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Pathways and Mechanisms that Prevent Genome Instability in *Saccharomyces cerevisiae*

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ABSTRACT Genome rearrangements result in mutations that underlie many human diseases, and ongoing genome instability likely contributes to the development of many cancers. The tools for studying genome instability in mammalian cells are limited, whereas model organisms such as *Saccharomyces cerevisiae* are more amenable to these studies. Here, we discuss the many genetic assays developed to measure the rate of occurrence of Gross Chromosomal Rearrangements (called GCRs) in *S. cerevisiae*. These genetic assays have been used to identify many types of GCRs, including translocations, interstitial deletions, and broken chromosomes healed by *de novo* telomere addition, and have identified genes that act in the suppression and formation of GCRs. Insights from these studies have contributed to the understanding of pathways and mechanisms that suppress genome instability and how these pathways cooperate with each other. Integrated models for the formation and suppression of GCRs are discussed.

KEYWORDS DNA repair; DNA replication; genome rearrangements; telomerase; translocations

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Gross Chromosomal Rearrangements (GCRs)

Genome stability is critical for cell survival and normal cell growth. Genomic rearrangements (herein called GCRs) include translocations, deletions, and amplifications. GCRs are associated with many human diseases including, but not limited to, cancers. The association of GCRs with different diseases has driven interest in how GCRs arise and are normally prevented. Remarkably, eukaryotic genomes are normally quite stable, despite the fact that they include many features that are at risk for causing the formation of GCRs, including duplicated sequences and double-strand break (DSB)-inducing sites (Gordenin and Resnick 1998; Lambert et al. 2005; Lemoine et al. 2005; Casper et al. 2009; Mizuno et al. 2009; Paek et al. 2009; Aksenova et al. 2013; Song et al. 2014).

A wide variety of GCRs have been observed in mammalian cancers (Inaki and Liu 2012; Janssen and Medema 2013; Macintyre et al. 2016). The most common cancers, excepting leukemias and lymphomas, often have large numbers of GCRs (Mitelman et al. 2006, 2007; Gordon et al. 2012; Cancer Genome Atlas Research Network et al. 2013) as well as ongoing genome instability (Nowell 1976; Campbell et al. 2010; Gundem et al. 2015; Gibson et al. 2016; Uchi et al. 2016). Many of the genes that are defective in inherited cancer susceptibility syndromes act in DNA damage response pathways (Friedberg et al. 2006; Ciccia and Elledge 2010), and these pathways suppress GCRs in the model organism Saccharomyces cerevisiae (Chen and Kolodner 1999; Myung et al. 2001a,b,c). Thus, both inherited and sporadic cancers may have genetic or epigenetic defects that destabilize their genomes.

Despite the considerable interest in studying genome instability in higher eukaryotes, the lack of facile genetic systems has limited progress in these organisms. In contrast, the conservation of DNA metabolism pathways has allowed experimental insights from more genetically tractable model systems to be applied to human diseases. Early S. cerevisiae studies identified rearrangements mediated by repetitive genomic features, including the ribosomal DNA array, CUP1 repeats, tRNA genes, Ty retrotransposon-related elements, and the 94 kb “Hawthorne” deletion between the homologous MATa and HMR loci (Hawthorne 1963; Rothstein 1979; Roeder and Fink 1980; Liebman et al. 1981; Rothstein et al. 1987; Christman et al. 1988; Keil and McWilliams 1993). At the same time, genome features designed to drive the formation of GCRs were engineered into normal S. cerevisiae chromosomes, demonstrating that GCRs could be observed (Mikus and Petes 1982; Sugawara and Szostak 1983; Haber and Thorburn 1984; Suroskey and Tye 1985; Jinks-Robertson and Petes 1986; Kupiec and Petes 1988; Gordenin et al. 1993; Henderson and Petes 1993). In the last 15–20 years, considerable progress has been made in developing assays for detecting GCRs and structurally characterizing these GCRs, which has provided insights into both GCR-formation and GCR-suppression mechanisms. This article reviews our current understanding of GCRs in S. cerevisiae. We predict that the extensive knowledge that has accumulated in these areas should greatly facilitate the study of genome instability in higher eukaryotes.

How GCRs Arise

Based on the evidence described below, our current view is that GCRs are generated through normal DNA repair and homeostasis processes that act on some form of DNA damage
but do so inappropriately. In these cases, the original sequence and structure of the genome are not restored. Importantly, GCRs are not damaged chromosomes themselves, but rather are the result of error-prone processing of damaged chromosomes. Most of the GCRs recovered in genetic assays appear to be stable, even when the GCR has undergone multiple rounds of rearrangement to reach its final structure. The stability of recovered GCRs is not surprising given that GCRs occur at low rates and are identified by plating cells on medium that selects for the presence of a GCR; in such selective medium, other rearranged chromosomes and chromosome fragments that are not under selection are likely lost due to segregation during the > 20 cell divisions required to form a S. cerevisiae colony from a single cell (Joseph and Hall 2004).

In most cases of spontaneous GCRs, the precise nature of the initiating damage is unknown; however, much of the genetic evidence described below strongly implicates DNA replication errors as an important but probably not the exclusive source of the broken chromosomes that result in GCRs (Figure 1). Replication errors could occur when replication encounters templates that are difficult to copy such as: (1) damaged DNA, including oxidatively damaged DNA; (2) difficult-to-replicate sequences, such as inverted repeats that can form a palindrome or interstitial telomere sequences; and (3) a block on the template, such as a bound protein or a transcriptional intermediate like a stable three-stranded RNA–DNA hybrid (R-loop) (Lambert et al. 2005; Lemoine et al. 2005; Casper et al. 2009; Mizuno et al. 2009; Paek et al. 2009; Aksenova et al. 2013; Song et al. 2014; Santos-Pereira and Aguilara 2015). These interactions potentially result in stalled replication forks, which are thought to be unstable, or structures like extruded palindromes that can be cleaved to generate DSBs. In some cases, regression of stalled forks may be linked to a restart mechanism involving template switching; these events likely prevent the formation of substrates that can lead to GCRs. In other cases, replication of nicked substrates or the action of nucleases and/or helicases might lead to replication fork collapse and the formation of DSBs (Figure 1) (Flores-Rozas and Kolodner 2000; Michel 2000). Replication can also misincorporate ribonucleotides that are then cleaved by topoisomerase I to produce aberrant DNA structures (Kim et al. 2011; Williams et al. 2013; Allen-Soltero et al. 2014). Other potential sources of damage include resection from unprotected telomeres and breakage of dicentric chromosomes formed by end-to-end fusion of chromosomes in strains with defects in telomere maintenance (Lydall and Weinert 1995; Craven et al. 2002; Maringele and Lydall 2002; Pennaneach and Kolodner 2004). Analysis of the structure of > 1000 GCR structures indicates that GCRs can be formed by mechanisms modeled on the assumption that the initiating damage is a DSB (Putnam et al. 2004, 2005, 2014; Pennaneach and Kolodner 2009; Chan and Kolodner 2012). Thus, for simplicity, we show DSBs as the initiating damage in this review, but we note that DSBs, if they are involved, are likely the result of processing more complicated forms of initiating DNA damage.

The most likely outcome for any DSB during the S- or G2-phases of the cell cycle is the initiation of homologous recombination (HR) with the sister chromatid (or a homologous chromosome in a diploid) to repair the DSB, or in some cases help rebuild replication forks (Figure 1). The result of this processing suppresses any genomic rearrangements and conserves the overall genome structure. Crucial players in this “conservative” repair reaction likely include proteins that mediate HR, sister chromatid cohesion, and DNA damage checkpoint signaling.

When sister chromatid recombination does not occur, then several “nonconservative” repair reactions can compete for these DSBs and lead to the formation of GCRs (Figure 1). DSBs can be repaired by different pathways, and in many cases, the intermediates formed in one repair pathway are substrates for other pathways. Thus, a single form of initiating damage can result in multiple types of GCRs (Figure 2), including terminal deletions healed by the addition of a de novo telomere, intra- or interchromosomal translocations, formation of hairpin-mediated inversions, and fusions to the telomeres of other chromosomes. The number of categories of GCRs shown in Figure 2 increases if additional factors are considered, including whether the initial rearrangement leads to chromosomes with one or two centromeres and whether additional rearrangements occur (described in detail below). Any observed GCR is the result of the individual steps that tend to be fastest during processing of the damage, given the nature of the damage, the chromosomal sequence context for the damage, the presence or absence of defects in specific DNA-processing pathways, and the idiosyncratic history of that particular event. Despite this complexity, the rates at which GCRs accumulate and the spectrum of GCR structures observed in the presence of different genetic defects have provided substantial insights into the mechanisms that form and prevent GCRs.

Measuring Genome Instability

Overview

Methods for studying GCRs fall into two general categories. The first category, termed here “directed assays,” detects rearrangements mediated by specific sequence features. These assays usually probe high-frequency events, often mediated by a specific mechanism and often select for a specific rearrangement. For example, synchronous cleavage of an HO endonuclease site has been used to monitor DSB-mediated HR between specific target sequences (Connolly et al. 1988; Ira et al. 2003). Directed assays are useful for mechanistic studies (McEachern and Haber 2006; Mehta and Haber 2014) but may not necessarily detect the types of spontaneous GCRs that are associated with different diseases and arise due to DNA damage that occurs during normal cell growth. The second category, termed here “undirected assays,” detects GCRs that occur at low rates and targets native DNA sequences, DNA structures, and DNA damage but does not
depend on specific engineered GCR-inducing structures or reflect the formation of a specific rearrangement. Undirected assays can probe the spectrum of spontaneous GCRs that grossly rearrange the genome and the broad diversity of pathways and mechanisms that impact the formation and suppression of GCRs. However, because the events occur at low frequencies, undirected assays usually provide more limited mechanistic insights than the directed assays. In this section, we will focus on many of the undirected assays used for studying GCRs.

The "classical" GCR assay

A key observation about the nature of some canavanine-resistant (Can') \emph{S. cerevisiae} mutations that proved to be GCRs led to the development of a series of undirected GCR assays (Figure 3). Most Can' mutations are point mutations in \emph{CAN1}. However, some Can' mutations are GCRs causing a deletion of \emph{CAN1}, which can form because \emph{CAN1} is on a terminal nonessential region of the left arm of chromosome V (Tishkoff et al. 1997; Chen et al. 1998). Modification of this chromosomal region by inserting a second marker, \emph{URA3}, into the \emph{HXT13} gene generated an assay that selected for GCRs (Figure 4) (Chen and Kolodner 1999). This modified strain is sensitive to both Can and 5-fluoroorotic acid (5-FOA), and double-drug-resistant progeny arise at a rate that can be measured by fluctuation analysis [for a methods paper, see Schmidt et al. (2006a)]. Except in the case of a small number of mutants that accumulate point mutations at high rates or
after treatment with some DNA-damaging agents (Myung et al. 2001b; Myung and Kolodner 2003), all of the double-drug-resistant progeny result from the formation of GCRs associated with the codeletion of CAN1 and URA3 (Figure 4). As a consequence, this assay, which we refer to as the “classical” GCR assay has been used to measure the rate of accumulating...
GCRs and, when coupled with detailed structural analysis of the GCRs that occur, can be used to determine the rate of accumulating specific types of GCRs.

**Undirected loss GCR assays**

The classical GCR assay (Figure 4 and Figure 5A) can be described as an “undirected loss GCR assay,” in which GCRs are selected on the basis of the loss of genetic markers in haploid strains. Undirected loss GCR assays share a key property: the placement of the selectable markers defines a “breakpoint region.” The breakpoint region is the portion of the chromosome arm where one of the rearrangement breakpoints must occur; one end is the most centromeric counter-selectable marker, and the other end is the most telomeric essential gene (Figure 4 and Figure 5). Varying the chromosomal features in the breakpoint region has been a key feature of many next-generation assays described below and affects both the rearrangement rate and the sequences targeted at the other rearrangement breakpoint(s). This second rearrangement breakpoint, when there is one, can in principle be in any region of the genome provided that no essential genes are deleted by the formation of the GCR. Because of this latter requirement, virtually all translocations observed using undirected loss GCR assays in haploid strains are nonreciprocal; these translocations are associated with an intact copy of the target chromosome (Chen et al. 1998; Chen and Kolodner 1999; Pennaneach and Kolodner 2009; Putnam et al. 2009a, 2014). The accumulation of nonreciprocal translocations suggests that GCRs primarily form in S- or G2-phase after the donor chromosome is replicated or that their formation involves some type of copying mechanism like break-induced replication (BIR) (Bosco and Haber 1998; Flores-Rozas and Kolodner 2001) and that their formation involves some type of copying mechanism like break-induced replication (BIR) (Bosco and Haber 1998; Flores-Rozas and Kolodner 2001).

A number of next-generation undirected loss GCR assays have been devised in haploid strains. (1) Many assays have been developed in which potential at-risk sequences have been tested for their effects on the formation of GCRs. These at-risk sequences include HO endonuclease sites (Figure 5B) and a Ty1 element (Figure 5C), as well as tri-nucleotide repeat sequences, G-quadruplex motifs, GC-rich human minisatellite sequences, inverted Alu repeats, or inducible genes (Myung and Kolodner 2003; Sikdar et al. 2008; Kerrest et al. 2009; Chan and Kolodner 2011; Piazza et al. 2012; Y. Zhang et al. 2012, 2013; Paeschke et al. 2013). (2) A number of assays have utilized a CAN1-URA3 cassette that could be inserted at various locations to probe the effect of endogenous and engineered features such as single-copy sequences (Figure 5D), low-copy number repeat sequences (Figure 5E), or a short-homology region generated by ~100 bp of a Ty-related δ sequence and a repetitive leucine tRNA (Figure 5F) (Putnam et al. 2009a, 2016). (3) A variant assay involving selection by ADE2 and CAN1 has been used to monitor terminal chromosome loss and SFA1-CUP1 cassette amplification due to rearrangements mediated by a LYS2 cassette containing an Alu sequence-derived direct or inverted repeat (Figure 5G) (Narayanan et al. 2006). (4) Selection against CAN1 alone can, in some genetic backgrounds, also identify chromosomal rearrangements similar to the observation of the first mutator mutants having high GCR rates (Figure 5H) (Chen et al. 1998; Craven et al. 2002). (5) The nonessential terminal region of chromosome VII L has also been engineered by insertion of URA3 and HIS3 markers to allow detection of GCRs, which demonstrated that features of the classical GCR assay could be generalized to another chromosome (Figure 5I) (Myung et al. 2001c). (6) The nonessential terminal region of chromosome XV L has been probed using CAN1 and ADE2 as markers (Figure 5J) (Hackett et al. 2001) and CAN1 and URA3 as markers (Figure 5K) (Kanellis et al. 2007). (7) A cassette bearing an intron-containing version of the URA3 gene, with or without intronic interstitial telomeric repeats, was inserted on chromosome III and used to demonstrate that these repeats increased the rate of loss.

![Figure 3](image-url)

**Figure 3** CanR progeny recovered from haploid *S. cerevisiae* strains. The CAN1 gene (green), which encodes a transporter that imports both arginine and the toxic arginine analog canavanine, is present on the terminal nonessential portion of the left arm of chromosome V, which is bounded by the TEL05 telomere (“tg”) and the essential PCM1 gene (green). Most CanR mutants isolated are due to point mutations in CAN1 indicated in red; however, some are GCRs that result in deletion of regions of the nonessential portion of chromosome V that includes the CAN1 gene. CanR, canavanine-resistant; GCRs, Gross Chromosomal Rearrangements.
of URA3 due to the formation of GCRs [assay not illustrated; Aksenova et al. (2013)]. In this assay, the URA3 insertion was within the essential region of chromosome III, and the observed rearrangements retained both fragments of the broken chromosome, including the retention of an 80-kb acentric minichromosome. (8) Haploid α cells can segregate variants that lose the MAT locus and can undergo illegitimate mating with other α strains (Figure 6A). This assay selects for both rearrangements of chromosome III as well as chromosome loss (Lemoine et al. 2005; Yuen et al. 2007). (9) In a yeast artificial chromosome (YAC)-based assay, GCRs that mediated the loss of URA3 and ADE2 but retained TRP1 were monitored (Figure 6B) (Huang and Koshland 2003; Wahba et al. 2013). Finally, (10) a system for monitoring...
Comparison of a variety of haploid GCR assays that select for loss of markers. A number of variant GCR assays that select for loss of markers in haploid strains have been developed in *S. cerevisiae* utilizing chromosomes V (blue), VII (brown), and XV (green). For each assay, the nonessential (light color) and essential regions (dark color) of the chromosome arm are shown along with the relevant marker genes (red text), the breakpoint region (red horizontal line), and homologies to other regions of the genome (yellow boxes). The chromosome V L assays, which have a nonessential region telomeric to *PCM1*, are (A) the classical GCR assay selecting for loss of *CAN1* and *URA3* (Chen and Kolodner 1999), (B) assays introducing an *HO-URA3* cassette either telomeric or centromeric to *CAN1* indicated by one of the other of the dashed green boxes (Myung and Kolodner 2003), (C) the tyGCR assay in which Ty912 is inserted into the breakpoint region of the classical GCR assay (Chan and Kolodner 2011), (D) the "unique sequence" or uGCR assay (Putnam et al. 2009a), (E) the "duplication" or dGCR assay in which the *DSF1-HXT13* segmental duplication is in the breakpoint region (Putnam et al. 2009a), (F) the "short duplication" or sGCR assay that includes the *SUP53* tRNA gene and 100 bp of a Ty-related delta sequence in the breakpoint region (Putnam et al. 2016), (G) an assay that selects for loss of *CAN1* and screens for loss of *ADE2* by colony color and screens for amplification of a *CUP1-SFA1* cassette (Indicated by one of the other of the dashed green boxes) by increased drug resistance (Narayanan et al. 2006), and (H) an assay that selects only for loss of *CAN1* in strains with high GCR rates (Tishkoff et al. 1997; Chen et al. 1998; Craven et al. 2002). (I) The chromosome VII L assay, which has a nonessential region telomeric to *BRR6*, involves selection for loss of *URA3* and screening for loss of *HIS3* (Myung et al. 2001c). The chromosome XV L assays, which have a nonessential region telomeric to *PSF3*, include (I) an assay that has *CAN1* and *ADE2* telomeric to two homology regions (H1 and H2) and selects for loss of *CAN1* followed by screening for loss of *ADE2* by colony color (Hackett et al. 2001), and (K) a modified chromosome XV L assay that has *CAN1* and *URA3* telomeric to the homology regions (Kanellis et al. 2007). CanR, canavanine-resistant; GCRs, Gross Chromosomal Rearrangements.
translocations between a number of normal chromosomes and a YAC in HR-defective mutants was developed (Tennyson et al. 2002). In this assay, the centromere of the YAC was flanked by negative selection markers (CYH2 and CAN1), and the terminal region of the YAC contained positive selection markers (URA3 and HIS3) (Figure 6C). This assay is similar to the classical GCR assay, but it works by selecting for retention of a terminal region of the YAC and loss of the centromeric region of the YAC.

**Undirected gain GCR assays**

Haploid strain-based assays that select for amplification of genetic markers that have dose-dependent effects are termed here “undirected gain GCR assays.” These assays are, in principle, less restrictive than undirected loss GCR assays because any chromosome can break at any site and the break healed by joining to a copy of a telomere-terminated fragment containing the selected genetic markers, provided that intact copies of the two chromosomes involved are maintained (Koszul et al. 2004; Libuda and Winston 2006; Payen et al. 2008; Green et al. 2010; H. Zhang et al. 2013). In practice, these assays mostly select for breakpoints in repeated sequences (H. Zhang et al. 2013) and are most useful for studying how cells maintain genome stability when repeated sequences are present (Deininger and Batzer 1999; Lobachev et al. 2000).

Multiple undirected gain GCR assays have been implemented in haploid cells. (1) Several assays have been devised that select for amplification of engineered markers that occurs when a broken chromosome is healed by joining to a telomere-terminated fragment containing the selected markers. The amplification markers include a SFA1-CUP1 cassette whose amplification causes increased resistance to formaldehyde and copper (Figure 6D) (H. Zhang et al. 2013), and the ade3-2 allele whose amplification causes strains to change color from pink to red (Figure 6E) (Green et al. 2010). (2) Other assays have taken advantage of the fact that deletion of one of the copies of a set of duplicated genes present in the S. cerevisiae genome can sometimes cause slow growth that can be suppressed by amplification of the remaining paralog. Such assays have utilized the RPL20A/RPL20B pair (Figure 6F) (Koszul et al. 2004; Payen et al. 2008) and the HTA1-HTB1/HTA2-HTB2 pair (Figure 6G) (Libuda and Winston 2006). (3) Selection of specific forms of gene duplication has been monitored by the reactivation of the ura2-15-30-72 allele. This allele has three nonsense mutations in the 5′ end of the gene and can be reactivated by gene duplication when the 3′-end of the URA2 is inserted in-frame into another open reading frame (Figure 6H) (Schacherer et al. 2005).

**Diploid GCR assays**

Diploid GCR assays are similar to undirected gain GCR assays in that they are not constrained by the loss of essential genes and, in principle, allow for a greater diversity of GCRs to occur (Hiraoka et al. 2000; Umezu et al. 2002; H. Zhang et al. 2013). This lack of constraint on where breakpoint junctions occur tends to lead to the formation of GCRs by HR between repetitive elements, which are distributed throughout the genome, especially in regions containing essential genes.

Only a relatively small number of diploid strain-based GCR assays have been constructed. (1) Several assays have monitored for loss of a single counterselectable marker, such as URA3 or CAN1, which can also measure chromosome loss (Hiraoka et al. 2000; Klein 2001; Umezu et al. 2002). Variants of these kinds of diploid assays have been performed in haploid cells that are disomic for a chromosome marked with CAN1 (Admire et al. 2006; Paek et al. 2009). (2) Assays that detect amplification of an SFA1-CUP1 cassette have been used to detect GCRs in diploid strains, which are mostly mediated by Ty × Ty HR (H. Zhang et al. 2013). Finally, (3), amplification of the ura2-15-30-72 allele has also been studied in diploids, and selects for gene duplications and translocations as seen in the haploid assay (Schacherer et al. 2007).

**Structural Analysis of GCRs**

**Methods for analyzing GCRs**

Determining the structure of individual GCRs is important for understanding the mechanisms by which GCRs are formed. S. cerevisiae has advantages that facilitate the analysis of GCR structures, including the relatively small size of the genome, its organization into 16 chromosomes, the availability of the genome sequence, and the presence of a limited number of repeated sequences. Even with these advantages, elucidating the structure of individual GCRs including determining the connectivity of each segment at the DNA sequence level can be very difficult. A number of methods have been used to characterize GCRs; however, often no single method is sufficient to determine the complete GCR structure. Consequently, most studies have not determined complete structures but have inferred them from the limited available data.

Methods that have been used to characterize GCRs include the following. (1) Pulsed-Field Gel Electrophoresis can detect aberrantly-sized chromosomes, and can provide information about the composition of these chromosomes by analyzing them by Southern blotting with appropriate hybridization probes (Figure 7A) (Chen et al. 1998; Narayanan et al. 2006; Pennaneach and Kolodner 2009; Chan and Kolodner 2011; Putnam et al. 2014; Serero et al. 2014; Deng et al. 2015). (2) PCR-based strategies for mapping, amplifying, and sequencing junction breakpoints have been used to characterize GCRs (Figure 7B) (for a methods paper see Schmidt et al. 2006a). Modifications of the original arbitrary-primed PCR strategies, involving use of telomere-specific primers and the ligation of linkers onto genomic DNA digested with restriction enzymes, have the potential to simplify the amplification of fragments containing junction sequences (Smith et al. 2004). The junction sequences determined by these methods provide insights into the structure of GCRs. (3) Array Comparative Genome Hybridization (aCGH) using
Figure 6 Comparison of haploid GCR assays that select for amplification of markers or loss of internal markers. (A) The “a-like faker” mating assay that uses mating and selection to detect loss of information at the MAT locus (Lemoine et al. 2005; Yuen et al. 2007). (B) A YAC-based GCR assay that selects for loss of URA3 and ADE2 but retention of TRP1, which also detects translocations involving fragments of native S. cerevisiae chromosomes (Huang and Koshland 2003; Wahba et al. 2013). (C) A YAC-based GCR assay that selects for retention of the terminal YAC arm and loss of the remainder of the chromosome, and detects translocations involving fragments of native S. cerevisiae chromosomes (Tennyson et al. 2002). (D) Amplification of a SFA1-CUP1 cassette causes increased resistance to formaldehyde and copper ions that detects amplification resulting from HR-mediated unequal crossing over (Zhang et al. 2013a). (E) Amplification of ade3-2 resulting from HR-mediated unequal crossing over causes S. cerevisiae colonies to undergo a color change from pink to red (Green et al. 2010). (F) An assay for suppressors of the slow growth phenotype of an rpl20aΔ mutant strain selects for amplification of RPL20B (Koszul et al. 2004; Payen et al. 2008). (G) An assay for suppressors of the slow growth phenotype of an hta1Δ htb1Δ double-mutant strain selects for amplification of the centromere (black circle) proximal HTA2 and HTB2 resulting from the...
densely tiled microarrays can provide a detailed map of the copy number changes (duplications and deletions) associated with a GCR (Figure 7C) (Lemoine et al. 2005, 2008; Pennaneach and Kolodner 2009; Putnam et al. 2009a; Zheng et al. 2016). However, aCGH provides no information about the connectivity of these changes, and any predicted GCR structure must be confirmed using secondary analyses. (4) Multiplex Ligation-mediated Probe Amplification (MLPA) (Schouten et al. 2002), which measures copy number changes at low resolution, has been used to rapidly and inexpensively identify duplication of chromosome arms associated with GCRs (Figure 7D) (Chan and Kolodner 2012). Like aCGH, MLPA requires secondary analysis to provide the connectivity information to confirm predicted GCR structures. (5) PCR amplification of the breakpoints predicted from the nature of the breakpoint region has been used for junction verification and, in some cases, was followed by DNA sequencing (Figure 7E) (Mieczkowski et al. 2003; Putnam et al. 2009a; Chan and Kolodner 2011, 2012). In cases where the breakpoints are difficult to amplify by PCR, such as those that occur between Ty elements, restriction mapping by Southern blotting with appropriate probes has been useful (Lemoine et al. 2005). (6) Given the relatively small size of the S. cerevisiae genome, whole-genome Next-Generation Sequencing of multiplexed libraries constructed from different individual GCR-containing isolates is a powerful and relatively inexpensive method for characterizing GCRs (Figure 7F) (Putnam et al. 2014; Serero et al. 2014; Zheng et al. 2016). However, use of this method for GCR analysis is relatively new. It has proven challenging to extract breakpoint sequences for breakpoint junctions mediated by repetitive regions, although variations between different repeated sequence elements can be exploited to detect rearrangement breakpoints (Putnam et al. 2009a); this approach has also been used to map crossovers (Smith et al. 2007; St Charles et al. 2012; Rosen et al. 2013; Song et al. 2014; Laureau et al. 2016; Zheng et al. 2016).

**Structures of GCRs selected in haploid strains**

**De novo telomere addition-mediated GCRs:** The most prevalent type of GCR selected in the classical GCR assay in wild-type and some mutant strains is a terminally-deleted chromosome in which a de novo telomere is added at the broken end of the chromosome (Figure 2 and Figure 4) (Chen et al. 1998; Chen and Kolodner 1999; Myung et al. 2001a,c; Myung and Kolodner 2002). Telomerase and some but not all of the other telomere maintenance proteins are required to form these GCRs (Myung et al. 2001a). These GCRs form by telomerase targeting telomere-like TG sequences, which can be as short as two bases (Putnam et al. 2004). Analysis of the sequences of de novo telomeres provided insights into how the telomerase guide RNA is copied by telomerase (Putnam et al. 2004). Initially, the observation of de novo telomere additions seemed to contradict the specificity of telomerase for extending preexisting telomeres. However, telomerase preferentially extends extremely short telomeres, suggesting similar mechanisms for de novo telomere addition and extension of normal telomeres (Arneric and Lingner 2007; Chang et al. 2007; Sabourin et al. 2007). The high proportion of de novo telomere addition events obtained in GCR assays contrasts with the very low level of telomere additions targeted to HO endonuclease-induced DSBs that are not associated with telomere “seed” sequences (Schulz and Zakian 1994; Bosco and Haber 1998; Mangahas et al. 2001). One explanation for the difference may be that HO-induced DSBs do not provide a sequence or chromatin context that is amenable to de novo telomere addition.

**GCRs with breakpoints at regions of short or no homology:** Fusion of the broken assay chromosome to another chromosomal fragment can generate an interstitial deletion, if the terminal portion of the same chromosomal arm is captured, or a translocation, if a fragment of another chromosome is captured (Figure 2 and Figure 4) (Chen and Kolodner 1999; Myung et al. 2001a,c; Myung and Kolodner 2002; Pennaneach and Kolodner 2004). In GCR assays with only unique sequences in the breakpoint region, junctions typically form between sequences with little or no homology (Chen and Kolodner 1999; Putnam et al. 2005). The lengths of the sequence identities at the junctions were shorter when HR was defective (average length of 3.0 bases) and longer in when non-homologous end joining (NHEJ) was defective (average length of 6.1 bases), suggesting that both NHEJ and some type of HR can generate these GCRs (Putnam et al. 2005). In spite of the lack of homology at breakpoints, translocations with identical junction sequences have been recovered multiple times (Putnam et al. 2005), although the mechanisms and/or genomic features that underlie their formation have not yet been elucidated.

The junction sequences can be used to predict the structure of the rearranged chromosomes. In many cases, the junction sequences suggested the existence of monocentric products, including interstitial deletions, monocentric translocations, or, in the case of some GCRs identified in telomerase-defective strains, circular chromosomes (Chen and Kolodner 1999; Myung et al. 2001a,c; Putnam et al. 2005; Pennaneach and Kolodner 2009). In all cases where monocentric interstitial deletion and monocentric translocation GCRs were studied further, the structures predicted by the breakpoint junction formation of a circular chromosome (Libuda and Winston 2006). (H) Reactivation of ura2-15-30-72, which has three nonsense mutations in the 5′-end of the gene (asterisks), by selecting for uracil prototrophy has identified the formation of large duplications in which the 3′-end of the ura2 allele is fused in-frame to another open reading frame resulting in expression of a functional Ura2 fusion protein (Schacherer et al. 2005). ATCase, aspartate carbamyltransferase; Can9, canavanine-resistant; GCRs, Gross Chromosomal Rearrangements.
Figure 7 Methods used to investigate the structures of Gross Chromosomal Rearrangements (GCRs). (A) Pulsed-field gel electrophoresis (PFGE) can separate individual *S. cerevisiae* chromosomes. Southern blotting with probes to a specific chromosome, in this case the GCR assay chromosome, reveals that all of the GCR-containing isolates have rearranged assay-containing chromosomes that are larger than the corresponding chromosome in a wild-type strain or the parental strain, which is the strain from which the GCR-containing isolates were derived. (B) PCR mapping and junction amplification can be used to map and sequence rearrangements in GCRs recovered from assays such as the classical GCR assay, where the general region in which one breakpoint must occur is known. A series of overlapping PCR products (primers are depicted as gray arrows, and PCR products are depicted as black lines) are generated in separate reactions that probe the breakpoint region. In the GCR-containing isolate, failure of some reactions (red crosses) allows approximate localization of one end of the rearranged assay chromosome. Primers within the last mapping region can be combined with a series of arbitrary primers containing randomized sequences (colored arrows). The products generated by successful PCR reactions (green checkmarks) can be sequenced to determine the breakpoint sequence. (C) Array comparative genomic hybridization (aCGH), in which genomic DNA from a wild-type or parental strain is labeled with one fluorophore and genomic DNA from a GCR-containing isolate is labeled with another fluorophore, and the DNAs are then competitively hybridized to chips containing immobilized oligonucleotides that sample regions across the entire genome. The log2 of the ratios of signals at each genomic position (green trace) reveal regions of copy number changes, including deleted and amplified regions. (D) Multiplexed ligation-mediated primer amplification (MLPA) probes the copy number at selected regions of the genome. For each location, a primer pair is annealed to single-stranded genomic DNA and ligated to form a ssDNA product of a unique size. Ligation products are linearly amplified with a primer pair that adds a 1198

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sequences were confirmed (Pennaneach and Kolodner 2009; Putnam et al. 2009a, 2014).

In other cases, the junction sequences indicate the initial formation of three types of dicentric chromosomes (Figure 2 and Figure 4) (Myung et al. 2001c; Pennaneach and Kolodner 2004; Chan and Kolodner 2011; Putnam et al. 2014). (1) Dicentric translocations form when the broken assay chromosome is joined to a fragment of another chromosome such that the captured fragment contains a centromere and is terminated with a telomere. (2) Telomeric fusions form when the broken assay chromosome is fused to the telomere of another otherwise intact chromosome. (3) Inverted duplications (also called isoduplications due to their similarity to mammalian isochromosomes formed by centromere–centromere fusion) form when the broken assay chromosome is fused to a nearly identical copy of itself in the inverted orientation. Inverted duplications could form either by fusion to or invasion of a sister chromatid or, more likely, by formation of a hairpin-terminated chromosome that is then replicated (Pennaneach and Kolodner 2004, 2009; Narayanan et al. 2006; Putnam et al. 2014; Deng et al. 2015).

When predicted dicentric chromosomes have been further studied, evidence was found for secondary rearrangements that inactivated one of the two centromeres (Pennaneach and Kolodner 2009; Chan and Kolodner 2011, 2012; Putnam et al. 2014). Secondary rearrangements included: (1) dicentric chromosome breakage and healing of the DSB by de novo telomere addition, (2) dicentric chromosome breakage and formation of one or more secondary chromosomal fusions (typically but not exclusively by HR between repeated sequences such as Ty-related sequences) to generate a multipartite monocentric translocation, and (3) mutation or deletion of one of the centromeres. These additional rearrangements are consistent with early studies showing that dicentric chromosomal translocations are prone to breakage when the two centromeres are pulled into different cells during mitosis (Scherer et al. 1982; Kramer et al. 1994; Thrower et al. 2003).

**GCRs mediated by nonallelic recombination between large regions of homology:** In GCR assays with a repeated sequence in the breakpoint region, the predominant types of GCRs recovered are translocations mediated by HR between the repeated sequence in the breakpoint region and a related sequence elsewhere in the genome (Figure 8) (Putnam et al. 2009a; Chan and Kolodner 2011, 2012). For example, in a duplication-mediated GCR assay (also called the dGCR or yel072w::CAN1/URA3 assay), which contains the chromosome V L **HXT13-DSF1** sequences in the breakpoint region, the GCRs recovered were predominantly formed by HR with **HXT13-DSF1**-related sequences on chromosome IV L, X R, or XIV R (Putnam et al. 2009a). The formation of the duplication-mediated GCRs required DSB repair pathways, suggesting that they were formed by BIR, a half-crossover mechanism, or HR between more than one broken chromosomes (McEacharn and Haber 2006; Deem et al. 2008).

Other studies have analyzed GCRs whose formation is mediated by repeated Ty elements (Lemoine et al. 2005, 2008; Argueso et al. 2008; Chan and Kolodner 2011); in these cases, the GCRs detected appeared to be translocations or deletions mediated by HR between Ty elements. Insertion of a full length Ty1 element, Ty912, into the breakpoint region of the classical GCR assay chromosome resulted in an increased GCR rate (Chan and Kolodner 2011). The observed GCRs were mediated by HR between Ty912 and one of at least 254 known Ty or solo δ sequences in the *S. cerevisiae* genome (Chan and Kolodner 2011, 2012). The GCR products were either monocentric translocations, if Ty912 and the recombination target had the same orientation relative to their respective centromeres, or dicentric translocations, if their orientations were the reverse of each other relative to their respective centromeres. As for dicentric translocations formed by nonrepetitive sequences (see section **GCRs with breakpoints at regions of short or no homology**), Ty-mediated dicentric chromosomes underwent one or more secondary rearrangements to yield stable monocentric translocations. Remarkably, rearrangements involving Ty912 preferentially targeted only a small subset of the Ty elements in the genome (six Ty elements accounted for 63% of the GCRs recovered) (Chan and Kolodner 2012), one of which had been previously been identified as a fragile site under low DNA polymerase α conditions (Lemoine et al. 2005).

An unusual type of GCR, observed in the classical GCR assay, involved multiple HR events between **CAN1** and its distant homologs **LYP1** and **ALP1** (Schmidt et al. 2006b). These GCRs appeared to involve an initial crossover between **CAN1** and **LYP1**, which would potentially give rise to a dicentric GCR, and a second crossover between **LYP1** and **ALP1**, which is adjacent to **LYP1** but in an inverted orientation, that potentially converted the predicted dicentric GCR to a monocentric GCR. Some examples of **CAN1-LYP1-ALP1-LYP1-ALP1** translocations involving four crossovers were also observed (Schmidt et al. 2006b). These multipartite rearrangements appeared to reflect short sequence homology-mediated HR events that switch between **CAN1**, **LYP1**, and **ALP1**. These
types of events were initially observed in strains with an sgs1 mutation and another mutation that increased the GCR rate, similar to the template switching observed in HXT13-DSF1 duplication-mediated GCRs in sgs1 single mutants (Putnam et al. 2009a), and were subsequently demonstrated with model HR substrates in wild-type strains (Smith et al. 2007; Anand et al. 2014). The observation of these unusual translocations demonstrates the promiscuity that HR can display during the processes that yield translocations.

Several studies have examined the formation of GCRs that create segmental duplications. In one study, duplication of the RPL20B region was selected for in haploid strains and resulted in tandem duplications or duplications mediated by the formation of nonreciprocal translocations (Koszul et al. 2004). Two types of breakpoints mediated these events: (1) short microhomologies like those seen in the classical GCR assay and (2) Ty element-related sequences. Another study selected for amplification of a SFA1-CUP1 cassette that was inserted between two Ty elements. In this study, the amplification events were mediated by unequal crossing over between Ty elements (H. Zhang et al. 2013).

**Continuously shortening chromosomes:** Analysis of GCR-containing strains has also revealed an unexpected type of fragmented chromosome lacking a telomere, which existed as a population of continually shortening chromosomes (Pennaneach and Kolodner 2009). These shortening chromosomes were seen in mutants defective for the checkpoints that cause cell cycle delay or arrest in response to DSBs. It appears that the loss of sequences from the broken end of these chromosomes during each round of replication may be slow enough that the cells containing such chromosomes can divide many times before growth terminates due to loss of essential genes and dilution of their encoded essential gene products. It is also possible that these chromosomes were stabilized by other mechanisms that can synthesize DNA, but not a telomere, onto the broken end of the fragmented chromosomes (Maringele and Lydall 2004).

**Structures of GCRs selected in diploid strains**

A limited number of studies have characterized in detail the GCRs selected in diploid strains. In one diploid assay, URA3 was inserted in different positions along one copy of chromosome III, and 5-FOA-resistant progeny were selected and analyzed (Umezu et al. 2002). URA3 was lost by multiple mechanisms, including: (1) chromosome loss; (2) mitotic HR between the two copies of chromosome III in the region between URA3 and the centromere combined with segregation of progeny lacking URA3 during cell division; (3) gene conversion of the inserted URA3 allele; (4) HR-mediated interstitial deletion of URA3; and (5) both interchromosomal and intrachromosomal translocations mediated by HR with a Ty element located between URA3 and the centromere. In the case of the interchromosomal translocations, the fate of the nonchromosome III target chromosome was not analyzed, so it is not known if the resulting translocations were reciprocal or nonreciprocal. In some cases, a region of chromosome III at the breakpoint junction was duplicated or triplicated (Umezu et al. 2002); studies of amplified regions associated with the formation of Ty element-mediated translocations selected in haploid GCR assays have provided structures for these types of amplified regions (Pennaneach and Kolodner 2009; Chan and Kolodner 2011, 2012).

In a second diploid assay, a SFA1-CUP1 cassette was inserted onto both copies of chromosome V R, followed by selection for amplification of the SFA1-CUP1 cassette

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**Figure 8** In the presence of homologies, HR can mediate both conservative repair as well as error-prone repair leading to the formation of a GCR. (A) After the formation of a DSB within a region of homology to different sites in the genome (or adjacent to the region of homology followed by resection into the homology), allelic HR targeted to the sister chromatid can repair the DSB such that the original structure of the chromosome is preserved and no GCR is formed. (B) If an ectopic homology is targeted, such as through BIR or a half-crossover mechanism, a GCR is formed and chromosomal regions lacking centromeres are lost. Note that the normal HR machinery is involved in both mechanisms that repair the initiating DSB. BIR, break-induced replication; DSBs, double-strand breaks; GCRs, Gross Chromosomal Rearrangements; HR, homologous recombination.
encoded proteins; many of these data are accessible through resources such as the Saccharomyces Genome Database and BioGRID (Cherry 2015; Oughtred et al. 2016).

Models for interactions between mutations have been strongly influenced by the analysis of biochemical pathways. In these analyses, synergistic interactions between mutations are often thought to indicate interactions that inactivate independent pathways that perform the same function (Kaelin 2005; Ooi et al. 2006). Similarly, epistatic interactions between mutations are often thought to indicate that these mutations affect the same pathway (Kaelin 2005; Ooi et al. 2006). This conceptual framework, termed here the “biochemical model,” is appropriate for understanding some GCR-suppressing interactions (Figure 9), such as the partial redundancy between the DNA damage checkpoint protein kinases Tel1 (homolog of human ATM) and Mec1 (homolog of human ATR) (Myung et al. 2001c; Craven et al. 2002; Mieczkowski et al. 2003). Deletion of the TEL1 gene causes no increase in the GCR rate relative to the wild-type strain (Myung et al. 2001c). In contrast, mec1 mutations cause a ~200-fold increase, and the combination of mec1 and tel1 mutations causes a ~13,000-fold increase in GCR rates (Myung et al. 2001c). Consistent with this synergistic increase in GCR rates, both protein kinases phosphorylate the same SQ and TQ sites in many common substrate proteins (Kim et al. 1999), and partial redundancy has also been observed for roles in telomere maintenance (Ritchie et al. 1999) and the DNA damage checkpoint response (Sanchez et al. 1996; Vialard et al. 1998). However, the extreme increase in GCR rate in the mec1 tel1 double mutant likely reflects the deregulation of multiple processes that interact with each other including telomere maintenance and checkpoint responses (Pennaneach and Kolodner 2004). Another example consistent with the biochemical model is the observation of epistatic interactions within a pathway. Mutations in SGS1 or TOP3, which encode proteins that interact physically and biochemically (Gangloff et al. 1994; Ng et al. 1999), increase GCR rates in the classical GCR assay by ~20-fold, and the sgs1 top3 double mutant has a GCR rate similar to both of the single mutants (Myung et al. 2001b).

For many other genetic interactions, the biochemical model is not appropriate, nor is the tendency to classify all synergistic genetic interactions as “buffering” interactions on the basis of this model (Hartman et al. 2001; Segre et al. 2005). In cases where mutations show interactions in GCR assays, and/or show growth-based synthetic interactions, the relevant genes can act within the same pathway as well as act in separate pathways that have different functions. In the case of the apparently paradoxical within-pathway interactions, an analysis by Heyer and colleagues has described mechanisms that may underlie these kinds of interactions (Zinovyev et al. 2013). When interacting genes function in nonredundant pathways, other models can sometimes explain these interactions.

In the “damage/response model,” one gene plays a role in generally repairing DNA damage and the other plays a role in
preventing DNA damage from generating GCRs (Figure 9). An example of a gene involved in these types of interactions is PIF1, which encodes a DNA helicase that plays a crucial role in suppressing de novo telomere additions by telomerase (Schulz and Zakian 1994; Zhou et al. 2000). Inactivation of the nuclear form of PIF1 with the pif1-m2 mutation causes an increase in GCR rates and synergistic increases in GCR rates when combined with a wide variety of mutations in genes that likely directly or indirectly suppress the accumulation of DNA damage (Figure 10A) (Myung et al. 2001a). The effect of PIF1-mediated suppression of telomerase is emphasized by the fact that deletion of PIF1 eliminates the duplication-mediated GCRs formed by HR typically seen in the duplication-mediated GCR assay, presumably by channeling damaged DNAs into de novo telomere addition reactions (Putnam et al. 2009a).

In the “suppression/repair model,” one gene plays a role in preventing metabolic errors during DNA replication and another gene plays a role in the repair of the damage after it has occurred (Figure 9). An obvious gene that plays a role in a damage suppression pathway is TSA1, which encodes the major thioredoxin peroxidase that protects S. cerevisiae from oxidative stress (Chae et al. 1994; Park et al. 2000). Defects in TSA1 cause increased GCRs and cause synergistic interactions with defects in multiple DNA repair pathways (Huang et al. 2003; Huang and Kolodner 2005).

Analyses of GCR data must also take into account several additional complications. (1) Genes that might be expected to fit the biochemical model for interactions may only be partially redundant, and consequently mutations in such genes may show both synergistic interactions and also result in distinct rates of accumulating GCRs, have distinct sets of interactions with mutations in other genes, and/or give rise to distinct classes of GCRs. An example of this model is the partial redundancy between TEL1 and MEC1 (Myung et al. 2001c) discussed above, which is consistent with the view that Mec1 and Tel1 likely act on distinct but overlapping sets of targets (Morrow et al. 1995; Sanchez et al. 1996; Vialard et al. 1998). (2) Genes may have dual roles in repairing DNA damage and preventing the formation of GCRs as a result of DNA damage, which complicates any analysis by the damage/response model. An example of this type of gene is RAD52, which
suppresses GCRs by mediating allelic HR, but also promotes the formation of GCRs in duplication-mediated assays by mediating nonallelic HR (Figure 8B). Hence, rad52 mutations cause increased GCR rates in single-copy sequence-mediated assays but decreased GCR rates in duplication-mediated assays (Chen and Kolodner 1999; Putnam et al. 2009a). (3) The formation of a selectable GCR requires both DNA damage and formation of an aberrant chromosome that is stable enough so that cells containing the GCR can survive under selective conditions. The generation of GCRs is thus a form of “non-conservative” DNA repair that does not restore the structure and sequence of the original undamaged chromosomes. As such, the formation of GCRs is dependent on DNA repair mechanisms, and inactivation of pathways required to generate GCRs, as suggested for the Rad1-Rad10 endonuclease (Figure 10B) (Hwang et al. 2005), can play crucial roles on the effects of individual mutations or combinations of mutations have on the recovery of GCRs.

A global view of genome instability suppressing genes

Considerable effort has been focused on the identification of Genome Instability Suppressing (GIS) genes. To date, these studies have identified 171 nonessential S. cerevisiae genes in which mutations cause increased GCR rates in normally growing cells [discussed in Putnam et al. (2016)], and 29 essential genes in which mutations potentially cause increased GCR rates (Table 1). Validation studies suggest that this list is close to a complete list of the nonessential genes that act to suppress GCRs (Putnam et al. 2016). In contrast, there have been very limited studies on genes that act to suppress GCRs that are induced by exogenous DNA-damaging agents (Myung and Kolodner 2003) or by defects in essential genes (Chen and Kolodner 1999; Huang and Koshland 2003; Shah et al. 2012; Albuquerque et al. 2013; Y. Zhang et al. 2013). Advances in these areas may come from studies examining the remodeling of growth-based genetic interaction networks by DNA-damaging agents (Bandyopadhyay et al. 2010; Srivas et al. 2016) and systematic screening of hypomorphic alleles of essential genes. Known GIS genes play significant roles in DNA replication, DNA repair, DNA damage checkpoints, telomere maintenance, response to oxidative stress, cell cycle

Figure 10 Gross Chromosomal Rearrangement (GCR) rates of single and double mutants showing the effect of combining rad1, rad10, or pif1-m2 mutations with mutations affecting other pathways. (A) Combining a pif1-m2 mutation with many mutations affecting chromosome homeostasis causes a synergistic increase in GCR rates in the classical GCR assay (left), but is suppressed by mutations affecting specific pathways (right). GCR rates are displayed as horizontal bars, and related genotypes are connected by lines. Column 1: pif1-m2 single mutant. Column 2: double mutants with increased GCR rates. Column 3: single mutations that in combination with the pif1-m2 mutation increase the GCR rate. Column 4: pif1-m2 single mutant. Column 5: double mutants with decreased GCR rates. Column 6: single mutations that in combination with a pif1-m2 mutation decrease the GCR rate. The synergistically increased rates likely result from the mechanism depicted by the damage/response model, as PIF1 functions to suppress the formation of de novo telomere addition GCRs (Myung et al. 2001a), and many of the interacting genes are implicated in repairing or preventing the formation of DNA damage. Note that the increased GCR rate caused by a pif1-m2 mutation is suppressed by combining it with mutations affecting several pathways, including de novo telomere addition (est1, est2, est3, tlc1, yku70, yku80, cdc13-2, smn1-13, sir1, sir2, sir3, and sir4), the Ctf8-Ctf18-Dcc1 alternative RFC complex, and components of the spindle checkpoint (mad2, mad3, bub2, and bub3). Data are from a summary of the previous literature (Putnam et al. 2012). (B) Deletion of RAD1 or RAD10, which disrupts the Rad1-Rad10 endonuclease that targets nonhomologous ssDNA overhangs (Sugasawa et al. 1997), suppresses the GCR rates caused by many (left), but not all (right), mutations that cause high GCR rates in the classical GCR assay (Hwang et al. 2005). Rates displayed as in panel A. Column 1: the rad1 and rad10 single mutants. Column 2: double mutants with decreased rates. Column 3: single mutations that cause increased GCR rates in the classical GCR assay. Column 4: the rad1 and rad10 single mutants. Column 5: double mutants whose GCR rates are not affected by rad1 or rad10 mutations. Column 6: single mutations that are not suppressed by rad1 or rad10 mutations. Suppression of the formation of GCRs likely indicates a role for the cleavage of ssDNA overhangs during formation of many types of GCRs involving steps where regions of microhomology anneal to each other (Figure 2). The lack of suppression of the pif1-m2 GCR rate by rad1 or rad10 mutations could be consistent with reports that an endonucleolytic activity of telomerase can cleave non-TG-containing portions of ssDNA tails (Collins and Greider 1993; Cohn and Blackburn 1995; Melek et al. 1996). The lack of suppression of the exo1 GCR rate by rad1 or rad10 mutations could be consistent with defects in resection of double-strand breaks and other substrates in exo1 mutant strains (Zhu et al. 2008).
control, protein sumoylation, subsets of the nuclear pore, and chromatin assembly (see below).

Additionally, some genes like TLC1 and DNL4 are not GIS genes, but defects in these genes do cause genome instability in combination with other mutations, and we have termed them cooperating GIS (cGIS) genes. cGIS genes likely play essential roles. Known cGIS genes likely play redundant or accessory roles with other genes in suppressing GCRs. Systematic genetic interaction analysis has led to the identification of 438 GIS genes (Putnam et al. 2016). However, additional analyses are required to both validate these interactions and to test predicted interactions involving genes encoding these complexes and other pathways. It will also be of interest to extend these genetic interactions to mutations in essential genes, although such studies are likely to be complicated by growth defects caused by mutations in essential genes. Known cGIS genes define a much broader set of biological functions than those implicated by the GIS genes. These functions include multiple complexes in transcription, mRNA processing, and protein degradation, as well as additional pathways in DNA repair and cell cycle control (see below). Moreover, defects in cGIS genes can also have important impacts on the spectrum of observed GCR structures (Myung et al. 2001c; Putnam et al. 2014).

Finally, ~9200 double mutants with reduced GCR rates have been identified (Putnam et al. 2016). However, most of these double mutants will require extensive validation because genetic interactions that result in reduced growth rates can appear as if they result in reduced GCR rates in semi-quantitative patch test assays. By carefully validating and extending the systematic genetic interaction studies performed to date and possibly incorporating genetic interaction data from other types of studies, it should be possible to ultimately define in detail the genetic network that supports the formation of GCRs and the pathways that promote the formation of GCRs in mutants with high GCR rates or after treatment with DNA-damaging agents.

### Table 1, continued

| ORF | Gene | ORF | Gene | ORF | Gene |
|-----|------|-----|------|-----|------|
| YBR136W | MEC1 | YPR018W | RLF2 | YMR106C | YKU80 |
| YLR288C | MEC3 | YDR255C | RMD5 | YML002W | YML002W |
| YLI128W | MET18 | YPL024W | RMI1 | YML020W | YML020W |
| YMR167W | MLH1 | YLO50C | RML2 | YGR270W | YTA7 |
| YL061W | MMP1 | YDR279W | RHN202 | YM273C | ZDS1 |
| YPR164W | MMS1 | YLR154C | RNH203 |

Note that quantitative and semiquantitative Gross Chromosomal Rearrangement rate data are not available for all of the essential genes listed in this table.

### Table 1, Genes implicated in suppressing genome instability in S. cerevisiae

| ORF | Gene | ORF | Gene |
|-----|------|-----|------|
| YML086C | ALO1 | YGL087C | MMS2 |
| YOR141C | ARP8 | YEL019C | MMS21 |
| YL115W | ASF1 | YBR098W | MMS4 |
| YPL115C | BEM3 | YIR002C | MPR1 |
| YBR290W | BSD2 | YCL061C | MRC1 |
| YML102W | CAC2 | YMR224C | MRE11 |
| YMR038C | CCS1 | YOL090W | MSH2 |
| YJL194W | CDC6 | YDR097C | MSH6 |
| YDL017W | CDC7 | YBR195C | MS1 |
| YFR036W | CDC26 | YGR257C | MTM1 |
| YCR094W | CDC50 | YDR386W | MUS81 |
| YLR418C | CDC73 | YHL023C | NPR3 |
| YDL164C | CDC9 | YBR288W | NSE3 |
| YGL003C | CDH1 | YKR082W | NUP133 |
| YBR274W | CHK1 | YAR002W | NUP60 |
| YPL008W | CHL1 | YDL116W | NUP84 |
| YOR039W | CKB2 | YML060W | OGG1 |
| YPR119W | CLB2 | YBR060C | ORC2 |
| YPR120C | CLB5 | YIR008C | ORC3 |
| YPL256C | CLN2 | YNL261W | ORC5 |
| YLI123C | CSM2 | YDR112C | PDS1 |
| YMR048W | CSM3 | YOR386W | PHR1 |
| YOR078C | CTF18 | YML061C | PIF1 |
| YPR135W | CTF4 | YBL051C | PIN4 |
| YHR191C | CTF8 | YNL102W | POL1 |
| YJR006C | CTX2 | YDL102W | POL3 |
| YDR052C | DBF4 | YLB035C | POL12 |
| YCL016C | DCC1 | YBR088C | POL2 |
| YPL194W | DCC1 | YIR043C | POL32 |
| YOR080W | DIA2 | YIR008C | PRI1 |
| YHR164C | DNA2 | YKL045W | PR2 |
| YOR005C | DNL4 | YKL116C | PR1 |
| YDR440W | DOT1 | YOL146W | PSF3 |
| YLR090C | DPB1 | YML095C | RAD10 |
| YGL043W | DST1 | YOR368W | RAD17 |
| YDL101C | DUN1 | YCR066W | RAD18 |
| YDR359C | EAF1 | YER173W | RAD24 |
| YOR144C | ELG1 | YKL113C | RAD27 |
| YKL048C | ELM1 | YDR419W | RAD30 |
| YMR219W | ESC1 | YER162C | RAD62 |
| YDR363W | ESC2 | YNL250W | RAD50 |
| YLR233C | EST1 | YLR032W | RAD5 |
| YLR318W | EST2 | YER095W | RAD51 |
| YIL009C-A | EST3 | YML032C | RAD52 |
| YOR033C | EXQ1 | YL153C | RAD53 |
| YNL153C | GIM3 | YGL163C | RAD54 |
| YPL137C | GIP3 | YDR076W | RAD55 |
| YKL017C | HCS1 | YDR004W | RAD57 |
| YGL194C | HOS2 | YDL059C | RAD59 |
| YKL101W | HSL1 | YDR014W | RAD61 |
| YOR025W | HST3 | YGL058W | RAD6 |
| YDR191W | HST4 | YDR217C | RAD9 |
| YDR225W | HTA1 | YBR073W | RADH5 |
| YPL017C | IRC5 | YL139C | REV7 |
| YDR322W | IRC3 | YAR007C | RFA1 |
| YBR245C | ISW1 | YNL312W | RFA2 |
| YJR054W | KCH1 | YL173C | RFA3 |
| YDR499W | LCD1 | YIR068W | RFC2 |
| YDR439W | LSR4 | YOL094C | RFC4 |
| YBL023C | MCM2 | YBR087W | RFC5 |
| YLR274W | MCM5 | YLR453C | RFC6 |

Note that quantitative and semi-quantitative Gross Chromosomal Rearrangement rate data are not available for all of the essential genes listed in this table.

**Pathways implicated in the suppression of spontaneous genome rearrangements**

**DNA repair pathways:** DNA repair pathways were implicated in the suppression of GCRs by the identification of the first mutants with increased GCR rates (Tishkoff et al. 1997; Chen et al. 1998; Chen and Kolodner 1999; Myung et al. 2001a, b; Myung and Kolodner 2002; Putnam et al. 2009a), and subsequent studies identifying GIS and cGIS genes (Huang et al. 2016).
2003; Smith et al. 2004; Kanellis et al. 2007; Stirling et al. 2011; Putnam et al. 2016) have supported the view that DNA repair pathways are central to the suppression of GCRs. The central role of DNA damage and how that damage is processed in the suppression of genome instability is also emphasized by the increase in GCR rates observed when cells are treated with DNA-damaging agents (Myung and Kolodner 2003).

Despite the general importance of DNA repair pathways in suppressing GCRs, not all DNA repair pathways contribute equally (Figure 11). For example, base-excision repair (BER) genes generally play little or no role in suppressing spontaneous GCRs. A possible exception is OGG1 (Huang and Kolodner 2005), which encodes 8-oxoguanine glycosylase/lyase; however, OGG1 deletions might increase the rates of forming de novo telomere addition GCRs due to effects of deletion of OGG1 on the adjacent PIF1 gene. Similarly, defects in nucleotide-excision repair (NER) do not generally affect GCR rates; however, those that do also affect NER genes that play roles in other processes (Hwang et al. 2005; Putnam et al. 2016). Remarkably, DNA repair defective mutations that have little effect in GCR assays tend to have fewer genetic interactions causing synthetic growth interactions under normal growth conditions than mutations having larger effects in GCR assays (Tong et al. 2004; Collins et al. 2007; Costanzo et al. 2010). The relationship between genome instability and genetic interactions might reflect the relative importance of different repair pathways in the repair of the spontaneous DNA damage that underlies the formation of GCRs (see section DNA replication).

HR acts to both suppress and generate GCRs. Both HR and BIR depend on Rad52 and have two major subpathways defined by dependence on the Rad51 pairing and strand-exchange protein or the Rad59 strand annealing protein (for a review, see Krogh and Symington (2004)). During normal growth, HR acts in error-free repair of DSBs (and potentially other damage) in S- or G2-phase using the intact sister chromatid as a donor for repair of the DSB; this type of allelic sister chromatid HR suppresses the formation of GCRs (Figure 8). Thus, loss of HR, either by a rad52 mutation or the combination of the rad51 and rad59 mutations, will substantially increase the GCR rate in assays that only have single-copy sequences in the assay breakpoint region (Chen and Kolodner 1999; Myung et al. 2001a; Putnam et al. 2009a).

The GCRs selected in the classical GCR assay are a mixture of de novo telomere additions, translocations, and interstitial deletions, which appear to be formed by NHEJ, based on the short or lack of homologous sequences at the breakpoint junctions (Chen and Kolodner 1999; Myung et al. 2001a; Putnam et al. 2005). Mutations in HR pathway genes that affect only one HR subpathway often have intermediate effects on GCR rates (Figure 11) (Chen and Kolodner 1999; Myung et al. 2001a). In contrast, GCR assays with homologies to ectopic sites in the breakpoint region can select for translocation, duplication, or deletion GCRs that are generated by nonallelic HR (Figure 8B). In these homology-containing GCR assays, a rad52 mutation decreases the rate of accumulating GCRs due to loss of nonallelic HR; however, the rate is not reduced to wild-type levels because error-free allelic HR that suppresses some GCRs is also eliminated (Putnam et al. 2009a; Chan and Kolodner 2011). In contrast, deletion of RAD52 caused
a greater decrease in the rate of Ty-mediated GCRs because deletion of \textit{RAD52} causes greater defects in HR. These results indicate that not only are the two HR subpathways partially redundant but that HR with individual Ty targets shows a unique dependence on one or the other of the HR subpathways.

The Mre11-Rad50-Xrs2 (MRX) complex plays an important role in initiating resection at DSBs during HR in \textit{S. cerevisiae} [for a review, see Krogh and Symington (2004)] and likely promotes error-free sister chromatid HR (Hartsuiker \textit{et al.} 2001), in addition to having roles in NHEJ, the intra-S checkpoints, and telomere length maintenance (Moore and Haber 1996; Boulton and Jackson 1998; D’Amours and Jackson 2001). It also plays an important role in sensing DNA damage in different DNA damage checkpoints (see below). Deletions of genes encoding the MRX complex cause dramatic increases in GCR rates in multiple GCR assays (Figure 11), including assays with and without homologies in the breakpoint regions (Chen and Kolodner 1999; Putnam \textit{et al.} 2009a; Chan and Kolodner 2011). Defects in the MRX complex also alter the GCR spectrum by reducing the formation of \textit{de novo} telomere addition GCRs (Chen and Kolodner 1999; Putnam \textit{et al.} 2009a; Chan and Kolodner 2011). Mutations in \textit{MRE11} that affect the MRX nuclease activity, which acts in end resection, and deletion of \textit{SAE2}, which acts in conjunction with MRX to cleave DNA hairpins at DSBs, also alter the types of GCRs formed (Smith \textit{et al.} 2005; Putnam \textit{et al.} 2014; Deng \textit{et al.} 2015). Thus, in contrast to the deletion of \textit{MRE11}, \textit{Mre11} nuclease defects and deletion of \textit{SAE2} result in large increases in isoduplications, which are thought to be mediated by the formation of hairpin structures at DSBs (Lobachev \textit{et al.} 2002; Putnam \textit{et al.} 2014; Deng \textit{et al.} 2015). It seems likely that mutations affecting the MRX complex increase the formation of GCRs due to a variety of reasons, including defects in promoting sister chromatid HR, in DNA damage checkpoints, in NHEJ, in telomere maintenance, and in hairpin cleavage.

Multiple proteins process HR intermediates, including the Mph1-Mte1 complex that mediates dissolution of D-loops, the Sgs1-Top3-Rmi1 complex that unwinds double Holliday junctions, the Yen1 Holliday junction resolvasse, and the Sxl1-Slx4 and Mms4-Mus81 structure-selective endonucleases whose human homologs act cooperatively in the cleavage of double Holliday junctions (Fabre \textit{et al.} 2002; Krogh and Symington 2004; Munoz-Galvan \textit{et al.} 2012; Castor \textit{et al.} 2013; Garner \textit{et al.} 2013; Mazon and Symington 2013; Wyatt \textit{et al.} 2013; Silva \textit{et al.} 2016; Xue \textit{et al.} 2016; Yimit \textit{et al.} 2016). These proteins can also play roles in DNA replication, including termination of replication (Boddy \textit{et al.} 2001; Mundbjerg \textit{et al.} 2015), establishing BIR from DSBs (Pardo and Aguilera 2012) and promoting resection of DSBs (Gravel \textit{et al.} 2008; Zhu \textit{et al.} 2008). Defects in \textit{YEN1} do not cause increased GCR rates in the assays studied to date (Figure 11) (Smith \textit{et al.} 2004; Doerfler \textit{et al.} 2011; Putnam \textit{et al.} 2016), consistent with the observation that \textit{Yen1} plays little if any role in HR when Mus81-Mms4 is present (Blanco \textit{et al.} 2010). Defects in the genes encoding the other protein complexes cause increased GCR rates (Figure 11) (Myung \textit{et al.} 2001b; Hwang \textit{et al.} 2005; Putnam \textit{et al.} 2009a, 2012; Chan and Kolodner 2011; Doerfler \textit{et al.} 2011; Allen-Soltero \textit{et al.} 2014). Interestingly, defects in the genes encoding these complexes, particularly the Sgs1-Top3-Rmi1 complex, cause larger increases in GCR rates in duplication-mediated GCR assays compared to single-copy sequence-mediated GCR assays such as the classical GCR assay; defects in \textit{SLX1}, \textit{SLX4}, and \textit{MPH1} cause little or no increase in GCR rates in single-copy sequence-mediated GCR assays (Putnam \textit{et al.} 2009a). These results suggest that nonallelic HR is minimized by unwinding D-loops (Mph1-Mte1) or by reversing double Holliday junctions (Sgs1-Top3-Rmi1). Remarkably, the absence of \textit{Sgs1} promotes GCRs formed by HR between \textit{CAN1} and its divergent homologs \textit{ALP1} and \textit{LYP1}, which likely reflects template switching during nonallelic HR and a relaxation of heteroduplex rejection (Myung \textit{et al.} 2001b; Spell and Jinks-Robertson 2004; Schmidt \textit{et al.} 2006b; Smith \textit{et al.} 2007). Defects in Sgs1-Top3-Rmi1 and Mms4-Mus81 could also cause defects in processing HR intermediates during error-free repair, which could allow damaged DNAs to be acted on by GCR-generating processes such as \textit{de novo} telomere addition or NHEJ.

NHEJ by itself appears to play only a small role in suppressing the spontaneous formation of GCRs (Figure 11) (Myung \textit{et al.} 2001a; Putnam \textit{et al.} 2012, 2014, 2016). Deletion of \textit{DNL4} or \textit{LIF1}, which encode the DNA ligase involved in NHEJ, caused little if any increase in GCR rates in GCR assays that only contain single-copy DNA sequences in the assay chromosome breakpoint region (Myung \textit{et al.} 2001a; Putnam \textit{et al.} 2014) and tended to reduce the GCR rates of mutants that have increased GCR rates in the classical GCR assay, consistent with a role for NHEJ in generating GCRs such as translocations selected in these assays (Myung \textit{et al.} 2001a). However, deletion of \textit{DNL4} did cause a modest increase in GCR rates in a duplication-mediated GCR assay, consistent with the possibility that NHEJ channels some DNA damage away from HR, which normally promotes the formation of GCRs by nonallelic HR (Putnam \textit{et al.} 2014). Deletion of \textit{YKU70} or \textit{YKU80} also caused only small increases in GCR rates, most notably in duplication-mediated GCR assays, similar to the effect of a \textit{DNL4} deletion (Chen and Kolodner 1999; Myung \textit{et al.} 2001a; Putnam \textit{et al.} 2014). However, because \textit{Ku70} and \textit{Ku80} play a role in the synthesis of telomeres by telomerase, they are required for the formation of \textit{de novo} telomere addition GCRs and, as a consequence, \textit{yku70} and \textit{yku80} mutations suppressed the increased GCR rate caused by a \textit{pif1} mutation (Figure 10A) (Myung \textit{et al.} 2001a).

DNA mismatch repair (MMR) corrects mispaired bases that arise due to errors during DNA replication, and defects in MMR underlie both inherited and sporadic cancers [reviewed in Lagerstedt Robinson \textit{et al.} (2007), Fishel (2015), Reyes \textit{et al.} (2015), Heinen (2016)]. MMR also repairs mispaired bases that are formed in heteroduplex HR intermediates.
(White et al. 1985; Bishop et al. 1987; Borts et al. 1990; Reenan and Kolodner 1992; Haber et al. 1993; Alani et al. 1994; Tham et al. 2016). In addition, MMR has also been implicated in suppressing the formation of GCRs (Figure 11) (Myung et al. 2001b; Putnam et al. 2009a), primarily due to the role of MMR in suppressing HR between divergent homologous sequences, sometimes called homologous recombination (Bailis and Rothstein 1990; Datta et al. 1996; Myung et al. 2001b; Spell and Jinks-Robertson 2004; Sugawara et al. 2004; Tham et al. 2016). msh2 and msh6 mutations, which inactivate the Msh2-Msh6 mispair recognition complex, resulted in increased GCR rates in duplication-mediated GCR assays with homologies to ectopic sites in the breakpoint region. In contrast, an msh3 mutation, which inactivates the Msh2-Msh3 mispair recognition complex, caused little increase in GCR rates in duplication-mediated GCR assays (Putnam et al. 2009a). The importance of Msh2-Msh6 relative to Msh2-Msh3 in suppressing the formation of these duplication-mediated GCRs is consistent with a heteroduplex rejection mechanism; heteroduplexes formed in this assay are predicted to primarily contain base:base mispairs, which are more readily recognized by Msh2-Msh6 than by Msh2-Msh3 [reviewed in Reyes et al. (2015) and Groothuizen and Sixma (2016)]. Similarly, an msh2 mutation also increased the rate of GCRs selected in GCR assays that only contain single-copy sequences in the breakpoint region, and a fraction of the GCRs recovered were translocations with extended regions of imperfect homology at their breakpoints (Myung et al. 2001b). Another key MMR protein complex, Mlh1-Pms1, at best had a minor role in the suppression of duplication-mediated GCRs (Putnam et al. 2009a), consistent with the fact that Mlh1-Pms1 plays a major role in mispair correction [reviewed in Reyes et al. (2015), Groothuizen and Sixma (2016)] but only plays a minor role in suppression of homeologous recombination (Datta et al. 1996; Sugawara et al. 2004). Sgs1 also plays an important role in both the suppression of homeologous recombination and the suppression of duplication-mediated GCRs, although it may act at a different mechanistic step to Msh2-Msh6, as combining sgs1 and msh2 mutations resulted in a synergistic increase in the rate of both homeologous recombination and duplication-mediated GCRs (Myung et al. 2001b; Spell and Jinks-Robertson 2004; Sugawara et al. 2004; Putnam et al. 2009a).

Postreplication repair (PRR), which is a DNA damage tolerance pathway rather than a DNA repair pathway [reviewed in Branzei (2011), Branzei and Szakal (2016)], plays different roles in the suppression and formation of GCRs that can be identified using different types of GCR assays. Mutations in the upstream genes, RAD6 and RAD18, which encode a ubiquitin E2 conjugase and a ubiquitin E3 ligase, respectively, result in dramatically increased GCR rates in a duplication-containing GCR assay (Putnam et al. 2010). These increased GCR rates caused by rad6 and rad18 mutations are largely similar to the increased GCR rates caused by a mutation that eliminates the Rad6-Rad18-dependent PCNA monoubiquitination site (Hoege et al. 2002; Putnam et al. 2010); these mutations causing increased GCR rates are also epistatic to deletion of the SRS2 antirecombinase, which is upstream of PRR (Lawrence and Christensen 1979). Several subpathways exist downstream of Rad6 and Rad18, including RAD5-dependent subpathways that may act to regress replication forks or to mediate cross-fork template switching (Goldfuss et al. 2006; Blastyak et al. 2007; Branzei et al. 2008), and are more important for suppressing GCRs than the downstream translesion polymerases that act in bypassing lesions during DNA replication (Motegei et al. 2006; Putnam et al. 2010). Rad5 is a DNA helicase and a ubiquitin E3 ligase, and both activities are required for repair of UV damage (Gangavarapu et al. 2006); however, only the helicase activity of Rad5 is important in suppressing the formation of duplication-mediated GCRs (Putnam et al. 2010). In contrast, defects in PRR genes by themselves cause little or no increase in GCR rates in GCR assays that only contain single-copy sequences in the assay chromosome breakpoint region (though differing effects have been observed for rad5 and rad18 deletions in different studies), and suppress the increased GCR rates caused by other mutations in these assays (Figure 11) (Motegei et al. 2006; Kats et al. 2009; Putnam et al. 2010). A simple explanation for the assay-specific effects of PRR defects is that PRR downregulates HR in response to DNA replication-induced DNA damage; consequently, PRR defects would result in increased nonallelic HR and increased GCRs selected in duplication-mediated GCR assays, as well as increased allelic HR and suppression of GCRs selected in single-copy sequence-mediated GCR assays.

Mutations in most NER genes, except for genes encoding the Rad1-Rad10 endonuclease, have little or no effect on GCR rates in any of the GCR assays tested (Figure 11) (Hwang et al. 2005; Putnam et al. 2016). However, deletions of RAD1 and RAD10 cause increased rates in duplication-mediated GCR assays. In contrast, these deletions strongly suppress GCR rates in single-copy sequence-mediated GCR assays caused by many other mutations (Figure 10B) (Hwang et al. 2005; Putnam et al. 2009a). Rad1-Rad10 plays roles in other processes besides NER, including processing of HR intermediates (Schiestl and Prakash 1988, 1990; Sugawara et al. 1997), resolving interstrand cross-links (Niedernhofer et al. 2004), and microhomology-mediated end-joining (Ma et al. 2003). Because Rad1-Rad10 is thought to trim unmatched ssDNA overhangs in different types of HR and NHEJ intermediates as well as cleave ssDNA branches, Rad1-Rad10 may facilitate the formation of GCRs by processing DSBs so that they can participate in NHEJ and de novo telomere addition reactions (Hwang et al. 2005). In contrast, similar cleavage of branched intermediates formed during nonallelic HR might reduce the formation of these HR-dependent GCRs.

**DNA replication:** Spontaneous errors during DNA replication are an important source of the DNA damage that underlies increased genome instability (Flores-Rozas and Kolodner
2000; Michel 2000). For example, DNA replication defects can result in increased accumulation of HR intermediates (Zou and Rothstein 1997), and dysregulation of replication origins results in increased rates of accumulating GCRs (Lengronne and Schwob 2002; Watanabe et al. 2002). Several lines of indirect evidence are also consistent with the notion that DNA replication errors play a major role in the formation of GCRs. (1) Multiple DNA repair pathways, such as HR and PRR (see section DNA repair pathways), which play important roles in suppressing the formation of GCRs, also act in the repair of damaged DNA replication forks and in the formation of new replication fork-like structures during DSB repair, which is a type of DSB repair [reviewed in Anand et al. (2013), Mehta and Haber (2014)]. (2) S-phase DNA damage and replication checkpoints both suppress spontaneous GCRs and stabilize damaged replication forks (Lopes et al. 2001; Myung et al. 2001c; Myung and Kolodner 2002) (see section S-phase checkpoints). Finally, (3) DNA repair-defective mutations cause increased GCR rates and tend to have large numbers of synthetic genetic interactions with other mutations resulting in growth defects (Tong et al. 2004; Collins et al. 2007; Costanzo et al. 2010), suggesting that repair of DNA damage, possibly occurring during DNA replication, is required during normal growth. Moreover, defects in some essential DNA replication genes have been shown to cause increased GCR rates (Figure 11) (Chen and Kolodner 1999; Putnam et al. 2009a; Chan and Kolodner 2011; Stirling et al. 2011; Shah et al. 2012; Y. Zhang et al. 2013), although definitive analysis of all DNA replication genes has not yet been performed. It should be noted that, in many cases, the defects in essential genes that have been reported to cause increased GCR rates have not been validated using quantitative GCR rate assays that definitively detect the formation of GCRs.

Hypomorphic alleles and alleles that reduce the expression of proteins involved in origin recognition and firing—ORC2, ORC3, ORC5, SLD2, PSF3, CDC7, DBF4, CDC6, and TAH11—have been implicated as causing increased genomic instability (Huang and Kosland 2003; Stirling et al. 2011; Y. Zhang et al. 2012, 2013). Additionally, hypomorphic alleles of genes encoding DNA polymerases and primases, e.g., POL1, POL12, POL2, POL3, PRI1, and PRI2, and the replicative helicases MCM2 and MCM5, have been implicated in causing increased genome instability (Putnam et al. 2009a; Stirling et al. 2011; Shah et al. 2012; Zhang et al. 2012, 2013b). At least one mutation in POL30, which encodes the S. cerevisiae homolog of PCNA, caused a modest increase in GCR rates whereas at least two other pol30 mutations did not cause increased GCR rates (Chen et al. 1998; Chen and Kolodner 1999); because POL30 is an essential gene and because PCNA functions in many processes besides DNA replication, additional studies will be required to determine if replication defects caused by pol30 mutations cause increased GCR rates. Similarly, hypomorphic alleles of RFC2, RFC4, and RFC5, which affect replication factor C, which loads PCNA onto DNA, also cause increased GCR rates (Chen and Kolodner 1999; Myung et al. 2001c; Stirling et al. 2011; Y. Zhang et al. 2012, 2013). Temperature-sensitive and other hypomorphic alleles of RFA1 and truncations of RFA2 and RFA3, which encode subunits of the single-stranded DNA-binding Replication Protein A (RPA), also cause large increases in GCR rates (Chen et al. 1998; Chen and Kolodner 1999; Wang et al. 2005; Y. Zhang et al. 2012, 2013); however, RPA plays multiple roles during DNA metabolism, so these effects may not be specific to DNA replication defects. Deletion of RAD27, which encodes the S. cerevisiae homolog of human Flap Endonuclease 1 (FEN1) and is required for processing the 5′-ends of Okazaki fragments, causes a large increase in genome instability in multiple GCR assays (Chen and Kolodner 1999; Putnam et al. 2009a; Chan and Kolodner 2011). The synthetic lethality observed between rad27 mutations and HR defects implies that the failure to correctly process Okazaki fragments results in DSBs that then result in increased levels of GCRs (Tishkoff et al. 1997; Symington 1998; Loeillet et al. 2005). Some hypomorphic or reduced-expression alleles of DNA2, which encodes a nuclease–helicase involved in Okazaki fragment maturation and has additional roles in regulating telomere length, cause a modest increase in GCR rates (Budd et al. 2006; Stirling et al. 2011; Y. Zhang et al. 2012, 2013). A temperature-sensitive allele of CDC9, which encodes the replicative DNA ligase that primarily functions during lagging strand synthesis, also causes a large increase in GCR rate (Chan and Kolodner 2011; Stirling et al. 2011). Deletions of MRC1 and TOF1, which encode proteins implicated in stabilizing stalled replication forks (Katou et al. 2003) and mediating sister chromatid cohesion (Xu et al. 2007), cause modest increases in spontaneous GCR rates in single-copy sequence-mediated GCR assays and larger increases in GCR rates in duplication-containing GCR assays (Pennaneach and Kolodner 2009; Putnam et al. 2009a, 2012). Moreover, consistent with the genetic evidence for MRC1 and TOF1 acting in parallel pathways in sister chromatid cohesion (Xu et al. 2007), mrc1 tof1 double-mutant strains have increased GCR rates relative to the mrc1 and tof1 single-mutant strains (Putnam et al. 2009a, 2012). Based on the observed effects of mutations in the limited number of replication genes analyzed to date, it will be of interest to more exhaustively analyze different defects in essential replication genes for their effects in different quantitative GCR assays.

S-phase checkpoints: S-phase checkpoints were originally identified as pathways that promote cell cycle delay or arrest in S-phase in response to treatment with exogenous DNA-damaging agents (Weinert and Hartwell 1988; Lowndes and Murguia 2000; Michelson and Weinert 2000; Zhou and Elledge 2000; Putnam et al. 2009b). Normally, S-phase checkpoints prevent cells from entering mitosis with unrepaired DNA damage; however, in the presence of some types of long-lived and unrepairable damage, S. cerevisiae cells can undergo a process called adaptation in which cell division can occur even in the presence of S-phase checkpoint signaling (Sandell and Zakian 1993; Toczyński et al. 1997; Lee et al. 1998). Triggering the S-phase checkpoints has multiple
cellular consequences: (1) stalled replication forks are maintained in a state that allows them to resume DNA synthesis (Lopes et al. 2001; Tercero and Diffley 2001); (2) late origins are prevented from firing (Santocanale and Diffley 1998; Shirahige et al. 1998); (3) DNA replication is slowed (Paulovich et al. 1997a); (4) cell morphological events and polarized cell growth are delayed (Enserink et al. 2006; Smolka et al. 2006); (5) a transcriptional response driving the production of dNTPs is induced (Allen et al. 1994); (6) progression into anaphase is prevented (Sanchez et al. 1999); and (7) genome-wide postreplicative cohesion is triggered (Strom et al. 2007; Unal et al. 2007). Strikingly, mutations affecting S-phase checkpoints, and in particular the replication checkpoint, cause increases in genome instability in multiple GCR assays (Figure 11) (Myung et al. 2001c; Myung and Kolodner 2002; Huang and Koshal; Putnam et al. 2009a; Chan and Kolodner 2011), consistent with a role for DNA replication errors in the formation of GCRs. In contrast, defects in the classical G1 and G2 DNA damage checkpoints and the mitotic spindle checkpoints had little if any effect on the rate of accumulating GCRs (Myung et al. 2001c).

S-phase checkpoints appear to comprise two separate checkpoints: the DNA replication checkpoint and the intra-S checkpoint. The DNA replication checkpoint is triggered by defects in the replication fork and appears to help maintain damaged replication forks in a state that can resume replication; this stabilization may either be due to suppression of HR acting on stalled replication forks or suppression of mechanisms that generate HR substrates as a result of stalled replication forks (Lisby et al. 2004; Lambert et al. 2007). In contrast, the intra-S checkpoint causes reduced rates of DNA replication and slower cell cycle progression in response to treatment with DNA-damaging agents (Paulovich et al. 1997b; Lowndes and Murguia 2000). Some components of the S-phase checkpoints appear to be specific to the replication checkpoint (RFC5, MRC1, and DPB11) or the intra-S checkpoint (RAD9, RAD17, RAD24, MEC3, and SGS1) (Lowndes and Murguia 2000; Michelson and Weinert 2000; Zhou and Elledge 2000). After phosphorylation by Mec1 or Tel1, Mrc1 and Rad9 separately bind and activate Rad53 and act in the replication checkpoint and intra-S checkpoint, respectively. In contrast, many S-phase checkpoint components act in both pathways (Paulovich et al. 1997a;b; Santocanale and Diffley 1998; Shirahige et al. 1998; Frei and Gasser 2000; Lowndes and Murguia 2000; Zhou and Elledge 2000; Myung and Kolodner 2002), particularly the signal transduction kinases and the effector functions of the checkpoint pathways. Moreover, the two S-phase checkpoints likely have some amount of overlap, as damaged replication forks that are not properly stabilized by the replication checkpoint could undergo modification into substrates that trigger the intra-S checkpoint. Strains with defects in both pathways, such as combining an rfc5-1 or dpb11-1 mutation with a mutation in the rad9, rad17, rad24, or mec3 group, have increased rates of accumulating GCRs (Myung and Kolodner 2002).

The types of GCRs formed in strains with different S-phase checkpoint defects are distinct. In single-copy sequence-mediated GCR assays, the replication checkpoint-specific defect rfc5-1 and the downstream kinase defect mec1 cause the accumulation of only de novo telomere addition GCRs (Myung et al. 2001c; Putnam et al. 2014). This distribution may be due to the inability of strains with defects in Mec1 activation to phosphorylate Cdc13, a protein that plays a role in telomere maintenance (see below), and prevent the recruitment of telomerase to DSBs thereby preventing de novo telomere addition at DSBs (Zhang and Durocher 2010). In duplication-containing GCR assays, mec1 mutations cause increased GCR rates that are higher than in single-copy sequence-mediated GCR assays (Putnam et al. 2009a), suggesting that mec1 defects suppress GCRs through multiple mechanisms whereas the increase in de novo telomere additions in single-copy sequence-mediated GCR assays is likely due only to an increase in the efficiency of de novo telomere addition. Interestingly, strains with a dun1 mutation, which affects a step downstream of mec1, also only accumulate de novo telomere addition-mediated GCRs (Myung et al. 2001c), which could suggest additional levels of control of de novo telomere addition or the accumulation of damage that is readily recognized by telomere maintenance proteins.

In contrast, tel1 mutants do not have increased GCR rates but have an altered GCR spectrum as tel1 mutants do not accumulate de novo telomere addition GCRs (Myung et al. 2001c; Putnam et al. 2014), but rather show an increase in the accumulation of translocations and isoduplications relative to wild-type strains (Myung et al. 2001c; Putnam et al. 2014). As for mec1 mutants, these changes in distribution likely represent changes in the efficiency of different repair pathways, with tel1 mutations causing decreases in the efficiency of de novo telomere additions and a decrease in the efficiency of the pathways that cleave DNA hairpins that can form at DSBs (Putnam et al. 2014). Supporting the view that tel1 mutations do not eliminate de novo telomere additions, tel1 mutations do not suppress the increased GCR rates of pif1 mutants (Myung et al. 2001a; Putnam et al. 2014). Unlike the mec1, tel1, dun1, and rfc5-1 defects, checkpoint defects caused by rad9, mec3, rad53, and chk1 mutations do not dramatically alter the spectrum of GCRs recovered (Myung et al. 2001c; Myung and Kolodner 2002), consistent with the possibility that these defects do not alter telomerase activity.

**Chromatin assembly, remodeling, and modification:** DNA replication and chromatin assembly are coordinated in eukaryotic cells (Nelson et al. 2002), and failure to complete chromatin assembly during DNA replication causes S-phase arrest (Ye et al. 2003). The chromatin-assembly factor I (CAF-I) and replication-coupling assembly factor (RCAF) complexes assemble chromatin after DNA synthesis (Ransom et al. 2010). CAF-I, which is comprised of Rlf2/Cac1, Cac2, and Msi1/Cac3 in *S. cerevisiae*, acts as a histone H3-H4 chaperone and also binds PCNA, which targets CAF-I to the replication fork. RCAF consists of Asf1 and a dimer of histones H3 and
H4, and RCAF also forms a complex with Rtt109 that acts as an acetyltransferase that promotes the acetylation of histone H3 on K56 (Recht et al. 2006; Driscoll et al. 2007; Han et al. 2007; Tsubota et al. 2007; Ransom et al. 2010). CAF-I and RCAF also function to terminate the DNA damage checkpoint (Kim and Haber 2009). Deletions of RLFI2, CAC2, MSI1, and ASF1 all caused increased GCR rates, and asf1 mutations (and to a lesser extent rlf2 mutations) synergized with defects in HR, suggesting that HR suppresses the formation of GCRs in rlf2 and asf1 mutants (Myung et al. 2003). asf1 mutant strains, and to a lesser extent rlf2 mutant strains, have increased levels of Ddc2-GFP foci (Kats et al. 2006), which are a cytological marker of checkpoint activation and DSBs (Melo et al. 2001). This result suggests that defects in replication-associated chromatin assembly result in damaged and possibly broken chromosomes that could underlie the formation of GCRs. This conclusion is consistent with the synergistic increase in GCR rate seen when rlf2 or asf1 mutations are combined with a rlf1 mutation (Myung et al. 2003), which increases the efficiency of healing broken chromosomes by de novo telomere addition, resulting in GCRs (see section Telomere maintenance). Interestingly, deletion of RLFI2 resulted in synergistic increases in GCR rates when combined with defects in the DNA damage checkpoint but not the DNA replication checkpoint, whereas the deletion of ASF1 resulted in a modest synergistic increase in GCR rates when combined with DNA damage checkpoints defects and a much stronger synergistic increase in GCR rates when combined with DNA replication checkpoint defects (Myung et al. 2003). Similarly, S-phase progression of asf1 mutants showed a dependence on the DNA replication checkpoint, whereas S-phase progression of rlf2 mutants did not show clear checkpoint dependence (Kats et al. 2006). These results suggest that in the absence of RCAF, replication fork instability due to reduced nucleosome disassembly in front of the fork or due to defects of nucleosome assembly after the fork has passed results in increased GCR rates, whereas CAF-I defects may result in some type of DNA damage that persists or occurs after DNA replication is completed and results in high GCR rates.

Control of replication-associated H3-K56 acetylation appears to play an important role in proper chromatin assembly. This histone mark is added to Asf1-presented H3-H4 dimers by Rtt109 in S-phase (Recht et al. 2006; Driscoll et al. 2007; Han et al. 2007; Tsubota et al. 2007), is removed in G2-phase by the Hst3 and Hst4 histone deacetylases in S. cerevisiae (Celic et al. 2006; Maas et al. 2006), and plays a role in promoting expression of some S-phase genes including those encoding histones (Xu et al. 2005). Deletion of ASFI or RTT109 results in similar levels of increased GCR rates, increased sensitivity to DNA-damaging agents, slowed growth, increased checkpoint activation, increased Rad52 foci [a cytological marker of HR intermediates (Lisby et al. 2001, 2003)], and increased sister chromatid HR (Myung et al. 2003; Kats et al. 2006; Driscoll et al. 2007; Putnam et al. 2009a, 2012, 2016; Chan and Kolodner 2011, 2012; Munoz-Galvan et al. 2013). Similarly, mutations in the genes encoding histone H3, which prevent acetylation of H3-K56, also resulted in increased GCR rates albeit not as high as caused by asf1 or rtt109 mutations (Chan and Kolodner 2011, 2012). Thus, in aggregate, these results suggest that acetylation of histone H3-K56 accounts for some of the role of RCAF in suppressing GCRs. In addition, strains with an asf1 mutation, an rtt109 mutation, or mutations in the genes encoding histone H3 preventing acetylation of H3-K56, had increased levels of aneuploidy, predominantly involving duplication of chromosomes XII and VII (Chan and Kolodner 2011, 2012). In contrast, the Asf1-Vps75 histone acetyltransferase did not appear to play a role in suppressing either GCRs or aneuploidy (Chan and Kolodner 2012).

Cells lacking H3-K56 acetylation have very similar phenotypes to those with hyperacetylation of H3-K56 resulting from defects in HST3 and HST4, including increased GCR rates, sensitivity to DNA-damaging agents, increased checkpoint activation, increased Rad52 foci, and increased sister chromatid HR (Celic et al. 2008; Kadyrova et al. 2013; Munoz-Galvan et al. 2013; Che et al. 2015; Putnam et al. 2016). In addition, hst3 hst4 double-mutant strains appear to have defects in sister chromatid cohesion and in BIR due to inhibition of repair DNA synthesis (Thaminy et al. 2007; Che et al. 2015). Remarkably, at least some defects in the hst3 hst4 double-mutant strain can be suppressed by overexpression of Rfc1 (Celic et al. 2008), which is a subunit of the PCNA clamp loader, and by inactivation of the alternative clamp loaders Ctf18, Rad24, and Elg1, which are involved in activation of the DNA damage checkpoint and removal of PCNA [reviewed in Kupiec (2016)]. These results could be consistent with the ability of increased recruitment of CAF-I by PCNA to suppress the defect caused by hyperacetylation of H3-K56. Taken together, the similarities between the hyperacetylation and hypoacetylation of H3-K56 argue that they may affect the same process, and possibly that DNA replication and/or repair of DNA replication errors depends upon having unmarked histones preceding the replication fork and marked histones following it.

In addition to CAF-I and RCAF, there are many other proteins and protein complexes that remodel and/or modify chromatin [reviewed in Cairns (2009), Gerhold et al. (2015)]. Most of these have been discovered through studies of transcription and gene regulation. Some, like the Swr1 complex and the Ino80 complex, have been implicated in DNA repair, as have histone modifications that occur in response to treating cells with DNA-damaging agents (Morrison et al. 2004; van Attikum et al. 2004, 2007). However, defects affecting some of these proteins and protein modifications have been reported to only modestly increase sensitivity to DNA-damaging agents, to only modestly decrease excision from DSBs (Morrison et al. 2004; van Attikum et al. 2004, 2007; Chen et al. 2012; Costelloe et al. 2012), and in some cases to cause increased GCR rates (Myung et al. 2003; Putnam et al. 2009a, 2012, 2016). However, the observed increases in GCR rates reported were relatively small,
and only a small number of the genes encoding any individual chromatin modification/remodeling complexes were identified in genetic screens for GCR-suppressing genes, consistent with only minor roles in suppressing GCRs. In contrast, many more genes encoding such complexes were identified in the genetic screen for cGIS genes (Putnam et al. 2016). Therefore, with the exception of CAF-I and RCAF, most chromatin remodeling and modifying complexes likely play minor roles in suppressing GCRs by themselves but may cooperate with other complexes and pathways to suppress GCRs.

**Telomere maintenance:** In *S. cerevisiae*, telomeres are maintained by the reverse transcriptase telomerase, consisting of the proteins Est1, Est2, and Est3, and the RNA subunit TLC1 [reviewed in Kupiec (2014)]. In the absence of telomerase, telomeres undergo continuous shortening, which eventually leads to senescence (Lundblad and Szostak 1989; Singer and Gottschling 1994; Shore 1998). The onset of senescence occurs when erosion of at least one chromosome leads to activation of a DNA damage checkpoint response (d’Adda di Fagagna et al. 2003; Abdallah et al. 2009; Xu et al. 2013). Within the senescing cell population, survivors can arise that maintain their chromosome ends by one of two different HR-mediated processes that can be distinguished due to differences in the resulting telomeric structures (amplification of either Y’ subtelomeric regions or telomeric repeats) and the genetic requirements for the formation of each type of survivor [reviewed in McEachern and Haber (2006)].

McClintock first demonstrated that telomeres protect chromosome ends, preventing breakage–fusion–bridge cycles (McClintock 1939; de Lange 2002). In *S. cerevisiae* strains that have recovered from senescence caused by loss of telomere maintenance, the absence of telomerase activity does not cause increased GCR rates because, under these conditions, HR maintains telomeres (Myung et al. 2001a; McEachern and Haber 2006). Similarly, the deletion of many genes encoding factors required for optimal telomere maintenance result in shortened telomeres (e.g., tel1, rnh201, sin3, soh1, ctk1, nam7, and xrn1) (Askree et al. 2004; Gatbonton et al. 2006; Ungar et al. 2009) and do not result in increased GCR rates (Putnam et al. 2016), although some deletions (e.g., mre11, xrs2, and rad50) that result in shorter telomeres as well as other defects do cause increased GCR rates (Chen and Kolodner 1999). Synergistic increases in GCR rates are seen when telomerase defects (e.g., tlc1 and est2) or defects resulting in shorter telomeres reflecting reduced efficiency of telomere maintenance (e.g., tel1) are combined with defects in other pathways including HR (e.g., rad51 and rad59) and the DNA damage checkpoints (e.g., mec1), but not the replication checkpoint (Myung et al. 2001a). Analysis of the structure of the GCRs recovered from these types of double-mutant strains has revealed the formation of monocentric translocations and circular chromosomes as well as denticentric translocations including translocations mediated by telomere-to-telomere fusions, telomere to broken chromosome end fusions, broken chromosome end-to-end fusions, and dicentric isoduplications, all of which are subsequently resolved to monocentric translocations by additional rounds of rearrangement (Myung et al. 2001a; Craven et al. 2002; Pennaneach and Kolodner 2004, 2009). The observation of GCRs that did not appear to involve telomere-to-telomere or telomere-to-DSB fusions suggests that, in addition to GCRs mediated by aberrant telomeres, there may also be increased general chromosome fragmentation in strains with telomerase dysfunction-driven genome instability. Many of the same types of GCRs, as well as truncated chromosomes potentially healed by *de novo* telomere addition, can be seen in senescent est1Δ cells that have been stabilized by the reintroduction of EST1 (Hackett et al. 2001).

Together, these results provide some insight into how genome instability is driven by telomere dysfunction. Erosion of telomeres past a critical length eliminates the protective features that keep telomeres from being recognized as DNA damage and allows them to be acted upon by other DNA repair pathways [reviewed in Eckert-Boulet and Lisby (2010)]. HR is the most efficient pathway that acts on the resulting chromosome ends, channeling them into alternative telomere maintenance pathways. However, when HR or the DNA damage checkpoints are compromised, the deprotected telomeres and telomeres formed by HR can be acted on by other repair pathways leading to GCRs (Pennaneach and Kolodner 2004, 2009). In addition, Exo1 and potentially other enzymes can degrade the deprotected ends to produce substrates for BIR (Dewar and Lydall 2010); these substrates can lead to both nonreciprocal monocentric and denticentric translocations with other chromosomes and can undergo intramolecular hairpin formation leading to dicentric isoduplications (Pennaneach and Kolodner 2004, 2009). Mutations that result in inefficient telomere maintenance leading to shortened telomeres (e.g., tel1) also show similar genetic interactions with HR and checkpoint defects, resulting in increased rates of accumulating GCRs, particularly those mediated by telomere-to-telomere fusion (Craven et al. 2002; Pennaneach and Kolodner 2004, 2009). Consistent with these results, expression of a Cdc13-Ext2 fusion, which allows telomere extension in the absence of Tel1 and Mec1 (Tsukamoto et al. 2001), reduced the frequency of chromosomal rearrangements in a mec1 tel1 double mutant (McCulley and Petes 2010). It should be noted that 205 mutations have been identified as causing shortened telomeres (Askree et al. 2004; Gatbonton et al. 2006; Ungar et al. 2009); however, many of these mutations have not yet been studied in GCR assays to determine if they cause increased GCR rates by themselves or in combination with other mutations.

**Suppression of inappropriate telomere addition:** A key problem for cells with functional telomerase is to ensure that telomere addition is properly targeted to the chromosome ends and does not occur at DSBs. The earliest studies of GCRs observed GCRs that appeared to be formed by chromosome
breakage followed by healing of the broken chromosomes by de novo telomere addition; these telomere additions did not appear to target any type of significant telomere seed sequence (Chen et al. 1998; Chen and Kolodner 1999). At least three mechanisms suppress de novo telomere additions at DSBs, thereby facilitating the repair of DSBs by HR.

The first mechanism is the regulation of telomerase by the Pif1 DNA helicase (Schulz and Zakian 1994; Zhou et al. 2000; Mangahas et al. 2001). The Pif1 DNA helicase was identified in a genetic screen to detect telomere maintenance functions (Schulz and Zakian 1994; Zhou et al. 2000), and mutations in PIF1 result in a 240- to 1000-fold increase in the rate of accumulating spontaneous GCRs in which terminal chromosome deletions are healed by de novo telomere addition (Myung et al. 2001a). Thus, Pif1 defines an enzymatic pathway that suppresses de novo telomere additions and de novo telomere addition-driven genome instability (Schulz and Zakian 1994; Zhou et al. 2000; Myung et al. 2001a); however, other components of this pathway, if any exist, have not yet been identified. Consistent with this result, the increase in GCR rate caused by pif1 mutations can be suppressed by mutations in genes encoding proteins and RNA required for normal telomerase activity (est1, est2, est3, and dcl1), Cdc13 (cdc13), and Ku (yku70 and yku80) (Figure 10A) (Myung et al. 2001a). The GCR spectrum in pif1 mutant strains is most consistent with a role of Pif1 in suppressing de novo telomere addition by removal of telomerase from DSBs (Eugster et al. 2006; Boule and Zakian 2007; Li et al. 2014) and not the recently discovered role of Pif1 in recombination-coupled DNA synthesis (Saini et al. 2013; Wilson et al. 2013); however, both roles might act to promote de novo telomere addition, as the failure of recombination-coupled DNA synthesis in pif1 mutants might generate substrates for telomerase or block their processing by other pathways like BIR.

The second mechanism is the inhibition of the action of telomerase at DSBs by the DNA damage checkpoint kinase Mec1, which phosphorylates Cdc13, preventing the accumulation of Cdc13 at DSBs (Zhang and Durocher 2010) (see section S-phase checkpoints). Because Cdc13 facilitates the recruitment of telomerase at DSBs where de novo telomere additions occur (Bianchi et al. 2004), Mec1 activity down-regulates de novo telomere additions and de novo telomere addition-driven GCRs.

The third mechanism is that de novo telomere addition may be limited by the normal cell cycle regulation of telomerase activity. Telomere maintenance functions act on normal telomeres starting in late S-phase (Marand et al. 2000), and the activity of telomere maintenance functions on telomere “seed” sequences located near an HO-induced DSB appears to be upregulated in G2 (Diede and Gottschling 1999). Spontaneous GCRs appear to result from errors or damage that occur during S-phase (Myung et al. 2001c; Myung and Kolodner 2002); therefore, this normal regulation of telomerase activity, combined with the activation of S-phase checkpoints by DNA damage potentially reduces de novo telomere addition-driven GCRs.

The Hrq1 helicase has also been suggested to play a role in suppressing de novo telomere additions (Bochman et al. 2014). This conclusion was based on the observation that the GCR spectrum in the classical assay in a wild-type strain had no de novo telomere additions (0%), and the GCR spectrum of the hrq1Δ mutant was dominated by de novo telomere additions (77%) (Paeschke et al. 2013; Bochman et al. 2014). However, in other studies, the GCR spectrum of the wild-type strain in the classical GCR assay is typically dominated by de novo telomere additions (Chen and Kolodner 1999; Putnam et al. 2004). Moreover, while the hrq1Δ mutation causes increased GCR rates, it did not cause the same GCR rate in both duplication-mediated and single-copy sequence-mediated GCR assays like a pif1 mutation that results in increased de novo telomere additions (Putnam et al. 2010). Thus, it seems unlikely that Hrq1 plays a Pif1-like role in suppressing de novo telomere addition.

Smc5-6 and protein sumoylation: S. cerevisiae contains three complexes containing members of the structural maintenance of chromosome (SMC) family [reviewed in Jeppsson et al. (2014), Kschonsak and Haering (2015)]. Cohesin (Smc1-Smc3) and condensin (Smc2-Smc4) play important roles during mitosis in sister chromatid cohesion and chromosome condensation. The third complex, made up of Smc5-Smc6 and a number of non-Smc proteins (Nse1-Nse6), is important for some types of DNA repair including promoting error-free sister-chromatid HR (De Piccoli et al. 2009). Consistent with these results, mutations in several genes encoding the Smc5-Smc6 cohesion complex cause increased GCR rates (Figure 11) (De Piccoli et al. 2006; Hwang et al. 2008; Stirling et al. 2011; Albuquerque et al. 2013). The most studied allele, a hypomorphic allele of SMC6, smc6-9, causes increased rates of accumulating GCRs that were primarily nonreciprocal translocations with microhomology breakpoints; the formation of these translocations was dependent on HR and Pol32, which is a subunit of DNA polymerase δ, suggesting the involvement of BIR in their formation (De Piccoli et al. 2006; Hwang et al. 2008; Stirling et al. 2011). Mutations in MMS21/NSE2 and NSE3 cause increased GCR rates in quantitative assays (Hwang et al. 2008; Albuquerque et al. 2013), whereas other SMC family complexes have not been as extensively investigated (Huang and Koshland 2003; Stirling et al. 2011).

Mms21/Nse2 is a small ubiquitin-like modifier (SUMO) E3 ligase that is a component of the Smc5-Smc6 complex and mediates the addition of the ubiquitin-like SUMO protein onto different target proteins (Zhao and Blobel 2005). The MMS21 gene is essential in S. cerevisiae; however, its sumoylation activity is dispensable for viability when the mitotic SUMO E3 ligases, Siz1 and Siz2, are functional (Reindle et al. 2006). Mms21 has a different subset of sumoylation targets and plays a more important role in suppressing GCRs than Siz1 or Siz2 (Albuquerque et al. 2013). Moreover, ESC2, which encodes a protein with multiple SUMO-like domains (Novatchkova et al. 2005), functions in conjunction with
Smc5-Smc6 in the repair of DNA damage during replication (Mankouri et al. 2009; Choi et al. 2010) and plays an important role in suppressing GCRs (Putnam et al. 2009a; Allen-Soltero et al. 2014). Esc2 is also a positive regulator of protein sumoylation by Mms21 (Albuquerque et al. 2013), suggesting that esc2 and mms21 mutants share a common defect. Mms21 targets include nucleolar proteins, such as RNA polymerase I, Fob1, and Tof2, as well as cohesin and condensin subunits (Albuquerque et al. 2013); however, the specific sumoylation events that are responsible for suppressing GCRs have not yet been determined.

Slx5-Slx8 is a SUMO-targeted E3 ubiquitin ligase complex (Prudden et al. 2007; Xie et al. 2007) that localizes preferentially to the nuclear pores where long-lived DSBs and eroded telomeres are relocalized and repair by HR is suggested to occur (Nagai et al. 2008). This relocalization appears to be dependent on sumoylation of proteins bound to the damaged DNA (Chung et al. 2015; Churikov et al. 2016, Horigome et al. 2016). Consistent with a role in this process, mutations affecting some of the nuclear pore subcomplexes, such as nup84, nup120, and nup133, cause increased GCR rates (Putnam et al. 2012, 2016), and cause lethality when combined with mutations such as rad27, which are thought to cause increased levels of the DNA damage that can underlie GCRs (Loeillet et al. 2005). Deletion of SLX5 or SLX8 causes a large increase in GCR rates in duplication-mediated but not single-copy sequence-mediated GCR assays (Putnam et al. 2009a) and an increase in the general level of sumoylated proteins, with the strongest influence being on the level of Mms21 targets (Albuquerque et al. 2013). Both the positive regulators of sumoylation of Mms21 targets (MMS21 and ESC2) and the negative regulators of sumoylation of Mms21 targets (SLX5 and SLX8) play roles in suppressing GCRs. Thus, regulating the levels of sumoylation by Mms21 and potentially the dynamics of these events is likely important in maintaining genome stability.

**Oxidative stress response:** Increased levels of oxidative stress also underlie increased genome instability. Deletions of TSA1, encoding the major thioredoxin peroxidase that scavenges hydrogen peroxide in S. cerevisiae, and SKN7 and YAP1, encoding transcription factors that control an oxidative stress model, transient underwinding of dsDNA behind the transcription machinery was proposed to promote pairing with the nascent RNA molecule (Liu and Wang 1987). In addition, recent experiments have indicated that the HR machinery can utilize RNA molecules and that Rad51-dependent HR can promote the formation of R-loops in strains with RNA metabolism defects (Wahba et al. 2013; Keskin et al. 2014), suggesting that RNA–DNA hybrids do not exclusively result from long-lived transcription intermediates.

**R-loop formation:** R-loops are three-stranded RNA–DNA hybrids in which a stretch of RNA displaces one strand of a complementary dsDNA molecule and are formed during transcription [reviewed in Costantino and Koshland (2015), Santos-Pereira and Aguilera (2015), Sollier and Cimprich (2015)]. In transcription, R-loops are thought to be mostly transient; however, features of the displaced ssDNA strand, such as its propensity to form secondary structure, have been suggested to facilitate the formation of long-lived R-loops [reviewed in Costantino and Koshland (2015)]. Similarly, defects in RNA processing and transcriptional elongation, including indirect topological defects induced by loss of the Top1 or Top2 topoisomerases, have been linked to the formation of R-loops (El Hage et al. 2014). In the “thread-back model,” transient underwinding of dsDNA behind the transcription machinery was proposed to promote pairing with the nascent RNA molecule (Liu and Wang 1987). In addition, recent experiments have indicated that the HR machinery can utilize RNA molecules and that Rad51-dependent HR can promote the formation of R-loops in strains with RNA metabolism defects (Wahba et al. 2013; Keskin et al. 2014), suggesting that RNA–DNA hybrids do not exclusively result from long-lived transcription intermediates.

R-loops can be removed in several ways. First, helicases, such as Sen1 (homolog of human senataxin), can unwind RNA–DNA hybrids (Mischo et al. 2011). Second, the RNA strand of RNA–DNA hybrids can be degraded by RNase H
enzymes [reviewed in Cerritelli and Crouch (2009)]. RNase H1, which is encoded by RNH1, can only degrade stretches of consecutive ribonucleotides, and RNase H2, which is encoded by RNH201, RNH202, and RNH203, can cleave single misincorporated ribonucleotides in addition to degrading longer stretches of RNA [reviewed in Cerritelli and Crouch (2009)]. Third, RNA export, such as that mediated by the THO complex, and RNA degradation, such as that mediated by the RNA exosome, also reduce the level of R-loops, potentially through interactions with unpaired portions of the RNA molecules that are not in the RNA–DNA hybrid (Wahba et al. 2011, 2013; Luna et al. 2012).

Several lines of evidence indicate that R-loops can be a source of DNA damage leading to GCRs. First, many mutations that cause increased R-loop formation also cause increased formation of Rad52-GFP foci, which in many cases can be suppressed by overexpression of RNase H1 (Gomez-Gonzalez et al. 2009; Mischo et al. 2011; Wahba et al. 2011; Stirling et al. 2012; Castellano-Pozo et al. 2013). While these data suggest that R-loops may be processed to DSBs, leading to the formation of HR intermediates, it is possible that in some cases Rad52 foci could reflect R-loop formation by HR. Second, a number of mutations that cause accumulation of R-loops also cause synthetic growth defects when combined with mutations in S-phase checkpoint genes and some HR genes (Gomez-Gonzalez et al. 2009; Mischo et al. 2011). Third, some mutations that cause accumulation of R-loops also cause increased rates of HR of direct-repeat recombination substrates (Huertas and Aguilera 2003; Mischo et al. 2011; Castellano-Pozo et al. 2013), plasmid loss (Castellano-Pozo et al. 2013), small increases in GCR rates in the classical GCR assay (deletion of HPR1) (Gomez-Gonzalez et al. 2009), increased GCRs in a S. cerevisiae artificial chromosome (YAC)-based GCR assay (Wahba et al. 2011), and an increase in LOH on chromosomes III and XII in diploid strains, mediated by nonreciprocal translocations between homologous chromosomes (Wahba et al. 2011). Fourth, loss of both RNase H activities causes increased accumulation of damage in the G2–M-phase of the cell cycle (Amon and Koshland 2016); however, increases in mitotic recombination in strains with RNase H deficiencies has been alternately attributed to primarily R-loops (O’Connell et al. 2015), only ribonucleotide misincorporation by DNA polymerases (Conover et al. 2015), or both (Cornelio et al. 2017). Fifth, overexpression of SPT2, which appears to result in increased R-loop formation, causes increased accumulation of GCRs (Sikdar et al. 2008). In many cases, these increased levels of genome instability can be suppressed by overexpression of RNH1. How R-loops cause DNA damage is unclear. Current models include the possibility of collisions between replication forks and R-loops as well as through cleavage of the R-loop by nucleases, such as those involved in NER [reviewed in Sollier and Cimprich (2015)], resulting in a DSB. In contrast to the accumulated data suggesting that R-loops mediate genome instability, one recent report suggests that transient RNA–DNA hybrids are formed at resected DSBs and help promote repair, potentially by promoting further resection via disruption of the adjacent chromatin structure (Ohle et al. 2016). These results suggest that RNA–DNA hybrids may both promote genome instability and promote DSB repair, depending on the precise context of the hybrid.

The following pathways have been implicated in suppressing R-loop-mediated genome instability: (1) transcription initiation [BUR2; Wahba et al. (2011); (2) transcription elongation by the PAF1 complex [CDC73 and LEO1; Wahba et al. (2011, 2013)] and Spt2 (Sikdar et al. 2008; Wahba et al. 2011); (3) transcriptional repression by the RPD3 histone deacetylase complex [SIN3, RPD3, and SDS3; Wahba et al. (2011); Chan et al. (2014)], Not5, and Sbh3 (Wahba et al. 2011); (4) mediator functions [MED1, MED5, MED12, MED13, and CDK8; Wahba et al. (2011, 2013)]; (5) transcriptional termination by CFIA [CLP1, PCF11, RNA15, CFT2, and FIP1; Stirling et al. (2012)], Pbp1 (Salvi et al. 2014), Sen1 (Mischo et al. 2011), and Rtt103 (Stirling et al. 2012); (6) RNA transport by the THO complex (THO1, HPR1, MFT1, and THP2) and Npl3 (Huertas and Aguilera 2003; Gomez-Gonzalez and Aguilera 2007; Gomez-Gonzalez et al. 2009; Wahba et al. 2011; Stirling et al. 2012; Castellano-Pozo et al. 2013; Pfeiffer et al. 2013); (7) RNA degradation by Kem1/Xrn1, Rrp6, and Try4 (Wahba et al. 2011, 2013); and (8) the Srm1 Ran guanyl-nucleotide exchange factor (Stirling et al. 2012). Consistent with the observations that most mutations causing the accumulation of R-loops that have been tested in GCR assays cause only small increases in GCR rates (Gomez-Gonzalez et al. 2009), most of these genes and pathways were not identified in a genome-wide screen for genes that suppress the accumulation of GCRs (Putnam et al. 2016). However, several of these genes and pathways were identified in a screen for cGIS genes (see section A global view of genome instability suppressing genes) (Putnam et al. 2016). Thus, it seems likely that mutations causing the accumulation of R-loops result in DNA damage that is acted on by different pathways including checkpoints and HR, which suppress the formation of GCRs that might otherwise result from R-loop formation.

Ribonucleotide misincorporation: Misincorporation of single ribonucleotide bases by replicative DNA polymerases has recently been identified as a source of DNA damage. An estimated 10,000 ribonucleotides are removed during each cell division via a process called ribonucleotide excision repair (Nick McElhinny et al. 2010b; Sparks et al. 2012; Chon et al. 2013). These repair events are dependent upon the ability of RNase H2 to cleave single ribonucleotides in DNA (Jeong et al. 2004) in conjunction with nick-directed DNA synthesis by DNA polymerase δ, flap cleavage by Rad27/FEN1, and ligation of the flap-excised product by DNA ligase (Stith et al. 2008; Burgers 2009; Sparks et al. 2012). RNase H2-defective mutants have a weak mutator phenotype, primarily due to the accumulation of two-base deletion mutations in repeat sequences (Nick McElhinny et al. 2010a; Kim et al. 2016).
2011; Allen-Soltero et al. 2014). The mutations appear to result from the cleavage of the DNA strand containing the misincorporated ribonucleotide by the topoisomerase Top1, leading to formation of a ssDNA gap, followed by realignment of the DNA strands and repair of the gap (Kim et al. 2011). Mutations in the genes encoding RNase H2 also cause little or no increase in the rate of accumulating GCRs (Huang et al. 2003; Sikdar et al. 2008; Putnam et al. 2016; Allen-Soltero et al. 2014); however, there is evidence for increased mitotic recombination in diploid strains due to misincorporated ribonucleotides (Conover et al. 2015; O’Connell et al. 2015; Cornelio et al. 2017). In addition, RNase H2 mutations cause decreased growth rates, altered cell cycle distribution, and aberrant cell morphology when combined with mutations affecting DNA damage signaling (e.g., rad53), PRR (e.g., rad5 and rad6), or HR (e.g., rad52, rad51, sgs1, mre11, and mus81) (Allen-Soltero et al. 2014). In some cases, the decreased growth rates of the double mutants were suppressed by a rad51 mutation, implicating recombination intermediates as a cause of the slow growth. Moreover, many of the rnh double mutants with slow growth phenotypes also had synergistic increases in GCR rates, and in some, but not all, of the double mutants the increased GCR rates as well as the aberrant cell morphology could be suppressed by top1 and rad51 mutations (Allen-Soltero et al. 2014). Thus, RNase H2-defective mutations appear to act as damage-generating defects in the damage/response GCR model and primarily lead to increased accumulation of GCRs when combined with defects in pathways that process this damage. In some cases, these increased levels of GCRs appear to result from the cleavage of misincorporated ribonucleotides by Top1, potentially leading to the formation of inappropriate HR intermediates.

Perspectives

In the 20 years since the identification of the first S. cerevisiae mutants with increased rates of accumulating GCRs and the development of the first quantitative GCR assays, considerable insights have been obtained into how spontaneous GCRs arise and are prevented. As discussed in this review, these include: (1) the identification of genes and pathways that suppress the formation of GCRs, (2) the identification of pathways that form GCRs, and (3) the initial identification of an extensive genetic network that functions in the suppression of GCRs. However, there are several aspects of the genome instability problem that are not as well-understood.

First, the spectrum of GCRs has only been determined for a small proportion of strains containing either individual or combinations of GCR-causing mutations, despite the fact that the structures of these GCRs provide important clues into the underlying mechanisms by which GCRs can be formed. Moreover, even for better-studied mutant strains with altered GCR rates and altered GCR structures, the number of GCRs analyzed has been relatively small (< 20); it is unclear whether increasing the number of GCRs analyzed per strain would provide greater insight. Although the analysis of the structures of GCRs is still time-consuming and expensive, modern techniques like next-generation whole-genome sequencing have improved our ability to analyze more GCRs to thoroughly characterize more mutant strains and more samples per mutant.

Second, only a limited analysis of the role of essential genes in suppressing GCRs has been performed. These studies are complicated by several technical factors: (1) different hypomorphic alleles of an individual gene often cause different phenotypes and the available collection of alleles for any gene might not encompass all possible defects that might result from mutations in that gene; and (2) strains containing defects in essential genes often grow poorly, which complicates systematic screening efforts. Despite these problems, some essential genes are known that act in processes that are known or suspected to play roles in suppressing GCRs or in which defects might be expected to increase GCR rates. Analysis of existing mutations in these genes and screening for new mutations that cause altered GCR rates and altered GCR spectra should provide important insights and useful tools for understanding DNA metabolic errors that underlie the formation of GCRs.

Third, and finally, identification of genetic interactions that cause increased GCR rates in both hypothesis-driven and systematic studies is in its infancy given the large numbers of GIS and cGIS genes identified to date (for example, see Myung et al. (2001a), Hwang et al. (2005), Putnam et al. (2016)). Despite the technical challenges, fully characterizing even small portions of the total network of these interactions, particularly in conjunction with fully characterizing the structures of the GCRs that result from genetic interactions that cause altered GCR rates, has the potential to greatly improve our understanding of how these pathways function to preserve the structure of the genome.

The ultimate goal of studying the pathways that suppress and promote the formation of GCRs is to understand the underlying mechanisms that generate the DNA damage that initiates the formation of GCRs. One of the challenges of such studies is that the rates of accumulating GCRs are low even in mutants with high GCR rates. Thus, it is currently impossible to follow a single GCR-generating event from initiating damage to final GCR. However, a clearer understanding is likely to emerge from the analysis of the structure of GCRs, a full characterization of the genetic interactions between GCR-causing/-altering mutations, and integration of these data with data from other mechanistic studies.

Studies of the pathways that prevent or promote GCRs in S. cerevisiae are particularly relevant to our understanding of genome instability in cancer. The accumulation of genome rearrangements or GCRs is characteristic of many cancers (Lengauer et al. 1998; Thompson and Compton 2011; Vogelstein et al. 2013; Kass et al. 2016). Whether there is a genetic basis for the accumulation of GCRs in cancer, either inherited or somatic, has not been well-established for all cancers that appear to show ongoing genome instability. There are some clear examples of genetic defects that
underlie human cancers with genome instability where the comparable defect in *S. cerevisiae* or other model organisms, including human cell lines, causes genome instability. For example, defects in the mediator protein BRCA2, which is essential for HR because it loads RAD51 onto DNA [reviewed in West (2003)] likely result in genome instability similar to loss of the *S. cerevisiae* mediator protein Rad52 (Tutt et al. 1999; Yu et al. 2000). Defects in other genes that act in the BRCA2-dependent HR and DNA damage response pathways, such as BRCA1, the genes encoding BRCA1- and BRCA2-interacting proteins, and the Fanconi Anemia genes, also appear to result in increased genome instability [reviewed in Moldovan and D'Andrea (2009), Konstantinopoulou et al. (2015)]. In the case of the *S. cerevisiae* genes encoding homologs or functional analogs of these proteins, defects in these genes are known to cause increased GCR rates (Chen and Kolodner 1999; Myung et al. 2001b,c; Yan et al. 2010; Chan and Kolodner 2011; Putnam et al. 2016). Other examples include the BLM gene, DNA damage response genes such as ATM and ATR, and the MMR genes (Gobbini et al. 2013; Sarbajna and West 2014; Lee et al. 2016; Schmidt and Pearson 2016); MMR suppresses the accumulation of mutations as well as GCRs that are mediated by HR between divergent sequences (Putnam et al. 2009a; Chan and Kolodner 2011). It is difficult to directly screen for GCR-suppressing genes in mammalian cells due to the lack of convenient genetic tests. However, mining cancer genomics data using a list of the human homologs of *S. cerevisiae* GIS genes has identified many GIS genes that are potentially defective in cancers with genome instability, further establishing *S. cerevisiae* as a useful tool for obtaining insights into genome instability in cancer (Putnam et al. 2016).

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