

# A protein interaction map for cell polarity development

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Many genes required for cell polarity development in budding yeast have been identified and arranged into a functional hierarchy. Core elements of the hierarchy are widely conserved, underlying cell polarity development in diverse eukaryotes. To enumerate more fully the protein–protein interactions that mediate cell polarity development, and to uncover novel mechanisms that coordinate the numerous events involved, we carried out a large-scale two-hybrid experiment. 68 Gal4 DNA binding domain fusions of yeast proteins associated with the actin cytoskeleton, septins, the secretory apparatus, and Rho-type GTPases were used to screen an array of yeast transformants that express ~90% of the predicted *Saccharomyces cerevisiae* open reading frames as Gal4 activation domain fusions. 191 protein–protein interactions were detected, of which 128 had not been described previously. 44

interactions implicated 20 previously uncharacterized proteins in cell polarity development. Further insights into possible roles of 13 of these proteins were revealed by their multiple two-hybrid interactions and by subcellular localization. Included in the interaction network were associations of Cdc42 and Rho1 pathways with proteins involved in exocytosis, septin organization, actin assembly, microtubule organization, autophagy, cytokinesis, and cell wall synthesis. Other interactions suggested direct connections between Rho1- and Cdc42-regulated pathways; the secretory apparatus and regulators of polarity establishment; actin assembly and the morphogenesis checkpoint; and the exocytic and endocytic machinery. In total, a network of interactions that provide an integrated response of signaling proteins, the cytoskeleton, and organelles to the spatial cues that direct polarity development was revealed.

## Introduction

Cell polarity is an essential characteristic of virtually every cell type (Drubin, 2000). In response to a cue acting at a specific site on the cell cortex, a cascade of events involving receptors, signaling proteins, the cytoskeleton, and organelles

results in an asymmetric distribution of cellular components (Drubin and Nelson, 1996). The budding yeast *Saccharomyces cerevisiae* has been critical for elucidation of proteins and mechanisms that underlie cell polarity development. Growth of the yeast cell is polarized to direct budding during cell division and projection formation during mating. As in other eukaryotic cells, polarized growth is mediated by a series of steps involving cortical landmarks, Rho GTPases, and a polarized actin cytoskeleton. Secretion is targeted to the bud or mating projection, allowing selective growth in

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that area (for reviews see Drubin and Nelson, 1996; Chant, 1999; Pruyne and Bretscher, 2000a,b).

Several Rho type GTPases function in the establishment and maintenance of cell polarity (Bender and Pringle, 1989; Johnson and Pringle, 1990; Matsui and Toh-e, 1992; Drgonová et al., 1996; Imai et al., 1996; Kamada et al., 1996; Robinson et al., 1999). One of these, Cdc42, is a crucial factor in the switch from isotropic to polarized growth that occurs when the cyclin-dependent protein kinase Cdc28 is activated by G1 cyclins (Adams et al., 1990; Ayscough et al., 1997). A decisive event for the establishment and maintenance of cell polarity is the recruitment of Cdc42 to the cell surface and its activation in response to positional cues and cell cycle signals (Chant, 1999). In budding cells, spatial markers left by previous cell divisions stimulate the local activation of the Ras-related Rsr1/Bud1 GTPase, which recruits and activates Cdc42 via interaction with the guanidine nucleotide exchange factor Cdc24 (Ruggieri et al., 1992; Bender, 1993; Zheng et al., 1995; Park et al., 1999). In haploid cells exposed to mating pheromone, the protein Far1 interacts with Cdc24 and recruits Cdc42 to the tip of the mating projection (Butty et al., 1998). The activated GTP-bound form of Cdc42 interacts with several proteins that are presumed to be effectors that transduce its signal to bring about polarization of the actin cytoskeleton (Cvrcková et al., 1995; Brown et al., 1997; Chen et al., 1997; Evangelista et al., 1997; Bi et al., 2000). Actin cables are proposed to serve as tracks for vesicle, organelle, and mRNA transport, whereas cortical actin patches are important for endocytosis (Pruyne and Bretscher, 2000a,b). Largely unknown are how cortical cues lead to localized activation of Rho GTPases, how their activation polarizes the spatial distribution of cytoskeletal proteins, the secretory apparatus, and other cellular constituents, and what mechanisms coordinate the many events that underlie cell polarity development. For example, at the site of bud formation, several Rho proteins function together with associated protein kinases and other effector proteins, and the cytoskeleton and secretory apparatus become organized around these signaling proteins. Bud morphogenesis requires spatial and temporal coordination of these events, but little is known of the coordinating mechanisms.

The yeast two-hybrid system (Fields and Song, 1989) is a powerful method for identifying pairs of proteins that associate with each other, and it can be used in a high-throughput manner (Uetz et al., 2000; Ito et al., 2001). Uetz et al. (2000) constructed an array of yeast transformants, each of which expresses one of the ~6,000 predicted yeast ORFs as a fusion to an activation domain (Hudson et al., 1997). This array was screened by a simple automated procedure in which protein–protein interactions responsible for positive responses were identified by the position within the array. A similar strategy was used for analysis of protein–protein interactions of vaccinia virus (McCraith et al., 2000). One advantage of the array-based approach is that each individual assay is compared with multiple identical assays, making it easier to distinguish bona fide interactions from background due to nonspecific activation of the reporter gene. Here we present the results of an array-based two-hybrid experiment designed to systematically detect protein–protein interactions involved in yeast cell polarity development. The pro-

teins screened included Cdc42 and other Rho-type GTPases, their regulators and effectors, actin cytoskeleton-associated proteins, septin-associated proteins, and proteins involved in secretion. Our aims were to identify new links in the network of protein–protein associations controlling polarized growth and to provide biological context for ORFs of unknown functions, with the goal of understanding their functional roles. Owing to high conservation of cell polarity development pathways, this information should be useful for developing a deeper understanding of cell polarity development in all types of eukaryotic cells (Drubin and Nelson, 1996; Pruyne and Bretscher, 2000a,b).

## Results and discussion

### Overview and general considerations

68 proteins with various functions in cell polarity development were used as DNA binding domain hybrids for two-hybrid screens. These included Rho-type GTPases and their regulators and effectors, actin cortical patch components, septin-associated proteins, and proteins involved in secretion (Table I). The yeast ORF-Gal4 activation domain fusion array used in our experiments expresses ~85–90% of the predicted ORFs of *S. cerevisiae* (Hudson et al., 1997; Uetz et al., 2000). 14 proteins, Aip2, Bud5, Bud6, Bud7, Bud9, Cap2, Cdc3, Cdc10, Iqg1, Kin1, Msb1, Sec9, Snc1, and Snc2, showed no reproducible two-hybrid interactions when used as baits in our screens. Screens of the other 54 baits found from 1 to 13 interactions each. Overall, 196 reproducible two-hybrid positives were detected that describe 191 putative protein–protein interactions involving 110 proteins (Table I and Figs. 1–3). 128 interactions had not been described previously and 44 involve 20 proteins of unknown function. The results of this study clearly do not represent all of the detectable or probable interactions between the proteins examined. The lack of an interaction detected in this analysis is not necessarily meaningful, as some constructs in the array might not express the expected fusion proteins or might express them in a nonfunctional form due to the Gal4 fusion. Differences in fusion construction, construct expression, strain background, and selection stringency are also factors that may account for discrepancies between the set of interactions seen here and those found in other studies.

To observe the subcellular localization of the proteins of unknown function, we expressed 13 of them in yeast under control of their own promoters as fusions with yellow fluorescent protein, a variant of the *A. victoria* green fluorescent protein (Niedenthal et al., 1996; Miller et al., 1999). Results of the localization experiments are shown in Table II and Figs. 4–6. Of the 128 new interactions, many appear plausible on the basis of genetic or localization criteria. The significance of others remains unclear. The two-hybrid results derived from these screens should be considered as a set of putative interactions requiring further verification. It is also important to note that an interaction might be direct, or might be bridged by a protein or proteins that bind to both the bait and the prey protein.

As shown in Fig. 1, two-hybrid interactions were observed not only between proteins involved in the same polarity-related process, but also between proteins involved in distinct

Table I. Summary of protein–protein interactions detected in two-hybrid screens

Protein		Interacting protein(s)	
Abp1	Actin binding protein involved in cortical actin assembly, has SH3 domain	Cla4 <sup>a</sup> (AD)	PAK kinase required for cytokinesis
		Rvs167 (BD)	Protein that affects actin distribution and bipolar budding, has an SH3 domain
		Srv2 (AD)	Adenylate cyclase-associated protein (CAP) that may provide a link between growth signals and the cytoskeleton
		Ynl094w <sup>a</sup> (AD)	Protein of unknown function
		Yor284w <sup>a</sup> (AD)	Protein of unknown function
Act2	Protein involved in cortical actin assembly	Rvs167 <sup>a</sup> (BD)	Protein that affects actin distribution and bipolar budding, has an SH3 domain
Act1	Actin, involved in cell polarization, endocytosis, cytoskeletal function	Cof1 (BD)	Cofilin, actin binding and severing protein
		Las17 (BD)	WASP homologue involved in cortical actin assembly
		Pfy1 (BD)	Profilin, can act to prevent actin polymerization and to complex with monomeric actin
		Rvs167 (BD)	Protein that affects actin distribution and bipolar budding, has an SH3 domain
		Srv2 (AD,BD)	Adenylate cyclase-associated protein (CAP) that may provide a link between growth signals and the cytoskeleton
Aip1	Actin interacting protein involved in disassembly of actin filaments	Srv2 (BD)	Adenylate cyclase-associated protein (CAP) that may provide a link between growth signals and the cytoskeleton
Air1	RING finger protein that affects RNA processing	Cdc24 <sup>a</sup> (BD)	GEF for Cdc42, involved in bud emergence, bud site selection, growth of mating projection
Apg17	Protein essential for autophagy	Apg17 <sup>a</sup> (AD,BD)	Protein essential for autophagy
		Exo84 <sup>a</sup> (BD)	Subunit of the exocyst complex, required for exocytosis
		Myo1 <sup>a</sup> (BD)	Myosin heavy chain (myosin II), involved in septation and cell wall organization
		Nip100 <sup>a</sup> (BD)	Mitotic spindle positioning protein, dynactin complex protein associated with the spindle
		Rho1–GTP <sup>a</sup> (BD)	GTP-binding protein required to activate the PKC1 pathway and $\beta$ -1,3-glucan synthase, member of the rho subfamily of ras-like proteins
		Rho2–GTP <sup>a</sup> (BD)	GTP-binding protein, member of the rho subfamily of ras-like proteins
		Sro77 <sup>a</sup> (BD)	Protein that functions together with Sec9p in exocytosis downstream of the Rho3p GTPase
		Ykr083c <sup>a</sup> (AD)	Protein of unknown function
Apg7	Conjugation protein essential for autophagy	Sso2 <sup>a</sup> (BD)	Syntaxin homologue (t-SNARE) involved in vesicle transport from Golgi to plasma membrane
Arp1	Actin-related protein of the dynactin complex, required for mitotic spindle orientation and nuclear migration	Nip100 (BD)	Mitotic spindle positioning protein, dynactin complex protein associated with the spindle
Bcy1	Regulatory subunit of cAMP-dependent protein kinases	Sro77 <sup>a</sup> (BD)	Protein that functions together with Sec9p in exocytosis downstream of the Rho3p GTPase
Bem1	Protein required for cell polarization and bud formation, has two SH3 domains	Boi2 (BD, AD)	Bem1p-binding protein, involved in bud formation, has an SH3 domain, Boi1 homologue
		Cdc24 (AD,BD)	GEF for Cdc42, involved in bud emergence, bud site selection, growth of mating projection
		Cdc42–GDP (AD,BD)	Rho type GTPase involved in bud site assembly and cell polarity
		Cdc42–GTP (BD)	Rho type GTPase involved in bud site assembly and cell polarity

Table I. Summary of protein–protein interactions detected in two-hybrid screens (Continued)

Protein		Interacting protein(s)	
Bem1 (continued)	Protein required for cell polarization and bud formation, has two SH3 domains	Far1 (AD)	Inhibitor of CDK–cyclin complexes involved in cell cycle arrest for mating and polarized growth of mating projection
		Sec15 <sup>a</sup> (AD)	Component of exocyst complex required for exocytosis
		Ste20 (AD)	PAK kinase of the pheromone pathway; also regulates polarized growth
		Swe1 <sup>a</sup> (AD)	Serine/tyrosine dual-specificity protein kinase; able to phosphorylate Cdc28p on tyrosine and inhibit its activity
		Bem4 <sup>a</sup> (AD)	Bud emergence protein, interacts with Rho type GTPases
Bem3	GAP for Cdc42p and Rho1p	Cla4 <sup>a</sup> (AD)	PAK kinase required for cytokinesis
		Zds1 <sup>a</sup> (AD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds2
		Zds2 <sup>a</sup> (AD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1
		Bem3 <sup>a</sup> (BD)	GAP for Cdc42p and Rho1p
		Cdc11 <sup>a</sup> (AD)	Septin, involved in cytokinesis
Bem4	Bud emergence protein, interacts with Rho type GTPases	Cdc12 <sup>a</sup> (AD)	Septin, involved in cytokinesis
		Cdc24 <sup>a</sup> (BD)	GEF for Cdc42, involved in bud emergence, bud site selection, growth of mating projection
		Cdc42–GDP (BD)	Rho type GTPase involved in bud site assembly and cell polarity
		Cdc42–GTP (BD)	Rho type GTPase involved in bud site assembly and cell polarity
		Gic1 <sup>a</sup> (BD)	Effector of Cdc42p, important for bud emergence, Gic2 homologue
		Nfi1 <sup>a</sup> (AD)	Septin-interacting protein
		Rho1–GTP (BD)	GTP-binding protein required to activate the PKC1 pathway and $\beta$ -1,3-glucan synthase, member of the rho subfamily of ras-like proteins
		Rho2–GTP (BD)	GTP-binding protein, member of the rho subfamily of ras-like proteins
		Rho4–GTP (BD)	GTP-binding protein of the rho subfamily of ras-like proteins
		Rsr1–GDP <sup>a</sup> (BD)	GTP-binding protein of the ras superfamily involved in bud site selection
Bni1	Formin protein involved in cytoskeletal polarization and cytokinesis	Rsr1–GTP <sup>a</sup> (BD)	GTP-binding protein of the ras superfamily involved in bud site selection
		Spr28 <sup>a</sup> (AD)	Septin-related protein expressed during sporulation
		Msb3 <sup>a</sup> (BD)	Protein involved in bud emergence
		Pfy1 (BD)	Profilin, can act to prevent actin polymerization and to complex with monomeric actin
		Rho1–GTP (BD)	GTP-binding protein required to activate the PKC1 pathway and $\beta$ -1,3-glucan synthase, member of the rho subfamily of ras-like proteins
Bni4	Protein linking chitin synthase III to septins of the neck filaments	Zds2 <sup>a</sup> (BD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1
		Msb2 <sup>a</sup> (BD)	Protein involved in bud emergence
Bnr1	Bni1p-related formin protein	Pfy1 (BD)	Profilin, can act to prevent actin polymerization and to complex with monomeric actin
		Ste20 (AD)	PAK kinase of the pheromone pathway; also regulates polarized growth
Boi1	Bem1p-binding protein, involved in bud formation, has an SH3 domain, Boi2 homologue	Yer124c <sup>a</sup> (AD)	Protein of unknown function
		Zds2 <sup>a</sup> (AD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1

Table I. Summary of protein–protein interactions detected in two-hybrid screens (Continued)

Protein		Interacting protein(s)	
Boi2	Bem1p-binding protein, involved in bud formation, has an SH3 domain, Boi1 homologue	Bem1 (BD, AD)	Protein required for cell polarization and bud formation, has two SH3 domains
		Cdc42–GTP (BD)	Rho type GTPase involved in bud site assembly and cell polarity, GTP bound form
		Cla4 <sup>a</sup> (AD)	PAK kinase required for cytokinesis
		Mrs6 <sup>a</sup> (AD)	Rab geranylgeranyltransferase regulatory component (component A) and rab GDI
		Msb1 <sup>a</sup> (AD)	Protein involved in cell polarity and bud emergence
		Ste20 (AD)	PAK kinase of the pheromone pathway; also regulates polarized growth
		Yer124c <sup>a</sup> (AD)	Protein of unknown function
		Zds2 <sup>a</sup> (AD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1
Bub2	Protein required for cell cycle arrest in response to loss of microtubule function	Gic1 <sup>a</sup> (BD)	Effector of Cdc42p, important for bud emergence, Gic2 homologue
Bud2	GTPase-activating protein for Rsr1, involved in bud site selection	Cln2 <sup>a</sup> (AD)	G1/S-specific cyclin
Bud8	Protein required for bipolar budding	Ste20 <sup>a</sup> (AD)	PAK kinase of the pheromone pathway; also regulates polarized growth
		Ykl082c <sup>a</sup> (AD)	Protein of unknown function
		Cap2 (AD)	Actin-capping protein, β subunit
Cap1	Actin-capping protein, α subunit	Gic2 <sup>a</sup> (AD)	Effector of Cdc42p, important for bud emergence, Gic1 homologue
		Ypr171w <sup>a</sup> (AD)	Protein of unknown function
Cap2	Actin-capping protein, β subunit	Cap1 (BD)	Actin-capping protein, α subunit
Cdc11	Septin, involved in cytokinesis	Bem4 <sup>a</sup> (BD)	Bud emergence protein, interacts with Rho-type GTPases
		Cdc12 (AD,BD)	Septin, involved in cytokinesis
		Nfi1 (AD)	Septin-interacting protein
		Spr28 <sup>a</sup> (AD)	Septin-related protein expressed during sporulation
		Yor084w <sup>a</sup> (AD)	Protein of unknown function
		Zds2 <sup>a</sup> (BD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1
		Bem4 <sup>a</sup> (BD)	Bud emergence protein, interacts with Rho-type GTPases
		Cdc11 (AD,BD)	Septin, involved in cytokinesis
Cdc12	Septin, involved in cytokinesis	Cdc12 (AD,BD)	Septin, involved in cytokinesis
		Cla4 <sup>a</sup> (BD)	PAK kinase required for cytokinesis
		Gic1 <sup>a</sup> (BD)	Effector of Cdc42p, important for bud emergence, Gic2 homologue
		Gic2 <sup>a</sup> (BD)	Effector of Cdc42p, important for bud emergence, Gic1 homologue
		She3 <sup>a</sup> (AD)	Protein required for mother cell-specific expression of HO
		Air1 <sup>a</sup> (AD)	RING finger protein that affects RNA processing
Cdc24	GEF for Cdc42, involved in bud emergence, bud site selection, growth of mating projection	Bem1 (AD,BD)	Protein required for cell polarization and bud formation, has two SH3 domains
		Bem4 <sup>a</sup> (AD)	Bud emergence protein, interacts with Rho-type GTPases

Table I. Summary of protein–protein interactions detected in two-hybrid screens (Continued)

Protein		Interacting protein(s)	
Cdc24 (continued)	GEF for Cdc42, involved in bud emergence, bud site selection, growth of mating projection	Cdc42–GDP (BD)	Rho-type GTPase involved in bud site assembly and cell polarity
		Ent2 <sup>a</sup> (AD)	Epsin homologue required for endocytosis
		Far1 (AD)	Inhibitor of CDK-cyclin complexes involved in cell cycle arrest for mating and polarized growth of mating projection
		Rsr1–GDP (BD)	GTP-binding protein of the ras superfamily involved in bud site selection
		Sec15 <sup>a</sup> (AD)	Component of exocyst complex required for exocytosis
		Ste20 (AD)	PAK kinase of the pheromone pathway; also regulates polarized growth
		Swe1 <sup>a</sup> (AD)	Serine/tyrosine dual-specificity protein kinase; able to phosphorylate Cdc28p on tyrosine and inhibit its activity
		Ygr221c <sup>a</sup> (AD)	Protein of unknown function
Cdc42–GDP	Rho type GTPase involved in bud site assembly and cell polarity, GDP-bound form	Bem1 (AD)	Protein required for cell polarization and bud formation, has two SH3 domains
		Bem4 (AD, BD)	Bud emergence protein, interacts with Rho type GTPases
		Cdc24 (AD)	GEF for Cdc42, involved in bud emergence, bud site selection, growth of mating projection
Cdc42–GTP	Rho type GTPase involved in bud site assembly and cell polarity, GTP bound form	Bem1 (AD)	Protein required for cell polarization and bud formation, has two SH3 domains
		Bem4 (AD)	Bud emergence protein, interacts with Rho type GTPases
		Boi2 (AD)	Bem1p-binding protein, involved in bud formation, has an SH3 domain, Boi1 homologue
		Cla4 (AD)	PAK kinase required for cytokinesis
		Gic1 (AD)	Effector of Cdc42p, important for bud emergence, Gic2 homologue
		Gic2 (AD)	Effector of Cdc42p, important for bud emergence, Gic1 homologue
		Rgal (AD)	Rho-type GTPase activating protein (GAP) for Cdc42
		Ste20 (AD)	Serine/threonine protein kinase of the pheromone pathway; also participates in the pathway regulating filamentous growth
Chs4	Protein that stimulates chitin synthase III activity	Yil007c <sup>a</sup> (AD)	Protein of unknown function
Cka1	Casein kinase II catalytic (α) subunit	Rho3–GTP <sup>a</sup> (BD)	GTP-binding protein involved in control of actin cytoskeleton and exocytosis, member of the rho subfamily of ras-like proteins
Cka2	Casein kinase II catalytic (α') subunit	Rho3–GTP <sup>a</sup> (BD)	GTP-binding protein involved in control of actin cytoskeleton and exocytosis, member of the rho subfamily of ras-like proteins
Ckb1	Casein kinase II regulatory (β) subunit	Rho3–GTP <sup>a</sup> (BD)	GTP-binding protein involved in control of actin cytoskeleton and exocytosis, member of the rho subfamily of ras-like proteins
Cla4	PAK kinase required for cytokinesis	Abp1 <sup>a</sup> (BD)	Actin binding protein involved in cortical actin assembly, has SH3 domain
		Bem3 <sup>a</sup> (BD)	GAP for Cdc42p and Rho1p
		Boi2 <sup>a</sup> (BD)	Bem1p-binding protein, involved in bud formation, has an SH3 domain, Boi1 homologue
		Cdc12 <sup>a</sup> (AD)	Septin, involved in cytokinesis



Table I. Summary of protein–protein interactions detected in two-hybrid screens (Continued)

Protein		Interacting protein(s)	
Cla4 (continued)	PAK kinase required for cytokinesis	Cdc42–GTP (BD)	Rho type GTPase involved in bud site assembly and cell polarity
		Gic1 <sup>a</sup> (BD)	Effector of Cdc42p, important for bud emergence, Gic2 homologue
		Gic2 <sup>a</sup> (BD)	Effector of Cdc42p, important for bud emergence, Gic1 homologue
		Msb2 <sup>a</sup> (BD)	Protein involved in bud emergence
		Rga1 (BD)	Rho type GTPase-activating protein (GAP) for Cdc42p
		Slc2 <sup>a</sup> (BD)	Talin-like protein involved in membrane cytoskeleton assembly and required for cell polarization; also required for the internalization phase of endocytosis
		Zds2 <sup>a</sup> (BD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1
Cln2	G1/S-specific cyclin	Bud2 <sup>a</sup> (BD)	GTPase-activating protein for Rsr1, involved in bud site selection
Cof1	Cofilin, actin binding and severing protein	Act1 (AD)	Actin, involved in cell polarization, endocytosis, cytoskeletal functions
Cm1	Coronin, actin-bundling protein	Svl3 <sup>a</sup> (AD)	Protein involved in vacuolar uptake of endocytosed vital dyes
		Ynl094w <sup>a</sup> (AD)	Protein of unknown function
Dfg5	Protein required for cell polarity, apical growth, and pseudohyphal growth	Gic1 <sup>a</sup> (BD)	Effector of Cdc42p, important for bud emergence, Gic2 homologue
Ent2	Epsin homologue required for endocytosis	Cdc24 <sup>a</sup> (BD)	GEF for Cdc42, involved in bud emergence, bud site selection, growth of mating projection
		Sro77 <sup>a</sup> (BD)	Protein that functions together with Sec9p in exocytosis downstream of the Rho3p GTPase
Exo84	Subunit of the exocyst complex, required for exocytosis	Apg17 <sup>a</sup> (AD)	Protein essential for autophagy response to nutritional stress
		Sec15 (AD)	Component of exocyst complex required for exocytosis
Far1	Inhibitor of CDK-cyclin complexes involved in cell cycle arrest for mating and polarized growth of mating projection	Bem1 (BD)	Protein required for cell polarization and bud formation, has two SH3 domains
		Cdc24 (BD)	GEF for Cdc42, involved in bud emergence, bud site selection, growth of mating projection
		Bem4 <sup>a</sup> (AD)	Bud emergence protein, interacts with Rho-type GTPases
		Bub2 <sup>a</sup> (AD)	Protein required for cell cycle arrest in response to loss of microtubule function
		Cdc12 <sup>a</sup> (AD)	Septin, involved in cytokinesis
Gic1	Effector of Cdc42p, important for bud emergence, Gic2 homologue	Cdc42–GTP (BD)	Rho-type GTPase involved in bud site assembly and cell polarity
		Clc4 <sup>a</sup> (AD)	PAK kinase required for cytokinesis
		Dfg5 <sup>a</sup> (AD)	Protein required for cell polarity, apical growth, and pseudohyphal growth
		Gic1 (AD,BD)	Effector of Cdc42p, important for bud emergence, Gic2 homologue
		Gic2 (AD,BD)	Effector of Cdc42p, important for bud emergence, Gic1 homologue
		Hof1 <sup>a</sup> (AD)	Protein involved in cytokinesis, has an SH3 domain
		Ste50 <sup>a</sup> (AD)	Protein required for feedback control of pheromone-induced signal transduction
		Ykl082c <sup>a</sup> (AD)	Protein of unknown function
		Ycr086w <sup>a</sup> (AD)	Protein of unknown function

Table I. Summary of protein–protein interactions detected in two-hybrid screens (Continued)

Protein		Interacting protein(s)	
Gic1 (continued)	Effector of Cdc42p, important for bud emergence, Gic2 homologue	Zds1 <sup>a</sup> (AD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds2
		Zds2 <sup>a</sup> (AD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1
		Cap1 <sup>a</sup> (AD)	Actin-capping protein, $\alpha$ subunit
		Cdc12 <sup>a</sup> (AD)	Septin, involved in cytokinesis
		Cdc42–GTP (BD)	Rho-type GTPase involved in bud site assembly and cell polarity
Gic2	Effector of Cdc42p, important for bud emergence, Gic1 homologue	Clc4 <sup>a</sup> (AD)	PAK kinase required for cytokinesis
		Gic1 (AD,BD)	Effector of Cdc42p, important for bud emergence, Gic2 homologue
		Rga1 <sup>a</sup> (BD)	Rho-type GTPase-activating protein (GAP) for Cdc42p
		Ste50 <sup>a</sup> (AD)	Protein required for feedback control of pheromone-induced signal transduction
		Ycr086w <sup>a</sup> (AD)	Protein of unknown function
		Ykl082c <sup>a</sup> (AD)	Protein of unknown function
		Zds1 <sup>a</sup> (AD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds2
Hof1	Protein involved in cytokinesis, has an SH3 domain	Zds2 <sup>a</sup> (AD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1
		Gic1 <sup>a</sup> (BD)	Effector of Cdc42p, important for bud emergence, Gic2 homologue
Hsl7	Negative regulatory protein of the Swe1p protein kinase	Ynl094w (AD)	Protein of unknown function
Kin3	Serine/threonine protein kinase, unknown function	Sro77 <sup>a</sup> (BD)	Protein that functions together with Sec9p in exocytosis downstream of the Rho3p GTPase
Las17	WASP homologue involved in cortical actin assembly	Act1 (AD)	Actin, involved in cell polarization, endocytosis, cytoskeletal functions
		Rvs167 (AD, BD)	Protein that affects actin distribution and bipolar budding, has an SH3 domain
		Slc1 (BD)	Protein involved in assembly of cortical actin cytoskeleton, has three SH3 domains
		Yhr133c <sup>a</sup> (AD)	Protein of unknown function
		Ypl246c <sup>a</sup> (AD)	Protein of unknown function
Mrs6	Rab geranylgeranyltransferase regulatory subunit and rab GDI	Boi2 <sup>a</sup> (BD)	Bem1p-binding protein, involved in bud formation, has an SH3 domain, Boi1 homologue
Msb1	Protein involved in cell polarity and bud emergence	Boi2 <sup>a</sup> (BD)	Bem1p-binding protein, involved in bud formation, has an SH3 domain, Boi1 homologue
Msb2	Protein involved in bud emergence	Bni4 <sup>a</sup> (AD)	Protein linking chitin synthase III to septins of the neck filaments
		Clc4 <sup>a</sup> (AD)	PAK kinase required for cytokinesis
Msb3	Protein involved in bud emergence	Bni1 <sup>a</sup> (AD)	Formin protein involved in cytoskeletal polarization and cytokinesis
		Spa2 <sup>a</sup> (AD)	Protein involved in cell polarity and cell fusion during mating
Msb4	Protein involved in bud emergence	Spa2 <sup>a</sup> (AD)	Protein involved in cell polarity and cell fusion during mating
		Apg17 <sup>a</sup> (AD)	Protein essential for autophagy response to nutritional stress
Myo1	Myosin heavy chain (myosin II), involved in septation and cell wall organization	Spr3 <sup>a</sup> (AD)	Sporulation-specific septin
		Ypr188c <sup>a</sup> (AD)	Protein of unknown function

Table I. Summary of protein–protein interactions detected in two-hybrid screens (Continued)

Protein		Interacting protein(s)	
Nfi1	Septin-interacting protein	Bem4 <sup>a</sup> (BD)	Bud emergence protein, interacts with Rho type GTPases
		Cdc11 <sup>a</sup> (BD)	Septin, involved in cytokinesis
		Nip100 <sup>a</sup> (BD)	Mitotic spindle positioning protein, dynactin complex protein associated with the spindle
		Apg17 <sup>a</sup> (AD)	Protein essential for autophagy response to nutritional stress
		Arp1 (AD)	Actin-related protein of the dynactin complex, required for mitotic spindle orientation and nuclear migration
Nip100	Mitotic spindle positioning protein, dynactin complex protein associated with the spindle	Nfi1 <sup>a</sup> (AD)	Septin-interacting protein
		Nip100 (AD,BD)	Mitotic spindle positioning protein, dynactin complex protein associated with the spindle
		Pac11 (AD)	Protein with similarity to rat dynein intermediate chain; required in the absence of Cin8p, member of WD (WD-40) repeat family
		Rho1–GTP <sup>a</sup> (BD)	GTP-binding protein required to activate the PKC1 pathway and β-1,3-glucan synthase, member of the rho subfamily of ras-like proteins
		Rho2–GTP <sup>a</sup> (BD)	GTP-binding protein, member of the rho subfamily of ras-like proteins
		Sro77 <sup>a</sup> (BD)	Protein that functions together with Sec9p in exocytosis downstream of the Rho3p GTPase
		Nip100 (BD)	Mitotic spindle positioning protein, dynactin complex protein associated with the spindle
Pac11	Protein with similarity to rat dynein intermediate chain	Nip100 (BD)	Mitotic spindle positioning protein, dynactin complex protein associated with the spindle
Pfs1	Protein required for sporulation	Yil007c <sup>a</sup> (BD)	Protein of unknown function
Pfy1	Profilin, can act to prevent actin polymerization and to complex with monomeric actin	Act1 (AD)	Actin, involved in cell polarization, endocytosis, cytoskeletal functions
		Bni1 (AD)	Formin protein involved in cytoskeletal polarization and cytokinesis
		Bnr1 (AD)	Bni1p-related formin protein
		Srv2 (AD)	Adenylate cyclase–associated protein (CAP) that may provide a link between growth signals and the cytoskeleton
Pkc1	Protein kinase C, regulates MAP kinase cascade involved in regulating cell wall metabolism	Rho1–GTP (BD)	GTP-binding protein required to activate the PKC1 pathway and β-1,3-glucan synthase, member of the rho subfamily of ras-like proteins
		Ygr221C <sup>a</sup> (BD)	Protein of unknown function
		Zds2 <sup>a</sup> (BD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1
		Cdc42 (BD)	Rho-type GTPase involved in bud site assembly and cell polarity
Rga1	Rho type GTPase-activating protein (GAP) for Cdc42p	Clg4 <sup>a</sup> (AD)	PAK kinase required for cytokinesis
		Gic2 <sup>a</sup> (AD)	Effector of Cdc42p, important for bud emergence, Gic1 homologue
		Rho1 (AD,BD)	GTP-binding protein required to activate the PKC1 pathway and β-1,3-glucan synthase, member of the rho subfamily of ras-like proteins
		Rga1 (AD,BD)	Rho type GTPase-activating protein (GAP) for Cdc42 and Rho1
Rho1–GTP	GTP-binding protein required to activate the PKC1 pathway and β-1,3-glucan synthase, member of the rho subfamily of ras-like proteins, GTP-bound form	Apg17 <sup>a</sup> (AD)	Protein essential for autophagy response to nutritional stress
		Bem4 (AD)	Bud emergence protein, interacts with Rho type GTPases
		Bni1 (AD)	Formin protein involved in cytoskeletal polarization and cytokinesis

Table I. Summary of protein–protein interactions detected in two-hybrid screens (Continued)

Protein		Interacting protein(s)	
Rho1–GTP (continued)	GTP-binding protein required to activate the PKC1 pathway and β-1,3-glucan synthase, member of the rho subfamily of ras-like proteins, GTP-bound form	Nip100 <sup>a</sup> (AD)	Mitotic spindle positioning protein, dynactin complex protein associated with the spindle
		Pkc1 (AD)	Protein kinase C, regulates MAP kinase cascade involved in regulating cell wall metabolism
		Shc1 <sup>a</sup> (AD)	Protein involved in cell wall chitin synthesis or deposition
		Yil007c <sup>a</sup> (AD)	Protein of unknown function
		Zds2 <sup>a</sup> (AD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1
Rho2–GTP	GTP-binding protein, member of the rho subfamily of ras-like proteins, GTP bound form	Apg17 <sup>a</sup> (AD)	Protein essential for autophagy response to nutritional stress
		Bem4 (AD)	Bud emergence protein, interacts with Rho type GTPases
		Nip100 <sup>a</sup> (AD)	Mitotic spindle positioning protein, dynactin complex protein associated with the spindle
Rho3–GTP	GTP-binding protein, member of the rho subfamily of ras-like proteins, GTP bound form	Cka1 <sup>a</sup> (AD)	Casein kinase II catalytic (α) subunit
		Cka2 <sup>a</sup> (AD)	Casein kinase II catalytic (α') subunit
		Ckb1 <sup>a</sup> (AD)	Casein kinase II regulatory (β) subunit
Rho4–GTP	GTP-binding protein of the rho subfamily of ras-like proteins, GTP bound form	Bem4 (AD)	Bud emergence protein, interacts with Rho type GTPases
		Yil007c <sup>a</sup> (AD)	Protein of unknown function
Rpn4	Subunit of the regulatory particle of the proteasome	Yil007c <sup>a</sup> (BD)	Protein of unknown function
Rsr1–GDP	GTP-binding protein of the ras superfamily involved in bud site selection, GDP-bound form	Bem4 <sup>a</sup> (AD)	Bud emergence protein, interacts with Rho type GTPases
		Cdc24 (AD)	GEF for Cdc42, involved in bud emergence, bud site selection, growth of mating projection
		Sec15 <sup>a</sup> (AD)	Component of exocyst complex required for exocytosis
Rsr1–GTP	GTP-binding protein of the ras superfamily involved in bud site selection, GTP-bound form	Bem4 <sup>a</sup> (AD)	Bud emergence protein, interacts with Rho type GTPases
Rvs161	Protein required for viability after N, C, or S starvation, for internalization step of endocytosis, and for cell fusion during mating; roles in endocytosis and in cell fusion are independent of one another	Rvs167 (AD,BD)	Protein that affects actin distribution and bipolar budding, has an SH3 domain
Rvs167	Protein that affects actin distribution and bipolar budding, has an SH3 domain	Abp1 (AD)	Actin binding protein involved in cortical actin assembly, has SH3 domain
		Act2 <sup>a</sup> (AD)	Protein involved in cortical actin assembly
		Act1 (AD)	Actin, involved in cell polarization, endocytosis, cytoskeletal functions
		Las17 (AD, BD)	WASP homologue involved in cortical actin assembly
			Protein required for viability after N, C, or S starvation, for internalization step of endocytosis, and for cell fusion during mating; roles in endocytosis and in cell fusion are independent of one another
		Rvs161 (AD, BD)	Protein that affects actin distribution and bipolar budding, has an SH3 domain
		Rvs167 (AD, BD)	Protein that affects actin distribution and bipolar budding, has an SH3 domain
		Slal (BD)	Protein involved in assembly of cortical actin cytoskeleton, has three SH3 domains
			Talin-like protein involved in membrane cytoskeleton assembly and required for cell polarization; also required for the internalization phase of endocytosis
		Srv2 (AD)	Adenylate cyclase–associated protein (CAP) that may provide a link between growth signals and the cytoskeleton

Table I. Summary of protein–protein interactions detected in two-hybrid screens (Continued)

Protein	Interacting protein(s)
Rvs167 (continued)	Ybr108c (AD) Protein of unknown function
	Yjr083c <sup>a</sup> (AD) Protein of unknown function
	Ygr268c <sup>a</sup> (AD) Protein of unknown function
	Ynl086w <sup>a</sup> (AD) Protein of unknown function
	Ynl094w <sup>a</sup> (AD, BD) Protein of unknown function
	Yor284w <sup>a</sup> (AD) Protein of unknown function
	Ypr171w <sup>a</sup> (AD) Protein of unknown function
Sec15	Ysc84 <sup>a</sup> (AD) Protein of unknown function, has an SH3 domain
	Bem1 <sup>a</sup> (BD) Protein required for cell polarization and bud formation, has two SH3 domains
	Cdc24 <sup>a</sup> (BD) GEF for Cdc42, involved in bud emergence, bud site selection, growth of mating projection
	Exo84 (BD) Subunit of the exocyst complex, required for exocytosis
Shc1	Rsr1–GDP <sup>a</sup> (BD) GTP-binding protein of the ras superfamily involved in bud site selection
	Rho1–GTP <sup>a</sup> (BD) GTP-binding protein required to activate the PKC1 pathway and $\beta$ -1,3-glucan synthase, member of the rho subfamily of ras-like proteins
She3	Cdc12 <sup>a</sup> (BD) Septin, involved in cytokinesis
Sla1	Las17 (AD) WASP homologue involved in cortical actin assembly
	Rvs167 (AD) Protein that affects actin distribution and bipolar budding, has an SH3 domain
	Srv2 (AD) Adenylate cyclase-associated protein (CAP) that may provide a link between growth signals and the cytoskeleton
	Ygr268c <sup>a</sup> (AD) Protein of unknown function
	Ynl094w <sup>a</sup> (AD) Protein of unknown function
	Ypr171w <sup>a</sup> (AD) Protein of unknown function
	Ysc84 <sup>a</sup> (AD) Protein of unknown function, has an SH3 domain
Sla2	Clas4 <sup>a</sup> (AD) PAK kinase required for cytokinesis
	Rvs167 (BD) Protein that affects actin distribution and bipolar budding, has an SH3 domain
	Ynl094w <sup>a</sup> (AD) Protein of unknown function
	Yor284w <sup>a</sup> (AD) Protein of unknown function
Spa2	Ysc84 <sup>a</sup> (AD) Protein of unknown function, has an SH3 domain
	Msb3 <sup>a</sup> (BD) Protein involved in bud emergence
Spr28	Msb4 <sup>a</sup> (BD) Protein involved in bud emergence
	Bem4 <sup>a</sup> (BD) Bud emergence protein, interacts with Rho type GTPases
Spr3	Cdc11 <sup>a</sup> (BD) Septin, involved in cytokinesis
	Myo1 <sup>a</sup> (BD) Myosin heavy chain (myosin II), involved in septation and cell wall organization
Spr6	Zds2 <sup>a</sup> (BD) Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1
Sro77	Apg17 <sup>a</sup> (AD) Protein essential for autophagy response to nutritional stress
	Bcy1 <sup>a</sup> (AD) Regulatory subunit of cAMP-dependent protein kinases
	Ent2 <sup>a</sup> (AD) Epsin homologue required for endocytosis
	Kin3 <sup>a</sup> (AD) Serine/threonine protein kinase, unknown function

Table I. Summary of protein–protein interactions detected in two-hybrid screens (Continued)

Protein	Interacting protein(s)
Sro77 (continued)	Nip100 <sup>a</sup> (AD) Mitotic spindle positioning protein, dynactin complex protein associated with the spindle
	Yap1801 <sup>a</sup> (AD) Protein homologous to clathrin assembly polypeptide AP180; interacts with Pan1p
	Yip1 <sup>a</sup> (AD) Protein involved in vesicular transport; interacts with transport GTPases Ypt1p and Ypt31p at the Golgi membrane
	Ynl094w <sup>a</sup> (AD) Protein of unknown function
	Yor197w <sup>a</sup> (AD) Protein of unknown function
	Abp1 (BD) Actin binding protein involved in cortical actin assembly, has SH3 domain
	Act1 (AD,BD) Actin, involved in cell polarization, endocytosis, cytoskeletal functions
Srv2	Aip1 (AD) Actin interacting protein involved in disassembly of actin filaments
	Pfy1 (BD) Profilin, can act to prevent actin polymerization and to complex with monomeric actin
	Rvs167 (BD) Protein that affects actin distribution and bipolar budding, has an SH3 domain
	Sla1 (BD) Protein involved in assembly of cortical actin cytoskeleton, has three SH3 domains
	Srv2 (AD,BD) Adenylate cyclase-associated protein (CAP) that may provide a link between growth signals and the cytoskeleton
	Yhr070w <sup>a</sup> (AD) Protein of unknown function
	Yhr070w <sup>a</sup> (AD) Protein of unknown function
Sso1	Syntaxin homologue (t-SNARE) involved in vesicle transport from Golgi to plasma membrane
Sso2	Yap1801 (AD) Protein homologous to clathrin assembly polypeptide AP180; interacts with Pan1p
	Apg7 <sup>a</sup> (AD) Protein essential for autophagy response to nutritional stress
Ste20	Yap1801 (AD) Protein homologous to clathrin assembly polypeptide AP180; interacts with Pan1p
	Bem1 (AD) Protein required for cell polarization and bud formation, has two SH3 domains
	Bem4 <sup>a</sup> (AD) Bud emergence protein, interacts with Rho-type GTPases
	Boi1 (AD) Bem1p-binding protein, involved in bud formation, has an SH3 domain, Boi2 homologue
	Boi2 (AD) Bem1p-binding protein, involved in bud formation, has an SH3 domain, Boi1 homologue
	Bud8 <sup>a</sup> (BD) Protein required for bipolar budding
	Cdc42-GTP (BD) Rho-type GTPase involved in bud site assembly and cell polarity
Ste50	Gic1 (BD) Effector of Cdc42p, important for bud emergence, Gic2 homologue
	Gic2 (BD) Effector of Cdc42p, important for bud emergence, Gic1 homologue
Svl3	Crm1 <sup>a</sup> (BD) Protein involved in vacuolar uptake of endocytosed vital dyes
Swe1	Bem1 <sup>a</sup> (BD) Serine/threonine dual-specificity protein kinase; able to phosphorylate Cdc28p on tyrosine and inhibit its activity

Table I. Summary of protein–protein interactions detected in two-hybrid screens (Continued)

Protein		Interacting protein(s)	
Swe1 (continued)	Serine/tyrosine dual-specificity protein kinase; able to phosphorylate Cdc28p on tyrosine and inhibit its activity	Cdc24 <sup>a</sup> (BD)	GEF for Cdc42, involved in bud emergence, bud site selection, growth of mating projection
		Ynl094w <sup>a</sup> (AD)	Protein of unknown function
Yal004w	Protein of unknown function	Zds2 <sup>a</sup> (BD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1
Yap1801	Protein homologous to clathrin assembly polypeptide AP180; interacts with Pan1p	Sro77 <sup>a</sup> (BD)	Protein that functions together with Sec9p in exocytosis downstream of the Rho3p GTPase
		Sso1 (BD)	Syntaxin homologue (t-SNARE) involved in vesicle transport from Golgi to plasma membrane
		Sso2 (BD)	Syntaxin homologue (t-SNARE) involved in vesicle transport from Golgi to plasma membrane
Ybr108c	Protein of unknown function	Rvs167 <sup>a</sup> (BD)	Protein that affects actin distribution and bipolar budding, has an SH3 domain
Ycr086w	Protein of unknown function	Gic1 <sup>a</sup> (BD)	Effector of Cdc42p, important for bud emergence, Gic2 homologue
		Gic2 <sup>a</sup> (BD)	Effector of Cdc42p, important for bud emergence, Gic1 homologue
Yel023	Protein of unknown function	Zds2 <sup>a</sup> (BD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1
Yer124c	Protein of unknown function	Boi1 <sup>a</sup> (BD)	Bem1p-binding protein, involved in bud formation, has an SH3 domain, Boi1 homologue
		Boi2 <sup>a</sup> (BD)	Bem1p-binding protein, involved in bud formation, has an SH3 domain, Boi1 homologue
		Zds2 <sup>a</sup> (BD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1
Ygr221c	Protein of unknown function	Cdc24 <sup>a</sup> (BD)	GEF for Cdc42, involved in bud emergence, bud site selection, growth of mating projection
		Pkc1 <sup>a</sup> (AD)	Protein kinase C; regulates MAP kinase cascade involved in regulating cell wall metabolism
Ygr268c	Protein of unknown function	Rvs167 <sup>a</sup> (BD)	Protein that affects actin distribution and bipolar budding, has an SH3 domain
		Sla1 <sup>a</sup> (BD)	Protein involved in assembly of cortical actin cytoskeleton, has three SH3 domains
Yhr070w	Protein of unknown function	Srv2 <sup>a</sup> (BD)	Adenylate cyclase-associated protein (CAP) that may provide a link between growth signals and the cytoskeleton
Yhr133c	Protein of unknown function	Las17 <sup>a</sup> (BD)	WASP homologue involved in cortical actin assembly
Yhr149C	Protein of unknown function	Zds1 <sup>a</sup> (AD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds2
		Zds2 <sup>a</sup> (AD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1
		Chs4 <sup>a</sup> (AD)	Protein that stimulates chitin synthase III activity
Yil007C	Protein of unknown function	Pis1 <sup>a</sup> (AD)	Protein required for sporulation
		Rho1–GTP <sup>a</sup> (BD)	GTP-binding protein required to activate the PKC1 pathway and $\beta$ -1,3-glucan synthase, member of the rho subfamily of ras-like proteins
		Rho4–GTP <sup>a</sup> (BD)	GTP-binding protein of the rho subfamily of ras-like proteins
Yip1	Protein involved in vesicular transport; interacts with transport GTPases Ypt1p and Ypt31p at the Golgi membrane	Rpn4 <sup>a</sup> (AD)	Subunit of the regulatory particle of the proteasome
		Sro77 <sup>a</sup> (BD)	Protein that functions together with Sec9p in exocytosis downstream of the Rho3p GTPase

Table I. Summary of protein–protein interactions detected in two-hybrid screens (Continued)

Protein		Interacting protein(s)	
Yjr083c	Protein of unknown function	Rvs167 <sup>a</sup> (BD)	Protein that affects actin distribution and bipolar budding, has an SH3 domain
Ykl082c	Protein of unknown function	Bud8 <sup>a</sup> (BD)	Protein required for bipolar budding
		Gic1 <sup>a</sup> (BD)	Effector of Cdc42p, important for bud emergence, Gic2 homologue
		Gic2 <sup>a</sup> (BD)	Effector of Cdc42p, important for bud emergence, Gic1 homologue
Ykr083c	Protein of unknown function	Zds2 <sup>a</sup> (BD)	Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1
		Ap17 <sup>a</sup> (BD)	Protein essential for autophagy response to nutritional stress
Ynl086w	Protein of unknown function	Rvs167 <sup>a</sup> (BD)	Protein that affects actin distribution and bipolar budding, has an SH3 domain
Ynl094w	Protein of unknown function	Abp1 <sup>a</sup> (BD)	Actin binding protein involved in cortical actin assembly, has SH3 domain
		Crn1 <sup>a</sup> (BD)	Coronin, actin-bundling protein
		Hsl7 (BD)	Negative regulatory protein of the Swe1p protein kinase
		Rvs167 <sup>a</sup> (AD,BD)	Protein that affects actin distribution and bipolar budding, has an SH3 domain
		Sla1 <sup>a</sup> (BD)	Protein involved in assembly of cortical actin cytoskeleton, has three SH3 domains
		Sla2 <sup>a</sup> (BD)	Talin-like protein involved in membrane cytoskeleton assembly and required for cell polarization; also required for the internalization phase of endocytosis
Yor084w	Protein of unknown function	Sro77 <sup>a</sup> (BD)	Protein that functions together with Sec9p in exocytosis downstream of the Rho3p GTPase
		Swe1 <sup>a</sup> (BD)	Serine/tyrosine dual-specificity protein kinase; able to phosphorylate Cdc28p on tyrosine and inhibit its activity
		Cdc11 <sup>a</sup> (BD)	Septin, involved in cytokinesis
Yor197w	Protein of unknown function	Sro77 <sup>a</sup> (BD)	Protein that functions together with Sec9p in exocytosis downstream of the Rho3p GTPase
Yor284w	Protein of unknown function	Abp1 <sup>a</sup> (BD)	Actin binding protein involved in cortical actin assembly, has SH3 domain
		Rvs167 <sup>a</sup> (BD)	Protein that affects actin distribution and bipolar budding, has an SH3 domain
		Sla2 <sup>a</sup> (BD)	Talin-like protein involved in membrane cytoskeleton assembly and required for cell polarization; also required for the internalization phase of endocytosis
Ypl246c	Protein of unknown function	Las17 <sup>a</sup> (BD)	WASP homologue involved in cortical actin assembly
Ypr171w	Protein of unknown function	Cap1 <sup>a</sup> (BD)	Actin-capping protein, $\alpha$ subunit
		Rvs167 <sup>a</sup> (BD)	Protein that affects actin distribution and bipolar budding, has an SH3 domain
		Sla1 <sup>a</sup> (BD)	Protein involved in assembly of cortical actin cytoskeleton, has three SH3 domains
Ypr188c	Protein of unknown function	Myo1 <sup>a</sup> (BD)	Myosin heavy chain (myosin III), involved in septation and cell wall organization
Ysc84	Protein of unknown function, has an SH3 domain	Rvs167 <sup>a</sup> (BD)	Protein that affects actin distribution and bipolar budding, has an SH3 domain
		Sla1 <sup>a</sup> (BD)	Protein involved in assembly of cortical actin cytoskeleton, has three SH3 domains
		Sla2 <sup>a</sup> (BD)	Talin-like protein involved in membrane cytoskeleton assembly and required for cell polarization; also required for the internalization phase of endocytosis



Table I. Summary of protein–protein interactions detected in two-hybrid screens (Continued)

Protein	Interacting protein(s)
Zds1	Bem3 <sup>a</sup> (BD) GAP for Cdc42p and Rho1p
	Gic1 <sup>a</sup> (BD) Effector of Cdc42p, important for bud emergence, Gic2 homologue
	Gic2 <sup>a</sup> (BD) Effector of Cdc42p, important for bud emergence, Gic1 homologue
	Yhr149c <sup>a</sup> (BD) Protein of unknown function
	Zds2 <sup>a</sup> (AD,BD) Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1
Zds2	Bem3 <sup>a</sup> (BD) GAP for Cdc42p and Rho1p
	Bni1 <sup>a</sup> (AD) Formin protein involved in cytoskeletal polarization and cytokinesis
	Boi1 <sup>a</sup> (BD) Bem1p-binding protein, involved in bud formation, has an SH3 domain, Boi2 homologue
	Boi2 <sup>a</sup> (BD) Bem1p-binding protein, involved in bud formation, has an SH3 domain, Boi1 homologue
	Cdc11 <sup>a</sup> (AD) Septin, involved in cytokinesis
	Cla4 <sup>a</sup> (AD) PAK kinase required for cytokinesis
	Gic1 <sup>a</sup> (BD) Effector of Cdc42p, important for bud emergence, Gic2 homologue
	Gic2 <sup>a</sup> (BD) Effector of Cdc42p, important for bud emergence, Gic1 homologue
	Pkc1 <sup>a</sup> (AD) Protein kinase C; regulates MAP kinase cascade involved in regulating cell wall metabolism
	Rho1-GTP <sup>a</sup> (BD) GTP-binding protein required to activate the PKC1 pathway and beta-1,3-glucan synthase, member of the rho subfamily of ras-like proteins
	Spr6 <sup>aa</sup> (AD) Sporulation-specific protein
	Yal004w <sup>a</sup> (AD) Protein of unknown function
	Yel023c <sup>a</sup> (AD) Protein of unknown function
	Yer124c <sup>a</sup> (AD) Protein of unknown function
	Yhr149c <sup>a</sup> (BD) Protein of unknown function
	Ykl082c <sup>a</sup> (AD) Protein of unknown function
	Zds1 <sup>a</sup> (AD,BD) Protein with effects on cell polarity and transcriptional silencing, homologue of Zds2
	Zds2 <sup>a</sup> (AD,BD) Protein with effects on cell polarity and transcriptional silencing, homologue of Zds1

A total of 191 reproducible two-hybrid interactions involving 110 proteins were detected. Proteins are listed in alphabetical order. Each pairwise interaction appears twice in the table, once under the bait protein and once under the interacting prey protein. Entries in the second column are noted as BD (binding domain) or AD (activation domain) to signify the direction of the two-hybrid interaction.

<sup>a</sup>Interactions not previously identified.

processes. These two classes of interaction can, respectively, provide novel insights into the biochemical mechanisms responsible for each process and into the regulatory mechanisms that coordinate the different processes spatially and temporally within a cell. Interaction of a protein with others involved in a process distinct from the one it was originally implicated in might reflect an underlying regulatory mechanism linking the two processes, or it might indicate that one

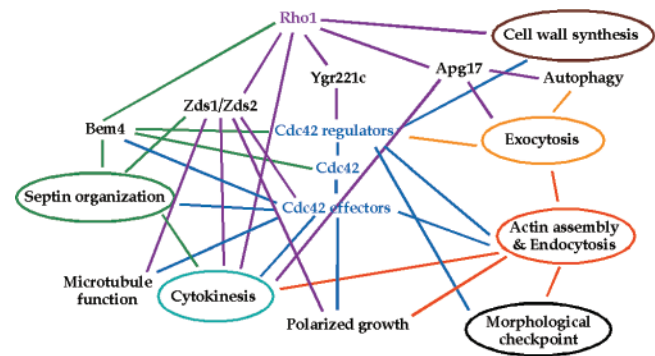


Figure 1. **Schematic overview of connections between processes involved in cell polarity development.** Major processes are color coded in this and the following figures: blue, Cdc42-signaling pathways; purple, Rho1-signaling pathways; green, septin organization; red, actin organization and endocytosis; yellow, exocytosis; brown, cell wall synthesis; turquoise, cytokinesis. Only individual proteins that appear to be branchpoints or major nodal connections between different processes are depicted. Bem4, for example, shows interactions with both Rho1 and Cdc42 GTPase pathways and with the septins. Zds1 and Zds2 link Rho1 with Cdc42 effectors and downstream processes. Ygr221c also shows interactions with both Cdc42 and Rho1 pathways. Apg17 shows interactions with proteins involved in cytokinesis, exocytosis, and Rho1 function.

of the interacting proteins has a previously unrecognized function. Additionally, it is not possible to know the directionality of the flow of information through the protein interaction network. Finally, further studies are required to determine when, where, and why two proteins interact. Here we discuss some interactions that appear particularly significant or provocative.

### Cdc42 effectors

Activation of the Cdc42 GTPase is a key event in establishment and maintenance of cell polarity. Yeast cells deficient in Cdc42 function grow isotropically and are unable to form buds, mating projections, or pseudohyphae. They are unable to properly organize the actin cytoskeleton, septins, or the secretory pathway. Cdc42 interacts with several effector proteins that transduce its signal to bring about several processes, including polarization of the actin cytoskeleton (Cvrcková et al., 1995; Brown et al., 1997; Chen et al., 1997; Evangelista et al., 1997; Bi et al., 2000; Jaquenod and Peter, 2000). Protein–protein interactions detected in our two-hybrid screens suggest connections between Cdc42, its regulatory and effector proteins, and proteins involved in several different processes required for cell polarity development (Figs. 1–3 and Table I).

Screening with mutant Cdc42 baits locked in the GDP or GTP state, we found interactions between Cdc42 and several of its known regulators and effector proteins: Cdc24, Rga1, Bem1, Bem4, Cla4, Ste20, Gic1, and Gic2. Two-hybrid interactions were observed between Cdc42 GAPs and Cdc42 effectors. The GAP Rga1 interacted with Gic2, and the GAP Bem3 interacted with Cla4. It is possible that these interactions were bridged by the Cdc42 protein itself (Kozminski et al., 2000). However, if these interactions are direct, they might reflect a feedback mechanism for Cdc42 regulation.

Table II. Cellular localization of YFP-tagged proteins encoded by novel ORFs

Protein	Null mutant phenotype	Two-hybrid interactions	Homologues <sup>a</sup>	YFP fusion location	Figure
Ykl082c	Lethal <sup>b</sup>	Bud8, Zds2, Gic1, Gic2	<i>D. melanogaster</i> CG13648 (21%); CG9274 (22%) <i>C. elegans</i> ZK354.3 (25%); C17F3.3 (27%) <i>S. pombe</i> Spac8c9.10cp (24%); Spbc1861.01cp (20%)	Nucleolus	Fig. 4, A and B
Ycr086w	Viable, benomyl sensitive <sup>c</sup>	Gic1, Gic2	None known	Punctate localization at nuclear periphery, nuclear envelope	Fig. 4, C and D
Ygr221c	Viable, sensitive to nonhydrolyzable GDP analogues <sup>c</sup>	Cdc24, Pkc1	<i>S. cerevisiae</i> Yhr149c (32%); Muc1(23%)	Bud tip, bud neck	Fig. 4, E and F
Yhr149c	Viable <sup>b</sup>	Zds1, Zds2	<i>S. cerevisiae</i> Ygr221c (32%) <i>H. sapiens</i> ZNF9 (26%) <i>M. musculus</i> CNBP (26%) <i>D. melanogaster</i> CG9715 (28%); CG3800 (28%) <i>C. elegans</i> GLH-4 (25%)	Bud tip, bud neck	Fig. 4, O and P
Yil079c/Air1	Viable <sup>b</sup>	Cdc24	<i>D. melanogaster</i> DS02740.2:BG:DS02740.2 (32%) <i>H. sapiens</i> PSMD9 (35%)	No detectable signal	Data not shown
Yer124c	Viable <sup>b</sup>	Boi1, Boi2, Zds2	<i>D. melanogaster</i> CG9588 (28%) <i>C. elegans</i> C44B7.1 (31%); Y42H9AR.F (30%) <i>S. pombe</i> Spac2h10.02cp (27%)	Cytoplasm	Data not shown
Yil007c	Viable <sup>b</sup>	Rho1, Rho4, Pfs1, Chs4, Rpn4	<i>S. cerevisiae</i> Ynl047p (24%) <i>H. sapiens</i> USP8 (23%) <i>D. melanogaster</i> CG13648 (22%) <i>S. cerevisiae</i> Crp1 (25%)	Actin patches	Figs. 4, K and L, and 5
Ylr423c/Apg17	Viable <sup>b</sup>	Rho1, Rho2, Apg17, Exo84, Myo1, Nip100, Sro77, Ykr083c	<i>S. pombe</i> Spac17a5.10p (31%)	Cytoplasm	Data not shown
Ypr171w	Viable <sup>b</sup>	Cap1, Rvs167, Sla1	None known	2–5 fast moving dots around cell periphery	Figs. 4, M and N, and 6
Ygr268c	Viable <sup>b</sup>	Rvs167, Sla1	None known	No detectable signal	Data not shown
Yor284w	Viable <sup>b</sup>	Abp1, Rvs167, Sla2	<i>S. pombe</i> Spbc29b5.04cp (26%)	Actin patches	Unpublished data
Yjr083c	Viable <sup>b</sup>	Rvs167			
Ynl094w	Viable <sup>b</sup>	Abp1, Crn1, Hsl7, Rvs167, Sla1, Sla2, Sro77, Swe1			

Proteins are listed in the order in which they are discussed in the text. Percentages refer to amino acid identity between homologues.

<sup>a</sup>Information on homologues from other species is taken from the Yeast Proteome Database at <http://www.proteome.com>.

<sup>b</sup>Information on these phenotypes of null mutants is taken from Winzeler et al. (1999).

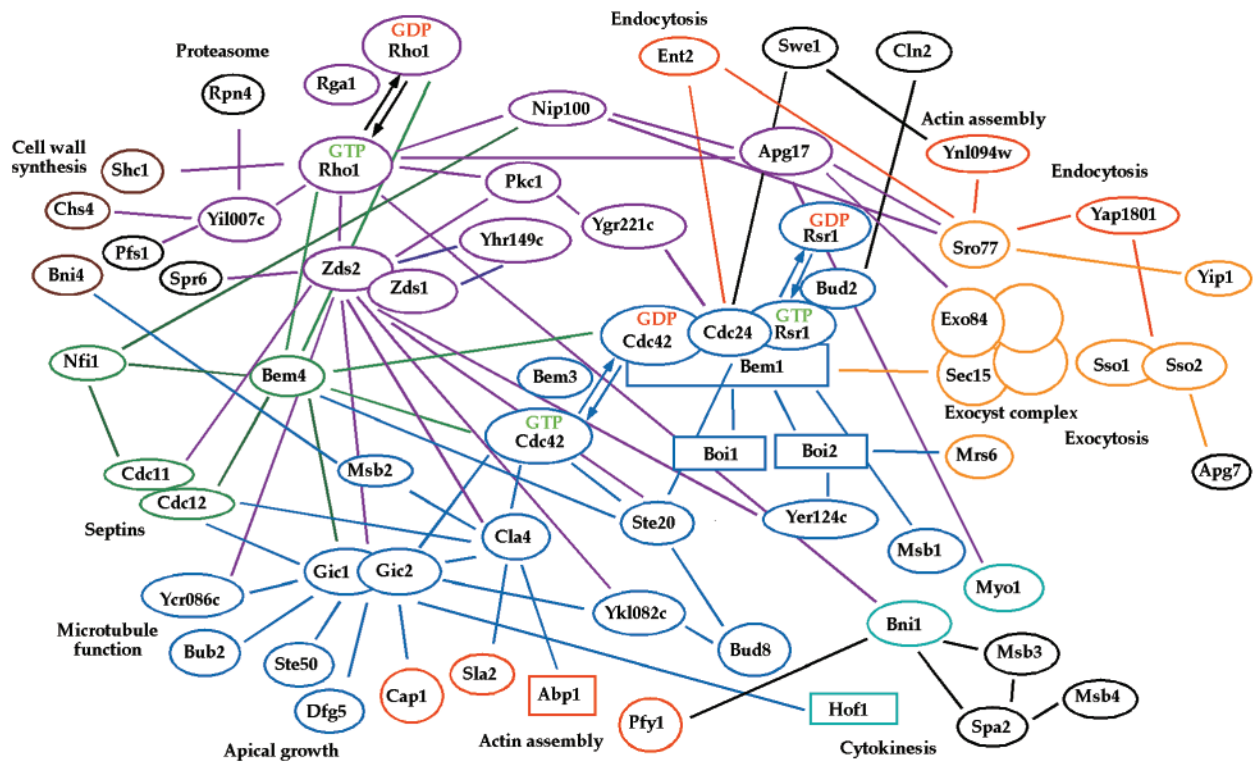
<sup>c</sup>Information on these phenotypes of null mutants is taken from Rieger et al. (1999).

The Cla4 p21-activated protein kinase (PAK)\* showed two-hybrid interactions with several proteins. Its interaction with the septin Cdc12 suggests that a direct interaction might underlie the role of this PAK in regulation of septin filament organization and cytokinesis (Benton et al., 1997; Weiss et al., 2000). The relevance of this interaction is supported by the observation that a *cla4 cdc12* double mutant is a synthetic lethal (Cvrcková et al., 1995). Two-hybrid interactions between Cla4 and the cortical patch proteins Sla2 and Abp1 suggest a previously unrecognized regulatory role associated with cortical actin patches. Both Abp1 and Sla2 have functions in cortical patch assembly and in endocytosis, a process that is intimately linked to cortical patches (Lila and Drubin, 1997; Wesp et al., 1997). Sla2 is required to nucleate actin assembly in permeabilized yeast cells (Li et al., 1995; Ayscough et al., 1997) and it mediates polarization of actin cortical patches in a Cdc42-dependent process (Yang et al., 1999). The *cla4* null mutant, like an *sla2* mutant, is defective in actin nucleation in permeabilized yeast cells (Eby et al., 1998). Colocalization of Sla2 with actin is most evident in unbudded and small-budded cells, suggesting that its activity might be most important early in the cell cycle (Yang et al., 1999). The kinase activity of Cla4 also appears to be required at an early stage of the cell cycle, as inhibition

of the Cla4 kinase in unbudded cells, but not at later stages, leads to hyperpolarized bud growth and defects in cytokinesis (Weiss et al., 2000). Perhaps Cla4 regulates the polarity of cortical patches via an interaction with Sla2. The NH<sub>2</sub>-terminal region of Cla4, which appears to have a function in maintaining cell polarity (Bi et al., 2000), contains proline-rich motifs which might be binding sites for the SH3 domain of Abp1 (Weiss et al., 2000). Both Sla2 and Abp1 have vertebrate homologues, and it will be important to test these for interactions with and regulation by PAK kinases (Engqvist-Goldstein et al., 1999; Kessels et al., 2000). Interestingly, PAK family protein kinase was implicated previously in the regulation of yeast class I myosins, and Abp1, Sla2, and class I myosins are each implicated in separate mechanisms to activate the Arp2/3 complex (Wu et al., 1996, 1997; Evangelista et al., 2000; Lechler et al., 2000; Goode et al., 2001; M. Duncan, J. Cope, and D. Drubin, personal communication).

Multicopy expression of *MSB2* suppresses the defects of a *cdc24* mutant (Bender and Pringle, 1992), but the function of the Msb2 protein is unknown. A two-hybrid interaction between Cla4 and Msb2 suggests that Msb2 is also part of the Cdc42 regulatory pathway. We found that Msb2 interacts with Bni4, a protein that targets chitin deposition to sites of polarized growth by linking chitin synthase to septins (DeMarini et al., 1997). Msb2 might coordinate cell wall

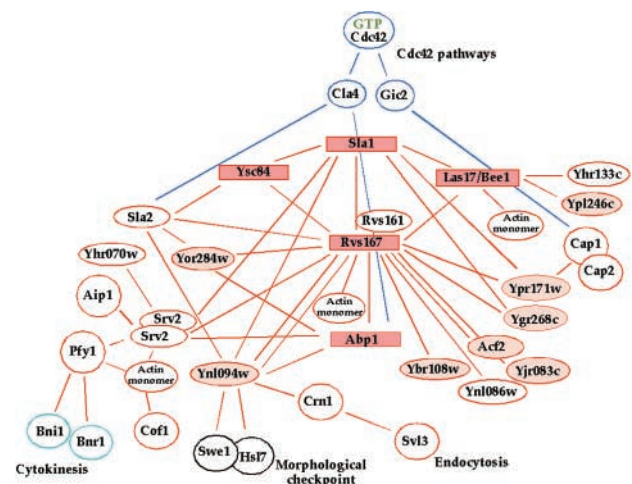
\*Abbreviation used in this paper: PAK, p21-activated protein kinase.



**Figure 2. Interaction map for proteins involved in Cdc42- and Rho1-regulated processes and in other cell polarity development pathways.** Proteins that regulate Cdc42 function or that transduce signals from activated Cdc42 are shown in blue. Rho1 and its effectors are shown in purple. Cdc42-regulated pathways show interactions with proteins involved in septin organization via interactions with Bem4; with Rho1 via interactions with Zds2 and Ygr221c; and with proteins involved in cell cycle control, endocytosis, and polarized exocytosis. Cdc42 effector proteins show interactions with proteins involved in cytokinesis, microtubule stability, polarized growth, actin assembly, polarized secretion, and cell wall synthesis. Proteins involved in septin organization may interact with Rho1 via Bem4. Rho1 involvement in nuclear migration, actin/myosin ring contraction, and septum formation (exocytosis) during cytokinesis is suggested by Apg17-mediated connections between proteins involved in these processes. Other interactions suggest connections between late exocytic and early endocytic processes, between early and late steps in secretory pathways, and between exocytosis and autophagy.

growth with other Cdc42-regulated processes. Cla4 also showed two-hybrid interactions with the Cdc42 effectors Gic1 and Gic2 and with Zds2, a protein that might be a regulator of Cdc42 and Rho1 (Bi and Pringle, 1996). As discussed below, Zds2 and its homologue Zds1 showed interactions with Rho1 and several proteins downstream of Cdc42 and may therefore connect the Rho1 and Cdc42 pathways.

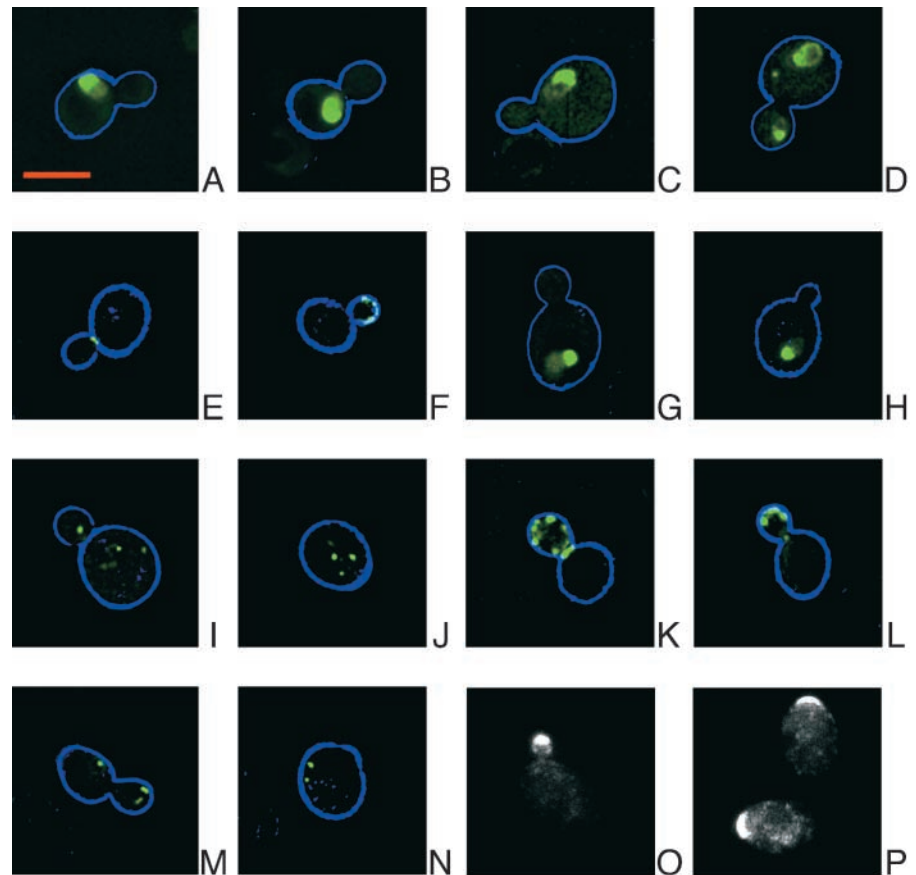
The homologous Cdc42 effectors Gic1 and Gic2 (Brown et al., 1997; Chen et al., 1997; Jaquenod and Peter, 2000) also showed interactions with Ste50, a protein that positively regulates the Ste11 kinase in the pheromone response pathway (Xu et al., 1996), in the Hog1 osmotic stress pathway (Posas et al., 1998), and during pseudohyphal growth (Ramezani Rad et al., 1998). Ste50 and the pheromone response pathway have been implicated recently in maintenance of cell wall integrity in budding cells (Cullen et al., 2000). Dfg5, another protein required for polarized and pseudohyphal growth (Mösch and Fink, 1997), also interacts with Gic1. These interactions may be involved in maintaining polarized growth during budding and mating and in reestablishing polarity after osmotic stress (Brewster and Gustin, 1994). An interaction between Gic2 and the Cap1 subunit of the actin filament capping protein suggests a possible role in regulating actin assembly and, therefore, a potential novel link between Cdc42 and the actin cytoskeleton.



**Figure 3. Protein interactions involved in actin assembly and actin functions in endocytosis, cytokinesis, and morphogenesis.** Cdc42 effectors show interactions with proteins involved in endocytosis and cytokinesis. Interactions between Ynl094w, several actin cytoskeleton proteins, and Swe1 and Hsl7 may underlie the morphogenesis checkpoint that monitors actin assembly. Several interactions between SH3 domain-containing proteins (shaded rectangles) and proteins containing proline-rich putative SH3 binding sites (shaded ovals) are shown.



**Figure 4. Fluorescence micrographs of proteins tagged at the COOH terminus with YFP (A–N).** YFP signal is shown in green. Cells were outlined by staining with Alexa fluor 633 conjugated to concanavalin A (blue). (A and B) Ykl082c-YFP; (C and D) Ycr086w-YFP; (E and F) Ygr221c-YFP; (G and H) Yil079c/Air1-YFP; (I and J) Ylr423c/Apg17-YFP; (K and L) Ypr171w-YFP; (M and N) Yor284w-YFP. (O and P) Immunofluorescence micrographs of Yhr149c tagged with a 13Myc epitope. GFP-tagged Yhr149 exhibits the same localization although the GFP signal is extremely weak. Bar, 5  $\mu$ m.



Apical bud growth appears to stimulate establishment of a distal bud site landmark that functions in the bipolar budding pattern seen in diploids. Several interactions may shed new light on this process. Gic1 and Gic2 both interact with Zds2, and all three proteins showed interactions with Ykl082c, an essential protein of unknown function (Winzeler et al., 1999). Ykl082c also showed interactions with Bud8, a protein that appears to be a component of the distal bud site tag (Zahner et al., 1996; Harkins et al., 2001). Recent findings also suggest that Ste20 PAK kinase, a Cdc42 effector, regulates the pattern of diploid bud site selection via Bud8 (Sheu et al., 2000). Ste20 was found to affect bipolar bud site selection through its regulation of apical growth in the bud. The decreased period of polarized bud growth seen in *ste20* mutants reduced the accuracy of bud site selection in diploid cells and produced a unipolar budding pattern like that of the *bud8* mutant. Interestingly, we found that Bud8 interacts with Ste20. The Ykl082c protein may also be involved in polarized growth and participate in this process. We found that haploid cells containing the genomic Ykl082c-YFP fusion were slow growing and temperature sensitive. Heterozygous diploids appeared to have a cell cycle delay in late mitosis, suggesting a possible defect in nuclear migration (data not shown). Curiously, YFP-tagged Ykl082c localized to the nucleolus (Table II and Fig. 4, A and B). Nucleolar localization may be connected to its interaction with Zds2, which in addition to its effects on cell polarity also has a role in gene silencing and interacts with the nucleolar protein Sir2 (Roy and Runge, 2000). Nucleolar sequestration via association with a multiprotein complex containing Sir2 has been found

to control the functions of regulatory proteins, including the protein phosphatase Cdc14 that regulates mitotic exit (Shou et al., 1999; Visintin and Amon, 2000).

The double mutant *gic1 gic2* has depolarized microtubules as well as a disorganized actin cytoskeleton (Brown et al., 1997). We found two novel interactions for Gic1 and Gic2 that suggest that these proteins may directly affect microtubule polarization and nuclear migration during mitosis. The first is an interaction between Gic1 and Bub2, which functions in the microtubule/spindle checkpoint (Hoyt et al., 1991). The second is with an uncharacterized protein, Ycr086w. The *ycr086w* null mutant is benomyl sensitive and has impaired nuclear migration (Rieger et al., 1999). YFP-tagged Ycr086w localizes to the nuclear periphery in a punctate pattern (Table II and Fig. 4, C and D). Other interactions of Gic1 and Gic2 with the septin Cdc12 and with Hof1/Cyk2, an SH3-domain containing protein involved in cytokinesis (Kamei et al., 1998; Lippincott and Li, 1998a; Vallen et al., 2000), suggest that Gic1 and Gic2 might regulate cytokinesis, particularly septum formation. In total, these interactions suggest that Gic1 and Gic2 have the potential to regulate microtubule polarity and to coordinate nuclear migration and division with cytokinesis (Pereira et al., 2000). Gic1 also interacts with Bem4, which is interesting because Bem4 also interacts with the septins Cdc11 and Cdc12 and with several GTPases, including Cdc42 (and Rsr1, see below), and is thought to have a role in GTPase localization or regulation (Hirano et al., 1996; Mack et al., 1996). It is tempting to speculate that these Bem4 interactions might target Cdc42 and other GTPases to the bud neck to regulate septation.



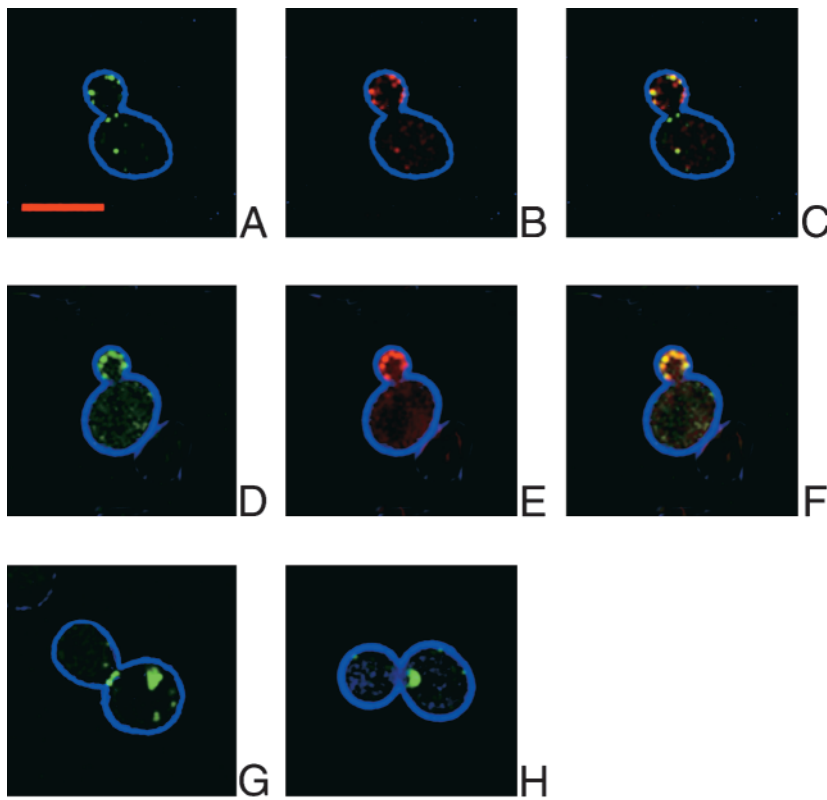


Figure 5. **Fluorescence micrographs of Ypr171w-YFP showing localization to actin cortical patches.** Cells were outlined by staining with Alexa fluor 633 conjugated to concanavalin A (blue). (A and D) Ypr171w-YFP (green); (B and E) Abp1-CFP (red); (C and F) merged image. (G and H) Ypr171w-YFP (G) and Abp1-CFP (H) in an *ark1 prk1* deletion strain. Bar, 5  $\mu$ m.

### Cdc42 regulators

The guanidine nucleotide exchange factor Cdc24 is required for activation of Cdc42 (Zheng et al., 1994). We found novel interactions between Cdc24 and several other proteins. One of the most interesting is Ygr221c, a protein of unknown function. Consistent with a function for Ygr221c as a positive GTPase regulator, the *ygr221c* null mutant is sensitive to a GDP analogue that inhibits G protein activation by GTP (Rieger et al., 1999). Ygr221c also interacted with the yeast protein kinase C (Pkc1), which functions downstream of the Rho1 GTPase. Therefore, Ygr221c may provide a regulatory connection between Rho1- and Cdc42-regulated pathways. In support of the *in vivo* relevance of these two-hybrid interactions, YFP-tagged Ygr221c localizes to sites of cell growth, including the nascent bud site, bud tips, and bud necks, similar to the pattern observed for Cdc42 (Table II and Fig. 4, E and F; S. Tcheperegine and E. Bi, personal communication). A homologue of Ygr221c, Yhr149c, was identified as a dosage suppressor of a *cdc42-118* polarized growth defect (M. Lau, S. Gadde, and K. Kozminski, personal communication). Like Ygr221c, Yhr149c localizes to sites of cell growth (Fig. 4, Q and R; S. Tcheperegine and E. Bi, personal communication). Yhr149c was used as a bait in a two-hybrid screen and found to interact with Zds1 and Zds2, suggesting that it may be involved in coordinating Rho1- and Cdc42-regulated pathways (see below).

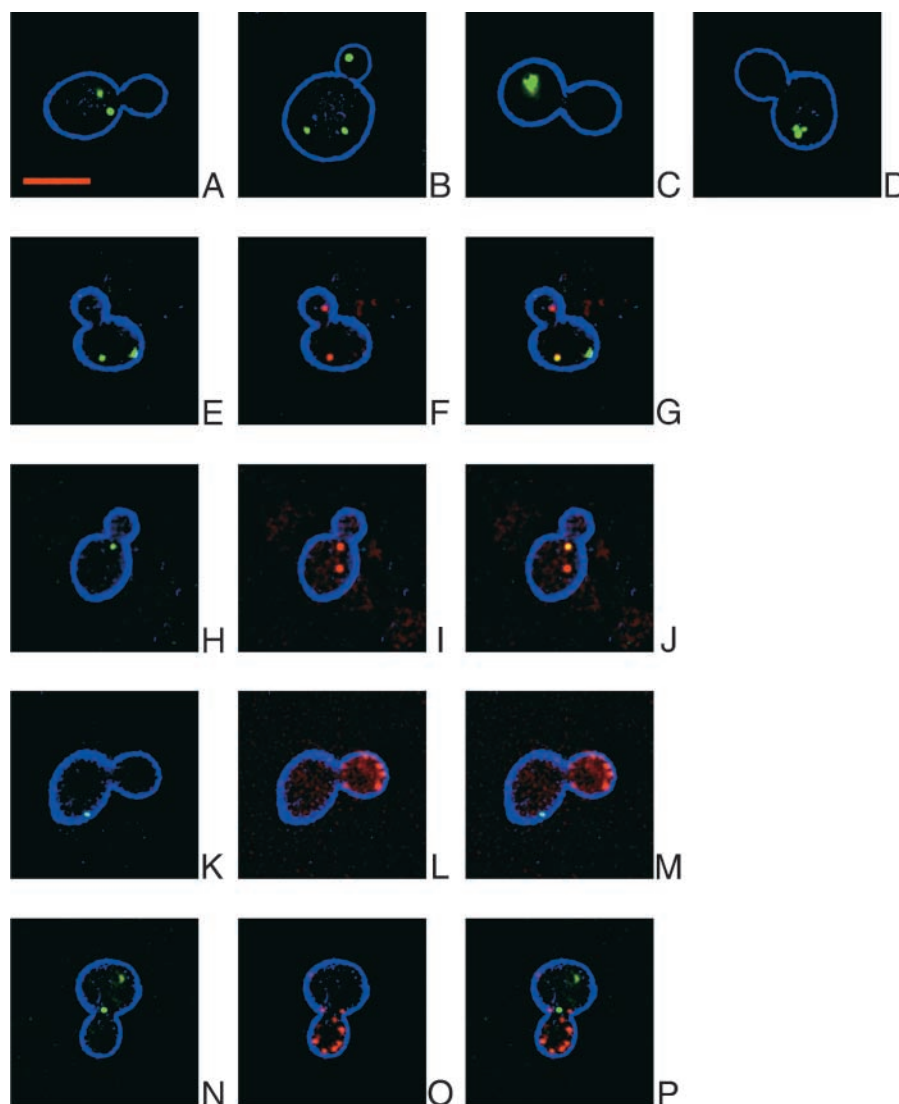
Cdc24 localizes to the nucleus during the G1 phase of the cell cycle (Toenjes et al., 1999; Nern and Arkowitz, 2000; Shimada et al., 2000). We detected interactions between Cdc24 and Yil079c. Yil079c was found recently to have a role in regulation of nuclear RNA processing and named Air1 (Inoue et al., 2000). YFP-tagged Yil079c localized to

the nucleolus (Fig. 4, G and H). This result is particularly intriguing in light of the fact that the human Cdc42 was recently found to stimulate RNA splicing (Wilson and Cerione, 2000; Wilson et al., 2000).

Cdc24 was also found to interact with the epsin Ent2 (Wendland et al., 1999). Ent2 and other epsins are clathrin-binding proteins that function during the internalization step of endocytosis (Chen et al., 1998). They are also essential for normal cortical actin patch assembly (Wendland et al., 1999; Tang et al., 2000). Cortical actin patch proteins are essential for the internalization step of endocytosis (Kübler and Riezman, 1993), and the cortical patches are concentrated proximal to sites of rapid exocytosis (Pruyne and Bretscher, 2000b). The interaction between Cdc24 and an epsin might target the endocytic pathway to bud tips, where it would be in proximity with the exocytic pathway. As each process retrieves components necessary for the other, both may be made more efficient by this proximity.

Zds1 and Zds2 are homologous proteins. The double mutant *zds1 zds2* has abnormally elongated buds, abnormal septin localization, and a cytokinesis defect (Bi and Pringle, 1996). Zds1 localizes to bud tips in small- and medium-budded cells. Based on genetic interactions, Zds1 and Zds2 seem to be negative regulators of the polarized growth and septation processes initiated by Cdc42 activation (Bi and Pringle, 1996). Two-hybrid interactions of Zds1 and Zds2 with the Cdc42 effectors Gic1, Gic2, and Cla4, and with other proteins that are likely to function downstream of these effectors (Table I and Figs. 1 and 2), provide support for a role in regulation of Cdc42-dependent pathways. Intriguingly, Zds2 also showed interactions with Rho1 and its downstream effectors Pkc1 and Bni1, suggesting either a mechanism to coordinate Cdc42 and Rho1

**Figure 6. Fluorescence micrographs of Yor284w-YFP showing the effect of actin depolarization (A–D), localization to the spindle pole body (E–J), and localization relative to the actin cytoskeleton (K–P).** Cells were outlined by staining with Alexa fluor 633 conjugated to concanavalin A (blue). (A and B) Yor284w-YFP; (C and D) Yor284w-YFP in an *ark1 prk1* deletion strain. (E and H) Yor284w-YFP (green); (F and I) Spc29-CFP (red); (G and J) merged image. (K and N) Yor284w-YFP (green); (L and O) Abp1-CFP (red); (M and P) merged image. Bar, 5  $\mu$ m.



pathways, or that Zds2 has distinct roles in the two pathways. Zds2 also interacts with the septin Cdc11, a sporulation-specific protein, Spr6 (Kallal et al., 1990), and three proteins of unknown function, Yer124c, Yal004w, and Yel023c.

Cell polarity develops in response to cortical cues. In budding yeast, cortical markers left by previous cell divisions result in recruitment and local activation of the Rsr1/Bud1 GTPase. Rsr1 is linked to Cdc42 via interaction with Cdc24 (Ruggieri et al., 1992; Bender, 1993; Zheng et al., 1995; Chant, 1999; Park et al., 1999) and via the scaffold protein Bem1, whose two-hybrid interactions are described in a subsequent paragraph. We detected a novel interaction between Rsr1 and Bem4, a protein mentioned above as interacting with Gic1 and the septins Cdc11 and Cdc12. Bem4 interacts with both the GTP- and GDP-bound forms of Rsr1 (Table I), as it does in its interactions with Rho-type GTPases (Hirano et al., 1996; Mack et al., 1996). As suggested above, Bem4 might bring multiple GTPases to the bud neck.

The activity of the Cdc28 cyclin-dependent kinase is required to recruit Cdc24 to the plasma membrane in G1 to coordinate cell polarity development with the nuclear division cycle (Jaquenod and Peter, 2000). We found that Bud2, the GTPase-activating protein that regulates Rsr1

(Bender, 1993; Park et al., 1993, 1999), interacts with the cyclin Cln2, which activates Cdc28 in G1. Bud2 might be a target of the Cln2-Cdc28 kinase to regulate polarity in G1. The observation that a *bud2 cln2* double mutant is a synthetic lethal provides support for this possibility (Benton et al., 1993; Cvrcková and Nasmyth, 1993).

Bem1 interacts with several proteins involved in Cdc42 activation and is thought to act as a scaffold for proteins involved in cell polarity development (Chant, 1999; Moskow et al., 2000). Here, Bem1 and Cdc24 were found to interact with Swe1. Swe1 is a protein kinase that phosphorylates and inhibits Cdc28 in a morphogenesis checkpoint response that monitors actin perturbation (McMillan et al., 1998) and septin assembly (Barral et al., 1999; McMillan et al., 1999; Shulewitz et al., 1999; Lew, 2000; Longtine et al., 2000). Interactions between Swe1, Bem1, and Cdc24 raise the possibility that Swe1 might also monitor assembly of the Bem1-Cdc24-Cdc42 complex at the bud site. Alternatively, these interactions may reflect a role suggested for Swe1 in adaptation to defects in polarity establishment (Weiss et al., 2000).

The Bem1 protein, via its two SH3 domains, interacts with Boi1 and Boi2 (Bender et al., 1996; Matsui et al., 1996). Boi1 and Boi2 are homologous proteins and they themselves con-

tain SH3 domains. We found that Bem1, Boi1, and Boi2 participate in several previously unreported protein–protein interactions. Both Boi1 and Boi2, as well as Zds2, showed interactions with Yer124c, an uncharacterized protein. Expression of Yer124c appears to be cell cycle regulated, with transcript levels peaking in G1 (Spellman et al., 1998). The protein contains a motif that is a potential SH3 domain ligand and which binds specifically to the Boi1 SH3 domain (unpublished data). The Boi1 bait was an activator, so that two-hybrid positives could not be easily detected, but several other new interacting partners were identified in the Boi2 screen. One of these is Msb1, which has been implicated genetically in Cdc42-regulated processes. *MSB1* is a multicopy suppressor of *cdc24*, *cdc42*, and *bem4* mutants (Bender and Pringle, 1989; Mack et al., 1996), and the *msb1* null mutant is synthetic lethal with a *bem1* null (Bender and Pringle, 1991).

### Connections between Cdc42-regulated pathways and the secretory pathway

Actin cables and a class V myosin are required for accumulation of secretory vesicles at the growing tips of yeast cells (Pruyne and Bretscher, 2000a,b). However, an unresolved question is how vesicle fusion at the plasma membrane is properly targeted. Therefore, it is noteworthy that Rsr1, Bem1, and Cdc24 were all found to interact with the exocyst component Sec15. The exocyst is a multiprotein complex thought to dock secretory vesicles at sites of polarized growth (Ter Bush and Novick, 1995; Ter Bush et al., 1996). An interaction between Sec15 and the activated Sec4 Rab GTPase induces formation of the exocyst complex and vesicle docking on the plasma membrane (Guo et al., 1999b). Recently, Rho1 was shown to interact with Sec3 and be required for localization of the exocyst to the bud tip (Guo et al., 2001). A connection between the exocyst and the GTPases that function during bud initiation may allow Rsr1-, Cdc42-, and Rho1-regulated processes to be coordinated with exocytosis to initiate bud growth. One or more of these GTPases might regulate exocyst assembly.

An additional link between the polarity-regulating Rho GTPases and exocytosis was suggested by the observation that Boi2 interacts with the yeast Rab escort protein Mrs6. Mrs6 is required for Sec4-dependent transport of secretory vesicles to the plasma membrane (Fujimura et al., 1994; Jiang and Ferro-Novick, 1994; Bauer et al., 1996; Alory and Balch, 2000). This interaction, like those between Sec15, Bem1, and Rsr1, suggests a link between regulators of bud initiation and the secretory apparatus. The possibility that Boi1 and Boi2 affect secretion is supported by the finding that the budding defect of a *boi1 boi2* double mutant is suppressed by overproduction of the Rho3 GTPase (Bender et al., 1996; Matsui et al., 1996). Rho3 specifically regulates vesicle transport and fusion during exocytosis (Adamo et al., 1999; Robinson et al., 1999).

### Rho1 effectors

The Rho1 GTPase is a major regulator of cell polarity and cell wall synthesis in *S. cerevisiae* (Yamochi et al., 1994; Drgonová et al., 1996; Kamada et al., 1996; Qadota et al., 1996). The GTP-bound form of Rho1 activates 1,3- $\beta$ -glucan synthase, which catalyzes the synthesis of the major structural

component of the cell wall, and Pkc1, which controls a mitogen-activated protein kinase cascade—regulating cell wall metabolism and actin polarity (Paravicini et al., 1992; Delley and Hall, 1999). We found that Rho1 interacts with Bem4, Rga1, Pkc1, and Bni1. The formin protein Bni1 is thought to be a cortical anchor that directs actin polarity and nuclear migration (Imamura et al., 1997; Fujiwara et al., 1998, 1999; Vallen et al., 2000), in part via an interaction with profilin (Pfy1). An interaction of Bni1 with Spa2 localizes Bni1 to the bud growth sites, where it mediates reorganization of the actin cytoskeleton and concentration of polarized growth to bud tips during apical growth (Fujiwara et al., 1998; Sheu et al., 2000). Bni1 is also connected to Cdc42 pathways (Evanangelista et al., 1997; Jaquenod and Peter, 2000).

New interactions for Rho1 and its associated proteins suggest possible roles in cell wall synthesis during sporulation, starvation-induced autophagy, and cytokinesis. A role for Rho1 in cell wall synthesis during sporulation was suggested previously by the finding that a *bem2* Rho1-GAP mutant has a sporulation defect due to loss of cell wall integrity (Cid et al., 1998). We found that Bem4 interacted with the sporulation-specific septin Spr28 (De Virgilio et al., 1996; Fares et al., 1996), as well as with the septins involved in vegetative growth. Rho1 also interacted with Shc1, a protein required for maintenance of cell wall integrity under osmotic stress (Hong et al., 1999). *SHC1* expression is upregulated during sporulation and it is involved in the chitin synthase III-dependent formation of the spore wall chitosan layer (Bulawa, 1993). Shc1 has homology to the Chs4 protein (Cid et al., 1995; Trilla et al., 1997), which stimulates chitin synthase III activity (Bulawa, 1993; DeMarini et al., 1997; Trilla et al., 1997). Rho1 also interacted with a novel protein, Yil007c, which may have a function in regulating cell wall synthesis and other processes during sporulation. When used as bait in two-hybrid screens, Yil007c interacted with Chs4 and with Pfs1, a protein required for sporulation (Deng and Saunders, 2001). Pfs1 is a homologue of the *S. pombe* protein tea1, which regulates polarized growth (Mata and Nurse, 1997) and contains kelch repeats, structures thought to mediate binding interactions with actin filaments (Mata and Nurse, 1997). Yil007c is homologous to a human proteasome regulatory subunit (Watanabe et al., 1998), but had not been implicated as functioning with the yeast proteasome (Russell et al., 1999). However, we found an interaction between Yil007c and the proteasome subunit Rpn4, supporting such a role and suggesting a novel function in cell wall synthesis regulation. A Yil007c-YFP fusion localized diffusely in the cytoplasm (data not shown).

Rho1 also interacted with Ylr423c/Apg17, a protein that was shown recently to regulate autophagy by interacting with and activating the Apg1 kinase (Kamada et al., 2000). Autophagy is a poorly understood starvation-induced process by which cytoplasm is surrounded by a double membrane which then fuses with the vacuole or lysosome. Autophagy is induced by downregulation of the phosphatidylinositol kinases Tor1 and Tor2 (Ohsumi, 1999; Kamada et al., 2000). The interaction between Rho1 and Apg17 suggests that autophagy may be regulated in part by Rho1. In addition to its role in regulation of protein synthesis, Tor2 has an essential function in cell cycle-depen-

dent organization of the actin cytoskeleton (Helliwell et al., 1998). Overexpression of *PKC1*, *RHO1*, or *ROM2*, a gene that encodes a Rho1 guanine nucleotide exchange factor, suppresses the actin organization defect of a *tor2* mutant. Perhaps Apg17 acts as an effector of Rho1 in a Tor2-dependent pathway that modulates cell polarity and autophagy.

Apg17 interacted with several proteins in addition to Rho1, including Rho2, Myo1, Nip100, Exo84, and Sro77, and it had been reported previously to make additional two hybrid interactions (Ito et al., 2001). Interactions with Exo84 and Sro77 suggest a connection to exocytosis. Exo84 is an exocyst component (Guo et al., 1999a), and Sro77 and its homologue Sro7 regulate vesicle docking and membrane fusion at the plasma membrane (Lehman et al., 1999). Interactions with Nip100 and Myo1 suggest that Apg17 may have a role in cytokinesis or that Myo1 and Nip100 have roles in autophagy. Nip100 is a yeast dynactin component involved in nuclear division and migration (Kahana et al., 1998; Fujiwara et al., 1999). Myo1 is a type II myosin that functions in the contractile ring (Bi et al., 1998; Lippincott and Li, 1998b). Sro77 and Sro7 have been found to form a complex with Myo1 (Kagami et al., 1998). The *Drosophila* homologue of Sro77 and Sro7, the *lethal(2) giant larvae* gene product, also interacts with myosins (Strand et al., 1994). During cytokinesis, targeted exocytosis at the site of cell division is coordinated with, and possibly guided by, contraction of the actinomyosin ring (Hales et al., 1999; Vallen et al., 2000). Perhaps a Myo1–Sro77 complex couples septum formation to contraction of the actomyosin ring, with Myo1 playing a specialized role in vesicle targeting to the bud neck (Schott et al., 1999). Interactions between Apg17 and Nip100, Myo1, Sro77, and Exo84 might be part of a mechanism coordinating nuclear migration, actomyosin ring contraction, and exocytosis during cytokinesis or autophagy (Kahana et al., 1998; Fujiwara et al., 1999; Hales et al., 1999). YFP-tagged Ylr423c/Apg17 localized in punctate patches in the cytoplasm (Fig. 4, I and J). Perhaps these patches play a role in autophagocytic vesicle formation.

### Connections between Rho1 and Cdc42 pathways

As discussed above, Ygr221c interacts with both Cdc24 and the Rho1 effector Pkc1. This interaction is quite interesting as a potential means for Pkc1 to regulate Cdc42 function and cell polarity. Cell wall stress induces hyperactivation of Rho1, which in turn results in a transient loss of actin polarity in order to depolarize cell wall synthesis and repair widespread cell wall damage (Delley and Hall, 1999). An undefined Pkc1-dependent pathway controls actin depolarization. Depolarization is dependent on Pkc1 but not on the Pkc1-activated mitogen-activated protein kinase cascade, which is necessary for repolarization. The interactions between Pkc1, Ygr221c, and Cdc24, together with the proposed function of Ygr221c as a GTPase regulatory protein (Rieger et al., 1999), suggest that Pkc1 could affect the actin cytoskeleton by inhibiting Cdc42 function through an interaction with Ygr221c. Zds1 and Zds2 might also monitor and regulate Cdc42 in response to Rho1. Zds2 interacts with both Rho1 and the Rho1 effectors Pkc1 and Bni1, as well as with several proteins in Cdc42-regulated pathways. Interestingly, when Yhr149c, the homologue

of the Cdc42-interacting protein Ygr221c, was used as bait in a two-hybrid screen, Zds1 and Zds2 were both found to interact with Yhr149c. These interactions suggest that Yhr149c may also be involved in coordinating Rho1- and Cdc42-regulated pathways.

### Actin cortical patch assembly, the morphogenesis checkpoint, and endocytosis

Actin cortical patches are one of the major cytoskeletal structures in yeast and are essential for normal endocytosis, cell growth, and morphology (Botstein et al., 1997; Pruyne and Bretscher, 2000b). Patches are associated with invaginations of the plasma membrane (Mulholland et al., 1994) and are found in polarized clusters at regions of cell growth in budding cells. Numerous cortical patch proteins have been identified. How these proteins function in patch assembly and endocytosis are largely unknown. Patch assembly probably begins with the association of assembly factors recruited to the plasma membrane by Cdc42-associated proteins, and is then followed by nucleation of actin filaments and actin-dependent association of proteins regulating filament assembly and stability (Ayscough et al., 1997; Botstein et al., 1997; Pruyne and Bretscher, 2000b). Our results confirm several interactions between patch proteins, identify new interactions, and suggest roles for several uncharacterized proteins in patch assembly or patch-mediated endocytosis (Fig. 3).

Sla2 (related to mammalian Hip1), Sla1, Las17/Bee1 (related to mammalian WASp/SCAR), Rvs167 (related to mammalian amphiphysin), and Abp1 (related to mammalian Abp1) all function in actin nucleation and assembly (Holtzman et al., 1993; Amberg et al., 1995; Li et al., 1995; Li, 1997; Lila and Drubin, 1997; Wesp et al., 1997; Ayscough et al., 1999; Balguerie et al., 1999; Yang et al., 1999; Goode et al., 2001). Las17/Bee1 and Abp1 both localize with and activate the Arp2/3 complex to nucleate actin filament assembly (Madania et al., 1999; Winter et al., 1999; Goode et al., 2001). Sla1, Rvs167 and Abp1 might share functions in actin cortical patch assembly because they interact with overlapping sets of proteins and show synthetic-lethal genetic interactions (Holtzman et al., 1993; Lila and Drubin, 1997). The actin monomer binding adenylate cyclase regulatory subunit Srv2 can, for example, apparently interact with all three proteins to mediate the association of monomeric actin with the actin-nucleating complex (Freeman et al., 1996; Lila and Drubin, 1997).

Sla1, Rvs167, and Abp1 contain SH3 domains that are important for their function (Lila and Drubin, 1997; Ayscough et al., 1999), and several of the proteins with which they interact contain proline-rich regions that are potential SH3 domain binding sites. Sla1 and Rvs167 both showed interactions with Las17/Bee1 (Li, 1997) and Ysc84 (Madania et al., 1999). Ysc84 itself contains an SH3 domain that might make other protein contacts. Two proteins of unknown function, Ygr268c and Ypr171w, also interacted with Sla1 and Rvs167. As noted in Fig. 3, Ygr268c and Ypr171w contain proline-rich motifs that are potential SH3 domain binding sites. Ypr171w also interacted with Cap1, the  $\alpha$  subunit of the yeast actin filament capping protein, which regulates the growth of actin filaments (Amatruda and Cooper, 1992; Amatruda et al., 1992). Thus, Ypr171w



may function as a link between actin-nucleating complexes and the actin-capping protein, perhaps coordinating the nucleation and elongation of actin filaments. YFP-tagged Ypr171w was observed at growth sites in the bud in a punctate pattern and at the bud neck of large-budded cells (Fig. 4, K and L). Coexpression of Ypr171w-YFP with CFP-tagged Abp1, an actin cortical patch component, demonstrated that Ypr171w colocalizes with some, but perhaps not all, Abp1-containing actin cortical patches (Fig. 5, A–F). The punctate localization pattern is, like that of Abp1, disturbed in the *ark1 prk1* double deletion strain (Fig. 5, G and H), which has abnormal actin clumps (Cope et al., 1999). However, Ypr171w localization to the bud neck is still seen in the *ark1 prk1* mutant (Fig. 5 G). A Ygr268c-YFP fusion localized diffusely in the cytoplasm (data not shown).

Another uncharacterized protein, Yor284w, interacted with cortical patch components Sla2, Rvs167, and Abp1. Sla2 localizes to sites of polarized growth independently of actin (Ayscough et al., 1997) and mediates an early step in the polarization of actin cortical patches (Yang et al., 1999). Rvs167 also affects patch polarization (Balguerie et al., 1999), perhaps via the interaction observed here with Sla2. Colocalization of Sla2 with actin is most visible in unbudded and small-budded cells, implying that its patch assembly activity is most important early in the cell cycle (Yang et al., 1999). Expression of Yor284w peaks in the G1 phase of the cell cycle (Spellman et al., 1998), supporting the idea that it plays a role in this process. The Yor284w-YFP fusion localized to a few distinct, mobile punctate structures in the cell (Figs. 4, M and N and 6, A and B). In many cases these dots were observed moving rapidly around the cell periphery. The relationship of these structures to cortical patches is unclear. Yor284w appears in a stationary, diffuse cytoplasmic clump in the *ark1 prk1* double deletion strain (Fig. 6, C and D), suggesting that its localization is dependent on actin polarization. However, coexpression of Yor284w-YFP with CFP-tagged Spc29 spindle pole body protein (Fig. 6, E–J) and CFP-tagged Abp1 (Fig. 6, K–P) showed that the Yor284w-containing dots do not localize to cortical patches, but that a subset of them colocalize with the spindle pole body.

Four other proteins that interact with Rvs167 contain proline-rich potential SH3 domain binding sites. One is Acf2, a protein implicated in cortical actin assembly (Lechler and Li, 1997), whereas the others, Ybr108w, Yjr083c, and Ynl094w, are proteins of unknown function. Ybr108w has been found to interact with both Rvs167 and Rvs161 (Bon et al., 2000), a protein that forms a complex with Rvs167 (Navarro et al., 1997). A Yjr083c-YFP fusion localized diffusely in the cytoplasm (data not shown).

Ynl094w showed interactions with five cortical patch proteins. It interacted with Sla2 and with three SH3 domain proteins involved in actin nucleation, Sla1, Rvs167, and Abp1. Ynl094w also interacted with the actin-bundling protein Crn1 (Goode et al., 1999) and with Sro77, a protein which functions in polarized secretion (Kagami et al., 1998; Lehman et al., 1999). These interactions suggest that Ynl094w may link actin nucleation to exocytosis. Other interactions suggest that Ynl094w might function in the morphogenesis checkpoint response. Because this response is poorly understood, two-hybrid interactions involving the

checkpoint proteins might provide important insights into the mechanisms for monitoring the cytoskeleton. Ynl094w interacted with two proteins involved in regulation of the morphogenesis checkpoint, Swe1 and Hsl7 (Shulewitz et al., 1999). In addition to monitoring the actin cytoskeleton (McMillan et al., 1998; Lew, 2000), Swe1 may monitor septin organization via an interaction with Hsl7 and Hsl1 at the bud neck (Barral et al., 1999; McMillan et al., 1999; Shulewitz et al., 1999; Lew, 2000; Longtine et al., 2000). The fact that Ynl094w showed interactions with Swe1 and Hsl7 and with five cortical patch proteins suggests that Swe1 and Hsl7 might monitor actin assembly via an interaction with Ynl094w. Ynl094w has been found to localize to actin cortical patches (L. Tseng, M. Schulewitz, and J. Thorner, personal communication).

### Interactions of the secretory apparatus

Polarized growth and budding require the delivery of proteins and lipids to specific sites on the plasma membrane. Under cell cycle control, exocytosis first becomes localized to regions of cell growth at the presumptive bud site. As a bud emerges, exocytosis initially localizes to a small region at the bud tip, then becomes delocalized in the bud, and finally it becomes localized to the bud neck, mirroring cortical actin cytoskeleton organization at each stage (Pruyne and Bretscher, 2000b). The mechanisms that insure this continual coordination between the exocytic machinery and the actin cytoskeleton have yet to be fully elucidated. The Rho3 GTPase interacts with elements of the exocytic machinery to control transport of secretory vesicles and vesicle docking and fusion at the plasma membrane. Vesicle transport is dependent on function of the class V myosin Myo2 (Schott et al., 1999). Vesicle fusion occurs through an interaction with Exo70 (Adamo et al., 1999; Robinson et al., 1999), a component of the exocyst complex. Rho3 can also affect organization of the actin cytoskeleton (Imai et al., 1996). We found that Rho3 interacts with three subunits of casein kinase II. This observation is interesting because one function of casein kinase II is to maintain actin cytoskeleton polarity (Rethinaswamy et al., 1998). Our results suggest that casein kinase II might therefore function as an effector of Rho3 to regulate actin cytoskeleton organization, and that Rho3 might coordinate secretory and actin cytoskeletal organization.

The vesicle-docking protein Sro77, homologous to the *Drosophila* protein *lethal(2) giant larvae* gene product, showed numerous interactions implicating this protein in regulatory, cytoskeletal, and endocytic roles (Table I). As mentioned above, Sro77 showed interactions with Apg17 and Nip100. It also showed interactions with the epsin Ent2 and with Yap1801, both clathrin-binding proteins that function during the internalization step of endocytosis (Chen et al., 1998; Wendland and Emr, 1998; Wendland et al., 1999). Sro77 and the related protein Sro7 might therefore also function in the early steps of endocytosis, or they may coordinate endocytosis and exocytosis. The v-SNAREs Snc1 and Snc2 appear to be involved in both exocytic and endocytic transport at the plasma membrane. Snc1 and Snc2 can interact with endosomal t-SNAREs and *snc* mutants are defective in endocytosis as well as exocytosis (Gurunathan et al., 2000). Perhaps the plasma membrane t-SNAREs and

their regulators, such as Sro7/Sro77, are also able to participate in both processes. Similarly, an interaction we observed between Sro77 and Yip1, which recruits the Ypt1 and Ypt31 transport GTPases to the Golgi apparatus, suggests similar possible relationships between proteins involved in early and late steps of exocytosis and/or endocytosis.

Sro77 also showed an interaction with Bcy1, the regulatory subunit of cAMP-dependent protein kinases (Cannon et al., 1990). In epithelial cells, exocytosis is stimulated by the cAMP-dependent protein kinase PKA (Takuma, 1990; Koh et al., 2000), which appears to regulate SNARE complex formation (Foster et al., 1998). Perhaps SNARE assembly in *S. cerevisiae* is also regulated in response to cAMP-dependent protein kinase activity.

Further Sro77 interactions were observed with several uncharacterized proteins, including Ynl094w, which may be a link between the secretory apparatus and actin organization (see above), and Kin3, a protein kinase of unknown function.

Sso1 and Sso2 are syntaxin homologue t-SNAREs that mediate vesicle targeting to the plasma membrane during exocytosis (Aalto et al., 1993). Sso2 interacted with Apg7, a regulator of autophagy, revealing another possible connection between exocytic and autophagocytic processes. Apg7 has homology to the E1 family of ubiquitin-activating enzymes and mediates a novel protein conjugation reaction required for autophagy (Mizushima et al., 1998; Kim et al., 1999; Tanida et al., 1999). Perhaps Apg7-mediated modification of plasma membrane t-SNAREs recruits them for formation of autophagocytic vesicles or for processes related to exocytosis.

*MSB3* and *MSB4* are multicopy suppressors of bud emergence mutations and appear to link Cdc42 to the actin cytoskeleton (Bach et al., 2000; Bi et al., 2000). Surprisingly, Msb3 and Msb4 were also found to have GAP activity towards the Rab GTPases Sec4 and Ypt6, respectively (Albert and Gallwitz, 1999, 2000). Therefore, Msb3 and Msb4 may have roles in exocytosis. Sec4 is required for formation of the exocyst complex and for vesicle docking at the plasma membrane (Walworth et al., 1992; Guo et al., 1999b), whereas Ypt6 is required for vesicle transport from the endoplasmic reticulum to the Golgi apparatus (Lupashin et al., 1996). In our screens, both Msb3 and Msb4 interacted with Spa2, a protein that concentrates polarized growth to bud and mating projection tips during apical growth, and to the septum during cytokinesis (Fujiwara et al., 1998; Sheu et al., 2000). Sec4 is partially delocalized in *spa2* mutants (Sheu et al., 2000), and Spa2 is required for normal localization of secretory vesicles to the cell fusion zone during mating (Gammie et al., 1998). These genetic observations and the interactions with Msb3 and Msb4 provide support for a role for Spa2 in polarized exocytosis.

## Conclusions

We have reported here the results of a two-hybrid study of proteins involved in cell polarity development, a highly complex process involving cortical cues, signaling proteins, the cytoskeleton, and the secretory apparatus, each of which is itself characterized by considerable complexity. Elucidation of the mechanisms that underlie cell polarity development is a daunting task, due to the vast number of proteins involved. The result of our studies is a protein interaction map that helps define the scope of the problem of under-

standing cell polarity development and can be used to guide further genetic and biochemical studies. Because most of the proteins and processes included in this study are highly conserved, this map should prove useful for studies of polarity development in diverse cell types. Among interactions identified in this map are some that implicate new proteins in polarity development, and others that suggest modes for coordinating distinct processes involved in polarity development. Our localization of previously uncharacterized proteins implicated here in polarity development is only the first step in verification of the biological relevance of each interaction. Future studies must address when, where, and why each interaction occurs and how these interactions are regulated. Despite years of genetic analysis of cell polarity development in budding yeast, we were able to implicate uncharacterized proteins in this process, and to suggest novel functions for proteins studied previously. Genetic studies may have missed much of this information, due to factors including redundancy, lack of appropriate alleles, homeostasis mechanisms, and checkpoints that mask the underlying mutant defect by arresting a process before an informative phenotype develops. In total, the large number of interactions that we identified among proteins involved in diverse aspects of cell polarity development suggests a high level of integration in the functioning of these proteins.

## Materials and methods

### Generation of DNA binding domain hybrids

Transformants containing Gal4 DNA binding domain hybrids were constructed in the  $\alpha$  mating type of the yeast strain PJ694 (*MAT $\alpha$  trp1-901 leu2-3,112 ura3-52 his3-200 gal4 $\Delta$  gal80 $\Delta$  LYS2::GAL1-HIS3 GAL2-ADE2 met2::GAL7-lacZ*) (James et al., 1996) as described (McCraith et al., 2000; Uetz et al., 2000). Recombination (Ma et al., 1987) of the linearized vector pOBD2 (McCraith et al., 2000) with PCR fragments corresponding to each of the yeast ORFs was used to generate the hybrids (Hudson et al., 1997). Transformation was carried out using the lithium acetate procedure (Ito et al., 1983). After transformation, cells were plated on synthetic trp media. Yeast media were prepared as described (Sherman et al., 1986). Cdc3, Cdc11, Cdc12, and Bud8 baits were made in the vector pGDBU and transformants selected on ura media (James et al., 1996).

Several GTPase baits contained cysteine-to-serine amino acid substitutions to prevent prenylation and facilitate nuclear entry, and other substitutions that affect GTP binding and hydrolysis to favor either the GTP- or GDP-bound form: Rho1-GTP (Q68H, C206S), Rho2-GTP (Q 65H, C188S), Rho3-GTP (G25V, C228S), Rho4-GTP (Q70H, C228S), Cdc42-GTP (G12V, C188S), Cdc42-GDP (D57Y, C188S), Rsr1-GTP (G12V), and Rsr1-GDP (K16N). Gic1 and Gic2 fusions were truncations lacking 30 residues at the COOH terminus because the full-length protein was an activator. The Sso1(1–515), Sso2(1–266), and fusions were truncations that removed predicted transmembrane domains at their COOH termini. The Msb2 fusion contained a truncation, Msb2(1186–1306) that removed predicted transmembrane domains at the NH<sub>2</sub> and COOH termini. The Bud8 and Bud9 fusions also contained truncations, Bud8(534–578) and Bud9(480–521), that removed predicted transmembrane domains.

### Two-hybrid screens

Screens of the yeast ORF activation domain fusion array were performed in a manner similar to that described previously (McCraith et al., 2000; Uetz et al., 2000). This array was expressed in the  $\alpha$  mating type of strain PJ694 (*MAT $\alpha$  trp1-901 leu2-3,112 ura3-52 his3-200 gal4 $\Delta$  gal80 $\Delta$  LYS2::GAL1-HIS3 GAL2-ADE2 met2::GAL7-lacZ*) (James et al., 1996). To screen for protein-protein interactions, we mated a transformant containing one of the DNA binding domain hybrids to all of the transformants of the array, selecting diploids using markers carried on the two-hybrid plasmids. The diploids were then transferred to selective plates deficient in histidine, and colonies positive for the two-hybrid reporter *HIS3* gene were identified by their positions in the array.

Two-hybrid screens can generate significant numbers of false positives that are not reproducible in duplicate screens. Random generation of histidine-positive colonies can result from overexpression of a fusion protein that affects transcription or cell metabolism, rearrangements or deletions of the DNA-binding domain plasmid, recombinational events between plasmids, or genomic rearrangements of the host strain. To identify reproducible two-hybrid interactions rapidly, we duplicated the array so that each ORF-Gal4 activation domain fusion is represented twice on a microassay plate. The entire array is contained in duplicate on 16 microassay plates of 768 colonies each. Only protein combinations that resulted in histidine prototrophy for both duplicate colonies of a given activation domain fusion were scored as two-hybrid interactions. We estimate that 10–20% of the yeast ORF-Gal4 activation domain fusions are not expressed due to errors in the PCR amplification of the ORFs. In addition, there are likely to be other constructs that are expressed poorly or in a nonfunctional form due to improper folding.

All pinning steps were carried out using a Biomek 2000 robot (Beckman Coulter) and a 768-pin replicating tool (UW Scientific Instruments, Machine/Optical Division). Strains containing the Gal4-DNA binding-domain hybrids were first tested on plates of synthetic his media with different concentrations of 3-aminotriazole to determine the level of stringency needed to eliminate background activation of the *HIS3* reporter gene. Strains were grown overnight at 30°C in 25 ml of trp synthetic medium, centrifuged at 1,000 rpm for 2 min and resuspended in 5–7 ml of medium. The cell suspension was transferred to 16 plates of solid YEPD medium. The yeast ORF activation domain fusion array was then replica-pinned onto the plates. Plates were incubated at 30°C for 2–4 d to allow mating, and then cells were replica-pinned to synthetic trp leu medium. After 2–4 d, cells were replica-pinned onto his synthetic media containing the appropriate concentration of 3-aminotriazole. Plates were incubated at 30°C for 7–10 d and then scored for two-hybrid positives.

### Generation of ORFs tagged with CFP or YFP

A PCR-based method was used to integrate a gene encoding either YFP or CFP at the 3' end of the targeted yeast ORF such that each fusion protein is expressed under the control of its native promoter (Wach et al., 1997). Detailed protocols are described at [http://depts.washington.edu/~yeastrc/fm\\_home3.htm](http://depts.washington.edu/~yeastrc/fm_home3.htm). The template for integration of YFP was the plasmid pDH6, which contains the YFP ORF followed by the *kan<sup>r</sup>* gene. pDH6 was made by replacing the *Ava*I–*Asc*I fragment encoding GFP in pFA6a-GFP(S65T)KanMX6 (Wach et al., 1997) with the *Ava*I–*Asc*I fragment encoding YFP from pDH5. pDH5 was derived from pFA6a-GFP(S65T)HIS3MX6 by site-directed mutagenesis using the QuikChange method as described by the supplier (Stratagene). The mutations in YFP as compared with the original GFP are: S65G, V68L, Q69K, S72A, Q80R, and T203Y. The template for integration of CFP was plasmid pDH3, which contains the CFP ORF followed by the *kan<sup>r</sup>* gene. pDH3 was derived from pFA6a-GFP(S65T)KanMX6 by site-directed mutagenesis using the QuikChange method. The mutations in CFP as compared with the original GFP are: F64L, S65T, Y66W, Q80R, N146I, M153T, V163A, and N164H. Integrations were checked by PCR.

### Fluorescence microscopy

Cells containing YFP or CFP fusion proteins were grown on solid YPD medium overnight at 30°C and then resuspended in PBS containing 1.3 µg/ml concanavalin A tagged with Alexa 633 (Molecular Probes) and incubated for 30 min at 30°C. Cells were washed twice with PBS and resuspended in S medium or SD complete medium (1.7 g/liter Difco yeast nitrogen base without amino acids or ammonium sulfate, 5 g/liter ammonium sulfate, 0.1% casamino acids, 25 µg/ml uracil, 50 µg/ml adenine, 100 µg/ml tryptophan, 2% glucose). Cells were mounted in one of two ways. An aliquot of cells (3 µl) was mixed on the slide with an equal volume of SD complete medium containing 1.2% SeaPlaque low melting temperature agarose (FMC BioProducts) at 40°C. A coverslip (No. 1.5) was quickly added and pressed firmly. Alternatively, a cushion of 1.2% SeaKem LE agarose (FMC BioProducts) in SD complete medium was poured into 0.5-mm concavity slides (PGC Scientific) and pressed flat with another slide. Once the agar was solidified, an aliquot (15 µl) of cells was pipetted onto the cushion and covered with a coverslip (No. 1.5). The latter method is preferable for examination of actin cytoskeletal components.

Fluorescence microscopy was performed on a DeltaVision microscope with a Photometrics Quantix camera. The filter sets were from Omega. The images were sharpened by two dimensional deconvolution using the SoftWorX software (Applied Precision, Inc.).

To localize Yhr149c, the COOH terminus was tagged with a 13Myc epitope using the PCR-based method of Longtine et al. (1998) in the strain

DDY1102 (MATa/MATα ade2-1/ADE2 his3Δ200/his3Δ200 leu2-3,112/leu2-3,112 ura3-52/ura3-52 LYS2/lys2-801) (Kozminski et al., 2000). Log phase cells were processed for indirect immunofluorescence microscopy and images were acquired as described by Kozminski et al. (2000). Mouse anti-Myc antibody (9E10; Santa Cruz Biotechnology, Inc.) and FITC-conjugated donkey anti-mouse antibody (Jackson ImmunoResearch Laboratories) were diluted 1:50 and 1:100, respectively.

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## References

- Aalto, M.K., H. Ronne, and S. Keranen. 1993. Yeast syntaxins Sso1p and Sso2p belong to a family of related membrane proteins that function in vesicular transport. *EMBO J.* 12:4095–4104.
- Adamo, J.E., G. Rossi, and P. Brennwald. 1999. The Rho GTPase Rho3 has a direct role in exocytosis that is distinct from its role in actin polarity. *Mol. Biol. Cell.* 10:4121–4133.
- Adams, A.E.M., D.I. Johnson, R.M. Longnecker, B.F. Sloat, and J.R. Pringle. 1990. *CDC42* and *CDC43*, two additional genes involved in budding and the establishment of cell polarity in the yeast *Saccharomyces cerevisiae*. *J. Cell Biol.* 111:131–142.
- Albert, S., and D. Gallwitz. 1999. Two new members of a family of Ypt/Rab GTPase activating proteins. Promiscuity of substrate recognition. *J. Biol. Chem.* 274:33186–33189.
- Albert, S., and D. Gallwitz. 2000. Msb4p, a protein involved in Cdc42p-dependent organization of the actin cytoskeleton, is a Ypt/Rab-specific GAP. *Biol. Chem.* 381:453–456.
- Alory, C., and W.E. Balch. 2000. Molecular basis for Rab prenylation. *J. Cell Biol.* 150:89–103.
- Amatruda, J.F., and J.A. Cooper. 1992. Purification, characterization, and immunofluorescence localization of *Saccharomyces cerevisiae* capping protein. *J. Cell Biol.* 117:1067–1076.
- Amatruda, J.F., D.J. Gattermeir, T.S. Karpova, and J.A. Cooper. 1992. Effects of null mutations and overexpression of capping protein on morphogenesis, actin distribution and polarized secretion in yeast. *J. Cell Biol.* 119:1151–1162.
- Amberg, D.C., E. Basart, and D. Botstein. 1995. Defining protein interactions with yeast actin in vivo. *Nat. Struct. Biol.* 2:28–35.
- Ayscough, K.R., J. Stryker, N. Pokala, M. Sanders, P. Crews, and D.G. Drubin. 1997. High rates of actin filament turnover in budding yeast and roles for actin in establishment and maintenance of cell polarity revealed using the actin inhibitor latrunculin-A. *J. Cell Biol.* 137:399–416.
- Ayscough, K.R., J.J. Eby, T. Lila, H. Dewar, K.G. Kozminski, and D.G. Drubin. 1999. Sla1p is a functionally modular component of the yeast cortical actin cytoskeleton required for correct localization of both Rho1p-GTPase and Sla2p, a protein with talin homology. *Mol. Biol. Cell.* 10:1061–1075.
- Bach, S., O. Bouchat, D. Portetelle, and M. Vandenbol. 2000. Co-deletion of the *MSB3* and *MSB4* coding regions affects bipolar budding and perturbs the organization of the actin cytoskeleton. *Yeast.* 16:1015–1023.
- Balguerie, A., P. Sivadon, M. Bonneau, and M. Aigle. 1999. Rvs167p, the budding yeast homolog of amphiphysin, colocalizes with actin patches. *J. Cell Sci.* 112:2529–2537.



- Barral, Y., M. Parra, S. Bidlingmaier, and M. Snyder. 1999. Nim1-related kinases coordinate cell cycle progression with the organization of the peripheral cytoskeleton in yeast. *Genes Dev.* 13:176–187.
- Bauer, B.E., S. Lorenzetti, M. Miaczynska, D.M. Bui, R.J. Schweyen, and A. Ragini. 1996. Amino- and carboxy-terminal domains of the yeast Rab escort protein are both required for binding of Ypt small G proteins. *Mol. Biol. Cell.* 7:1521–1533.
- Bender, A. 1993. Genetic evidence for the roles of the bud-site-selection genes *BUD5* and *BUD2* in control of the Rsr1p (Bud1p) GTPase in yeast. *Proc. Natl. Acad. Sci. USA.* 90:9926–9929.
- Bender, A., and J.R. Pringle. 1989. Multicopy suppression of the *cdc24* budding defect in yeast by *CDC42* and three newly identified genes including the *ras*-related gene *RSR1*. *Proc. Natl. Acad. Sci. USA.* 86:9976–9980.
- Bender, A., and J.R. Pringle. 1991. Use of a screen for synthetic lethal and multicopy suppressor mutants to identify two new genes involved in morphogenesis in *Saccharomyces cerevisiae*. *Mol. Cell. Biol.* 11:1295–1305.
- Bender, A., and J.R. Pringle. 1992. A Ser/Thr-rich multicopy suppressor of a *cdc24* bud emergence defect. *Yeast.* 8:315–323.
- Bender, L., H.S. Lo, H. Lee, V. Kokojan, J. Peterson, and A. Bender. 1996. Associations among PH and SH3 domain-containing proteins and Rho-type GTPases in yeast. *J. Cell Biol.* 133:879–894.
- Benton, B.K., A.H. Tinklenberg, D. Jean, S.D. Plump, and F.R. Cross. 1993. Genetic analysis of Cln/Cdc28 regulation of cell morphogenesis in budding yeast. *EMBO J.* 12:5267–5275.
- Benton, B.K., A. Tinklenberg, I. Gonzalez, and F.R. Cross. 1997. Cla4p, a *Saccharomyces cerevisiae* Cdc42p-activated kinase involved in cytokinesis, is activated at mitosis. *Mol. Cell. Biol.* 17:5067–5076.
- Bi, E., and J.R. Pringle. 1996. *ZDS1* and *ZDS2*, genes whose products may regulate Cdc42p in *Saccharomyces cerevisiae*. *Mol. Cell. Biol.* 16:5264–5275.
- Bi, E., P. Maddox, D.J. Lew, E.D. Salmon, J.N. McMillan, E. Yeh, and J.R. Pringle. 1998. Involvement of an actomyosin contractile ring in *Saccharomyces cerevisiae* cytokinesis. *J. Cell Biol.* 142:1301–1312.
- Bi, E., J.B. Chiavetta, H. Chen, G.-C. Chen, C.S.M. Chan, and J.R. Pringle. 2000. Identification of novel, evolutionarily conserved Cdc42p-interacting proteins and of redundant pathways linking Cdc24p and Cdc42p to actin polarization in yeast. *Mol. Biol. Cell.* 11:773–793.
- Bon, E., P. Recordon-Navarro, P. Durrens, M. Iwase, A. Toh-e, and M. Aigle. 2000. A network of proteins around Rvs167p and Rvs161p, two proteins related to the yeast actin cytoskeleton. *Yeast.* 16:1229–1241.
- Botstein, D., D. Amberg, J. Mulholland, T. Huffaker, A. Adams, D. Drubin, and T. Stearns. 1997. The yeast cytoskeleton. In *The Molecular and Cellular Biology of the Yeast Saccharomyces: Cell Cycle and Cell Biology*. J.R. Pringle, J.R. Broach, and E.W. Jones, editors. Cold Spring Harbor Laboratory Press, Cold Spring Harbor, NY. 1–90.
- Brewster, J.L., and M.C. Gustin. 1994. Positioning of cell growth and division after osmotic stress requires a MAP kinase pathway. *Yeast.* 10:425–439.
- Brown, J.L., M. Jaquenoud, M.-P. Gulli, J. Chant, and M. Peter. 1997. Novel Cdc42-binding proteins Gic1 and Gic2 control cell polarity in yeast. *Genes Dev.* 11:2972–2982.
- Bulawa, C.E. 1993. Genetics and molecular biology of chitin synthesis in fungi. *Annu. Rev. Microbiol.* 47:505–534.
- Butty, A.-C., P.M. Pryciak, L.S. Huang, I. Herskowitz, and M. Peter. 1998. The role of Far1p in linking the heterotrimeric G protein to polarity establishment proteins during yeast mating. *Science.* 282:1511–1516.
- Cannon, J.F., R. Gitan, and K. Tatchell. 1990. Yeast cAMP-dependent protein kinase regulatory subunit mutations display a variety of phenotypes. *J. Biol. Chem.* 265:11897–11904.
- Chant, J. 1999. Cell polarity in yeast. *Annu. Rev. Cell Dev. Biol.* 15:365–391.
- Chen, G.-C., Y.-J. Kim, and C.S.M. Chan. 1997. The Cdc42 GTPase-associated proteins Gic1 and Gic2 are required for polarized growth in *Saccharomyces cerevisiae*. *Genes Dev.* 11:2958–2971.
- Chen, H., S. Fre, V. Slepnev, M. Capua, K. Takei, M. Butler, P. Di Fiore, and P. De Camilli. 1998. Epsin is an EH-domain-binding protein implicated in clathrin-mediated endocytosis. *Nature.* 394:793–797.
- Cid, V.J., A. Durán, F. del Rey, M.P. Snyder, C. Nombela, and M. Sánchez. 1995. Molecular basis of cell integrity and morphogenesis in *Saccharomyces cerevisiae*. *Microbiol. Rev.* 59:345–386.
- Cid, V.J., R. Cenamor, M. Sánchez, and C. Nombela. 1998. A mutation in the Rho1-GAP-encoding gene *BEM2* of *Saccharomyces cerevisiae* affects morphogenesis and cell wall functionality. *Microbiology.* 144:25–36.
- Cope, M.J.T.V., S. Yang, C. Shang, and D.G. Drubin. 1999. Novel protein kinases Ark1p and Prk1p associate with and regulate the cortical actin cytoskeleton in budding yeast. *J. Cell Biol.* 144:1203–1218.
- Cullen, P.J., J. Schultz, J. Horecka, B.J. Stevenson, Y. Jigami, and G.F. Sprague, Jr. 2000. Defects in protein glycosylation cause *SHO1*-dependent activation of a *STE12* signaling pathway in yeast. *Genetics.* 155:1005–1018.
- Cvrcková, F., and K. Nasmyth. 1993. Yeast G1 cyclins CLN1 and CLN2 and a GAP-like protein have a role in bud formation. *EMBO J.* 12:5277–5286.
- Cvrcková, F., C. De Virgilio, E. Manser, J.R. Pringle, and K. Nasmyth. 1995. Ste20-like protein kinases are required for normal localization of cell growth and for cytokinesis in budding yeast. *Genes Dev.* 9:1817–1830.
- De Virgilio, C., D.J. DeMarini, and J.R. Pringle. 1996. *SPR28*, a sixth member of the septin gene family in *Saccharomyces cerevisiae* that is expressed specifically in sporulating cells. *Microbiology.* 142:2897–2905.
- Delley, P.-A., and M.N. Hall. 1999. Cell wall stress depolarizes cell growth via hyperactivation of RHO1. *J. Cell Biol.* 147:163–174.
- DeMarini, D.J., A.E.M. Adams, H. Fares, C. De Virgilio, G. Valle, J.S. Chuang, and J.R. Pringle. 1997. A septin-based hierarchy of proteins required for localized deposition of chitin in the *Saccharomyces cerevisiae* cell wall. *J. Cell Biol.* 139:75–93.
- Deng, C., and W. Saunders. 2001. *PFS1*, a novel gene required for prospore membrane formation at selected spindle poles in *Saccharomyces cerevisiae*. *Mol. Biol. Cell.* In press.
- Drgonová, J., T. Drgon, K. Tanaka, R. Kollár, G.-C. Chen, R.A. Ford, C.S.M. Chan, Y. Takai, and E. Cabib. 1996. Rho1p, a yeast protein at the interface between cell polarization and morphogenesis. *Science.* 272:277–279.
- Drubin, D.G., editor. 2000. *Cell Polarity*. Oxford University Press, Oxford. 313 pp.
- Drubin, D.G., and W.J. Nelson. 1996. Origins of cell polarity. *Cell.* 84:335–344.
- Eby, J.J., S.P. Holly, F. van Drogen, A.V. Grishin, M. Peter, D.G. Drubin, and K.J. Blumer. 1998. Actin cytoskeleton organization regulated by the PAK family of protein kinases. *Curr. Biol.* 8:967–970.
- Engqvist-Goldstein, Å.E., M.M. Kessels, V.S. Chopra, M.R. Hayden, and D.G. Drubin. 1999. An actin-binding protein of the Sla2/huntingtin interacting protein 1 family is a novel component of clathrin-coated pits and vesicles. *J. Cell Biol.* 147:1503–1518.
- Evangelista, M., K. Blundell, M.S. Longtine, C.J. Chow, N. Adames, J.R. Pringle, M. Peter, and C. Boone. 1997. Bni1p, a yeast formin linking Cdc42p and the actin cytoskeleton during polarized morphogenesis. *Science.* 276:118–122.
- Evangelista, M., B.M. Klebl, A.H.Y. Tong, B.A. Webb, T. Leeuw, E. Leberer, M. Whiteway, D.Y. Thomas, and C. Boone. 2000. A role for myosin-I in actin assembly through interactions with Vrp1p, Bee1p, and the Arp2/3 complex. *J. Cell Biol.* 148:353–362.
- Fares, H., L. Goetsch, and J.R. Pringle. 1996. Identification of a developmentally regulated septin and involvement of the septins in spore formation in *Saccharomyces cerevisiae*. *J. Cell Biol.* 132:399–411.
- Fields, S., and O. Song. 1989. A novel genetic system to detect protein-protein interactions. *Nature.* 340:245–246.
- Foster, L., B. Yeung, M. Mohtashami, K. Ross, W.S. Trimble, and A. Klip. 1998. Binary interactions of the SNARE proteins syntaxin-4, SNAP23, and VAMP-2 and their regulation by phosphorylation. *Biochemistry.* 37:11089–11096.
- Freeman, N.L., T. Lila, K.A. Mintzer, Z. Chen, A.J. Pahk, R. Ren, D.G. Drubin, and J. Field. 1996. A conserved proline-rich region of the *Saccharomyces cerevisiae* cyclase-associated protein binds SH3 domains and modulates cytoskeletal localization. *Mol. Cell. Biol.* 16:548–556.
- Fujimura, K., K. Tanaka, A. Nakano, and A. Toh-e. 1994. The *Saccharomyces cerevisiae* *MSI4* gene encodes the yeast counterpart of component A of Rab geranylgeranyltransferase. *J. Biol. Chem.* 269:9205–9212.
- Fujiwara, T., K. Tanaka, A. Mino, M. Kikyo, K. Takahashi, K. Shimizu, and Y. Takai. 1998. Rho1p-Bni1p-Spa2p interactions: implication in localization of Bni1p at the bud site and regulation of the actin cytoskeleton in *Saccharomyces cerevisiae*. *Mol. Biol. Cell.* 9:1221–1233.
- Fujiwara, T., K. Tanaka, E. Inoue, M. Kikyo, and Y. Takai. 1999. Bni1p regulates microtubule-dependent nuclear migration through the actin cytoskeleton in *Saccharomyces cerevisiae*. *Mol. Cell. Biol.* 19:8016–8027.
- Gammie, A.E., V. Brizzio, and M.D. Rose. 1998. Distinct morphological phenotypes of cell fusion mutants. *Mol. Biol. Cell.* 9:1395–1410.
- Goode, B.L., J.J. Wong, A.-C. Butty, M. Peter, A.L. McCormack, J.R. Yates, D.G. Drubin, and G. Barnes. 1999. Coronin promotes the rapid assembly and cross-linking of actin filaments and may link the actin and microtubule cytoskeletons in yeast. *J. Cell Biol.* 144:83–98.
- Goode, B.L., A.A. Rodal, G. Barnes, and D.G. Drubin. 2001. Activation of the



- Arp2/3 complex by the actin filament binding protein Abp1p. *J. Cell Biol.* 153:627–634.
- Guo, W., A. Grant, and P. Novick. 1999a. Exo84p is an exocyst protein essential for secretion. *J. Biol. Chem.* 274:23558–23564.
- Guo, W., D. Roth, C. Walch-Solimena, and P. Novick. 1999b. The exocyst is an effector for Sec4p, targeting secretory vesicles to sites of exocytosis. *EMBO J.* 18:1071–1080.
- Guo, W., F. Tamanoi, and P. Novick. 2001. Spatial regulation of the exocyst complex by Rho1 GTPase. *Nat. Cell Biol.* 3:353–360.
- Gurunathan, S., D. Chapman-Shimshoni, S. Trajkovic, and J.E. Gerst. 2000. Yeast exocytic v-SNAREs confer endocytosis. *Mol. Biol. Cell.* 11:3629–3643.
- Hales, K.G., E. Bi, J.-Q. Wu, J.C. Adam, I.-C. Yu, and J.R. Pringle. 1999. Cytokinesis: an emerging unified theory for eukaryotes? *Curr. Opin. Cell Biol.* 11: 717–725.
- Harkins, H.A., N. Pagé, L.R. Schenkman, C. De Virgilio, S. Shaw, H. Bussey, and J.R. Pringle. 2001. Bud8p and Bud9p, proteins that may mark the sites for bipolar budding in yeast. *Mol. Biol. Cell.* 12:2497–2518.
- Helliwell, S.B., I. Howald, N. Barbet, and M.N. Hall. 1998. TOR2 is part of two related signaling pathways coordinating cell growth in *Saccharomyces cerevisiae*. *Genetics*. 148:99–112.
- Hirano, H., K. Tanaka, K. Ozaki, H. Imamura, H. Kohno, T. Hihara, T. Kamayama, K. Hotta, M. Arisawa, T. Watanabe, H. Qadota, Y. Ohya, and Y. Takai. 1996. *ROM7/BEM4* encodes a novel protein that interacts with the Rho1p small GTP-binding protein in *Saccharomyces cerevisiae*. *Mol. Cell Biol.* 16:4396–4403.
- Holtzman, D.A., S. Yang, and D.G. Drubin. 1993. Synthetic-lethal interactions identify two novel genes, *SLA1* and *SLA2*, that control membrane cytoskeleton assembly in *Saccharomyces cerevisiae*. *J. Cell Biol.* 122:635–644.
- Hong, S.K., S.B. Han, M. Snyder, and E.Y. Choi. 1999. *SHC1*, a high pH inducible gene required for growth at alkaline pH in *Saccharomyces cerevisiae*. *Biochem. Biophys. Res. Commun.* 255:116–122.
- Hoyt, M.A., L. Totis, and B.T. Roberts. 1991. *S. cerevisiae* genes required for cell cycle arrest in response to loss of microtubule function. *Cell*. 66:507–517.
- Hudson, J.R., Jr., E.P. Dawson, K.L. Rushing, C.H. Jackson, D. Lockshon, D. Conover, C. Lanciult, J.R. Harris, S.J. Simmons, R. Rothstein, and S. Fields. 1997. The complete set of predicted genes from *Saccharomyces cerevisiae* in a readily usable form. *Genome Res.* 7:1169–1173.
- Imai, J., A. Toh-e, and Y. Matsui. 1996. Genetic analysis of the *Saccharomyces cerevisiae* *RHO3* gene, encoding a Rho-type small GTPase, provides evidence for a role in bud formation. *Genetics*. 142:359–369.
- Imamura, H., K. Tanaka, T. Hihara, M. Umikawa, T. Kamei, K. Takahashi, T. Sasaki, and Y. Takai. 1997. Bni1p and Bnr1p: downstream targets of the Rho family small G-proteins which interact with profilin and regulate actin cytoskeleton in *Saccharomyces cerevisiae*. *EMBO J.* 16:2745–2755.
- Inoue, K., T. Mizuno, K. Wada, and M. Hagiwara. 2000. Novel RING finger proteins, Air1p and Air2p, interact with Hmt1p and inhibit the arginine methylation of Npl3p. *J. Biol. Chem.* 275:32793–32799.
- Ito, H., Y. Fukuda, K. Murata, and A. Kimura. 1983. Transformation of intact yeast cells treated with alkali cations. *J. Bacteriol.* 153:163–168.
- Ito, T., T. Chiba, R. Ozawa, M. Yoshida, M. Hattori, and Y. Sakaki. 2001. A comprehensive two-hybrid analysis to explore the yeast protein interactome. *Proc. Natl. Acad. Sci. USA*. 98:4569–4574.
- James, P., J. Halladay, and E.A. Craig. 1996. Genomic libraries and a host strain designed for highly efficient two-hybrid selection in yeast. *Genetics*. 144: 1425–1436.
- Jaquenod, M., and M. Peter. 2000. Gic2p may link activated Cdc42p to components involved in actin polarization, including Bni1p and Bud6p (Aip3p). *Mol. Cell Biol.* 20:6244–6258.
- Johnson, D.I., and J.R. Pringle. 1990. Molecular characterization of *CDC42*, a *Saccharomyces cerevisiae* gene involved in the development of cell polarity. *J. Cell Biol.* 111:143–152.
- Jiang, Y., and S. Ferro-Novick. 1994. Identification of yeast component A: reconstruction of the geranylgeranyltransferase that modifies Ypt1p and Sec4p. *Proc. Natl. Acad. Sci. USA*. 91:4377–4381.
- Kagami, M., A. Toh-e, and Y. Matsui. 1998. Sro7p, a *Saccharomyces cerevisiae* counterpart of the tumor suppressor *l(2)gl* protein, is related to myosins in function. *Genetics*. 149:1717–1727.
- Kahana, J.A., G. Schlenstedt, D.M. Evanchuk, J.R. Geiser, M.A. Hoyt, and P.A. Silver. 1998. The yeast dyadactin complex is involved in partitioning the mitotic spindle between mother and daughter cells during anaphase B. *Mol. Biol. Cell*. 9:1741–1756.
- Kallal, L.A., M. Bhattacharyya, S.N. Grove, R.F. Iannaccone, T.A. Pugh, D.A. Primerano, and M.J. Clancy. 1990. Functional analysis of the sporulation-specific *SPR6* gene of *Saccharomyces cerevisiae*. *Curr. Genet.* 18:293–301.
- Kamada, Y., H. Qadota, C.P. Python, Y. Anraku, Y. Ohya, and D.E. Levin. 1996. Activation of protein kinase C by Rho1 GTPase. *J. Biol. Chem.* 271:9193–9196.
- Kamada, Y., T. Funakoshi, T. Shintani, K. Nagano, M. Ohsumi, and Y. Ohsumi. 2000. Tor-mediated induction of autophagy via an Apg1 protein kinase complex. *J. Cell Biol.* 150:1507–1513.
- Kamei, T., K. Tanaka, T. Hihara, M. Umikawa, H. Imamura, M. Kikyo, K. Ozaki, and Y. Takai. 1998. Interaction of Bnr1p with a novel Src homology 3 domain-containing Hof1p. Implication in cytokinesis in *Saccharomyces cerevisiae*. *J. Biol. Chem.* 273:28341–28345.
- Kessels, M.M., Å.E. Engqvist-Goldstein, and D.G. Drubin. 2000. Association of mouse actin-binding protein 1 (mAbp1/SH3P7), a Src kinase target, with dynamic regions of the cortical actin cytoskeleton in response to Rac GTPase activators. *Mol. Cell Biol.* 11:393–412.
- Kim, J., V.M. Dalton, K.P. Eggerton, S.V. Scott, and D.J. Klionsky. 1999. Apg7p/Cvt2p is required for the cytoplasm-to-vacuole targeting, macroautophagy, and peroxisome degradation pathways. *Mol. Biol. Cell*. 10:1337–1351.
- Koh, D.S., M.W. Moody, T.D. Nguyen, and B. Hille. 2000. Regulation of exocytosis by protein kinases and Ca(2+) in pancreatic duct epithelial cells. *J. Gen. Physiol.* 116:507–520.
- Kozminski, K.G., A.J. Chen, A.A. Rodal, and D.G. Drubin. 2000. Functions and functional domains of the GTPase Cdc42p. *Mol. Biol. Cell*. 11:339–354.
- Kübler, E., and H. Riezman. 1993. Actin and fimbrin are required for the internalization step of endocytosis in yeast. *EMBO J.* 12:2855–2862.
- Lechler, T., and R. Li. 1997. In vitro reconstitution of cortical actin assembly sites in budding yeast. *J. Cell Biol.* 138:95–103.
- Lechler, T., A. Shevchenko, and R. Li. 2000. Direct involvement of yeast type I myosins in Cdc42-dependent actin polymerization. *J. Cell Biol.* 148:363–373.
- Lehman, K., G. Rossi, J.E. Adamo, and P. Brennwald. 1999. Yeast homologues of tomosyn and lethal giant larvae function in exocytosis and are associated with the plasma membrane SNARE, Sec9. *J. Cell Biol.* 146:125–140.
- Lew, D.J. 2000. Cell-cycle checkpoints that ensure coordination between nuclear and cytoplasmic events in *Saccharomyces cerevisiae*. *Curr. Opin. Genet. Dev.* 10:47–53.
- Li, R. 1997. Bee1, a yeast protein with homology to Wiscott-Aldrich syndrome protein, is critical for the assembly of cortical actin cytoskeleton. *J. Cell Biol.* 136:649–658.
- Li, R., Y. Zheng, and D.G. Drubin. 1995. Regulation of cortical actin cytoskeleton assembly during polarized cell growth in budding yeast. *J. Cell Biol.* 128: 599–615.
- Lila, T., and D.G. Drubin. 1997. Evidence for physical and functional interactions among two *Saccharomyces cerevisiae* SH3 domain proteins, an adenyl cyclase-associated protein and the actin cytoskeleton. *J. Cell Biol.* 136:649–658.
- Lippincott, J., and R. Li. 1998a. Dual function of Cyk2, a Cdc15/PSTPIP family protein, in regulating actomyosin ring dynamics and septin distribution. *J. Cell Biol.* 143:1947–1960.
- Lippincott, J., and R. Li. 1998b. Sequential assembly of myosin II, an IQGAP-like protein, and filamentous actin to a ring structure involved in budding yeast cytokinesis. *J. Cell Biol.* 140:355–366.
- Longtine, M.S., A. McKenzie III, D.J. DeMarini, N.G. Shah, A. Wach, A. Brachat, P. Phillipsen, and J.R. Pringle. 1998. Additional modules for versatile and economical PCR-based gene deletion and modification in *Saccharomyces cerevisiae*. *Yeast*. 14:953–961.
- Longtine, M.S., C.L. Theesfeld, J.N. McMillan, E. Weaver, J.R. Pringle, and D.J. Lew. 2000. Septin-dependent assembly of a cell cycle-regulatory module in *Saccharomyces cerevisiae*. *Mol. Cell Biol.* 20:4049–4061.
- Lupashin, V.V., S. Hamamoto, and R.W. Schekman. 1996. Biochemical requirements for the targeting and fusion of ER-derived transport vesicles with purified yeast Golgi membranes. *J. Cell Biol.* 132:277–289.
- Ma, H., S. Kunes, P.J. Schatz, and D. Botstein. 1987. Plasmid construction by homologous recombination in yeast. *Gene*. 58:201–216.
- Mack, D., K. Nishimura, B.K. Dennehey, T. Arbogast, J. Parkinson, A. Toh-e, J.R. Pringle, A. Bender, and Y. Matsui. 1996. Identification of the bud emergence gene *BEM4* and its interactions with rho-type GTPases in *Saccharomyces cerevisiae*. *Mol. Cell Biol.* 16:4387–4395.
- Madania, A., P. Dumoulin, S. Grava, H. Kitamoto, C. Schäfer-Brodbeck, A. Souillard, V. Moreau, and B. Winsor. 1999. The *Saccharomyces cerevisiae* homo-

- logue of human Wiskott-Aldrich syndrome protein Las17p interacts with the Arp2/3 complex. *Mol. Biol. Cell.* 10:3521–3538.
- Mata, J., and P. Nurse. 1997. *tea1* and the microtubular cytoskeleton are important for generating global spatial order within the fission yeast cell. *Cell.* 89: 939–949.
- Matsui, Y., and A. Toh-e. 1992. Yeast *RHO3* and *RHO4* ras superfamily genes are necessary for bud growth, and their defect is suppressed by a high dose of bud formation genes *CDC42* and *BEM1*. *Mol. Cell. Biol.* 12:5690–5699.
- Matsui, Y., R. Matsui, R. Akada, and A. Toh-e. 1996. Yeast *src* homology region 3 domain-binding proteins involved in bud formation. *J. Cell Biol.* 133:865–878.
- McCraith, S., T. Holtzman, B. Moss, and S. Fields. 2000. Genome-wide analysis of vaccinia virus protein-protein interactions. *Proc. Natl. Acad. Sci. USA.* 97: 4879–4884.
- McMillan, J.N., R.A.L. Sia, and D.J. Lew. 1998. A morphogenesis checkpoint monitors the actin cytoskeleton in yeast. *J. Cell Biol.* 142:1487–1499.
- McMillan, J.N., M.S. Longtine, R.A.L. Sia, C.L. Theesfeld, E.S.G. Bardes, J.R. Pringle, and D.J. Lew. 1999. The morphogenesis checkpoint in *Saccharomyces cerevisiae*: cell cycle control of Swe1p degradation by Hsl1p and Hsl7p. *Mol. Cell. Biol.* 19:6929–6939.
- Miller, D.M., N.S. Desai, D.C. Hardin, D.W. Piston, G.H. Patterson, J. Fleenor, S. Xu, and A. Fire. 1999. Two-color GFP expression system for *C. elegans*. *Biotechniques.* 26:914–918.
- Mizushima, N., T. Noda, T. Yoshimori, Y. Tanaka, T. Ishii, M.D. George, D.J. Klionsky, M. Ohsumi, and Y. Ohsumi. 1998. A protein conjugation system essential for autophagy. *Nature.* 395:395–398.
- Mösch, H.-U., and G.R. Fink. 1997. Dissection of filamentous growth by transposon mutagenesis in *Saccharomyces cerevisiae*. *Genetics.* 145:671–684.
- Moskow, J.J., A.S. Gladfelter, R.E. Lamson, P.M. Pryciak, and D.J. Lew. 2000. Role of Cdc42p in pheromone-stimulated signal transduction in *Saccharomyces cerevisiae*. *Mol. Cell. Biol.* 20:7559–7571.
- Mulholland, J., D. Preuss, A. Moon, A. Wong, D. Drubin, and D. Botstein. 1994. Ultrastructure of the yeast actin cytoskeleton and its association with the plasma membrane. *J. Cell Biol.* 125:381–391.
- Navarro, P., P. Durrrens, and M. Aigle. 1997. Protein-protein interaction between the *RVS161* and *RVS167* gene products of *Saccharomyces cerevisiae*. *Biochim. Biophys. Acta.* 1343:187–192.
- Nern, A., and R.A. Arkowitz. 2000. Nucleocytoplasmic shuttling of the Cdc42p exchange factor Cdc24p. *J. Cell Biol.* 148:1115–1122.
- Niedenthal, R.K., L. Riles, M. Johnston, and J.H. Hegemann. 1996. Green fluorescent protein as a marker for gene expression and subcellular localization in budding yeast. *Yeast.* 12:773–786.
- Ohsumi, Y. 1999. Molecular mechanism of autophagy in yeast, *Saccharomyces cerevisiae*. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 354:1577–1581.
- Paravicini, G., M. Cooper, L. Friedli, D.J. Smith, J.-L. Carpentier, L.S. Klig, and M.A. Payton. 1992. The osmotic integrity of the yeast cell requires a functional *PKC1* gene product. *Mol. Cell. Biol.* 12:4896–4905.
- Park, H.-O., J. Chant, and I. Herskowitz. 1993. *BUD2* encodes a GTPase-activating protein for Bud1/Rsr1 necessary for proper bud-site selection in yeast. *Nature.* 365:269–274.
- Park, H.-O., A. Sanson, and I. Herskowitz. 1999. Localization of Bud2p, a GTPase-activating protein necessary for programming cell polarity in yeast to the presumptive bud site. *Genes Dev.* 13:1912–1917.
- Pereira, G., T. Hofken, J. Grindlay, C. Manson, and E. Schiebel. 2000. The Bub2p spindle checkpoint links nuclear migration with mitotic exit. *Mol. Cell.* 6:1–10.
- Posas, F., E.A. Witten, and H. Saito. 1998. Requirement of STE50 for osmotic stress-induced activation of the STE11 mitogen-activated protein kinase in the high-osmolarity glycerol response pathway. *Mol. Cell. Biol.* 18:5788–5796.
- Pruyne, D., and A. Bretscher. 2000a. Polarization of cell growth in yeast. I. Establishment and maintenance of polarity states. *J. Cell Sci.* 113:365–375.
- Pruyne, D., and A. Bretscher. 2000b. Polarization of cell growth in yeast. II. The role of the cortical actin cytoskeleton. *J. Cell Sci.* 113:571–585.
- Qadota, H., C.P. Python, S.B. Inoue, M. Arisawa, Y. Anraku, Y. Zheng, T. Watanabe, D.E. Levin, and Y. Ohya. 1996. Identification of yeast Rho1p GTPase as a regulatory subunit of 1,3- $\beta$ -glucan synthase. *Science.* 272:279–281.
- Ramezani Rad, M., G. Jansen, F. Buhning, and C.P. Hollenberg. 1998. Ste50p is involved in regulating filamentous growth in the yeast *Saccharomyces cerevisiae* and associates with Ste11p. *Mol. Gen. Genet.* 259:29–38.
- Rethinaswamy, A., M.J. Birnbaum, and C.V. Glover. 1998. Temperature-sensitive mutations of the *CKA1* gene reveal a role for casein kinase II in maintenance of cell polarity in *Saccharomyces cerevisiae*. *J. Biol. Chem.* 273:5869–5877.
- Rieger, K.-J., M. El-Alama, G. Stein, C. Bradshaw, P.P. Slonimski, and K. Maundrell. 1999. Chemotyping of yeast mutants using robotics. *Yeast* 15:973–986.
- Robinson, N.G.G., L. Guo, J. Imai, A. Toh-e, Y. Matsui, and F. Tamanoi. 1999. Rho3 of *Saccharomyces cerevisiae*, which regulates the actin cytoskeleton and exocytosis, is a GTPase which interacts with Myo2 and Exo70. *Mol. Cell. Biol.* 19:3580–3587.
- Roy, N., and K.W. Runge. 2000. Two paralogs involved in transcriptional silencing that antagonistically control yeast life span. *Curr. Biol.* 10:111–114.
- Ruggieri, R., A. Bender, Y. Matsui, S. Powers, Y. Takai, J.R. Pringle, and K. Matsumoto. 1992. *RSR1*, a ras-like gene homologous to *Krev-1* (*smg21A/rap1A*): role in the development of cell polarity and interactions with the Ras pathway in *Saccharomyces cerevisiae*. *Mol. Cell. Biol.* 12:758–766.
- Russell, S.J., K.A. Steger, and S.A. Johnston. 1999. Subcellular localization, stoichiometry, and protein levels of 26 S proteasome subunits in yeast. *J. Biol. Chem.* 274:1943–1952.
- Schott, D., J. Ho, D. Pruynne, and A. Bretscher. 1999. The COOH-terminal domain of Myo2p, a yeast myosin V, has a direct role in secretory vesicle targeting. *J. Cell Biol.* 147:791–807.
- Sherman, F., G.R. Fink, and J.B. Hicks. 1986. Methods in Yeast Genetics. Cold Spring Harbor Laboratory, Cold Spring Harbor, NY.
- Sheu, Y.-J., Y. Barral, and M. Snyder. 2000. Polarized growth controls cell shape and bipolar bud site selection in *Saccharomyces cerevisiae*. *Mol. Cell. Biol.* 20: 5235–5247.
- Shimada, Y., M.-P. Gulli, and M. Peter. 2000. Nuclear sequestration of the exchange factor Cdc24 by Far1 regulates cell polarity during yeast mating. *Nat. Cell Biol.* 2:117–124.
- Shou, W., J.H. Seol, A. Shevchenko, C. Baskerville, D. Moazed, Z.W. Chen, J. Jang, A. Shevchenko, H. Charbonneau, and R.J. Deshaies. 1999. Exit from mitosis is triggered by Tem1-dependent release of the protein phosphatase Cdc14 from nucleolar RENT complex. *Cell.* 97:233–244.
- Shulewitz, M.J., C.J. Inouye, and J. Thorner. 1999. Hsl7 localizes to a septin ring and serves as an adapter in a regulatory pathway that relieves tyrosine phosphorylation of Cdc28 protein kinase in *Saccharomyces cerevisiae*. *Mol. Cell. Biol.* 19:7123–7137.
- Spellman, P.T., G. Sherlock, M.Q. Zhang, V.R. Iyer, K. Anders, M.B. Eisen, P.O. Brown, D. Botstein, and B. Futcher. 1998. Comprehensive identification of cell cycle-regulated genes of the yeast *Saccharomyces cerevisiae* by microarray hybridization. *Mol. Biol. Cell.* 9:3273–3297.
- Strand, D., R. Jakobs, G. Merdes, B. Neumann, A. Kalmes, H.W. Heid, I. Husmann, and B.M. Mechler. 1994. The *Drosophila lethal(2)giant larvae* tumor suppressor protein forms homo-oligomers and is associated with nonmuscle myosin II heavy chain. *J. Cell Biol.* 127:1361–1373.
- Takuma, T. 1990. Evidence for the involvement of cAMP-dependent protein kinase in the exocytosis of amylase from parotid acinar cells. *J. Biochem. (Tokyo).* 108:99–102.
- Tang, H.-Y., J. Xu, and M. Cai. 2000. Pan1p, End3p, and Slp1p, three yeast proteins required for normal cortical actin cytoskeleton organization, associate with each other and play essential roles in cell wall morphogenesis. *Mol. Cell. Biol.* 20:12–25.
- Tanida, I., N. Mizushima, M. Kiyooka, M. Ohsumi, T. Ueno, Y. Ohsumi, and E. Kominami. 1999. Apg7p/Cvt2p: a novel protein-activating enzyme essential for autophagy. *Mol. Biol. Cell.* 10:1367–1379.
- TerBush, D.R., and P. Novick. 1995. Sec6, Sec8, and Sec15 are components of a multisubunit complex which localizes to small bud tips in *Saccharomyces cerevisiae*. *J. Cell Biol.* 130:299–312.
- TerBush, D.R., T. Maurice, D. Roth, and P. Novick. 1996. The exocyst is a multi-protein complex required for exocytosis in *Saccharomyces cerevisiae*. *EMBO J.* 15:6483–6494.
- Toenjes, K.A., M.M. Sawyer, and D.I. Johnson. 1999. The guanine-nucleotide-exchange factor Cdc24p is targeted to the nucleus and polarized growth sites. *Curr. Biol.* 9:1183–1186.
- Trilla, J.A., T. Cos, A. Durán, and C. Roncero. 1997. Characterization of *CHS4* (*CAL2*), a gene of *Saccharomyces cerevisiae* involved in chitin biosynthesis and allelic to *SKT5* and *CSD4*. *Yeast.* 13:795–807.
- Uetz, P., L. Giot, G. Cagney, T.A. Mansfield, R.S. Judson, J.R. Knight, D. Lockshon, V. Narayan, M. Srinivasan, P. Pochart, A. Qureshi-Emili, Y. Li, B. Godwin, D. Conover, T. Kalbfleisch, G. Vijayadmodar, M. Yang, M. Johnston, S. Fields, and J.M. Rothberg. 2000. A comprehensive analysis of protein-protein interactions in *Saccharomyces cerevisiae*. *Nature.* 403:623–627.
- Vallen, E.A., J. Caviston, and E. Bi. 2000. Roles of Hof1p, Bni1p, Bnr1p, and

- Myo1p in cytokinesis in *Saccharomyces cerevisiae*. *Mol. Biol. Cell.* 11:593–611.
- Visintin, R., and A. Amon. 2000. The nucleolus: the magician's hat for cell cycle tricks. *Curr. Opin. Cell Biol.* 12:372–377.
- Wach, A., A. Brachat, C. Alberti-Segui, C. Rebischung, and P. Philippsen. 1997. Heterologous *HIS3* marker and GFP reporter modules for PCR-targeting in *Saccharomyces cerevisiae*. *Yeast.* 13:1065–1075.
- Walworth, N., P. Brennwald, A.K. Kabcnell, M. Garrett, and P. Novick. 1992. Hydrolysis of GTP by Sec4 protein plays an important role in vesicular transport and is stimulated by a GTPase-activating protein in *Saccharomyces cerevisiae*. *Mol. Cell. Biol.* 12:2017–2028.
- Watanabe, T.K., A. Saito, M. Suzuki, T. Fujiwara, E. Takahashi, C.A. Slaughter, G.N. DeMartino, K.B. Hendil, C.H. Chung, N. Tanahashi, and K. Tanaka. 1998. cDNA cloning and characterization of a human proteasomal modulator subunit, p27 (PSMD9). *Genomics.* 50:241–250.
- Weiss, E.L., A.C. Bishop, K.M. Shokat, and D.G. Drubin. 2000. Chemical genetic analysis of the budding-yeast p21-activated kinase Cla4p. *Nat. Cell Biol.* 2:677–685.
- Wendland, B., and S. Emr. 1998. Pan1p, yeast eps15, functions as a multivalent adaptor that coordinates protein-protein interactions essential for endocytosis. *J. Cell Biol.* 141:71–84.
- Wendland, B., K.E. Steece, and S.D. Emr. 1999. Yeast epsins contain an essential N-terminal ENTH domain, bind clathrin and are required for endocytosis. *EMBO J.* 18:4388–4393.
- Wesp, A., L. Hicke, J. Palecek, R. Lombardi, T. Aust, A.L. Munn, and H. Riezman. 1997. End4p/Sla2p interacts with actin-associated proteins for endocytosis in *Saccharomyces cerevisiae*. *Mol. Biol. Cell.* 8:2291–2306.
- Wilson, K.F., and R.A. Cerione. 2000. Signal transduction and post-transcriptional gene expression. *Biol. Chem.* 381:357–365.
- Wilson, K.F., W.J. Wu, and R.A. Cerione. 2000. Cdc42 stimulates RNA splicing via the S6 kinase and a novel S6 kinase target, the nuclear cap-binding complex. *J. Biol. Chem.* 275:37307–37310.
- Winter, D., T. Lechler, and R. Li. 1999. Activation of the yeast Arp2/3 complex by Bee1p, a WASP-family protein. *Curr. Biol.* 9:501–504.
- Winzeler, E.A., D.D. Shoemaker, A. Astromoff, H. Liang, et al. 1999. Functional characterization of the *S. cerevisiae* genome by gene deletion and parallel analysis. *Science.* 285:901–906.
- Wu, C., S.F. Lee, E. Furmaniak-Kazmierczak, G.P. Cote, D.Y. Thomas, and E. Leberer. 1996. Activation of myosin-I by members of the Ste20p protein kinase family. *J. Biol. Chem.* 271:31787–31790.
- Wu, C., V. Lytvyn, D.Y. Thomas, and E. Leberer. 1997. The phosphorylation site for Ste20p-like protein kinases is essential for the function of myosin-I in yeast. *J. Biol. Chem.* 272:30623–30626.
- Xu, G., J. Jansen, D.Y. Thomas, C.P. Hollenberg, and M. Ramezani Rad. 1996. Ste50p sustains mating pheromone-induced signal transduction in the yeast *Saccharomyces cerevisiae*. *Mol. Microbiol.* 20:773–783.
- Yamochi, W., K. Tanaka, H. Nonaka, A. Maeda, T. Musha, and Y. Takai. 1994. Growth site localization of Rho1 small GTP-binding protein and its involvement in bud formation in *Saccharomyces cerevisiae*. *J. Cell Biol.* 125:1077–1093.
- Yang, S., M.J.T.V. Cope, and D.G. Drubin. 1999. Sla2p is associated with the yeast cortical actin cytoskeleton via redundant localization signals. *Mol. Biol. Cell.* 10:2265–2283.
- Zahner, J.E., H.A. Harkins, and J.R. Pringle. 1996. Genetic analysis of the bipolar pattern of bud site selection in the yeast *Saccharomyces cerevisiae*. *Mol. Cell. Biol.* 16:1857–1870.
- Zheng, Y., R. Cerione, and A. Bender. 1994. Control of the yeast bud-site assembly GTPase Cdc42. Catalysis of guanine nucleotide exchange by Cdc24 and stimulation of GTPase activity by Bem3. *J. Biol. Chem.* 269:2369–2372.
- Zheng, Y., A. Bender, and R.A. Cerione. 1995. Interactions among proteins involved in bud-site selection and bud-site assembly in *Saccharomyces cerevisiae*. *J. Biol. Chem.* 270:626–630.