$SCF^{\beta TrCP}$ mediates stress-activated MAPK-induced Cdc25B degradation

Sanae Uchida[1], Nobumoto Watanabe[2], Yasusei Kudo[3], Katsuji Yoshioka[4], Tsukasa Matsunaga[5], Yukihito Ishizaka[6], Hitoshi Nakagama[7], Randy Y. C. Poon[8] and Katsumi Yamashita[5,*]

[1]Venture Business Laboratory, Center for Innovation, Kanazawa University, Kakuma, Kanazawa 920-1192, Ishikawa, Japan
[2]Chemical Library Validation Team, Chemical Biology Core Facility, Chemical Biology Department, RIKEN ASI, Wako 351-0198, Saitama, Japan
[3]Department of Oral Maxillofacial Pathobiology, Division of Frontier Medical Science, Graduate School of Medical Sciences, Hiroshima University, Hiroshima 734-8553, Japan
[4]Division of Molecular Cell Signaling, Cancer Research Institute, Kanazawa University, Kakuma, Kanazawa 920-1192, Ishikawa, Japan
[5]Division of Pharmaceutical Sciences, Institute of Medical, Pharmaceutical and Health Sciences, Kanazawa University, Kakuma, Kanazawa 920-1192, Ishikawa, Japan
[6]Division of Intractable Diseases, Research Institute, National Center for Global Health and Medicine, Tokyo 162-8655, Japan
[7]Early Oncogenesis Research Project, National Cancer Center Research Institute, Tokyo 104-0045, Japan
[8]Division of Life Science, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong
*Author for correspondence (katsumi@kenroku.kanazawa-u.ac.jp)

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Summary

Cdc25A, which is one of the three mammalian CDK-activating Cdc25 protein phosphatases (Cdc25A, B and C), is degraded through $SCF^{\beta TrCP}$-mediated ubiquitylation following genomic insult; however, the regulation of the stability of the other two Cdc25 proteins is not well understood. Previously, we showed that Cdc25B is primarily degraded by cellular stresses that activate stress-activated MAPKs, such as Jun NH_2-terminal kinase (JNK) and p38. Here, we report that Cdc25B was ubiquitylated by $SCF^{\beta TrCP}$ E3 ligase upon phosphorylation at two Ser residues in the βTrCP-binding-motif-like sequence D^{94}AGLCMDSPSP^{104}. Point mutation of these Ser residues to alanine (Ala) abolished the JNK-induced ubiquitylation by $SCF^{\beta TrCP}$, and point mutation of DAG to AAG or DAA eradicated both βTrCP binding and ubiquitylation. Further analysis of the mode of βTrCP binding to this region revealed that the PEST-like sequence from E^{82}SS to D^{94}AG is crucially involved in both the βTrCP binding and ubiquitylation of Cdc25B. Furthermore, the phospho-mimetic replacement of all 10 Ser residues in the E^{82}SS to SPSP^{104} region with Asp resulted in βTrCP binding. Collectively, these results indicate that stress-induced Cdc25B ubiquitylation by $SCF^{\beta TrCP}$ requires the phosphorylation of $S^{101}PS^{103}P$ in the βTrCP-binding-motif-like and adjacent PEST-like sequences.

Key words: Cdc25B, $SCF^{\beta TrCP}$, Phosphorylation, PEST-like

Introduction

Cdc25 dual-specificity phosphatases promote cell cycle progression via the activation of cyclin-dependent kinase (CDK)–cyclin by removing inhibitory phosphate groups on CDK (Morgan, 1995; Boutros et al., 2006). Higher Metazoa possess three isoforms of Cdc25: Cdc25A, B and C. These are largely considered to serve roles in different phases of the cell cycle: Cdc25A in the G1 to S phase, and Cdc25B and C in the G2 to M phase (Boutros et al., 2006). However, this is not strictly correct because the depletion of either one or two *Cdc25* genes does not produce a defective phenotype in the normal cell cycle, indicating that their roles overlap in somatic cell-cycle control (Chen et al., 2001; Lincoln et al., 2002; Ferguson et al., 2005; Ray et al., 2007; Lee et al., 2009).

Of the three mammalian Cdc25 isoforms, Cdc25A has received special attention because it is a target of the DNA replication or damage checkpoint (Donzelli and Draetta, 2003; Bartek et al., 2004) and is the only Cdc25 that is essential to mouse embryogenesis (Ray et al., 2007; Lee et al., 2009). Cdc25A is phosphorylated rapidly by CHK1 upon genomic damage or replication arrest, and this is followed by the phosphorylation of crucial Ser residues in the βTrCP-binding DSG (Asp-Ser-Gly) motif by NEK11 (Busino et al., 2003; Jin et al., 2003; Melixetian et al., 2009), which initiates $SCF^{\beta TrCP}$-mediated ubiquitylation and degradation (Busino et al., 2004). Moreover, Cdc25A is directly linked to tumorigenesis, and the frequent overexpression of Cdc25A in human cancers is well documented (Kristjansdottir and Rudolph, 2004; Boutros et al., 2007).

The WD repeat-containing F-box protein βTrCP is a substrate-binding component of SCF (Skp1–cullin-1–F-box protein) E3 ubiquitin ligase that recognises the doubly phosphorylated conserved motif DSGxxS (S can be replaced by T, and x represents any amino acid) (Winston et al., 1999; Latres et al., 1999). $SCF^{\beta TrCP}$ targets a number of proteins that regulate the cell cycle and apoptosis (Frescas and Pagano, 2008). In particular, some proteins that control the G2–M transition, such as Cdc25A, Emi1, Wee1A and Bora, are $SCF^{\beta TrCP}$ substrates, and most of them contain the above-mentioned βTrCP-binding sequence (Busino et al., 2003; Jin et al., 2003; Margottin-Goguet et al., 2003; Guardavaccaro et al., 2003; Watanabe et al., 2004; Seki et al., 2008). Wee1 kinase is also a substrate of $SCF^{\beta TrCP}$, but its proposed βTrCP-binding sequence deviates from the consensus sequence (Watanabe et al., 2004). The consensus sequence and its deviated phosphopeptides bind βTrCP by forming hydrogen bonds and electrostatic interactions (Wu et al., 2003). In addition to such phosphopeptides, Cdc25A and Cdc25B possess the non-phosphorylated βTrCP-binding sequence DDGxxD (Kanemori et al., 2005).

Similar to Cdc25A, Cdc25B can transform retinoblastoma-protein-negative cells or normal cells when coexpressed with the oncogenic Ras (Galaktionov et al., 1995). Cdc25B overexpression is also found in human cancers and is correlated with a poor prognosis, as in the case of Cdc25A (Kristjansdottir and Rudolph, 2004; Boutros et al., 2007). The tumorigenic activity of Cdc25B is partly explained by an increase in hyperplasia or susceptibility to carcinogens in Cdc25B transgenic mice (Ma et al., 1999; Yao et al., 1999). Moreover, Cdc25B overexpression accelerates mitotic entry (Karlsson et al., 1999) and overrides the radiation-induced G2 checkpoint in vitro (Miyata et al., 2001).

Recently, we showed that Cdc25B is degraded rapidly by non-genotoxic stimuli that activate stress-responsive MAPKs, such as Jun N-terminal kinase (JNK) and p38 (Uchida et al., 2009). Our results suggested that these kinases phosphorylate specific Ser residues in the N-terminal region (S101 and S103) to induce Cdc25B degradation. We also found that HeLa cells expressing the non-phosphorylatable S101A mutant Cdc25B were more refractory to anisomycin-induced G2 arrest than wild-type HeLa cells.

Here, we report that JNK-induced Cdc25B ubiquitylation is mediated by the F-box protein βTrCP-containing SCF ubiquitin ligase. We show that S101 and S103 are phosphorylated upon non-genotoxic stress and that βTrCP binds the sequence around S101 and S103 of Cdc25B in a phosphorylation-dependent manner, even when the DSG consensus βTrCP-binding sequence is replaced with DAG. Our data also indicate that full binding and ubiquitylation of Cdc25B by SCF$^{\beta TrCP}$ requires an upstream ESS (Glu-Ser-Ser)-rich PEST-like sequence, as well as DAG and S101 and S103 phosphorylation.

Results

Ubiquitylation of Cdc25B is carried out by SCF$^{\beta TrCP}$ and is controlled by JNK

Our previous report suggested that non-genotoxic stress-induced Cdc25B degradation was mediated by the ubiquitin–proteasome pathway via S101 and S103 phosphorylation by JNK or p38 (Uchida et al., 2009). Fig. 1A shows that the amino acid sequence surrounding S101 and S103 of Cdc25B is similar to that in Cdc25A, which is a substrate of SCF$^{\beta TrCP}$ E3 ubiquitin ligase (Busino et al., 2003; Jin et al., 2003). Despite the overall similarity, the crucial βTrCP-binding motif of Cdc25A (DSG) is replaced with DAG in Cdc25B, and DAG is reported to be inactive for βTrCP binding in humans and *Xenopus* Cdc25A (Busino et al., 2003; Jin et al., 2003; Kanemori et al., 2005).

The corresponding region of Cdc25B, including the human splice variants Cdc25B2 and Cdc25B3 and mouse Cdc25B1, has a similar amino acid sequence (Fig. 1A) (Baldin et al., 1997; Kakizuka et al., 1992). As indicated in Fig. 1B, human Cdc25B3,

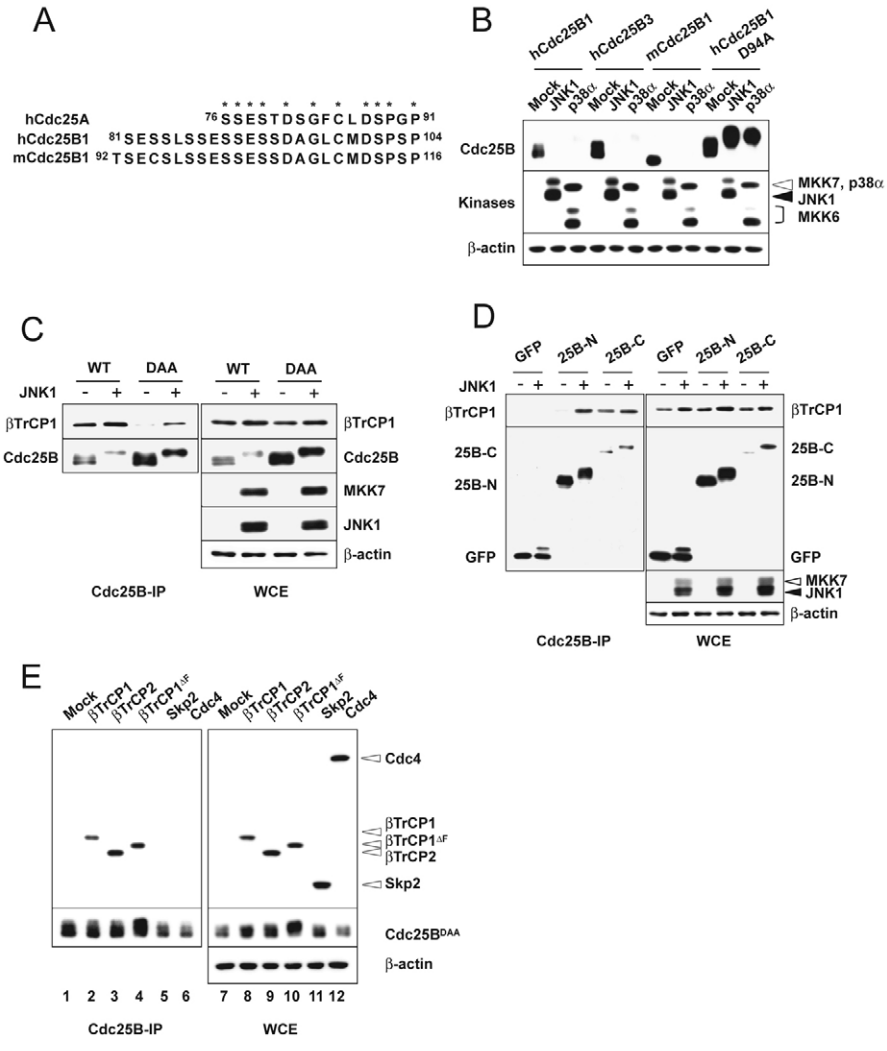

Fig. 1. βTrCP binds Cdc25B. (**A**) The aligned amino acid sequences of human (h) and mouse (m) Cdc25B and human Cdc25A, required for βTrCP binding. Asterisks indicate amino acids common to all three peptides. (**B**) Each FLAG-tagged cDNA of human Cdc25B1 and B3 and mouse Cdc25B1 was co-transfected with either JNK1 and its activator MKK7 or p38α and its activator MKK6, followed by immunoblotting to detect the expression of the indicated proteins (JNK1 or p38α was co-transfected with its respective activator, MKK7 or MKK6, unless stated otherwise and the coexpression of JNK1 and MKK7 or p38α with MKK6 is shown as JNK1 or p38, respectively, thereafter). The expression of human Cdc25B1 with a mutation at D94 to A of DAG (D94A) was also determined. (**C**) Either a FLAG–Cdc25B^{WT} or FLAG–Cdc25B^{DAA} with mutations in the constitutive βTrCP-binding sequence DDG was co-transfected with Myc-βTrCP1 in the presence or absence of JNK1. Then, 24 hours later, either Cdc25B binding to βTrCP1 or recovered Cdc25B was determined by immunoprecipitation with anti-FLAG beads, followed by immunoblotting with anti-Myc or anti-FLAG antibodies (Cdc25B-IP lanes). The expression of the indicated proteins is also shown (WCE lanes). (**D**) The βTrCP1 binding to Cdc25B fragments of the N-terminal 175 amino acids (1–175; 25B–N) or C-terminal fragment (180–580; 25B–C), both of which contain an N-terminal FLAG tag and C-terminal GFP tag, was examined as described in C. FLAG–GFP was used as a control (Cdc25B-IP lanes). The expression of the indicated proteins is shown (WCE lanes). (**E**) FLAG–Cdc25B^{DAA} and Myc-tagged F-box proteins were co-transfected and their interaction was determined by immunoprecipitation and immunoblotting. The interaction between Cdc25B^{DDA} and βTrCP1$^{\Delta F}$ lacking an F-box sequence was also determined (Cdc25B-IP lanes). The expression of the indicated proteins is also shown (WCE lanes).

mouse Cdc25B1 and human Cdc25B1 were also degraded on coexpression with JNK or p38 (hereafter, we refer to human Cdc25B1 as Cdc25B). Interestingly, the Cdc25B D94A mutant was refractory to JNK- or p38-induced degradation, suggesting the involvement of βTrCP binding (Fig. 1B).

Next, we investigated the JNK-dependent interaction between βTrCP1 and Cdc25B. We compared βTrCP binding to the Cdc25B of the wild type and a mutant that lacked the constitutive βTrCP-binding motif by mutating $D^{254}DG$ to DAA, which hereafter is referred to as $Cdc25B^{DAA}$. Although wild-type Cdc25B bound βTrCP1 irrespective of the JNK activity, $Cdc25B^{DAA}$ interacted with βTrCP1 in a JNK-dependent manner (Fig. 1C). JNK induced wild-type Cdc25B degradation and apparent Cdc25B binding was not enhanced. Given the JNK-induced wild-type Cdc25B degradation that occurred, several times more βTrCP was estimated to bind Cdc25B on coexpression with JNK. Likewise, the Cdc25B N-terminal fragment displayed JNK-dependent βTrCP1 binding, whereas the C-terminal fragment with the DDG site showed that βTrCP bound in a JNK-independent manner (Fig. 1D). Furthermore, $Cdc25B^{DAA}$ interacted with βTrCP1 and βTrCP2, but not with other F-box proteins such as Skp2 and Cdc4 (Fig. 1E). $Cdc25B^{DAA}$ was stabilised when co-transfected with the F-box deletion mutant $βTrCP1^{ΔF}$, which lacks ubiquitylation activity because of its inability to bind to the core SCF complex, but retains substrate-binding ability via an intact WD domain (Fig. 1E).

Next, we investigated the ubiquitylation of Cdc25B by $SCF^{βTrCP}$ in vitro. ^{35}S-labelled $Cdc25B^{DAA}$ was efficiently ubiquitylated by SCF containing βTrCP1 or βTrCP2, in a JNK-dependent manner. By contrast, no ubiquitylated signal was detected when Skp2 or Cdc4 was used as the F-box protein (Fig. 2A). Furthermore, $βTrCP1^{ΔF}$ did not ubiquitylate Cdc25B (Fig. 2B). Note that $SCF^{βTrCP1}$ and $SCF^{βTrCP2}$ could ubiquitylate $Cdc25B^{DAA}$ without JNK, but JNK clearly enhanced the ubiquitylation (Fig. 2A,B). A high level of ubiquitylation was observed in the absence of JNK when wild-type Cdc25B was used for the in vitro ubiquitylation assay (Fig. 2C). Nevertheless, slight enhancement of Cdc25B ubiquitylation by $SCF^{βTrCP1}$ was observed in the presence of JNK activity (Fig. 2C). These results indicate that $SCF^{βTrCP}$ binds and ubiquitylates Cdc25B in a JNK-dependent manner, which is independent of the DDG constitutive binding site, and that a new JNK-regulated βTrCP-binding site is located in the N-terminal 175 amino acids of Cdc25B.

Our previous investigation suggested that S101 and S103 were possible target sites of JNK or p38 (Uchida et al., 2009). Therefore, we assessed the contributions of S101 and S103 to $SCF^{βTrCP}$-mediated $Cdc25B^{DAA}$ ubiquitylation. As indicated in Fig. 2D, whereas the ubiquitylation of Cdc25B was greatly compromised by S101A or S103A mutations, it was almost completely abolished with a S101A, S103A double mutant. These results indicate that the effects of S101 and S103 on Cdc25B ubiquitylation were collaborative. Other Cdc25B proteins, such as human Cdc25B3 and mouse Cdc25B1, were also ubiquitylated by $SCF^{βTrCP1}$ in the presence of JNK1 (supplementary material Fig. S1A). Intriguingly, $Cdc25B^{D94A}$ was hardly ubiquitylated (supplementary material Fig. S1A), suggesting that D94 in DAG is involved in JNK-induced Cdc25B ubiquitylation. Moreover, in such wild-type or mutant Cdc25B, βTrCP1 binding to Cdc25B proteins were roughly proportional to their ubiquitylation level (supplementary material Fig. S1B). Collectively, these results clearly indicate that JNK-induced Cdc25B degradation is mediated by $SCF^{βTrCP1}$, and that the phosphorylation of Cdc25B S101 and S103 plays an important role in this process.

JNK-induced Cdc25B degradation is aborted by βTrCP depletion

Next, we assessed the effects of βTrCP depletion on JNK-induced Cdc25B degradation using siRNA that targets both βTrCP1 and βTrCP2. We used either one siRNA, used in previous investigations

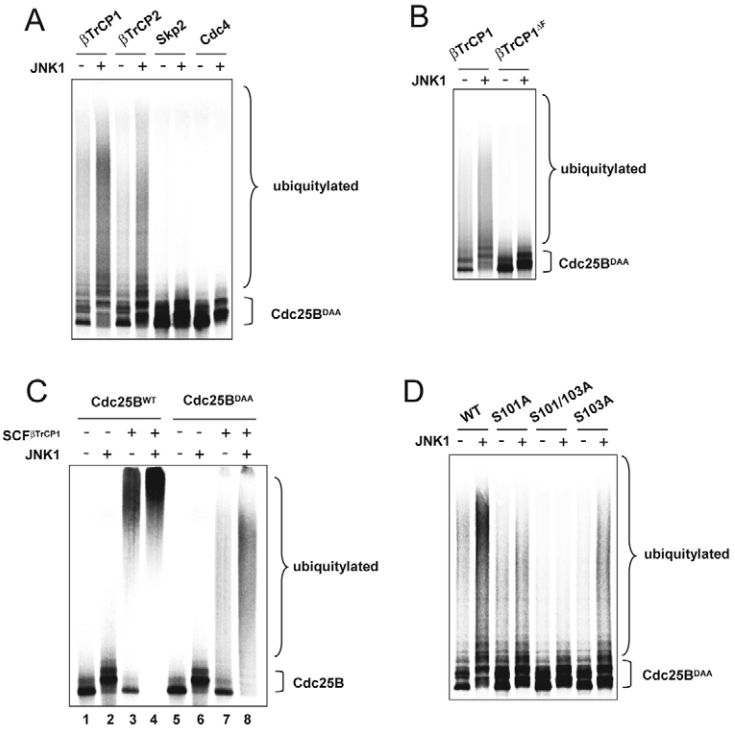

Fig. 2. Cdc25B is ubiquitylated by $SCF^{βTrCP}$ in vitro.
(**A**) [^{35}S]methionine-labelled $Cdc25B^{DAA}$ was incubated with each SCF complex in the presence or absence of JNK1, and ubiquitylation was determined as described in the Materials and Methods. (**B**) [^{35}S]methionine-labelled $Cdc25B^{DAA}$ was incubated with each $SCF^{βTrCP1}$ or $SCF^{ΔβTrCP1}$ complex in the presence or absence of JNK1, and ubiquitylation was determined as described in A. (**C**) $SCF^{βTrCP1}$-mediated ubiquitylation of [^{35}S]methionine-labelled $Cdc25B^{WT}$ (wild type) or $Cdc25B^{DAA}$ was determined as described in A. (**D**) [^{35}S]methionine-labelled $Cdc25B^{DAA}$ S101 and S103 (wild type), or with a mutation of S101A, S103A, or S101A and S103A (S101/103A), was incubated with $SCF^{βTrCP1}$ to determine ubiquitylation as described in A.

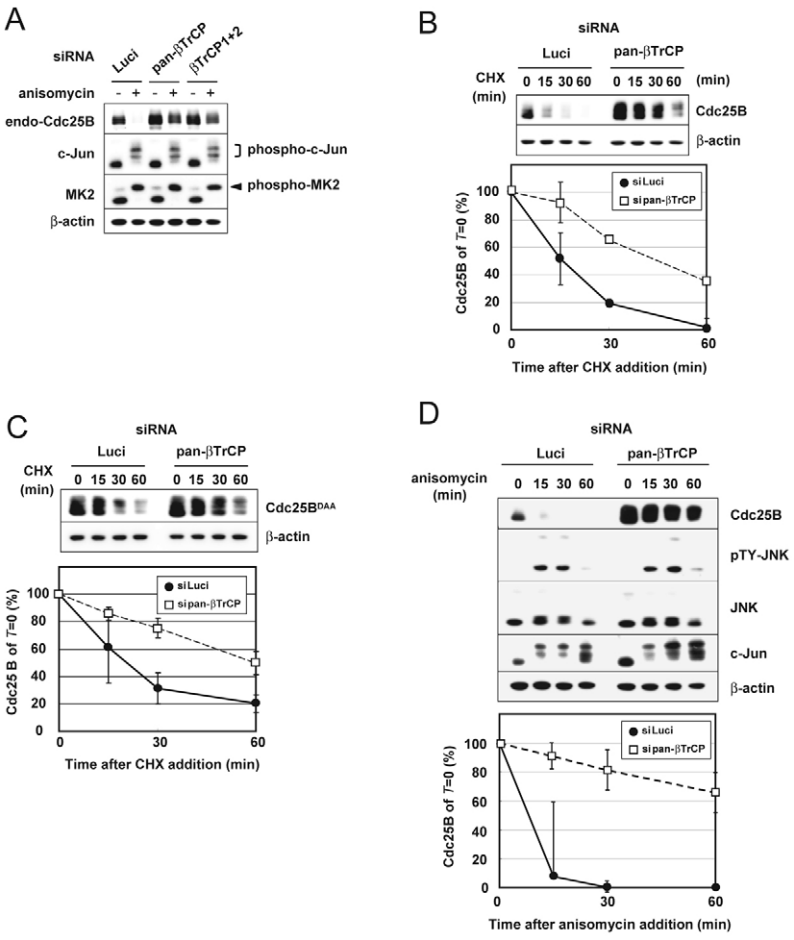

Fig. 3. βTrCP1 and 2 depletion stabilises Cdc25B. (**A**) HeLa cells were depleted of both βTrCP1 and 2 with siRNA (either pan-βTrCP or combined siRNA for βTrCP1 and 2). Luci indicates siRNA against luciferase, used as a control. After 24 hours, HeLa cells were treated with 50 ng/ml anisomycin for 30 minutes. The expression of endogenous Cdc25B was also determined by immunoprecipitation followed by immunoblotting. The expression of the other indicated proteins (Jun, MK2 and β-actin) was also determined by immunoblotting. (**B**) HeLa-W40 cells transfected with siRNA for either Luci or pan-βTrCP were treated with cycloheximide (CHX; 50 μg/ml), and expression of the indicated proteins was determined by immunoblotting at the indicated times. The relative Cdc25B expression is shown in the lower panel with the value at time 0 set at 100. The bars indicate the standard deviation (s.d.) of three independent experiments. (**C**) The expression of Cdc25B^{DAA} in HeLa-DAA34 cells in the presence of CHX was determined as described in B. (**D**) HeLa-W40 cells transfected with siRNA for either for Luci or pan-βTrCP were treated with 50 ng/ml anisomycin, and the expression of the indicated proteins was determined as described in B.

(Margottin-Goguet et al., 2003; Guardavaccaro et al., 2003) (denoted here as pan-βTrCP) or two in combination, which enabled us to knockdown either βTrCP1 or βTrCP2 specifically (denoted as βTrCP1 and 2). The effect on βTrCP depletion on introducing these siRNAs to HeLa-W40 cells that stably express FLAG–Cdc25B (Uchida et al., 2009) is shown in supplementary material Fig. S2A (we show only the expression of βTrCP1 because we had no specific antibody to βTrCP2). The results also indicated that the application of such siRNA to HeLa-W40 cells enhanced the expression of FLAG–Cdc25B and endogenous Cdc25A, suggesting that both Cdc25A and Cdc25B are destroyed via a βTrCP-mediated pathway, even in the absence of cellular stress (supplementary material Fig. S2A).

First, we examined the stability of endogenous Cdc25B after siRNA depletion of βTrCP1 and 2 with either siRNA for pan-βTrCP or combined siRNA for βTrCP1 and 2. As shown in Fig. 3A, βTrCP depletion substantially increased the resistance of endogenous Cdc25B under anisomycin stress. Moreover, transiently expressed Cdc25B^{DAA} also became refractory to the JNK-induced degradation on βTrCP1 and 2 depletion (supplementary material Fig. S2B). Because the depletion of βTrCP1 and 2 with the two siRNA treatments gave similar results (Fig. 3A and supplementary material Fig. S2A), we mainly used pan-βTrCP siRNA in the subsequent experiments.

Next, we asked whether the half-life of Cdc25B was affected by βTrCP depletion. HeLa-W40 cells stably expressing FLAG–Cdc25B were depleted of βTrCP1 and 2 with pan-βTrCP siRNA and the expression of Cdc25B protein was determined in the presence of cycloheximide. As indicated in Fig. 3B, wild-type Cdc25B appeared to be stabilised in βTrCP-depleted cells. Interestingly, the steady-state expression of constitutively expressed Cdc25B^{DAA} in HeLa-DAA34 cells was also less affected in βTrCP-depleted cells (Fig. 3C), suggesting that the SCF$^{\beta TrCP}$-mediated ubiquitin–proteasome pathway controls Cdc25B stability in unstressed conditions, through a site other than the DDG βTrCP-binding site.

We further investigated the involvement of βTrCP in anisomycin-induced Cdc25B degradation. FLAG–Cdc25B^{WT}-expressing HeLa-W40 cells were transfected with either luciferase or pan-βTrCP siRNA, followed by a 50 ng/ml anisomycin challenge. βTrCP1 and 2 depletion strongly compromised anisomycin-induced Cdc25B degradation (Fig. 3D). βTrCP depletion of FLAG–Cdc25B^{DAA}-expressing HeLa-DAA34 cells had similar effects (supplementary material Fig. S2B). Collectively, these results unequivocally indicate that SCF$^{\beta TrCP}$ directly controls the non-genotoxic stress-induced instability of Cdc25B. Furthermore, these results also suggest that a site other than the constitutive binding site DDG controls the steady-state stability of Cdc25B.

JNK phosphorylates Cdc25B under stressful conditions

Next, we investigated whether JNK or p38 phosphorylated S101 and S103 by raising antibodies that recognised S101-, S103- or S101 and S103-phosphorylated Cdc25B; the antibody specificity is shown in supplementary material Fig. S3A. Using these

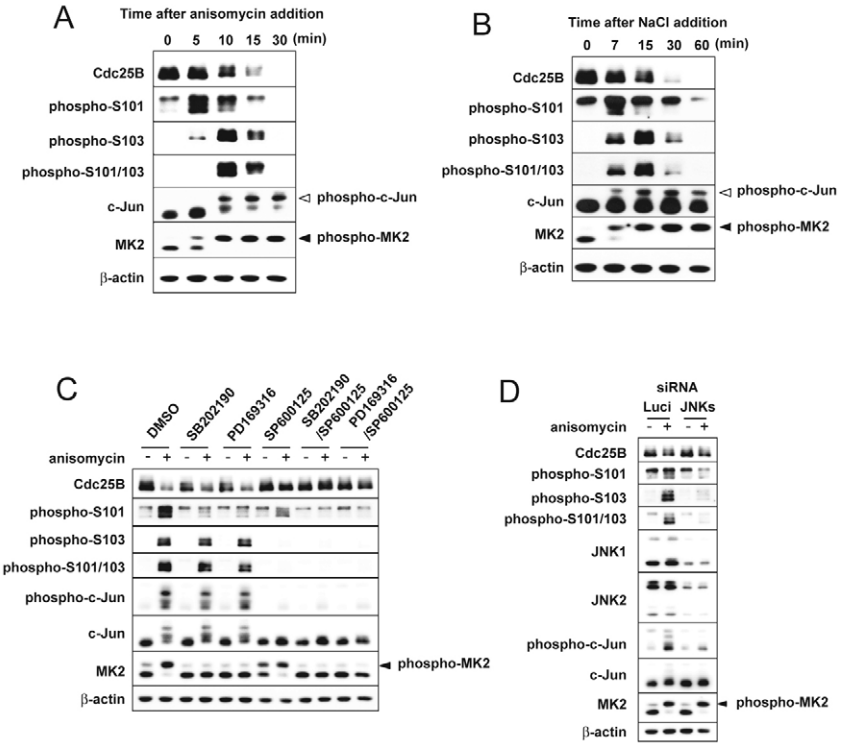

Fig. 4. Cdc25B S101 and S103 are phosphorylated by non-genotoxic insults. (**A**) HeLa-W40 cells that expressed FLAG–Cdc25B were treated with 50 ng/ml anisomycin. At the indicated times Cdc25B was immunoprecipitated, and phosphorylation was detected with antibodies. The expression of FLAG–Cdc25B, Jun, MK2 and β-actin are also shown. (**B**) HeLa-W40 cells were treated with 300 mM NaCl, and phosphorylation at S101 and S103 and the expression of the indicated proteins was detected, as described in A. (**C**) HeLa-W40 cells were treated with each inhibitor (5 μM each of SB202190 and PD169316 for p38 and 20 μM SP600125 for JNK, or a combination of SB and SP or PD and SP to inhibit p38 and JNK) 1 hour before the 50 ng/ml anisomycin challenge. Cell extracts were prepared after 10 minutes, and Cdc25B was immunoprecipitated. Phosphorylation at S101 and S103 and the expression of the indicated proteins were determined by immunoblotting. (**D**) HeLa-W40 cells were treated with siRNA for Luc or JNK (the siRNA for JNK was a mixture of one siJNK1 and two siJNK2). After 24 hours, the cells were treated with 50 ng/ml anisomycin for 10 minutes and cell extracts were prepared. The phosphorylation of Cdc25B at S101 and S103 and the expression of the indicated proteins were determined by immunoblotting.

antibodies, we investigated the phosphorylation status of S101 and S103 under either unstressed or stressed conditions. Conventional HeLa cells were not useful in these experiments because we could not recover enough Cdc25B by immunoprecipitation to detect its phosphorylation. We therefore used HeLa-W40 cells for phosphorylation analyses. Although a slight, but obvious, phosphorylated S101 (S101-*P*) signal was detected under unstressed conditions, S101 phosphorylation increased dramatically within 5 minutes of the 50 ng/ml anisomycin treatment, concomitant with p38 activation, as determined by the appearance of the phosphorylated form of MK2 (Fig. 4A). Unlike S101, the S103 phosphorylation signal was undetectable at time 0. A slight increase in phosphorylation was detected at 5 minutes and a much stronger signal was detected at 10 minutes, at which point JNK was fully activated, as determined by the Jun-*P* signal. The results for S103-*P* were similar to those for S101 and S103 double phosphorylation, for which the maximum level was detected at 10 minutes. Cdc25B phosphorylation decreased at 15 minutes and disappeared completely thereafter as a result of Cdc25B degradation. Similar results were obtained when stress was induced with 300 mM NaCl (Fig. 4B) or ultraviolet (UV) irradiation (supplementary material Fig. S3B). The steady-state phosphorylation of S101 and the similarity in the pattern between S103-*P* and the double S101-*P* and S103-*P* suggest that the phosphorylation of S103 occurs in S101-phosphorylated Cdc25B, because S101 is always phosphorylated in the absence of stress.

Next, we investigated the effects of the p38 inhibitors SB202190 and PD169316 (abbreviated to SB and PD, respectively) or the JNK inhibitors SP600125 (abbreviated to SP) on Cdc25B phosphorylation in HeLa-W40 cells. First, we determined suitable concentrations of these inhibitors for the specific inhibition of the respective kinases, because these kinases are often cross-inhibited by such inhibitors. As shown in supplementary material Fig. S4A, 20 μM SB inhibited both p38 and JNK activity, as determined by the disappearance of the phosphorylated MK2 and phosphorylated Jun signals, respectively, and it specifically inhibited p38 at a concentration as low as 5 μM without JNK inhibition. Supplementary material Fig. S4B,C also shows that 5 μM PD and 20 μM SP are suitable for the specific inhibition of p38 and JNK, respectively, without obvious cross-inhibition. As indicated in Fig. 4C, anisomycin-induced S101 phosphorylation was reduced by the p38 inhibitors SB and PD, but these inhibitors did not affect S103 phosphorylation. However, the JNK inhibitor SP completely inhibited S103, and modest inhibition of S101 phosphorylation was also observed. The role of JNK in S103 and S101 phosphorylation was also indicated by the siRNA depletion of JNK1 and JNK2 in anisomycin-treated HeLa-W40 cells, where the S101-*P* signal was reduced and the S101-*P*-103-*P* signal was almost completely abolished by the knockdown of both JNK1 and 2 (Fig. 4D). In a similar context, the clear reduction of the expression of endogenous Cdc25B by the transfection of wild-type, but not the kinase-dead mutant JNK1, also suggests that JNK functions in the degradation of endogenous Cdc25B (supplementary material Fig. S4D).

Collectively, these and our previous results indicate that the enhanced phosphorylation at S101 caused by p38 and JNK and de novo phosphorylation of S103 by JNK play crucial roles in stress-induced Cdc25B degradation. Furthermore, the S101-*P* signal detected under unstressed conditions did not disappear completely with the p38 inhibitors or JNK inhibitor, suggesting that an unidentified kinase(s) that phosphorylates S101 is involved in steady-state Cdc25B degradation.

The βTrCP-binding-motif-like DAG is essential for $SCF^{\beta TrCP}$-mediated Cdc25B ubiquitylation

The above results suggested that DAG, previously believed to be inactive, is functional in βTrCP-mediated Cdc25B ubiquitylation. To explore this possibility, we made a mutant Cdc25B in which

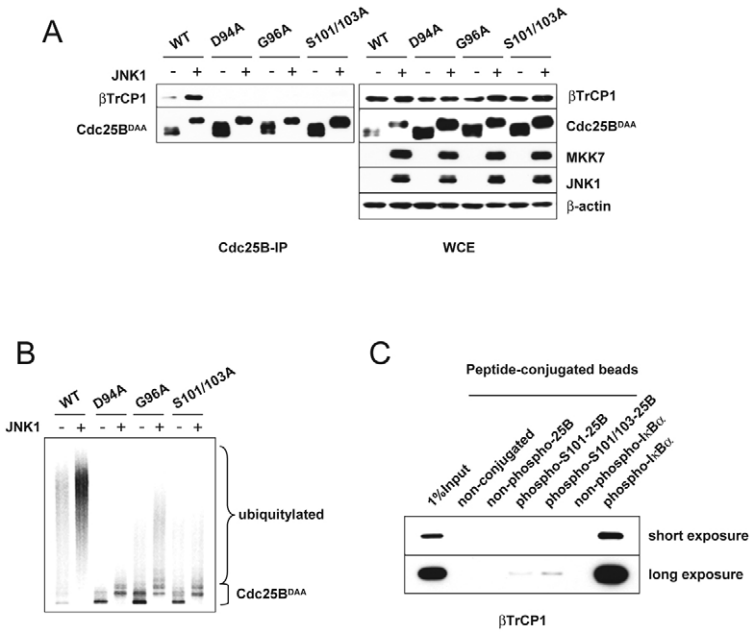

Fig. 5. Cdc25B peptide from D^{94}AG to S^{101}PSP is essential, but not sufficient, for Cdc25B ubiquitylation by SCF$^{\beta TrCP}$. (**A**) FLAG–Cdc25B of the wild type or indicated mutants was co-transfected with Myc–βTrCP1 in the presence or absence of JNK1. Then, 24 hours later, Cdc25B-bound βTrCP1 was detected by the immunoprecipitation of Cdc25B, followed by immunoblotting (Cdc25B-IP lanes). The expression of indicated proteins proteins is also shown (WCE lanes). (**B**) In vitro ubiquitylation by SCF$^{\beta TrCP1}$ of Cdc25B^{DAA} with wild-type DAG, or G96A or the double S101A, S103A mutations (S101/103A) was determined, as described in Fig. 2A. (**C**) Phosphorylated or unphosphorylated Cdc25B peptides, based on the sequence DAGLCMDSPSP that were conjugated with agarose beads, were incubated with Myc–βTrCP1-expressing Cos7 cell extracts and the βTrCP1 bound to peptides was detected by immunoblotting.

DAG was mutated to AAG (D94A), as the Asp in DSG plays a crucial role in substrate binding to βTrCP (Wu et al., 2003), and investigated whether the DAG in Cdc25B functions in JNK-induced βTrCP binding. FLAG–Cdc25B^{D94A} was co-transfected with βTrCP1 in the presence or absence of JNK1, and its binding to βTrCP1 was determined. Interestingly, Cdc25B^{D94A} failed to bind βTrCP1 (Fig. 4A). Cdc25B^{G96A} (DAA instead of DAG) was also unable to bind βTrCP1 (Fig. 4A). Furthermore, supplementary material Fig. S5A shows that both Cdc25B^{D94A} and Cdc25B^{G96A} were refractory to JNK-induced degradation (see also Fig. 1B). As expected, the Cdc25B S101A, S103A double mutant also lost βTrCP-binding ability. These results suggest that the Cdc25B peptide from D94 to S101 is a minimal requirement for βTrCP binding (see Fig. 1A). Moreover, the steady-state expression of such mutant Cdc25B was much higher than that of the wild-type protein (Fig. 5A). Therefore, the DAG sequence seems to be deeply involved in both the steady-state and stress-induced degradation of Cdc25B.

Next, we investigated how mutations in the DAG sequence affected in vitro Cdc25B ubiquitylation. Cdc25B^{D94A} was not ubiquitylated by SCF$^{\beta TrCP1}$, even in the presence of JNK activity; its ubiquitylation level was much less than that of the S101A, S103A double mutant (Fig. 5B). Cdc25B ubiquitylation was also greatly compromised by a G96A mutation, suggesting that G96 plays a role in Cdc25B binding to βTrCP. Cdc25B^{D94A} was phosphorylated at S101 and S103 when JNK1 was co-transfected (supplementary material Fig. S5B), showing that the phosphorylation of SPSP occurs irrespective of DAG. These results indicate that DAG in Cdc25B is necessary for ubiquitylation by SCF$^{\beta TrCP}$.

To elucidate whether a peptide encompassing DAG to SPSP was sufficient for βTrCP binding, we analysed βTrCP1 binding using the DAGLCMDSPSP peptide, in the unphosphorylated, S101-*P* and S101-*P*–P103-*P* forms. Peptide-conjugated beads were incubated with crude cell extracts prepared from βTrCP1-transfected Cos7 cells, and peptide-bound βTrCP1 was detected by immunoblotting. The unphosphorylated and phosphorylated IκBα peptides containing the conserved consensus βTrCP-binding sequence were used as controls. Fig. 5C shows that βTrCP1 barely bound the Cdc25B phospho-peptide under conditions where strong binding to the phosphorylated IκBα peptide was detected. Faint βTrCP1 signals that indicated binding to the doubly phosphorylated Cdc25B peptide were in fact detected by longer exposure. Taken together, these results strongly support the idea that DAG is a crucial sequence for JNK-induced Cdc25B ubiquitylation, but that the doubly phosphorylated DAGLCMDSPSP alone is insufficient for βTrCP binding.

The PEST-like sequence plays an important role in SCF$^{\beta TrCP}$-mediated Cdc25B ubiquitylation

Compared with Cdc25A, human Cdc25B possesses a longer PEST-like sequence that is rich in Glu (E) and Ser but lacks Pro (P), and is located upstream from DAG (Fig. 1A). This PEST-like sequence might contribute to βTrCP binding because phosphorylation or the presence of acidic amino acids N-terminal to the consensus DSG and DDG sequences facilitates βTrCP binding (Jin et al., 2003; Kanemori et al., 2005; Westbrook et al., 2008). The PEST-like sequence in Cdc25B comprises 12 amino acids, which consists of three ESS units and one LSS unit. We mutated all eight Ser to non-phosphorylatable Ala (S83A–S93A) and examined the binding of this sequence to βTrCP1. This Cdc25B^{8SA} mutant [denoted '8SA (–PEST)' in Fig. 5] was unable to bind βTrCP1 and was resistant to JNK-induced degradation (Fig. 6A and supplementary material Fig. S6A).

Next, we examined how many of the Cdc25B ESS–LSS sequences were necessary for βTrCP binding. We made a series of mutants with Ser-to-Ala mutations in the AA units, in which 2SA represents S83 and S84 to A, 4SA represents S83, S84, S86 and S87 to A, 6SA represents S86, S87, S89, S90, S92 and S93 to A, and 8SA is as described above (–PEST; see Fig. 6B) in the Cdc25^{DAA} background. The βTrCP-binding activity of these mutants was roughly proportional to the number of intact SS sequences (Fig. 6B). Consistent with these results, the degree of JNK-dependent ubiquitylation decreased in Cdc25B that lacked SS sequences (Fig. 6C). Cdc25B with fewer SS sequences was more refractory to JNK-induced degradation (supplementary

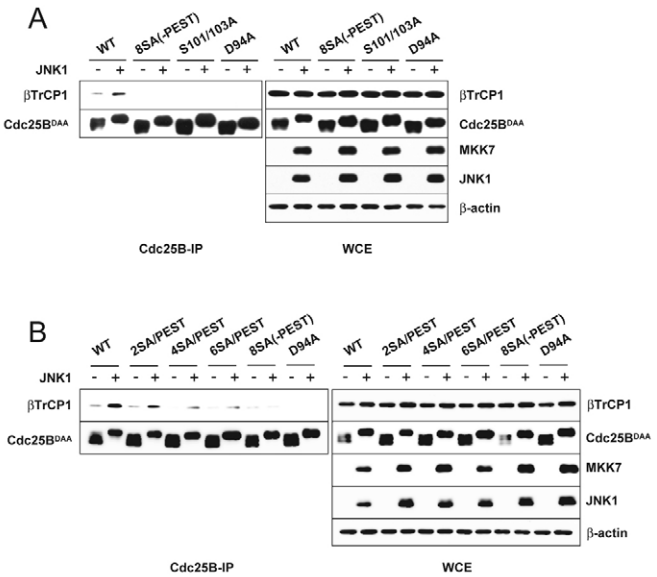

Fig. 6. The PEST-like sequence is required for efficient ubiquitylation of Cdc25B. (**A**) The following FLAG–Cdc25B^{DAA}-based mutants were co-transfected with Myc–βTrCP1 in the presence or absence of JNK1: WT with an intact PEST-like sequence; 8SA(–PEST) with mutations of eight Ser residues in the PEST-like sequence to alanine; the double S101A, S103A (S101/103A); or D94A. After 24 hours, Cdc25B was immunoprecipitated, and Cdc25B-bound βTrCP1 was detected by immunoblotting (Cdc25B-IP lanes). The expression of the indicated proteins was also determined (WCE lanes). (**B**) FLAG–Cdc25B^{DAA} with an intact PEST-like sequence (WT) or with SS to AA mutations of two Ser residues in three ESS units or one LSS unit was co-transfected with Myc–βTrCP1 in the presence or absence of JNK. The Cdc25B-bound βTrCP1 and protein expression are shown as indicated in A. Cdc25B^{D94A} was used as a negative control. (**C**) The ^{35}S-labelled Cdc25B^{DAA}-based proteins used in B were processed to detect in vitro ubiquitylation, as described in Fig. 2A.

material Fig. S6B). Of the four 2SA mutants (S83A and S84A, S86A and S87A, S89A and S90A, S92A and S93A), the mutant with SS mutations closest to DAG (S92A and S93A) was the most refractory to JNK-induced degradation and the least ubiquitylated, suggesting that ESS phosphorylation closer to DAG is more important for degradation (supplementary material Fig. S6C). The mutation in either E88 or E91 did not have any effect on JNK-induced degradation (supplementary material Fig. S6D), excluding the possibility that the PEST-like sequence itself is a core βTrCP-binding site. Moreover, S101 and S103 are phosphorylated in Cdc25B^{8SA}, indicating that the phosphorylation of S101 and S103 is independent of the PEST-like sequence (supplementary material Fig. S6E). Collectively, these results clearly indicate that a PEST-like sequence located upstream of DAG plays a crucial role in SCF^{βTrCP}-mediated Cdc25B ubiquitylation.

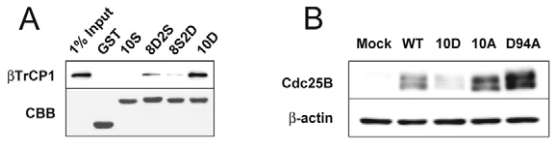

Fig. 7. A peptide encompassing the region between E^{82}SS and S^{101}PSP is a possible βTrCP-binding sequence in Cdc25B. (**A**) GST-fused Cdc25B-derived peptides consisting of the sequence E82SS to S101PSP were mixed with crude cell extracts prepared from Myc-tagged βTrCP1-transfected Cos7 cells, and this was followed by the recovery of proteins bound to GST-fused peptides. The recovered βTrCP1 was detected with anti-Myc antibody. The reaction mixture included 1 μM staurosporine to avoid the phosphorylation of Ser residues in the peptides by kinases present in the cell extracts. (**B**) FLAG–Cdc25B of wild type, 10D (all Ser residues in E^{82}SS to S^{101}PSP were replaced with Asp), 10A (all Ser residues in E^{82}SS to S^{101}PSP were replaced with Ala) or D94A were transfected into HeLa cells and their expression was determined by immunoblotting.

A stretch of PEST-like sequence up to S^{101}PSP of Cdc25B is a possible minimum sequence required for JNK-induced βTrCP binding

Next, we investigated the requirement of the PEST-like sequence and S^{101}PSP in βTrCP binding. Given the difficulty synthesising Ser-rich peptides and their phosphorylated forms, we made GST-fused peptides running from E^{82}SS to S^{101}PSP and their phospho-mimetic mutants, purified them from *Escherichia coli*, and investigated their binding to βTrCP1. The GST-fused peptides used were as follows: 10S (non-phosphorylated form), 8D2S (S-to-D mutation in the PEST-like sequence), 8S2D (D^{101}PDP mutant) and 10D (all S to D; Fig. 7A). Such *E. coli*-produced proteins were mixed with Myc–βTrCP1-expressing Cos7 cell extracts in the presence of 1 μM staurosporine to avoid phosphorylation of the GST-fused peptides by the kinases in Cos7 cell extracts. Peptide-bound βTrCP1 was detected by immunoblotting. As expected, the βTrCP1 bound to the phospho-mimetic peptides, but not the unphosphorylated one (Fig. 7A). βTrCP1 bound strongly to GST–10D, and less strongly to GST–8D2S and GST–8S2D. No βTrCP1 binding was detected for the GST-10S peptide. These results strongly suggest that the phosphorylation of Ser residues is required in the βTrCP-binding peptide consisting of the sequence from E^{82}SS to S^{101}PSP.

Next, we examined the stability of the Cdc25B^{10D} mutant in HeLa cells. Cdc25B of wild type, 10D, 10A (all Ser residues in E^{82}SS to S^{101}PSP were replaced by non-phosphorylatable Ala), and D94A were transfected to HeLa cells and their expression was detected in the absence of stress. As indicated in Fig. 7B, the expression of the phospho-mimetic Cdc25B^{10D} mutant was less than that of the wild type, indicating that Cdc25B^{10D} is unstable, even under unstressed conditions, supporting the idea that full βTrCP binding requires phosphorylation.

Finally, we investigated the contribution of the DAG and DDG βTrCP-binding sites to Cdc25B stability in stressed and unstressed conditions. FLAG–Cdc25B of wild type, Cdc25B^{D94A}, Cdc25B^{DAA} or Cdc25B$^{D94A/DAA}$ was transfected to HeLa cells and its expression was determined by immunoblotting. Typical expression of such mutants under anisomycin stress is shown in Fig. 8A. βTrCP1 binding to the Cdc25B mutant in the presence of JNK activity is also shown in supplementary material Fig. S7. As expected, Cdc25B^{WT} and Cdc25B^{DAA} were susceptible to anisomycin treatment and Cdc25B^{D94A} was more refractory to it. The

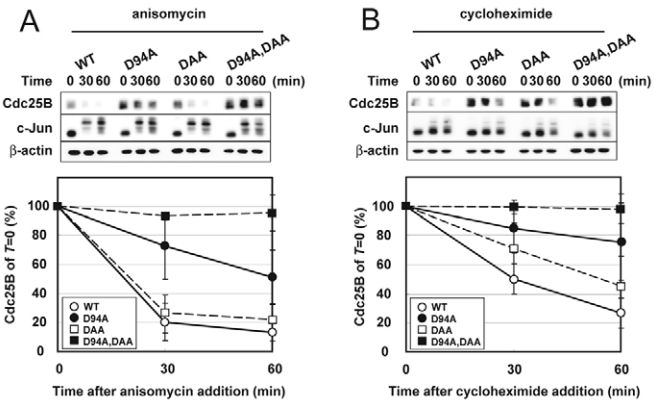

Fig. 8. DAG and DDG collaboratively regulate Cdc25B stability. FLAG-tagged Cdc25B^{WT}, Cdc25B^{D94A}, Cdc25B^{DAA} or Cdc25B$^{D94A/DAA}$ was transfected into HeLa cells, which were treated with 100 ng/ml anisomycin (**A**) or 50 μg/ml cycloheximide (**B**) 24 hours after transfection. Crude cell extracts were prepared at the indicated times and the expression of Cdc25B, Jun and β-actin was determined by immunoblotting. The relative expression of Cdc25B is also shown with the value at time 0 set to 100. The bars indicated the s.d. of five independent experiments. In A and B, the relative densitometric values of the expression of Cdc25B^{WT}, Cdc25B^{D94A}, Cdc25B^{DAA} and Cdc25B$^{D94A/DAA}$ were 1, 1.98±0.79, 1.77±0.59 and 4.21±1.2, respectively.

degradation of Cdc25B$^{D94A/DAA}$ was quite stable under anisomycin stress. These results indicate that the newly identified DAG βTrCP-binding sequence is responsible for stress-induced Cdc25B degradation. We also investigated the stability of such Cdc25B proteins in the presence of cycloheximide to estimate their steady-state stability (Fig. 8B). Cdc25B^{DAA} was more stable than Cdc25B^{WT}, but Cdc25B^{D94A} was even more stable than Cdc25B^{WT} or Cdc25B^{DAA}. Here again, the degradation of Cdc25B$^{D94A/DAA}$ was not observed with cycloheximide. These results suggest that the newly identified Cdc25B N-terminal βTrCP-binding region controls Cdc25B stability under both stressful and steady-state conditions and that the N-terminal DAG and constitutive DDG βTrCP binding sites cooperatively control Cdc25B stability.

Discussion

Previously, we showed that the cellular stresses that activate JNK or p38 induce Cdc25B degradation and that S101 and S103 are involved in Cdc25B stability (Uchida et al., 2009). We also suggested the involvement of the ubiquitin–proteasome system in stress-induced Cdc25B degradation. In this report, we identified SCF$^{\beta TrCP}$ as the ubiquitin ligase responsible for non-genotoxic stress-induced Cdc25B degradation. Moreover, S101 and S103 are highly phosphorylated by such stresses and are involved in ubiquitylation by SCF$^{\beta TrCP}$.

Our results indicate that non-canonical D^{94}AG and S^{101}PSP in Cdc25B play important roles in βTrCP binding. Moreover, an upstream PEST-like sequence starting from E^{82}SS turned out to have a crucial role in βTrCP binding to Cdc25B. Human Cdc25B has a longer PEST-like sequence than Cdc25A. The entire 12-amino-acid PEST-like sequence was essential for proper ubiquitylation. These results strongly indicate that the PEST-like sequence and SPSP cooperate with DAG for Cdc25B ubiquitylation under conditions that activate p38 and JNK. Moreover, the newly identified βTrCP-binding sequence around DAG is probably involved in Cdc25B degradation in collaboration with DDG under both stress-induced and steady-state conditions, given that the Cdc25B$^{D94A/DAA}$ double mutant was stable irrespective of cellular stress and SCF$^{\beta TrCP}$ barely ubiquitylated Cdc25B$^{D94A/DAA}$. Hence, we confidently conclude that Cdc25B stability is regulated mainly by SCF$^{\beta TrCP}$-mediated ubiquitylation via two independent sites: DAG and DAA.

The Ser residues in S^{101}PSP, located downstream from D94AG, are highly phosphorylated upon JNK and p38 activation. In addition, a GST-fused phospho-mimetic peptide consisting of E^{82}SS to S^{101}PSP bound βTrCP1, whereas that with the wild-type PEST-like sequence with SPSP did not, suggesting that the highly phosphorylated PEST-like sequence in Cdc25B is crucial for βTrCP binding. These results strongly suggest that full phosphorylation of the stretch from E^{82}SS to S^{101}PSP is required for Cdc25B to bind βTrCP. Such phosphorylation might confer a negative charge. The importance of phosphorylation in the upstream sequences to the core DSG sequence has also been reported in Cdc25A and REST (Jin et al., 2003; Westbrook et al., 2008). The stability of *Xenopus* Cdc25A was also found to be strongly affected by negatively charged amino acids surrounding the constitutive βTrCP-binding motif DDG (Kanemori et al., 2005). Hence, the βTrCP-binding-motif-like DAG sequence in Cdc25B functions in βTrCP binding by virtue of the strong negative charge resulting from acidic residues, which might enable a strong interaction with βTrCP. Analysis of the crystal structure should confirm this.

Under non-genotoxic stress, the Ser residues of the SPSP sequence are preferentially phosphorylated by p38 and JNK. Interestingly, S101 was weakly but constitutively phosphorylated under steady-state conditions when both p38 and JNK were inactive. These results indicate that an unidentified proline-directed kinase(s) phosphorylates S101 in the steady-state condition, which might contribute to Cdc25B degradation during the interphase. In this context, Isoda et al. reported the inhibition of phosphorylation by the CDK inhibitor p21 in the corresponding Ser residue in *Xenopus* Cdc25A (Isoda et al., 2009). Perhaps the interphase-specific CDK–cyclins that are active from the G1 phase to the S phase, such as Cdk2–cyclin E, Cdk2–cyclin A, and possibly Cdk4–cyclin D, phosphorylate S101 to keep Cdc25B expression low. The identification of a kinase that phosphorylates Cdc25B S101 under steady-state conditions is probably important for understanding the post-translational regulation of Cdc25B. A need for phosphorylation in the Cdc25B PEST-like sequence for βTrCP binding was also suggested. Given that the phosphorylation of Ser residues in the PEST-like sequence is a prerequisite for βTrCP binding, it is also important to identify the kinase(s) responsible for a full understanding of Cdc25B regulation. More work is needed to understand the regulation of Cdc25B stability by phosphorylation under steady-state and stress-induced conditions.

In conclusion, we identified a new site in Cdc25B for non-genotoxic stress-induced βTrCP binding and proved that SCF$^{\beta TrCP}$ is the responsible ubiquitin ligase. The newly identified site is DAG, which is thought to be inactive in βTrCP binding; it is surrounded by an upstream PEST-like sequence and a downstream SPSP. Our results suggest that the full phosphorylation of the PEST-like sequence and SPSP are required for βTrCP binding and that the new site and the previously reported DDG constitutive βTrCP binding site collaboratively regulate the stability of Cdc25B under both stress-induced and steady-state conditions. Cdc25B and Cdc25A are overexpressed in many tumours, and their overexpression is correlated with a poor prognosis (Kristjansdottir and Rudolph, 2004; Boutros et al., 2007). The uncontrolled

expression of Cdc25B is itself toxic, as it induces premature entry into M phase (Karlsson et al., 1999) and possibly genomic instability. Further studies that elucidate the regulation of Cdc25B stability should increase our understanding of the role of Cdc25B in cell cycle control and the contribution of the deregulation of Cdc25B stability to tumorigenesis.

Materials and Methods

Reagents and plasmids

Reagents of the highest grade were obtained from Wako (Osaka, Japan) or Sigma. The following siRNAs were purchased from Dharmacon: βTrCP1–βTrCP2 [denoted as pan-βTrCP siRNA in reports by Margottin-Goguet et al. and Guardavaccaro et al. (Margottin-Goguet et al., 2003; Guardavaccaro et al., 2003)], βTrCP1 (5′-UGACAACACUAUCAGAUUA-3′), and βTrCP2 (5′-GGACUUUAUUACCGCUUUA-3′). The validated stealth RNAi for JNK1 (5′-GGGCCUACAGAGAGCTAGUUCUUAU-3′) and JNK2 (5′-GCCCAAGGGAUUGUUUGUGCUGCAU-3′ and 5′-GCCAACUGUGAGGAAUUAUGUCGAA-3′) were obtained from Invitrogen. The siRNA for luciferase (5′-CGUACGCGGAAUACUUCGA-3′) was obtained from Qiagen. Anisomycin, SB202190, PD169316 and SP600125 were obtained from Calbiochem. The following cDNAs were used: human Cdc25B1, human Cdc25B3, mouse Cdc25B1, mouse p38α, mouse MKK6, mouse JNK1, mouse MKK7, human βTrCP1, human βTrCP2, human Skp1, human Skp2, human Cdc4, human Cul1 and mouse Rbx1. FLAG-, HA- and Myc-tagged expression plasmids were constructed using the pEF6/Myc-His vector, which includes the EF1α promoter (Invitrogen), as described elsewhere (Uchida et al., 2004). The mutant versions of the above cDNAs were generated by PCR-based mutagenesis, and their nucleotide sequences were confirmed by sequencing.

Antibodies and proteins

Active JNK1 kinase was purchased from Invitrogen. The rabbit antibody specific for Cdc25B S101-*P* was obtained from GenScript Corporation using NH_2-MD-*P*SPSPMDPHMAEC-COOH as the antigen. The rabbit antibodies specific for S103-*P*, and S101-*P* and S103-*P* were obtained from IBL (Japan) using NH_2-MDSP-*P*SPMDPHMAEC-COOH and NH_2-MD-*P*SP-*P*SPMDPHMAEC-COOH as the respective antigens. Each anti-phosphorylated antibody was affinity purified with antigen peptide before use. The antibodies purchased were as follows: mouse anti-TrCP1 was purchased from Zymed; Cdc25A (F-6), Cdc25B (C-20) and JNK1 (C-17) antibodies were from Santa Cruz Biotechnology; anti-actin, Myc tag (9B11), HA tag 262K, phosphoylated JNK–T183/Y185 (G9), MK2, Jun and phosphorylated Jun-S63II were obtained from Cell Signaling. The anti-Cdc25B (AF1649) was obtained from R&D Systems. Secondary antibodies labelled with horseradish peroxidase were purchased from DAKO. Anti-FLAG–M2-agarose beads were purchased from Sigma. The rabbit anti-FLAG serum was raised in-house. *E. coli*-produced GST-fused Cdc25B peptides encompassing $E^{82}SS$ to $S^{101}PSP$ and the phospho-mimetic mutant versions were purified from IPTG-induced BL21 cells with glutathione beads (GE Healthcare).

Cells, cell culture and siRNA or plasmid transfection

HeLa and Cos7 cells were grown in Dulbecco's modified Eagle's medium (DMEM) containing high glucose (Sigma) supplemented with 10% foetal bovine serum (FBS; Hyclone) and antibiotics. HeLa-W40 cells that constitutively expressed FLAG-tagged wild-type Cdc25B under the EF1α promoter were also cultured under the same conditions (Uchida et al., 2009). We also isolated HeLa cells constitutively expressing the FLAG-tagged $Cdc25B^{DAA}$ mutant (HeLa-DAA34 cells). In these cells, the expression of external Cdc25B was roughly 20- to 40-fold higher than that of endogenous Cdc25B. Plasmids were transiently transfected with Lipofectamine 2000 (Invitrogen). The amount of plasmid DNA used for transfection was ~500 ng for a six-well plate. HeLa and Cos7 cells were used for assays of stability (degradation) and for protein–protein interaction, respectively. The siRNA was transfected using Lipofectamine RNAiMAX (Invitrogen).

Biochemical methods and in vitro ubiquitylation assay

Crude extraction of proteins for analysis followed by immunoblotting or immunoprecipitation was performed as described previously (Uchida et al., 2004). The in vitro ubiquitylation assay was performed essentially as described previously (Watanabe et al., 2004). Briefly, HA-tagged Rbx1, Skp2 and Cul1, and Myc-tagged F-box proteins were coexpressed in Cos7 cells, and the SCF complex was recovered by immunoprecipitation with anti-Myc–agarose (MBL, Japan). [^{35}S]methionine-labelled Cdc25B was prepared with a TNT-coupled transcription and translation system (Promega). The reaction mixture in a total volume of 20 μl contained SCF-complex on beads, ^{35}S-labelled Cdc25B (2 μl), 20 μg bovine ubiquitin (Sigma), 0.8 μg human recombinant E1 enzyme (BIOMOL), 1 μg human 6xHis–Ubc5 (Wako, Osaka, Japan) and an ATP-regenerating system (2 mM ATP, 10 mM creatine phosphate, 0.35 IU/ml creatine kinase, 0.6 IU/ml inorganic pyrophosphatase), supplemented with 5 μM MG132, 0.5 μM okadaic acid and 1 μM ubiquitin-aldehyde (Boston Biochem). When necessary, recombinant active JNK1 (25 ng) was added to the reaction. The mixtures were incubated at 37°C for 2 hours, followed by sodium dodecyl sulphate–polyacrylamide gel electrophoresis (SDS-PAGE) in a 2–15% gradient gel, and the ubiquitylated Cdc25B was visualised using the FUJI BAS system.

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http://jcs.biologists.org/cgi/content/full/124/15/2816/DC1

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