Mechanistic insights into global suppressors of protein folding defects

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Abstract: Most amino acid substitutions in a protein either lead to partial loss of function or are near neutral. Several studies have shown the existence of second-site mutations that can rescue defects caused by diverse loss of function mutations. Such global suppressor mutations are key drivers of protein evolution. However, the mechanisms responsible for such suppression remain poorly understood. To address this, we characterized multiple suppressor mutations both in isolation and in combination with inactive mutants. We examined six global suppressors of the bacterial toxin CcdB, the known M182T global suppressor of TEM-1 β-lactamase, the N239Y global suppressor of p53-DBD and three suppressors of the SARS-CoV-2 spike Receptor Binding Domain. The suppressors both alone, and in conjunction with inactive mutants, stabilise the protein both thermodynamically and kinetically *in-vitro*, predominantly through acceleration of the refolding rate. When coupled to inactive mutants they promote increased *in-vivo* solubilities as well as regain-of-function phenotypes. In the case of CcdB, where novel suppressors were isolated, we determined the crystal structures of three such suppressors to obtain insight into the specific molecular interactions responsible for the observed effects. While most individual suppressors result in small stability enhancements relative to wildtype, which can be combined to yield significant stability increases, thermodynamic stabilisation is neither necessary nor sufficient for suppressor action.

Keywords: protein stability, folding kinetics, differential scanning fluorimetry, vaccine, distal suppressor.

Introduction

Correlated mutational data extracted from multiple sequence alignments, can guide structure prediction of a protein (1) or help in the determination of interfacial residues responsible for binding to various partners (2). Experimental studies have often led to the identification of second suppressor mutations which can alleviate the defects in folding, function and stability of the protein caused by an initial deleterious mutation. Such compensatory mutations, often occur within the same gene, highlighting the role of intragenic suppression in evolution (3).

Suppressors can be either spatially proximal or distal to the inactivating mutation. Distal suppressors, are typically able to suppress multiple inactivating mutations, not necessarily in proximity to each other, and are often referred to as global suppressors. Prior studies have suggested that such suppressors function either by (a) increasing global thermodynamic stability (4), (b) enhancing the activity of the native protein without any effect on stability (5), or (c) improving the folding of the native protein without substantial enhancement of the thermodynamic stability (6). In laboratory-based evolution experiments, it has been shown that the evolution of new function is accompanied by second-site compensatory mutations, which compensate for the probable destabilizing function altering mutations (7). Previous studies have primarily focused on thermodynamic rather than kinetic effects of mutations on protein stability and function, though the latter may be more relevant *in vivo* (8).

Here, we endeavour to provide insights into the mechanisms responsible for global suppression. The primary experimental system utilised is a 101-residue homo-dimeric protein, CcdB (Controller of Cell Death protein B), which is a part of the toxin-antitoxin (CcdB-CcdA) module involved in the maintenance of F-plasmid in *Escherichia coli* (9). We probe effects of multiple global suppressors of CcdB, on the folding kinetics, stability, *in vivo* solubility and *in vivo* activity of the protein. The suppressors are able to rescue folding defects of the inactive mutants, through thermodynamic and kinetic stabilization, with the largest effects on refolding rates. To understand the structural basis of stabilization, crystal structures of three CcdB suppressor mutants, namely, S12G, V46L and S60E,

were solved. We probed the effects of the suppressor mutants on aggregation, binding and thermal tolerance. We also examined the effects on stability and folding of two known global suppressors: M182T of TEM-1 β-lactamase, an extended spectrum β-lactamase (ESBL) enzyme conferring antibiotic resistance against third generation cephalosporins and N239Y in the DNA binding domain (DBD) of p53, a critical tumour suppressor protein, which is known to suppress the effect of oncogenic inactive mutants. We additionally examined similar parameters for recently isolated suppressor mutations in RBD (Receptor Binding Domain of spike glycoprotein of SARS-CoV2), (10). The analysis of data for these diverse systems provided general insights into the mechanism of action of global suppressors.

Results

Phenotypic characterisation of putative second-site suppressor mutations in CcdB

Previous characterisation of a single site saturation mutagenesis (SSM) library of ~1600 CcdB mutants led to the identification of five partial (or) complete loss-of-function mutants, varying in their substitutional patterns of sizes and polarities, and were termed as parent inactive mutants (PIMs), (namely,V5F, V18W, V20F, L36A and L83S) (8,11,12). Second-site saturation mutagenesis libraries, generated by individually incorporating each PIM into the SSM library, were exhaustively screened for suppressors by checking their GyrA14-binding abilities using the technique of yeast surface display coupled to FACS (1). PIMs bound GyrA14 poorly. Two residues, R10 and E11, located on an exposed loop region far from the site of PIMs, were identified as sites for distal suppressors (Figure 1A). The global suppressor R10G rescued GyrA14-binding defects at all five PIM positions, and increased the apparent T_m by 8 °C, relative to WT CcdB (1) but E11R was not characterized. Subsequently, another putative global suppressor S12G was identified by analyzing saturation suppressor libraries using FACS coupled to deep sequencing (13). S12, located beside R10 and E11 on the exposed loop, is involved in hydrogen bonding with the cognate antitoxin CcdA (Figure 1A). Phenotypes of the E11R

and S12G CcdB mutants were studied here after cloning the mutants both individually and in combination with PIMs into the *E. coli* expression vector pBAD24, under the control of the P_{BAD} promoter (14). This allows for tuneable expression with glucose (repressor) and arabinose (inducer). The plasmids were individually transformed into the CcdB-sensitive *E.coli Top10*pJAT strain.. The cells were grown at different concentrations of glucose and arabinose (8,12) to allow increasing levels of CcdB expression. Mutant phenotypes were studied as a function of varying repressor (glucose) and inducer (arabinose) concentrations. For WT and the fully active mutants E11R and S12G, the cells fail to grow even at the highest glucose (repressor) concentration (0.2% glucose), because even very low levels of active CcdB result in cell death. The inactive mutants grow even at higher concentrations of arabinose (7×10^{-5}% arabinose). In the background of the E11R or S12G suppressor mutations, with the exception of V18W-S12G, the WT-like phenotype of the remaining (PIM, suppressor) pairs is restored at lower glucose concentrations (≤0.2%), leading to cell death (Figure 1B).

To examine the relative *in vivo* solubility levels (proxy for folded functional forms of proteins), *E. coli* strain *Top10GyrA* was individually transformed with each mutant. The solubilities of the PIMs were significantly lower than that of WT CcdB and suppressors E11R and S12G (Supplementary Table S1). However, the solubilities of the inactive mutants in the background of the suppressors was significantly enhanced (Supplementary Figure S1A). These results reveal that lowered activity and decrease in solubility of the inactive proteins are both improved in the background of the suppressors.

Enhancement of thermal and chemical stability of multiple inactive mutants by global suppressors

The purified proteins (4 μM) were subjected to thermal denaturation using nanoDSF and the apparent T_m was calculated (Figure 1D). S12G had a 2 °C higher T_m, indicating that the mutation is stabilising (Supplementary Table S1). Further the inactive mutant-suppressor pairs showed increased apparent thermal stabilities (~5-12 °C) relative to the inactive mutants. The ability of the purified proteins to bind to CcdA peptide (8 μM) was also examined by monitoring thermal denaturation using binding

of Sypro orange dye (15), both in the absence and presence of CcdA peptide (45-72). Relative to the free proteins, apparent T_m's of the CcdA-bound complexes showed increments (Supplementary Figure S1B) due to stability-enhancements of the proteins in the presence of peptide (1).

Equilibrium unfolding experiments for the CcdB mutants were carried out by nanoDSF. The data were fitted to $N_2 \leftrightarrow 2D$ unfolding models for homo-dimeric CcdB as described (14,16). The fraction unfolded of different CcdB mutants (200 mM HEPES, pH 8.4) in the presence of GdnCl is plotted as a function of denaturant concentration (Figure 1C). The midpoint of chemical denaturation (C_m), ΔG^o and m-values were measured for all the CcdB mutants (Supplementary Table S4). The suppressor S12G alone is 0.8 kcal/mol more stable than the WT, and the double mutants are apparently 2.5-5.0 kcal/mol more stable than the inactive mutants (Figure 1D). The significant difference in the apparent effect of the suppressor in the context of PIM relative to WT, is likely due to the high tendency of inactive mutants to aggregate over time thereby reducing the amount of functionally folded form. Surprisingly, E11R is 3.1 kcal/mol less stable than WT as assayed by chemical denaturation studies and has a T_m 2 °C lower than WT but still acts as global suppressor.

Suppressor substitutions accelerate the refolding rate and reduce the unfolding rate of the WT and multiple inactive mutants

Refolding and unfolding kinetics for CcdB mutants were also monitored by time-course fluorescence spectroscopy at 25 °C using nanoDSF (16). Refolding was performed at pH 8.4, at final GdnCl concentrations ranging from 0.5 M-1.5 M. During refolding, the two monomers rapidly associate in a diffusion limited process (17). Refolding for the WT occurs with a fast and a slow phase as observed earlier (17). The suppressors E11R and S12G refold at a faster rate compared to the WT. Relative to the WT, the inactive mutants refold slowly, whereas their refolding rates were enhanced (both fast and slow phase) in the background of the suppressor (Figure 2A, Supplementary Table S2). The fast phase of refolding for L83S-E11R could not be captured owing to its fast refolding kinetics. The noise

associated with refolding kinetics of L36A-S12G in the presence of 1 M GdnCl is due to the faster kinetics of refolding and high dead time of about ~15 seconds associated with the instrument.

The unfolding trace of WT CcdB when fitted to the three-parameter unfolding equation, gives a fitted unfolding rate of 0.05 s^{-1}. S12G shows a much slower rate of unfolding. For all the PIMs, we observed very fast unfolding even at low GdnCl concentrations, whereas the mutant-suppressor pairs had slower unfolding rates relative to the individual PIMs, though typically faster than the rates for WT and the suppressors E11R and S12G (Figure 2B, Supplementary Table S2). Refolding and unfolding reactions were carried out at three different GdnCl concentrations and the observed rate constants and m values were plotted as a function of GdnCl concentration (Supplementary Figure S2, Supplementary Table S3). Using this, the refolding rate constants for both fast and slow phases, and unfolding rate constants were calculated at 0 M GdnCl as described previously (16) for relative comparison (Supplementary Table S3). These experiments correlate with other results and indicate that the suppressors E11R and S12G have lower to marginally higher thermal stabilities than WT and that all the mutant-suppressor pairs are both kinetically and thermodynamically more stable than the corresponding PIMs.

Rescue of activity and stability of refolded CcdB proteins by the global suppressors

Microscale thermophoresis (MST) was used to measure the binding affinities of fluorescently labeled GyrA14 (used at a fixed concentration of 70 nM) to unlabelled CcdB mutant proteins (native, native in GdnCl and refolded proteins). The obtained data indicates that WT CcdB, S12G and E11R bind GyrA14 with K_D's of about 2.2, 2.3 and 1.2 nM respectively which is consistent with the SPR binding studies (Figure 2C, Supplementary Figure S3A, Supplementary Table S1). Labeled GyrA14 also bound with similar affinity to the native and refolded proteins in 1.5 M GdnCl (Figure 2C, Supplementary Figure S3B-C, Supplementary Table S1), indicating that refolding was reversible. The C_m of GyrA14 was determined to be 4.48 M, confirming that it was folded at 1.5 M GdnCl used in the above refolding assay (Supplementary Figure S3D).

The refolded CcdB proteins and the native proteins in the presence of 1.5 M GdnCl were also subjected to thermal denaturation, and the apparent T_m was calculated (Figure 2D, Supplementary Table S4). The near identicality of the T_m's for native and refolded proteins, further confirms that the mutants refold reversibly. Except for the PIMs V18W and V20F, all the other mutants showed clear thermal transitions confirming that they were in a folded conformation in the presence of GdnCl. The suppressors improved the T_m of the refolded proteins, relative to the PIMs.

Enhancement of thermal tolerance of the CcdB mutants by the global suppressors

The binding of purified CcdB mutants to their target GyrA14, was also probed using SPR. WT CcdB, S12G and E11R bind to GyrA14 with K_D's of about 1.4, 2.6 and 2.5 nM respectively (Supplementary Figure S4, Supplementary Table S1). An increased affinity for DNA Gyrase for the inactive mutant-suppressor pairs was observed in all the cases, consistent with functional rescue. The apparent low affinity of these inactive mutants may also arise due to the inability to estimate the fraction of active protein for these purified mutants. The SEC profile of the PIM L36A, shows a significant amount of aggregation as well as degradation as compared to the WT, suppressor S12G and the double mutant L36A-S12G (Figure 2F). All the SEC experiments were carried out using 100 µg of protein at a flow rate of 0.5 mL/min. For the other mutants, due to poor yields and high tendency to aggregate, SEC was not performed. Thermal tolerance of E11R, S12G, L36A, L36A-E11R,L36A-S12G and WT CcdB, was also assessed by determining the binding of CcdB proteins to GyrA14 after prolonged heat stress followed by cooling to room temperature (Figure 2E, Supplementary Table S4). The S12G mutant retained 4% activity after incubation at 80 °C for 1 hr, representing a five-fold improvement over WT, whereas the double mutants L36A-E11R and L36A-S12G showed three-fold and ten-fold improvement over WT respectively. Surprisingly, L36A-E11R had residual activity at 40 °C, as compared to E11R alone which lost activity at this temperature.

Thermodynamic and kinetic stabilisation mediated by the M182T global suppressor substitution in extended spectrum TEM-1 β lactamases conferring antibiotic resistance

TEM-1 β-lactamase, a 263 residue monomeric enzyme confers resistance to β-lactam antibiotics (18). There have been several studies on its stability and folding kinetics making it a suitable system to study the effect of global suppressor substitutions (19,20). Located far from the active site, M182T, a drug-resistant clinically isolated mutation showing extended spectrum β-lactamase (ESBL) activity, increases protein expression and restores stability defects caused by active-site substitutions (21). M182T rescues a folding-defective M69I mutant thereby conferring resistance to inhibitors such as clavulanate (Inhibitor-resistant TEM β-lactamases, IRTs), and a core engineered substitution L76N, where L76 has been shown to be sensitive to substitutions(6,22) with M182T being distant from the primary mutation (Figure 3A).

In the present study, we characterized the global suppressor M182T and observed its effect on stability and folding of known inactive mutants (Figure 3). We determined the MIC and IC_{90} of the TEM-1 WT, M182T, M69I, M69I-M182T, L76N and L76N-M182T for both ampicillin and cefotaxime, a third-generation cephalosporin (Figure 3B-C, Supplementary Table S5). In line with a previous study, we found that the M182T suppressor alone and the M69I-M182T double mutant have comparable values to that of the WT (23) and M69I respectively (24), however M182T rescues the activity of the inactive enzyme mutant L76N (Figure 3B-C, Supplementary Table S5) (22,25). Further the activity of the purified mutants was monitored *in vitro* with nitrocefin (Figure 3D). The results obtained showed similar effects of the M182T substitution on WT or M69I or L76N background as observed *in vivo* (Figure 3D and Supplementary Figure S5C-E).

The M182T suppressor substitution enhanced both the thermal and chemical stability of the WT protein as well as the inactive mutants M69I and L76N (Figure 3E-F, Supplementary Table S5), in agreement with previously published results (26). When compared with WT, M69I and L76N are less stable (Figure 3G). The suppressor alone is 6 °C, 1.8 kcal/mol more stable than the WT, and M69I-

M182T and L76N-M182T are 7 °C, 2 kcal/mol and 8 °C, 1.7 kcal/mol more stable than the inactive mutants M69I and L76N respectively (Figure 3G).

Refolding (in 0.5 M GdnCl) and unfolding (in 2.5 M GdnCl) kinetics for all the mutants (5 μM) were also monitored using nanoDSF. M182T shows a slightly slower rate of unfolding whereas the inactive mutants M69I and L76N, had two and three fold faster unfolding rates respectively as compared to the WT. The mutant-suppressor pairs however had a slower rate of unfolding as compared to the individual inactive mutants (Figure 3H and Supplementary Figure S5B, Supplementary Table S5). The refolding rate constants for each of these mutants, were also calculated for both fast and slow phases. The M182T suppressor alone, refolds at a faster rate compared to the WT. The inactive mutants showed slower refolding kinetics than the WT. In the background of the suppressor, however the inactive mutants refold at a faster rate (both fast and slow phase) (Figure 3I and Supplementary Figure S5A, Supplementary Table S5).

The refolded TEM-1 proteins and the native proteins in the presence of 0.5 M GdnCl were also subjected to thermal denaturation, and the apparent T_m was calculated (Figure 3J, Supplementary Table S5) which was similar in both the cases. Except for the inactive mutant L76N, all the other mutants showed a proper transition indicating that they were in a folded conformation in the presence of GdnCl and the T_m of the refolded suppressors were also higher than the corresponding inactive mutants (Figure 3J). Further, lactamase activity of native and refolded proteins, both in 0.5 M GdnCl, monitored by nitrocefin hydrolysis yielded results consistent with the other studies (Figure 3D and Supplementary Figure S5C-E).

These experiments indicate that the M182T suppressor alone and in the mutant-suppressor pairs (M69I-M182T and L76N-M182T) rescues the folding defects of inactive mutants and confers higher thermodynamic and kinetic stability relative to the inactive mutants. This is in contrast to a previous study (6) which indicated that the L76N-M182T double mutant was destabilized relative to the L76N inactive mutant, despite the fact that the double mutant showed higher activity *in vivo*. We show that

the major contribution to stability mediated by the M182T suppressor substitution is a high refolding rate which allows reversible refolding, even in the background of the inactive mutants.

Rescue of common oncogenic mutations by an N239Y global suppressor in p53-DBD

~ 50% of human cancers are associated with structurally- or functionally – defective inactive mutations of p53, a transcription factor acting as tumor suppressor, owing to the thermodynamic instability of its core, the DNA Binding Domain (DBD) (27–30). Previous studies have identified second-site suppressor mutations in the DBD which could restore the WT p53 functionality (31). One such suppressor mutation, N239Y in the L3 loop of the DBD, could globally rescue multiple missense mutations located at varying regions of the protein by thermodynamic stabilisation of the inactivated core (32,33). The activity of two of the destabilising oncogenic mutations, located in the core of the DBD, V143A and V157F, were restored by N239Y (27,32–34).

In the current study, we aimed to obtain mechanistic insight into the N239Y-mediated suppression of the inactivating p53 mutations, V143A and V157F (Figure 4A). The double mutants V143A-N239Y and V157F-N239Y showed enhanced expression in the soluble fraction *in vivo* in *E. coli*, relative to their corresponding inactive mutants. WT and N239Y single suppressor mutant showed comparable soluble expression and yield (Figure 4B). The inactive mutants, V143A and V157F, owing to their low expression levels and aggregation-prone natures, could not be purified or characterised. N239Y, in isolation and in conjunction with the inactive mutants, marginally enhanced the thermal and chemical stabilities of the WT p53 (Figure 4C-D, Supplementary Table S6). Relative to the WT protein, the suppressor N239Y alone, and the mutants, V143A-N239Y, V157F-N239Y enhance the apparent thermal stabilities by ~1.3 °C, 1 °C and 3 °C respectively. The N239Y, V143A-N239Y and V157F-N239Y have marginal increments in their thermodynamic stabilities over the WT protein in the range of ~ 0.1 -0.4 kcal/mol (Figure 4E).

Refolding (in 2 M urea) and unfolding (in 4.4 M urea) kinetics for the WT and mutants were monitored using nanoDSF at 15 °C. The unfolding traces, yielded comparable slow-phase unfolding rates for the

WT and N239Y proteins (0.003 s^{-1} and 0.0025 s^{-1} respectively), whereas the unfolding rates for the double mutants were slightly lower than that for the WT (0.0017 s^{-1} for V143A-N239Y and 0.0019 s^{-1} for V157F-N239Y) (Figure 4F and Supplementary Figure S5G, Supplementary Table S6). The fast-phase unfolding rates for the single and double mutants were marginally lower than that for the WT (Supplementary Table S6). The refolding traces, yielded slow-phase refolding rates which were remarkably increased by ~20 and ~10 folds for N239Y and V143A-N239Y respectively, relative to the WT. V157F N239Y refolded with a similar slow-phase rate constant, when compared with the WT. With respect to the fast phase , V157F-N239Y refolds faster than the WT by ~ 3.5 folds, whereas the N239Y and V143A-N239Y refold with similar or marginal increments when compared with the WT (Figure 4G and Supplementary Figure S5F, Supplementary Table S6).

Thermal denaturation of the refolded p53 proteins, along with the native proteins in 0.5 M urea as controls was carried out (Figure 4H). ~ 3 °C increment was observed for the apparent T_m of refolded V157F-N239Y relative to that of the refolded WT, whereas the apparent T_m's for the refolded proteins of N239Y and V143A-N239Y were similar to that for the refolded WT (Figure 4H, Supplementary Table S6).

Thus, the N239Y suppressor mutation likely rescues the inactivated destabilised p53 core by marginal enhancement of the thermodynamic and more importantly the kinetic stability of the proteins containing the suppressor, with the largest effect on the refolding rates.

Effect of global suppressor substitutions in WT background

In order to further, investigate the role of suppressors on protein stability in the WT background, we performed detailed thermodynamic and kinetic studies of the suppressors alone in CcdB and mRBD proteins (Figure 5). In a recent study employing the PIMs L36A, V18D, V18G and V20G (chosen to span a range of stabilities), several other CcdB suppressor substitutions were also identified using yeast surface display coupled to deep sequencing (13). In the present study, we selected three such suppressor substitutions, Y8D, V46L and S60E with ΔT_m>3 °C (Figure 5A). The purified proteins

were subjected to chemical denaturation (Figure 5B). The suppressors Y8D, V46L and the suppressor S60E were ~3 kcal/mol and ~4 kcal/mol respectively more stable than the WT (Figure 5C, Supplementary Table S7). The suppressors were also subjected to unfolding (in 4.5 M GdnCl) and refolding (in 2 M GdnCl) kinetic studies. The unfolding rates of the suppressors were 2-2.5 times slower than the WT (Figure 5D and Supplementary Figure S6B, Supplementary Table S8), whereas the fast and slow phase refolding rates of the suppressors were 2-5 times and 9-14 times faster than the WT respectively (Figure 5E and Supplementary Figure S6A, Supplementary Table S8). Further, the proteins were refolded in 1, 2, 3 and 4 M GdnCl and subjected to thermal denaturation. Native protein at the same GdnCl concentrations was used as control (Figure 5F and Supplementary Figure S6E-H). The WT could refold back till 2 M GdnCl, whereas the suppressors Y8D, V46L and suppressor S60E could refold even at 3 and 4 M GdnCl respectively (Supplementary Figure S6E-H). In all cases, the refolded proteins have a broader transition than the native proteins in GdnCl, likely due to the formation of aggregates during refolding.

Next, we investigated the role of the suppressor substitutions in the context of the receptor binding domain (RBD) of SARS-CoV-2 (35). Using similar saturation suppressor methodology, we recently identified three suppressors of folding defective mutants in this protein (10). These suppressors, D389E, L390M and P527I are located on the protein surface (Figure 5G). When individually introduced into WT mRBD, they show a ΔT_m of ~3 °C (Figure 5H) (10). The suppressors were also subjected to unfolding (in 3 M GdnCl) and refolding (in 0.5 M GdnCl) kinetic studies. The unfolding rates of the suppressors were ~4 times slower than the WT for the fast and 2 times slower than the WT for slow phases (Figure 5I and Supplementary Figure S6D, Supplementary Table S8), whereas the refolding rates of the suppressors were 2.5-7 times faster than the WT (Figure 5J and Supplementary Figure S6C, Supplementary Table S8). Further, the proteins were refolded in 0.5, 1, and 2 M GdnCl and subjected to thermal denaturation with native proteins in the same GdnCl concentrations as control (Figure 5K). The WT could refold till 1 M GdnCl, whereas the suppressors D389E, L390M and P527I

refolded back to the native state even at 2 M GdnCl (Supplementary Figure S6I-K). The binding of the native proteins, native proteins in 0.5 M GdnCl and refolded proteins in 0.5 M GdnCl with ACE2-hFc neutralizing antibody were also measured using ProteOn (Figure 5L). All the refolded proteins showed binding to the ACE2-hFc, indicating that the proteins were properly refolded back to their functional conformation (Supplementary Figure S6L-O) and that chemical denaturation of RBD was reversible.

Structural insights into stabilization by CcdB suppressor mutants

The structures of the S12G, V46L and S60E mutants of CcdB were solved to resolutions of 1.63 Å, 1.35 Å and 1.93 Å respectively. (Figure 6).

The structures of S12G, V46L and S60E (Figure 6A, 6D, 6G) consist of a single chain in the asymmetric unit, with two chloride ions. One of the ions, which is also present in the WT structure 3VUB, interacts electrostatically with H85[Nε2], R86[NH1], H55[N] and a hydrogen bonding interaction with a symmetry equivalent T7[Oγ1]. The second Cl^- ion in S12G interacts with S38[N], R15[NH2] and a water O[220]. Although there is a water molecule at this position in the WT structure (3VUB), addition of a water in S12G resulted in an unusually low B-factor whereas a Cl^- ion fits well without any negative density and a B-factor of 20 $Å^2$. The density for the last residue I101 was not visible in the map for S12G. The electron density map in the region of residues 40-45 for S12G, 43-45 for V46L and 41-42 for S60E was very poor, as a result the side chains could not be fitted. One of the residues in S12G, R40 lies outside but close to the allowed region of the Ramachandran Plot. The mutant structures are very similar to the WT structure (3VUB) with an RMSD of 0.26, 0.39 and 0.39 Å for S12G (Figure 6B), V46L (Figure 6E) and S60E (Figure 6H) respectively.

For S12G, the variation is mainly in the loop region between Y8-Y14 and A39-V46, indicated in Figure 6B by a star. There are two water molecules (254 and 228) in S12G in place of the two conformers of S12[OH] of 3VUB (Figure 6C). A cluster of water molecules at a hydrogen bonding distance from G12 stabilizes the loop and anchors it via interactions with the backbone atoms of neighbouring residues (Figure 6C) reducing the average B-factor in this region (Figure 6J). These two water

molecules substitute for the hydroxyl group of both the conformers of serine in the WT structure. Since the S12G has an additional Cl^- ion, an additional comparison was done with the structure 4VUB (WT CcdB) which has the second Cl^- ion in the same position as found in S12G. It was found that although the absolute B-factor of S12G and 4VUB were similar in the 8-12 region and lower than that of 3VUB, it was lowest for S12G in the region 39-46 amongst the three structures. The relative B-factors are very similar in both 3VUB and 4VUB when normalized, so the 3VUB structure was used as a reference.

For V46L, the loop region A39-V46, exhibits a major deviation from WT CcdB, as indicated in Figure 6E by a star. L46 is involved in a hydrogen-bond interaction with R62 and hydrophobic interactions with M64 (Figure 6F). The hydrogen-bond interactions are formed between the main chain oxygen atom of L46 and side chain nitrogen atoms of R62 (NH1, NH2). The average B-factors of the V46L structure are lower than the WT with the most reductions in the loops 8-14 and 39-46 (Figure 6J).

For S60E also the major deviation, is in the starred loop region A39-V46 (Figure 6H). E60 is involved in a series of salt-bridge interactions with R48, H55 and R62 (Figure 6I). The salt bridge interactions are formed between the side chain oxygen atoms of E60 (OE1 and OE2) and side chain nitrogen atoms of R48 (NE, NH1), H55 (ND1, NE1) and R62 (NE). There is a change in the orientation of the mobile R48 side chain resulting in salt bridge interactions with E60 (Figure 6I). The S60E mutation has resulted in reduced B-factor differences between the side chain and main chain in many regions, including R48, resulting in overall stabilisation of the structure. The average B-factors of the S60E structure are also lower than the WT with the most reductions in the loops 8-14 and 39-46 (Figure 6J).

Enhanced stability is neither necessary not sufficient for a mutant to act as a global suppressor

While most suppressor mutations described above confer enhanced stability in the WT background, it is not known if all stabilized mutants will act as suppressors. Two such CcdB mutants, L42E and S43T, that enhanced the thermodynamic stability and one mutant M32T that was less thermodynamically stable than WT, similar to E11R were characterised. From our previous studies that have characterised a large number of CcdB mutants by YSD, L42E and S43T were seen to exhibit higher binding than

WT and were presumed to be more stable (36). However, these mutants were not identified as suppressors using YSD (13). In the same study, M32T was identified as a suppressor (13). This was surprising as M32 is buried and substitution by a polar residue should be destabilizing. We confirmed this by DSF measurements on purified protein (Figure 7B). We therefore introduced the M32T, L42E and S43T mutations individually in the background of various parent inactive mutants, and the binding to GyrA14 was measured by FACS as described previously (36,37). It was observed that L42E and S43T failed to enhance the binding to GyrA14 of any of the inactive mutants whereas M32T was able to rescue the folding defect of V20F and L36A inactive mutants (Figure 7A). Next, we characterised the thermodynamic and kinetic stabilities of the purified M32T, L42E and S43T proteins. We observed that though the thermal and chemical stabilities of L42E and S43T were higher than WT (Figure 7B-D, Supplementary Table S9), the folding kinetic parameters were similar to WT (Figure 7E-F, Supplementary Table S9). Additionally, although M32T was thermodynamically less stable than WT, it showed faster refolding (Figure 7F, Supplementary Table S9), thus indicating that faster refolding rather than enhanced stability is sufficient to rescue folding defects of mutants (Figure 7B-F). We also measured the thermal stability of the refolded proteins in 1.5 M GdnCl and subjected them to thermal denaturation (Figure 7G, Supplementary Table S9). The refolded L42E and S43T proteins had higher thermal stabilities while the refolded M32T had lower thermal stability than the refolded WT protein (Figure 7G, Supplementary Table S9). These observations demonstrate that enhanced thermal stability alone is insufficient to confer a global suppressor property to a mutant.

Discussion

In this work, we examine the mechanisms by which a second (suppressor) mutation alleviates the protein defects caused by the initial loss of function causing point mutant. Previous studies have shown physically interacting residues to coevolve (38) or mutate with substitutions bearing shape or charge complementarities for stability compensation (1). The location of suppressor mutations may be either spatially proximal or distal from the site of the original mutation but are usually found on the surface (39). Global suppressors are expected to have a WT like phenotype, when present as single mutants (1). Some plausible mechanisms responsible for global suppression are: a) improving the foldability of the protein without impacting stability (6), b) increasing global thermodynamic stability (4,40,41) thereby compensating a folding defect caused by an initial destabilising albeit function altering mutation (7,25,42), c) improving the specific activity of the protein, for example through a mutation at a functionally important residue (5).

In previous studies, we identified several global suppressors of inactivating mutations of the bacterial toxin, CcdB (1,13). In the present study we characterised the mechanisms of suppression by the E11R and S12G global suppressors in considerable detail, and extended these studies to four other global suppressors, Y8D, V46L, S60E and M32T. Non active-site, buried mutations typically affect the levels of correctly folded protein (43). The presence of low levels of active, folded CcdB protein is sufficient to kill the cells and rescue the inactive phenotype caused by the PIMs. This was confirmed *in vivo* by growth assays and estimation of solubility levels. Equilibrium thermal and chemical denaturation studies reveal a large enhancement in the apparent stability of PIM-suppressor proteins with respect to the PIMs in isolation. Surprisingly, the suppressor mutations E11R and M32T show decreased stability, relative to WT CcdB, and the remaining suppressors shows marginal improvements in stability. There is however, a non-additivity of the apparent stabilising effect of E11R and S12G in the presence and absence of the PIM. This might be attributed to the fact that the stability of the PIMs are difficult to measure accurately because of their aggregation-prone nature.

Kinetic studies were used to further elucidate the mechanism of action of such distal global suppressors. Several studies have shown the importance of kinetic stability in the evolutionary optimization and regulation of protein function (8,44–46). Kinetic destabilisation leads to diseases associated with protein misfolding (47,48). Therefore, a mutation which enhances kinetic stability can be important in both physiological and biopharmaceutical contexts, for example increasing shelf life of monoclonal antibodies and enhancing vaccine immunogenicity (10,49).

Relative to the WT protein, we observe that the increment in the folding rate parameters is typically larger than the decrement in the unfolding rate parameters. This suggests that additional favourable interactions resulting from the mutation are formed prior to the folding transition state, lowering its energy, relative to the unfolded state. In the case of the CcdB S12G, V46L and S60E; β-lactamase M182T and p53 N329Y mutants, for which crystal structures are available, additional non-covalent interactions present, relative to corresponding WT structure are seen. For these CcdB suppressors, the structural changes are complex and unlikely to be predicted from modelling studies.

In order to understand the role of thermodynamic versus kinetic stability as a criterion for global suppression, we investigated several other CcdB mutants based on their relative thermal stability and ability to act as a suppressor. Similar to E11R, the M32T mutant was also thermodynamically less stable as compared to the WT, but was still able to act as a suppressor (Figure 7). In contrast, L42E and S43T, though more stable than the WT, were unable to suppress the folding defects of the inactive mutants, suggesting that enhanced thermodynamic stability alone is not essential for suppression. Therefore, the findings collectively indicate the role of kinetic stability, in particular an increase in the refolding rate constant as being primarily responsible for the suppressor phenotype.

None of the CcdB suppressor mutations are seen in naturally occurring paralogs. The positions 10, 12 and 46 in CcdB are involved in interactions with one of the ligands- the antitoxin CcdA and mutations at these positions as well as the nearby E11 residue will affect CcdA interaction and conformation of the CcdA interacting loop from residues 9 to 15 (^{9}KRESRYR^{15}). S60E, though not involved directly

in CcdA interaction, alters the conformation and rigidity of the 39-46 loop that contacts CcdA and might therefore affect CcdB function. V46L also similarly affects the rigidity of the 8-14 and 39-46 loops important for CcdA binding and GyrA14 rejuvenation (50). In CcdB, the E11R and M32T suppressor mutations had lower stability than WT and conversely, the L42E mutant which is more stable than WT, failed to act as a suppressor. These data demonstrate that while most suppressor mutations show small stabilization effects in the WT background, increased stability is neither necessary nor sufficient for global suppressor mutations.

In the present work, we focus on protein folding kinetics studied *in vitro* whereas *in vivo*, for several proteins, folding occurs co-translationally and/or is assisted by molecular chaperones (51). How suppressor mutations affect the kinetics and yield of co-translational or chaperone mediated folding/unfolding is beyond the scope of the present work and it is likely that the different proteins studied make use of different chaperone systems and span both cytoplasmic and periplasmic folding compartments. Nevertheless, it is clear from the present studies that acceleration in folding kinetics *in vitro* is associated with enhanced yield of active protein *in vivo* whether in the context of *E. coli* or yeast (13,36). A previous study from our laboratory, which looked at the effects of overexpression of a number of different chaperones on ccdB mutant phenotypes reported the rescue of inactive, folding defective CcdB mutants which occurred exclusively in the two *E. coli* strains overexpressing ATP-independent chaperones (SecB and Trigger factor), that act early in *in vivo* folding and not in the strains overexpressing ATP-dependent chaperones that act in the later stages of the folding pathway (8). One of the important inferences from this study was that mutational effects on folding, rather than stability, influenced CcdB mutant activity *in vivo*, consistent with the present results. Till date, there have been reports on the detailed investigation of the Hsp70 and Hsp90-mediated stability and activity of p53 DBD (52–54), the GroEL/ES chaperonin system making transient interactions and inhibiting the folding of β-lactamase precursor (55,56), and of a strongly bound complex of the GroEL chaperone

with the receptor-binding domain of the SARS CoV2 spike protein (57). However, none of these discuss the effects of suppressor mutations on chaperone mediated folding kinetics.

We have summarized the effect of the suppressor mutations characterized in the present study on various thermodynamic and kinetic parameters in the background of both WT and inactive mutants (Figure 8, Supplementary Table S11). For the PIM/Suppressor pair analysis, we excluded the p53DBD double mutants since we did not have the corresponding inactive mutants for comparison. Relative to the WT, the individual suppressors have marginal enhancement in thermal stability (ΔT_m) and significant changes in the chemical stability ($\Delta\Delta G°$) (Figure 8A). However, in the background of the inactive mutants, the suppressors cause significant enhancement in both thermal (ΔT_m) and chemical stabilities ($\Delta\Delta G°$) (Figure 8B). One suppressor has a similar rate constant as the WT for the slow phase of refolding and one PIM-suppressor pair has a similar burst phase of refolding as the inactive mutant, . However, all other suppressors or PIM-suppressor pairs have altered refolding and unfolding kinetics. To further delineate the parameters which are most effected by the suppressor mutations we calculate the average fold change of each parameter by the suppressor mutations (Supplementary Table S11) as follows:

$P_{avg} = \frac{\sum_1^n \boldsymbol{Pi}}{\boldsymbol{n}}$,……..Equation 1

where P_{avg} is the average fold change of a parameter P,

P_i is the fold change of that parameter in the background of the suppressor which is = $P_i = P_{supp}/P_{wt}$, or

$P_i = P_{(inactive,\ suppressor)}/P_{inactive}$

and n is the number of mutants. A non-parametric Mann Whitney test is performed to show that the mean of the distributions of each of these values of P_i is significantly higher (or lower) than 1 (Figure 8C-D and Supplementary Table S11) and confirm that enhancement of refolding kinetics by suppressor mutants is statistically significant in the background of both WT and inactive mutations.

For relatively stable proteins such as CcdB (T_m= 66 °C) and mRBD (T_m= 50.4 °C) which are not folding defective or aggregation prone, it is not easy to isolate mutants with improved stability, or to screen for suppressors. This can be overcome by first introducing a destabilizing mutation (Parent Inactive Mutation or PIM) into a saturation mutagenesis library, followed by screening for suppressors (1). We have recently shown that such an approach (10,13) can robustly be used to identify multiple individual suppressor mutations. While each suppressor significantly improves the activity of the PIM, as seen in the present work, these typically have only a small stabilization effect when introduced in the WT background i.e. the apparent stabilization of PIM by suppressor is not quantitatively transferable to WT. Overall, the effects of suppressors on the refolding rate parameters were larger than on the unfolding rate parameters. This was observed across multiple suppressors in multiple proteins, suggesting this to be the primary mechanism through which such suppressors function.

Materials and Methods

Plasmids and Host Strains

CcdB: The ccdB gene was cloned under the control of P_{BAD} promoter in pBAD24 vector (14). Two *Escherichia coli* host strains *Top10*pJAT and *Top10GyrA* were used. *Top10*pJAT is a CcdB sensitive strain and was used for screening the phenotypes. The pJAT8araE plasmid which encodes for the arabinose transporter area was introduced into the *TOP10* strains to ensure that in all cells there is approximately equal amounts of arabinose uptake (58). *Top10GyrA* is resistant to the action of CcdB toxin and was used for monitoring the expression of mutant proteins. The strain contains a GyrA462 mutation in its genome that prevents CcdB from binding to Gyrase (9). The *Saccharomyces cerevisiae* strain EBY100 was used for yeast surface display to monitor the binding and expression of the displayed proteins cloned in the yeast surface display vector pPNLS (59).

TEM-1 and p53-DBD: WT and mutant TEM-1 β lactamase with a C-terminal 6xHistidine tag were cloned and expressed under the control of the T7 promoter in the pET-24a vector. The native signal sequence was used for efficient secretion in the *Escherichia coli* host strain BL21 (DE3) pLysE. WT and mutant p53-DBD genes with N-terminal 6xHistidine tag were cloned and expressed under the control of the T7 promoter in the pET-15b vector. *Escherichia coli* host strain BL21 Rosetta (DE3) was used for expressing the p53-DBD proteins.

mRBD: mRBD WT and mutants were expressed from mammalian cell culture as described previously (35) under the control of the CMV promoter along with a tPA signal sequence for efficient secretion.

Mutagenesis

CcdB: For single mutants V5F, Y8D, E11R, S12G, V18W, V20F, M32T, L36A, S43T, V46L, S60E and L83S, as well as for double mutants, V18W-E11R, V20F-E11R, L36A-E11R, L83S-E11R, V20F-M32T, L36A-M32T, V18W-L42E, V20F-L42E, L36A-L42E, L83S-L42E, V20F-S43T and L36A-S43T the ccdB gene was amplified in two fragments with the desired point mutations. The fragments had overlapping regions (introduced during PCR) of 15-20 nucleotides, which were then recombined

using Gibson assembly or *in vivo* recombined with pPNLS vector for YSD as described earlier (37). Amplification was done using Phusion Polymerase from NEB as per the manufacturer's protocol. The double mutants V5F-S12G, V18W-S12G, V20F-S12G, L36A-S12G and L83S-S12G were synthesized by GeneArt (Germany).

TEM-1 and p53-DBD: The TEM-1 β lactamase WT and mutants M182T, M69I, M69I-M182T, L76N, L76N-M182T and p53-DBD WT and mutants N239Y, V143A, V157F, V143A-N239Y, V157F-N239Y were synthesized by GenScript (USA).

mRBD (331-532): The mRBD (331-532) codon optimised for human cell expression was synthesized by GenScript (USA) (35). For single mutants D389E, L390M and P527I, the RBD gene was amplified in two fragments with the desired point mutations. The fragments had overlapping regions (introduced during PCR) of 15-20 nucleotides, which were then recombined using Gibson assembly. Amplification was done using Phusion Polymerase from NEB as per the manufacturer's protocol.

Protein expression and purification

CcdB: WT CcdB and all mutants were expressed from the arabinose promoter P_{BAD} in the pBAD24 vector in the CcdB resistant Top10Gyrase strain of *E. coli*. The purification of the CcdB mutants were carried out as described previously (16). Briefly, 500 mL of LB medium (HiMedia) was inoculated with 1% of the primary inoculum and grown at 37 °C until the OD_{600} reached 0.6. Cells were then induced with 0.2% (w/v) arabinose and grown at 37 °C for 5 hours for WT CcdB, Y8D, E11R, S12G, M32T, L42E, S43T, V46L, S60E and the double mutants V18W-S12G, V20F-S12G, L36A-S12G and L83S-S12G, at 25 °C overnight for the inactive mutants V18W, V20F, L36A and L83S and at 20 °C overnight for the double mutants L36A-E11R and L83S-E11R. Cells were harvested, re-suspended in HEG re-suspension buffer pH 7.4 (10 mM HEPES, 50 mM EDTA, 10% glycerol containing 10 mM PMSF) and lysed by sonication. The supernatant was incubated with Affi-gel15 (Biorad) coupled to CcdA peptide (residues 46-72) and incubated overnight at 4 °C. The unbound fraction was removed

and washed with five times the bed volume of coupling buffer pH 8.3 (0.05 M Sodium Bicarbonate, 0.5 M Sodium Chloride). The elutions were carried out with 0.2 M Glycine, pH 2.5 into a tube containing an equal volume of 400 mM HEPES, pH 8.4, 4 °C (8,16). The eluted fractions were subjected to 15% Tricine SDS-PAGE and the protein concentration was determined. Yield for all mutants varied from 0.3-12 mg/L depending upon the amount of protein in the soluble fraction. Fractions containing pure protein were pooled and stored at −80 °C.

V5F and V5F-S12G could not be purified using affinity chromatography against immobilised CcdA because of their low expression, solubility and inability to bind to the CcdA column. V18W-E11R and V20F-E11R could not be used for further biophysical studies owing to their high tendency to aggregate.

TEM-1 β lactamase: The TEM-1 β lactamase mutants were purified as described previously (22) with slight modifications. The recombinant BL-21 (λDE3, plysE) strains were grown in TB medium at 37 °C containing 50 μg/mL kanamycin until the OD_{600} reached 0.8 and protein expression was induced by addition of 1.0 mM IPTG. The induced cultures were grown overnight with shaking at 30 °C and were harvested by centrifugation. The periplasmic fraction was obtained by osmotic shock by resuspending first in lysis buffer, pH 7.0 (10 mM HEPES, 0.5 mM EDTA, 20% sucrose, 0.05% SDS, lysozyme and protease inhibitor) at 37 °C with shaking for 1 hr, followed by addition of an equal volume of ice cold milliQ water, incubated at 4 °C for an hour, followed by addition of 100 μL of 2 M $MgCl_2$. The clarified lysates were loaded on 2 ml of Q-Sepharose fast flow (Amersham Biosciences, Uppsala, Sweden). The elutes obtained by a gradient of 100-500mM NaCl in 10 mM HEPES, 10% glycerol pH 7.0, were further subjected to Ni-NTA purification by mixing with 2 mL of Ni-Sepharose resin (GE Healthcare) for 4 hrs and the bound proteins were eluted with a gradient of 100-500 mM imidazole in 10 mM HEPES, 300 mM NaCl, 10% glycerol (pH 7.0). The purified proteins were subjected to 15% Tricine SDS-PAGE, concentrated, buffer exchanged to remove imidazole, and

finally stored in storage buffer (10 mM HEPES, 300 mM NaCl, 10% glycerol, pH 7.0) at -80 °C until further use. Yield for all mutants varied from 0.5-10 mg/L.

p53-DBD: The p53-DBD mutants were purified as described previously (60) with slight modifications. The recombinant BL-21 Rosetta (DE3) strains were grown in TB medium at 37 °C containing 100 µg/mL ampicillin until the OD_{600} reached 1.0. 100 µM $ZnSO_4$ was added and incubated at 25 °C for 30 mins. Protein expression was induced by addition of 1.0 mM IPTG. The induced cultures were grown for 20 hours with shaking at 25 °C and were harvested by centrifugation. Cells were harvested, re-suspended in lysis buffer pH 7.2 (50 mM NaH_2PO_4, 100 mM NaCl, containing 10 mM PMSF and 10 mM DTT) and lysed by sonication. The clarified lysates were loaded first with 2 ml of DEAE Sepharose fast flow (GE Healthcare) and the elutes obtained by a gradient of 100-500 mM NaCl in 50 mM NaH_2PO_4, pH 7.2, were further subjected to Ni-NTA purification by mixing with 2 mL of Ni-Sepharose resin (GE Healthcare) for 4 hrs. The bound proteins were eluted with a gradient of 100-500 mM imidazole in 50 mM NaH_2PO_4, 500 mM NaCl, (pH 7.2) containing 10 mM DTT. The purified proteins were subjected to 15% Tricine SDS-PAGE, concentrated and finally stored in storage buffer (50 mM NaH_2PO_4, 500 mM NaCl, 500 mM imidazole, 10 mM DTT, pH 7.2) at -80 °C until further use. The inactive mutants V143A, V157F, could not be used for biophysical studies because of their low expression, solubility, poor yields and high tendencies towards aggregation after purification. Yield for the WT and the mutants varied from 0.5-2 mg/L.

mRBD (331-532): Expression and purification of the mRBD and the single mutants D389E, L390M and P527I was carried out as described previously (35). Briefly, proteins were expressed by transient transfection of Expi293 cells and purified by Ni-NTA chromatography. The eluted fractions were pooled and dialysed thrice using a 3-5 kDa (MWCO) dialysis membrane (40mm flat width) (Spectrum Labs) against 1X PBS, pH 7.4 (storage buffer). The eluted fractions were subjected to 15% Tricine SDS-PAGE and the protein concentration was determine by measuring the A_{280} and using an extinction coefficient of 33850 $M^{-1}cm^{-1}$.

***In vivo* activity of the different CcdB mutants**

WT and mutant CcdB were transformed into *E. coli Top10*pJAT, grown for 1 hour in 1 ml LB media containing 0.2% glucose (highest repressor level to avoid leaky expression). After 1 hour, the cells were pelleted and glucose was removed by subjecting cells to three washes with 1 ml LB. Finally, equal amounts of cells resuspended in 1 ml of LB media and serially diluted were spotted on seven agar plates (LB agar plates containing 100 µg/mL ampicillin, 20 µg/mL gentamycin) containing various amounts (%) of glucose (repressor) and arabinose (inducer) concentrations (i.e. 2×10^{-1} % glucose, 4×10^{-2} % glucose, 7×10^{-3} % glucose, 0 % glucose/arabinose, 2×10^{-5} % arabinose, 7×10^{-5} % arabinose and 2×10^{-2} % arabinose) at 37 ˚C. Since active CcdB protein kills the cells, colonies are obtained only for mutants that show an inactive phenotype under the above conditions (8).

***In vivo* Solubility Estimation**

CcdB: Solubility levels were monitored for all the single and double mutants in *E. coli Top10Gyrase* in the presence of 0.2% arabinose as described previously (8). Cultures were grown in LB media, induced with 0.2% arabinose at an OD_{600} of 0.6 and grown for 5 hours at 37 °C. 2×10^{9} cells were centrifuged (1800g, 10 min, RT). The pellet was resuspended in 500 µL HEG buffer pH 7.4 (10 mM HEPES, 50 mM EDTA, 10% glycerol containing 10 mM PMSF) and sonicated. 250 µL was taken as Total Cell Lysate and the remaining 250 µL was centrifuged (11000 g, 10 min, 4 °C). 250 µL was taken as supernatant and the pellet was resuspended in 250 µL HEG buffer pH 8.4 and all the fractions were subjected to 15% Tricine SDS-PAGE. Solubility of all mutants was quantitated by estimating relative amounts of CcdB in supernatant and pellet fractions by the Geldoc software (Quantity One) (8,61).

p53 DBD: Solubility levels were monitored for all the single and double mutants in *E. coli* BL-21 Rosetta (DE3) cells. Cultures were grown in LB media till they attain OD_{600} values of 1.0, followed by incubation with 100 µM $ZnSO_4$ at 25 °C for 30 minutes and induction with 1.0 mM IPTG, for 20 hours at 25 °C. 2×10^{9} cells were centrifuged (1800g, 10 min, RT) and the pellet was resuspended in

500 µL lysis buffer pH 7.2 (50 mM NaH_2PO_4, 100 mM NaCl, containing 1 mM PMSF and 10 mM DTT) and sonicated. 250 µL was taken as Total Cell Lysate and the remaining 250 µL was centrifuged (11000 g, 10 min, 4 °C). 250 µL was taken as supernatant and the pellet was resuspended in 250 µL lysis buffer pH 7.2 and all the fractions were subjected to 15% Tricine SDS-PAGE. Solubility of all mutants was quantitated by estimating relative amounts of the p53 DBD protein in supernatant and pellet fractions by the Geldoc software (Quantity One) (8,61).

Thermal stability measurements by TSA and nanoDSF

CcdB: The thermal shift assay was conducted in an iCycle Q5 Real Time Detection System (Bio-Rad, Hercules, CA) using 4 µM of the CcdB protein in 200 mM HEPES, pH 8.4 and 2.5X Sypro orange dye in a 96-well iCycleiQPCR plate. The plate was heated from 20 to 90 °C. with a ramp of 0.5 °C/min. The fluorescence data following CCD detection was plotted as a function of temperature and fitted to a standard, four parameter sigmoidal equation y= LL+{UL-LL}/{1+exp((T_m-T)/a)}, where y is the observed fluorescence signal, LL and UL are the minimum and maximum intensities in the transition region respectively, 'a' is the slope of the transition, T_m is the melting temperature, and T is the experimental temperature (15).

nanoDSF (Prometheus NT.48) was also used to carry out thermal unfolding experiments of the CcdB mutants. The assays were carried out with 4 µM of each protein and the apparent thermal stability (T_m) was determined by monitoring the changes in the fluorescence ratio (F350/F330) as a function of temperature as described earlier (16).

Briefly, the first derivative of the ratio ($F' = \frac{d\frac{F350}{F330}}{dT}$) is normalised using Equation 2:

$$Normalised\ Fluorescence\ (F_N{}') = \frac{y - y_{min}}{y_{max} - y_{min}} \ldots(2),$$

where y is the first derivative of the observed fluorescence (F350/F330 ratio), y_{min} is value of the first derivative minimum and y_{max} is the value of the first derivative maximum.

A subset of the CcdB mutants were also refolded in 1.5 M GdnCl and subjected to thermal denaturation

with native protein in 1.5 M GdnCl as a control. For thermal denaturation, the samples were filled into capillaries and then placed the instrument. The capillaries were then heated from 20 to 90 °C with a ramp of 1 °C /min. For the highly stable mutants Y8D, V46L and S60E as well as WT, refolding was carried out in 1, 2, 3, 4 and 5 M GdnCl and refolded protein subjected to thermal denaturation. Native protein in 1, 2, 3, 4 and 5 M GdnCl was also taken as control.

TEM-1 β lactamase, p53-DBD, and mRBD (331-532): nanoDSF (Prometheus NT.48) was also used to probe the thermal unfolding of the TEM-1 β lactamase, p53-DBD and mRBD mutants. The assays were carried out with 4 µM of each protein and the apparent thermal stability (T_m) was determined by monitoring the changes in the fluorescence ratio (F350/F330) as a function of temperature.

For the TEM-1 β lactamase, the ratio F350/F330 is normalised using Equation 3:

$$Normalised\ Fluorescence\ (F_N) = \frac{y - y_{min}}{y_{max} - y_{min}} \ldots(3),$$

where y is the observed fluorescence (F350/F330 ratio), y_{min} is value of the ratio minimum and y_{max} is the value of the ratio maximum.

For the p53-DBD, the first derivative of the 330 wavelength ($F330' = \frac{dF330}{dT}$) is normalised using Equation 4:

$$Normalised\ Fluorescence\ (F330_N{}') = \frac{y - y_{min}}{y_{max} - y_{min}} \ldots(4),$$

where y is the first derivative of the observed fluorescence (F330), y_{min} is value of the first derivative minimum and y_{max} is the value of the first derivative maximum at 330.

For the mRBD mutants, normalization was carried out similar to CcdB mutants using Equation 2.

Samples were heated from 20 to 90 °C with a ramp of 1 °C /min. TEM-1 β lactamase and p53 DBD were refolded in 0.5 M GdnCl and 0.5 M urea respectively and subjected to thermal denaturation along with the native proteins in 0.5 M GdnCl and 0.5 M urea as their respective controls. For the highly stable mRBD mutants D389E, L390M and P527I as well as WT, refolding was carried out in 0.5, 1, 2, and 3 M GdnCl and refolded protein subjected to thermal denaturation with native protein in 0.5, 1,

2, and 3 M GdnCl as controls.

Isothermal denaturation of purified proteins

CcdB: Briefly, all the CcdB mutant proteins were overnight dialysed four times in total of 2 litres of 200 mM HEPES, pH 8.4 using Tube-O-Dialyser (4kDa MWCO, GBiosciences). The chemical stability (C_m) was then determined using 5 µM of proteins by monitoring the changes in the fluorescence ratio (F350/F330), after overnight incubation at 25 °C containing various concentrations of the denaturant (GdnCl). The GdnCl concentrations were estimated from refractive index measurements using a refractometer. The data was analyzed using Sigmaplot™ for Windows™ scientific graphing software, and the plots were fitted to a two-state unfolding model ($N_2 \leftrightarrow 2U$). The fraction unfolded for all CcdB mutants was calculated as described (14,16) and is summarized below. The spectroscopic signal (Y) of a protein solution (F_{350}/F_{330} ratio by nano-DSF) is related to the fraction of unfolded protein (f_u) by:

$$f_u = (Y - Y_f)/(Y_u - Y_f) \quad (5)$$

where Y_f and Y_u are the values of Y for the folded and unfolded protein respectively. These change linearly with the denaturant concentration ([D]), as follows:

$$Y_f = y_f + m_f[D] \quad (6)$$

$$Y_u = y_u + m_u[D] \quad (7)$$

where y_f and y_u are the folded and unfolded parameters at zero denaturant concentration. m_f and m_u are the denaturation dependence of Y for the folded and unfolded state respectively. C_m is the denaturant concentration at which f_u=1. The data are analyzed to yield to obtain the free energy of unfolding at zero denaturant, $\Delta G^o = \Delta G^o_D - m_{equi}[D]$, where ΔG^o_D is the measured free energy of denaturation at denaturant concentration [D] and m_{equi} encapsulates the denaturant dependence of ΔG^o_D (62). For homodimeric CcdB, ΔG^o_D is related to f_u by the following equation:

$f_u = ½[-z \pm \sqrt{(z^2+4z)}]$, where $z = e^{-\Delta G^\circ_D/RT}/2P_t$, where P_t is the total protein concentration in terms of

monomer units, R is the universal gas constant and T is the absolute temperature (14).

TEM-1 β lactamase and p53-DBD: Equilibrium unfolding experiments of the monomeric TEM-1 β lactamase and p53-DBD mutants were also carried out by nanoDSF (Prometheus NT.48). The stability to chemical denaturation (C_m) was determined by monitoring the changes in the fluorescence ratio (F350/F330), after overnight incubation at 25 °C in the final storage buffer for TEM-1mutants containing various concentrations of the denaturant (GdnCl) and overnight incubation at 15 °C in the final storage buffer for p53-DBD mutants containing various concentrations of the denaturant (Urea). The data was analyzed using Sigmaplot™ for Windows™ scientific graphing software, and the data were fit to a two-state unfolding model (N↔U) . Isothermal denaturation was carried out at a fixed protein concentration of 5 µM for all the proteins. The fraction unfolded for all the TEM-1 β lactamase and p53-DBD mutants were calculated in a similar way as described above.

For all the various classes of proteins used in the study (CcdB, p53-DBD and TEM-1-β-lactamase), the isothermal equilibrium denaturation experiments (for a particular protein) are performed in the same nanoDSF instrument (Prometheus NT.48) at the same LED settings (100%) and at identical temperatures and buffer conditions for each set of WT and mutant proteins.

Refolding and unfolding kinetics of purified proteins

CcdB: Briefly, the refolding rates were measured using different concentrations (1 µM -5 µM) of the dialysed proteins in 200 mM HEPES, pH 8.4 denatured in 0.2-4 M GdnCl and subsequently diluted to final denaturant concentrations varying from 0.1 M to 1.5 M of GdnCl, and the changes in the fluorescence ratio (F350/F330) were monitored as a function of time. To measure the unfolding kinetics, protein in native buffer (200 mM HEPES, pH 8.4) was diluted into the same buffer containing 8 M GdnCl to a final concentration of GdnCl varying from 2 to 4 M and the changes in the fluorescence ratio (F350/F330) were monitored as a function of time. Refolding kinetic traces of fluorescence intensity from 0.1 M to 1.5 M GdnCl as a function of time for different CcdB mutants were normalized from 0 to 1 between native and denatured baseline, as described previously (8,16,17). Unfolding

kinetic traces of fluorescence intensity from 2 to 4 M GdnCl as a function of time for different CcdB mutants in 200 mM HEPES, pH 8.4 were normalized from 0 to 1 between native and denatured baseline, as described previously (16,17). For the stable CcdB mutants (Y8D, V46L and S60E as well as WT CcdB) refolding and unfolding was carried out in 2 M and 4.5 M GdnCl respectively in 200 mM HEPES, pH 8.4 at 25 °C and normalisation was done as described above. The data was analyzed using Sigmaplot™ for Windows™ scientific graphing software and plots were fitted to a 5 parameter equation for exponential decay for refolding ($y=a_0+a1*\exp(-kf_1*x)+a2*\exp(-kf_2*x)$), and a 3 parameter exponential rise for unfolding ($y=A_0+A1*(1-\exp(-ku_1*x))$) as described previously (17), where x is the time of refolding/unfolding. Both refolding and unfolding studies of all the mutants were also carried out at three different denaturant concentration and the observed rates were plotted as a function of denaturant condition to determine the refolding and unfolding m values ($M^{-1}s^{-1}$). This was further used to extrapolate the unfolding and refolding rates of all the mutants to 0 M GdnCl concentration for relative comparison as described by the following equation $k_{obs}=k_0+m_{kinetic(F/U)}[D]$, where k_{obs} is the observed refolding/unfolding rate constant in s^{-1} at a particular denaturant concentration, k_0 is the extrapolated refolding/unfolding rate constant at 0 M denaturant in s^{-1}, $m_{kinetic(F)}$, $m_{kinetic(U)}$ is the slope of a plot of the refolding or unfolding rate constant respectively as a function of denaturant concentration in units of $M^{-1}s^{-1}$ and D is the denaturant concentration in units of M.

TEM-1 β lactamase, p53-DBD and mRBD (331-532): Refolding and unfolding kinetics of the TEM-1 β lactamase and mRBD mutants at 25 °C and of the p53-DBD mutants at 15 °C were also monitored by nanoDSF using PR.Time Control software (Prometheus NT.48). Briefly, the refolding rates for the TEM-1 β lactamase and the mRBD mutants were measured using 5 µM of the proteins denatured in storage buffer containing 3 M GdnCl and subsequently diluted to a final concentration of 0.5 M of GdnCl, and the changes in the fluorescence ratio (F350/F330) were monitored as a function of time. For the p53 DBD mutants, the refolding rates were measured using 4 µM of the proteins denatured in

the final storage buffer containing 4 M urea and subsequently diluted to a final concentration of 2 M urea.

To measure the unfolding kinetics, protein in native storage buffer was diluted into buffer containing 2.5 M GdnCl for TEM-1 β lactamase and 3 M GdnCl for mRBD mutants and 4.4 M Urea for p53-DBD and the changes in the fluorescence ratio (F350/F330) were monitored as a function of time. Refolding and unfolding kinetic traces were normalized from 0 to 1 between native and denatured baselines. The data for the TEM-1 β lactamase mutants was analyzed using Sigmaplot™ for Windows™ scientific graphing software and plots were fitted to a 5 parameter equation for exponential decay for refolding ($y=a_0+a1*exp(-kf_1*x)+a2*exp(-kf_2*x)$), yielding slow and fast phase rate constants and a 3 parameter exponential rise for unfolding ($y=A_0+A1*(1-exp(-ku_1*x))$) as described above, where x is the time of refolding/unfolding. The data for the mRBD mutants was analyzed using Sigmaplot™ for Windows™ scientific graphing software and plots were fitted to a 3 parameter equation for exponential decay for refolding ($y=a_0+a1*exp(-kf_1*x)$), and a 5 parameter exponential rise for unfolding ($y=A_0+A1*(1-exp(-ku_1*x))+a2*(1-exp(-ku_2*x))$), yielding slow and fast phase rate constants as described above, where x is the time of refolding/unfolding. The data for the p53 DBD mutants was analyzed using Sigmaplot™ for Windows™ scientific graphing software and plots were fitted to a 5 parameter equation for exponential decay for refolding ($y=a_0+a1*exp(-kf_1*x)+a2*exp(-kf_2*x)$), yielding slow and fast phase rate constants and a 5 parameter equation for exponential rise for unfolding ($y=A_0+A1*(1-exp(-ku_1*x))+a2*(1-exp(-ku_2*x))$), yielding slow and fast phase rate constants as described above, where x is the time of refolding or unfolding.

For all the various classes of proteins used in the study (CcdB, p53-DBD, TEM-1-β-lactamase and mRBD), the kinetics experiments (for a particular protein) are performed in the same nanoDSF instrument (Prometheus NT.48) at the same LED settings (100%) and at identical temperatures and buffer conditions for each set of WT and mutant proteins.

Binding of native and refolded CcdB proteins to GyrA14 by MicroScale Thermophoresis (MST)

6.6 µM GyrA14 (in 1X PBS) was labeled using the RED-NHS Monolith™ Protein Labeling Kit (NanoTemper Technologies) according to the manufacturer's instructions. After labeling, the protein was eluted by gravity flow using a PD MiniTrap™ G-25 (GE Healthcare) Sephadex column into 200 mM HEPES, pH 8.4 which was also used as assay buffer for MST experiments. The binding of 70 nM of labeled GyrA14 to refolded CcdB mutants in 1.5 M GdnCl (also in 0.1 M GdnCl for V18W, V18W-S12G, V20F and V20F-S12G) as well as native CcdB proteins, not subjected to refolding, in presence of 1.5 M GdnCl (also in 0.1 M GdnCl for V18W, V18W-S12G, V20F and V20F-S12G) was measured. Samples were loaded into Monolith™ NT.115 MST Standard Capillaries (NanoTemper Technologies) and binding measured using a Monolith NT.115 instrument with MO.Control software at room temperature (LED/excitation power setting 100%, MST power setting 80-100%). Data was analyzed using MO.Affinity Analysis software (version 2.2.5, NanoTemper Technologies) at different standard MST-off times.

Affinity and thermal tolerance of the CcdB proteins measured by Surface Plasmon Resonance (SPR)

All SPR experiments were performed with a Biacore 2000 (Biacore, Uppsala, Sweden) optical biosensor at 25 °C. 35 µg/mL of GyrA14 was used for immobilization at 30 µl/min flow rate for 180 s. 1000 resonance units of GyrA14 were attached by standard amine coupling to the surface of a research-grade CM5 chip. A sensor surface (without GyrA14) that had been activated and deactivated served as a negative control for each binding interaction. The E11R CcdB mutant proteins (E11R, L36A-E11R and L83S-E11R) were overnight dialysed three times against a total 6 litres of 1X PBS, pH 7.4 using Tube-O-Dialyser (4 kDa MWCO, GBiosciences). The remaining proteins were in 200 mM HEPES-0.1 M glycine, pH 8.4. Different concentrations of the dialysed CcdB mutants were run across each sensor surface in a running buffer of PBS (pH 7.4) containing 0.005% Tween surfactant. Protein concentrations ranged from 3 nM to 5 µM. Both association and dissociation were measured

at a flow rate of 30 µl/min. In all cases, the sensor surface was regenerated between binding reactions by one to two washes with 4 M $MgCl_2$ for 10 –30 s at 30 µL/min. Each binding curve was corrected for nonspecific binding by subtraction of the signal obtained from the negative control flow cell. The kinetic parameters were obtained by fitting the data to a simple 1:1 Langmuir interaction model by using BIA EVALUATION 3.1 software as described previously (8,63). Thermal tolerance of the CcdB mutants E11R, S12G, L36A, L36A-E11R and L36A-S12G and WT CcdB using 500 nM of protein was assessed by their ability to bind GyrA14 after heat stress. The protein sample was incubated at 40 °C and 80 °C respectively for 1 h in a PCR cycler (BioRad) with a heated lid to prevent evaporation. The samples were cooled to 25 °C and binding affinity to GyrA14 was determined by SPR experiments as described above The fraction of active protein following thermal stress was quantitated by measuring the RUs at the end of the association time period relative to those for the same protein incubated throughout at 25 °C. This was designated as Residual activity.

MIC and IC_{90} determination of TEM-1 β lactamase mutants:

Cultures were grown overnight at 37 °C in LB broth with 50 µg/mL kanamycin. The overnight cultures were diluted 1:10^4 and 30 µL was inoculated into 500 µL of fresh LB broth supplemented with 50 µg/mL kanamycin, 100 µM IPTG inducer, and various concentrations of ampicillin and cefotaxime. The concentrations of ampicillin used for MIC determination were 0, 25, 50, 100, 200, 300, 400, 500, 600, 800, 1000, 1500, 2000, 2500, 3000 and 4000 µg/mL. The concentrations of cefotaxime tested were 0, 1, 2, 3, 4, 5, 6, 8, 10, 15, 20 and 30 µg/mL. The cultures were then incubated at 37 °C with shaking for 24 hrs following which OD_{600} measurements were carried out on Varioskan Flash (ThermoScientific) using Nunclon delta surface plates (ThermoScientific). and the MIC was determined by recording the lowest concentration of ampicillin or cefotaxime on which no growth was observed. In practice, this was an all or none phenomenon (24).

IC_{90} was derived directly from the plate data measurements. Briefly, *E. coli* BL-21 (λDE3, plysE) containing the pET24a plasmid that encodes TEM-1 β-lactamase mutants was grown overnight in LB broth with 50 μg/mL kanamycin. Overnight cultures were diluted 1:100 into LB broth with 50 μg/mL kanamycin and incubated for 4 hrs at 37 °C to mid-log phase (OD_{600} ~0.6). Ten-fold serial dilutions of each culture were made, and 100 μL of each dilution was spread onto LB agar plates containing 100 μM IPTG inducer and 0-4000 μg/mL ampicillin and 0-50 μg/mL of cefotaxime, in a series of two-fold increases. After incubation for 24 hrs at 37 °C, colony forming units (cfu) on each plate were counted to calculate the cfu/mL of culture, and IC_{90} was defined as the concentration of ampicillin or cefotaxime that reduces cfu/mL of culture by ≥90% (22).

Nitrocefin assay of TEM-1 β lactamase mutants: TEM-1 β -lactamase activity was assayed as described previously (6). Briefly the rate of nitrocefin (50 μM) hydrolysis was observed at 486 nm at 25 °C for 60 minutes in 10 mM HEPES, 300 mM NaCl, 10% glycerol (pH 7.0) using10 nM native protein, native protein in 0.5 M GdnCl and refolded protein in 0.5 M GdnCl. Activity measurements were carried out on Varioskan Flash (ThermoScientific) using Nunclon delta surface plates (ThermoScientific).

SPR-binding of native, native in presence of GdnCl and refolded mRBD proteins with immobilized ACE2-hFc: Binding studies of various mRBD mutants with ACE2-hFc neutralizing antibody were carried out using the ProteOn XPR36 Protein Interaction Array V.3.1 from Bio-Rad as described previously (35). Briefly, following activation of the GLM sensor chip with EDC and sulfo-NHS (Sigma), Protein G (Sigma) was coupled at 10 μg/mL in the presence of 10 mM sodium acetate buffer pH 4.5 at 30 μL/min for 300 seconds until ~3500-4000 RU was immobilized. After quenching the excess sulfo-NHS esters using 1 M ethanolamine, ~1000 RU of ACE2-hFc was immobilized at a flow rate of 5 μg/mL for 100 seconds on various channels except one blank channel that served as the reference channel. Native mRBD proteins, proteins in 0.5 M GdnCl and refolded protein in 0.5 M

GdnCl were passed at a flow rate of 30 μL/min for 200 seconds over the chip surface, followed by a dissociation step of 400 seconds. A lane without any immobilization was used to monitor non-specific binding. After each kinetic assay, the chip was regenerated in 0.1 M Glycine-HCl (pH 2.7). 50 nM of the mRBD proteins in 1X PBS were used in all cases for the binding studies. The response units for each of the native protein, native protein in 0.5 M GdnCl and refolded proteins in 0.5 M GdnCl was used for relative comparisons. For the studies carried out in GdnCl, the running buffer did not have any GdnCl and the jumps obtained in all the channels were removed after reference subtraction.

Crystallization of CcdB mutants

5 mg/ml of the purified mutants of CcdB, S12G, V46L and S60E CcdB, in 1X PBS pH 7.4 and 1 mM EDTA was screened for crystallization with Hampton Research screens by the sitting drop method using the Mosquito crystallization robot facility at NCBS/Instem. Plates were incubated at 18 °C. Crystals appeared in a few conditions after approximately 20 days. Two conditions had mountable crystals: 0.2 M calcium chloride dihydrate, 20% w/v PEG 3350, pH 5.1 (PEG/Ion 1, condition 7) and 0.2 M ammonium chloride, 20% w/v PEG 3350, pH 6.3 (PEG/Ion 1, condition 9). The initial crystals diffracted to ~2.5 Å. Conditions were further optimized to obtain single crystals for better diffraction quality. The best crystals were obtained in the condition 0.15 M calcium chloride dihydrate, 20% w/v PEG 3350 for S12G; 0.20 M calcium chloride dihydrate, 25% w/v PEG 3350, pH 5.1 with 20% glycerol (cryo) for V46L; 0.20 M calcium chloride dihydrate, 10% w/v PEG 3350; pH 5.1 with 20% glycerol (cryo) for S60E, with a protein:precipitant ratio of 1:2 at 18 °C using the hanging drop method.

Data collection and processing of CcdB mutants

Diffraction data was collected at 100K using Rigaku FR-X with R-AXIS IV++ detector facility at NCBS/Instem for S12G. For V46L, diffraction data was collected at 100K using XRD2 beamline with Dectris Pilatus-6M detector facility at Elettra synchrotron, Trieste, Italy. For S60E, diffraction data was collected at 100K using Rigaku MicroMax-007HF with mar345dtb detector facility at home-

source MBU, IISc. The crystals diffracted to 1.63Å, 1.35 Å and 1.93 Å for S12G, V46L and S60E respectively. Data was processed using iMosflm (64,65) with an overall completeness of 90.6% for S12G, 100% for V46L and 97.5% for S60E. For S12G, the crystal belonged to the C2 space group, with the unit cell parameters, while the pointless predicted I2. Thus, the data was re-scaled in I2 with unit cell parameters a = 35.57; b = 36.53; c = 67.53 and β = 93.69°. The V46L and S60E crystals belonged to the C2 space group with unit cell parameters a = 75.10; b = 36.76; c = 35.91 and β = 115.19° for V46L and a = 74.81; b = 36.64; c = 35.67 and β = 114.97° for S60E. The structure was solved by molecular replacement using PHASER (66) with 3VUB (67) as the starting model. After iterative cycles of refinement using Refmac (68,69) and manual model building using Coot (70,71), the final model consisted of 816 protein atoms, 95 water and two Cl^- ion with an R_{factor} and R_{free} of 22.8 and 26.9 respectively for S12G. For V46L, the final model consisted of 814 protein atoms, 167 water and two Cl^- ion with an R_{factor} and R_{free} of 16.2 and 18.4 respectively. For S60E, the final model consisted of 820 protein atoms, 98 water and two Cl^- ion with an R_{factor} and R_{free} of 17.0 and 21.4 respectively. Composite omit maps were calculated around the 12th, 46th and 60th residue for S12G and S60E respectively. The final model was validated using the validation server (https://validate.wwpdb.org). Data processing and refinement statistics are given in Supplementary S10. The server "https://swift.cmbi.umcn.nl/servers/html/listavb.html" was used for calculating the average B-factors.

Analysis of expression and GyrA14 binding of CcdB mutants on the yeast cell surface

Plasmids expressing Aga2p fusions of L42E, inactive mutants (V5F, V18W, V20F, L36A, L83S), the double mutants of L42E made in the background of the inactive mutants, and WT CcdB were transformed into *Saccharomyces cerevisiae* EBY100 cells as described (36). Briefly, the amount of CcdB protein expressed on the yeast cell surface was estimated by chicken anti-HA antibodies from Bethyl labs (1:600 dilution) and the GyrA14 binding activity on the yeast cell surface was estimated by incubating the induced CcdB mutants with 100 nM FLAG tagged GyrA14, followed by washing

with FACS buffer and subsequent incubation with mouse anti-FLAG antibodies, at a dilution ratio of 1:300 as described previously (36). This was followed by washing the cells twice with FACS buffer, and incubating with goat anti-chicken antibodies conjugated to Alexa Fluor 488 (1:300 dilution) for expression, and rabbit anti-mouse antibodies conjugated to Alexa Fluor 633 (1:1600 dilution) for binding, for 20 minutes at 4 °C. The flowcytometry was performed using a BD Aria III instrument.

Declarations:

Author Contributions: R.V., G.C. and J.B. designed the experiments. G.C. performed the experiments and analyzed the data for PIMs, single and double mutants of S12G, Y8D, M32T, L42E, S43T, V46L, S60E mutants of CcdB, TEM-1 β-lactamase mutants and mRBD mutants. J.B. performed the experiments and analyzed the data for, single and double mutants of E11R. G.C. and J.B. purified the p53-DBD mutants and J.B. performed the experiments and analyzed the data for the p53-DBD mutants. K.M. and P.G. screened the conditions, set up the crystals and solved the structure for S12G, V46L and S60E. S.A. cloned and purified the Y8D, V46L, L42E, S60E, CcdB mutants and the mRBD mutants. G.C and S.A. cloned the single and double mutants of CcdB and performed the FACS studies. R.V, G.C. and J.B. wrote most of the manuscript with critical inputs and review from all other authors.

Competing Interest Statement: None.

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Data availability: Crystal structures of the CcdB mutants have been deposited in PDB with PDB IDs: 7EPG (CcdB S12G), 7EPJ (CcdB V46L) and 7EPI (CcdB S60E). The validation reports of the structures are submitted along with the manuscript. The structures will be available after publication. The data relevant to the figures in the paper have been made available within the article and in the supplementary information section. All unique/stable reagents generated in this study are available from the Lead Contact Prof. Raghavan Varadarajan (varadar@iisc.ac.in) without restriction.

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Statistical analysis: All the experiments are carried out in biological replicates (n=2), and the listed errors are the standard errors derived from the values obtained for individual replicates. For the nanoDSF and MST measurements, each experiment has been carried out twice, each time with two sets of capillaries (n=4) and the listed errors are the standard errors derived from the values obtained for individual replicates. The SPR experiments in Supplementary Figure S4 have been performed once at each concentration with four different concentrations of the protein and the listed error is the standard error derived from the values at multiple concentrations. The P values for comparing the kinetic parameters, were analysed with a two-tailed Mann Whitney test using the GraphPad Prism software 8.0.0 (* indicates $P < 0.05$, ** indicates $P < 0.005$, *** indicates $P < 0.0005$).

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Figures

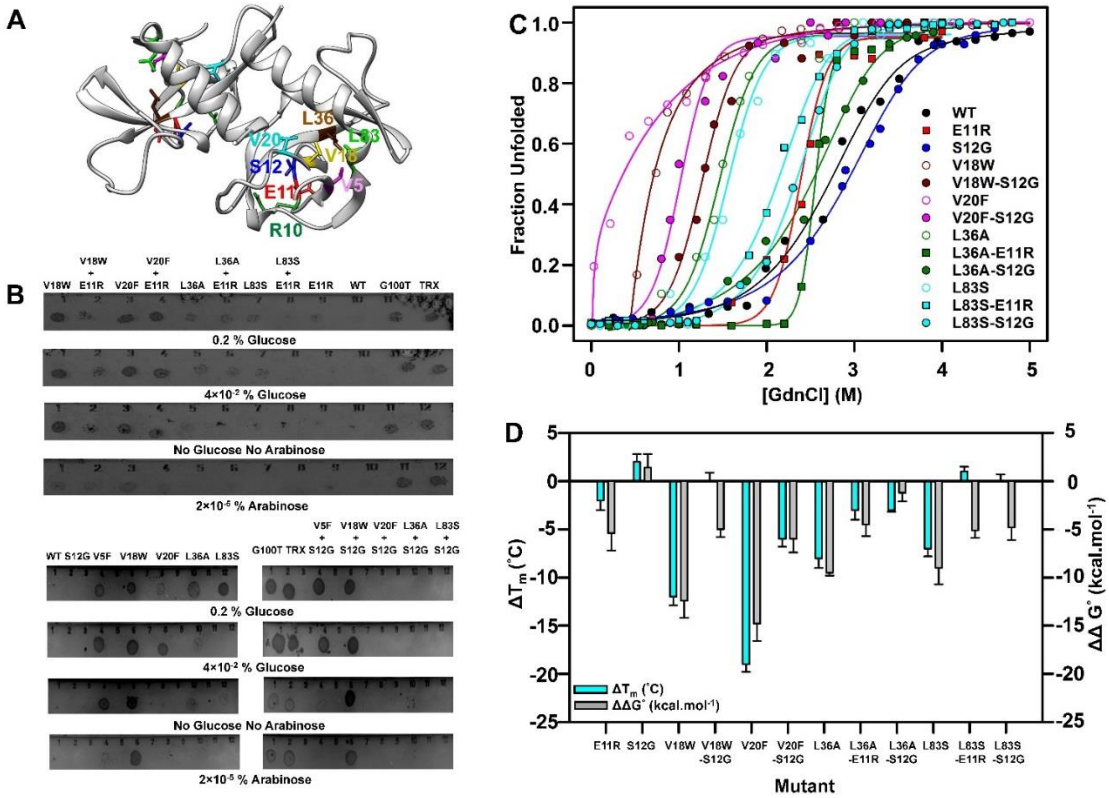


Figure 1. **Folding defects rescued by suppressors.** (A) Experimentally obtained inactive mutants and distal suppressors mapped onto the crystal structure of dimeric CcdB (PDB ID 3VUB (67)). The distal suppressors R10, E11and S12, are mapped on an exposed loop region while the PIMs V5, V18 V20, L36A and L83S are present in the core of the protein. (B) *In-vivo* activity of the PIMs at 37 °C in the background of the suppressor E11R and S12G. The condition where growth ceased was reported as the active condition. Four representative conditions are shown. (C) Equilibrium GdnCl denaturation profiles using nanoDSF is shown. The experimental data are shown in symbols, while the fits are shown in solid lines. (D) The difference in thermal stability, ΔT_m (in cyan), and thermodynamic stability assayed by chemical denaturation, $\Delta\Delta G^{\circ}$ (in grey) of the different CcdB mutants (Mutant-WT). The error bars wherever shown represent the standard deviation from two independent experiments, each performed in duplicates.

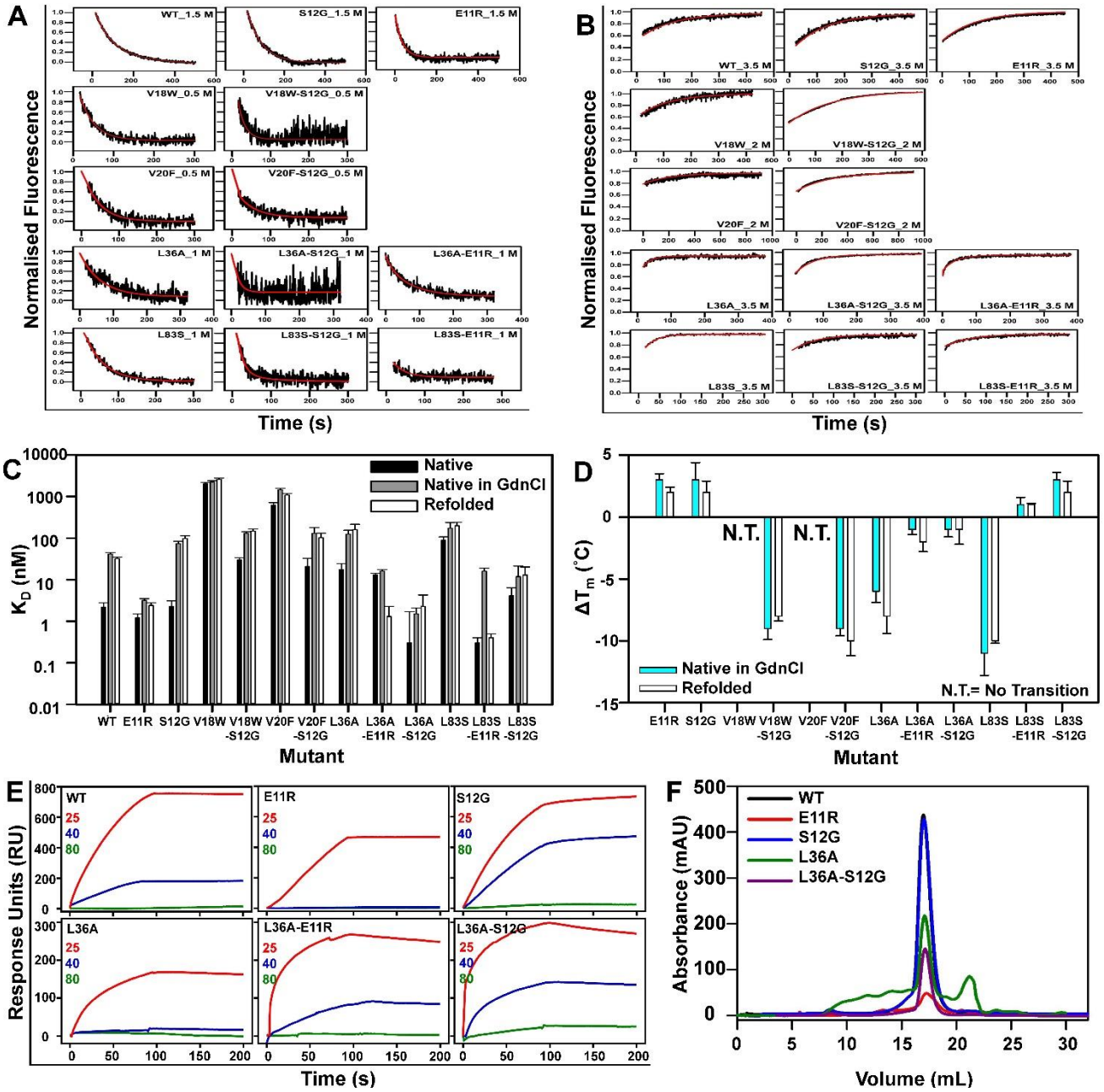


Figure 2: Kinetic and thermodynamic stabilisation by the CcdB suppressor mutants. (A) CcdB proteins exhibit biphasic refolding kinetics with a fast and slow phase whereas (B) unfolding of CcdB proteins follows single exponential kinetics. The experimental kinetic traces obtained at different GdnCl concentrations are shown in black, while the fits are shown in red**.** (C) Interaction between native (black), native protein in GdnCl (grey) and refolded (white) CcdB mutant proteins and labeled GyrA14 analyzed by MST. (D) The difference in apparent thermal melting temperatures (ΔT_m= Mutant-WT) for native proteins in GdnCl (cyan), and refolded proteins (grey). The error bars wherever

shown represent the standard deviation from two independent experiments, each performed in duplicates. (E) Binding of 500 nM WT and mutant CcdB to immobilised GyrA14 measured by passing the same concentrations of the analyte (CcdB proteins), after heat stress at two different temperature (40 and 80 °C), followed by cooling back to 25 °C. A room temperature control (25 °C) was also used. The residual active fraction was calculated as described in the materials section. (F) The SEC profiles of a few of the CcdB mutants are shown. The PIM L36A shows aggregation as well as degradation as compared to the WT, and E11R and S12G suppressors. The L36A-S12G has a similar profile like the WT and S12G.

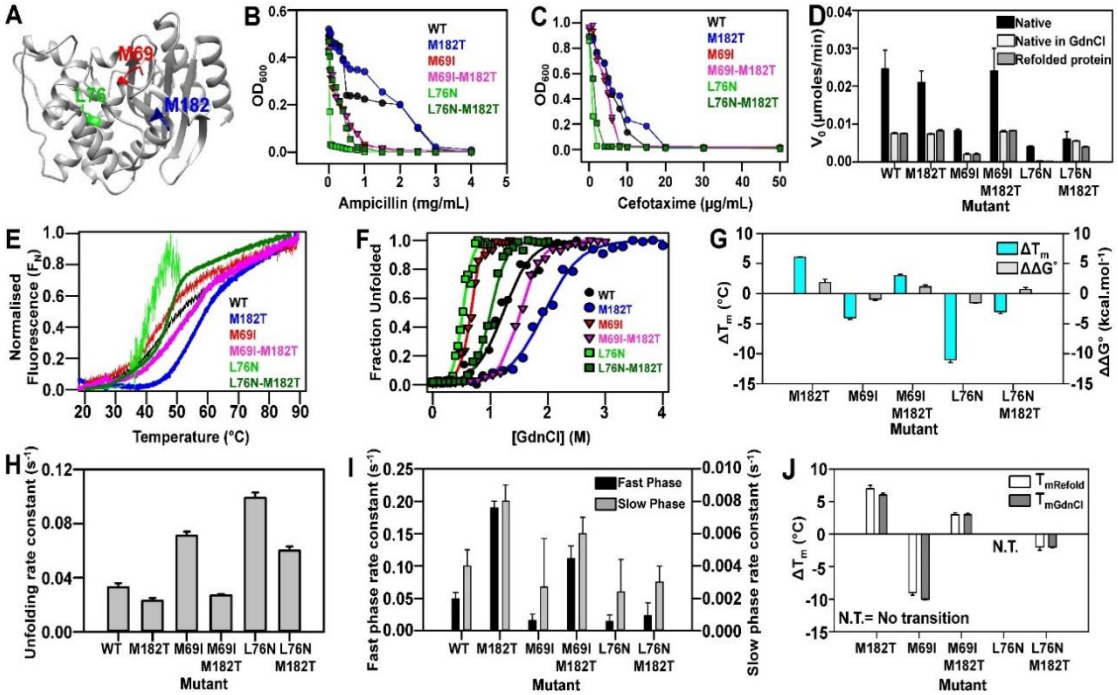


Figure 3. Enhancement of protein stability by M182T global suppressor in extended spectrum TEM-1 β lactamases. (A) Inactive mutants and distal suppressor M182T mapped onto the crystal structure of TEM-1 (PDB ID 1XPB (72)). The TEM-1 protein is shown in ribbon with the distal suppressor M182T, mapped on an exposed region, while the inactive mutants L76N and M69I are present in the core of the protein. (B-C) Influence of M182T substitution on TEM-1 mediated MIC levels using ampicillin (B) and cefotaxime (C) broth dilutions and pET24a plasmid. (D) The initial velocity (V_0) of the native enzyme (black), protein in 0.5 M GdnCl (light grey) and refolded protein in 0.5 M GdnCl (dark grey) at 25 °C with 10 nM protein and 50 µM of nitrocefin. (E-F) Thermal unfolding profile and equilibrium GdnCl denaturation of 10 µM of purified WT, and TEM-1 β lactamase mutants. (G) The difference in thermal stability, ΔT_m of native proteins (in cyan), and thermodynamic stability assayed by chemical denaturation, $\Delta\Delta G^{\circ}$ (in grey) of the different TEM-1 mutants (Mutant-WT). (H-I) The observed rate constants of unfolding (2.5 M GdnCl) and the observed rate constants of the fast phase (black) and slow phase (grey) of refolding (0.5 M GdnCl) of different mutants is represented. (J) The difference in thermal stability (ΔT_m= Mutant-WT) of 10 µM of native proteins (white) and refolded proteins in 0.5 M GdnCl (grey). The error bars wherever shown represent the standard deviation from two independent experiments, each performed in duplicates.

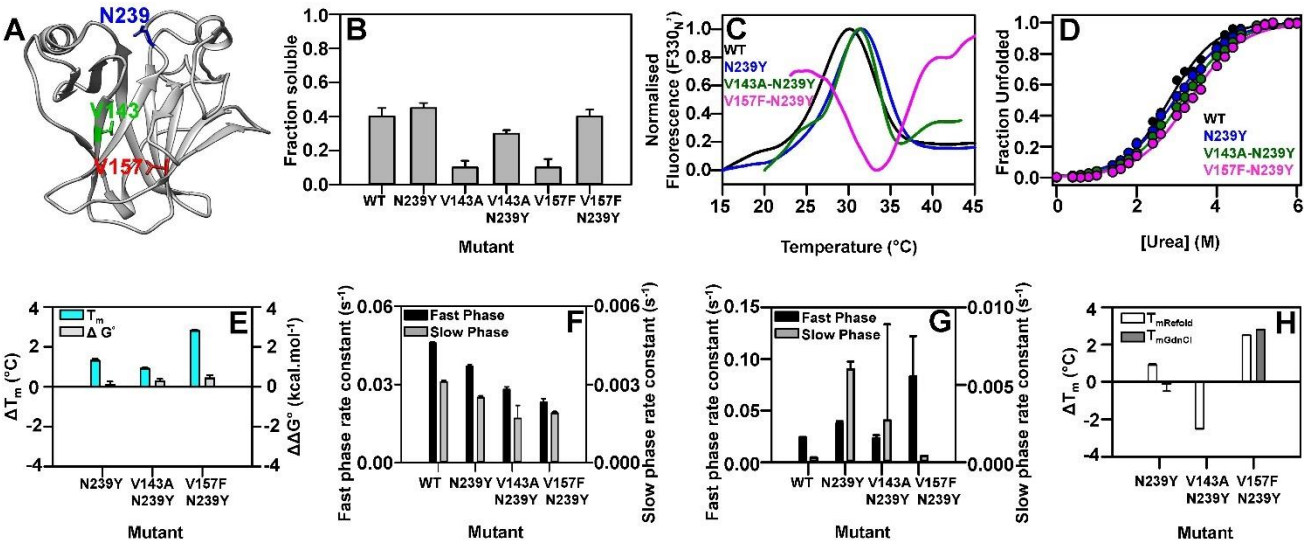


Figure 4. Characterisation of an N239Y global suppressor in DNA Binding Domain of p53. (A) Inactive mutants and distal suppressor N239Y mapped onto the crystal structure of p53-DBD (PDB ID 2OCJ (73)). The p53-DBD is shown in ribbon with the suppressor N239Y, mapped on an exposed region, while the inactive mutants V143A and V157F are present in the core of the protein. (B) Influence of N239Y substitution on p53-DBD solubility levels. (C-D) Thermal unfolding profile and equilibrium Urea denaturation respectively of purified WT and p53-DBD mutants. (E) The difference in thermal stability, ΔT_m of native proteins (in cyan), and thermodynamic stability assayed by chemical denaturation, $\Delta\Delta G^{\circ}$ (in grey) of the different p53-DBD mutants (Mutant-WT). (F-G) The observed rate constants of the fast phase (black) and slow phase (grey) of unfolding in 4.4 M Urea (F) and of refolding in 2 M Urea (G) of different mutants is represented. (H) The difference in thermal stability (ΔT_m= Mutant-WT) of 10 μM of native proteins (white) and refolded proteins in 0.5 M Urea (grey). The error bars wherever shown represent the standard deviation from two independent experiments, each performed in duplicates.

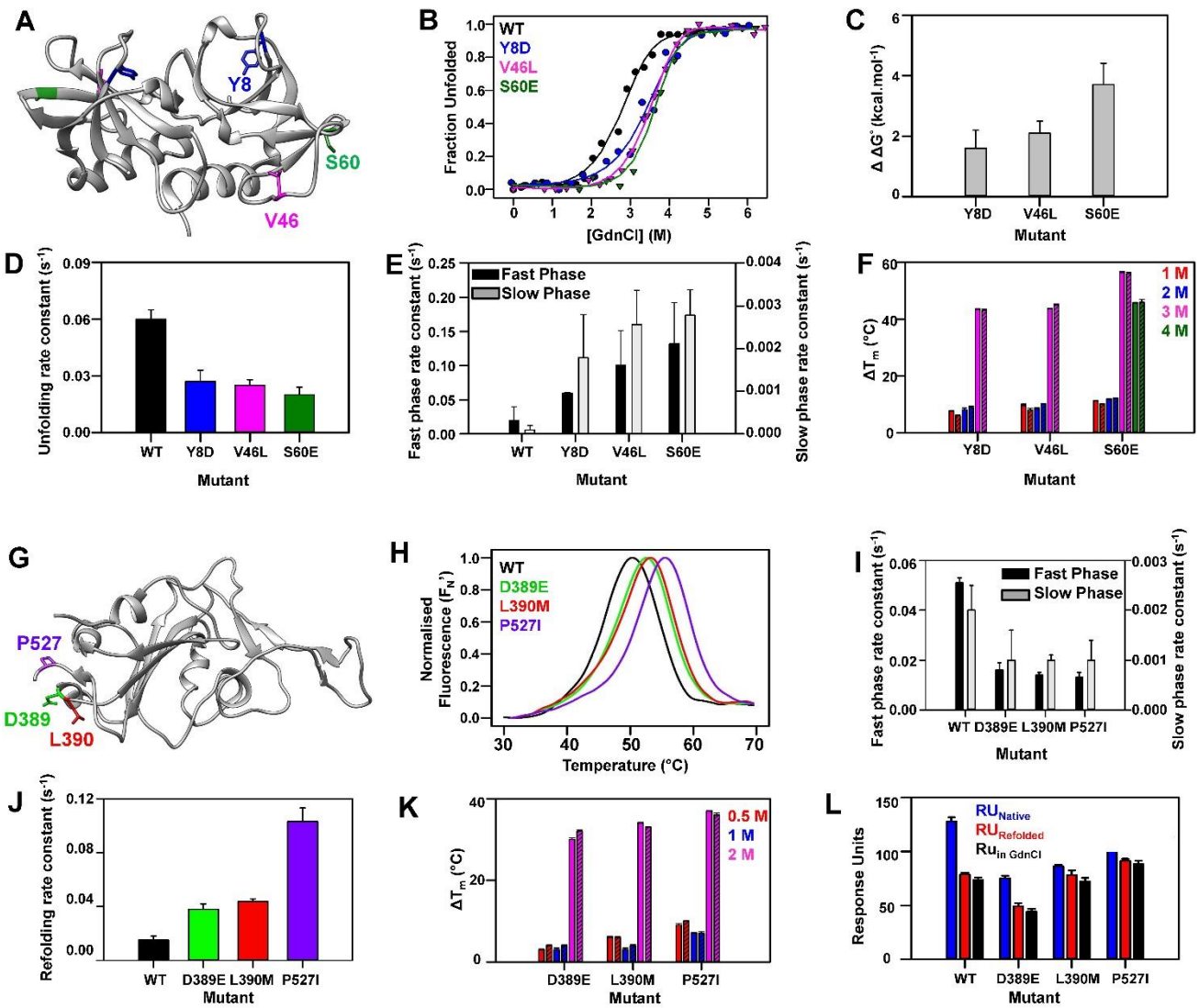


Figure 5. Enhancement in protein stability by highly stable suppressor mutations in CcdB and mRBD. (A-F) CcdB: (A) The distal suppressors Y8D, V46L, S60E on an exposed region mapped onto the crystal structure of CcdB (PDB ID 3VUB (67)). (B) Equilibrium GdnCl denaturation profiles assayed by nanoDSF. (C) Difference in thermodynamic stability assayed by chemical denaturation, $\Delta\Delta G^{\circ}$ (in grey) of the different CcdB suppressor mutants are plotted. (D-E) The observed rate constants of unfolding (4.5 M GdnCl) and the observed rate constants of the fast phase (black) and slow phase (grey) of refolding (2 M GdnCl) of different mutants. (F) The difference in thermal stability, (ΔT_m= Mutant-WT) of 5 µM of native proteins in 1 M, 2M, 3M, 4M GdnCl (solid bars), and refolded CcdB proteins in the same concentrations of GdnCl (striped bars). **(G-M) mRBD:** (G) The distal suppressors D389E, L390M, P527I on an exposed region mapped onto the crystal structure

of RBD (PDB ID 6ZER (74)). (H) Thermal unfolding profile of 10 µM of purified WT and mRBD mutants. (I-J) The observed rate constants of fast phase (black) and slow phase (grey) of unfolding (3 M GdnCl) and the observed rate constants of refolding (0.5 M GdnCl) of different mutants. (K) The difference in thermal stability, (ΔT_m= Mutant-WT) of 5 µM of native mRBD proteins in 0.5 M (red), 1M (blue), 2M (pink) GdnCl (solid bars), and refolded mRBD proteins in the same concentrations of GdnCl (striped bars). (L) Binding of 50 nM of native mRBD proteins (blue), native mRBD proteins in 0.5 M GdnCl (red solid) and refolded mRBD proteins in 0.5 M GdnCl (red striped) with ACE2-hFc neutralizing antibody is shown. The error bars wherever shown represent the standard deviation from two independent experiments, each performed in duplicates.

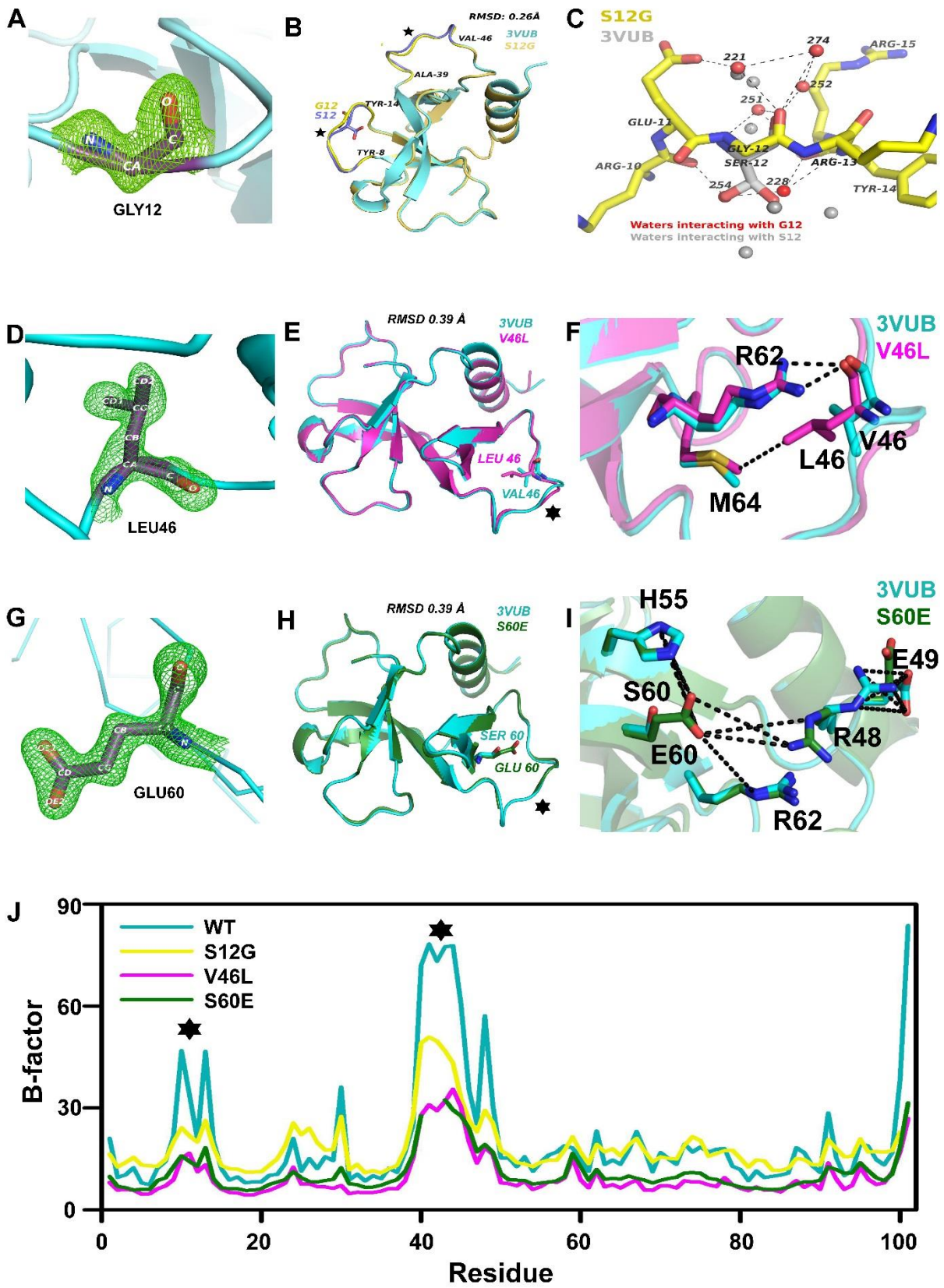


Figure 6. Structures of stabilised CcdB mutants. (A) Composite omit map at residue 12. (B) Structural superposition of WT (3VUB) and S12G monomers, regions displaying deviation are

indicated by ⋆. (C) Network of interactions at the 12th position in S12G. WT structure is shown with a grey backbone. S12 in 3VUB adopts two conformations with partial occupancy, the position of the corresponding hydroxyl group in each conformation is taken up by two water molecules in S12G. Water molecules directly interacting with G12 is shown in red and the corresponding water in 3VUB in grey. (D) Composite omit map at residue 46. (E) Structural superposition of WT and V46L monomers, regions displaying deviation are indicated by ⋆. (F) Network of interactions at the 46th position in V46L. WT structure is shown in cyan. Main chain of L46 is involved in H-bond interactions with side chain nitrogen of R62 and the side chain of L46 is involved in hydrophobic interactions with side chain of M64. (G) Composite omit map at residue 60. (H) Structural superposition of WT and S60E monomers, regions displaying deviation are indicated by ⋆. (I) Network of interactions at the 60th position in S60E. WT structure is shown in cyan. E60 is involved in salt bridge interactions with R48, H55 and R62. (J) Average B-factor plot of the residues in WT, S12G and S60E. Regions with large variability are indicated by "⋆".

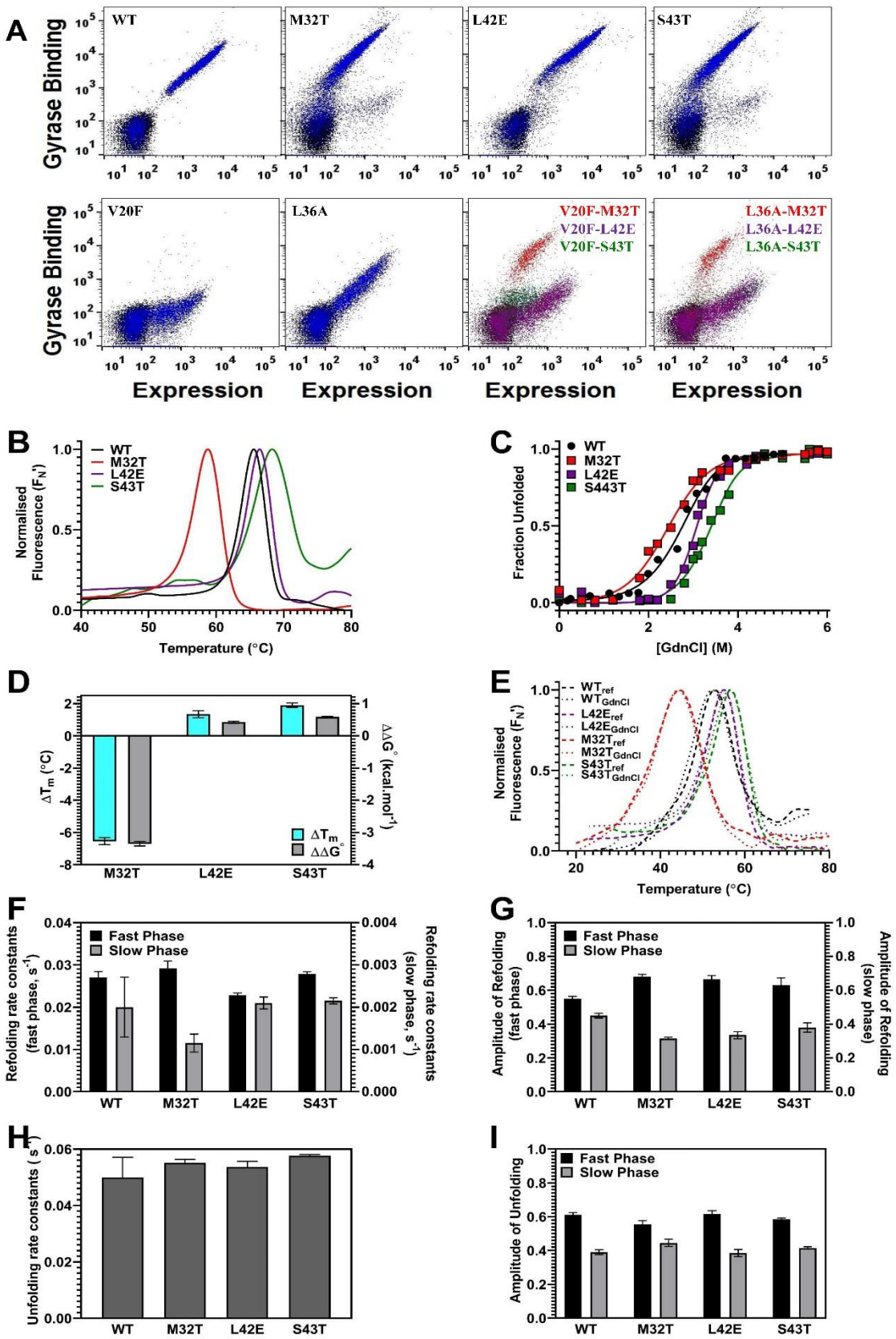


Figure 7. Enhanced stability is neither necessary not sufficient for a mutant to act as a global suppressor. (A) Analysis of yeast cell surface expression and GyrA14 binding of different CcdB

mutants and WT. CcdB WT and mutant plots (blue), are overlaid with plot of uninduced cells (black). In the last two panels, V20F-M32T, L36A-M32T plots (red) are overlaid with plots of V20F-L42E, L36A-L42E (purple) and V20F-S43T, L36A-S43T (green), only M32T is able to suppress the deleterious effects of the V20F and L36A mutations. (B-G) Kinetic and thermodynamic characterisation of L42E CcdB mutant. (B) Thermal unfolding profiles of 5 µM of CcdB-WT, M32T, L42E and S43T mutants carried out by nanoDSF. (C) Equilibrium GdnCl denaturation profiles of 5 µM of CcdB-WT, M32T, L42E and S43T mutants carried out by nanoDSF. (D) Difference (Mutant-WT) in thermal ΔT_m (in cyan), and thermodynamic stability assayed by chemical denaturation, $\Delta\Delta G^{\circ}$ (in grey) of the CcdB mutants. (E) Thermal unfolding profiles of 5 µM of native proteins in 1.5 M GdnCl (dotted lines) and refolded CcdB proteins in the same concentration of GdnCl (dashed lines). (F-G) The observed rate constants and amplitudes of the fast phase (black) and slow phase (grey) of refolding (1.5 M GdnCl) of WT and CcdB mutants (see also Supplementary Table S9). (H-I) The observed rate constants and amplitudes of unfolding (3.5 M GdnCl) of WT and CcdB mutants. The error bars wherever shown represent the standard deviation from two independent experiments, each performed in duplicates.

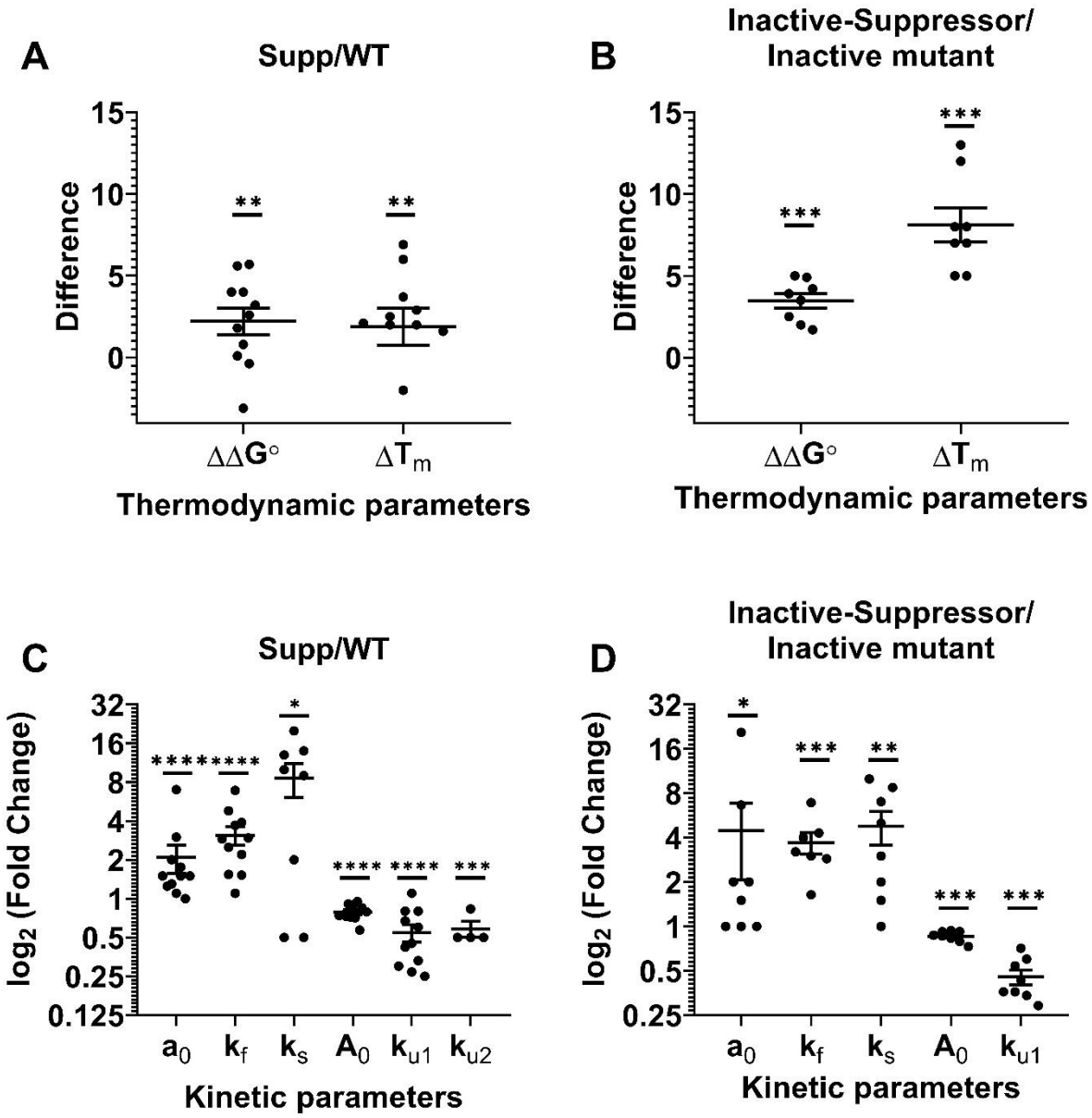
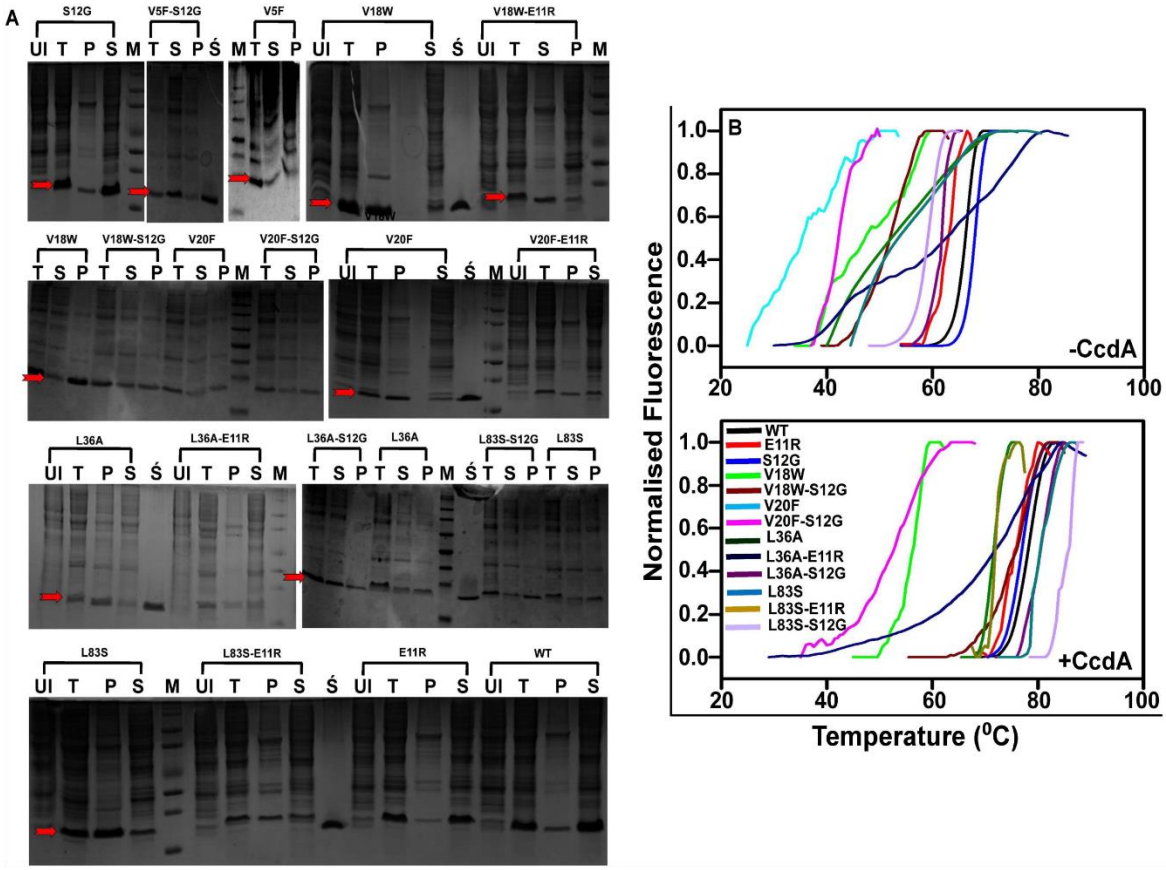
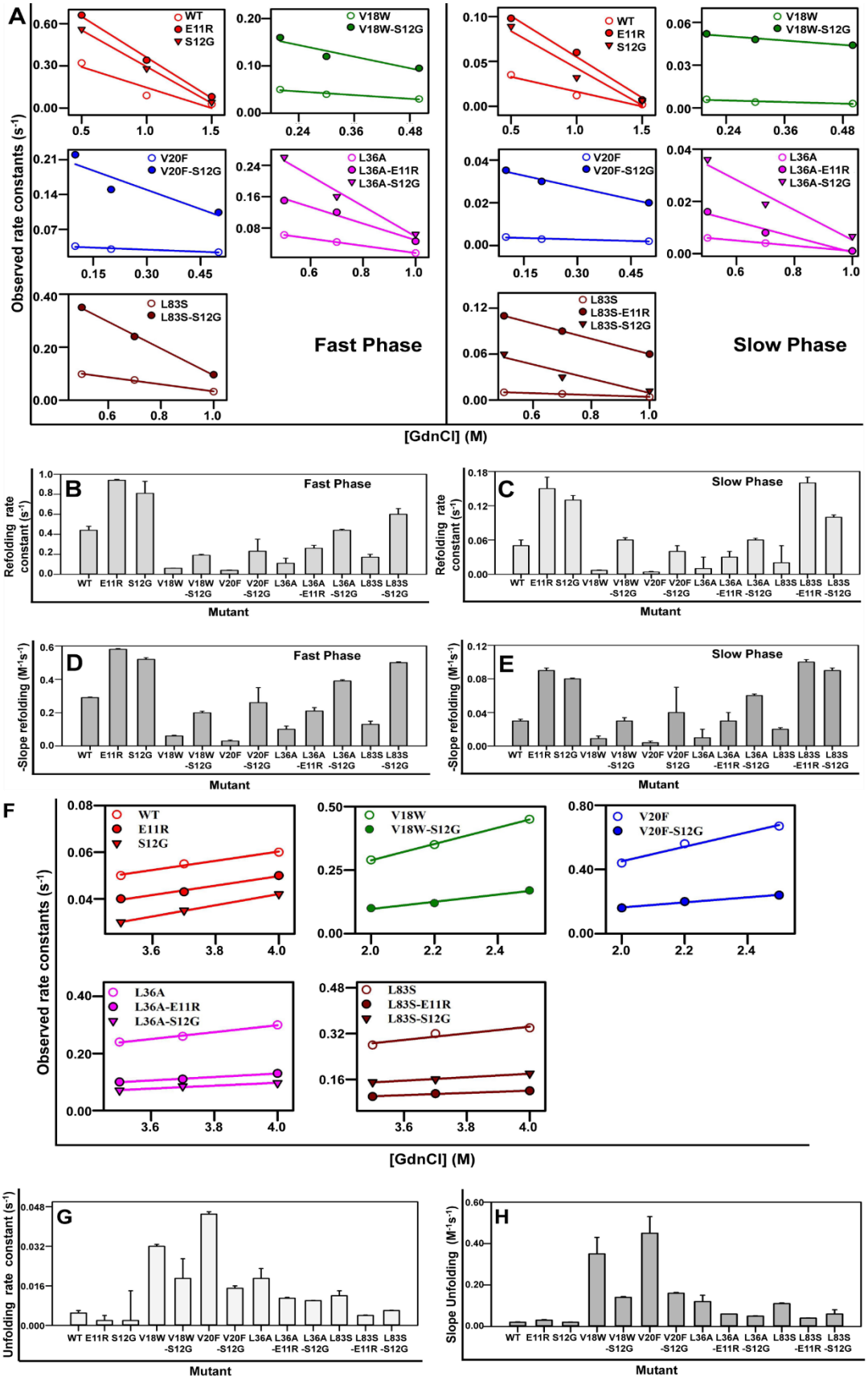


Figure 8. Mechanism of action of suppressor mutations. (A-B) Distribution of ΔT_m and $\Delta\Delta G°$ (Mean±SEM) for the suppressor mutations in the background of WT (A) or inactive mutant (B). Mann Whitney non-parametric test was performed for each of these parameters to examine if they are significantly different from zero. (C-D) Log_2 fold change of various parameters (Mean±SEM) for the suppressor mutations in the background of WT (A) or inactive mutant (B). Mann Whitney non-parametric test was performed for each of these parameters. The mean of the distributions of the values for each of the parameters are significantly higher than $log_2(2)$ for refolding, and lower than $log_2(2)$ for unfolding. P value indicated with *, ** and *** indicates < 0.05, < 0.005 and < 0.0005 respectively.

Supplementary Figures and Tables

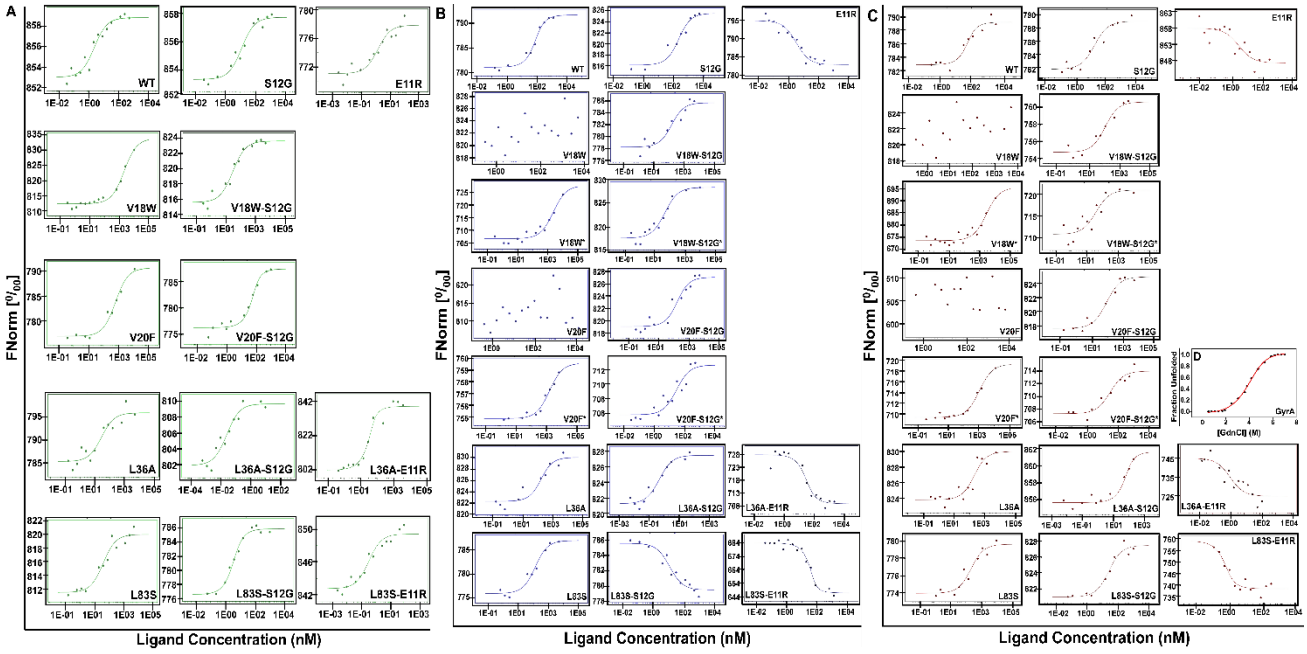


Supplementary Figure S1. Enhancement of solubility and stability by the suppressors (related to Figure 1). (A-B) Solubility and thermal stabilities of CcdB mutants, in presence and absence of the suppressors. (A) *In vivo* solubility estimates for CcdB mutants. UI, T, S and P are uninduced, total cell lysate, supernatant and pellet respectively. Ś is the purified CcdB WT protein used as standard and M is the molecular weight marker lane. The relative estimates of protein present in the soluble fraction and inclusion bodies for all mutants are shown in Supplementary Table S1. The red arrow indicates the band for the induced protein. (B) Thermal unfolding profile of purified WT CcdB and CcdB mutants in the absence and presence of 8 µM CcdA peptide (45-72) measured by a thermal shift assay (TSA). L83S-E11R and V20F are omitted in the top and bottom panels as they do not show clear thermal transitions in the absence and presence of CcdA respectively.

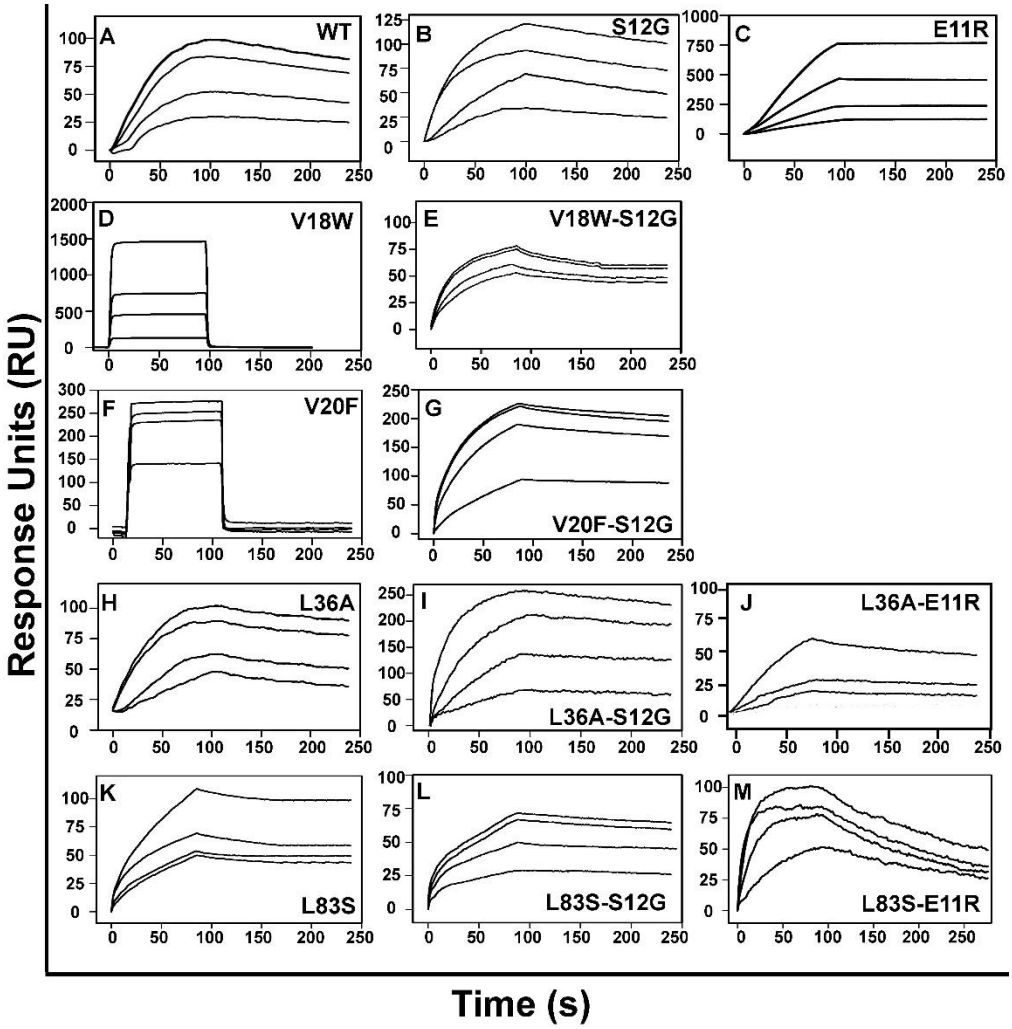


Supplementary Figure S2. Denaturant-dependent refolding and unfolding kinetics of CcdB mutant proteins (related to Figure 2). (A-E) Representative refolding rate constants of fast phase

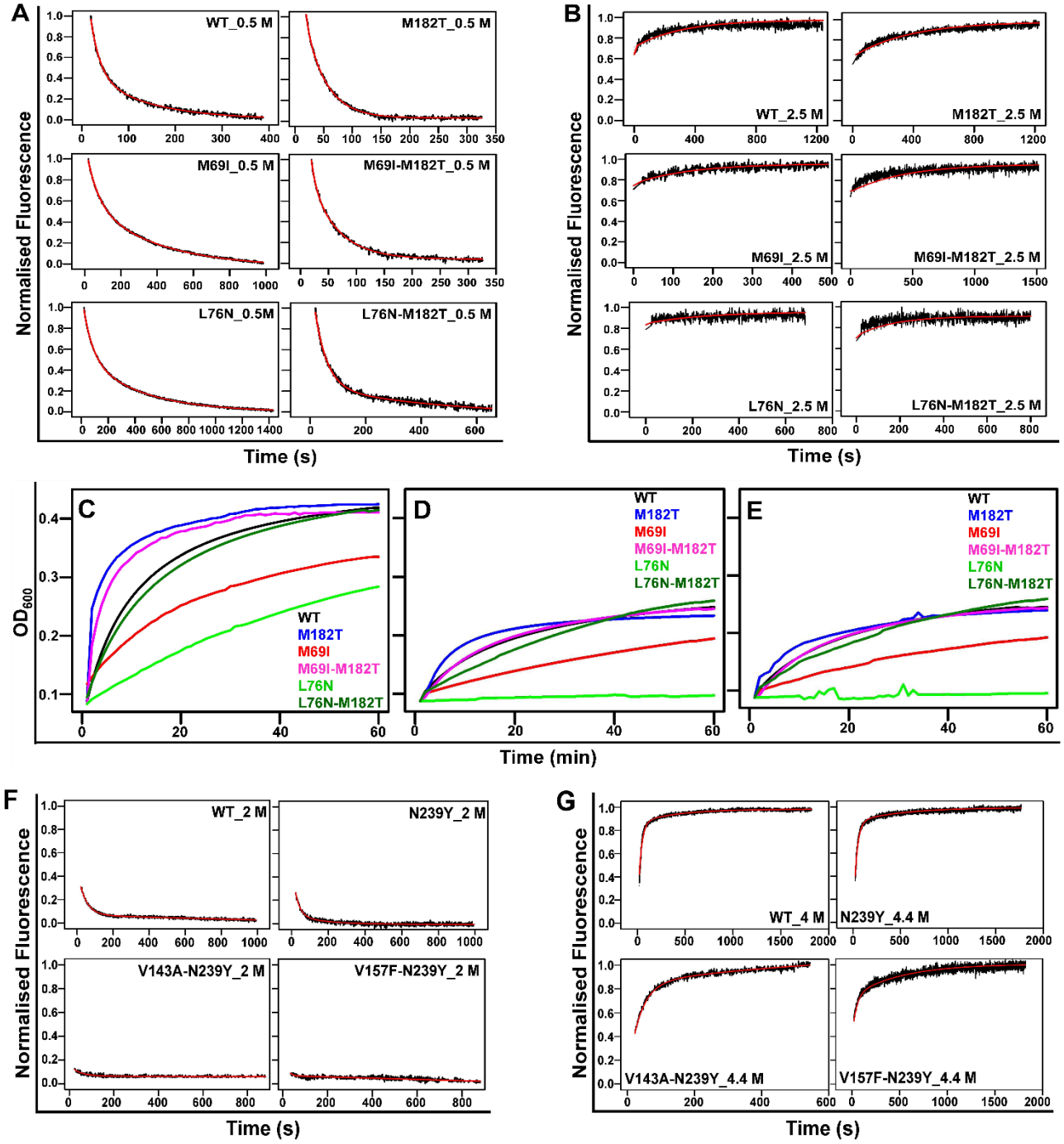
(left side) and slow phase (right panel) and (F-H) unfolding rate constants at 5 μM protein concentration of the WT and mutants are shown. The experimental rate constants (for refolding and unfolding) obtained at increasing final GdnCl concentrations are shown in dots, while fits are shown in solid lines. For refolding kinetics, the extrapolated rate constants and the magnitude of refolding m-values of the transition states at zero denaturant concentration of fast phase (B and D respectively) and slow phase (C and E respectively) are shown. Suppressor mutations significantly accelerate the refolding rate constants. For unfolding kinetics, the extrapolated rate constants (G) and the magnitude of unfolding m-values (H) at zero denaturant concentration are shown. Suppressor mutations decrease the unfolding rate constants. The error bars wherever shown represent the standard deviation from two independent experiments, each performed in duplicates (see also Supplementary Table S3).



Supplementary Figure S3. Interaction of native, native in the presence of GdnCl and refolded CcdB WT and mutant proteins with labeled GyrA14 analyzed by MicroScale Thermophoresis (related to Figure 2). GyrA14 was labeled and used at a concentration of 70 nM and titrated with different concentrations of native (A), native in the presence of GdnCl (B) and refolded (C) WT and CcdB mutants. All studies were carried out in 200 mM HEPES, pH 8.4, at 27 °C. The normalised fluorescence FNorm [$^0/_{00}$] is plotted as a function of [CcdB]. For each capillary (each measuring point), an MST trace is recorded. All traces are then normalised to start at 1000. For each trace, the FNorm value for the dose- response curve is calculated from Fhot (MST laser on)/Fcold (MST laser off). The dissociation constants (K_D) listed in Supplementary Table S1, were determined employing standard data analysis with MO.Affinity Analysis Software (1). (D) Equilibrium GdnCl denaturation profile of 5 µM of GyrA14 carried out in 1X PBS, pH 7.5 at 25 °C using nanoDSF. The experimental data is shown in black dots, while the fit is shown in a red line. The C_m of GyrA14 is 4.48 M thus proving it to be stable and folded in the MST studies carried out in the presence of 1.5 M GdnCl.

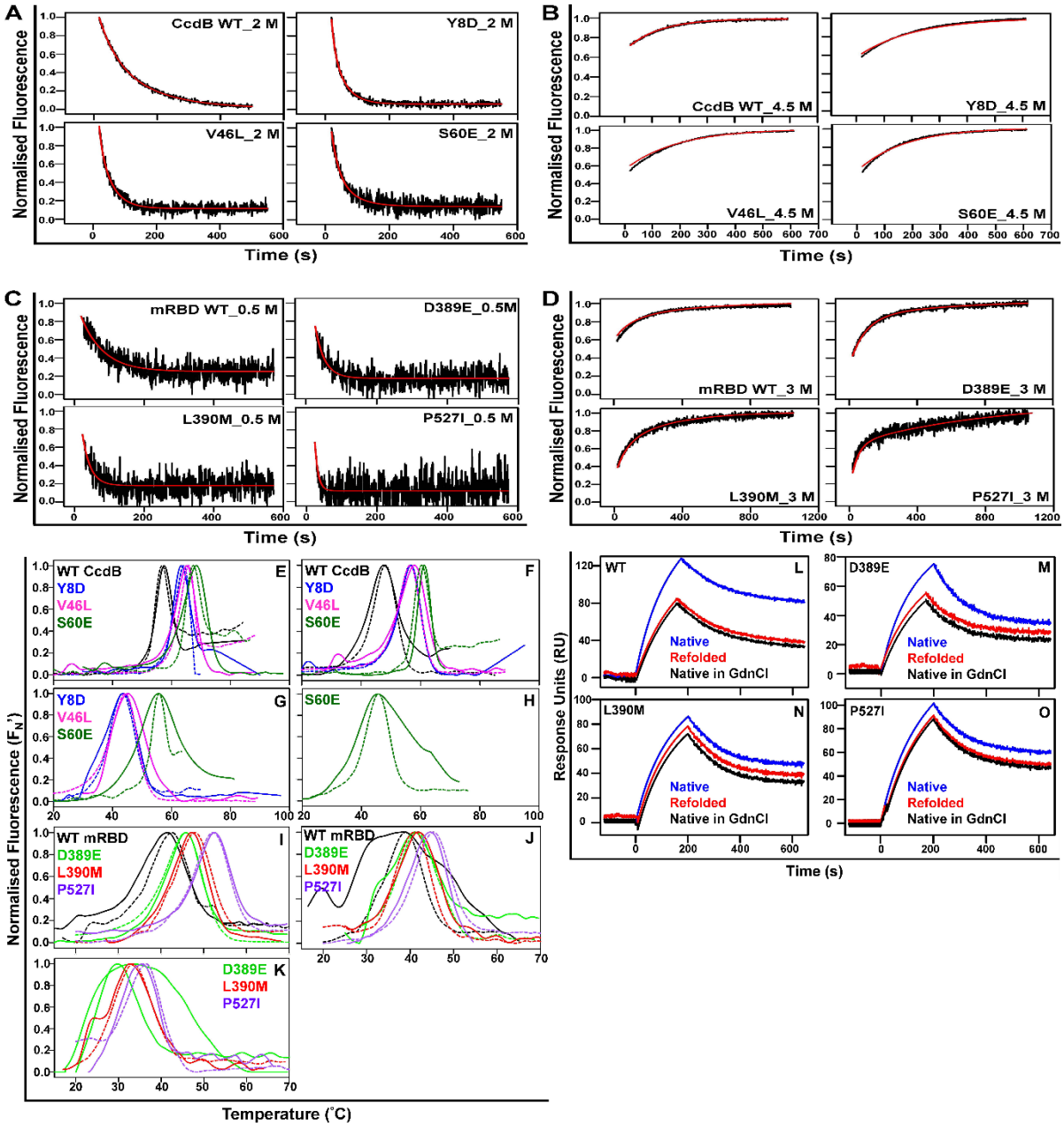


Supplementary Figure S4. Binding of GyrA14 to CcdB proteins (related to Figure 2). Overlays show the binding kinetics with analyte concentration increasing from the bottom to the top curve in all cases of (A) WT CcdB (3, 6, 12.5, 25 nM); (B) S12G (3, 6, 25, 50 nM); (C) E11R (50, 100, 200, 500 nM); (D) V18W (200, 500, 1000, 2000 nM); (E) V18W-S12G (200, 500, 1000, 2000 nM); (F) V20F (200, 1000, 2000, 5000 nM); (G) V20F-S12G (100, 200, 500, 1000 nM) ; (H) L36A (12.5, 25, 100, 200 nM); (I) L36A-S12G (3, 6, 12.5, 25 nM); (J) L36A-E11R (10, 21.4, 32, 64.2 nM); (K) L83S (200, 500, 1000, 2000 nM); (L) L83S-S12G (200, 500, 1000, 2000 nM); (M) L83S-E11R (50, 100, 200, 500 nM). The ligand GyrA14 was immobilized on the CM5 chip by standard amine coupling. Binding was measured by passing varying concentrations of the analyte (CcdB proteins) over the ligand (GyrA14) immobilised chip and the data was fitted to the 1:1 Langmuir Interaction model to obtain the kinetic parameters (Supplementary Table S1).



Supplementary Figure S5. Refolding and unfolding kinetics, and hydrolysis activities of TEM-1 β-lactamase mutant proteins (related to Figure 3) as well as refolding and unfolding kinetics of p53-DBD mutant proteins (related to Figure 4). (A) TEM-1 proteins exhibit biphasic refolding kinetics with a fast and slow phase whereas (B) unfolding follows single exponential kinetics. Representative kinetic traces at 5 μM protein concentrations of WT and TEM-1 mutants are shown in presence of 0.5 M GdnCl for refolding and 2.5 M GdnCl for unfolding. The experimental kinetic traces

obtained at the indicated GdnCl concentration are shown in black, while the fits are shown in red**.** The measured kinetic parameters are listed in Supplementary Table S6. The lactamase activities of the WT and mutants in the following conditions – (C) native, (D) native proteins in 0.5 M GdnCl and (E) refolded proteins in 0.5 M GdnCl, were assayed by observing the rate of nitrocefin hydrolysis (50 μM) at 486 nm at 25 °C at a protein concentration of 10 nM. The M182T suppressor rescues the activity of M69I and L76N mutants. (F) p53-DBD proteins exhibit biphasic refolding kinetics with a significant burst, fast and slow phase whereas (G) unfolding of p53-DBD follows biphasic exponential kinetics with fast and slow phases. Representative kinetic traces at 5 μM protein concentration of WT and p53-DBD mutants are shown in the presence of 2 M Urea for refolding and 4.4 M Urea for unfolding. The experimental kinetic traces obtained are shown in black, while the fits are shown in red**.** The measured kinetic parameters are listed in Supplementary Table S7.



Supplementary Figure S6. Refolding and unfolding kinetics, and thermal denaturation studies of stabilised CcdB and mRBD proteins with suppressor mutations; binding studies of the mRBD proteins to ACE2-hFc neutralizing antibody (related to Figure 5). (A) Biphasic refolding kinetics with a fast and slow phase and (B) single exponential unfolding kinetics of CcdB mutant proteins. Representative kinetic traces at 5 μM protein concentration of WT CcdB; Y8D; V46; S60E are shown. (C) mRBD proteins exhibit single phase refolding kinetics with a significant burst phase whereas (D) unfolding of mRBD proteins follows biphasic exponential kinetics with burst, fast and slow phases. Representative kinetic traces at 5 μM protein concentration of WT mRBD; D389E; L390M; P527I are

shown. The experimental kinetic traces obtained at different GdnCl concentrations are shown in black, while the fits are shown in red**.** The measured kinetic parameters are listed in Tables S9 for CcdB and mRBD mutants.

(E-H) Thermal denaturation traces of 5 µM of native CcdB proteins in (E) 1 M, (F) 2 M, (G) 3 M and (H) 4 M GdnCl (represented by dashed lines) and refolded CcdB proteins in the same concentrations of GdnCl (represented by solid lines). WT CcdB failed to show any transition at 3 M, whereas Y8D and V46L failed to show a thermal unfolding transition at 4 M. S60E showed a thermal transition at 4 M. (I-K) Thermal denaturation traces of 5 µM of native mRBD proteins in (I) 0.5 M, (J) 1 M and (K) 2 M (represented by dashed lines) and refolded mRBD proteins in same concentrations of GdnCl (represented by solid lines). mRBD WT failed to show any transition at 2 M, whereas the stabilised mutants show thermal unfolding upto 2M GdnCl. (L-O) Overlays show the ACE2-hFc binding of the WT and mRBD mutants in the following conditions – native, native in 0.5 M GdnCl and refolded in 0.5 M GdnCl for (L) WT mRBD, (M) D389E, (N) L390M and (O) P27I. The ligand ACE2-hFc was immobilized on Protein-G immobilised GLM sensor chip. Binding was measured by passing 50 nM of the analyte (mRBD proteins) over the ligand (ACE2-hFc) immobilised chip.

Supplementary Table S1 (Related to Figure 1 and 2). Fractional solubilities, thermal stabilities (determined by nanoDSF) and GyrA14 binding affinities (determined by SPR and MST) of different CcdB mutants[1]. Binding affinities of refolded proteins and proteins in GdnCl were also measured by MST. SPR experiments were carried out at 25 °C, pH 7.4 and MST experiments were carried out at 25 °C, pH 8.4.

Mutants	Fraction Soluble	T_m (°C)	K_D (nM) SPR	MST Studies		
				K_D (nM) Native	K_D (nM) Native in GdnCl	K_D (nM) Refolded
WT	1.0	66±0.8	1.4±0.6	2.2±0.6	41.8±3.2	32.2±2.7
E11R	0.9	64±1.0	2.5±0.3	1.2±0.3	3.2±0.3	2.4±0.4
S12G	0.9	68±0.8	2.6±1.4	2.3±0.8	74.5±10	99±15
V18W	0.2	54±09	NB	2046.9±132	2241.8[3]±168	2577.4[a]±196
V18W-E11R[2]	0.6	-	-	-	-	-
V18W-S12G	0.6	66±0.9	57±13.2	30.2±4	132.2±12	149.3±16
V20F	0.3	47±0.8	NB	623.5±92	1465.1[4]±117	1078.0[b]±102
V20F-E11R[2]	0.5	-	-	-	-	-
V20F-S12G	0.4	60±0.8	12.7±4	20.9±12	130.9±48	103.6±29
L36A	0.3	58±1.0	9.5±4	17.5±7	125.2±30	162.0±54
L36A-E11R	0.6	63±1.0	3.0±1.3	13±1.3	16.0 ±1.3	1.3±1.0
L36A-S12G	0.7	63±0.2	0.4±0.7	0.3±1.4	1.5±0.6	2.3±2
L83S	0.4	59±0.8	75.0±15.3	88.7±19	175.3±63	199.4±45
L83S-E11R	0.5	67±0.5	6.8±2.9	0.30±0.1	16±2.9	0.4±0.1
L83S-S12G	0.5	66±0.7	7.2±11.3	4.12±2.3	11.9±9.4	13±7.2

[1]Reported standard errors are derived from two independent experiments, each performed in duplicates.

[2]Mutants could not be purified.

[3,4] Refolded in 0.1 M GdnCl. All the other proteins were refolded in 1.5 M GdnCl.

NB: No Binding.

Supplementary Table S2 (Related to Figure 2). Kinetic Parameters for refolding and unfolding of CcdB mutants measured under different buffer conditions at 25 °C, pH 8.4[1].

Mutant	[GdnCl] (Refold/ Unfold) (M)	Refolding					Unfolding		
		Fast Phase			Slow Phase		A0	A1	ku_1 (s^{-1})
		a0	a1	kf_1 (s^{-1})	a2	kf_2 (s^{-1})			
WT	**(1.5/3.5)**	0.02± 0.02	0.55± 0.03	0.027 ±0.02	0.43± 0.03	0.002± 0.001	0.60± 0.03	0.40± 0.01	0.05± 0.05
E11R	**(1.5/3.5)**	0.14± 0.03	0.44± 0.08	0.080 ±0.01	0.42± 0.04	0.02± 0.0066	0.51± 0.04	0.49± 0.04	0.04± 0.08
S12G	**(1.5/3.5)**	0.03± 0.03	0.79± 0.02	0.041 ±0.05	0.18± 0.02	0.001± 0.003	0.44± 0.02	0.56± 0.03	0.03± 0.03
V18W	**(0.5/2.0)**	0.03± 0.06	0.52± 0.03	0.030 ±0.03	0.45± 0.06	0.003± 0.01	0.63± 0.09	0.37± 0.09	0.29± 0.03
V18W-S12G	**(0.5/2.0)**	0.20± 0.01	0.40± 0.08	0.095 ±0.13	0.40± 0.06	0.015± 0.044	0.46± 0.03	0.54± 0.03	0.10± 0.05
V20F	**(0.5/2.0)**	0.02± 0.05	0.71± 0.06	0.024 ±0.01	0.27± 0.06	0.002± 0.07	0.76± 0.01	0.24± 0.01	0.44± 0.08
V20F-S12G	**(0.5/2.0)**	0.02± 0.07	0.67± 0.15	0.104 ±0.09	0.31± 0.08	0.02± 0.002	0.66± 0.04	0.34± 0.03	0.16± 0.04
L36A	**(1.0/3.5)**	0.05± 0.09	0.55± 0.04	0.016 ±0.08	0.40± 0.08	0.001± 0.001	0.77± 0.08	0.27± 0.09	0.24± 0.02
L36A-E11R	**(1.0/3.5)**	0.10± 0.02	0.53± 0.03	0.046 ±0.02	0.36± 0.03	0.001± 0.001	0.61± 0.01	0.39± 0.01	0.17± 0.08
L36A-S12G	**(1.0/3.5)**	0.10± 0.01	0.54± 0.07	0.064 ±0.01	0.34± 0.05	0.007± 0.0066	0.64± 0.02	0.36± 0.02	0.07± 0.03
L83S	**(1.0/3.5)**	0.03± 0.01	0.62± 0.01	0.032 ±0.05	0.35± 0.02	0.004± 0.006	0.77± 0.03	0.23± 0.03	0.28± 0.09
L83S-E11R	**(1.0/3.5)**	0.62±0. 04	-	-	0.38± 0.04	0.035± 0.001	0.72± 0.01	0.28± 0.02	0.10± 0.03
L83S-S12G	**(1.0/3.5)**	0.02± 0.07	0.62± 0.02	0.096 ±0.08	0.36± 0.01	0.012± 0.01	0.71± 0.06	0.29± 0.06	0.15± 0.08

[1]Reported standard errors are derived from two independent experiments, each performed in duplicates.

Supplementary Table S3 (Related to Figure 2). Relative Kinetic Parameters for *in vitro* Refolding and Unfolding of CcdB mutants extrapolated to zero denaturant[1].

Mutants	Refolding				Unfolding	
	Fast Phase		Slow Phase			
	$m_{kinetic\ fast}$ value ($M^{-1}s^{-1}$)	rate constant[2] (s^{-1})	$m_{kinetic\ slow}$ value ($M^{-1}s^{-1}$)	rate constant[2] (s^{-1})	$m_{kinetic\ (U)}$ value ($M^{-1}s^{-1}$)	rate constant[2] (s^{-1})
WT	0.29±0.004	0.44±0.04	0.03±0.002	0.05±0.01	0.02±0.002	0.005±0.01
E11R	0.58±0.005	0.94±0.009	0.09±0.003	0.15±0.02	0.02±0.003	0.002±0.02
S12G	0.52±0.010	0.81±0.12	0.08±0.001	0.13±0.008	0.02±0.001	0.002±0.008
V18W	0.06±0.005	0.06±0.001	9e-3±0.003	7e-3±0.001	0.35±0.08	0.032±0.08
V18W-S12G	0.20±0.009	0.19±0.01	0.03±0.004	0.06±0.004	0.14±0.004	0.019±0.004
V20F	0.03±0.006	0.04±0.004	4e-3±0.002	4e-3±0.001	0.45±0.08	0.045±0.01
V20F-S12G	0.26±0.09	0.23±0.12	0.04±0.03	0.04±0.01	0.16±0.004	0.015±0.01
L36A	0.10±0.02	0.11±0.05	0.01±0.01	0.01±0.02	0.12±0.03	0.019±0.04
L36A-E11R	0.21±0.02	0.26±0.03	0.03±0.01	0.03±0.01	0.06±0.0001	0.011±0.003
L36A-S12G	0.39±0.007	0.44±0.01	0.06±0.002	0.06±0.04	0.05±0.001	0.010±0.001
L83S	0.13±0.02	0.17±0.03	0.02±0.002	0.02±0.003	0.11±0.003	0.012±0.02
L83S-E11R	-[3]	-[3]	0.10±0.003	0.16±0.01	0.04±0.0008	0.004±2e-3
L83S-S12G	0.50±0.005	0.60±0.057	0.09±0.003	0.10±0.004	0.06±0.02	0.006±0.001

[1]Reported standard errors are derived from two independent experiments, each performed in duplicates.

[2]Reported rate constants are extrapolated to 0 M GdnCl for relative comparison among different mutants.

[3] Fast phase of refolding couldn't be captured.

Supplementary Table S4 (Related to Figure 2). Thermodynamic stability parameters (C_m, ΔG^0, m_{equi}), following chemical denaturation and melting temperatures of refolded and native proteins in presence of 1.5 M GdnCl ($T_{mRefold}$, T_{mGdnCl}) determined by nanoDSF, of different CcdB mutants[1]. Residual activity after high temperature incubation of CcdB mutants was determined by SPR at room temperature.

Mutants	**C_m (M)**	**ΔG^0 (kcal.mol^{-1})**	**m_{equi} (kcal.mol^{-1}M^{-1})**	**$T_{mRefold}$ (°C)**	**T_{mGdnCl} (°C)**	**Residual activity (%)**	
						40 °C	**80 °C**
WT	2.8±0.1	21.1±0.7	4.97±0.5	53±0.5	52±0.8	24	0.8
E11R	2.3±0.2	18.0±1.8	4.55±0.5	55±0.4	55±0.5	1.2	0.6
S12G	3.0±0.3	21.9±1.4	4.90±0.2	55±0.9	55±1.4	61	3.7
V18W	0.8±0.7	11.0±1.8	4.00±1.2	[2]	[2]	-	-
V18W-S12G	1.3±0.09	13.5±0.8	4.87±0.2	45±0.4	43±0.9	-	-
V20F	0.3±0.02	8.6±1.8	4.06±0.2	[3]	[3]	-	-
V20F-S12G	1.0±0.4	12.1±1.4	4.88±0.2	43±1.2	43±0.6	-	-
L36A	1.5±0.4	13.9±0.3	4.45±1.4	45±1.4	46±0.9	11.7	0.4
L36A-E11R	2.4±0.4	18.9±1.2	4.50±0.5	51±0.8	51±0.4	34	2.4
L36A-S12G	2.4±0.3	18.8±0.9	4.82±0.7	52±1.2	51±0.6	47.6	9.1
L83S	1.6±0.1	14.4±1.7	4.43±0.8	43±0.2	41±1.8	-	-
L83S-E11R	2.1±0.2	18.3±3.2	4.73±0.5	54±0.1	53±0.6	-	-
L83S-S12G	2.3±0.9	18.6±1.3	4.70±0.9	55±0.9	55±0.6	-	-

[1]Reported standard errors are derived from two independent experiments, each performed in duplicates.

[2,3] Could not be refolded in 1.5 M GdnCl. All the other proteins were refolded in 1.5 M GdnCl.

-Not determined.

Supplementary Table S5 (Related to Figure 3). Top: MIC and IC_{90} for ampicillin and cefotaxime from OD_{600} and plate data measurements, thermodynamic stability parameters (C_m, ΔG^0, m_{equi}), apparent thermal stability (T_m), thermal stabilities of refolded proteins and native proteins in presence of 0.5 M GdnCl ($T_{mRefold}$, T_{mGdnCl}), of different TEM-1 β-lactamase mutants[1]. **Bottom:** Kinetic Parameters for refolding and unfolding of TEM-1 β-lactamase mutants measured in 0.5 M and 2.5 M GdnCl respectively carried out in 10 mM HEPES, 300 mM NaCl, 10% glycerol, pH 7.0, at 25 °C[1].

Mutants	**Ampicillin (µg/mL)**		**Cefotaxime (µg/mL)**		**C_m (M)**	**ΔG^0 (kcal.mol^{-1})**	**m_{equi} (kcal.mol^{-1}M^{-1})**	**T_m (°C)**	**$T_{mRefold}$ (°C)**	**T_{mGdnCl}, (°C)**
	MIC	**IC_{90}**	**MIC**	**IC_{90}**						
WT	≈3000	4000	16	10	1.2±0.1	2.9±0.5	2.4±0.1	51±0.2	41±0.4	41±0.2
M182T	≈3000	4000	16	15	1.9±0.3	4.7±0.6	3.1±0.3	57±0.1	47±0.3	48±0.5
M69I	≈800	1000	8	6	0.6±0.1	2.0±0.2	2.1±0.2	47±0.3	31±0.1	32±0.4
M69I-M182T	≈800	1000	8	6	1.4±0.2	4.0±0.3	2.8±0.1	54±0.2	44±0.2	44±0.3
L76N	≈50	20	2	<1	0.5±0.1	1.1±0.1	1.8±0.2	40±0.5	NT	NT
L76N-M182T	≈1500	1500	4	4	1.1±0.2	2.8±0.3	2.3±0.4	48±0.3	39±0.1	39±0.5

Mutants	**Refolding**					**Unfolding**		
	Fast Phase			**Slow Phase**		**A0**	**A1**	**ku_1 (s^{-1})**
	a0	**a1**	**kf_1 (s^{-1})**	**a2**	**kf_2 (s^{-1})**			
WT	0.01±0.02	0.51±0.03	0.049±0.01	0.48±0.03	0.004±0.001	0.65±0.03	0.35±0.01	0.03±0.003
M182T	0.03±0.03	0.53±0.08	0.19±0.01	0.44±0.04	0.008±0.001	0.56±0.04	0.44±0.04	0.02±0.002
M69I	0.03±0.03	0.55±0.02	0.016±0.01	0.42±0.02	0.003±0.004	0.71±0.02	0.29±0.03	0.07±0.003
M69I-M182T	0.03±0.06	0.52±0.03	0.11±0.02	0.45±0.06	0.006±0.001	0.65±0.09	0.35±0.09	0.03±0.001
L76N	0.02±0.01	0.60±0.08	0.014±0.01	0.38±0.06	0.002±0.002	0.79±0.03	0.21±0.03	0.10±0.004
L76N-M182T	0.03±0.05	0.68±0.06	0.023±0.02	0.29±0.06	0.003±0.001	0.68±0.01	0.32±0.01	0.06±0.003

[1]Reported standard errors are derived from two independent experiments, each performed in duplicates.

NT- No Transition: Not refolded in 0.5 M GdnCl. All the other proteins were refolded in 0.5 M GdnCl.

Supplementary Table S6 (Related to Figure 4). Top: Fractional solubilities, thermodynamic stability parameters (C_m, ΔG^0, m_{equi}), apparent thermal stabilities (T_m), thermal stabilities of refolded and native proteins in the presence of 0.5 M Urea ($T_{mRefold,}$,$T_{m,urea}$) determined by nanoDSF, of different p53 mutants[1]. **Bottom:** Kinetic Parameters for refolding and unfolding of p53 mutants measured in 2 M and 4.4 M Urea respectively carried out in 50 mM NaH_2PO_4, 500 mM NaCl, 500 mM imidazole, 10 mM DTT, pH 7.2 at 15 °C[1].

Mutants	**Fraction soluble**	**C_m (M)**	**ΔG^0 (kcal.mol^{-1})**	**m_{equi} (kcal.mol^{-1}M^{-1})**	**T_m (°C)**	**$T_{m,refold}$ (°C)**	**$T_{m,urea}$ (°C)**
WT	0.4±0.05	2.8±0.02	2.5±0.1	0.9±0.01	30±0.1	29±0.1	29±0.1
N239Y	0.5±0.05	3.0±0.05	2.6±0.2	0.9±0.02	32±0.1	29±0.4	30±0.1
V143A	0.1±0.04	ND	ND	ND	ND	ND	ND
V143A-N239Y	0.3±0.02	3.1±0.1	2.7±0.1	0.9±0.002	31±0.1	29±0.1	27±0.1
V157F	0.1±0.05	ND	ND	ND	ND	ND	ND
V157F - N239Y	0.4±0.04	3.3±0.05	2.9±0.1	0.9±0.005	33±0.1	32±0.1	32±0.1

Mutants	**Refolding**					**Unfolding**				
	Fast Phase			**Slow Phase**						
	a0	**a1**	**kf_1 (s^{-1})**	**a2**	**kf_2 (s^{-1})**	**A0**	**A1**	**ku_1 (s^{-1})**	**A2**	**ku_2 (s^{-1})**
WT	0.68± 0.01	0.14± 0.0004	0.024 ±0.0003	0.18± 0.005	0.0003± 0.00001	0.35± 0.01	0.53± 0.01	0.046± 0.0005	0.12± 0.002	0.003± 0.00005
N239Y	0.73± 0.002	0.14± 0.0004	0.037 ±0.0003	0.13± 0.007	0.006± 0.005	0.32± 0.009	0.56± 0.009	0.037± 0.0006	0.12± 0.002	0.0025± 0.00007
V143A N239Y	0.86± 0.003	0.05± 0.0003	0.023 ±0.003	0.09± 0.005	0.003± 0.006	0.40± 0.01	0.37± 0.01	0.028± 0.001	0.23± 0.007	0.0017± 0.0005
V157F N239Y	0.87± 0.002	0.02± 0.001	0.083 ±0.04	0.11± 0.002	0.0004± 0.00001	0.49± 0.003	0.23± 0.003	0.023± 0.0015	0.28± 0.003	0.0019± 0.00006

[1]Reported standard errors are derived from two independent experiments, each performed in duplicates.
ND – Not determined as the corresponding proteins could not be purified.

Supplementary Table S7 (Related to Figure 5). Thermodynamic parameters (C_m, ΔG^0, m_{equi}), determined by nanoDSF, of CcdB mutants[1].

Mutants	C_m (M)	ΔG^0 (kcal.mol^{-1})	m_{equi} (kcal.mol^{-1}M^{-1})
CcdB WT	2.8±0.1	21.1±0.7	4.97±0.5
CcdB Y8D	3.1±0.3	22.7±1.2	5.00±0.1
CcdB V46L	3.2±0.3	23.2±1.4	5.01±0.3
CcdB S60E	3.5±0.5	24.8±1.1	5.03±0.2

[1]Reported standard errors are derived from two independent experiments, each performed in duplicates. WT values are taken from Supplementary Table S5.

Supplementary Table S8 (Related to Figure 5). Top: Kinetic Parameters for refolding and unfolding of stabilised CcdB mutants measured in 2 M and 4.5 M GdnCl respectively, carried out in 200 mM HEPES, pH 8.4 at 25 °C[1]. **Bottom:** Kinetic Parameters for refolding and unfolding of stabilised mRBD mutants in 0.5 M and 3 M GdnCl respectively, carried out in 1X PBS, pH 7.0 at 25 °C[1].

Mutants	Refolding (2 M)					Unfolding (4.5 M)		
	Fast Phase			Slow Phase		A0	A1	ku_1 (s^{-1})
	a0	a1	kf_1 (s^{-1})	a2	kf_2 (s^{-1})			
CcdB WT	0.03± 0.01	0.50± 0.02	0.020 ±0.01	0.47± 0.02	0.001± 0.001	0.73± 0.01	0.27± 0.02	0.060± 0.05
CcdB Y8D	0.01± 0.02	0.51± 0.03	0.06 ±0.01	0.48± 0.03	0.018± 0.001	0.58± 0.03	0.42± 0.01	0.027± 0.003
CcdB V46L	0.03± 0.03	0.53± 0.08	0.10 ±0.01	0.44± 0.04	0.026± 0.001	0.55± 0.04	0.45± 0.04	0.025± 0.002
CcdB S60E	0.03± 0.03	0.55± 0.02	0.13 ±0.01	0.42± 0.02	0.028± 0.004	0.52± 0.02	0.48± 0.03	0.020± 0.003

Mutants	Refolding (0.5 M)			Unfolding (3 M)				
				Fast Phase			Slow Phase	
	a0	a1	kf_1 (s^{-1})	A0	A1	ku_1 (s^{-1})	A2	ku_2 (s^{-1})
mRBD WT	0.20± 0.01	0.80± 0.02	0.015 ±0.003	0.58± 0.02	0.28± 0.03	0.051 ±0.002	0.14± 0.03	0.002± 0.0005
mRBD D389E	0.26± 0.03	0.74± 0.01	0.038 ±0.004	0.42± 0.03	0.48± 0.08	0.016 ±0.003	0.10± 0.04	0.001± 0.0006
mRBD L390M	0.25± 0.02	0.75± 0.03	0.044 ±0.002	0.43± 0.03	0.47± 0.08	0.014 ±0.001	0.12± 0.04	0.001± 0.001
mRBD P527I	0.35± 0.02	0.65± 0.01	0.103 ±0.01	0.33± 0.03	0.52± 0.02	0.013 ±0.002	0.15± 0.02	0.001± 0.0007

[1]Reported standard errors are derived from two independent experiments, each performed in duplicates.

Supplementary Table S9 (Related to Figure 7). Top: Thermodynamic parameters (C_m, ΔG^0, m_{equi}), apparent thermal stability (T_m), thermal stabilities of refolded and native proteins in presence of 1.5 M GdnCl ($T_{mRefold}$, T_{mGdnCl}). **Bottom:** Kinetic parameters for refolding and unfolding of CcdB WT M32T, L42E and S43T in 1.5 M and 3.5 M GdnCl respectively of CcdB WT and L42E carried out in 200 mM HEPES, pH 8.4 at 25 °C[1].

Mutants	**C_m (M)**	**ΔG^0 (kcal.mol^{-1})**	**m_{equi} (kcal.mol^{-1}M^{-1})**	**T_m (°C)**	**$T_{mRefold}$ (°C)**	**T_{mGdnCl} (°C)**
WT	2.8±0.1	21.1±0.7	4.97±0.5	66.0±0.8	53.0±0.5	52.0±0.8
M32T	2.4±0.2	18.2±0.5	4.59±0.2	58.9±0.3	44.5±0.2	44.3±0.1
L42E	3.1±0.1	21.5±0.03	4.60±0.3	67.4±0.2	54.9±0.1	55.1±0.1
S43T	3.2±0.2	21.7±0.2	4.51±0.4	68.2±0.1	56.6±0.3	56.3±0.1

Mutants	**Refolding**					**Unfolding**		
	Fast Phase			**Slow Phase**		**A0**	**A1**	**ku_1 (s^{-1})**
	a0	**a1**	**kf_1 (s^{-1})**	**a2**	**kf_2 (s^{-1})**			
WT	0.02± 0.02	0.55± 0.03	0.027 ±0.02	0.43± 0.03	0.002± 0.001	0.60 ± 0.03	0.40 ± 0.01	0.050± 0.05
M32T	0.04± 0.02	0.68± 0.02	0.029 ±0.01	0.28± 0.01	0.001± 0.0005	0.57 ± 0.01	0.43 ± 0.02	0.055± 0.01
L42E	0.03± 0.001	0.67± 0.01	0.023 ±0.01	0.33± 0.01	0.002± 0.001	0.63 ± 0.02	0.37 ±0.01	0.054± 0.001
S43T	0.02± 0.01	0.63± 0.02	0.028 ±0.02	0.35± 0.03	0.002± 0.001	0.59 ± 0.02	0.41 ± 0.02	0.058± 0.05

[1]Reported standard errors are derived from two independent experiments, each performed in duplicates. WT values of thermodynamic parameters are taken from Supplementary Table S5 and kinetic parameters are taken from Supplementary Table S2.

Supplementary Table S10 (Related to Figure 6). Data collection and refinement statistics for CcdB mutants.

Data collection	**S12G**	**V46L**	**S60E**
Space group	I2	C2	C2
a, b, c (Å)	35.57, 36.53, 67.53	75.10, 36.76, 35.91	74.81, 36.64, 35.67
α, β, γ (°)	90, 93.69, 90	90, 115.19, 90	90, 114.97, 90
Wavelength (Å)	1.5418	1.0358	1.5418
Resolution range (Å)	33.69 – 1.63 (1.72 – 1.63)	33.98-1.35 (1.43-1.35)	10.00-1.93 (2.03-1.93)
Total No. of reflections	48336 (6679)	114256 (14182)	22462 (2937)
No. of unique reflections	9822 (1360)	19433 (2799)	6557 (890)
Multiplicity	4.9 (4.9)	5.9 (5.1)	3.4 (3.3)
Completeness (%)	90.6 (86.9)	100 (100)	97.5 (91.6)
⟨I/σ(I)⟩	9.8 (4.8)	11.6 (3.7)	9.6 (3.8)
Wilson B factor (Å^2)	11.66	5.78	8.6
$R_{p.i.m.}$	0.041 (0.097)	0.043 (0.141)	0.081 (0.268)
R_{merge}	0.083 (0.195)	0.098 (0.288)	0.130 (0.424)
R_{meas}	0.093 (0.218)	0.108 (0.322)	0.154 (0.504)
CC1/2	0.995 (0.967)	0.994 (0.928)	0.99 (0.801)
Refinement			
R_{work} (%)	22.8	16.2	17.0
R_{free} (%)	26.9	18.4	21.4
RMSD			
Bond (Å)	0.0072	0.0138	0.0051
Angle (°)	1.4844	1.9222	1.3247
Ramachandran plot			
Ramachandran favoured (%)	98	100.0	99
Ramachandran allowed (%)	2	0	1
Ramachandran outliers (%)	0	0	0
Average B factor (Å^2)			
Overall	18.85	11.19	11.37
Protein	18.05	9.13	10.57
Solvent	25.77	21.25	18.08
Other	17.70	8.71	11.53
Total no of atoms			
Protein atoms	816	814	820
Solvent	95	167	98
Other	2 Cl^-	2 Cl^-	2 Cl^-
Z	1	1	1

* : values within brackets are for highest resolution shell.

Supplementary Table S11 (Related to Figure 8). Average fold change of various parameters (Mean±SEM) by the suppressor mutations.

Ratio	Refolding kinetic parameter ratio			Unfolding kinetic parameter ratio		
	Fast		Slow	Fast		Slow
	a_0	k_f	k_s	A_0	k_{u1}	k_{u2}
WT/ Suppressor	2.1±0.6	3.3±0.5	9.8±2.6	0.77±0.03	0.5±0.07	0.6±0.08
PIM/ PIM-Suppressor	4.5±2.4	3.7±0.6	4.8±1.2	0.86±0.03	0.45±0.05	-

SI References

1. C. J. Wienken, P. Baaske, U. Rothbauer, D. Braun, S. Duhr, Protein-binding assays in biological liquids using microscale thermophoresis. *Nat. Commun.* **1**, 1–7 (2010).