Shelterin components mediate genome reorganization in response to replication stress

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The dynamic nature of genome organization impacts critical nuclear functions including the regulation of gene expression, replication, and DNA damage repair. Despite significant progress, the mechanisms responsible for reorganization of the genome in response to cellular stress, such as aberrant DNA replication, are poorly understood. Here, we show that fission yeast cells carrying a mutation in the DNA-binding protein Sap1 show defects in DNA replication progression and genome stability and display extensive changes in genome organization. Chromosomal regions such as subtelomeres that show defects in replication progression associate with the nuclear envelope in *sap1* mutant cells. Moreover, high-resolution, genome-wide chromosome conformation capture (Hi-C) analysis revealed prominent contacts between telomeres and chromosomal arm regions containing replication origins proximal to binding sites for Taz1, a component of the Shelterin telomere protection complex. Strikingly, we find that Shelterin components are required for interactions between Taz1-associated chromosomal arm regions and telomeres. These analyses reveal an unexpected role for Shelterin components in genome reorganization in cells experiencing replication stress, with important implications for understanding the mechanisms governing replication and genome stability.

Shelterin | genome organization | replication | DNA damage | telomeres

The 3D organization of the eukaryotic genome creates specialized microenvironments that play important roles in various nuclear processes (1). In addition to regulation of gene expression, proper execution of the DNA replication program and DNA damage repair also involve dynamic organization of the genome (2, 3). Indeed, computational analyses indicate spatial segregation of replication origins based on their timing of firing during S-phase (4), suggesting that besides local chromatin structure, the 3D organization of chromosomes is an important contributing factor in the spatiotemporal control of replication (5, 6). Despite important advances, understanding the connections between diverse chromosomal events and genome organization remains an important challenge.

The complexities of genome organization have been studied in several model organisms, including the fission yeast *Schizosaccharomyces pombe*, for which the 3D organization has been explored at high resolution (7, 8). This simple eukaryote contains the basic chromosomal elements of more complex systems, including partitioning of the genome into euchromatin and heterochromatin domains. The *S. pombe* genome conforms to a Rabl organization pattern in which centromere clusters and telomere clusters are anchored at opposing sides of the nuclear periphery (9, 10). In addition, two key elements shape genome architecture: cohesin-dependent locally crumpled 50- to 100-kb repeating elements called "globules" on chromosome arms and the constraints imposed by the compaction of the chromatin fiber by heterochromatin domains such as at pericentromeric regions (8). The relatively small size of the *S. pombe* genome combined with the conserved genome organizational features provides an ideal system to explore connections between genome form and function.

Here, we show that cells carrying a mutation in the essential DNA-binding protein Sap1 display defects in replication progression, experience DNA damage, and undergo widespread genome reorganization. We find that several chromosomal arm regions associate specifically with telomeres in the *sap1* mutant. These interaction regions are generally adjacent to replication origins bound by Taz1 (11, 12), a counterpart of human TRF1/2 and a component of the Shelterin complex involved in telomeric end protection (13–15) and facilitation of proper replication of telomeres (16). Interestingly, Shelterin components are required to promote contacts between telomeres and chromosomal arm regions. We discuss the implications of these findings for understanding the mechanisms that ensure proper replication and protect genome stability.

Results

Defect in the Sap1 Protein Affects Genome Organization. Sap1 is an abundant nuclear protein that binds specific DNA elements distributed across the genome (17, 18). Multiple functions for Sap1 have been proposed, including a role in replication fork blocking (19–21), replication checkpoint activation (22), and genome organization (17). To gain further insight, we examined Sap1 subcellular localization. As previously shown (17), the Sap1 signal is concentrated within the nucleus in a diffuse pattern (Fig. S1*A*);

Significance

Genome organization affects many critical nuclear functions. Notably, the nuclear periphery has emerged as a specialized compartment for the regulation of transcription, replication, and DNA damage repair activities. Here, we find that cells carrying a mutation in the broadly distributed DNA-binding protein Sap1 experience replication stress and genome instability and undergo a genome reorganization featuring new contacts between chromosome arms and telomeres. These prominent new interactions are mediated by the Taz1–Shelterin telomere protection complex and include specific chromosome arm regions containing replication origins bound by Taz1. Our findings uncover an unexpected role for Shelterin in mediating genome reorganization in cells undergoing replication stress.

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however high-resolution microscopy revealed that Sap1 forms a matrix-like pattern (Fig. 1*A*). This localization was particularly interesting given the widespread distribution of Sap1 across the genome, including at solo LTRs and 13 copies of full-length *Tf2* retrotransposons (18), which are organized into nuclear foci (called "Tf bodies") in close proximity to the nuclear envelope (NE) (23, 24).

We considered that Sap1 binding to *Tf2* might be required for Tf body organization. To explore this possibility, we used a partial loss-of-function mutant, *sap1-1* (22). At restrictive temperature, *sap1-1* showed loss of Sap1 nuclear signal (Fig. S1*A*). Unlike the widely distributed WT Sap1 showing distinct peaks at nucleosome-free regions, the mutant protein was stable but unable to bind broadly across the genome (Fig. S1 *B*–*D*). ChIP analysis showed depletion of the mutant Sap1 from *Tf2* (Fig. 1*B* and Fig. S1*C*) correlating with an increase in *Tf2* foci in *sap1-1* cells (Fig. 1*C*), suggesting that Sap1 may have a role in clustering *Tf2* into Tf bodies.

Defects in Tf body organization in *sap1-1* cells might reflect broader changes in genome organization. We tested this possibility by performing FISH analysis of the *rtn1* locus, which was enriched for Sap1 binding in WT cells but was depleted in *sap1-1* cells (Fig. 1*B*). Compared with WT cells, the radial positioning of *rtn1* relative to the NE protein Bqt4 (25) was shifted more to the nuclear interior in *sap1-1* cells (Fig. 1*D*). Taken together, our results suggest that a defect in Sap1 affects genome organization, as indicated by disruption of Tf bodies and the altered positioning of other chromosome loci.

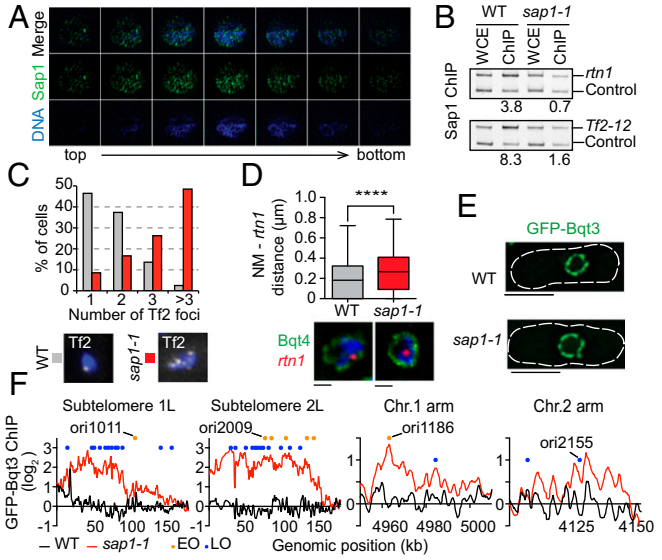

Fig. 1. Mutation in *sap1* affects the spatial positioning of chromosomes. (*A*) High-resolution microscopy analysis of Sap1 localization with DAPI staining. Images spanning from the top to the bottom of the cell are shown. (*B*) Sap1 ChIP-PCR analysis of *Tf2-12* and *rtn1* loci in WT and *sap1-1* cells. Relative ChIP enrichment is shown below. (*C*, *Upper*) FISH analysis of *Tf2* foci. The number of *Tf2* spots per cell was determined for WT and *sap1-1* cells. (*Lower*) Representative images are shown with DAPI staining. $n = 198$ for each strain. Images were collected using a 100 × 1.4 numerical aperture (NA) lens. (*D*, *Upper*) The position of the *rtn1* locus relative to the NE was determined by IF-FISH. (*Lower*) The box-plot diagram shows the distance distribution between the *rtn1* FISH signal and the NE (GFP-Bqt4). $^{****}P \leq 0.0001$ (three independent experiments, total $n = 457$ for WT and $n = 393$ for *sap1-1* cells; two-tailed Mann–Whitney test). (Scale bars, 0.5 μm.) (*E*) Focal plane images of WT and *sap1-1* cells expressing GFP-Bqt3. (Scale bars, 5 μm.) (*F*) GFP-Bqt3 ChIP enrichment across the subtelomeric region and several chromosomal arm regions in WT and *sap1-1* cells. Orange and blue circles represent early- and late-replication origins, respectively, as annotated by Hayashi and colleagues (48).

Nuclear Peripheral Association of Regions Containing Replication Origins in the *sap1* Mutant. Our results prompted us to perform a global analysis of genome positioning with respect to the nuclear periphery. To examine peripheral contacts, we performed ChIP-chip analysis of the nuclear membrane marker GFP-Bqt3 (25) and compared the contacts made with chromosome regions in WT and *sap1-1* cells. Importantly, GFP-Bqt3 decorated the NE in both WT and *sap1-1* cells (Fig. 1*E*). In agreement with the Rabl arrangement, specific regions of chromosomes associated with GFP-Bqt3. For example, GFP-Bqt3 was preferentially enriched at the centromere cores and telomeric regions of all three chromosomes (Fig. S2 *A* and *B*). In addition, we observed Bqt3 enrichment at *tRNA* clusters located at the heterochromatin boundaries of centromere 2 (Fig. S2*B*). Interestingly, GFP-Bqt3 remained associated with centromeres and telomeres in *sap1-1* cells and gained association with extended subtelomeric domains (>100 kb from each telomere) of chromosomes 1 and 2 but not chromosome 3 (Fig. 1*F* and Fig. S2*C*). Moreover, several regions of the chromosome arm showed GFP-Bqt3 enrichment in *sap1-1* cells, indicating a newly formed association with the nuclear periphery (Fig. 1*F* and Fig. S2*C*), whereas other regions, such as *tRNA* clusters, lost association with GFP-Bqt3 (Fig. S2*B*). These results demonstrate genome-wide changes in the contacts made with the NE in *sap1-1*.

Strikingly, we noticed that most regions that gained association with GFP-Bqt3 contained DNA replication origins (Table S1). The newly formed genomic contacts at extended subtelomeric domains coincided with late origin cluster zones (Fig. 1*F* and Fig. S2*C*) (11). The specific association of selected chromosome regions containing origins with the nuclear periphery in *sap1-1* cells suggested a possible connection between DNA replication activity and genome reorganization.

The *sap1* Mutant Shows DNA Replication Defects. We next examined if *sap1-1* affects DNA replication. To do so, we used the *cdc10-v50* mutant to synchronize cells and monitor DNA replication progression from G1 arrest. FACS analysis revealed that *sap1-1* cells spent a comparatively longer time in S-phase than WT cells (Fig. 2*A*), suggesting possible defects in replication in the mutant cells. To test for such defects, we examined the genome-wide replication profile by measuring BrdU incorporation in WT and *sap1-1* cells released from G1 arrest in the presence of hydroxyurea (HU). As expected, efficient firing of replication origins occurred in WT cells (Fig. S3*A*). However, BrdU incorporation in *sap1-1* cells was inefficient, particularly at subtelomeric regions containing clusters of late-replication origins that showed replication in this experimental set-up involving *cdc10-v50* (Fig. 2*B* and Fig. S3*B*). Some chromosomal arm regions that showed association with GFP-Bqt3 in *sap1-1* cells also showed low BrdU enrichment (Fig. 2*B*).

To investigate the effect of *sap1-1* on replication further, we examined its impact on the genome-wide distribution of Mcm6 protein during S-phase. Mcm6 is a component of the MCM (mini chromosome maintenance) complex, which is a putative DNA replicative helicase required for replication initiation and elongation (26). We found a striking reduction of Mcm6 in *sap1-1* cells, particularly between replication origins, as is consistent with abnormal replication progression (Fig. 2*C* and Fig. S3 *C* and *D*). Thus, global replication defects are indeed associated with loss of Sap1 function; however, the exact mechanism remains unknown.

***sap1* Mutant Cells Accumulate ssDNA and DNA Damage-Repair Foci.** Cells that experience replication stress tend to accumulate ssDNA, which can lead to genome instability (27, 28). To detect ssDNA, we quantified the number of Rad11 foci. Rad11 is a component of an ssDNA-binding complex called "replication protein A" (RPA), which is involved in DNA replication and/or DNA damage repair (28). Generally, WT S-phase cells have multiple faint Rad11 signals, and some mononucleated cells form a discrete single Rad11 focus in the nucleolus. However, we observed a significantly higher

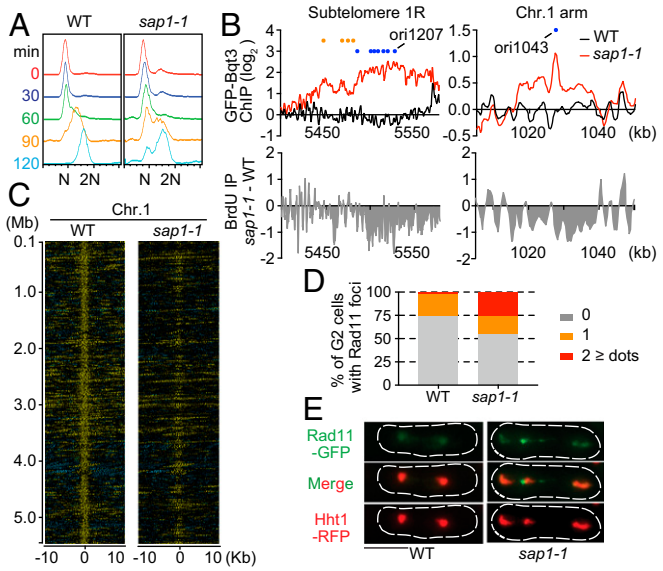

Fig. 2. *sap1-1* impacts DNA replication. (*A*) FACS profile of DNA content in WT and *sap1-1* cells. Cells carrying the *cdc10-v50* mutation were arrested in G1 and then released. Numbers on the left indicate the time in minutes after the release. (*B*) DNA replication profile in WT and *sap1-1* cells. The differences in BrdU incorporation were plotted across subtelomeric domains and at certain chromosome arm regions that gained association with Bqt3 in *sap1-1* cells. GFP-Bqt3 ChIP enrichment in WT and *sap1-1* is shown on the top. Orange and blue circles represent early- and late-replication origins, respectively. (*C*) Heat maps of Chr.1 for both WT and *sap1-1* cells showing the Mcm6 ChIP signal around replication origins (10-kb regions). (*D*) Rad11-GFP forms discrete foci in *sap1-1* cells. Cells expressing Rad11-GFP (green) and Hht1(histone H3)-RFP (red) were grown at 33 °C for 6 h. The percentage of mononuclear cells with Rad11-GFP foci ($n = 84$ for WT and $n = 103$ for *sap1-1* cells) is shown. (*E*) Mitotic cells expressing Rad11-GFP (green) and Hht1-RFP (red). *sap1-1* cells enter mitotic nuclear division in the presence of Rad11 foci. Chromatin (Hht1-RFP) appears fragmented and lags during the M-phase in *sap1-1* cells. Rad11-GFP forms a fine bridge between the daughter nuclei and is enriched near fragmented chromatin masses. (Scale bar, 5 μm.)

number of *sap1-1* cells than WT cells displaying two or more Rad11 foci in the chromatin hemisphere (Fig. 2*D* and Fig. S4*A*). Moreover, time-lapse microscopy revealed that *sap1-1* cells with Rad11 foci enter mitosis, resulting in the fragmentation of chromosomes (Fig. 2*E*, Fig. S4*B*, and Movies S1 and S2). This result indicates that replication stress may be a potential source of genome instability in *sap1-1* cells.

We also examined DNA damage-repair foci formation by monitoring the homologous recombination (HR) factor Rad52. Consistent with previous work (22), ~55% of *sap1-1* cells contained one or more Rad52 foci, whereas 11% of WT cells contained a single Rad52 focus (Fig. S4*C*). Furthermore, *sap1-1 rad52Δ* double-mutant cells showed a synthetic growth defect (Fig. S4*D*). Taken together, our study and others suggest that cells carrying a mutation in Sap1 experience problems with replication progression, ultimately resulting in the accumulation of DNA damage (22).

The *sap1-1* Genome Contains Rearrangements. Replication defects and DNA damage in *sap1-1* cells could cause genome instability, such as chromosomal rearrangements. Interestingly, *sap1-1* cells frequently produced revertants capable of growing at an otherwise nonpermissive temperature (37 °C) (Fig. 3*A*). Microarray comparative genome hybridization (CGH) analysis of a revertant showed amplification of the region encompassing the *sap1-1* locus (Fig. 3*B* and Fig. S5*A*). We confirmed the duplication of this region, which resulted in a slight increase in Sap1 mutant protein (Fig. S5*B*). The boundaries of the amplified region contain *wtf* (repeats often associated with *Tf LTRs*) bound by Sap1 in WT cells (Fig. 3*B*). Junction PCR analysis and subsequent Sanger sequencing revealed that the copy number gain resulted from direct tandem-oriented duplication (Fig. 3*C* and Fig. S5 *C* and *D*).

This rearrangement likely confers a survival advantage from the amplification of the *sap1-1* region and suppression of the mutant phenotype. However, we found a more widespread destabilizing effect that involved other repeat structures, including *wtfs* in other parts of the *sap1-1* genome. In addition to *wtfs* that flank *sap1*, recombination occurred between other tandem copies of *wtfs* (such as *wtf18–wtf13*) in *sap1-1* cells cultured at a semipermissive temperature (33 °C) (Fig. 3*C*). We also detected rearrangements in the subtelomeric repeats (Fig. S5*E*). These results clearly show that *sap1-1* is prone to more widespread genome instability.

Because substrates for recombination can be generated by stalled or collapsed replication forks (29), we looked for replication defects at *wtf* elements. Indeed, 2D gel analysis revealed prominent replication fork pausing at the *wtf9* region in *sap1-1* cells (Fig. 3*D*). We also found that Rad52 was required for tandem duplication mediated by *wtf* repeats (Fig. S5*F*). Strikingly, *sap1-1* cells lacking the well-defined checkpoint effector kinases Chk1 or Cds1 showed increased rearrangements (Fig. 3 *A* and *E*), suggesting that components of DNA damage and replication checkpoints are critical for suppressing genome instability in *sap1-1* cells.

We also tested whether de-repression of *wtf* elements could be involved in promoting rearrangement. The histone deacetylases Clr3 and Clr6 have been implicated in the repression of *wtf* (30). However, defects in the histone deacetylases had no effect on *wtf*-mediated genomic rearrangements (Fig. S5*G*). Therefore, de-repression of *wtf* alone is not sufficient to trigger rearrangements. Rather, genome instability in *sap1-1* is linked to defective replication

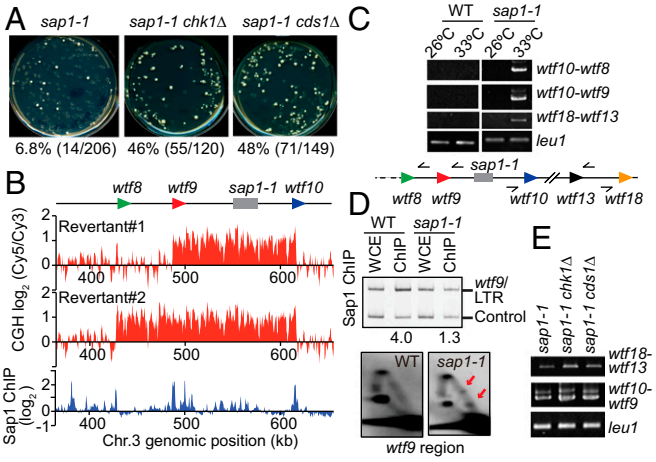

Fig. 3. Sap1 promotes genome integrity. (*A*) Frequency of revertant generation in *sap1-1* cells. The percentage of revertants (number of revertants/total number of colonies) is shown below. (*B*) Array CGH analysis of two independent revertants. The $\log_2$ (cy5/cy3 signal ratio) is shown across copy number gain regions in chromosome 3. Relative genomic positions of the *sap1* gene and *wtf* elements are shown on the top (not to exact scale). ChIP-chip of Sap1 is shown below. (*C*) Junction PCR to detect *wtf*-mediated duplication. The *sap1-1* strain was successively cultured at a semipermissive temperature (33 °C) in liquid medium. *leu1* was used as a PCR control. Arrowheads indicate divergently oriented primers used for junction PCR. (*D*) Sap1 ChIP-PCR (*Upper*) and 2D gel analysis (*Lower*) of the *wtf9* region. Relative ChIP enrichment is shown below the panel. Arrows in 2D gel analysis indicate fork pausing signals. (*E*) Junction PCR analysis of the indicated mutant strains. *leu1* was used as a PCR control.

and DNA damage repair and is also accompanied by alterations in 3D genome organization.

Genome-Wide Chromosome Conformation Capture Analysis Reveals Specific Interactions in the *sap1* Mutant. To obtain a detailed view of genome contacts in *sap1-1*, we performed genome-wide chromosome conformation capture (Hi-C) analyses. Two biological replicates were generated for both WT and *sap1-1* cells. The Hi-C contact maps were highly reproducible. We found that previously described features of genome organization such as centromere and telomere clusters and heterochromatin-mediated intra- and interchromosomal arm interactions observed within centromere proximal regions were unaffected in *sap1-1* cells (Fig. 4*A* and Fig. S6*A*). Scaling analysis revealed a slow decay in contact probability at distances <100 kb followed by a faster decay in *sap1-1* cells, as in WT cells (Fig. S6*B*), indicating the existence of globules. Indeed, cohesin-dependent globules along chromosome arms were evident in *sap1-1* cells, and the depletion of contact frequency (insulation) between regions separated by cohesin-bound globule boundaries was not affected (Fig. S6*C*). Consistently, the binding profile of cohesin subunit Psc3 was unchanged in *sap1-1* cells (Fig. S6*D*).

Strikingly, our analyses revealed several prominent new contacts in the *sap1-1* mutant that were not visible in WT cells. These contacts could be detected in *sap1-1* cells cultured at semipermissive temperature for only 6 h. A common feature among all new contacts was the involvement of telomeric regions of chromosomes 1 and 2 (Fig. 4*B*). We observed newly formed contacts between the subtelomeric regions of the two short arms (*tel1R* and *tel2L*) and all three centromeres (Fig. 4*B*). Intriguingly, we also observed prominent interactions between telomeres and specific arm regions (Fig. 4*B*). These interactions were mainly restricted to the arms of chromosomes 1 and 2 and were not observed on chromosome 3 (Fig. S6*E*).

We further validated the new contacts using live-cell microscopy and chromosome conformation capture (3C) assays. Time-lapse

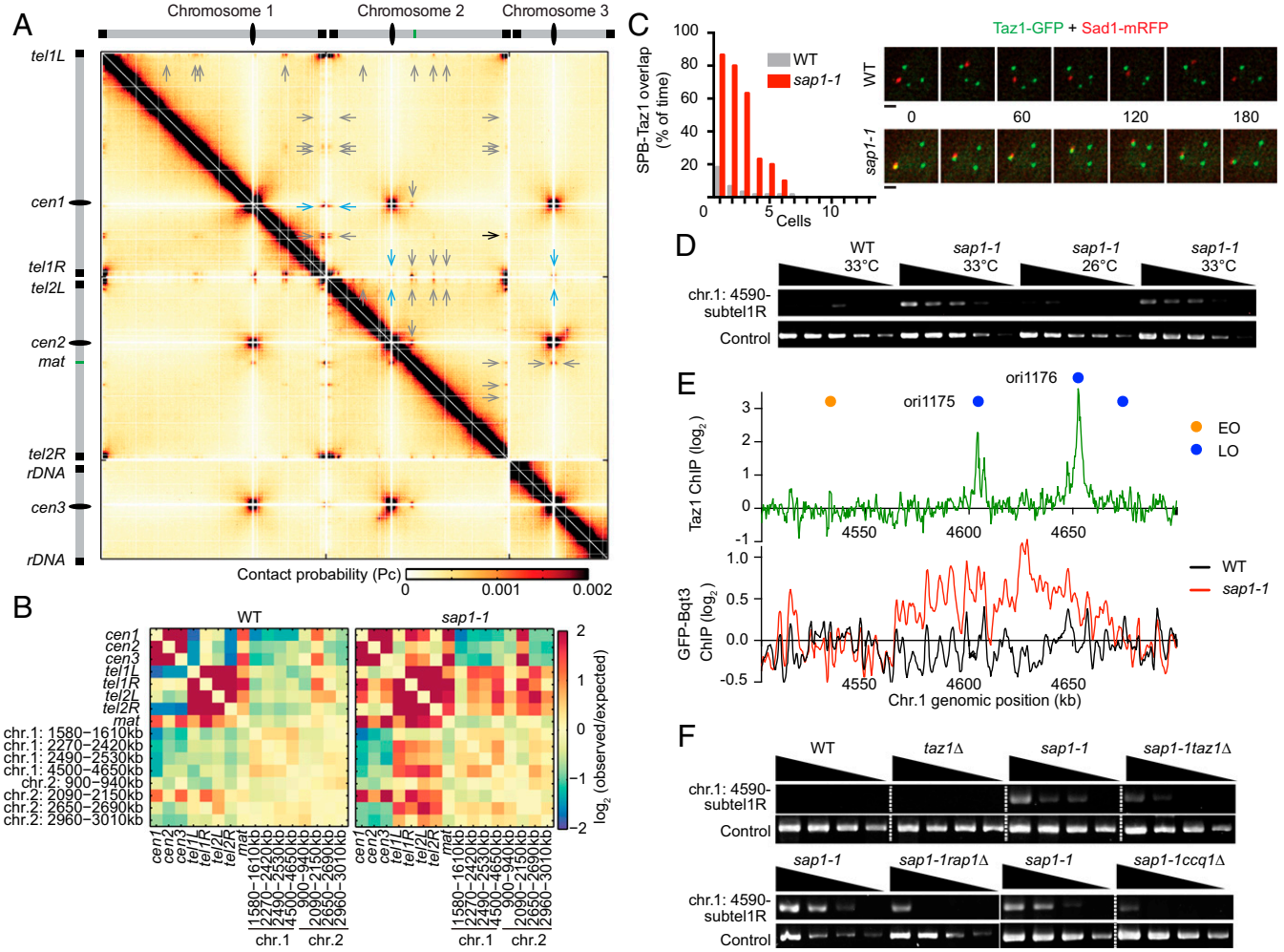

Fig. 4. Hi-C reveals new specific interactions in *sap1-1* mutants. (*A*) Genome-wide Hi-C heatmap for *sap1-1* at 10-kb resolution. Gray and blue arrows indicate the arm–subtelomere and centromere–subtelomere interactions, respectively. (*B*) Log_2 (observed/expected) contact frequency between centromeres, telomeres, and loci with emergent interactions in *sap1-1* for WT (*Left*) and *sap1-1* (*Right*) cells. (*C*) Time-lapse observation of Taz1-GFP (green) and Sad1-mRFP (red). (*Left*) The percentage of time points showing colocalization of Taz1-GFP and Sad1-mRFP during the 10-min time lapse at 10-s intervals. Thirteen WT and *sap1-1* cells were scored. (*Right*) Representative time-lapse images. Numbers indicate the time in seconds. (Scale bars, 1 μm). (*D*) 3C PCR analysis of *sap1-1*–specific interactions (chr.1: 4,590-kb region and subtelomere 1R, ∼1 Mb apart). A close-range interaction (≤10 kb) was used as a 3C control. Twofold serial dilutions of the 3C library were used as a PCR template. Strains were initially cultured at 26 °C and then were shifted to 33 °C for 6 h. (*E*) ChIP-chip of Taz1 and GFP-Bqt3 is shown at chromosome arms where new interactions emerge in *sap1-1* cells (chr.1: 4,590-kb region and subtelomere 1R). Orange and blue circles represent the early- and late-replication origins, respectively. (*F*) 3C PCR analysis of the *sap1-1*–specific interaction (chr.1: 4,590-kb region and subtelomere 1R) in the indicated mutants. Strains were initially cultured at 26 °C and then were shifted to 33 °C for 6 h. A close-range interaction (≤10 kb) was used as a 3C control. Twofold serial dilutions of the 3C library were used as a PCR template.

microscopy revealed an association between centromeres and telomeres in a significant proportion of *sap1-1* cells (Fig. 4*C* and Movies S3 and S4), in contrast to WT cells (Movies S5 and S6). Moreover, our 3C experiment detected an interaction between a region on the chromosome 1 arm (the genomic position of the 4,500- to 4,650-kb region) and *tel1R* in *sap1-1* cells, which are ∼1 Mb apart in linear genomic distance (Fig. 4*D*). This interaction was specific to *sap1-1* cells and was detected only when cells were cultured at semipermissive temperature.

To exclude the possibility that our 3C experiments detected genomic rearrangements rather than new interactions, we performed PCR analysis using genomic DNA from *sap1-1* cells. Importantly, no PCR amplification could be observed (Fig. S6*F*). Based on these results, we conclude that *sap1-1* mutant cells, which show replication defects and genome instability, undergo genome reorganization resulting in specific new interactions with telomeres.

Shelterin Mediates New Interactions. We noted that many of the arm regions that contacted telomeres contained previously described late origins that are bound by Taz1 (Fig. S6*E*) (11, 12). Notably, Taz1 peaks were generally observed at the edges rather than at the center of these interacting regions. This observation may be a consequence of our Hi-C analyses that excluded Taz1-bound repetitive telomeric sequences, which might interact directly with chromosomal internal sites showing Taz1 peaks. Thus, the detected interactions most likely reflect contacts between distal sequences neighboring direct interaction sites (i.e., telomeres and Taz1-associated arm regions).

We investigated whether Taz1–Shelterin affects interactions between telomeres and arm regions. To do so, we performed 3C analyses in *sap1-1* cells lacking Taz1 or other Shelterin subunits such as Rap1 or Ccq1. Remarkably, the loss of any of these factors significantly reduced the interaction between *tel1R* and a Taz1-associated arm region (chromosome 1: 4,500- to 4,650-kb region) that contains late origins and associates with the nuclear periphery in *sap1-1* cells (Fig. 4 *E* and *F*). Taz1 and Rap1 also interact with Bqt1 and Bqt2, which connect telomeres to the spindle pole body (SPB) upon entry into meiosis (31). However, telomeric association of arm regions was not affected in *sap1-1 bqt1Δ* and *sap1-1 bqt2Δ* double mutants (Fig. S6*G*). Together, these results implicate Taz1–Shelterin in mediating new interactions between chromosome arm regions and telomeres in *sap1-1* cells.

We also examined whether Shelterin components affects centromere–telomere contacts in *sap1-1* cells. We found that in *sap1-1* cells lacking Rap1, centromeres and telomeres remained associated with the nuclear periphery (Fig. S7 *A* and *B*); however, the number of cells showing association between these loci decreased (Fig. S7*C*). Thus, in addition to facilitating connections between telomeres and chromosome arm regions, Shelterin components also seems necessary to mediate centromere–telomere contacts in *sap1-1*.

We wondered whether the genome reorganization observed in *sap1-1* cells in response to replication stress is biologically relevant. Because certain types of DNA damage are targeted to nuclear compartments for specialized repair (32), we speculated that Shelterin-mediated association of arm regions with telomeres might affect the DNA damage-repair process. Indeed, the loss of Ccq1 or Rap1 in *sap1-1* mutant cells resulted in a considerable increase in the number of Rad52 repair foci (Fig. S7*D*).

Discussion

The organization of eukaryotic genomes impacts many aspects of genome function, including replication and DNA-repair processes (2, 3). We find that cells carrying a mutation in Sap1 that show replication defects and genome instability undergo changes in genome organization. A remarkable finding is that components of the Shelterin telomere protection complex promote interactions between telomeres and specific chromosomal arm regions. These results suggest an additional role for Shelterin in promoting genome reorganization with implications for understanding mechanisms that protect genome stability.

Sap1 has been suggested to play an important role in replication fork pausing at *rDNA* and retrotransposon *LTRs* (18, 20, 21). We show that Sap1 also facilitates replication progression, as indicated by 2D gel, Mcm6 localization, and BrdU incorporation analyses. In addition, replication defects are suggested by the accumulation of ssDNA and DNA repair foci in *sap1-1* cells. Sap1 might impact replication through local chromatin changes, e.g., by affecting nucleosome occupancy (33). Another possibility is that Sap1, with its matrix-like nuclear localization, might serve as an architectural protein that binds and constrains chromosomes to promote their spatial positioning and proper replication. Such a role might be analogous to DNA-binding proteins in higher eukaryotes, such as CTCF, which recruits cohesin involved in genome organization (34). However, Sap1 is dispensable for cohesin-dependent globules. Instead, our preliminary analysis indicates that Sap1 copurifies with topoisomerase II (https://ccrod.cancer.gov/confluence/download/attachments/101483286/Sap1TopII.pdf?api=v2) implicated in replication and chromosome organization (35, 36). Regardless of its exact function, loss of Sap1 function affects proper replication, structural integrity, and organization of the genome.

sap1-1 cells show widespread genome reorganization, including association of arm regions with telomeres and the nuclear periphery. Because the affected arm regions contain replication origins and experience replication stress, it is conceivable that Sap1 indirectly affects genome organization through its impact on DNA replication/repair. Moreover, a low level of genomic rearrangements might contribute to the new interactions detected. To this end, we note that specific new interactions occur rapidly in cells that are cultured at a semipermissive temperature for only 6 h. Although these interactions potentially could lead to recombination events, whole-genome sequencing of *sap1-1* did not reveal translocations between the newly interacting loci.

Our finding that Taz1–Shelterin mediates interactions between telomeres and arm regions has implications for understanding replication control and genome stability. Late firing of Taz1-affected origins requires telomere-associated Rif1, which also has been implicated in DNA repair (37, 38). However, Rif1 binds only a subset of Taz1-associated late origins (11, 38, 39), and it is conceivable that Shelterin-mediated telomeric association of these origins allows Rif1 acquisition to promote proper replication and DNA repair. In other words, Taz1-bound late origins in telomeric and arm regions might be controlled in a shared nuclear compartment. The physical proximity of regions experiencing replication stress to Rif1-enriched telomeres may also facilitate the resolution of DNA entanglements (40) and promote chromosome healing, in which telomerase "heals" dsDNA breaks (41). Finally, localization of these regions to the nuclear peripheral compartment may provide an opportunity to suppress and repair DNA damage, as observed in other systems (32, 42, 43). In this regard, we find that disruption of the telomeric association of arm regions in *sap1-1* cells lacking Shelterin components correlates with increased accumulation of DNA damage. Moreover, certain Shelterin components show negative genetic interactions with DNA repair and checkpoint factors (44).

Collectively, these results link changes in genome organization to replication stress, which is an early driver of oncogenesis (45). Tandem duplication of chromosomal segments is a dominant class of structural change found in breast and ovarian cancers (46) and is thought to arise from the repair of replication stress-associated DNA breaks (47). Insights gained from *S. pombe* may aid studies in higher eukaryotes, particularly those focusing on the mechanisms underlying structural abnormalities and nuclear reorganization in replication-stressed cells.

Materials and Methods

WT and mutant strains were initially cultured in yeast extract adenine (YEA)-rich medium at 26 °C and then were shifted to 33 °C for 6 h, unless otherwise

indicated. Growth conditions used to detect rearrangements, BrdU incorporation, and 2D gel analysis in *sap1-1* cells are detailed in *SI Materials and Methods*. A description of Hi-C, 3C, ChIP-chip, BrdU incorporation, nucleosome mapping, CGH, Junction PCR, Southern blotting, 2D gel analysis, and FISH procedures can be found in *SI Materials and Methods*. Primers used in this study are listed in Table S2.

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