturation of the native proSUMO protein. The SENP1-inhibitor interaction was further validated with the photo affinity probe 56. Under our experimental conditions, compound 11 is equipotent compared to the most potent SENP1 inhibitors known to us, published by Chen et al. [21] and Lindemann et al. [25]. Moreover, the selectivity profile of the developed inhibitor toward other DUB proteins is comparable to that of the aforementioned inhibitors. In addition, 11 also inhibits SENP2 very effectively. Thus, this compound represents a valuable small molecule tool to study SENP1/2-SUMO interactions in a biological context and to develop small molecule drugs for the treatment of SENP1/2-associated diseases.

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