

Integrated Synthetic, Biophysical and Computational Investigations of Covalent Inhibitors of Prolyl Oligopeptidase and Fibroblast Activation Protein

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Integrated Synthetic, Biophysical and Computational Investigations of Covalent Inhibitors of Prolyl Oligopeptidase and Fibroblast Activation Protein α

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KEYWORDS covalent druggability • serine proteases • quantum cluster chemical approach •
covalent inhibitors

ABSTRACT. Over the past decade, there has been an increasing interest in covalent inhibition
as a drug design strategy. Our own interest in the development of prolyl oligopeptidase
(POP) and fibroblast activation protein α (FAP) covalent inhibitors has led us to question
whether these two serine proteases were equal in terms of their reactivity towards
electrophilic warheads. To streamline such investigations, we exploited both computational
and experimental methods to investigate the influence of different reactive groups on both
potency and binding kinetics, using both our own series of POP inhibitors and others'

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3 discovered hits. A direct correlation between inhibitor reactivity and residence time was
4 demonstrated through quantum mechanics (QM) methods and further supported by
5 experimental studies. This computational method was also successfully applied to FAP, as an
6 overview of known FAP inhibitors confirmed our computational predictions that more
7 reactive warheads (e.g., boronic acids) must be employed to inhibit FAP than for POP.
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16 Introduction

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18 Following the resurgence of covalent inhibition in the last decade,¹⁻³ kinases and serine
19 proteases have been targeted with numerous covalent inhibitors,⁴ and covalent inhibitors
20 have reached the market (Figure 1). Among these targets are prolyl oligopeptidase (POP),
21 initially associated with neurodegenerative diseases,⁵⁻⁸ and fibroblast activation protein α
22 (FAP), a promising target for anti-cancer therapies.⁹⁻¹² In the past, our group and others have
23 reported a number of potent covalent POP inhibitors,⁸ including Cbz-Pro-Prolinal (**1**), JTP-
24 4819 (**2**), KYP-2047 (**3**), and bicyclic derivative **5**,¹³ as well as FAP covalent inhibitors such
25 as compounds **6**, **8**, and Talabostat (Figure 2). Although these two druggable targets have
26 been inhibited by many covalent inhibitors, the major differences lie in the chemical nature
27 of the warheads, or electrophilic functional groups that form covalent bonds with protein
28 residues.
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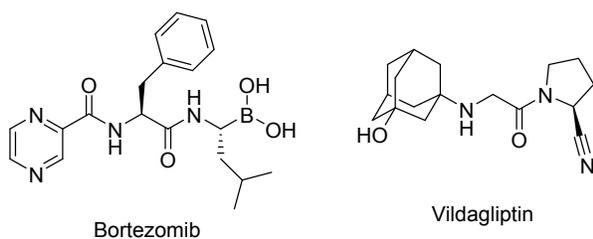


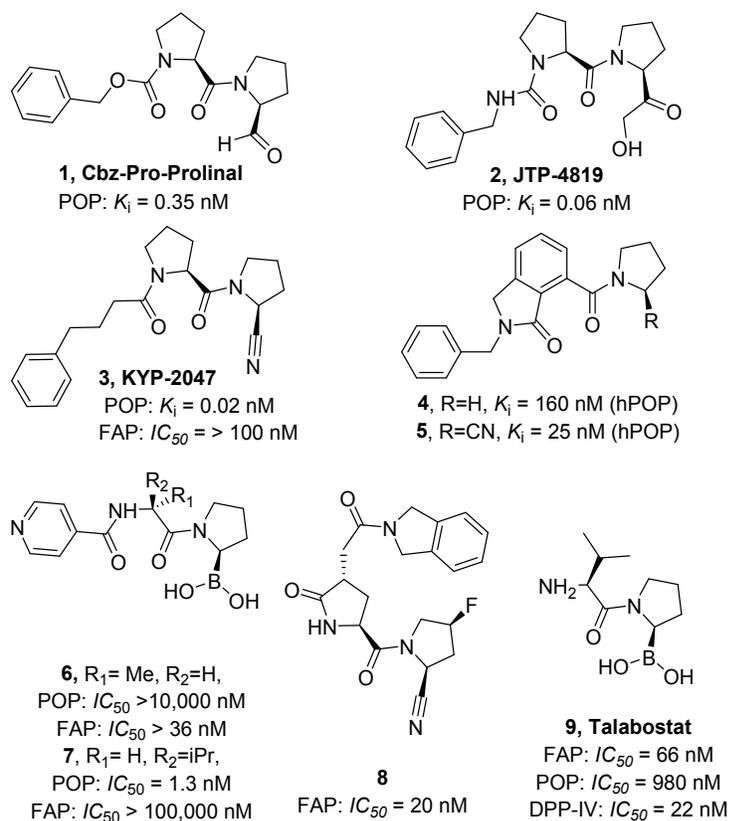
Figure 1. Selected marketed covalent inhibitors.

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3 Non-covalent inhibitors often bind and dissociate very quickly and exhibit short residence
4 times and are therefore often largely under thermodynamic control. In contrast, covalent
5 inhibitors are believed to often bind in a two-step process (Figure 3a): a fast, non-covalent
6 initial binding followed by a slower covalent bond formation. As a result, kinetic factors and
7 residence time cannot be ignored and could indeed be critical for inhibitor efficacy.³ Recently
8 the reactivity of the warheads used in covalent inhibition has been increasingly investigated
9 either experimentally^{14,15} or computationally¹⁶ as reactivity often dictates whether the
10 inhibitor will bind reversibly or irreversibly.¹⁷ Similarly, the reactivity of the protein's
11 catalytic residues in covalent inhibition has been investigated with focus on cysteines.¹⁸⁻²² A
12 very interesting method based on free energy perturbation (FEP) has recently been reported
13 which computes binding free energies including both covalent and non-covalent
14 contribution to binding.^{23,24}

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31 However, although these methods proved effective, the focus has been primarily on
32 cysteine residues and acrylamides as warheads, as kinase cysteines have likely been the
33 major targets for covalent inhibitors (often acrylamides) in the recent years²⁵. A number of
34 research groups are nowadays searching for alternative warheads and residues to bind to
35 (marketed covalent drugs are binding to serine) and computational methods must be
36 assessed.²⁶

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Prior to designing covalent inhibitors, the biological target must be first identified as
covalently druggable (i.e., can be targeted with covalent inhibitors). Unfortunately, there are
very few tools currently available, experimental or computational, to accomplish this. We
report herein a developed computational protocol using POP and FAP that could eventually
be used to (1) predict whether an enzyme is covalently druggable and (2) to identify

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3 potentially potent warheads. To illustrate the potential application of such a protocol: it took
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5 our team months to optimally express and purify POP and to optimize the *in vitro* activity
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7 assays, which was followed by months of synthesis until we found potent inhibitors. With
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9 our current computational protocol in hand, requiring only 2-3 weeks of calculations, we
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11 would have been able to make a more informed decision on whether to initiate our hit-
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13 discovery endeavor. Similarly, until this protocol was available, our efforts focused on the
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15 unsuccessful development of nitrile-containing FAP inhibitors. Running reactivity
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17 predictions before synthesis would have allowed us to opt for the appropriate warheads
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22 much earlier.



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Figure 2. Selected POP and FAP inhibitors.

As demonstrated via co-crystallization,^{27,28} POP inhibition can be achieved through covalent bond formation between the reactive group of a ligand and the catalytic serine in the active site (Ser554). The reaction of Ser554 with aldehyde **1** leads to the formation of a hemiacetal, which favorably mimics the tetrahedral intermediate of the endogenous catalytic reaction, stabilizing its presence in the active site (Figures 3b, 3c). In contrast, reaction with a nitrile group leads to a trigonal planar iminoether, an intermediate which less favorably mimics the amide group of the peptide substrates (Figure 3d). While maintaining favorable non-covalent interactions (e.g. via the scaffold) is essential for both potency and selectivity, modification of the covalent warhead is also expected to have a significant impact on the binding affinity and kinetics via its influence on the second step of the binding event (Figure 3a).

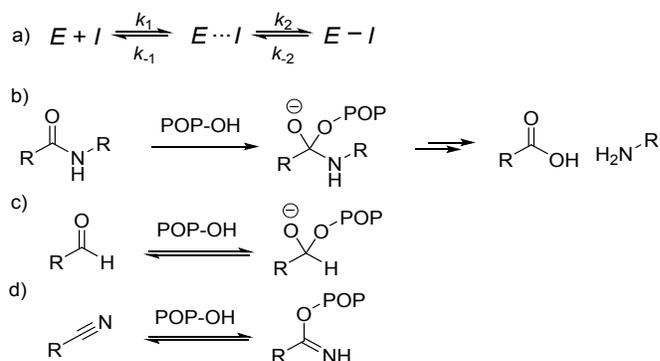


Figure 3. a) Two-step process for covalent inhibition. E: enzyme; I: inhibitor; E⋯I: non-covalent complex; k_1 : association rate constant; k_{-1} : dissociation rate constant. b) cleavage of a substrate; c) aldehyde inhibitor covalent binding; d) nitrile inhibitor covalent binding.

Herein, we describe our collaborative approach, including computational predictions and experimental evaluations, to the investigation of the relative reactivities of FAP and POP and the nature of the covalent warheads that are more likely to lead to potent inhibitors.

Results

Strategy. We sought to develop a computational protocol which would first be tested against experimental data collected on POP and then validated on a homologous enzyme, FAP (Figure 4).

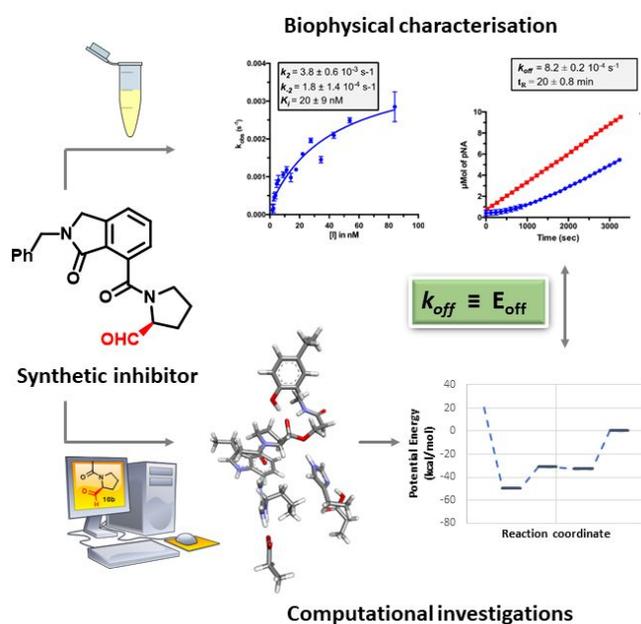
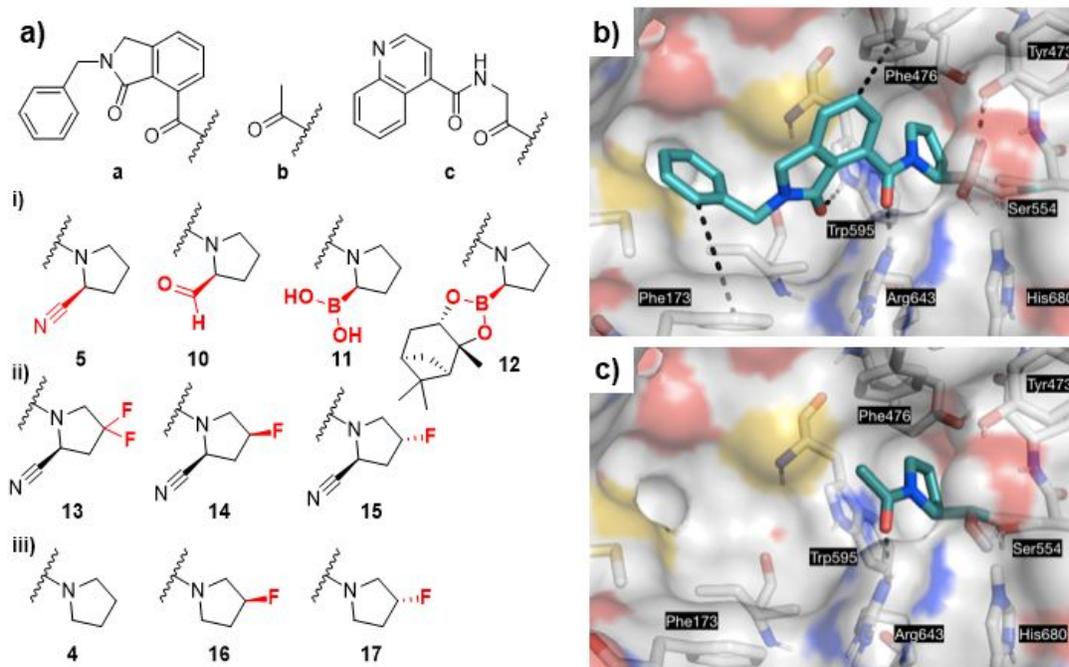


Figure 4. Computational model and experimental data collection. The residence times of various inhibitors depends on kinetics factors ($t_R = 1/k_{off}$), which are measured using biophysical methods. These kinetic parameters are related to the energy required for the inhibitors to break the covalent bond and leave the enzyme (E_{off}). Advantageously, E_{off} can be computed, ultimately demonstrating that computations can substitute complex, time-

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3 consuming, and expensive experiments for initial assessments as to whether a newly
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5 discovered target is covalently druggable.
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12 In order to probe the impact of the intrinsic reactivity of the warhead on the overall
13 binding process, we designed a series of inhibitors **5a**, **10a-17a** which complement
14 binding process, we designed a series of inhibitors **5a**, **10a-17a** which complement
15 previously reported inhibitors **5c**, **11c**, **13c-15c**²⁹ (Figure 5). Two strategies were envisioned:
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17 (1) substitution of the warhead – the nitrile, aldehyde, and boronic acid were selected, as
18 these are known to form covalent bonds with nucleophilic protein residues;^{30,31} and (2)
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20 modification of the electronic environment of a given warhead – electron withdrawing
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22 fluorine atoms could be introduced on the nitrile analogue, a strategy exploited to prepare
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24 FAP inhibitors (Figure 2).
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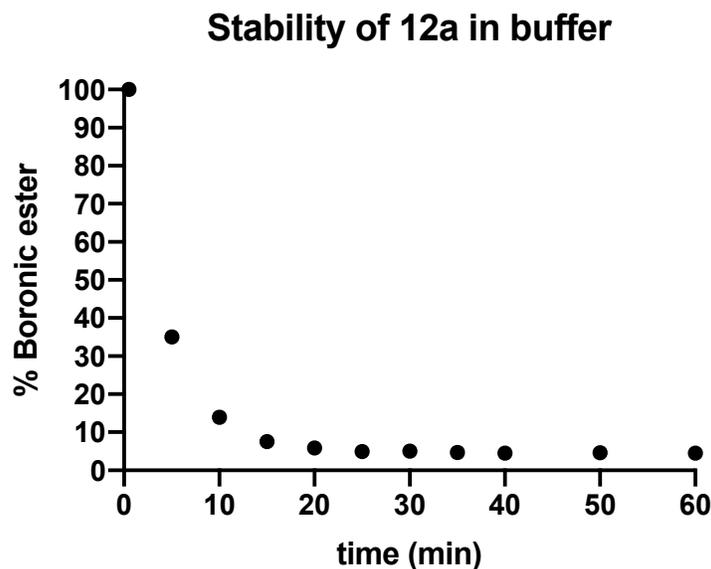
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3 **Figure 5.** Selected inhibitor structures. i) different reactive groups; ii) modulated nitrile
4 reactivity; iii) effects of fluorine atoms alone. b) Docked binding mode of boronic acid **11a**
5 into the POP active site. c) Snapshot of the POP active site and with **10b** bound to Ser554 and
6 the residues kept for the Quantum Chemical Cluster Approach (QCCA) study.
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16 **Chemistry.** The synthesis of bicyclic scaffold **a**, previously published by our group, has been
17 optimized and is presented in Scheme S1 in the Supporting Information.¹³ Bicyclic precursor
18 **18** (Scheme 1), previously discovered through a virtual screening/virtual optimization
19 strategy, was selected because of its straightforward and efficient synthesis. More
20 specifically, this core was readily available in only three synthetic steps and an overall yield
21 of 74% with no flash chromatography purification, offering the unprotected carboxylic acid
22 **18** as a diversity point.
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32 The individual proline analogs were then coupled to the scaffold **18** to afford the desired
33 inhibitors. Because the proline analogues were either commercially or readily available,
34 expedient and efficient synthesis of potential POP inhibitors was achieved in only 1-2 steps.
35 The synthesis of these selected analogues (**4a**, **5a** and **10a-17a**) is outlined in Schemes 1 and
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44 The boron-containing analogue **12a** was obtained by coupling scaffold **18** with the
45 commercially available proline analog **19** to yield product **12a** in moderate yield (Scheme 1).
46 Attempts at hydrolysis of boronic ester **12a** to obtain boronic acid **11a** were unsuccessful,
47 exhibiting solubility issues and yielding complex mixtures, so **12a** was utilized instead. Our
48 own liquid chromatography-mass spectrometry experiment revealed that the boronic ester
49 **12a** is nearly quantitatively hydrolyzed to boronic acid **11a** in the assay buffer (ca. 90% after
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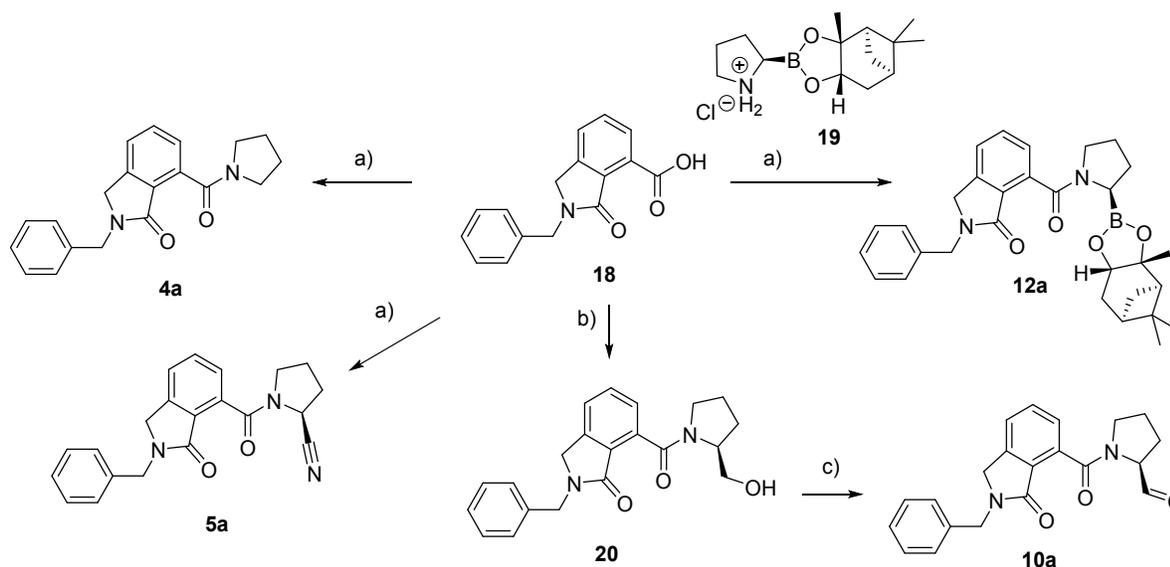
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3 10 minutes, Figure 6), and can therefore be tested as a pro-drug cleaved in the assay.
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5 Furthermore, our own *in vitro* assay controls show that the cleaved pinanediol exhibits no
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7 inhibitory activity against POP (data not shown).
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30 **Figure 6.** Liquid chromatography–mass spectroscopy study of boronic ester cleavage in the
31 POP buffer. The relative abundance of the boronic ester was recorded over one hour,
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33 plateauing at approximately 5% abundance.
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41 Synthesis of the potential inhibitor **10a** bearing an aldehyde as the warhead started with
42 the coupling of commercially available L-prolinol with scaffold **18**, to afford the primary
43 alcohol **20** in excellent yield. Further oxidation under Swern conditions led to the desired
44 aldehyde **10a**. Synthesis of the non-covalent analog **4a** was accomplished by coupling
45 scaffold **18** to pyrrolidine. The nitrile analog **5a** was obtained by coupling **18** with readily
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47 available (*S*)-pyrrolidine-2-carbonitrile (Scheme 1).
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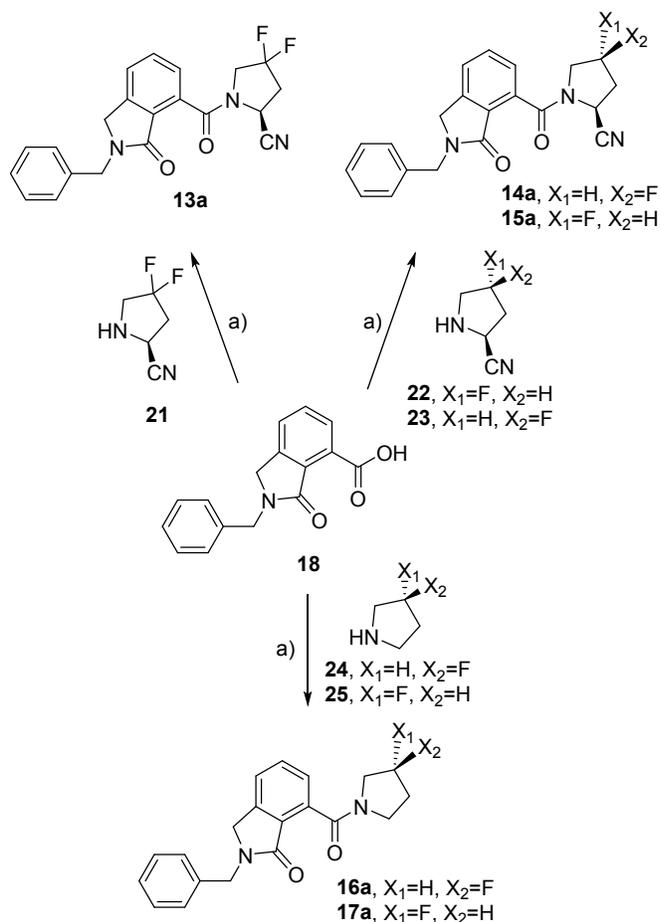
Scheme 1. Synthesis of diversely functionalized inhibitors.^a



^aReagents: a) i. PivCl, Et₃N, DCM, 0°C; ii. **amine** (see Experimental Section), rt, 18h (**4a**, 40%, **5a**, 92%, **12a**, 43%); b) i. PivCl, Et₃N, DCM, 0 °C; ii. Prolinol, 18h, rt (87%); c) DMSO, Oxalylchloride, DCM, -78°C (40%).

Synthesis of the selected fluorocyanopyrrolidine analogues began from readily available starting materials.³² Coupling of **18** with nitrile **21** led to the corresponding inhibitor **13a**. Reaction of readily available free amines **22** and **23** with the bicycle core **18** under standard coupling conditions afforded the intended inhibitors **14a** and **15a**, respectively. The non-covalent inhibitors **16a** and **17a** were prepared through coupling of carboxylic acid **18** with **24** and **25**, respectively.

Scheme 2.^a Synthesis of the fluorine-containing compounds.



^aReagents: a) i. PivCl, Et₃N, DCM, 0°C; ii. **amine** (see Experimental Section), rt, 18h (**13a**, 35%; **14a**, 30%; **15a**, 30% **16a**, 90%; **17a**, 90%)

Biophysical characterization. Next, these selected molecules were first evaluated for their inhibitory potency against recombinant human POP (Table 1). Figure 7 shows the dose-response curves for covalent inhibitors **10a** and **12a**. As expected, while non-functionalized pyrrolidine derivative **4a** exhibited a potency of 160 nM, the measured K_i values for the nitrile (**5a**), aldehyde (**10a**) and boronic ester (**12a**) derivatives were significantly lower. The high reactivity of aldehydes as electrophiles has often been a major issue for developing safe

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3 drugs, even in the discovery of Bortezomib (boronic acid proteasome inhibitor, Figure 1).^{33,34}
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5 In contrast, the lower reactivity of nitriles allowed medicinal chemists to use them as
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7 warhead in drugs such as Vildagliptin (nitrile-containing covalent DPP-IV inhibitor, Figure
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1). The reactivity of these warheads is further discussed below.

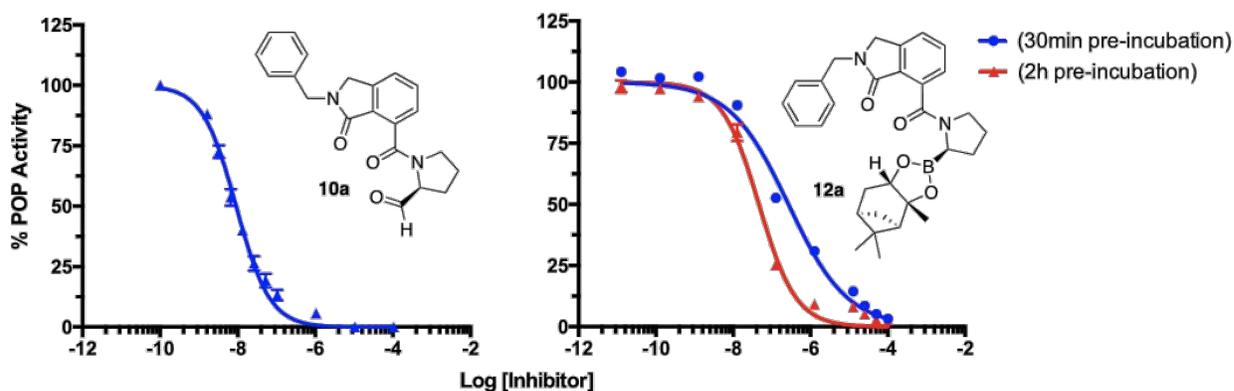


Figure 7. Dose-response curves of **10a** (left) and **12a** (right) against human recombinant POP after 30-minute pre-incubation periods. Boronic ester **12a** was additionally tested with a two-hour pre-incubation period to allow for *in situ* hydrolysis of the (+)-pinanediol protecting group.

As an observed effect of kinetic factors, the K_i decreases over time until equilibrium is reached. While the nitrile and aldehyde derivatives reached equilibrium after 30 minutes of pre-incubation, the boronic ester **12a** required a longer incubation period. This was most likely due to the rate of hydrolysis of the boronic ester to the boronic acid **11a**, which is required for enzyme binding. Residence time is largely controlled by binding kinetics of the covalent ligand, illustrating the importance of this property.^{2,35,36} Introduction of fluorine atoms onto the pyrrolidine ring of our lead compound **5a** led to complete loss (**15a**) or a

decrease (**13a**, **14a**) in potency. A similar decrease in affinity was also observed for the non-covalent inhibitors bearing a fluorine atom on the pyrrolidine ring (**4a** vs. **16a** and **17a**), suggesting that factors other than the nitrile reactivity modulate potency.

Additional biophysical characterization experiments were performed for select inhibitors **10a**, **12a**, and control **1**. To extract kinetic parameters, progress curve experiments were conducted at various inhibitor concentrations. Data from these curves were then used to extract the respective k_{obs} values, which were further plotted against inhibitor concentration; the resultant data was subsequently fitted to the corresponding equations (see Supporting Information) in order to retrieve the inhibitors' kinetic parameters. Finally, rapid dilution experiments were performed to obtain residence time t_R . (See Supporting Information for the raw data curves of the above-mentioned experiments.) Kinetic parameters of each compound are provided in Table 1. Unfortunately, any attempts to obtain kinetic parameters for the non-covalent, the prolinonitrile, and the fluorinated prolinonitrile derivatives proved unsuccessful, as the off rates were too quick to measure experimentally.

Table 1. Summary of the kinetic parameters measured experimentally.*

Cpd	K_i (nM) ^a	K_i (nM) ^b	K_i^* (nM) ^c	k_{on} ($10^5 \text{ M}^{-1} \text{ s}^{-1}$)	k_{off} (10^{-4} s^{-1})	t_R (min)	FAP ^d
1	1 ± 0.1	8 ± 1	0.4 ± 0.02	7.8 ± 2.2	3.9 ± 0.5	42 ± 5	< 5% ³⁷
4a	160 ± 40	-	-	-	-	< 1	<5%
5a	25 ± 4	-	25 ± 4	-	-	< 1	20%
10a	4.0 ± 0.4	20 ± 9	3.5 ± 0.2	1.86 ± 0.7	8.2 ± 0.2	20 ± 0.8	80% (11%)
12a	110 ± 40^e	60 ± 10	29 ± 2	0.04 ± 0.01	2.3 ± 0.3	73 ± 10	<5%

		22 ± 5 ^f						
	13a	3,300 ± 780	-	-	-	-	-	<5%
	14a	170 ± 40	-	-	-	-	-	<5%
	15a	> 100 μM	-	-	-	-	-	<5%
	16a	290 ± 50	-	-	-	-	-	<5%
	17a	620 ± 90	-	-	-	-	-	<5%

^aAffinity constant, measured by absorbance assay. ^bAffinity constant of the first step of the binding event, measured by dilution experiments. ^cAffinity constant of the second step of inhibition. ^dinhibition at 100 μM (at 1 μM). ^e30 minute E—I pre-incubation time. ^f2 hour E—I pre-incubation time. *missing parameters (-) indicate that the kinetics of the reaction were too quick to measure experimentally

Computational study. To study these kinetic parameters and provide insight into the development of effective prediction methods for covalent inhibitors, the quantum chemical cluster approach (QCCA)³⁸ was employed. Starting geometries were taken from crystal structures. The ligands were truncated to focus on energetics of covalent bond formation/breakage while maintaining the electronics of the electrophile (e.g., **10b** as a model for **10a**).

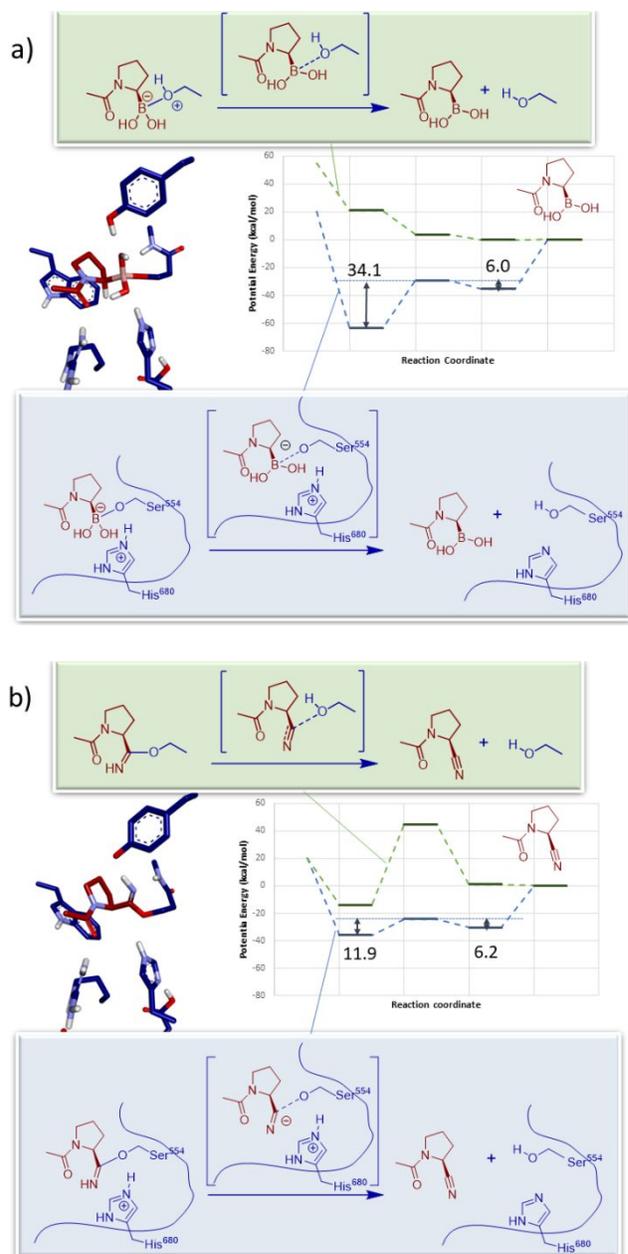


Figure 8. Data collected for boronic acid (a) and nitrile (b) as warhead. In blue is the energy of the enzyme-catalyzed reaction and in green the same reaction with no enzyme. Non-polar hydrogens are omitted for clarity. Similar data has been collected for all the probes and both proteins (Figure S15).

As per the QCCA protocol, the binding site was restricted to the catalytic triad residues along with other key residues, such as the backbone of residues contributing to the oxy-anion hole (Figure 5c). The second step of the binding process was then simulated to acquire several thermodynamic and kinetic parameters, such as binding energies and activation energies for binding and unbinding, which together with enzyme mobility and non-bonded interactions contribute to k_{on} and k_{off} (Table 2, Figure 8, SI). In order to develop a protocol that would minimize calculation time, we decided to compute the energy at evenly distributed distances only. As a result, the “ideal” distance or transition state distances were not necessarily assessed, only close-to-minima structures. Although the search for the energy at the optimal distances is expected to improve accuracy, it is also expected to significantly increase computational time and hence decrease efficiency, as locating a transition state is not a simple task. Rather, our method is expected to provide us with trends which would be accurate enough to make informed decisions on whether a target is covalently druggable. Considering this approximation, we also considered different levels of theory, from semiempirical (AM1) to higher levels (PBE0/def2-TZVP/D3BJ).

Table 2. Summary of the parameters obtained computationally (all values are in kcal/mol).

Cpd.	E_{off}		E_{on}		ΔG (cov. – non-cov.)		Binding Energy	
	POP	FAP	POP	FAP	POP	FAP	POP	FAP
5b	11.9	6.2	6.2	7.5	-5.7	1.3	-36.0	-27.0
10b	18.8	16.9	1.8	3.9	-17.0	-13.0	-49.9	-42.9
11b	34.1	26.0	6.0	<1.0 ^a	-28.1	-26.0	-63.5	-55.8
13b	14.2	12.6	8.4	5.9	-5.8	-6.7	-37.3	-29.1

14b	9.8	5.7	8.5	10.6	-1.3	4.9	-34.4	-25.4
15b^b	13.7	10.9	6.6	10.2	-7.1	-0.7	-39.2	-32.8

^a The compound forms a covalent bond without an energy barrier. ^b computed with the pseudo axial conformation (see text).

Discussion

The computational data suggests that the warhead does in fact have a direct influence on the kinetics and thus activity of the second step in ligand binding. According to this data, the aldehyde and boronic acid are predicted to have longer residence times than any of the nitrile derivatives, represented by significantly larger E_{off} values. This is consistent with the in-depth intrinsic electrophilicity analysis at the HF/def2-TZVP level of theory we have conducted on compounds **5b**, **10b** and **11b** (Tables S5-7) using our own QM package QUEMIST. This analysis is based on computing the LUMO energies of the three compounds, alongside intrinsic atomic orbital (IAO) atomic charges³⁹ for the reactive atoms (boron, carbonyl carbon and nitrile carbon) and total atomic nucleophilic superdelocalizabilities (TANS) for the reactive atoms.⁴⁰ The TANS is a measure of interaction with a nucleophile by an electrophile, and can be reliably used to compare two or more sites for this specific interaction. A high value of TANS is representative of a larger capacity of an atom to interact with a nucleophile through their LUMO orbital. According to this data (Tables S5-7), the boronic acid **11b** has the lowest LUMO energy (7.4 kcal/mol lower than the aldehyde and 5.3 kcal/mol lower than the nitrile) along with a higher IAO atomic charge for the reactive atom (0.74 vs. 0.33 for **10b** and 0.15 for **5b**) and a higher TANS for the reactive atom (9.84 vs. 1.24 for **10b** and 1.06 for **5b**). This analysis is also consistent with the binding energies presented

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3 in Table 2, which suggests the boronic acid is the strongest binder/more intrinsically
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5 reactive.
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8 The data also suggested that the nitriles had a slightly higher activation energy (E_{on}) in FAP
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10 than in POP. More surprisingly, the conversion of the aldehyde to the hemi-acetal and the
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12 boronic acid to the boronate in the active site appear to possess a very low energy barrier.
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14 This would imply that covalent bond formation is rapid, only limited by diffusion of the
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16 ligand into the active site and reorientation of the electrophilic warhead to allow covalent
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18 bond formation. This low energy barrier is attributed to two observations: (1) the ligands
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20 appear to be pre-activated by Tyr473 as they approach the nucleophilic serine, and (2) the
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22 transition states of these reactions resemble the transition state adopted by the natural
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24 substrates and are highly stabilized through hydrogen bonding. Interestingly, in the case of
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26 nitriles, the proximal Tyr473 hydroxyl group is properly positioned to transfer a proton to
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28 the forming imine despite the sp^2 character of this intermediate. While ligand-enzyme
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30 kinetics were the focus of these computations, we also observed that in the case of the nitrile,
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32 energy of the covalently bound state was not necessarily significantly lower than that of the
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34 non-covalent complexes, keeping in agreement with low residence time. We next
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36 investigated whether computing the full binding process was required. First, we computed
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38 the correlation between the binding energies and E_{off} for POP (Table 2; Figure S16),
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40 according to the Bell-Evans-Polanyi principle.⁴¹ This principle establishes a linear
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42 relationship between the activation energy and the enthalpy of reaction in the same family
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44 of reactions. The R^2 coefficient of 0.96 confirms a significant correlation between the binding
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46 energies and E_{off} , and suggest that future investigations should simply focus on ground
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48 states, thus streamlining the process. We next computed theoretical half-lives $t_{1/2}$ of both the
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3 initial bond formation as well as the bond breakage (Tables S3 and S4) which are
4 significantly lower than the residence times (Table 2). The bond formation/breaking was
5 significantly faster than the experimental residence time, suggesting that the inhibition
6 process is under thermodynamic control. Thus, the binding energies should also correlate
7 with the experimentally determined K_i values. We plotted the relevant graph (Figure S16)
8 and we observed no correlation between the binding energies and K_i values ($R^2 = 0.17$).
9 Several factors are responsible for this apparent lack of correlation: first, we computed the
10 binding energies of truncated fragments, while the K_i values were determined using the full
11 molecules. While we tried to obtain K_i values for the fragments alone, they showed no
12 activity in POP or FAP (data not shown), revealing the critical contribution of the rest of the
13 molecules to the binding affinity. Secondly, the K_i values were computed in solution, while
14 our computations were performed exclusively in the gas phase. We believe that for accurate
15 solvent effects an explicit solvent should be used,⁴² which can be reliably done using
16 molecular dynamics simulations. However, this is beyond the scope of our computations,
17 which intend to offer a qualitative analysis and trends with respect to reactive warheads. In
18 addition, the use of small fragments assumes that the warheads are properly positioned to
19 form a reversible covalent bond. Adding groups to these fragments certainly modulates these
20 optimal alignments hence the K_i . Finally, we observed that association rate of **10a** showed a
21 significant temperature dependence, which we attribute to the large conformational
22 rearrangement of POP that accompanies ligand binding,⁴³ a motion not considered when
23 computationally binding fragments.
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3 It should be noted that the objective of this research is to define whether a covalent bond
4 is possible (covalent druggability) and which warhead would be optimal but not whether a
5 given molecule is to be a strong inhibitor.
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10 Although the computational trends match the experimental trends, the computed low
11 energy barriers for the aldehyde and boronic acid contrast with the commonly reported slow
12 covalent binding step (Figure 3a). One such disagreement between computations and
13 experiment exists for compound **15a/b**. A closer look at the models revealed that the
14 preferred conformation (pseudo-axial fluorine) cannot geometrically form the covalent
15 bond and must rearrange into the less energetically favored pseudo-equatorial
16 conformation. We and others have previously found that fluorine atoms have major control
17 on five-membered ring conformations.⁴² This phenomenon was also observed in FAP by
18 Jansen *et al.*, with inhibitors bearing the *cis*-fluorine as in **14c** exhibiting potency two orders
19 of magnitude greater than those bearing the *trans*-fluorine as in **15c**.²⁹ Computations of
20 binding energies (from dissociated complexes to covalently bound complexes) suggests that
21 POP binds these fluorinated proline mimics more tightly than FAP. As discussed above, this
22 apparent discrepancy between experimental and computational results stems from the use
23 of ideally positioned fragments used in the computational investigations of the covalent
24 bond formation which experimentally do not inhibit the enzymes vs. the larger molecules
25 used in the *in vitro* assays.
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47 By means of progress curve analyses and rapid dilution experiments, relevant parameters
48 such as the K_i (affinity constant of the non-covalent component of binding), the K_i^* (affinity
49 of the second step of inhibition), k_{on} (association rate) and k_{off} (dissociation rate) were
50 experimentally determined (Table 1, see SI for details). As a control experiment, Cbz-Pro-
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3 prolinol (**1**) was first investigated, and the data obtained was in agreement with a previous
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5 report.³¹ The results for our designed inhibitors confirmed that the intrinsic reactivity of the
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7 warhead of the covalent inhibitor greatly influenced the on- and off-rates of ligand binding.
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9 The boronic ester inhibitor (**12a**) displayed the slowest on-rate of inhibition (k_{on}). As
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11 discussed above, hydrolysis of the boronic ester was an additional factor in the on-rate of
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13 inhibition.^{44,45} Similarly, aldehyde **10a**, although displaying significantly faster on-rates than
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15 boronic ester **12a**, interacted relatively slowly compared to nitrile **5a**, where no slow-binding
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17 was detected. The relatively slow binding of the aldehyde-containing inhibitor was
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19 attributed to the presence of a pre-existing equilibrium in aqueous solution of an active
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21 aldehyde form and an inactive hydrate form of the ligand, while no such equilibrium exists
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23 with nitriles. While fast binding was predicted when covalent bond formation was computed
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25 (k_2 in Figure 3a), k_{on} measures the entire two-step process.
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32 In agreement with the computations, aldehydes and boronic acids have the longest
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34 residence times. Experimentally, our aldehyde compound **10a** has a residence time 20
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36 minutes shorter than that of Cbz-Pro-prolinol (**1**). In contrast, boronic ester **12a** displayed
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38 nearly a four-fold longer residence time, rationalized by the additional stabilizing
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40 interactions of the resultant boronic acid hydroxyl groups with residues in the active site of
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42 POP, as proposed by docking and QM studies (Figures 5b, 5c). Nitrile inhibitor **5a** displayed
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44 a very short residence time, despite bearing the same scaffold as **12a** and **10a**, correlating
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46 with the low E_{off} computed in POP. These short residence times may also result from **5a**
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48 binding non-covalently as suggested by the small difference in energy between covalently
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50 bound and non-covalently bound complexes (Table 2). From the experimental data, we can
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52 conclude that the nitrile does not provide a strong enough covalent adduct needed to
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3 maintain a longer-bound time in POP, which is in agreement with the computations. As
4 discussed above, covalent ligand-protein complexes of both **12a** and **10a** with POP exhibit a
5 tetrahedral geometry, resembling that of the transition state geometry formed by the
6 enzyme while carrying out its peptidase activity. In contrast, the covalent complex resulting
7 from reaction with nitrile **5a** exhibits a trigonal planar geometry (Figure 3d).
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11 The computations suggested that the pre-orientation of the ligand by the tyrosine
12 facilitates rapid bond formation and, coupled to the small activation barrier, that the covalent
13 binding step may be very fast (Figure 8). This prediction is supported by kinetic results we
14 recently obtained for a related scaffold in which addition of a nitrile warhead actually led to
15 a moderate increase in the binding rate compared to the equivalent non-covalent inhibitor.⁴⁶
16 In contrast, the association rate for the covalent inhibitor would be lower than that of the
17 non-covalent analogue if bond formation were indeed rate-limiting.
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21 The correlation between computations and experiments provides validation for the QCCA
22 method's ability to predict the overall trends in binding kinetics in POP for covalent ligands
23 and gave us confidence in the data for FAP, an enzyme which is extremely difficult to express
24 and handle experimentally. Our computations indicate that the binding of our truncated
25 nitrile ligands to FAP should have greater E_{on} and smaller E_{off} likely rendering it less active,
26 while the aldehyde and boronic acid remain reactive enough to inhibit the enzyme. This
27 prediction is consistent with our literature survey, which revealed that although many POP
28 inhibitors feature a nitrile, most potent FAP inhibitors feature a boronic acid or an activated
29 nitrile (Figure 1). The computations were also in agreement with our experimental data on
30 FAP inhibitory activity of compound **5a** (20% inhibition at 100 μ M) and compound **10a** (80%
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3 inhibition at 100 μM), although the large bicyclic core of our inhibitor may also hinder
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5 binding to FAP.
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10 **Conclusion**

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12 In conclusion, this study aimed to streamline the investigation of two covalently druggable
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14 targets using computational methods to provide a better understanding of experimentally-
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16 obtained thermodynamic and kinetic factors involved in their covalent inhibition and to
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18 further study the factors controlling general covalent drug potency. With POP, an enzyme
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20 which can easily be expressed and purified, experimental and computational data were in
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22 excellent agreement and revealed that the commonly held belief that covalent bond
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24 formation is rate limiting for covalent inhibitors does not necessarily stand when highly
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26 reactive enzyme residues and/or inhibitors are involved. Our validated computational
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28 protocol then rationalized the wide use of boronic acids in FAP inhibition versus the more
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30 commonly used nitrile in POP inhibition. The results presented here are a first step towards
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32 using computational methods to complete a larger study of covalent binding kinetics, a
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34 concept which is entirely unaccounted for in current computational prediction tools such as
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36 molecular docking. The ability to integrate kinetic data into prediction tools will improve the
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38 ability to rank ligands shown to be active.
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45 Our collaborative approach to this model system aims to facilitate future covalent drug
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47 discovery endeavors. By applying our computational methods to predict the relative
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49 reactivity of a newly-discovered target's catalytic residue, biologists and chemists can
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51 determine whether the target is covalently druggable and therefore more efficiently design
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3 the most promising drug candidates. These predictions will, in the long run, save valuable
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5 time and resources in the very costly drug discovery and development processes.
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10 **Experimental Section.**

11 **Chemistry**

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15 **General information.** All commercially available reagents were used without further
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17 purification unless otherwise stated. The 4 Å molecular sieves were dried at 100°C prior to
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19 use. FTIR spectra were recorded using a Perkin-Elmer Spectrum One FT-IR. ¹H and ¹³C NMR
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21 spectra were recorded on Varian Mercury 400 MHz, Varian 300 MHz, Unity 500 MHz, Bruker
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23 400 MHz, or Bruker 500 MHz spectrometers. Chemical shifts are reported in ppm using the
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25 residual of deuterated solvents as internal standard. Thin layer chromatography
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27 visualization was performed by UV or by development using KMnO₄, H₂SO₄/MeOH, Mo/Ce,
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29 CAM solutions. Chromatography was performed on silica gel 60 (230-40 mesh) or using
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31 Biotage Isolera One purification system with ZIP cartridges. Low resolution mass
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33 spectrometry was performed by ESI using a Thermoquest Finnigan LCQ Duo. High resolution
34
35 mass spectrometry was performed by EI peak matching (70 eV) on a Kratos MS25 RFA
36
37 double focusing mass spectrometer or by ESI on a Ion Spec 7.0 T FTMS at McGill University.
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39 Prior to biological testing, reversed phase HPLC (water and MeCN or MeOH gradient) was
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41 used to verify the purity of compounds on an Agilent 1100 series instrument equipped with
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43 VWD-detector, C18 reverse column (Agilent, Zorbax Eclipse XDB-C18 150 mm 4.6 mm, 5
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45 μm), UV detection at 254 nm. All biologically tested compounds exhibited ≥95% purity.
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52 Measured purities for all tested compounds are listed in Table S1 in the Supporting
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55 Information.
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General Procedure for peptidic coupling. The carboxylic acid **18** (1 eq) was suspended in anhydrous DCM (0.1 M) under argon atmosphere, and Et₃N (5 eq) was added. The resultant solution was cooled to 0°C, and pivaloyl chloride (1.1 eq) was added. After 1h of stirring at 0°C, the amine (1.1 eq) was added, and the reaction stirred at room temperature overnight. Water was added, and the product was extracted with EtOAc or with DCM (depending on the amount of original DCM solvent). The combined organic layers were washed with 1M HCl, saturated NaHCO₃, and brine, dried over Na₂SO₄, filtered, and concentrated *in vacuo*. The crude residue was purified by flash chromatography on a silica gel column to give the product. Residues were triturated in hexanes and/or Et₂O and filtered under vacuum to give solids.

2-benzyl-7-(pyrrolidine-1-carbonyl)isoindolin-1-one (4a) Compound **4a** was synthesized following the general procedure for peptidic coupling, using pyrrolidine as the corresponding amine (40%). ¹H NMR (500 MHz, Chloroform-*d*) δ 7.52 (t, *J* = 7.6 Hz, 1H), 7.37 (dd, *J* = 7.5, 1.7 Hz, 2H), 7.34 – 7.25 (m, 5H), 4.97 – 4.80 (m, 1H), 4.73 – 4.50 (m, 1H), 4.24 (s, 2H), 3.92 – 3.75 (m, 1H), 3.75 – 3.59 (m, 1H), 3.42 – 3.20 (m, 1H), 3.17 – 2.99 (m, 1H), 2.06 – 1.73 (m, 4H); ¹³C NMR (126 MHz, CDCl₃) δ 24.61, 26.01, 45.70, 46.48, 48.25, 49.33, 77.16, 123.34, 126.22, 127.85, 128.28 (2C), 128.39 (2C), 128.91, 131.80, 135.51, 136.94, 141.76, 166.88, 167.02. Spectral and experimental data previously published by our group.¹³

1-(2-benzyl-3-oxoisoindoline-4-carbonyl)pyrrolidine-2-carbonitrile (5a) Compound **5a** was synthesized following the general procedure for peptidic coupling, using (*S*)-pyrrolidine-2-carbonitrile pTsOH salt as the corresponding amine (92%). ¹H NMR (400 MHz, Acetone-*d*₆) δ 7.70 – 7.48 (m, 2H), 7.47 – 7.38 (m, 1H), 7.37 – 7.13 (m, 5H), 5.03 – 4.54

(m, 3H), 4.41 (s, 2H), 3.79 – 3.66 (m, 0.5H), 3.38 – 3.17 (m, 1.5H), 2.48 – 2.34 (m, 1H), 2.34 – 2.21 (m, 1H), 2.21 – 2.07 (m, 1H), 2.04 – 1.96 (m, 1H); *Carbon peaks reported for major rotamer.* ^{13}C NMR (101 MHz, Acetone- d_6) δ 25.75, 29.84, 31.25, 46.56, 47.04, 48.58, 50.05, 119.70, 125.15, 126.83, 128.31, 128.84 (2C), 129.11, 129.55 (2C), 132.54, 134.47, 138.48, 143.32, 167.22, 167.88. Spectral and experimental data previously published by our group.¹³

(S)-1-(2-benzyl-3-oxoisindoline-4-carbonyl)pyrrolidine-2-carbaldehyde (10a). Oxalyl chloride (108 mg, 1.2 eq) was dissolved in DCM (3 mL), and the solution was cooled to – 78°C. DMSO (139 mg, 2.5 eq, in DCM, 2 mL) was added dropwise, and the solution stirred for 2 minutes. **20** (250 mg, 1 eq, in 2 mL DCM) was added dropwise, and the solution stirred for 15 minutes. Et₃N (361 mg, 5 eq) was added, and the solution stirred 15 mins. Water was added, and the mixture was warmed to room temperature. The product was extracted with EtOAc, and the combined organic layers were washed with brine, dried over Na₂SO₄, filtered, and concentrated in vacuo to give an orange oil, which was purified by flash chromatography on a silica gel column (eluent 100% EtOAc) to give the product as a white solid (100 mg, 40%). *R_f* 0.30 (100% EtOAc); IR (film) ν_{max} (cm⁻¹) 3387, 3006, 1675, 1626, 1601, 1434; ^1H NMR (500 MHz, Acetone- d_6) δ 10.13 – 9.17 (m, 1H), 7.76 – 7.20 (m, 8H), 4.94 – 4.58 (m, 2H), 4.56 – 4.18 (m, 3H), 3.91 – 3.11 (m, 2H), 2.29 – 2.09 (m, 1H), 2.02 – 1.76 (m, 3H); ^{13}C peaks reported for the major rotamer. ^{13}C NMR (126 MHz, Acetone) δ 14.50, 20.83, 23.27, 26.05, 27.59, 29.84, 32.28, 46.56, 49.28, 50.01, 60.53, 65.74, 124.86, 126.43, 128.31, 128.83 (2C), 129.54 (2C), 129.56, 132.49, 135.22, 138.54, 143.36, 167.38, 167.98, 170.88, 202.63; HRMS (ESI+): calculated for [C₂₁H₂₀N₂O₃ + H]⁺, 349.15467; found, 349.15418.

2-benzyl-7-((R)-2-((3aR,4R,6R,7aS)-3a,5,5-trimethylhexahydro-4,6-methanobenzo[*d*][1,3,2] dioxaborol-2-yl)pyrrolidine-1-carbonyl)isoindolin-1-one (12a).

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3 Compound **12** was synthesized following the general procedure for peptidic coupling, using
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5 **19** as the corresponding amine. The crude residue was purified using (1:1 EtOAc/hexanes)
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7 as the eluent system (43%, white foam); IR (film) ν_{\max} (cm^{-1}) 3225, 2922, 1686, 1606, 1451;
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9 *Peaks and coupling constants reported for major rotamer. Full integrated proton spectrum*
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11 *provided.* ^1H NMR (500 MHz, Chloroform-*d*) δ 7.52 (t, $J = 7.6$ Hz, 1H), 7.42 (d, $J = 7.5$ Hz, 1H),
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13 7.37 (d, $J = 7.6$ Hz, 1H), 7.35 – 7.26 (m, 5H), 4.84 (d, $J = 14.8$ Hz, 1H), 4.68 (d, $J = 14.8$ Hz,
14
15 1H), 4.39 (dd, $J = 8.9, 2.2$ Hz, 1H), 4.25 – 4.19 (m, 2H), 3.47 (dt, $J = 9.2, 6.3$ Hz, 1H), 3.42 –
16
17 3.31 (m, 1H), 3.22 (dd, $J = 17.3, 7.9$ Hz, 1H), 2.41 – 2.12 (m, 3H), 2.09 (t, $J = 5.5$ Hz, 1H), 2.01
18
19 – 1.85 (m, 5H), 1.61 (d, $J = 10.9$ Hz, 1H), 1.45 (s, 3H), 1.29 (s, 3H), 0.86 (s, 3H); ^{13}C NMR (126
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21 MHz, CDCl_3) δ 24.28, 26.43, 27.29, 27.30, 27.33, 28.92, 35.82, 38.39, 39.79, 44.60, 46.53,
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23 48.15, 49.31, 51.57, 77.16, 78.08, 86.04, 123.60, 127.03, 127.84, 128.42 (2C), 128.67, 128.92
24
25 (2C), 128.95, 131.65, 137.08, 141.75, 166.58, 166.69; ^{11}B NMR (161 MHz, CDCl_3) δ 32.45;
26
27 HRMS (ESI+): calculated for $[\text{C}_{30}\text{H}_{35}\text{B}_1\text{N}_2\text{O}_4 + \text{H}]^+$, 499.27736; found, 499.27634.
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34 **(S)-1-(2-benzyl-3-oxoisindoline-4-carbonyl)-4,4-difluoropyrrolidine-2-carbonitrile**

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36 **(13a)** Compound **13a** was synthesized following the general procedure for peptidic coupling,
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38 using **21** as the corresponding amine. The crude residue was purified using 3:1
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40 EtOAc/hexanes as the eluent system (30%, white solid); ($R_f = 0.53$; 3:1 EtOAc/hexanes); IR
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42 (film) ν_{\max} (cm^{-1}) 2918, 2850, 1666, 1604, 1411, 1108; ^1H NMR (500 MHz, CDCl_3) δ 7.75 –
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44 7.57, (m, 2H), 7.57 – 7.45 (m, 2H), 7.43 – 7.28 (m, 4H), 5.34 (br s, 0.5 H), 4.96 (d, $J = 14.9$ Hz,
45
46 0.5 H), 4.89 – 4.80 (m, 1H), 4.71 (br s, 0.5H), 4.62 (d, $J = 14.9$ Hz, 0.5 H), 4.41 – 4.24 (m, 2.5
47
48 H), 4.17 (t, $J = 15.1$ Hz, 0.5 H), 3.82 (br s, 0.5 H), 3.63 (br s, 0.5 H), 3.08 – 2.89 (m, 1H), 2.83
49
50 (t, $J = 13.2$ Hz, 0.5 H), 2.70 (t, $J = 13.2$ Hz, 0.5H); *Peaks include rotamers.* ^{13}C NMR (101 MHz,
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52 CDCl_3) δ 46.69, 49.62, 49.79, 52.76, 53.92 (t, $J = 31.9$ Hz), 77.16, 116.78, 124.96, 125.13,
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3 126.89, 127.97, 128.14, 128.23, 128.37 (2C), 129.11 (2C), 129.15, 131.68, 132.36, 132.79,
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5 136.30, 136.51, 141.93, 167.06, 167.52; HRMS (ESI+): calculated for $[C_{21}H_{17}F_2N_3O_2 + H]^+$,
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7 382.13616; found, 382.13599.
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9

10 **(2*S*,4*S*)-1-(2-benzyl-3-oxoisindoline-4-carbonyl)-4-fluoropyrrolidine-2-carbonitrile**

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12 **(14a)** Compound **14a** was synthesized following the general procedure for peptidic coupling,
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14 using **22** as the corresponding amine. The crude residue was purified using 100% EtOAc as
15
16 the eluent system (30%, white solid); R_f 0.18 (100% EtOAc); IR (film) ν_{max} (cm⁻¹) 3012,
17
18 2920, 1682, 1653, 1605, 1409, 1212; ¹H NMR (500 MHz, Chloroform-*d*) δ 7.72 – 7.41 (m,
19
20 3H), 7.40 – 7.20 (m, 5H), 5.58 – 5.18 (m, 1.6H), 4.87 (dd, J = 18.8, 14.9 Hz, 1H), 4.70 – 4.52
21
22 (m, 1.4H), 4.40 – 4.20 (m, 2H), 4.20 – 4.02 (m, 1H), 3.79 – 3.45 (m, 1H), 2.78 – 2.49 (m, 2H);
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24 *Carbon peaks reported for both rotamers.* ¹³C NMR (126 MHz, CDCl₃) δ 36.51, 36.67, 38.24,
25
26 38.40, 44.97, 46.60, 46.67, 47.12, 49.63, 49.77, 53.18, 53.37, 54.14, 54.33, 77.16, 90.34, 91.32,
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28 91.77, 92.76, 117.93 (2C), 124.53, 124.74, 126.89 (2C), 127.53 (2C), 128.10, 128.15, 128.27
29
30 (2C), 128.33 (2C), 129.07 (2C), 129.10 (2C), 132.38, 132.49, 132.66, 132.69, 136.38, 136.47,
31
32 141.77 (2C), 166.89, 166.91, 167.64, 167.66; HRMS (ESI+): calculated for $[C_{21}H_{18}FN_3O_2 +$
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34 $H]^+$, 364.14558; found, 364.14500.
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40 **(2*S*,4*R*)-1-(2-benzyl-3-oxoisindoline-4-carbonyl)-4-fluoropyrrolidine-2-carbonitrile**

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42 **(15)** Compound **15a** was synthesized following the general procedure for peptidic coupling,
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44 using **23** as the corresponding amine. The crude residue was purified using 1:1
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46 EtOAc/hexanes as the eluent system (30%, white solid); (R_f = 0.1; 1:1 EtOAc/hexanes); IR
47
48 (film) ν_{max} (cm⁻¹) 3008, 2920, 1686, 1648, 1603, 1413, 1205; ¹H NMR (400 MHz, Acetone-
49
50 *d*₆) δ 8.38 – 7.55 (m, 2H), 7.52 – 7.24 (m, 6H), 5.36 (dt, J = 52.2, 3.7 Hz, 1H), 5.15 – 4.65 (m,
51
52 3H), 4.55 – 4.17 (m, 2H), 3.96 – 3.43 (m, 2H), 2.99 – 2.83 (m, 1H), 2.75 – 2.52 (m, 1H); ¹³C
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3 NMR (101 MHz, Acetone) δ 29.84, 37.61 (d, $J = 22.3$ Hz), 45.37, 46.59, 49.99, 54.93 (d, $J =$
4 22.1 Hz), 88.77 (d, $J = 177.5$ Hz) 118.79, 125.61, 127.79, 128.31, 128.87, 129.56 (4C), 132.52,
5
6 133.90, 138.53, 143.46, 166.90, 167.78; HRMS (ESI+): calculated for $[\text{C}_{21}\text{H}_{18}\text{F}_1\text{N}_3\text{O}_2 + \text{H}]^+$,
7
8 364.14558. ^{13}C —F peak suppressed, HSQC provided as Supporting Information.
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12 **(S)-2-benzyl-7-(3-fluoropyrrolidine-1-carbonyl)isoindolin-1-one (16a) / (R)-2-benzyl-7-**
13 **(3-fluoropyrrolidine-1-carbonyl)isoindolin-1-one (17a)** Compounds **16a/17a** were
14 synthesized following the general procedure for peptidic coupling, using **24/25** as the
15 corresponding amines. The crude residues were purified using 100% EtOAc as the eluent
16 system (90%/90%, white solids); *As they are enantiomers, they gave identical spectral*
17 *properties.* R_f : 0.18 (100% EtOAc); IR (film) ν_{max} (cm^{-1}) 3005, 1682, 1627, 1607, 1433,
18 1206; ^1H NMR (500 MHz, Chloroform-*d*) δ 7.54 (td, $J = 7.5, 2.6$ Hz, 1H), 7.40 (t, $J = 7.5$ Hz,
19 2H), 7.34 – 7.22 (m, 5H), 5.26 (ddt, $J = 82.8, 52.9, 3.9$ Hz, 1H), 4.87 – 4.56 (m, 2H), 4.32 – 4.19
20 (m, 2H), 4.15 – 3.75 (m, 2H), 3.63 – 3.32 (m, 2H), 2.46 – 2.03 (m, 2H); *Carbon peaks reported*
21 *for both rotamers.* ^{13}C NMR (126 MHz, CDCl_3) δ 31.20, 31.37, 32.74, 32.91, 43.60, 45.90,
22 46.47, 49.37, 52.41, 52.60, 54.22, 54.40, 77.16, 92.06 (d, $J = 175.3$ Hz), 92.80 (d, $J = 177.7$
23 Hz), 123.68, 123.75, 126.28, 126.55, 127.86, 127.89, 128.20 (2C), 128.31 (2C), 128.34 (2C),
24 128.90 (2C), 128.92 (2C), 131.87, 131.99, 134.57, 134.59, 136.75, 136.81, 141.76, 141.82,
25 166.79, 166.83, 167.27, 167.31; HRMS (ESI+): calculated for $[\text{C}_{20}\text{H}_{19}\text{FN}_2\text{O}_2 + \text{Na}]^+$,
26 361.1323; found, 361.132.
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47 **(S)-2-benzyl-7-(2-(hydroxymethyl)pyrrolidine-1-carbonyl)isoindolin-1-one (20).**
48
49 Compound **20** was synthesized following the general procedure for peptidic coupling, using
50 L-prolinol as the corresponding amine. The crude residue was purified using 100% EtOAc as
51 the eluent system (87%, white solid); ($R_f = 0.15$; 100% EtOAc); IR (film) ν_{max} (cm^{-1}) 3434,
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3 2943, 1671, 1624, 1602, 1432; ¹H NMR (500 MHz, Chloroform-*d*) δ 7.56 (t, *J* = 7.6 Hz, 1H),
4 7.42 (t, *J* = 8.0 Hz, 2H), 7.36 – 7.31 (m, 2H), 7.31 – 7.25 (m, 3H), 4.91 – 4.76 (m, 2H), 4.74 –
5 4.59 (m, 2H), 4.35 (t, *J* = 7.7 Hz, 1H), 4.33 – 4.22 (m, 2H), 3.50 (t, *J* = 11.2 Hz, 1H), 3.29 (td, *J*
6 = 9.7, 6.8 Hz, 1H), 3.13 (ddd, *J* = 10.7, 7.8, 3.5 Hz, 1H), 2.26 – 2.15 (m, 1H), 2.16 – 2.08 (m,
7 1H), 2.04 – 1.93 (m, 1H), 1.82 – 1.69 (m, 1H); ¹³C NMR (126 MHz, Chloroform-*d*) δ 25.09,
8 27.56, 46.56, 49.30, 50.08, 59.46, 62.21, 77.16, 123.61, 125.90, 127.78, 127.91, 128.36 (2C),
9 128.93 (2C), 132.07, 135.46, 136.57, 141.90, 166.51, 167.01; HRMS (ESI+): calculated for
10 [C₂₁H₂₂N₂O₃ + Na]⁺, 373.15226; found, 373.15174.
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22 **Liquid Chromatography–Mass Spectroscopy study of the hydrolysis of the boronic ester.**

23
24 The stability of boronic ester **12a** in buffer was assessed by mass spectrometry using a
25 Dionex Ultimate 3000 UHPLC coupled to a Bruker Maxis Impact QTOF in positive ESI mode.
26 A 0.1 mL sample of **12a** in DMSO (100 mM stock) was added to 0.9 mL of buffer in a septum
27 capped vial and placed in the Ultimate 3000 autosampler. At 5 minute intervals, a 1 μL
28 aliquot of the mixture was injected into the QTOF by loop injection at a flow rate of 0.1
29 mL/min in a mobile phase consisting of a 1:1 mixture of water and acetonitrile and 0.1%
30 formic acid. The data was processed using the Bruker DataAnalysis software version 4.2.
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41 **Biological assays and biophysical characterization.**

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43 **FAP Assay.** The FAP assay was performed using the FAP Assay Kit from BPS BioScience.⁴⁷
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45 **POP Protein Expression.** POP was expressed and purified according to a procedure
46 previously described.⁴⁸
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50 **POP Activity Assays.** ZGP-pNA was obtained from Bachem (Bubendorf, Switzerland). IC₅₀
51 / *K_i* measurements were carried out as follows. The reactions were performed in micro titer
52 plates of 96 wells. For each reaction, activity buffer (A.B.) (140 μL, sodium phosphate 20 mM,
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3 NaCl 150 mM, β -mercaptoethanol 5 mM, EDTA 2 mM, 10% glycerol, 0.5 mg/mL BSA, pH=8)
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5 was pre-incubated for 30 min at 30°C with hPOP (20 μ L, 10 nM in A.B., final concentration of
6
7 1nM) and with the corresponding inhibitor solution (20 μ L) or activity buffer (controls).
8
9 Stock inhibitors were prepared in DMSO (100 mM); dilutions for inhibitor evaluation were
10
11 prepared from the stock in activity buffer. A control experiment with the same DMSO
12
13 concentration was performed. After pre-incubation, ZGP-pNA (20 μ L, 0.8 mM in A.B., final
14
15 concentration of 80 μ M) was added and formation of the product was followed by
16
17 absorbance at 405 nm every 30 sec. Initial velocity was measured for each concentration of
18
19 inhibitor and compared to the initial velocity of reactions that did not contain inhibitor. The
20
21 IC_{50} value was defined as the inhibitor concentration causing a 50 % decrease in activity. The
22
23 K_i was defined as $IC_{50}/(1+([S]/K_m))$. K_m of the substrate has been measured by monitoring
24
25 the initial velocity of the enzymatic reaction of 1nM of hPOP with various concentrations of
26
27 substrate. Data obtained were: $K_m = 74.6 \mu\text{M}$; $k_{\text{cat}} = 20.56 \text{ s}^{-1}$.
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34 **Progress curves.** The reactions were performed in micro titer plates of 96 wells. For each
35
36 reaction, 140 μ L of activity buffer was added, followed by 20 μ L of hPOP (10 nM in A.B.).
37
38 After 15 min of equilibration at 30 °C, 20 μ L of inhibitor solution was added (different
39
40 concentrations were prepared by serial dilution from an original 0.1M stock in DMSO that
41
42 was kept at -80 °C). Directly afterwards, 20 μ L of a 800 μ M substrate solution (30 % MeCN
43
44 in activity buffer). Once substrate was added, the absorbance at 405 nm was recorded every
45
46 30 sec. during a period of time ranging from 2h to 5h depending on the inhibitor. Data were
47
48 then fitted to the corresponding equations (see Supporting Information) in order to extract
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50 k_{obs} . These values were further plotted against inhibitor concentration used and the data
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3 fitted to the corresponding equations (see Supporting Information) in order to retrieve
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5 kinetic parameters.
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8 **Dilution experiment.** Inhibitor at a concentration of $100 \times K_i$ was pre-incubated with 200
9
10 nM of hPOP in activity buffer for 2 h at 30 °C. Rapid serial dilutions (two times 40-fold
11
12 dilution for a total of 1600-fold) were made with a substrate-containing buffer (Substrate
13
14 concentration = 80 μ M) pre-equilibrated at 30°C. Final concentrations of inhibitor were
15
16 0.06 $\times K_i$ and the concentration of enzyme was 0.125 nM. The absorbance at 405 nm was
17
18 immediately recorded every 30 sec for the first 60 minutes followed by every 2 minutes for
19
20 the next 5 hours. Data were then fitted to the corresponding equations (see Supporting
21
22 Information) in order to extract k_{off} .
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26 **Computational Chemistry.**

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29 **Preparation of the initial systems.** The crystal structures for POP and FAP - 2xdw (POP
30
31 bound to an aldehyde-containing inhibitor), 4an0 (POP bound to a nitrile-containing
32
33 inhibitor), 4bcb (POP bound to a nitrile-containing inhibitor) and 1z68 (FAP unbound) were
34
35 downloaded from the PDB. The six ligands (**5b**, **10b**, **11b**, **13b-15b**) were docked covalently
36
37 to 2xdw and 1z68 using our docking program FITTED.⁴⁹ These crystal structures and docked
38
39 poses were used to build starting structures. For example, docked poses in POP are similar
40
41 to the crystal structure with the proline ring properly positioned. However, the
42
43 stereochemistry of the acetal (from **10b**) and the orientation of the iminoether (from **5b**) are
44
45 inexact and are repositioned to generate starting structures. Then the FAP structure (1z68)
46
47 was superposed onto POP (2xdw) and the ligands added to FAP as docked in POP.
48
49 Considering the rigidity of the aldehyde-containing small molecule and the similarity
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3 between the FAP and POP catalytic triad and oxy-anion hole, the binding mode is very likely
4
5 similar.
6

7
8 The proteins were next truncated; the starting structures are provided as xyz coordinates
9
10 (mol2 format). For POP the following residues were kept: Asp149, Tyr473, Ser554, Asn555
11
12 (backbone NH), Trp595, Asp641, Arg643 and His680; for FAP: Arg123, Glu203, Tyr541,
13
14 Ser624, Tyr625 (backbone NH), Tyr656, Asp702 and His734. To ensure that all the hot spots
15
16 are removed, the systems were relaxed according to the following procedure:
17
18

- 19 • Hydrogens were optimized (AM1) with all heavy atoms frozen.
- 20
- 21 • The inhibitors were optimized (AM1) with all the protein heavy atoms frozen.
- 22
- 23 • The complexes were optimized (PBE0/def2-SVP) with only the α and β carbons of
- 24
25 the amino acids frozen (quantum chemical cluster approach).
26
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29 **Potential energy surface scans.** One dimensional potential energy surface (PES) scans were
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31 performed in ORCA v.4.0.1.2⁵⁰ at the PBE0/def2-SVP level of theory on the optimized
32
33 structures obtained as described above. The coordinate for the scans was the Ser(O)-
34
35 warhead(C) distance – 13 points were recorded for each scan. For each system the α and β
36
37 carbons of the amino acids were frozen, while the remaining atoms were allowed to move
38
39 freely. For each system the bound minima, the maxima (if applicable) and the unbound
40
41 minima were subjected to single point energy calculations at the PBE0/D3BJ/def2-TZVP
42
43 level of theory. To simulate the unbound states, optimizations were carried on the separate
44
45 partners (truncated proteins and ligands) at the PBE0/def2-SVP level of theory. Single point
46
47 energies calculations were then performed on the separated partners in gas phase at the
48
49 PBE0/def2-TZVP/D3BJ level of theory.
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ASSOCIATED CONTENT

Supporting Information. The following files are available free of charge.

NMR spectra; table of purities for biologically tested compounds; curves and equations corresponding to biological data; computational methods (PDF) and Molecular Formula Strings (CSV).

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. ‡These authors contributed equally.

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Notes

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3 Any additional relevant notes should be placed here.
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22 ABBREVIATIONS

23
24 POP: Prolyl oligopeptidase, FAP: fibroblast activation protein α ; PES: potential energy
25
26 surface; QM: quantum mechanics; FEP: free energy perturbation; QCCA: quantum chemical
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28 cluster approach
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Table of Content Graphics

