ARTICLES

Shugoshin collaborates with protein phosphatase 2A to protect cohesin

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Sister chromatid cohesion, mediated by a complex called cohesin, is crucial—particularly at centromeres—for proper chromosome segregation in mitosis and meiosis. In animal mitotic cells, phosphorylation of cohesin promotes its dissociation from chromosomes, but centromeric cohesin is protected by shugoshin until kinetochores are properly captured by the spindle microtubules. However, the mechanism of shugoshin-dependent protection of cohesin is unknown. Here we find a specific subtype of serine/threonine protein phosphatase 2A (PP2A) associating with human shugoshin. PP2A colocalizes with shugoshin at centromeres and is required for centromeric protection. Purified shugoshin complex has an ability to reverse the phosphorylation of cohesin *in vitro*, suggesting that dephosphorylation of cohesin is the mechanism of protection at centromeres. Meiotic shugoshin of fission yeast also associates with PP2A, with both proteins collaboratively protecting Rec8-containing cohesin at centromeres. Thus, we have revealed a conserved mechanism of centromeric protection of eukaryotic chromosomes in mitosis and meiosis.

Sister chromatid cohesion is carried out by a multisubunit complex, cohesin, consisting of two SMC (structural maintenance of chromosome) family proteins—a kleisin subunit Scc1/Rad21 and an accessory subunit Scc3 (also called stromal antigen (SA) in animal cells)[1–3]. Cohesion is maintained until metaphase when sister kinetochores attach to microtubules emanating from the opposite spindle poles. The cohesion at centromeres is especially important at this stage, because the establishment of bipolar spindle attachment depends on the tension generated by the pulling force of spindle microtubules and the counteracting force of centromeric cohesion of sister chromatids[4]. Indeed, in animal mitotic cells centromeric cohesin (and cohesion) persists until metaphase, whereas most cohesin dissociates from chromosome arms during prophase and prometaphase to resolve sister chromatids[3]. At the onset of anaphase, the anaphase promoting complex (APC)-dependent degradation of securin allows the activation of a specific endopeptidase, separase, which in turn cleaves and cleans off residual chromosomal Scc1/Rad21, allowing the separation of sister chromatids[5]. Thus, the dissociation of cohesin is regulated by at least two mechanisms in animal cells. During meiosis, the temporally staggered release of arm and centromeric cohesion is most striking. At the first meiotic division (meiosis I), Rec8—which replaces Scc1/Rad21 in meiosis—is cleaved along chromosome arms but is protected at centromeres, where it is only cleaved during the second division (meiosis II)[6,7].

In yeast and probably most eukaryotes, shugoshin (Sgo/MEI-S332) protects meiotic Rec8-containing cohesin from separase cleavage at meiosis I[6–12]. Human shugoshin (hSgo1; also called shugoshin-like 1 (SGOL1)), which is also expressed during proliferation, protects cohesin at centromeres for mitosis[13–15]. Phosphorylation of the cohesin subunit SA2 (an Scc3 homologue) by Polo-like kinase 1 (Plk1) is critical for prophase dissociation because the inactivation of Plk1, or the expression of a non-phosphorylatable form of SA2, substantially blocks dissociation of cohesin in early mitosis[16–18]. Moreover, the dissociation of sister chromatids in hSgo1-depleted cells is suppressed by expressing this mutant SA2 (ref. 15). In budding yeast and human cells, phosphorylation of the Scc1 subunit by Plk1 enhances its cleavability by separase[17,19,20], and this may similarly apply for the meiotic counterpart Rec8 (refs 21, 22). Therefore, a mechanism to protect cohesin at centromeres might be to inhibit its phosphorylation, but no evidence for this has been obtained as yet. It is also unknown whether shugoshin uses a similar mechanism to protect centromeric cohesin in both mitosis and meiosis. Therefore, we have investigated the mechanism by which shugoshin protects cohesin at the centromere.

Shugoshin associates with protein phosphatase 2A

To better understand shugoshin function, we sought to identify associating proteins by tagging hSgo1 with the Flag epitope and expressing the fusion protein in human embryonic kidney (HEK) 293T cells. Anti-Flag immunoprecipitates were analysed using liquid chromatography, followed by tandem mass spectrometry (LC–MS/MS)[23]. The majority of peptides identified in the analysis were those of serine/threonine protein phosphatase 2A (PP2A) (Fig. 1a). PP2A is known to act as a heterotrimeric complex consisting of a core dimer of the catalytic C subunit (PP2A-C) and the scaffold A subunit (PP2A-A), which recruits a third variable regulatory B subunit (PP2A-B/PR55/B55, PP2A-B′/PR61/B56, PP2A-B″ or PP2A-B‴) that controls substrate specificity or localization of PP2A[24]. Our MS analysis identified both core subunits PP2A-A and PP2A-C, and most isoforms of the regulatory B56 subunit, but not any isoforms of other B subunits, suggesting that hSgo1 specifically associates with PP2A containing the B56 subunit. Immunoprecipitation analysis of endogenous hSgo1 supported this conclusion (Fig. 1b) and yeast two-hybrid assays suggested direct association of hSgo1 with the PP2A-B56 subunit (Supplementary Fig. 1).

If PP2A functions together with hSgo1, PP2A would localize at the centromere during mitosis. Immunostaining experiments in HeLa cells indicated that the α isoform of PP2A-B56 (PP2A-B56α)

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colocalizes with hSgo1 at centromeres from mitotic prophase to metaphase (Fig. 1c). The signals of both proteins decreased at the onset of anaphase. Immunostaining after chromosome spreading further indicated that PP2A-B56α localizes at the inner centromere between a pair of sister kinetochores (Fig. 1d), like hSgo1 (refs 14, 15, 25). When immunostaining for the core subunits, PP2A-A and PP2A-C, was performed in fixed cells, we found that the signals were dispersed throughout the cell (data not shown). However, by extracting mitotic cells before fixation, we could detect signals of PP2A-A and PP2A-C at centromeres in prometaphase cells but not in anaphase cells (Fig. 1e). Whereas PP2A-B56α localized only at the inner centromere, PP2A-A and PP2A-C were additionally found at spindle poles during mitosis (Fig. 1e and Supplementary Fig. 2b). These results suggest that the PP2A core complex localizes at various places within mitotic cells, including centromeres, but the PP2A complex containing the B56 subunit preferentially localizes at the inner centromere.

PP2A is required for the protection of centromeric cohesion

To directly assess the importance of PP2A for protecting sister chromatid cohesion at centromeres, we constructed short interfering (si)RNAs against *PP2A-A* and treated HeLa cells with them, which resulted in considerable reduction of PP2A-A protein (Fig. 2a). PP2A-A depletion resulted in an accumulation of mitotic cells, with the prometaphase population being particularly increased in number (Fig. 2b). Chromosomes were highly condensed and the number of spindle poles was often increased (Fig. 2c and Supplementary Fig. 2a), consistent with previous observations using okadaic acid, a potent PP2A inhibitor[26,27]. To examine centromeric cohesion, we spread the chromosomes of mitotic cells treated with *PP2A-A* siRNAs after incubation with nocodazole for 4 h. In control cells, only ~5% of mitotic cells showed separation of sister chromatids. In PP2A-A-depleted cells, however, ~15% of mitotic cells showed loosened or lost centromere cohesion, and ~30% showed sister chromatid separation (Fig. 2d, e). This separation occurred at prometaphase rather than anaphase, because most PP2A-A-depleted mitotic cells showed positive staining for cyclin B1 (Fig. 2b). Immunostaining of *PP2A-A* siRNA-treated cells with anti-Rad21 antibodies showed that cohesin localization was accordingly lost in prometaphase cells (Fig. 2f). The poor penetrance of the phenotype

a

Protein symbol	Protein name	Peptides
PPP2CA/PPP2CB	PP2A catalytic subunit C, α or β isoform	2
PPP2R1B	PP2A regulatory subunit A (PR65), β isoform	8
PPP2R5A	PP2A regulatory subunit B (B56), α isoform	7
PPP2R5B	PP2A regulatory subunit B (B56), β isoform	1
PPP2R5C	PP2A regulatory subunit B (B56), γ isoform	7
PPP2R5D	PP2A regulatory subunit B (B56), δ isoform	9
PPP2R5E	PP2A regulatory subunit B (B56), ε isoform	4
SET	SET translocation (leukaemia-associated)	5
PRO1855	Hypothetical protein PRO1855	1
RBM10/RBM5	RNA binding motif protein, 10 or 5	1
RPL10A	Ribosomal protein L10a	1
RPL28	Ribosomal protein L	1
RPL7	Ribosomal protein L7	1
RPL7A	Ribosomal protein L7a	1
RPLP1	Ribosomal protein, large, P1	1

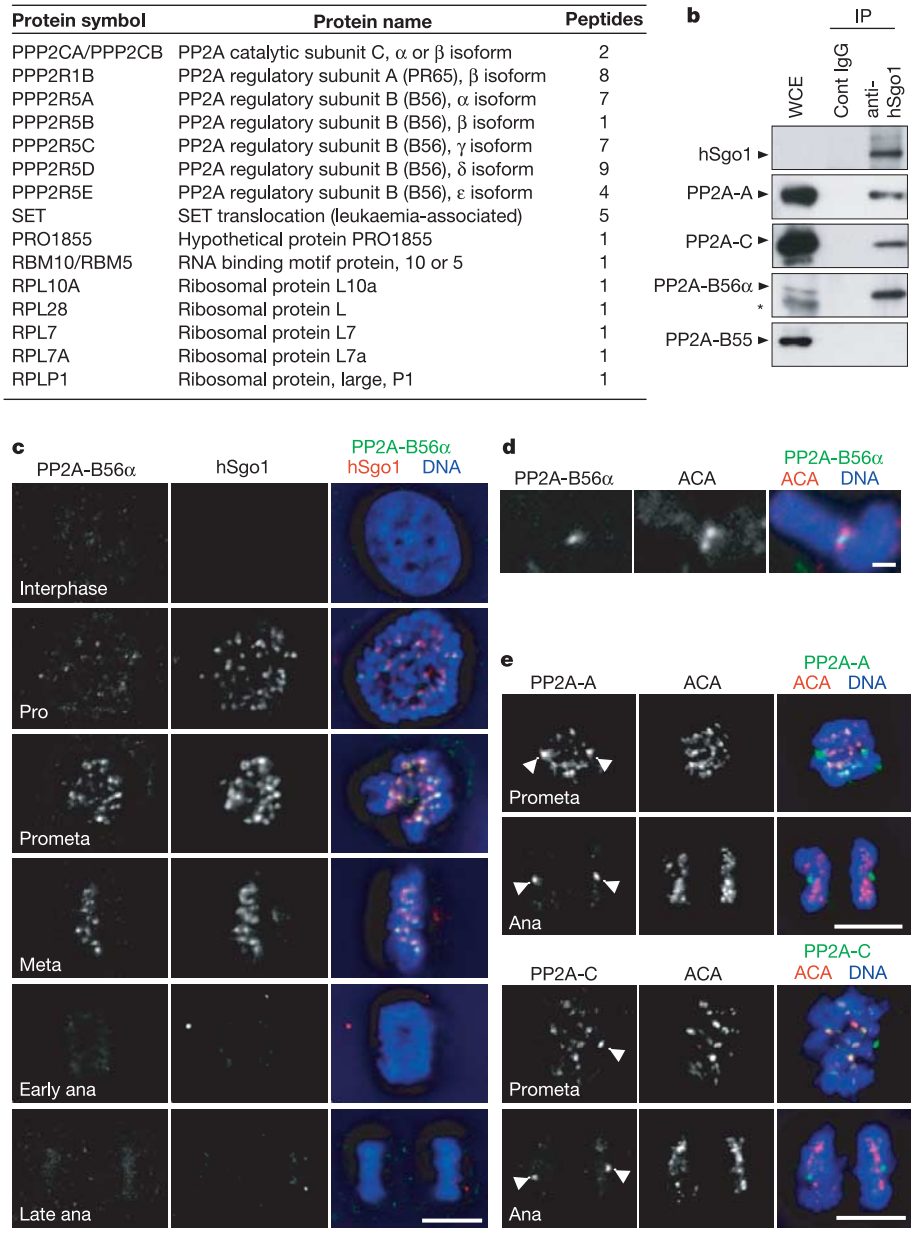

Figure 1 | PP2A associates and colocalizes with hSgo1. a, Proteins reproducibly detected in two independent hSgo1 immunoprecipitations by MS analysis are listed. The number of identified peptides of each protein is also shown. **b**, Immunoprecipitates (IP) from an extract of asynchronously growing HeLa cells, obtained using an anti-hSgo1 antibody or control (Cont) IgG, were analysed by western blotting using antibodies against the indicated proteins. An asterisk indicates a cross-reaction. WCE, 0.05% of the whole cell extract. **c**, HeLa cells were stained with anti-PP2A-B56α (green) and anti-hSgo1 (red) antibodies. DNA was counterstained using Hoechst 33342 (blue). PP2A-B56α colocalizes with Sgo1 at centromeres from mitotic prophase to metaphase in almost all cells ($n > 50$). Pro, prophase; Prometa, prometaphase; Meta, metaphase; Ana, anaphase. **d**, A single mitotic chromosome stained with anti-PP2A-B56α (green) and anti-centromere antibodies (ACA) (red). **e**, Mitotic cells were spun onto glass slides using a cytospin and pre-extracted before fixation. The cells were immunostained with anti-PP2A-A or anti-PP2A-C (green) and ACA (red). DNA was stained with Hoechst 33342 (blue). Signals on the spindle poles are indicated by arrowheads. Scale bars, 10 μm (**c**, **e**) and 1 μm (**d**).

after exposure to the *PP2A-A* siRNA can be explained by the residual amount of PP2A-A in the siRNA-treated cells (Fig. 2a), as a more severe phenotype was obtained by treating HeLa cells with okadaic acid (Supplementary Fig. 3). Taken together, we conclude that, like hSgo1, PP2A is required for centromeric protection of sister chromatid cohesion during prophase and prometaphase.

hSgo2 is required for the localization of PP2A at centromeres

Given that hSgo1 associates with PP2A, we examined the possibility that hSgo1 and PP2A require each other for their localization to centromeres (Fig. 3, and see also Supplementary Fig. 4). When PP2A-A was depleted by siRNA, centromeric hSgo1 signals became weakened (Fig. 3a), suggesting that PP2A has a role in facilitating hSgo1 localization to centromeres. In contrast, PP2A-B56 and PP2A-A localization was preserved at centromeres in the hSgo1-depleted cells (Fig. 3c, d), indicating that PP2A can associate with centromeres independently of hSgo1.

Human cells contain another shugoshin-like protein, hSgo2 (also known as SGOL2 and TRIPIN)[8], which has not been studied as yet. To gain a thorough understanding of the relationship between shugoshin and PP2A, we included hSgo2 in our analysis. We found that hSgo2 localizes at centromeres throughout prophase until metaphase, and disappears at anaphase (Supplementary Fig. 5), which is very similar to the localization of hSgo1 (refs 13–15, 25). Likewise, the depletion of hSgo2 using siRNA caused precocious dissociation of centromeric cohesin and separation of sister chromatids (Fig. 2), indicating that hSgo2 also functions in the centromeric protection of cohesin. The depletion of either hSgo1 or hSgo2 did not influence the localization of the other, indicating that they can independently localize to centromeres (Fig. 3a, b). Notably, the depletion of hSgo2 abolished the localization of PP2A (both the regulatory PP2A-B56 and core PP2A-A subunits) at centromeres (Fig. 3c, d). Consistent with this, PP2A coprecipitates with hSgo2; however, the association may occur through the core subunit PP2A-A

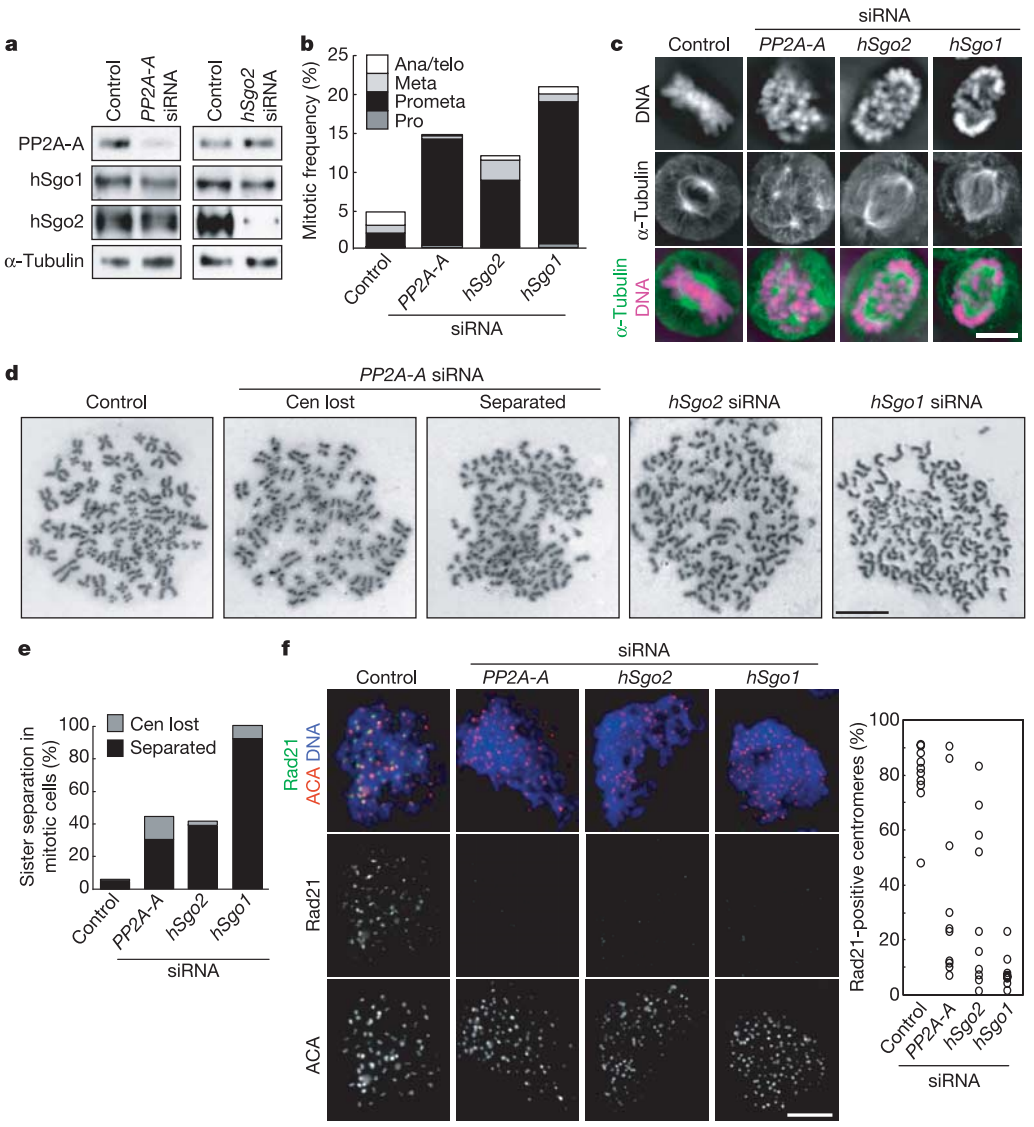

Figure 2 | PP2A is required for centromeric protection. **a**, Extracts from mitotic HeLa cells after exposure to siRNA were immunoblotted with the indicated antibodies. **b**, Mitotic index after siRNA treatment was determined by observing cell shape in living cells ($n > 560$). The mitotic phase was determined by staining for cyclin B1 and DNA in fixed cells ($n > 100$). **c**, Representative prometaphase or metaphase cells stained with anti-α-tubulin (green) and Hoechst 33342 (purple) are shown. **d**, **e**, Mitotic cells after siRNA exposure were treated with nocodazole for 4 h, and chromosomes were spread and stained with Giemsa (**d**). The frequency of cells showing sister chromatid separation ('Separated') or loss of centromeric cohesion ('Cen lost') was determined ($n > 100$) (**e**). **f**, Mitotic cells treated with the indicated siRNAs were spread by cytospin and stained with ACA (red) and anti-Rad21 (green). DNA was counterstained with Hoechst 33342 (blue). Average percentage of Rad21-positive centromeres are shown (one dot represents the average of positive centromeres within one cell). Scale bars, 10 μm (**c**, **d**, **f**).

rather than the regulatory subunit PP2A-B56 (Supplementary Figs 1 and 6). Curiously, when centromeric PP2A was displaced by *hSgo2* siRNA, hSgo1 localization was not impaired, although it was reduced by the depletion of PP2A (Fig. 3a). This may indicate that hSgo1 dynamically associates with centromeres, and that cytoplasmic PP2A may influence this interaction. If either hSgo1 or centromeric PP2A (using *hSgo2* siRNA) is absent from the centromere, the protection of sister centromeres is impaired, suggesting that both proteins collaboratively function at the centromere to protect the dissociation of cohesin.

The shugoshin complex counteracts phosphorylation of SA

Given that phosphorylation of the cohesin subunit SA2 (and presumably SA1) by Plk1 is critical for cohesin dissociation[17], we proposed that SA2 phosphorylation is counteracted by the shugoshin–PP2A complex at centromeres. To examine whether cohesin SA2 preserved around centromeres is indeed dephosphorylated *in vivo*, we prepared nocodazole-treated prometaphase cells in which cohesin is largely dissociated from the chromosome arms but tethered exclusively at centromeres, depending on shugoshin and PP2A (Fig. 2f). The cell extracts were fractionated into chromatin-bound and -unbound fractions, separated by SDS–polyacrylamide gel electrophoresis (SDS–PAGE), and blotted with anti-SA2 antibodies. As expected, SA2 showed slow electrophoretic migration in the prometaphase chromatin-unbound fraction, representing phosphorylation (presumably by Plk1)[17]. In contrast, chromatin-bound SA2 was mostly dephosphorylated (Fig. 4a). These results suggest that SA2 preserved at centromeres is dephosphorylated *in vivo*.

We next examined the biochemical properties of the shugoshin complex *in vitro*. We prepared a carboxy-terminal peptide of SA2 (SA2-C), in which most of the phosphorylation sites are included[17], and phosphorylated it with recombinant Plk1 *in vitro*. The phospholabelled SA2 fragment was then mixed with purified hSgo1 complex. The results show that immunoprecipitates of hSgo1 can dephosphorylate SA2-C, and that this phosphatase activity is inhibitable by okadaic acid (Fig. 4b). Similar phosphatase activity was detected in the hSgo2 immunoprecipitates. These phosphatase activities also dephosphorylated a C-terminal peptide of SA1 that had been phosphorylated by Plk1, but not histone H3 phosphorylated by Aurora B kinase, indicative of substrate specificity. Thus, the shugoshin complex has the ability to counteract the phosphorylation of Scc3/SA *in vitro*. Taken together, these results support the hypothesis that PP2A-dependent dephosphorylation of Scc3/SA prevents the dissociation of cohesin from centromeres, as part of the centromeric protection function of the shugoshin complex.

PP2A is required for centromeric protection in meiosis

Schizosaccharomyces pombe Sgo1 protects centromeric cohesin containing Rec8 from separase cleavage at meiosis I[8,9]. In a yeast two-hybrid screen searching for proteins that interact with Sgo1, we frequently isolated Par1—one of the PP2A-B56 homologues in fission yeast[28]. The interaction between Sgo1 and Par1 was confirmed by immunoprecipitation (Fig. 5a). In proliferating cells, Par1 localizes in the cytoplasm, and on the spindle pole body and the division septum (data not shown)[28,29]; however, it colocalizes with Sgo1 at centromeres during meiosis I (Fig. 5b). Sgo1 localization was not impaired in mutant *par1Δ* cells (data not shown). In contrast, the centromeric localization of Par1 was abolished in mutant *sgo1Δ* cells (Fig. 5c), indicative of the dependency of Par1 localization on shugoshin and reminiscent of the situation in human mitotic cells.

To examine whether Par1 is required for the protection of centromeric cohesin during meiosis, we analysed Rec8 localization at metaphase II—the period during which Rec8 is detected only at centromeres. We found that, like *sgo1Δ* cells, *par1Δ* cells mostly lost

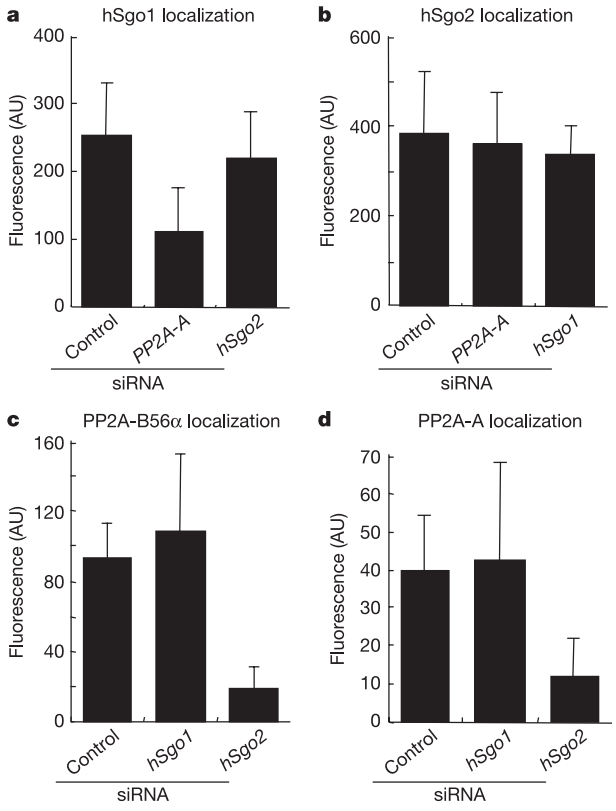

Figure 3 | Interdependency of shugoshin and PP2A for localization. **a**–**d**, Cells after siRNA treatment were stained with the indicated antibodies (**a**, hSgo1; **b**, hSgo2; **c**, PP2A-B56; **d**, PP2A-A; see also the representative stained cells in Supplementary Fig. 4). The intensities of the fluorescent centromeric signals in prometaphase cells were quantified as described in Methods. AU, arbitrary units. Error bars represent s.d. ($n = 20$).

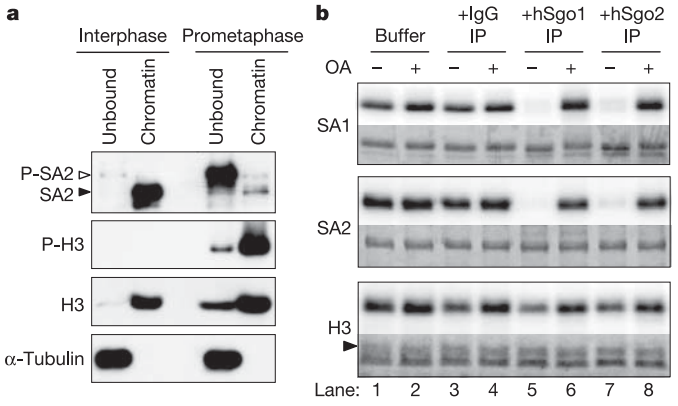

Figure 4 | Dephosphorylation of cohesin subunit SA. **a**, Chromatin-bound SA2 is dephosphorylated *in vivo*. Cell extracts prepared from interphase and prometaphase cells were fractionated into chromatin-bound and -unbound fractions and analysed by western blotting with the indicated antibodies. Four-times more of the chromatin-bound fractions were loaded. P-SA2, phosphorylated SA2; P-H3, histone H3 phosphorylated on Ser 10. In the mitotic chromatin-bound fraction, contaminated interphase chromatin is, if any, negligible (see Supplementary Fig. 9). **b**, Endogenous shugoshin associates with an okadaic-acid-inhibitable phosphatase activity that dephosphorylates cohesin subunit Scc3/SA. C-terminal peptides of SA1 or SA2 phosphorylated by Plk1, and a control histone H3 phosphorylated by Aurora B, were mixed with immunoprecipitation (IP) buffer (lane 1 and 2), control IgG immunoprecipitates (lane 3 and 4), immunoaffinity-purified hSgo1 (lane 5 and 6) or hSgo2 (lane 7 and 8) from HeLa cell extracts. Each sample was incubated in the presence (+) or absence (−) of 1 μM okadaic acid (OA) for 2 h. Autoradiography is shown in the upper panel, Coomassie blue staining in the lower panel.

centromeric Rec8 localization at this stage (Fig. 5d). Consistent with this observation, both of these mutant cell types showed precocious centromeric dissociation after meiosis I, and random chromosome segregation following meiosis II (Supplementary Fig. 7). *S. pombe* cells have another PP2A-B56 homologue, Par2, which is expressed at much lower levels[28] and contributes little to centromeric protection in meiosis (data not shown). Taken together, these results argue that, like Sgo1, Sgo1-associating PP2A (including Par1/PP2A-B56) has a crucial role in protecting cohesin at centromeres during meiosis I.

Individual protection ability of PP2A and shugoshin

Our current results in both human cells and fission yeast have raised the possibility that PP2A has an intrinsic ability to protect cohesin. Indeed, by ectopically localizing *S. pombe* Par1/PP2A-B56 to a specific site on a chromosome arm, we observed that the cohesion (and cohesin) at this site was partly preserved even after meiosis I—the period when arm cohesin should dissociate (Supplementary Fig. 8). To assess more thoroughly the individual ability of PP2A for centromeric protection, we used the 'ectopic protection system' in fission yeast, where coexpression of Rec8 and its protector blocks sister chromatid separation in mitosis, causing lethality[8]. We

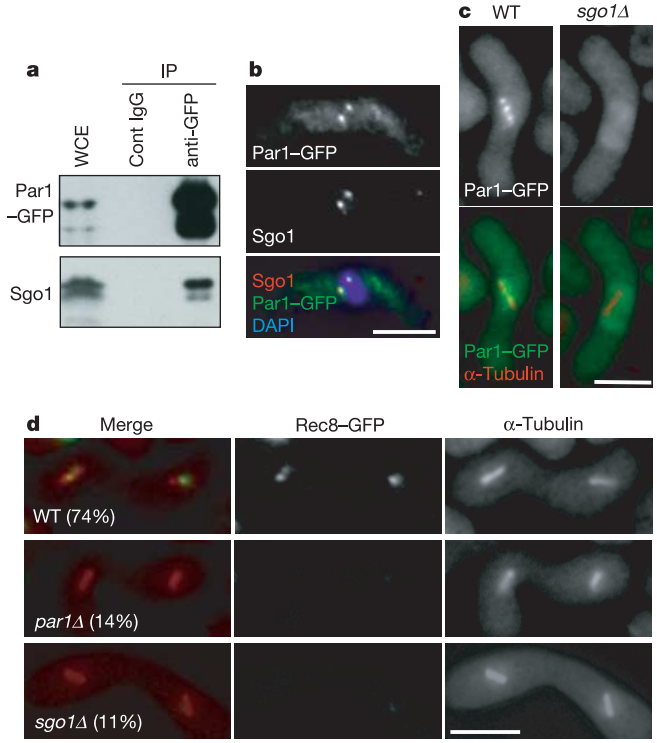

Figure 5 | *S. pombe* PP2A associating with Sgo1 is required for centromeric protection of Rec8-containing cohesin during meiosis I. **a**, Extracts, prepared from mitotic *par1*$^+$*–GFP* cells ectopically expressing Sgo1, were immunoprecipitated with control IgG or anti-GFP (green fluorescent protein) antibodies and analysed by western blotting using antibodies against GFP and Sgo1. WCE, 7.5% of the whole cell extract. **b**, Meiotic *par1*$^+$*–GFP* cells were arrested at metaphase I by repressing APC activation (*slp1*$^+$ and *cut23*$^+$ expression), and stained with DAPI (4,6-diamidino-2-phenylindole) and antibodies against Sgo1 and GFP. Colocalization was observed in most cells (95%, $n = 20$). **c**, As in **b**, fluorescence of Par1–GFP was examined at metaphase I in wild-type (WT) *sgo1*$^+$ and *sgo1Δ* cells. The spindles were visualized by expressing cyan fluorescent protein (CFP)–Atb2 (α2-tubulin). Par1–GFP was detected as dots in most metaphase I *sgo1*$^+$ cells (98%, $n = 219$), but never in *sgo1Δ* cells (0%, $n = 178$). **d**, The Rec8–GFP signal was monitored at prometaphase II in the indicated strains. Representative samples are shown together with the frequency of the cells showing centromeric Rec8–GFP ($n > 50$).

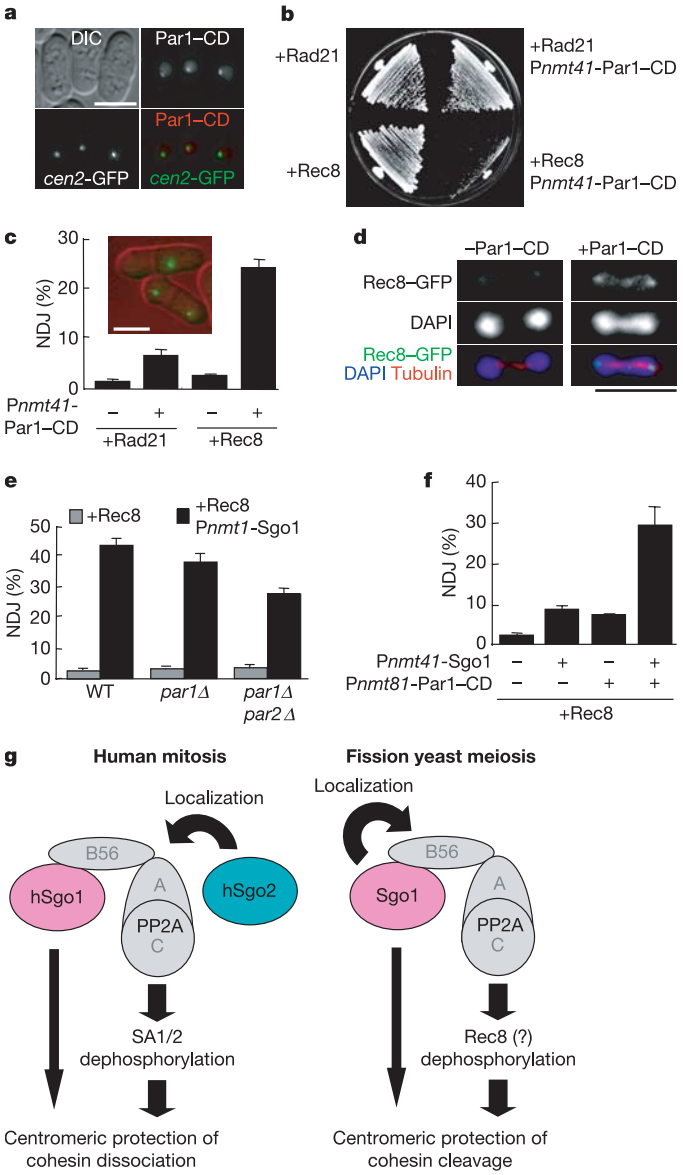

Figure 6 | Individual ability of PP2A and shugoshin for centromeric protection. **a**, Par1–CD proteins visualized by CFP localized in close vicinity to *cen2*-GFP in proliferating cells. **b**, The haploid *cen2-GFP* strains expressing the indicated genes by exogenous promoters (a constitutive promoter, P*adh1*, for *rad21*$^+$ and *rec8*$^+$, and a thiamine-repressible promoter, P*nmt41*, for *par1*$^+$*–CD*) were streaked on a thiamine-depleted plate. **c**, The strains in **b** were cultured at 30 °C for 15 h after thiamine depletion and the frequency of NDJ was counted among septated cells. Examples of *cen2*-GFP (green) in P*adh1-rec8*$^+$ P*nmt41-par1*$^+$*–CD* cells are shown. **d**, Centromeric Rec8–GFP signals are detected during anaphase in most *par1*$^+$*–CD*-expressing cells (81%) but in fewer non-expressing cells (19%). **e**, The indicated haploid *cen2-GFP* strains expressing Rec8 or Rec8 and Sgo1 (by the P*nmt1* promoter) were examined for the frequency of NDJ among septated cells. **f**, The haploid *cen2-GFP* P*adh1-rec8*$^+$ strains mildly expressing Sgo1 and/or Par1–CD were examined for the frequency of NDJ. Note the different strength of the thiamine repressible promoters (P*nmt1* > P*nmt41* > P*nmt81*). Error bars represent s.d. of triplicate samples (each $n > 100$) (**c**, **e**, **f**). Scale bars, 5 μm (**a**, **c**, **d**). **g**, Model for the collaboration of shugoshin and PP2A in protecting centromeric cohesin during human mitosis and fission yeast meiosis. PP2A containing the B56 subunit, which is recruited to the centromere by shugoshin (hSgo2 in human cells and Sgo1 in *S. pombe*), dephosphorylates cohesin subunits as a mechanism of protection. Human hSgo1 and *S. pombe* Sgo1 may have an individual activity for centromeric protection, apart from localizing PP2A to centromeres.

proposed that PP2A has an intrinsic ability to protect Rec8 without the help of Sgo1 once it is localized to centromeres. To test this, we endowed Par1 with its own ability to localize to centromeres by fusing its C-terminal end with the chromo domain (CD) of Swi6, which binds to Lys-9-methylated histone H3 largely locating at pericentromeric heterochromatin regions—the sites where Sgo1 usually localizes[8]. The engineered protein, Par1–CD, indeed localized at centromeres in mitotic cells in which Sgo1 is not expressed (Fig. 6a). Notably, coexpression of Par1–CD and Rec8 frequently led to blocked nuclear division, as centromere-associated *cen2*-GFP (green fluorescent protein) frequently segregated to the same side of a septated cell (Fig. 6b, c). This non-disjunction (NDJ) of sister chromatids presumably stems from persistent cohesion at anaphase because centromeric cohesin Rec8 was largely protected at this stage (Fig. 6d). Coexpression of Par1–CD with Rad21 caused a much weaker phenotype, indicative of the specificity of protection for the cohesin kleisin subunit (Fig. 6b, c). Finally, the protection is indeed executed by PP2A activity recruited by Par1–CD because the NDJ was suppressed by introducing a mutation in Ppa2, a major catalytic subunit of PP2A in fission yeast[30] (NDJ decreased from 24% to 7%). As Sgo1 is meiosis-specific and is not expressed in mitotic cells, these results demonstrate that centromeric localization of PP2A itself can protect Rec8 cohesin from cleavage, suggesting that dephosphorylation of cohesin Rec8 is a mechanism for the protection of sister centromeres in fission yeast.

We noticed that the ectopic protection mediated by Sgo1 overexpression was alleviated, but not abolished, when endogenous Par1 (or both Par1 and Par2) was depleted from the cells (Fig. 6e). This indicates that Sgo1 also has an individual ability to protect Rec8-containing cohesin without the aid of PP2A-B56 if sufficient amounts of protein are expressed. However, in physiological meiosis, this ability of Sgo1 is not sufficient to complement the loss of PP2A activity. The collaboration of Sgo1 and PP2A was further supported by the observation that coexpression of Sgo1 and Par1–CD mediated a synergistic effect on centromeric protection (Fig. 6f).

Discussion

In animal cells, most cohesin is removed from chromosome arms during prophase and prometaphase, triggered by Plk1-dependent phosphorylation of the Scc3/SA subunit of cohesin[17]. Here we have discovered that a B56-containing subtype of PP2A phosphatase associates with hSgo1 in human cells, playing a crucial part in preventing cohesin dissociation at centromeres. We have also demonstrated that chromatin-bound SA2 at centromeres is mostly dephosphorylated in prometaphase cells, whereas dissociated SA2 from the arms is phosphorylated (Fig. 4a). Furthermore, purified hSgo1 or hSgo2 complex can counteract Plk1-dependent SA phosphorylation *in vitro* (Fig. 4b). Thus, our results argue that dephosphorylation of Scc3/SA by shugoshin-associating PP2A is a mechanism for centromeric protection (Fig. 6g). Because dephosphorylated SA2 is detected only in the chromatin-bound fraction of cohesin, we suggest that the regulation takes place exactly at the sites where shugoshin–PP2A complexes localize. Previous results suggested that Plk-dependent phosphorylation of Scc1/Rad21 facilitates its cleavage by separase but is not essential[17,19,20], whereas phosphorylation of Rec8 might be crucial for cleavage[21,22]. Here we have demonstrated that *S. pombe* Par1/PP2A-B56 associating with Sgo1 is required and even sufficient for protecting cohesin Rec8 from separase cleavage. Moreover, PP2A-dependent cohesin protection requires the kleisin subunit Rec8 (Fig. 6b, c), suggesting that the extent of phosphorylation and/or its contribution to the susceptibility to separase cleavage is different between Scc1/Rad21 and Rec8. These results are consistent with the notion that PP2A activity counteracts the phosphorylation of Rec8, thereby protecting it from separase cleavage during meiosis I. Chromosome segregation in mouse meiosis is also disturbed by okadaic acid treatment, which results in premature separation of sister chromatids during meiosis I[31]. Thus, the shugoshin–PP2A system found in *S. pombe* meiosis is presumably applicable to mammalian meiosis. Taken together, centromeric protection of eukaryotic chromosomes may be executed at the level of dephosphorylation of cohesin subunits, and a subtype of PP2A containing the B56 subunit has a direct role in this process. This concept is applicable for both mitosis and meiosis, albeit the crucial target of dephosphorylation is different, being Scc3/SA in mitosis and Rec8 in meiosis (Fig. 6g).

The depletion of hSgo1 by siRNA caused precocious separation of centromeric cohesion (Fig. 2), although the centromeric localization of PP2A is preserved (Fig. 3c, d), suggesting that protection is not solely executed by linking PP2A to centromeres. Moreover, *hSgo2* siRNA caused fewer defects in protection than *hSgo1* siRNA (Fig. 2e). Therefore, hSgo2 might solely be required to tether PP2A to centromeres, whereas—besides facilitating PP2A function at centromeres—hSgo1 might have an additional role in protection (Fig. 6g). Supporting this notion, ectopic expression of *S. pombe* Sgo1 and Rec8 can enforce centromeric protection even in PP2A-B56-depleted cells (Fig. 6e). Because shugoshin closely associates with cohesin *in vivo*[8,12,32], we favour the possibility that Sgo1 physically protects cohesin against access by an inactivating enzyme (for example, Plk1 in human mitosis and Plk or separase in fission yeast meiosis). As Plk is suggested to phosphorylate and delocalize Sgo/MEI-S332 in *Drosophila*[33], PP2A might facilitate the localization of shugoshin, which is supported by our observation that hSgo1 localization partly depends on PP2A (Fig. 3a). Thus, shugoshin and PP2A may support each other, collaboratively protecting cohesin at centromeres. *S. pombe* Sgo1 has roles in both recruiting PP2A and protecting cohesin *per se* at centromeres. In contrast, hSgo1 is dispensable for localizing PP2A to centromeres but is required for centromeric protection, whereas hSgo2 is required for the recruitment of PP2A to centromeres, implying a 'division of labour' between these two shugoshin-like proteins in human cells. Thus, the interplay of shugoshin and PP2A is apparently conserved across human and fission yeast, or mitosis and meiosis (Fig. 6g).

PP2A is a family of abundantly expressed protein phosphatases, the activity of which is highly regulated and implicated in a multitude of cellular processes, such as signal transduction, development and tumorigenesis[34]. Chromosome mis-segregation in mitosis may contribute to tumorigenesis. Meiotic chromosome segregation is also important clinically, as failures in this process cause birth defects in humans. Our study may provide a novel link between PP2A and tumorigenesis or birth defects, and therefore is useful for future studies in those fields as well.

METHODS

Antibody production and immunofluorescence microscopy. Antibody production and immunofluorescence staining were performed as described in Supplementary Methods.

Quantification of fluorescent signals. To quantify the centromeric fluorescent signals, in-focus images of the cyclin B1-or phospho-H3-positive prometaphase cells were taken with the use of MetaMorph imaging software (Universal Imaging). We measured the maximum intensity among the centromeric signals within the cell and subtracted the background intensity of the region, which was measured directly adjacent to the centromere.

RNA interference. Synthetic sense and antisense siRNA oligonucleotides for *hSgo1* (ref. 14) and *hSgo2* (5′-GCACUACCACUUUGAAUAATT-3′), *PP2A-Aα* (5′-AGACUUGACAUGUUGGUUGTT-3′) and *PP2A-Aβ* (5′-UUUCUACUCC AAGUGCUAGTT-3′) were obtained from JbioS. Note that PP2A-B56 consists of five isoforms, whereas the PP2A-A core subunit has only two isoforms. Therefore, we constructed siRNAs against PP2A-A isoforms, rather than PP2A-B56 isoforms, to reduce PP2A activity. The presented data were obtained using the abovementioned siRNAs, but we confirmed that similar results were obtained by using another set of siRNAs: *hSgo2* (5′-GCUCUCAUGAACAAUAACUTT-3′), *PP2A-Aα* (5′-GCAUCAAUGUGCUGUCUGATT-3′) and *PP2A-Aβ* (5′-CGAC UCAACAGUAUUAAGATT-3′). Cells at 20% confluency in Opti-MEM medium (Invitrogen) were transfected with siRNA duplexes at a final concentration of 400 nM and Oligofectamine (Invitrogen) at 1:250, and complete medium containing 20% FBS was added at 1:1 after 6 h. After two days incubation, the

cells were examined. All control samples were similarly treated but were exposed to H_2O instead of siRNA reagent.

Preparation of HeLa cell extracts. Preparation of HeLa cell extracts and subsequent immunoprecipitation or fractionation are described in Supplementary Methods.

***In vitro* dephosphorylation assay.** To generate phosphorylated SA substrates, a 6 × His-tagged SA1 C-terminal peptide (amino acids 923–1258) or SA2 C-terminal peptide (amino acids 895–1232) was expressed in *Escherichia coli* strain BL21 and purified with Ni-NTA agarose (Qiagen), and labelled with [γ-^{32}P]ATP using recombinant Plk1 kinase (ref. 35). As a control, core histone proteins were labelled with [γ-^{32}P]ATP by recombinant Aurora B kinase. The immunoprecipitated complexes from HeLa cell extracts were collected after washing with immunoprecipitation buffer without phosphatase inhibitors (20 mM Tris-HCl, pH 7.5, 100 mM NaCl, 0.1% Tween 20, 10% glycerol and 10 mM β-mercaptoethanol). The equivalent of 3 μl of immunoprecipitated beads was preincubated with 1 μM of okadaic acid or dimethylsulphoxide (DMSO) for 20 min at room temperature (~20 °C), followed by the addition of ^{32}P-labelled SA substrates in a dephosphorylation buffer (50 mM Tris-HCl, pH 7.5, 100 mM NaCl, 0.01% Brij35, 2 mM $MnCl_2$, 0.1 mM EGTA, 2 mM dithiothreitol (DTT)) supplemented with 1 μg of BSA to a total reaction volume of 15 μl and incubated for 2 h at 30 °C with gentle agitation.

Chromosome spreading. Mitotic HeLa cells were collected by mitotic shake-off and treated with 330 nM nocodazole for 4 h. Chromosome spreading was performed as described previously[36].

Yeast experiments. All *S. pombe* strains used are listed in Supplementary Table 1. General methods for immunoprecipitation, culturing *S. pombe*, inducing meiosis and monitoring chromosome segregation were as described previously[8]. Further details of *S. pombe* experiments, as well as the yeast two-hybrid assay, are described in Supplementary Methods.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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