



HAL
open science

The *Saccharomyces cerevisiae* Homologue of Human Wiskott–Aldrich Syndrome Protein Las17p Interacts with the Arp2/3 Complex

Ammar Madania, Pascal Dumoulin, Sandrine Grava, Hiroko Kitamoto, Claudia Schärer-Brodbeck, Alexandre Soulard, Violaine Moreau, Barbara Winsor

► **To cite this version:**

Ammar Madania, Pascal Dumoulin, Sandrine Grava, Hiroko Kitamoto, Claudia Schärer-Brodbeck, et al.. The *Saccharomyces cerevisiae* Homologue of Human Wiskott–Aldrich Syndrome Protein Las17p Interacts with the Arp2/3 Complex. *Molecular Biology of the Cell*, 1999, 10, pp.3521 - 3538. hal-01632703

HAL Id: hal-01632703

<https://hal.science/hal-01632703>

Submitted on 10 Nov 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

The *Saccharomyces cerevisiae* Homologue of Human Wiskott–Aldrich Syndrome Protein Las17p Interacts with the Arp2/3 Complex

Ammar Madania,^{*,†} Pascal Dumoulin,^{*} Sandrine Grava,^{*} Hiroko Kitamoto,^{*,‡} Claudia Schärer-Brodbeck,[§] Alexandre Soulard,^{*} Violaine Moreau,^{*,||} and Barbara Winsor^{*,¶}

^{*}Mécanismes Moléculaires de la Division Cellulaire et du Développement, Unité Propre de Recherche 9005 du Centre National de la Recherche Scientifique, Institut de Biologie Moléculaire et Cellulaire, F-67084 Strasbourg, France; and [§]Biozentrum, University of Basel, CH-4056 Basel, Switzerland

Submitted February 26, 1999; Accepted July 28, 1999
Monitoring Editor: David Drubin

Yeast Las17 protein is homologous to the Wiskott–Aldrich Syndrome protein, which is implicated in severe immunodeficiency. Las17p/Bee1p has been shown to be important for actin patch assembly and actin polymerization. Here we show that Las17p interacts with the Arp2/3 complex. *LAS17* is an allele-specific multicopy suppressor of *ARP2* and *ARP3* mutations; overexpression restores both actin patch organization and endocytosis defects in *ARP2* temperature-sensitive (ts) cells. Six of seven *ARP2* ts mutants and at least one *ARP3* ts mutant are synthetically lethal with *las17Δ* ts confirming functional interaction with the Arp2/3 complex. Further characterization of *las17Δ* cells showed that receptor-mediated internalization of α factor by the Ste2 receptor is severely defective. The polarity of normal bipolar bud site selection is lost. Las17-gfp remains localized in cortical patches in vivo independently of polymerized actin and is required for the polarized localization of Arp2/3 as well as actin. Coimmunoprecipitation of Arp2p with Las17p indicates that Las17p interacts directly with the complex. Two hybrid results also suggest that Las17p interacts with actin, verprolin, Rvs167p and several other proteins including Src homology 3 (SH3) domain proteins, suggesting that Las17p may integrate signals from different regulatory cascades destined for the Arp2/3p complex and the actin cytoskeleton.

INTRODUCTION

Arp2p and Arp3p are essential ubiquitous proteins of the actin-related family localized in actin-rich cortical structures (McCollum *et al.*, 1996; Moreau *et al.*, 1996; Mullins *et al.*, 1997; Welch *et al.*, 1997b; Winter *et al.*, 1997). Analysis of yeast mutations shed light on their roles in the cortical cytoskeleton. Delocalization of actin patches and a slight accumulation of membranous vesicles resulted from a temperature-sensitive (ts) mutation in *S. cerevisiae* Arp2p (Moreau *et al.*, 1996). This mutant was defective for dye uptake and for internalization of a membrane transporter, uracil permease (Moreau *et al.*, 1997). A fission yeast cold-sensitive

ARP3 mutation caused disorganization of actin patches and defects in polarized growth (McCollum *et al.*, 1996). A ts mutation in *Saccharomyces cerevisiae* Arp3p impaired actin patch motility and caused accumulation of actin aggregates in the bud (Winter *et al.*, 1997). Arp2p and Arp3p were first isolated by purification of a profilin-binding complex from *Acanthamoeba*, which contained five additional peptides, p40, p35, p19, p18, and p14 (Machesky *et al.*, 1994). A homologous complex, purified from human platelets, localized at the leading edge of moving lamellipodia (Welch *et al.*, 1997b). Purification of the Arp2/3 complex from *S. cerevisiae* (Winter *et al.*, 1997) showed that it was homologous to the *Acanthamoeba* and human complexes with the exception that one subunit, p40 or Sop2p (Balasubramanian *et al.*, 1996), did not copurify (Winter *et al.*, 1997).

Structural modeling of Arp2p and Arp3p led to the hypothesis that Arp2p and Arp3p formed a heterodimer capable of nucleating actin polymerization at the pointed end of actin filaments (Kelleher *et al.*, 1995), whereas electronic microscopy of purified *Acanthamoeba* Arp2/3 complex showed the complex bound to the sides of actin filaments in

Present Addresses: [†]Atomic Energy Commission, Department of Molecular Biology, P.O. Box 6091, Damascus, Syria; [‡]Laboratory of Microorganism Genetic Diversity, National Institute of Agrobiological Resources, 2-1-2, Kan-nondai, Tsuba, Japan; and ^{||}European Molecular Biology Laboratory, 1 Meyerhofstrasse, 69117 Heidelberg, Germany.

[¶] Corresponding author. E-mail address: winsor@ibmc.u-strasbg.fr.

vitro (Mullins *et al.*, 1997). Arp2/3 complex promotes actin polymerization at the surface of the intracellular pathogen *Listeria monocytogenes* by recruiting host proteins through a surface protein, ActA (Welch *et al.*, 1997). The complex then nucleates actin filaments, generating propulsive force. However, Arp2/3 complex is also localized all along actin tails of moving bacteria and not just at actin polymerization sites on the *Listeria* cell surface (Welch *et al.*, 1998). Recent evidence indicated that the Arp2/3 complex alone was a weak nucleator, whereas ActA alone was not. Their combined action had a dramatic synergistic effect on nucleation of actin filaments (Welch *et al.*, 1998). Localization, nucleation, and cross-linking studies in *Acanthamoeba* have led to the proposition that the Arp2/3 complex promotes polymerization at the leading edge of membranes by attaching newly formed filaments to preexisting structures. Thus, as actin filaments grow at their membrane-proximal ends to drive motility, the bound Arp2/3 complex would be translocated away from the membrane (Mullins *et al.*, 1998b). More recently, in addition to nucleating actin at the barbed end of filaments, the Arp2/3 complex was shown to have high-affinity pointed end capping activity to induce branched networks of filaments *in vitro* (Mullins *et al.*, 1998a).

A novel yeast protein, Las17p/Bee1p, was shown to be a component of actin patches. Yeast cells deleted for the Wiskott-Aldrich Syndrome protein (WASP) homologue concentrated aberrant actin aggregates in the bud and were defective in actin patch assembly, budding, and cytokinesis (Li, 1997). Moreover, biochemical studies using permeabilized cells and rhodamine-labeled actin suggested that Las17p/Bee1p was required for actin polymerization and assembly *in vitro* (Lechler and Li, 1997). Las17p is proline-rich and shows homology to human WASP, mutations in which cause severe immunodeficiency (Amman and Hong, 1989). WAS patients show cytoskeletal abnormalities of lymphocytes and platelets (Molina *et al.*, 1992), failure of B cells to respond to polysaccharide antigens, and defective chemotaxis in neutrophils (Ochs *et al.*, 1980), suggesting that WASP is important in cytoskeletal reorganization necessary for the immunological response. WASP colocalized with polymerized actin in human cells and bound specifically to activated CDC42Hs (Apenström *et al.*, 1996; Kolluri *et al.*, 1996; Symons *et al.*, 1996). A more ubiquitously expressed homologue, N-WASP, was shown to bind actin, calmodulin, and Ash/Grb2p (abundant Src homology/growth factor receptor-bound protein 2), an Src homology 2/Src homology 3 (SH3) domain protein implicated in signal transduction from membrane receptors to effectors of the cytoskeleton (Miki *et al.*, 1996). Overexpression of either WASP or N-WASP in mammalian cells induced formation of actin clusters that colocalized with the overexpressed protein, indicating a role in actin polymerization (Miki *et al.*, 1996; Symons *et al.*, 1996). The vertebrate WASP family member Scar1/WAVE, like yeast Las17p, does not contain a recognizable GTPase binding site, but overexpression induced clustered actin filaments, demonstrating its involvement in actin reorganization (Miki *et al.*, 1998). WASP and Scar1 have now been shown to interact with actin via their WASP homology 2 (WH2) domains and with the p21 subunit of the Arp2/3 complex via their C-terminal acidic domains. Overexpression of these C-terminal acidic fragments caused delocaliza-

tion of the Arp2/3 complex with concomitant loss of actin spots and lamellipodia (Machesky and Insall, 1998).

We previously showed that in yeast, increased *LAS17* expression suppressed *arp2-1* growth thermosensitivity (Madania *et al.*, 1997). Here we present genetic, cellular, and biochemical evidence that Las17p functions with the Arp2/3 complex and raise the possibility that Las17p may be part of signaling pathways directed to the Arp2/3 complex and actin.

MATERIALS AND METHODS

Plasmids, Strains, Gene Banks, and Genetic Manipulations

Plasmids and yeast strains used in this study are listed in Tables 1 and 2. Strains are derived from YPH and FY strains, which are S288C derivatives. Genomic DNA banks used were constructed in 2 μ plasmids: Sau3A-derived fragments in pFL44 vector (from F. Lacroute), pGAD vector (from P. Bartel) (Fields and Song, 1989), multiple enzyme-derived fragments in pGAD424 (from P. James) (James *et al.*, 1996), or mechanically derived fragments cloned in pACTII (from P. Legrain) (Fromont-Racine *et al.*, 1997). The cDNA library used in two-hybrid screening was in pGAD-GH (from M. White). DNA manipulations were carried out by standard techniques (Sambrook *et al.*, 1989). Yeast cell cultures and genetic manipulations were carried out essentially as described in by Guthrie and Fink (1991). Yeast cells were transformed by the LiAc method using single-stranded carrier DNA and DMSO (Schiestl and Gietz, 1989; Hill *et al.*, 1991).

LAS17 Gene Deletion

Using PCR targeting with short flanking homology (Wach *et al.*, 1994) the complete *LAS17* coding region was deleted in three different diploid yeast strains: YPH501, FY1679, and W303 (Table 2). Oligonucleotides used to amplify the kanMX4 fragment on pFA6a-kanMX4 were 5'-AATTACAGTTCGTTACTTTAAGTGTGATAGCGGTGATTTAATGCTGCAGGTCGACGGATC-3' and 5'-ACATA-TTTTCTATAACAGTAGTTTCATCTTTGTTGCATTCATCCATCGAT-GAATTCGAGCTC-3'. Recombinants bearing the kanMX4 marker were selected on YPD plates containing G418 at 200 μ g/ml. Correct integration of the kanMX4 cassette was verified by PCR analysis of genomic DNA. Haploid *las17 Δ* strains (YMW17K1 and YMW17K2) were obtained by sporulation and dissection of heterozygous diploid disruptants; they appeared fully rescued at 37°C by plasmid-borne wild-type *LAS17*. The same methodology and oligonucleotides allowed us to create *las17 Δ ::HIS3* strains using plasmid pFA6a-HIS3MX6 as template. FDW174H is the resulting *las17 Δ ::HIS3* diploid strain.

Chromosomal Integration of Tagged ARP2 and ARP3 *ts* Alleles

Seven *ARP2* (*arp2-1* to *arp2-7*) *ts* mutations, initially obtained by PCR mutagenesis on plasmid pYCW207 (Moreau *et al.*, 1996), were integrated at the *ARP2* locus. The *ARP2* gene was tagged with *URA3* by cloning an *Xba*I-*Pvu*II fragment containing the *URA3* gene from pJJ244 (Jones and Prakash, 1990) blunt into the *Ssp*I site 130 bp downstream of the *ARP2* stop codon in plasmid pBES18 (Moreau *et al.*, 1996). This gave rise to pIMW18-U. Mutant alleles (*arp2-1* to *arp2-7*) were excised as 1.38-kb *Sac*I-*Ssp*I fragments from the mutant bank in pYCW207, purified, and ligated into the *Sac*I-*Sall* (blunted) sites of pBMW18-U. Wild-type and resulting mutant plasmids were digested with *Sac*I-*Kpn*I, and the 3.4-kb fragments containing the *ARP2* *ts* alleles with the downstream *URA3* marker were purified, transformed into YPH499, and selected on SC - Ura. Ura⁺ clones were tested for thermosensitive growth then for correct integration

Table 1. Plasmids used in this study

Plasmid	Description
pIMW18-U	pUC18 containing <i>ARP2</i> tagged with <i>URA3</i> (this study)
pIMW300	pUC18 containing <i>ARP3</i> as an 1.85-kb <i>Bam</i> HI insert (this study)
pYCW204	pUN60, <i>CENIV</i> , <i>URA3</i> , <i>SUP11</i> , <i>ARP2</i> (Moreau <i>et al.</i> , 1996)
pCMW306	pUN60, <i>CENIV</i> , <i>URA3</i> , <i>SUP11</i> , <i>ARP3</i> , constructed by ligating the <i>Sal</i> I- <i>Bam</i> HI fragment of pIMW300 into the same sites of pUN60 (this study)
pCMW304	pRS314 (Sikorski and Hieter, 1989), <i>ARP3:LEU2</i> (this study)
pYCW207	pUN90, <i>CENIV</i> , <i>HIS3</i> , <i>ARP2</i> (Moreau <i>et al.</i> , 1996)
pYEW170	pFL44, <i>2μD</i> , <i>URA3</i> , <i>LAS17</i> and flanking regions as a 4-kb <i>Bam</i> HI insert (this study)
pAS2	<i>2μD</i> , <i>TRP1</i> , <i>ADHpro-NLS-GAL4BD</i> , <i>HA</i> , <i>CYH2</i> , bait vector (Durfee <i>et al.</i> , 1993)
pAMW172	pAS2, <i>GAL4BD</i> fused to full-length <i>LAS17</i> (this study)
pDAB7	pAS2 derived, <i>CEN</i> , <i>GAL4BD</i> fused to full-length <i>ACT1</i> (Amberg <i>et al.</i> , 1995)
pACT2	<i>2μD</i> , <i>LEU2</i> , <i>ADHpro-NLS-GAL4AD</i> , <i>HA</i> , prey vector (Durfee <i>et al.</i> , 1993)
pAMW253	pACT2, <i>GAL4AD</i> fused to intronless full length <i>ARP2</i> (this study)
pAMW315	pACT2, <i>GAL4AD</i> fused to full length <i>ARP3</i> (this study)
pAMW173	pACT2, <i>GAL4AD</i> fused to full length <i>LAS17</i> (this study)
PGAD.GH	<i>2μD</i> , <i>LEU2</i> , <i>ADHpro-NLS-GAL4AD</i> , prey vector (Chien <i>et al.</i> , 1991)
pAMW200	pGAD.GH, <i>ARP2</i> (this study)
pAMW171	PGAD.GH, <i>LAS17</i> (<i>2μ</i> overexpression, this study)
pFA6a-kanMX4	pFA6a, cassette for resistance to G418 (Wach <i>et al.</i> , 1994)
pFA6a-HIS3MX6	pFA6a, <i>his3</i> complementing heterologous <i>HIS5</i> ORF from <i>S. pombe</i> (Wach <i>et al.</i> , 1997)
pFA6a GFPS65T-kanMX6	Same as pFA6a-kanMX4, containing GFP (S65T) upstream of the kanMX6 module (Wach <i>et al.</i> , 1997)

of the *URA3* cassette at the *ARP2* locus by PCR analysis of genomic DNA (our unpublished results). Haploid-tagged wild-type and mutants were mated with YPH500, and diploids were sporulated. In all 20 tetrads dissected for each cross, two ts *URA3* and two non-ts *ura3* spores were obtained (Table 2, YMW201U and YMW211U–YMW271U). In a similar manner, wild-type *ARP3* and the *arp3-14* mutant allele were tagged with the *LEU2* gene (Madania, 1998).

Construction of GFP Fusions with *LAS17*, *ARP2*, and *ARP3*

Stop codons of the *LAS17*, *ARP2*, and *ARP3* genes were replaced with the coding sequence of green fluorescent protein (GFP) by short flanking homology PCR targeting using the kanMX6 marker (Wach *et al.*, 1994). For *LAS17:GFP*, pFA6a-GFPS65TkanMX6 was used as template to amplify a 2.5-kb PCR fragment with oligonucleotides 5'-TAAAGTGGGAGCTCATGACGATATGGACAATGGTGATGATGGGCAGCGAGTAAAGGAGAGAAGAACTTT-3' and 5'-ACATAATTTCTATAACAGTAGTTTCATCTTTGTTGTCATTCCA-TCCGATGAATTCGAGCTC-3' as primers. This fragment was transformed into diploid FY1679, and G418-resistant recombinants were verified for correct integration by PCR across both borders. Sporulation and dissection of a heterozygous G418-resistant diploid revealed a 2:2 segregation of the kanMX6 marker, which coincided with GFP fluorescence. Strain FMW173GK (homozygous for *LAS17:GFP*) was constructed by mating a and α spores.

For GFP fusion with *ARP2*, the pFA6a-GFPS65TkanMX6 plasmid was modified to add a 5 \times glycine-alanine linker following the ORF and then used as template to amplify a 2.5-kb PCR fragment with oligonucleotides 5'-TGGCAAGAAAGCGGGCCATCTGCAATGACTAAATTTGGTCCAAGAGGATCCGGAGCAGGTGCT-3' and 5'-TCCATTTCCATTTTTCATTCGTAGATTTAACTTTTTTATTAAT-TCTTTTGTGTCGATGAATTCGAGCTCGTTT-3' as primers. A *ARP2:GFP* haploid strain was constructed and verified as above, and then α spores were mated to make strain FDW23GK. Growth of these strains was slow and temperature sensitive. To obtain *ARP2* strains with these fusion proteins that grew better, the GFP of modified pFA6a-GFPS65TkanMX6 plasmid was converted to *yEGFP* (Cor-

mack *et al.*, 1997) and integrated into one allele of the diploid *las17 Δ* strain, FDW174H, to create strain FDW180HK.

Similarly, to make a functional GFP fusion with *ARP3*, the stop codon of one allele of the *ARP3* gene was replaced by *yEGFP* using oligonucleotides 5-TATGGTCCGAAATTTGTTAGAAATTTTCAG-CCTTTTCAACATGGTTGGATCCGGAGCAGGTGCT-3' (*ARP3* in frame with *GAGAGAGAGA:EGFP*) and 5'-AGGGGCGTTTCAGT-TATTTGCATTTGTTTTTGTACCTTTTTCCCTTATAAGATCGATG-AATTCGAGCTGCTTT-3' as primers, and the resulting fragment was transformed into strain FY1679 to create strain FDW34GK and into FDW174H to create strain FDW190HK.

Cell Fixation, Phalloidin and Antibody Staining, and GFP Observation

Early log phase cells were fixed and stained as previously described (Pringle *et al.*, 1991), except that incubation with phalloidin was for 1 h with shaking at 4°C in the dark using 1 μ M TRITC-labeled phalloidin (Sigma, St. Louis, MO) or 1 μ M Alexa-594 phalloidin (Molecular Probes, Eugene, OR). Fixed cells were sometimes kept at 4°C for a maximum of 3 d before staining. For GFP observation, fixation time was reduced to 15 min. For in vivo observations of GFP fusion proteins, cells were grown in liquid YPD at 25°C to early log phase and then harvested, resuspended in 1 M sorbitol, and immediately observed using a GFP bandpass filter (excitation, 460–500; dichroic mirror, 505; emission, 510–560). Antibody staining of spheroplasts was as previously described (Moreau *et al.*, 1996) with C4 monoclonal mouse immunoglobulin G1 (IgG1) anti-actin antibody (Boehringer Mannheim, Indianapolis, IN) and polyclonal rabbit anti-GFP antibody (a gift from K. Sawin, London, United Kingdom). Preparations were analyzed and photographed using an Optiphot-2 microscope (Nikon, Melville, NY) equipped with fluorescent optics. Photographs were taken using 400ASA film and then scanned (300 dots per inch final resolution) or direct acquisitions were made with a Photonic (Milpitas, CA) Science charge-coupled device Coolview camera equipped with the Gel Grab 2.02 software program.

Table 2. Yeast strains used in this study

Strain	Genotype	Source
YPH499	<i>MATa, ade2-101, his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63, ura3-52</i>	P. Hieter
YPH500	<i>MATa, ade2-101, his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63, ura3-52</i>	P. Hieter
YPH501	<i>MATa, ade2-101, his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63, ura3-52</i>	P. Hieter
YMW11	<i>MATa, arp2::LEU2, ade2-101, his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63, ura3-52 (pYCW204)</i>	Moreau <i>et al.</i> (1996)
YMW81	<i>MATa, arp2-1(H330L), ade2-101, his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63, ura3-52</i>	Moreau <i>et al.</i> (1996)
YMW201U	<i>MATa, ARP2::URA3, ade2-101, his3-Δ200, leu2-1, lys2-801, trp1-Δ63, ura3-52</i>	This study
YMW211U	<i>MATa, arp2-1(H330L)::URA3, ade2-101, his3-Δ200, leu2-Δ1, lys2-80, trp1-Δ63, ura3-52</i>	This study
YMW221U	<i>MATa, arp2-2(G19D)::URA3, ade2-101, his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63, ura3-52</i>	This study
YMW231U	<i>MATa, arp2-7(F256K)::URA3, ade2-101, his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63, ura3-52</i>	This study
YMW241U	<i>MATa, arp2-4(L280P)::URA3, ade2-101, his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63, ura3-52</i>	This study
YMW251U	<i>MATa, arp2-5(L316S)::URA3, ade2-101, his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63, ura3-52</i>	This study
YMW261U	<i>MATa, arp2-6(G355 Y146N)::URA3, ade2-101, his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63, ura3-52</i>	This study
YMW271U	<i>MATa, arp2-7(F203Y)::URA3, ade2-101, his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63, ura3-52</i>	This study
YMW300T	<i>MATa, arp3Δ::TRP1, ade2-101, his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63 ura3-52</i>	This study
YMW301T	<i>MATa, ARP3, ade2-10, his3-Δ200, leu2-Δ1 lys2-801 trp1-Δ63 ura3-52</i>	This study
YMW311L	<i>MATa, arp3Δ::TRP1 ade2-101 his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63, ura3-52 (+pCMW 306)</i>	This study
YMW321L	<i>MATa, ARP3::LEU2, ade2-101, his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63, ura3-52</i>	This study
YMW171K	<i>MATa, arp3-14 (P33L aa 48-108Δ)::LEU2, ade2-101, his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63, ura3-52</i>	This study
YMW172K	<i>MATa, las17Δ::kanMX4, ade2-101, his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63, ura3-52</i>	This study
YMW173K	<i>MATa, las17Δ::kanMX4, ade2-101, his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63, ura3-52</i>	This study
YMW175K	<i>MATa, las17Δ::kanMX4, ade2-101, his3-Δ200, leu2-Δ1, lys2-801, trp1-Δ63, ura3-52</i>	This study
RH4207	<i>MATa, ura3-52, his3-Δ200, leu2-Δ1, arp2Δ::LEU2, trp1-Δ63 LAS17-PROTA::kanMX6 (pYEW248)</i>	This study
FY1679	<i>MATa, las17Δ::kanMX4, bar1::LYS2, ade2-101, his3-Δ200, leu2-Δ1, trp1-Δ63, ura3-52</i>	This study
FDW23GK	<i>MATa, his3-Δ200, leu2-Δ1, trp1-Δ63, ura3-52, GAL2</i>	B. Dujon/F. Winston (EUROFAN strain)
FDW24GK	<i>MATa, HIS3, LEU2, TRP1, ura3-52, GAL2</i>	This study
FDW34GK	<i>MATa, ARP2-S65TGFP::kanMX6, his3-Δ200, leu2-Δ1, trp1-Δ63, ura3-52, GAL2</i>	This study
FMW17GK	<i>MATa, ARP2-S65TGFP::kanMX6, his3-Δ200, LEU2, TRP1, ura3-52, GAL2</i>	This study
FDW174H	<i>MATa, ARP2, his3-Δ200, leu2-Δ1, trp1-Δ63, ura3-52 GAL2</i>	This study
FDW180HK	<i>MATa, ARP2-EGFP::kanMX6, HIS3, LEU2, TRP1, ura3-52 GAL2</i>	This study
FDW190HK	<i>MATa, ARP3, his3-Δ200, leu2-Δ, 1 trp1-Δ63, ura3-52, GAL2</i>	This study
W303	<i>MATa, ARP3-EGFP::kanMX6, HIS3, LEU2, TRP1, ura3-52, GAL2</i>	This study
Y187	<i>MATa, LAS17-GFP::kanMX4, his3-Δ200, leu2-Δ1, trp1-Δ63, ura3-52, GAL2</i>	This study
Y190	<i>MATa, LAS17-GFP::kanMX4, HIS3, LEU2, trp1-Δ63, ura3-52, GAL2</i>	This study
CG1945	<i>MATa, las17Δ::HISMx6, his3-Δ200, LEU2, TRP1, ura3-52, GAL2</i>	This study
	<i>MATa, las17Δ::HISMx6, his3-Δ200, LEU2, TRP1, ura3-52, GAL2</i>	This study
	<i>MATa, las17Δ::HISMx6, ARP2, his3-Δ200, LEU2, TRP1, ura3-52, GAL2</i>	This study
	<i>MATa, las17Δ::HISMx6, ARP2-EGFP::kanMX6, his3-Δ200, LEU2, TRP1, ura3-52, GAL2</i>	This study
	<i>MATa, las17Δ::HISMx6, ARP3, his3-Δ200, LEU2, TRP1, ura3-52, GAL2</i>	This study
	<i>MATa, las17Δ::HISMx6, ARP3-EGFP::kanMX6, his3-Δ200, LEU2, TRP1, ura3-52, GAL2</i>	This study
	<i>MATa, his3-Δ1, leu2-3,112, trp1-289, ura3-52</i>	P. Philippsen
	<i>MATa, his3-Δ1, leu2-3,112, trp1-289, ura3-52</i>	EUROFAN strain
	<i>MATa, gal4Δ, gal80Δ, his3, trp1-901, ade2-101, leu2-3,112, ura3-52, URA3::GAL1(UAS)-lacZ,</i> transformed by the FRYL yeast DNA genomic library	Durfee <i>et al.</i> (1993)
	<i>MATa, gal4Δ gal80Δ his3 trp-901 ade2-101 leu2-3,112 ura3-52 URA3::GAL1(UAS)-lacZ</i>	James <i>et al.</i> (1996)
	<i>LYS2::GAL1(UAS)-HIS3 cyh^r</i>	James <i>et al.</i> (1996)
	<i>MATa, gal4-542, gal80-538, his3, trp-901, ade2-101, leu2-3,112, ura3-52, URA3::GAL4(3x17mers)-</i> <i>CYC1(TATA)-lacZ,LYS2::GAL1(UAS)-GAL1(TATA)-HIS3, cyh^r</i>	P. Legrain
		Froment-Racine <i>et al.</i> (1997)

YMW strains and the RH strain are isogenic derivatives of YPH strains. Strain names beginning with F are isogenic FY1679 derivatives. Both of these series of strains are derivatives of S288C.

Latrunculin Treatment of GFP-labeled Cells

After growth to midlog phase at 25°C in liquid YPD, cells were concentrated to 10⁸ cells/ml. Latrunculin-A (Molecular Probes) in DMSO (from a 10 mM stock to give 100 μM final concentration) or an equivalent volume of DMSO was added to a 100 μl aliquot for each condition tested. Cells were fixed by adding 10 vol of YPD containing 3.7% formaldehyde and incubating with gentle shaking for 15 min.

Lucifer Yellow and FM4-64 Staining and α-Factor Uptake

Lucifer yellow (LY)-carbohydrazine (Fluka, Buchs, Switzerland) uptake, an indication of fluid phase endocytosis, was done as described by Dulic *et al.* (1991). Staining with the lipophilic dye FM4-64 [N-(3-triethylammoniumpropyl)-4-(p-diethylaminophenyl)-hexatrienyl] pyridinium dibromide] to follow uptake into mem-

branes was as described by Vida and Emr (1995). ³⁵S-Alpha factor uptake assays were performed as described (Dulic *et al.*, 1991). All strains were preincubated at 37°C for 15 min before the addition of alpha factor. The samples were processed as described above. All uptake assays were performed twice.

Immunoprecipitation of Las17p and Arp2p

To tag Las17p with protein A, the stop codon of the *LAS17* gene was replaced by the coding frame of the IgG binding domain of protein A using the kanMX6 selection marker as a PCR-synthesized fragment with short flanking homology on either side of the *LAS17* stop codon. pYM7 was the template source of protein A (Knop *et al.*, 1999), amplified with the same primers as for the *LAS17:GFP* fusion. The resulting 2.1-kb PCR fragment was transformed into the diploid strain FY1679, which was sporulated. G418-resistant progeny were verified for correct tag insertion by PCR. One of these haploids was crossed with a haploid *arp2Δ* rescued by hemagglutinin (HA)-tagged Arp2p (YMW15 + pYEW250) (Moreau *et al.*, 1996), and a recombinant haploid derivative was selected (strain YMW175K).

Whole-cell extracts were made by the liquid nitrogen grinding in 50 mM HEPES, pH 7.5, 100 mM KCl, 3 mM MgCl₂, 1 mM EGTA, 0.5% Triton X-100 buffer (Li, 1997) and resuspended at 10 mg/ml after clarification by 30 min of centrifugation at 20,000 × *g*. Eighty microliters of Las17-prot A extract and nontagged extract were incubated for 1 h at 4°C with 40 μl of IgG-Sepharose (6 Fast Flow; Pharmacia, Piscataway, NJ) suspension. Immunoprecipitation and washes were with starting buffer. Eluted proteins were precipitated with 10% trichloroacetic acid and resuspended in loading buffer. Samples were separated by 10% PAGE and blotted to nitrocellulose. Blots were incubated with appropriate primary and secondary antibodies and then developed with a Super Signal (Pierce, Rockford, IL) chemiluminescent kit for HRP.

IgG to reveal Las17-prot A was purified from nonimmunized rabbit serum by passage over a protein A-Sepharose column (Pharmacia CL-4B). Production and characterization of anti-Arp2p antibodies has been previously described (Moreau *et al.*, 1996).

Construction of GAL4 Fusion Plasmids for Two-Hybrid Interactions

LAS17 was amplified with oligonucleotides 5'-GGCGTGATTTAC-CATGGGACTCC-3' (with an *NcoI* site at the ATG of *LAS17*) and 5'-CATCTTCTCGAGCATTCCATTACCAA-3' (with an *XhoI* site just after the stop codon) using pAMW171 as template. A 1.9-kb *NcoI-XhoI* PCR fragment was cloned into the *NcoI-SalI* sites of pAS2 in fusion with *GAL4* binding domain (*GAL4BD*) to give pBMW172 and into the *NcoI-XhoI* sites of pACTII in fusion with *GAL4* activation domain (*GAL4AD*) to give pAMW173. Both pBMW172 and pAMW173 were able to rescue YMW171K (*las17Δ*) at 25 and 37°C (our unpublished data). All *GAL4* fusions constructed were systematically controlled by sequencing the fusion site. Two-hybrid *GAL4AD* constructions coding for wild-type Cdc42p and its activated form (Cdc42p^{G12V}) were kindly provided by E. Leberer (Leberer *et al.*, 1997) and by the Pringle laboratory (Cvrckova *et al.*, 1995).

Two-Hybrid Screens with LAS17 as Bait

cDNA Screen. Y190 strain (Durfee *et al.*, 1993) containing pBMW172 (*GAL4BD-LAS17*) was transformed with a yeast cDNA library in pGAD-GH (kindly provided by Michael White, University of Texas Southwestern Medical School, Dallas, TX) and plated on SC – Trp, Leu, and His supplemented with 35 mM 3-aminotriazole (3-AT). After incubation for 1 wk at 30°C, 309 colonies among 200,000 initial transformants were patched onto SC – Trp, Leu, and His 35 mM 3-AT plates and allowed to grow at 30°C for 2 d. These clones were then tested in a 5-bromo-4-chloro-3-indolyl-β-D-galactopyranoside (X-Gal) filter assay, and clones that turned blue were further ana-

lyzed. Plasmids were rescued and reintroduced into Y190 and Y190 containing pBMW172 and tested in the X-Gal colony filter assay. One hundred sixty plasmids giving a signal with pBMW172 were sequenced with oligonucleotides 5'-GGAATCACTACAGGGATG-3' to control in-frame fusions and with 5'-GAAGTGAAGTTGCGGGG-3' to determine the size of the fused protein. After elimination of redundant fusions, 23 different positive clones representing 10 different genes were identified and tested in β-galactosidase liquid culture assays.

Genomic DNA Screen. Yeast strain Y187 was transformed by standard procedures with DNA amplified from an aliquot of the FRYL library (Fromont-Racine *et al.*, 1997). Ten million yeast transformants were collected and pooled, and aliquots were stored at –80°C. To screen by mating, a tube containing 10⁷ transformants was equilibrated in fresh YPD then mixed with 2 × 10⁷ log phase CG1945 cells previously transformed with plasmid pBMW172 (*GAL4BD-LAS17*) and incubated for 6 h. Cells representing 1.15 × 10⁶ diploids were plated on SC – Trp, Leu, and His supplemented with 35 mM 3-AT and incubated at 30°C for 7 d. The clones thus obtained were assayed as described above then recycled, and plasmids were extracted and sequenced.

X-Gal Colony Filter Assay and β-Galactosidase Assay

β-Galactosidase activity of simple or double transformants of Y190 was assessed on nitrocellulose filters as described by Breeden and Nasmyth (1985). To quantitate β-galactosidase activity, freshly streaked Y190 double transformants were inoculated into 2.5 ml of liquid SC – Trp and Leu and allowed to grow overnight to OD_{600 nm} of ~1. β-Galactosidase activity was measured and expressed in Miller units (Kandels-Lewis and Seraphin, 1993).

RESULTS

LAS17 Is an Allele-specific Multicopy Suppressor of *ARP2* *ts* Mutations

To identify proteins that interact with Arp2p, we screened yeast multicopy genomic libraries for clones whose expression was able to rescue the temperature sensitivity of the *arp2-1* mutation in strain YMW81. In a preliminary screen using the Lacroute genomic bank we obtained several clones, the smallest of which contained a plasmid, pYEW170, with an insert of 4 kb covering several genes. Using the Fields and Bartel YL1/2/3 genomic bank, 24 plasmids were able to support growth at 37°C. Besides the *ARP2* gene, seven groups of inserts were identified. Sequencing of insert borders revealed that all seven clones contained a full-length *LAS17* coding sequence. Because the inserts of the two shortest clones did not overlap any adjacent coding regions, we concluded that *LAS17* was responsible for suppression.

Suppression of previously isolated *ts* mutations *arp2-1* to *arp2-7* (Moreau *et al.*, 1996) was tested to find out whether *LAS17* suppression was allele specific. Sequence changes in the *ARP2* gene were determined and are shown in Table 2. WT and mutant fragments tagged with the *URA3* gene were integrated into strain YPH499 at the *ARP2* locus (see MATERIALS AND METHODS), giving rise to strains YMW211U to YMW271U. We have previously shown that the *arp2-1* *ts* mutation causes delocalization of polarized cortical actin patches at 37°C (Moreau *et al.*, 1996). When strains YMW221U to YMW271U were stained with phalloidin, actin distribution appeared normal in most cells of

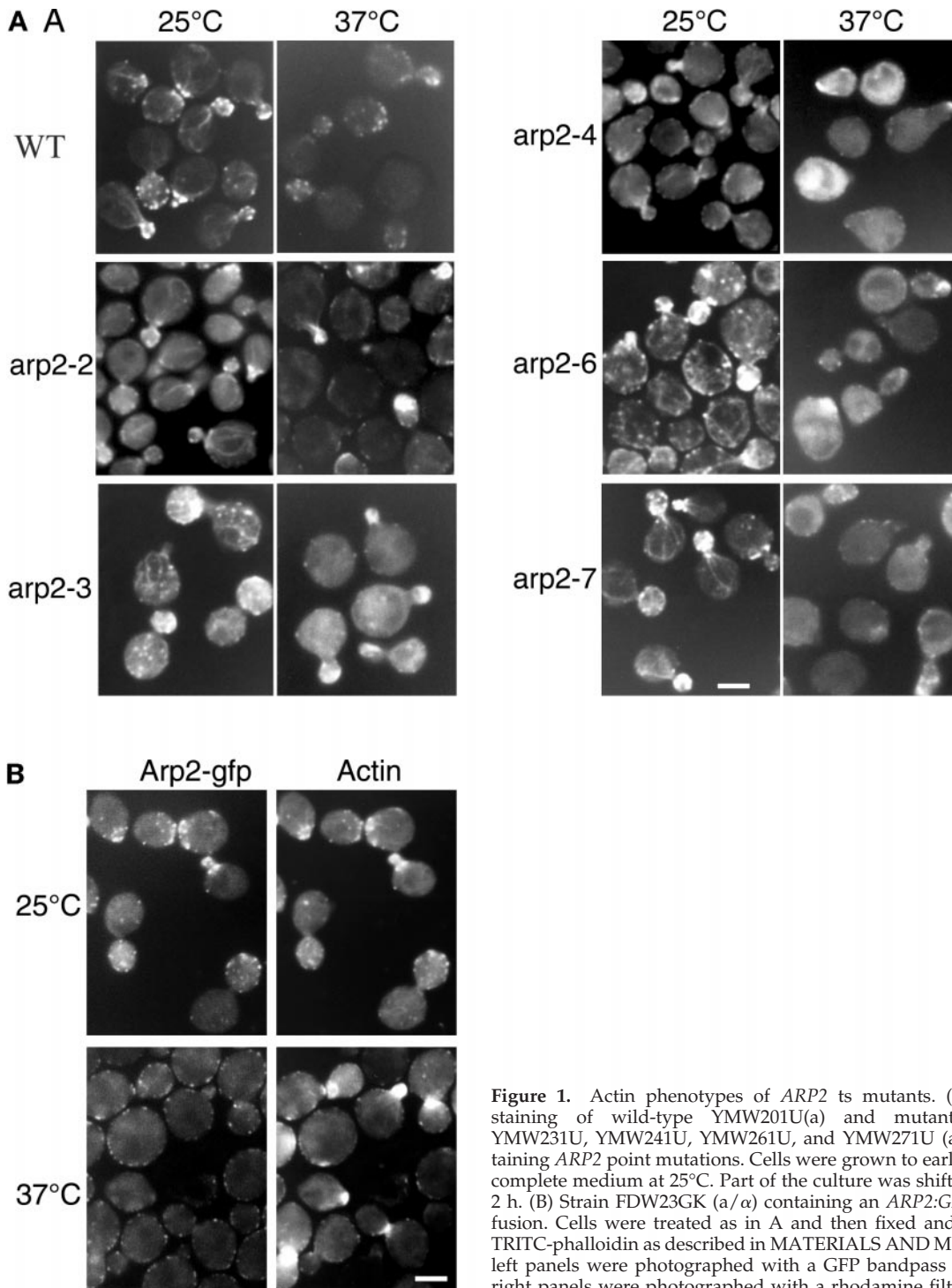


Figure 1. Actin phenotypes of *ARP2* ts mutants. (A) Phalloidin staining of wild-type YMW201U(a) and mutant YMW221U, YMW231U, YMW241U, YMW261U, and YMW271U (a) strains containing *ARP2* point mutations. Cells were grown to early log phase in complete medium at 25°C. Part of the culture was shifted to 37°C for 2 h. (B) Strain FDW23GK (a/a) containing an *ARP2::GFP* C-terminal fusion. Cells were treated as in A and then fixed and stained with TRITC-phalloidin as described in MATERIALS AND METHODS. The left panels were photographed with a GFP bandpass filter, and the right panels were photographed with a rhodamine filter. Bar, 5 μ m.

arp2-2, *arp2-4*, *arp2-5*, and *arp2-7* at 25°C, whereas *arp2-3* and *arp2-6* cells showed loss of actin organization at this temperature (Figure 1A). All mutants had lost the polarized distribution of actin patches after 2 h at the restrictive temperature. Actin clumps or aggregates in the bud or at the mother–daughter neck and an enlarged bud neck were ob-

served in budding cells of each of the ts mutants. Surprisingly, none of these mutant actin phenotypes was qualitatively different from those observed for the original *arp2-1* mutant. A similar ts phenotype also resulted from fusion of green fluorescent protein to the carboxyl terminus of the *ARP2* coding sequence (see MATERIALS AND METHODS).

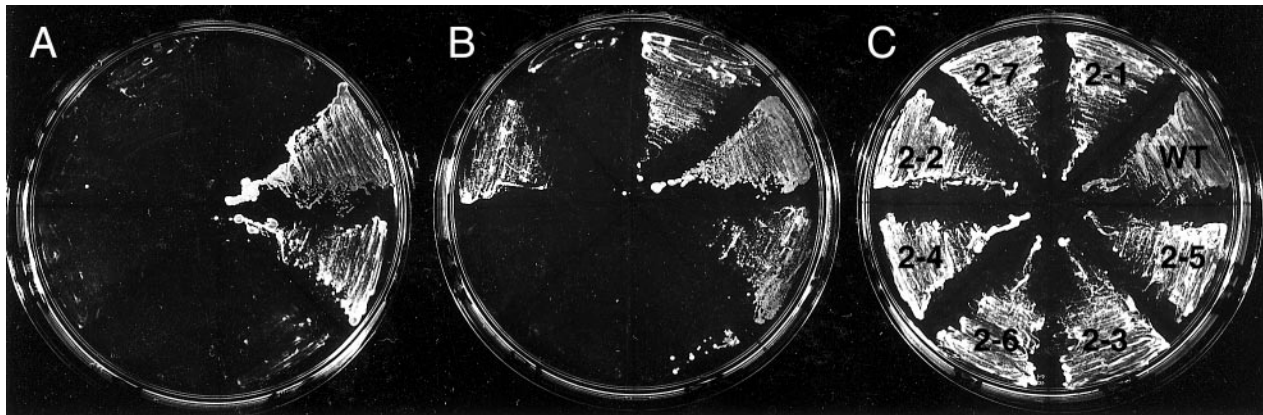


Figure 2. *LAS17* overexpression suppresses certain *ARP2* ts mutants. Seven *ARP2* ts strains (*arp2-1* to 2-7/YMW211U–YMW271U) and wild-type (YMW201U) described in Table 2 were transformed with pGAD (vector) (A), pAMW171 (*LAS17* in pGAD) (B), and pAMW200 (*ARP2* in pGAD) (C). Transformants were streaked on SC – Ura and Leu plates and incubated at 37°C for 4 d. Note that the *arp2-5* ts mutant grows at 37°C on minimal medium but is more ts on complete medium.

Examination of the *ARP2-GFP* strain did not reveal any Arp2-gfp fluorescence in the many phalloidin-staining actin aggregates present in buds or in mother–bud necks, whereas both actin and Arp2p were present in the remaining nonpolarized patches (Figure 1B).

These *ARP2* mutants were used to test allele specificity of *LAS17* suppression. When *ARP2* strains were transformed by a multicopy *LAS17* plasmid, pAMW171, the *arp2-2* mutant as well as the *arp2-1* mutant initially used in the selection were rescued at 37°C. The thermosensitivity of the other mutants was not relieved (Figure 2). This clearly shows that suppression is specific to certain point mutations and suggests that a specific interaction could be involved. Major mutant phenotypes such as disorganization of the actin cytoskeleton and deficient endocytosis were examined in *LAS17*-suppressed strains YMW211U, YMW221U, and YMW241U. *LAS17* overexpression suppressed actin cytoskeleton defects in the *arp2-1* mutant and partially suppressed defects of the *arp2-2* mutant at 37°C, in good correspondence with growth recovery. Figure 3A shows that even partial suppression in the *arp2-2* mutant is clearly visible; the majority of *arp2-2* ts cells containing overexpressed *LAS17* no longer showed aberrant clumped actin in the bud at 37°C (Figure 3A, b, lower panel). Actin patches were less concentrated in the buds than in rescued cells (Figure 3A, c, lower panel). Suppression of endocytosis as judged by the ability of cells to take up and deliver the fluorescent neutral dye Lucifer yellow-carbohydrazine to the vacuole by fluid phase endocytosis (Riezman, 1985) followed the same pattern of allele specificity as growth and actin defects. Even at permissive growth temperature after extended times (60 min here vs. 10 min normally), uptake was inhibited in the *arp2-2* mutant (Figure 3B, a, compared with the rescued mutant, c). The *LAS17* overexpression allowed LY uptake and accumulation in the vacuole in the *arp2-2* mutant (Figure 3B, b) although slightly less efficiently than for the *arp2-1* allele (our unpublished data). Investigation of the *arp2-4* allele revealed that the mutant was also endocytosis deficient but that *LAS17* overexpression did not rescue this deficiency.

LAS17 Overexpression Can Also Rescue Conditional Mutations in the *ARP3* Gene

Because Arp2p and Arp3p are part of the same macromolecular complex (Machesky *et al.*, 1994; Welch *et al.*, 1997b; Winter *et al.*, 1997), we questioned whether *LAS17* overexpression would also suppress the phenotype of *ARP3* conditional mutations. We have isolated recessive *ARP3* ts alleles on plasmids in an *arp3Δ* strain (Madania, 1998). The capacity of *LAS17* overexpression to rescue growth at non-permissive temperatures for six different mutants, *arp3-9* to *arp3-14*, was tested. Only one ts mutant, *arp3-9*, was well suppressed at 37°C. At 36°C *LAS17* overexpression allowed good growth of *arp3-9*, *arp3-10*, and *arp3-13* mutants and some growth of *arp3-12* mutant, whereas growth of *arp3-11* and *arp3-14* mutants was not rescued (Figure 4). Thus, *LAS17* is also an allele-specific suppressor of *ARP3* mutants indicating that Las17p interaction with the Arp2/3 complex is important for at least one essential function.

Synthetic Enhancement of *LAS17* Deletion with *ARP2* and *ARP3* Mutants

To gain further information on Las17p interactions with Arp2p and Arp3p, we looked for synthetic enhancement between *las17Δ* and *ARP2* or *ARP3* mutants. The *las17Δ* strain YMW172K was crossed with seven *URA3*-tagged *ARP2* and one *LEU2*-tagged *ARP3* integrated mutants (see MATERIALS AND METHODS). Viable haploid spores after meiosis were tested for G418 resistance (kanMX4 marker for *las17Δ*) and for uracil and leucine prototrophy (Table 3). As demonstrated by the absence of viable double mutants, six of seven different *ARP2* ts mutants, *arp2-1*, *arp2-2*, *arp2-3*, *arp2-4*, *arp2-5*, and *arp2-6*, are lethal in the absence of *LAS17*. Analysis of a cross between strain YMW321L bearing *arp3-14:LEU2* and strain YMW171K bearing *las17Δ* revealed no viable kanR Leu⁺ spores (Table 3). These synthetic lethality results between *las17Δ* and *ARP2* and *ARP3* ts mutants confirmed the importance of Las17p in the vital functions of Arp2p and Arp3p, prompting us to further investigate the cellular functions and interactions of Las17p.

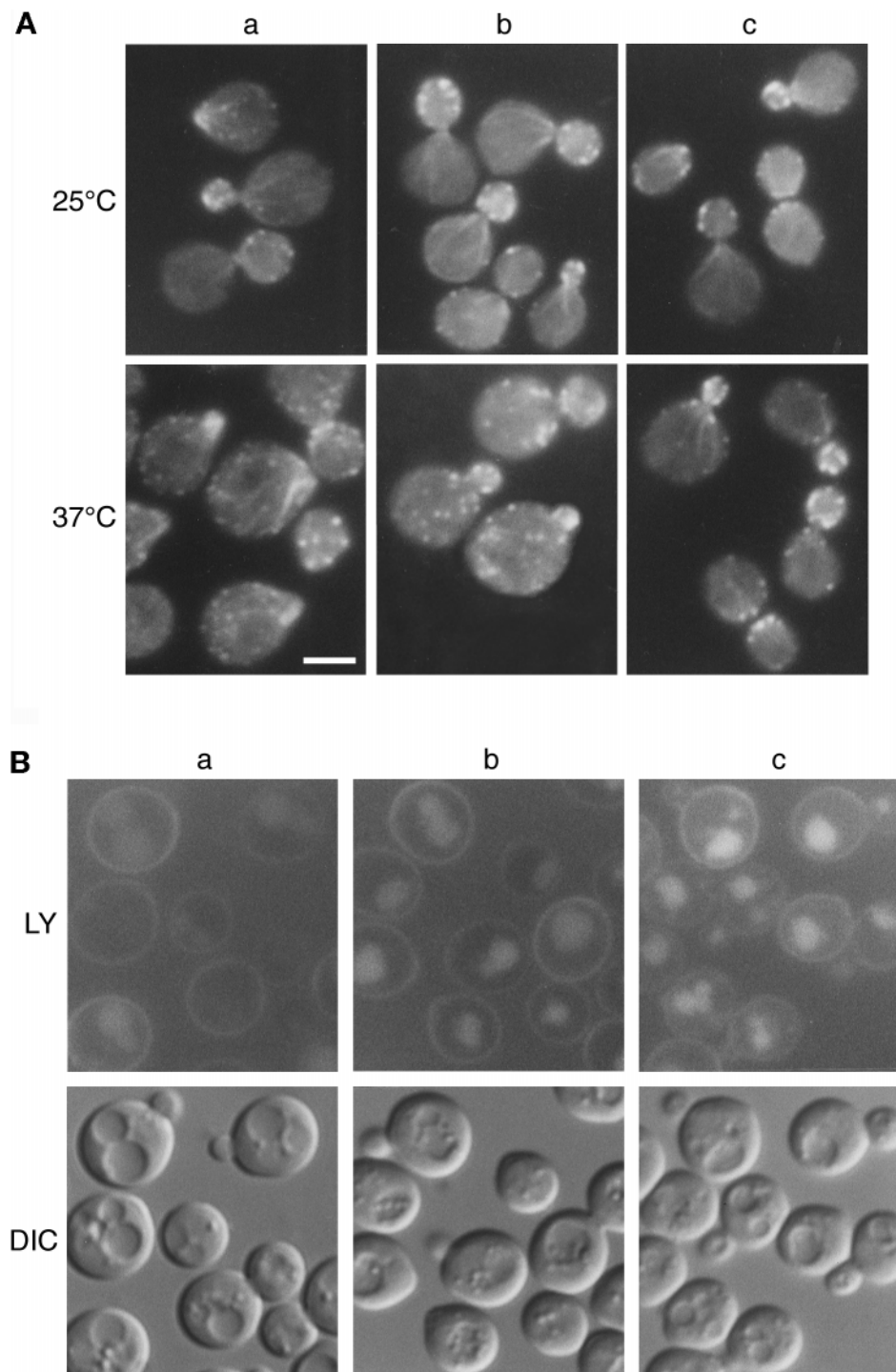


Figure 3. Suppression of *arp2-2* actin and endocytosis phenotypes by *LAS17*. Strain YMW221U (bearing the *arp2-2:URA3* ts allele) was transformed with vector (a), with pAMW171 (*LAS17* 2 μ) (b), and with pAMW200 (*ARP2* in pGAD) (c). (A) Transformants were grown at 25°C in liquid YPD to log phase and shifted to 37°C for 2 h. Cells were fixed, stained with TRITC-phalloidin, and photographed as described in MATERIALS AND METHODS. Bar, 5 μ m. (B) Transformants were grown in liquid YPD at 25°C to log phase and incubated for 1 h with LY as described in MATERIALS AND METHODS. Cells were photographed using an FITC filter (LY) or Nomarski optics (differential interference contrast [DIC]).

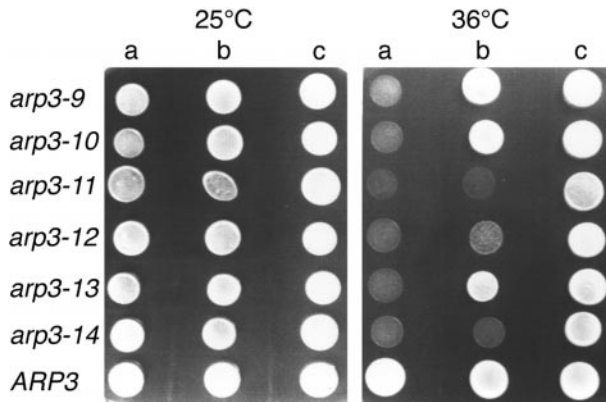


Figure 4. LAS17 allele-specific suppression of ARP3 ts mutants. The *arp3* Δ (YMW301T) strain rescued by five different ARP3 ts alleles (*arp3-9* to *arp3-13* and ARP3) and strain YMW321L (bearing the *arp3-14:LEU2* allele) were transformed by vector (a), pYEW170 (*LAS17*, 2 μ) (b), or pCMW304 rescue plasmid (*ARP3:LEU2*) (c). Freshly cultured transformants were spotted onto YNB – Leu and Ura plates, which were incubated at 25°C for 5 d or at 36°C for 3 d before being photographed.

Phenotypes of *las17* Δ Mutant Cells

Deletion of *LAS17* in the S288C strain background has been reported to cause temperature-sensitive growth, budding, and cytokinesis defects with aberrant actin bundles and lack of patches in the buds (Li, 1997). *las17* Δ cells showed misshapen unpinched bud necks and actin cortical patch defects as described (Li, 1997), except that actin-containing patches were visible in both the bud and the mother cell, as has been since reported (Karpova *et al.*, 1998). We found that deletion of *LAS17* results in lethality or temperature sensitivity, depending on the strain background. The phenotype was more severe in the W303 background than in the YPH or FY1679 background. Testing of *las17* Δ ts cells in the presence of osmoregulators showed that they were acutely osmosensi-

tive. Growth was completely inhibited at 25°C with 0.30 M NaCl or 1.8 M sorbitol added to complete medium.

Because *LAS17* overexpression suppressed defective endocytosis in certain ARP2 and ARP3 mutants, we also investigated endocytosis in *las17* Δ cells using a variety of methods. Three different reporter systems were used to reveal different aspects of endocytosis; LY for fluid phase endocytosis, the lipophilic vital stain FM4-64 to follow membrane internalization (Vida and Emr, 1995), and α -factor pheromone uptake to follow ligand-dependent receptor-mediated (Ste2p) endocytosis (Singer and Riezman, 1990; Riezman, 1993). Naqvi *et al.* (1998) have recently reported deficient LY endocytosis by *las17* Δ cells. Our independent results showed severe deficiency at the permissive growth temperature with no visible accumulation in the vacuole. We also examined strain YMW171K after incubation with FM4-64 to follow the intracellular fate of the dye. Very little dye was taken up by mutant relative to wild-type cells (Figure 5A). Nevertheless, trafficking through membrane compartments without accumulation in intermediary (endosomal) structures in addition to accumulation of weak fluorescence in membranes around the vacuole suggests that the dye progressed to its normal destination. Thus, the pathway from the plasma membrane to the vacuole appears to function normally.

Pheromone recognition and receptor internalization are the first steps in receptor-mediated endocytosis. The ability of cells to bind and internalize α -factor is constant throughout the cell cycle, allowing measurement of ligand-dependent internalization of the Ste2p receptor in growing cells (Zanolari and Riezman, 1991). To increase sensitivity to α -factor, strain YMW171K and its parent were first disrupted for the *BAR1* gene (MacKay *et al.*, 1988). Radioactive uptake of biosynthetically labeled α -factor across the plasma membrane was then quantified. Figure 5B shows that in cells grown at 24°C, tested before and after shift up to 37°C, α -factor binds to *las17* Δ cells. However, receptor-mediated endocytosis is severely deficient at 24°C, and uptake is indistinguishable from background at 37°C. Taken together

Table 3. Synthetic lethality of *las17* Δ with ARP2 and ARP3 mutant alleles

Cross	No. tetrads	No. spores <i>Ura3⁺kanR</i>	No. spores <i>Leu2⁺kanR</i>	No. viable spores	No. dead spores
<i>las17</i> Δ \times <i>arp2-1</i>	35	28		0	28
<i>las17</i> Δ \times <i>arp2-2</i>	18	15		0	15
<i>las17</i> Δ \times <i>arp2-3</i>	17	19		0	19
<i>las17</i> Δ \times <i>arp2-4</i>	17	16		0	16
<i>las17</i> Δ \times <i>arp2-5</i>	17	15		0	15
<i>las17</i> Δ \times <i>arp2-6</i>	15	12		0	12
<i>las17</i> Δ \times <i>arp2-7</i>	15	14		14	0
<i>las17</i> Δ \times ARP2	17	13		12	1
<i>las17</i> Δ \times <i>arp3-14</i>	44		37	0	37
<i>las17</i> Δ \times ARP3	45		53	48	5

Strain YMW172K (MAT α *las17*) was crossed with strains YMW201U (ARP2:*URA3*) and YMW211U to YMW271U (*arp2ts:URA3*). Strain YMW172K (MAT α *las17* Δ :*kanMX4*) was crossed with strains YMW311L (MAT α *ARP3:LEU2*) and YMW321L (MAT α *arp3-14:LEU2*). Diploids were sporulated, tetrads were dissected, and viable spores were tested for G418 resistance and for growth on SC – Ura at 25°C. The genotype of dead spores was inferred from that of viable spores in each tetrad tested. For each cross the number of tetrads was analyzed, and the number of double mutants and the number of viable and dead spores among these double mutants is indicated.

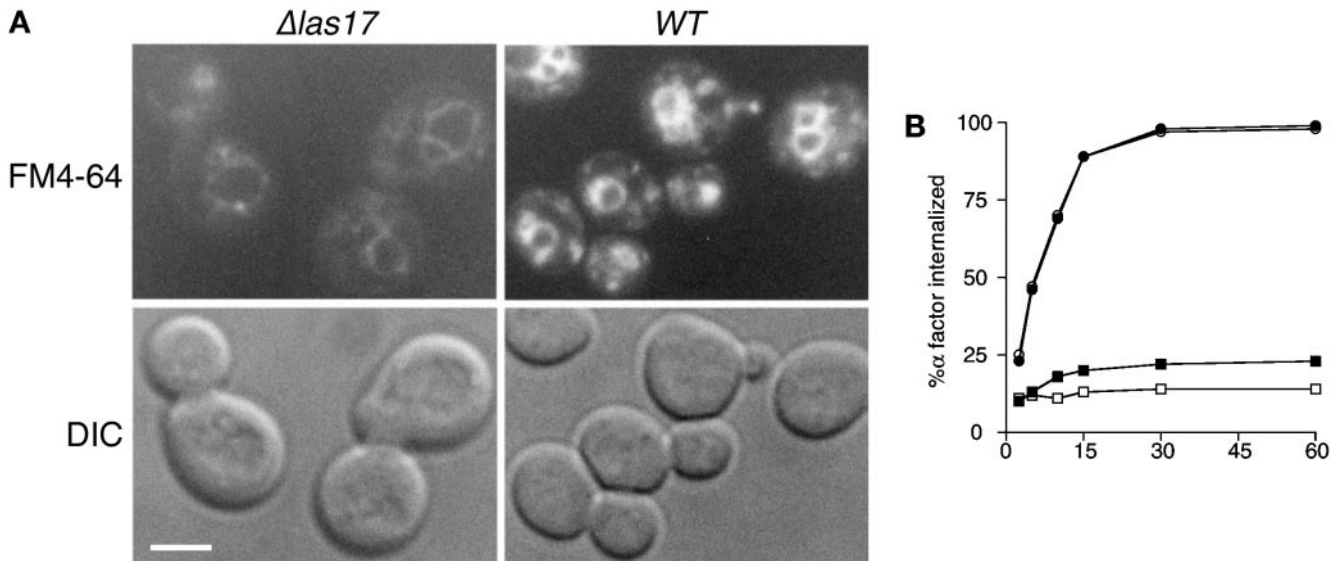


Figure 5. Endocytosis defects in *las17* Δ cells. (A) FM4-64 uptake by *las17* Δ cells. YMW171K (*las17* Δ) and YPH499 (WT) cells were grown to log phase in liquid YPD at 25°C and then concentrated and incubated for 15 min in 20 μ M FM4-64 followed by a 45-min chase in fresh YPD. Cells were photographed using an FITC filter (top panel) or DIC optics (bottom panel). Bar, 5 μ m. (B) Alpha factor internalization by *las17* Δ cells. *las17* Δ strain RH 4207 and its equivalent wild type were preincubated at 37°C for 15 min before the addition of 35 S-alpha factor. The samples were processed as described by Dulic *et al.* (1991). Results are from one of two independent experiments, which gave nearly identical results. ●, WT, 24°C; ■, *las17* Δ , 24°C; ○, WT, 37°C; □, *las17* Δ , 37°C.

these results allow us to conclude that Las17p is essential for the internalization step of endocytosis.

Las17p Is Also a Determinant for Polarity Development

The actin cytoskeleton is required for the diploid-specific bipolar budding pattern normally seen in wild-type cells, and mutations in a number of cortical patch components affect this pattern (Rodriguez and Paterson, 1990; Sivadon *et al.*, 1995; Vaduva *et al.*, 1997; Yang *et al.*, 1997). When the bipolar budding pattern was examined, most *las17* Δ diploid cells had randomly located bud scars, whereas wild-type cells showed a normal bipolar budding pattern (Figure 6). Thus, the choice of the bud site, an initial step in the determination of a growth polarity, appears to be the primary defect rather than bud emergence or growth.

Las17-gfp Localizes to Cortical Patches Independently of Polymerized Actin

Las17p has been shown to coprecipitate with G-actin and is important for in vitro reconstitution of cortical actin assembly sites (Lechler and Li, 1997; Li, 1997). To visualize Las17p in living cells, an in situ fusion with GFP was constructed to replace *LAS17* (see MATERIALS AND METHODS). *LAS17::GFP* spores grew well at all temperatures, confirming functionality. GFP fluorescence in strain FMW17GK localized in cortical patch structures concentrated at sites of bud emergence, in small buds and at the bud neck before cytokinesis. When *LAS17::GFP* cells were fixed and stained with phalloidin, actin and Las17-gfp patches colocalized (control cells; Figure 7). This in vivo colocalization confirms that estab-

lished using an overexpressed Myc-tagged Las17/Bee1p (Li, 1997). We then examined the consequences of disrupting the (polymerized) actin cytoskeleton with latrunculin-A on Las17p localization. The drug latrunculin-A binds G-actin (Coué *et al.*, 1987) and has been shown to rapidly disrupt the yeast actin cytoskeleton by inhibiting actin filament assembly (Ayscough *et al.*, 1997). FMW17GK cells expressing Las17-gfp were treated for 5, 15, or 30 min with 100 μ M latrunculin-A and then briefly fixed, washed, and stained with phalloidin. Actin filaments were no longer detectable by the 5 min time point, whereas Las17-gfp remained localized in cortical patch-like structures at presumptive bud sites,

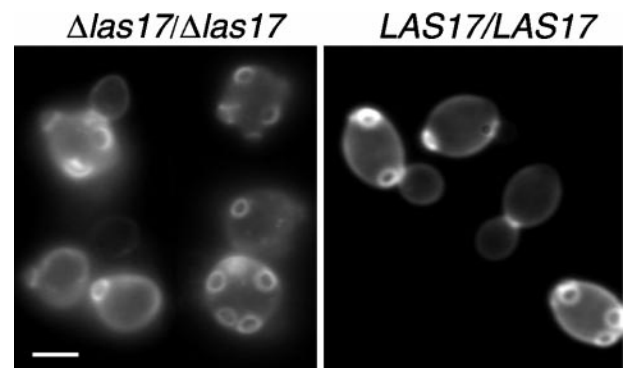


Figure 6. Bipolar budding defects in *las17* Δ /*las17* Δ cells. Strain FMW173K was grown overnight in YPD at 25°C. Cells were fixed and stained with calcofluor, washed, and observed in the microscope with a UV filter. Bar, 5 μ m.

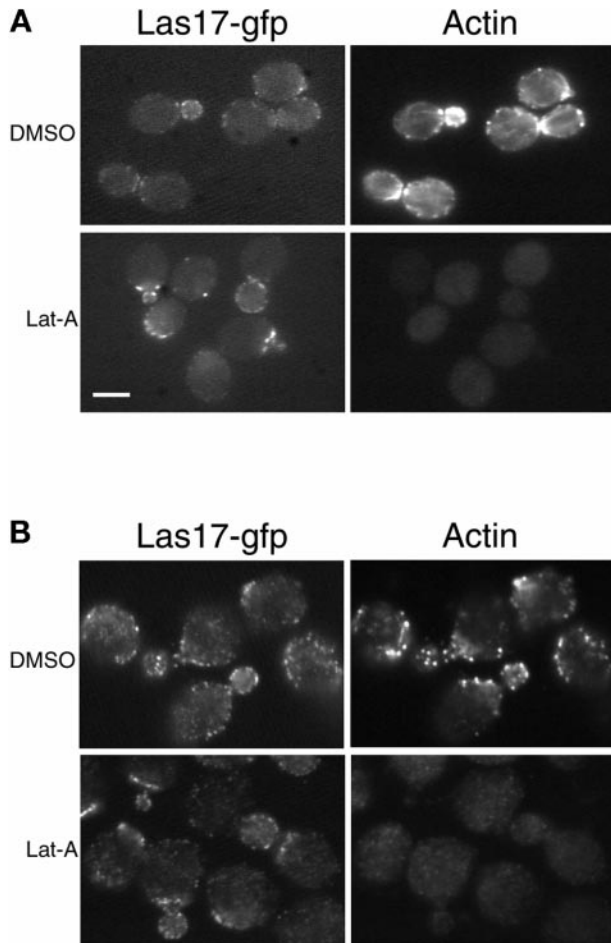


Figure 7. Functional Las17-gfp remains localized independently of actin. (A) Localization of Las17p at 25°C after treatment of cells with latrunculin-A. Strain YMW173G homozygous for *LAS17:GFP* was grown in liquid YPD to log phase at 25°C and incubated with latrunculin-A (100 μ M final concentration) in DMSO or an equivalent volume of DMSO. Images show cells fixed after 30 min exposure to latrunculin-A, which were briefly fixed and then stained with Alexa-phalloidin. Bar, 5 μ m. (B) Cells were grown as in A, fixed for 1 h, and then digested with zymolyase to make spheroplasts. Spheroplasts were labeled with rabbit anti-GFP IgG (left panels) and mouse monoclonal anti-actin IgG (right panels), which were revealed by goat anti-rabbit FITC and goat anti-mouse Cy5 antibodies using appropriate filters. No overlap between filter channels was detected in control exposures.

in small buds, and at the mother–daughter bud neck of dividing cells. This localization remained up to 30 min after latrunculin-A treatment (Figure 7A), although cells were slightly larger and more rounded than at the 5-min time point, indicating anisotropic cell growth. Las17p localization is thus maintained in the absence of actin cytoskeletal structures needed for polarized growth. Because Las17p might bind actin monomers or dimers not revealed by phalloidin staining, we also examined latrunculin-A-treated cells using anti-actin antibodies. After 30 min of latrunculin-A treatment, control cells (Figure 7B, upper panels) showed normal polarized distribution of both actin and Las17-gfp. How-

ever, no concentration of actin was detected in patch structures, whereas anti-GFP antibodies clearly revealed Las17-gfp concentrated in polarized patches (Figure 7B, lower panels) in the majority of cells.

Las17p Is Necessary for the Polarized Localization of Arp2p and Arp3p

We then addressed the question of whether Las17p was necessary for polarized localization of Arp2p and Arp3p. Because Arp2-gfp and Arp3-gfp fusion proteins as unique source of Arp caused ts growth in haploids (our unpublished observations), we tagged one allele in a diploid strain to render these fusion proteins functional. *ARP2:EGFP* and *ARP3:EGFP* were integrated on one allele of a *las17 Δ /las17 Δ* strain (FDW174H) giving rise to strains FDW180HK and FDW190HK, respectively. Diploid strains were no longer ts, and both Arp2-egfp (Figure 8A, strain FDW24GK) and Arp3-egfp (Figure 8B, strain FDW34GK) were localized in a polarized manner. In the absence of Las17p, Arp2-egfp and Arp3-egfp patches were clearly visible at the cortex (Figure 8, A and B, lower panels) but were not organized in a polarized manner. This depolarization of Arp2p patches was also observed (using Arp2p antibody) after latrunculin-A treatment (Ayscough *et al.*, 1997). Loss of patch organization indicates that Las17p is a necessary polarity determinant for the localization of the Arp2/3 complex as well as for actin patches as shown above.

Does Las17p Interact Physically with the Arp2/3 Complex ?

Because *LAS17* showed genetic and functional interactions with *ARP2* and *ARP3*, we asked whether Las17p could interact directly with Arp2p and/or Arp3p using the two-hybrid system. Constructions are described in MATERIALS AND METHODS. Las17p bait showed activation with actin as expected, but significant Las17p interaction was not detected with Arp2p or Arp3p fusions (Table 4). In light of specific genetic interactions between Las17p and Arp2p and Arp3p, we pursued the possibility of direct interaction between Las17p and the Arp2/3 complex by immunoprecipitation of Las17p from crude extracts. The *LAS17* gene was tagged in situ with a protein A-coding DNA fragment as described in MATERIALS AND METHODS. This strain was then crossed to an *arp2 Δ* strain complemented by *3HAC'ARP2* on pYEW248 (Moreau *et al.*, 1996) and recombinant doubly tagged spores were selected, giving rise to strain YMW175K.

To immunoprecipitate Las17p, protein A-Sepharose beads were incubated with IgG and then with whole cell extract from strain YMW175K as described in MATERIALS AND METHODS. Las17-prot A precipitated from the supernatant was visualized after SDS gel electrophoresis on blots with IgG (Figure 9A). Arp2p clearly precipitated with Las17-prot A after multiple washes (Figure 9B). Neither Las17-prot A nor Arp2p precipitated in a parallel control experiment from a nontagged wild-type extract (Figure 9, A and B, lane C). Analysis of the same fractions with specific anti-Arc35p/End9p antibodies (Brodbeck-Schärer, unpublished results) confirmed the presence of this Arp2/3 complex subunit in the immunoprecipitate with Arp2p. This result confirms that

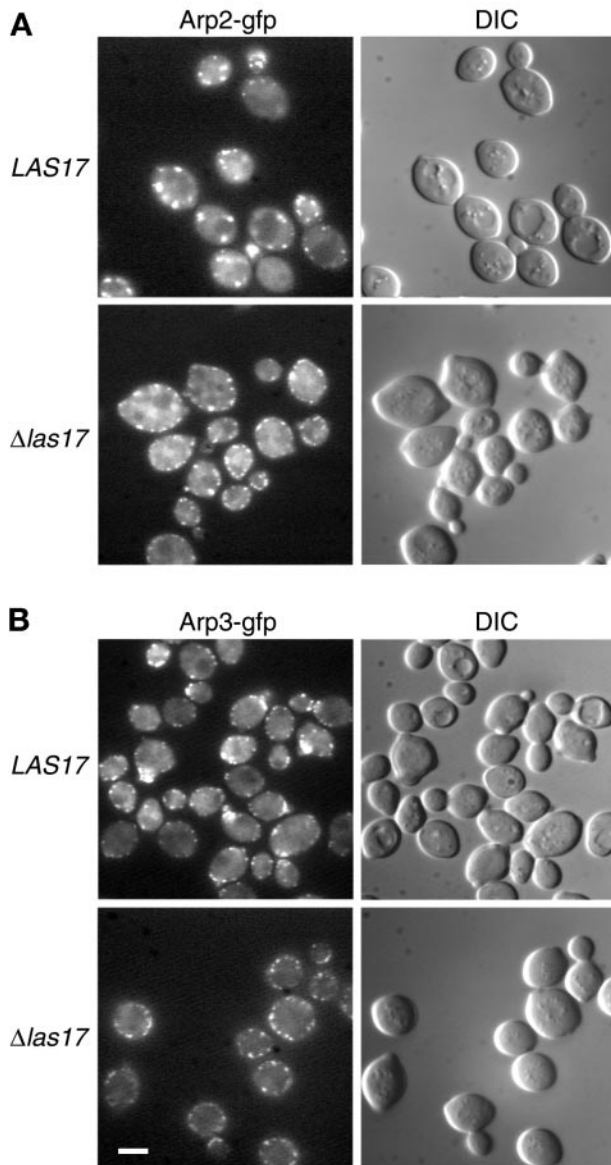


Figure 8. Loss of Arp2p and Arp3p polarity in *las17Δ* strains. (A) Localization of Arp2-gfp in wild-type and *las17Δ/las17Δ* cells. One allele of *ARP2* was replaced by an *ARP2:EGFP* (Cormack *et al.*, 1997) allele in FY1679 (WT) and in strain YMW173K (*las17Δ/las17Δ*) as described in MATERIALS AND METHODS. Cells were grown at 25°C in YPD, harvested, resuspended in 1 M sorbitol, and immediately put on slides for microscopic examination. Images were recorded using a GFP filter. (B) Localization of Arp3-gfp in wild-type and *las17Δ/las17Δ* cells. Experimental conditions were as in A. Bar, 5 μ m.

the genetic data presented above represents specific physical interaction between Las17p and the Arp2/3 complex.

The human homologue of Las17p, WASP, regulates actin polymerization and cytoskeleton rearrangements and has been shown to interact directly with activated CDC42Hs (Apenström *et al.*, 1996; Miki *et al.*, 1996; Symons *et al.*, 1996). We were intrigued to know whether Las17p interacted di-

Table 4. Interactions of two-hybrid fusion proteins with Las17p and actin baits

GAL4-AD (activation domain)	GAL4-BD (DNA binding domain) β -galactosidase activity (Miller units)	
	Las17p ¹⁻⁶⁴³ (pBMW172)	Act1p ¹⁻³⁷⁵ (pDAB7)
Vector (pACTII)	00.1 \pm 0.02	0.2 \pm 0.06
Act1p ⁻²⁴⁻³⁷⁵ (pAIP70)	3.5 \pm 0.5	1.4 \pm 0.07
Arp2p ¹⁻³⁹¹ (pAMW253)	\leq 0.1	\leq 0.2
Arp3p ¹⁻⁴⁴⁸ (pAMW315)	\leq 0.1	\leq 0.2
Las17p ¹⁻⁶⁴³ (pAMW173)	1.0 \pm 0.1	1.2 \pm 0.3
Act1p ⁻²⁸⁻³⁷⁵ (2 \times)	2.0 \pm 0.1	1.1 \pm 0.1
Rvs167p ⁶⁹⁻⁴⁸² (2 \times)	50 \pm 1	1.0 \pm 0.1
Rvs167p ¹⁹¹⁻⁴⁸² (pAIP38)	54 \pm 5	0.7 \pm 0.2
Rvs167p ²³⁹⁻⁴⁸² (2 \times)	122 \pm 3	\leq 0.2
Rvs167p ⁴⁰⁰⁻⁴⁸² (2 \times)	16 \pm 2	\leq 0.2
Vrp1p ⁴⁹²⁻⁸¹⁸ (2 \times)*	62 \pm 9	\leq 0.2
Vrp1p ⁷⁸³⁻⁸¹⁸ (1 \times)*	29 \pm 7	\leq 0.2
Lsb1p ⁸⁻²⁴¹ (37 \times)	58 \pm 5	\leq 0.2
Lsb2p ³⁻²¹⁵ (9 \times)	96 \pm 11	\leq 0.2
Lsb3p ¹⁸⁶⁻⁴⁵¹ (8 \times)	15 \pm 4	\leq 0.2
Ysc84p/Lsb4p ²⁷⁰⁻⁴⁶⁸ (10 \times)	6 \pm 0.2	\leq 0.2
Lsb5p ⁴⁰⁻²¹³ (11 \times)	34 \pm 1	\leq 0.2
Lsb6p ⁶⁷⁻⁶⁰⁷ (5 \times)	8 \pm 1	\leq 0.2

Vectors encoding fusions with the GAL4-(AD) were transformed into Y190 cells expressing GAL4-DB fusions with Las17p (pBMW172) or Act1p (pDAB7) and plated on SC - Trp and Leu plates. At least three colonies from each transformation were cultivated overnight in liquid selective medium (SC - Trp and Leu). β -Galactosidase activities were measured as described in MATERIALS AND METHODS. Values shown \pm SD. Most double transformants that did not show blue color in the filter test were considered as approximately equal (\approx) to background and were not assayed in liquid cultures. Plasmids marked with an asterisk were found in the FYRL genomic library; nonmarked entries are from the White cDNA library. Redundancy of the AD plasmids found is shown in parentheses. Not all candidates found are shown; interactions of the strongest and shortest fusions of each candidate are shown; longest fusions for Rvs167p and Vrp1p are also shown.

rectly with Cdc42p in *S. cerevisiae* because the Cdc42p consensus binding sequence is absent. To test these interactions in the two-hybrid system, a Las17p bait was tested for interaction with wild-type and activated Cdc42p (Cvrckova *et al.*, 1995; Leberer *et al.*, 1997), in addition to profilin and actin (Amberg *et al.*, 1995) as known interactants. No significant interactions with wild-type or activated Cdc42p were detected with these constructions.

To learn more about the interactions of Las17p, we used the two-hybrid system to screen a yeast cDNA library and a genomic DNA library for potential Las17p interacting proteins (see MATERIALS AND METHODS). In these screens (neither of which represent saturation) we found clones representing three known cytoskeletal proteins actin, verprolin, and Rvs167p (reduced viability upon starvation), and six proteins of unknown function, named LSB for Las seventeen binding proteins: Lsb1p (YGR136W), Lsb2p (YPR154w), Lsb3p (YFR024c-A), Lsb4p/Ysc84p (YHR016c), Lsb5p (YCL034w), and Lsb6p (YJL100w). Plasmids express-

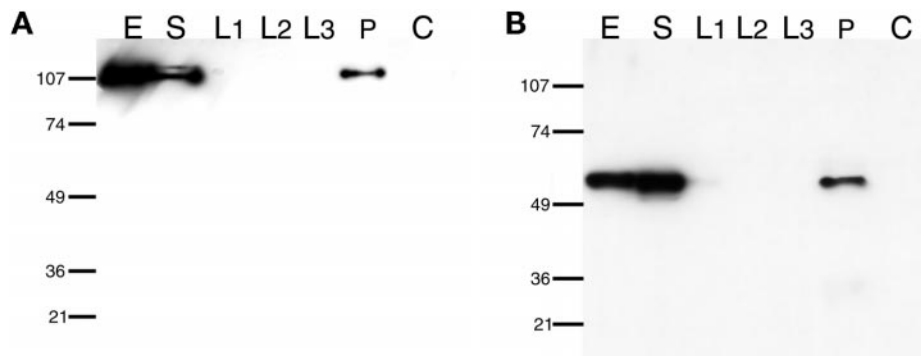


Figure 9. Coimmunoprecipitation of Las17p and Arp2p (Arp2/3 complex). Las17-prot A was immunoprecipitated from crude extracts of strain YMW175K, which contained a chromosomally integrated allele of protein A-tagged Las17p and plasmid-borne HA tagged Arp2p (described in MATERIALS AND METHODS). After precipitation with TCA, cell extract and each step of the immunoprecipitation were subjected to 10% SDS-PAGE and blotted to nitrocellulose. E, extract; S, supernatant; L1, wash 1; L2, wash 2; L3, wash 3; P, immunoprecipitate; C, control immunoprecipitate, mock IP from crude extract of the YMW175K parental strain without protein A tag. (A) Las17-protA detected with purified rabbit IgG. (B) HA-tagged Arp2p detected with mouse monoclonal anti-HA IgG.

ing these fusions were purified and transformed into strain Y190 expressing either Gal4DB-Las17p (pBMW172) or Gal4DB-Act1p (pDAB7). Results of β -galactosidase assays for the most informative in-phase clones are summarized in Table 4.

Of the known proteins found, a fusion containing actin with 27 additional aa at the amino terminus was found, similar to an extended actin (pAIP70) found in a screen against actin itself (Amberg *et al.*, 1995). Las17p showed strong two-hybrid interaction with multiple derivatives of the SH3 domain protein Rvs167p. Nine different truncations (from the cDNA library) gave strong interaction with the Las17p bait. Rvs167p, originally identified along with Rvs161p as being important for recovery from starvation, affects cytoskeletal organization (Bauer *et al.*, 1993; Sivadon *et al.*, 1995). The smallest interacting fusion (83 aa) contains only the SH3 domain plus 21 aa of the GPA (for rich in Gly, Pro, and Ala) domain, whereas the strongest interacting fusion (239–482) contains the SH3 domain plus the GPA domain. In addition, four more N-terminally extended clones, beginning at aa 220, 191, 183, and 69, showed interaction with actin, as was reported by Amberg *et al.* (pAIP38 aa 189–549), whereas shorter clones did not. Strikingly, for verprolin (Vrp1p/End5p), eight different genomic fragments (and one cDNA fragment) all contained the C-terminal extremity of the protein. The smallest fusion contained only the C-terminal 36 aa, and the strongest interacting fusion had 327 aa. These results “map” a major Las17p interaction with Vrp1p to the Vrp1p C-terminus.

Among the unknown candidates, sequence comparisons revealed that Lsb1p, Lsb2p, Lsb3p, and Lsb4/Ysc84 contain SH3 domains with high similarity to the SH3 domain of Rvs167p and to that of human Grb2p. Lsb1p/V25 (241 aa) and Lsb2p (215 aa) contain an N-terminal SH3 domain followed by a proline-rich acidic region. With 64% identity to each other they form a strongly interacting minimal family. Except for the SH3 domain, no significant homologies for Lsb1p/Lsb2p were detected with other proteins in databases. Lsb1p has been characterized in a comparative mRNA study as being highly expressed in high-density cultures and upon diauxic shift, but deletion of the gene

showed no particular phenotype (Wang *et al.*, 1997). Lsb3p (451 aa) and Ysc84p/Lsb4p (468 aa) are 67% identical to each other, forming another minimal family with a C-terminal SH3 domain. BLAST searches and sequence alignment revealed homology between these two proteins and an SH3-domain containing protein of unknown function from mouse (340 aa, cDNA clone ge:D85926). *YSC84/LSB4* was studied as an example of a divergently transcribed gene whose expression increased 5- to 10-fold during sporulation. However, its deletion caused no apparent phenotype for vegetative growth, progression into meiosis, or sporulation (Rocco *et al.*, 1993). These SH3 domain proteins are currently under investigation. Candidates Lsb5p and Lsb6p are unknown, but both have possible homologues in other organisms. Lsb5p (265 aa) is similar to a hypothetical *Schizosaccharomyces pombe* protein. Lsb6p (607 aa) is similar to a hypothetical *Caenorhabditis elegans* protein C56A3.8. Although the existence of possible homologues in other species suggests that these ORFs code for functional proteins, the biological relevance to Las17p remains to be established.

DISCUSSION

LAS17 Is Important for the Function of the Arp2/3 Complex

The phylogenetic conservation of the Arp2/3 complex and its localization to actin-rich cortical regions of cells suggest that it fulfills a common essential function in the cortical actin cytoskeleton. The Arp2/3 complex functions to bind and cross-link actin filaments (Mullins *et al.*, 1997, 1998b) and to nucleate actin polymerization required to produce movement at the cell surface (Mullins *et al.*, 1998b; Welch *et al.*, 1997a, 1998). Las17p/Bee1p has been shown to be involved in the actin cytoskeleton (Li, 1997) and in actin assembly in vitro (Lechler and Li, 1997). We addressed here the question of how Las17p produces its effects on actin organization. Our genetic evidence shows that Las17p plays an important role in the functioning of Arp2 and Arp3 proteins, thus linking it to the function(s) of the Arp2/3 complex. First, *LAS17* is an allele-specific suppressor of the

temperature-sensitive growth of *ARP2* and *ARP3* mutants. Defects in polarity of actin distribution and in fluid phase endocytosis were also suppressed. That is, no separation of function between actin defects and deficient endocytosis was apparent. Second, synthetic lethality of *las17Δ* with six of seven *ARP2* mutants and with an *ARP3* mutant indicates that these proteins affect the same cellular processes. Taken together, these results would tell us that Las17p plays an important role in the functions of the Arp2/3 complex but do not differentiate between stabilization of Arp2/3 complex interactions from regulation of actin-polymerizing function and/or signaling mechanisms mediated by Las17p.

***LAS17Δ* and *ts* Mutations in *ARP2* and *ARP3* Cause Similar Phenotypes**

Deletion of *LAS17* perturbs the organization of the actin cytoskeleton at permissive growth temperature (Li, 1997; this study) and is lethal at 37°C or is essential at all temperatures depending on the strain context. We have found a striking similarity between the *las17Δ* phenotype and the phenotypes of *ARP2* *ts* mutants. In addition to depolarization of actin patches, many *las17Δ* cells show actin aggregates in the bud and at the bud neck of large budded cells as is seen in *ARP* mutant cells. An independent study showed that aberrant aggregates in *las17Δ* cells, as do cables, contain Sac6p but lack normal patch components cofilin and Cap2p (Li, 1997). Nor do aggregates appear to contain Arp2p or Arp3p. Interestingly, Arp2p-gfp still colocalized with residual actin patches (Figure 1B; Dumoulin, unpublished observations). Recent microscopic studies have confirmed that cables and patches depend on each other for assembly and function (Karpova *et al.*, 1998). The fact that overexpression of *LAS17* suppresses the formation of such structures in *arp2-1* and *arp2-2* mutants implicates Las17p and the Arp2/3 complex together in filament organization. Abnormally enlarged necks between mother and daughter cells are a further common defect of *las17Δ* and certain *ARP2* mutant cells, suggesting that Las17p and Arp2p may both be important for cytokinesis and/or cell division. This is consistent with the previously shown genetic interactions between *arp2-1* and the septin *cdc10-1* mutations (Moreau *et al.*, 1996). In further characterization of *las17Δ* cells, deficient α factor uptake lets us conclude that Las17p is essential for ligand-dependent receptor-mediated internalization in addition to fluid phase endocytosis, whereas later steps of the endocytosis pathway are apparently functional. Internalization was severely deficient at 24°C, at which cells continued to divide, as we have previously described for *arp2-1* cells (Munn *et al.*, 1995; Moreau *et al.*, 1997). This step of endocytosis has also been shown to require actin and fimbrin and many other cytoskeletal proteins, including End3p, Sla2p/End4p, Vrp1p/End5 Rvs161/End6p, and Rvs167p (Raths *et al.*, 1993; Munn and Riezman, 1994; Munn *et al.*, 1995).

We also investigated the *in vivo* relationship of Las17p to polarity and actin organization. Loss of the bipolar budding pattern in growing diploid cells points to a possible role for Las17p in establishment of cell growth polarity. Furthermore, in the presence of latrunculin-A, functional Las17-gfp, probably with other proteins, remains in cortical patches in a polarized distribution in the absence of any detectable concentration of filamentous or total actin. Las17p must therefore be upstream of actin with respect to the flow of

polarity information. Interestingly, certain other proteins important for polarity establishment, such as Cdc42p and Bem1p (Ayscough *et al.*, 1997) as well as verprolin (Vaduva *et al.*, 1997), also show polarized localization independently of polymerized actin in virtually all cells, whereas others such as Bud6/Aip3p, Myo2p, and calmodulin appear to maintain only partial polarity. Still other proteins that are important for the actin cytoskeleton and secretion, such as Arp2p, Aip1p, Sec4p, Sec8p, and Smy1p are dependent on actin structures for their polarized localization (Ayscough *et al.*, 1997). The fact that *las17Δ* strains show increased sensitivity to latrunculin-A in growth tests (our unpublished results), in addition to being necessary for actin, Arp2p, and Arp3p localization, suggests that Las17p normally plays a role in polarized localization and in stabilization of the actin-polymerizing complex at the cortex. When the actin filament cytoskeleton is destroyed by latrunculin-A treatment, despite nonpolarized growth of cells (in the absence of increase of cell numbers), proteins such as Las17p and verprolin remain polarized, suggesting that the flow of polarity information necessary for polarized growth may also require interaction with actin filaments for these proteins to function with the Arp2/3 complex. Although Las17p is not essential for growth in all conditions, it is clearly a major determinant in multiple cellular processes implicating the actin cytoskeleton.

Elucidating Las17p Functions through its Interactions

Genetic evidence for functional interaction between *las17Δ* and *ARP2* and *ARP3* mutations is extended biochemically to indicate physical interaction with the coimmunoprecipitation of Arp2p and Las17p from crude extracts. How does high-copy expression of *LAS17* overcome specific *ARP2* and *ARP3* *ts* mutations? Las17p might interact directly with Arp2p or Arp3p despite the fact that we were unable to detect interactions between Las17p and Arp2p or Arp3p in two-hybrid tests. In this case, Arp2p or Arp3p might bind less tightly to Las17p, but higher expression of Las17p could compensate weak binding. Another interpretation of our results is that intermediary protein components are necessary to allow functional interaction of Las17p with the Arp2/3 complex. Las17p might interact with the Arp2/3 complex through contact with actin, with other subunits, or both. *In vitro* protein interaction between Las17p and actin was demonstrated by coimmunoprecipitation (Li, 1997), and the two proteins interact directly in the two-hybrid system. Direct interaction between bovine N-WASP and actin has also been shown *in vitro*. The WH2 domain or "verprolin homology" and the "cofilin homology" domains of N-WASP participated in actin binding (Miki *et al.*, 1996). Similar direct physical interactions with actin were confirmed for both WASP and SCAR (Machesky and Insall, 1998). Because the WH2 domain is rather well conserved in the C-terminal region of the yeast homologue, it likely to be the region of Las17p that interacts with actin:

```
GRGALLDQIRQ..GIQLNKT (WASP_human Swiss prot)
GRDALLDQIRQ..GIQL.KS(N-WASP;DDBJ accession D88460)
GRDALLASIRGAGGIGALRKV (La17_yeast; Swiss prot).
```

SCAR and WASP were recently found to regulate the actin cytoskeleton through the Arp2/3 complex. The C-

terminal WA fragment (WH2 and acidic domains) of both the WASP and the SCAR homologues bind the p21-Arc subunit (equivalent to *S. cerevisiae* Arc18p) of the Arp2/3 complex (Machesky and Insall, 1998). The *ARP2* allele-specific interactions we found with *las17Δ* are not inconsistent with a similar interaction in *S. cerevisiae*, because certain mutations could affect small subunit binding indirectly. However, we did not detect two-hybrid interactions between a full-length Las17p and Arp2p, Arp3p, Arc35p, Arc40p, or any of the small subunits Arc19p, Arc18p, or Arc15p tested as activation fusions (Table 4; our unpublished results).

During the revision of this manuscript several *in vitro* studies pertinent to our results have been published. Las17p (GST-Bee1p) and the Arp2/3 complex have been coimmunoprecipitated in yeast, an independent demonstration of the physical interaction we report here between Las17-protA and the Arp2/3 complex. This interaction required both Arc19p and Arc15p (Winter *et al.*, 1999). Simultaneous requirement of two or more subunits could be an explanation for the lack of two-hybrid interactions. Further knowledge of the Arp2/3 complex topology will be necessary to understand whether the mammalian and yeast results represent the same overall interactions. In addition to the activation of the *S. cerevisiae* Arp2/3 complex by Las17p *in vitro* (Winter *et al.*, 1999), the direct role of WASP (Yarar *et al.*, 1999) and SCAR (Machesky *et al.*, 1999) in the activation of the *in vitro* nucleation activity of the Arp2/3 complex to generate new filament barbed ends has been elucidated in mammalian cells.

It has been shown previously that Cdc42, activated with guanosine 5'-3-O-(thio)triphosphate, induces actin polymerization in neutrophils (Zigmond *et al.*, 1998). The Arp2/3 complex is one of the elements required for Cdc42-induced actin polymerization in *Acanthamoeba* (Mullins and Pollard, 1999) and *Xenopus* extracts (Ma *et al.*, 1998). Now, it has also been shown that the stimulation of actin nucleation by N-WASP binding to the Arp2/3 complex requires both the actin binding domain and the Arp2/3 complex binding domain of N-WASP, as is the case for SCAR activation of the Arp2/3 complex (Machesky *et al.*, 1999). Actin polymerization in the *Xenopus* system is enhanced by both Cdc42 and phosphatidylinositol-(4,5)-biphosphate, linking signal transduction pathway molecules to the stimulation of actin polymerization (Rohatgi *et al.*, 1999). Evidence that the combined action of WASP family members and the Arp2/3 complex are also directly dependent on Cdc42 *in vivo* (Castellano *et al.*, 1999) comes from experiments which used a modified plasma membrane receptor capable of inducible local recruitment of Cdc42 (or WASP) to show that activated Cdc42 (or WASP) triggered actin polymerization and subsequent formation of protrusions in whole cells.

Las17p Shows Two-Hybrid Interaction with SH3 Domain Proteins

Previous studies showed that proline-rich stretches of various proteins bind to SH3 domains (Ren *et al.*, 1993). SH3 domains are small regions (~60–80 aa) present in a large number of proteins showing similarity to a domain in c-src and v-src proto-oncogene proteins. The presence of several proline-rich stretches in Las17p suggests that it could interact directly with one or several SH3 domain proteins. In

two-hybrid screens with Las17p bait, five of the nine proteins we identified as Las17p interactants contained an SH3 domain. Although the strength of possible *in vivo* interactions between complete proteins cannot be implied directly from the activation values of two-hybrid interaction, clones representing the SH3 domain with or without other parts of these proteins interacted strongly with full-length Las17p. One of these SH3 domain proteins was Rvs167p, which contains three domains, BAR/RVS, GPA, and SH3. The SH3 domain with a few additional amino acids of the neighboring GPA domain was sufficient to show strong interaction with Las17p. Thus, in addition to the SH3 domain, Las17p-Rvs167p interaction may require participation of the GPA domain. Rvs167p is known to function with Rvs161p/End6p (Navarro *et al.*, 1997), which was also fished out in a screen for endocytosis-defective mutants as mentioned above (Munn *et al.*, 1995). In this screen we did not pick up Rvs161p (which is homologous to Rvs167p except for lack of the C-terminal SH3 domain) but it does interact with Las17p when tested directly (Recordon-Navarro, 1998), further suggesting that SH3 domains may not be solely responsible for interaction with Las17p. Rvs167p was previously found as an actin partner (Amberg *et al.*, 1995). Our results show that only Rvs167p fusions containing at least part of the N-terminal domain of Rvs167p interact with actin in two-hybrid tests (\geq aa 220–482; Table 4; our unpublished observations).

We also found that Las17p interacts strongly with verprolin (Vrp1/End5p). Verprolin has been shown to be part of the actin cytoskeleton and, like Las17p, is important for endocytosis and is a polarity determinant that localizes to polarized cortical patches independently of polymerized actin (Munn *et al.*, 1995; Vaduva *et al.*, 1997). Results of an independent communication have been presented showing that the C-terminal half of Las17p binds verprolin (Naqvi *et al.*, 1998). Our results show that interactions of several different fragments from a random genomic bank map the binding site of verprolin to the C terminus; a fragment of only 35 C-terminal amino acids is sufficient for strong binding to Las17p. This interaction is comparable with that of WASP (as bait) with the human homologue of verprolin, WIP (WASP-interacting protein), isolated in a two-hybrid screen. In two-hybrid tests a C-terminal 87-aa truncation of WIP no longer bound to WASP, in good agreement with our mapping of the verprolin-Las17 interaction. Overexpression of WIP affected cortical actin assembly, inducing the formation of actin-containing projections at the cell surface of human B cells (Ramesh *et al.*, 1997).

Given that the *las17Δ* genetic interaction with *ARP2* and *ARP3* mutants is allele specific, and that Las17p and Arp2p interact physically, Las17p is shown to be an effector of the Arp2/3 complex. These results coincide with multiple demonstrations in many systems of WASP family members' interaction with the Arp2/3 complex. We have also shown that Las17p interacts directly with actin, Rvs167p, and verprolin by two-hybrid analyses. Finally, results of our two-hybrid screen suggest that Las17p might interact with at least six other unknown proteins, four of which are SH3 domain proteins. The fact that Lsb1p has been localized in the nucleus by transposon tagging of genes with increased expression in stationary phase and that *LSB4/YSC84* expression is increased 5–10 times during sporulation raises the

question of how Las17p might integrate signals from different developmental processes. Possible implication of these new proteins in the actin cytoskeleton or in signaling mechanisms are currently under investigation.

Whereas Arp2p and Arp3p bind as a complex to actin filaments (Mullins *et al.*, 1997, 1998b), Las17p may bind only actin monomers, by analogy to SCAR and WASP (Machesky and Insall, 1998) and verprolin (Vaduva *et al.*, 1997), which bind actin monomers *in vitro*. The absence of a concentration of actin in Las17p patches after latrunculin-A treatment does not eliminate the possibility that Las17p recruits the first monomers to cortical sites, but further studies are needed to clarify this possibility. The suppression of mutations in Arp2/3 complex components by *LAS17* overexpression could then be explained by increasing monomeric actin at nucleation sites. The polarized localization of Las17p reflects its anchorage in areas of cell surface growth, hence its potential for involvement in both plasma membrane and intracellular signaling. An attractive possibility is that Las17p, in association with verprolin and Rvs167p (and perhaps with other proteins such as the Lsbp reported here), forms the essential part of a complex that remains anchored at the plasma membrane, receives diverse signals, and transmits them to the actin-polymerizing complex where Las17p plays a direct role in amplifying actin nucleation by the Arp2/3 complex.

ACKNOWLEDGMENTS

We thank S. Elledge, S.P. Bartel, A. Wach, and B. Cormack for plasmids and M. White, P. James, and M. Fromont-Racine for two-hybrid banks. This work was financed by French National Research (Centre National de la Recherche Scientifique) funding to the Unité Propre de Recherche 9005 laboratory and by a French Cancer Association (Association pour la Recherche sur le Cancer) grant to B.W. A.M. was supported by the Syrian Atomic Energy Commission, and H.K. was supported by the Japanese National Institute of Agrobiological Resources.

REFERENCES

Amberg, D.C., Basart, E., and Botstein, D. (1995). Defining protein interaction with yeast actin *in vivo*. *Nat. Struct. Biol.* 2, 28–35.

Amman, A.J., and Hong, R. (1989). Disorders of the T-cell system. In: *Immunological Disorders in Children*, ed. E.R. Stiehm, Philadelphia: W.B. Saunders, 257–315.

Apenström, P., Lindberg, U., and Hall, A. (1996). Two GTPases, Cdc42 and Rac, bind directly to a protein implicated in the immunodeficiency disorder Wiskott–Aldrich syndrome. *Curr. Biol.* 6, 70–75.

Ayscough, K., Stryker, J., Pokala, N., and Sanders, M. (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.

Balasubramanian, M.K., Feoktistova, A., McCullum, D., and Gould, K.L. (1996). Fission yeast Sop2: a novel and evolutionarily conserved protein that interacts with Arp3p and modulates profilin function. *EMBO J.* 15, 6426–6437.

Bauer, F., Urdaci, M., Aigle, M., and Crouzet, M. (1993). Alteration of a yeast SH3 protein leads to conditional viability with defects in cytoskeletal and budding patterns. *Mol. Cell. Biol.* 13, 5070–5084.

Breedon, L., and Nasmyth, K. (1985). Regulation of the yeast HO gene. *Cold Spring Harb. Symp. Quant. Biol.* 50, 643–650.

Castellano F.M.P., Guillemot, J.C., Gouin, E., Machesky, L., Cossart, P., and Chavrier, P. (1999). Inducible recruitment of Cdc42 or WASP to a cell-surface receptor triggers actin polymerization and filopodium formation. *Curr. Biol.* 9, 351–360.

Chien, C.T., Bartel, P.L., Sternglanz, R., and Fields, S. (1991). The two-hybrid system: a method to identify and clone genes for proteins that interact with a protein of interest. *Proc. Natl. Acad. Sci. USA* 88, 9578–9582.

Cormack, B., Bertram, G., Egerton, M., Gow, N., Falkow, S., and Brown, A. (1997). Yeast-enhanced green fluorescent protein (yEGFP), a reporter of gene expression in *Candida albicans*. *Microbiology* 143, 303–311.

Coué, M., Brenner, S., Spector, I., and Korn, E. (1987). Inhibition of actin polymerization by latrunculin A. *FEBS Lett.* 213, 316–318.

Cvrckova, F., De Virgilio, C., Manser, E., Pringle, J., and Nasmyth, K. (1995). Ste20-like protein kinases are required for normal localization of cell growth and for cytokinesis in budding yeast. *Genes & Dev.* 9, 1817–1830.

Dulic, V., Egerton, M., Elguindi, I., Raths, S., Singer, B., and Riezman, H. (1991). Yeast endocytosis assays. *Methods Enzymol.* 194, 697–710.

Durfee, T., Becherer, K., Chen, P., Yeh, S., Yang, Y., Kilburn, A.E., Lee, W., and Elledge, S. (1993). The retinoblastoma protein associates with protein phosphatase type I catalytic subunit. *Genes & Dev.* 7, 555–569.

Fields, S., and Song, O. (1989). A novel genetic system to detect protein-protein interactions. *Nature* 340, 245–246.

Fromont-Racine, M., Rain, J.C., and Legrain, P. (1997). Toward a functional analysis of the yeast genome through exhaustive two-hybrid screens. *Nat. Genet.* 16, 277–282.

Guthrie, C., and Fink, G.R. (1991). Guide to yeast genetics and molecular biology. In: *Methods in Enzymology*, San Diego: Academic Press, 1–933.

Hill, J., Ian, K.A., Donald, G., and Griffiths, D.E. (1991). DMSO-enhanced whole cell yeast transformation. *Nucleic Acids Res.* 19, 5791.

James, P., Halladay, J., and Craig, E. (1996). Genomic libraries and a host strain designed for highly efficient two-hybrid selection in yeast. *Genetics* 144, 1425–1436.

Jones, J.S., and Prakash, L. (1990). Yeast *Saccharomyces cerevisiae* selectable markers in pUC18 polylinkers. *Yeast* 6, 363–366.

Kandels-Lewis, S., and Seraphin, B. (1993). Involvement of U6 snRNA in 5' splice site selection. *Science* 262, 2035–2039.

Karpova, T.S., McNally, J.G., Moltz, S.L., and Cooper, J.A. (1998). Assembly and function of the actin cytoskeleton of yeast: relationships between cables and patches. *J. Cell Biol.* 142, 1501–1517.

Kelleher, J.F., Atkinson, S.J., and Pollard, T.D. (1995). Sequences, structural models and cellular localization of the actin-related proteins Arp2 and Arp3 from *Acanthamoeba*. *J. Cell Biol.* 131, 385–397.

Knop, M., Siegers, K., Pereira, G., Zachariae, W., Winsor, B., Nasmyth, K., and Schiebel, E. (1999). Epitope tagging of yeast genes using a PCR-based strategy: more tags and improved practical routines. *Yeast* 15, 963–972.

Kolluri, R., Tolia, K.F., Carpenter, C.L., Rosen, F.S., and Kirchhausen, T. (1996). Direct interaction of the Wiskott–Aldrich syndrome protein with the GTPase Cdc 42. *Proc. Natl. Acad. Sci. USA* 93, 5615–5618.

Leberer, E., Wu, C., Leeuw, T., Fourest-Lieuvain, A., Segall, J.E., and Thomas, D.Y. (1997). Functional characterization of the Cdc42 binding domain of yeast Ste20p protein kinase. *EMBO J.* 16, 83–97.

- Lechler, T., and Li, R. (1997). In vitro reconstitution of cortical actin assembly sites in budding yeast. *J. Cell Biol.* 138, 95–103.
- 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.
- Ma, L., Rohatgi, R., and Kirschner, M.W. (1998). The Arp2/3 complex mediates actin polymerization induced by the small GTP-binding protein Cdc42. *Proc. Natl. Acad. Sci. USA* 95, 15362–15367.
- Machesky, L., Mullins, R., Higgs, H., Kaiser, D., Blanchoin, L., May, R., Hall, M., and Pollard, T. (1999). Scar, a WASp-related protein, activates nucleation of actin filaments by the Arp2/3 complex. *Proc. Natl. Acad. Sci. USA* 96, 3739–3744.
- Machesky, L.M., Atkinson, S.J., Ampe, C., Vandekerckhove, J., and Pollard, T.D. (1994). Purification of a cortical complex containing two unconventional actins from *Acanthamoeba* by affinity chromatography on profilin-agarose. *J. Cell Biol.* 127, 107–115.
- Machesky, L.M., and Insall, R.H. (1998). Scar1 and the related Wiscott-Aldrich syndrome protein, WASP, regulate the actin cytoskeleton through the Arp2/3 complex. *Curr. Biol.* 8, 1347–1356.
- MacKay, V.L., Welch, S.K., Insley, M.Y., Manney, T.R., Holly, J., Saari, G.C., and Parker, M. (1988). The *Saccharomyces cerevisiae* *BAR1* gene encodes an exported protein with homology to pepsin. *Proc. Natl. Acad. Sci. USA* 85, 55–59.
- Madania, A. (1998). Etude fonctionnelle des protéines apparentées à l'actine, Arp2p et Arp3p; recherche de protéines interagissant chez la levure *Saccharomyces cerevisiae*. In: Institut de Biologie Moléculaire et Cellulaire, Strasbourg, France: Université Louis Pasteur, 1–113.
- Madania, A., Moreau, V., Martin, R., and Winsor, B. (1997). LAS17 is a multi-copy suppressor of *S. cerevisiae* *arp2-1*. *Yeast* 13, S144.
- McCullum, D., Feoktistova, A., Morpheu, M., Balasubramanian, M., and Gould, K.L. (1996). The *Schizosaccharomyces pombe* actin-related protein, Arp3, is a component of the cortical actin cytoskeleton and interacts with profilin. *EMBO J.* 15, 6438–6446.
- Miki, H., Miura, K., and Takenawa, T. (1996). N-WASP, a novel actin-depolymerizing protein, regulates the cortical cytoskeleton rearrangement in a PIP2-dependent manner downstream of tyrosine kinases. *EMBO J.* 15, 5526–5535.
- Miki, H., Seutsugo, S., and Takenawa, T. (1998). WAVE, a novel WASP-family protein involved in actin reorganization induced by Rac. *EMBO J.* 17, 6932–6941.
- Molina, I., Kenny, D., Rosen, F., and Remold-O'Donnell, E. (1992). T cell lines characterize events in the pathogenesis of the Wiscott-Aldrich syndrome. *J. Exp. Med.* 176, 867–874.
- Moreau, V., Galan, J.-M., Devilliers, G., Haguenaer-Tsapis, R., and Winsor, B. (1997). The yeast actin-related protein Arp2 is required for the internalization step of endocytosis. *Mol. Biol. Cell* 8, 1361–1375.
- Moreau, V., Madania, A., Martin, R.P., and Winsor, B. (1996). The *Saccharomyces cerevisiae* actin-related protein Arp2 is involved in the actin cytoskeleton. *J. Cell Biol.* 134, 117–132.
- Mullins, R., Heuser, J., and Pollard, T. (1998a). The interaction of Arp2/3 complex with actin: nucleation, high affinity pointed end capping, and formation of branching networks of filaments. *Proc. Natl. Acad. Sci. USA* 95, 6181–6186.
- Mullins, R., and Pollard, T. (1999). Rho-family GTPases require the Arp2/3 complex to stimulate actin polymerization in *Acanthamoeba* extracts. *Curr. Biol.* 9, 405–415.
- Mullins, R.D., Kellerher, J.F., Xu, J., and Pollard, T.P. (1998b). Arp2/3 complex from *Acanthamoeba* binds profilin and cross-links actin filaments. *Mol. Biol. Cell* 9, 841–852.
- Mullins, R.D., Stafford, W.F., and Pollard, T.P. (1997). Structure, subunit topology and actin-binding activity of the ARP2/3 complex from *Acanthamoeba*. *J. Cell Biol.* 136, 331–343.
- Munn, A.L., and Riezman, H. (1994). Endocytosis is required for the growth of vacuolar H⁺-ATPase-defective yeast: identification of six new END genes. *J. Cell Biol.* 127, 373–386.
- Munn, A.L., Stevenson, B.J., Geli, M.I., and Riezman, H. (1995). *end5*, *end6*, *end7*: mutations that cause actin delocalization and block the internalization step of endocytosis in *Saccharomyces cerevisiae*. *Mol. Biol. Cell* 6, 1721–1742.
- Naqvi, S., Zahn, R., Mitchell, D.A., Stevenson, B.J., and Munn, A.L. (1998). The WASp homologue Las17p functions with the WIP homologue End5/verprolin and is essential for endocytosis in yeast. *Curr. Biol.* 8, 959–962.
- Navarro, P., Durrens, P., and Aigle, M. (1997). Protein-protein interaction between the *RVS161* and *RVS167* gene products of *S. cerevisiae*. *Biochim. Biophys. Acta* 1343, 187–192.
- Ochs, H., Slichter, S., Harker, L., Von, B., Clark, R., and Wedgewood, R. (1980). The Wiscott-Aldrich syndrome: studies of lymphocytes, granulocytes and platelets. *Blood* 55, 243–252.
- Pringle, J.R., Adams, A.E., Drubin, D.G., and Haarer, B.K. (1991). Immunofluorescence methods for yeast. *Methods Enzymol.* 194, 565–602.
- Ramesh, N., Anton, I.M., Hartwig, J.H., and Geha, R.S. (1997). WIP, a protein associated with Wiscott-Aldrich syndrome protein, induces actin polymerization and redistribution in lymphoid cells. *Proc. Natl. Acad. Sci. USA* 94, 14671–14676.
- Raths, S., Rohrer, J., Crausaz, F., and Riezman, H. (1993). *end3* and *end4*: two mutants defective in receptor-mediated and fluid-phase endocytosis in *Saccharomyces cerevisiae*. *J. Cell Biol.* 120, 55–65.
- Recordon-Navarro, P. (1998). Interactions between Rvs161p and Rvs167p and Their Partners Related to the Actin Cytoskeleton in *Saccharomyces cerevisiae*. Bordeaux: Victor Segalen.
- Ren, R., Mayer, P., Cicchetti, P., and Baltimore, D. (1993). Identification of a ten amino acid proline-rich SH3 binding site. *Science* 259, 1157–1161.
- Riezman, H. (1985). Endocytosis in yeast: several of the yeast secretory mutants are defective in endocytosis. *Cell* 40, 1001–1009.
- Riezman, H. (1993). Yeast endocytosis. *Trends Cell Biol.* 3, 273–277.
- Rocco, V., Daly, M.J., Matre, V., Lichten, M., and Nicolas, A. (1993). Identification of two divergently transcribed genes centromere-proximal to the *ARG4* locus on chromosome VIII of *Saccharomyces cerevisiae*. *Yeast* 9, 1111–1120.
- Rodriguez, J.R., and Paterson, B.M. (1990). Yeast myosin heavy chain mutant: maintenance of the cell type specific budding pattern and the deposition of chitin and cell wall components requires an intact myosin heavy chain gene. *Cell Motil. Cytoskeleton* 17, 301–308.
- Rohatgi, R., Ma, L., Miki, H., Lopez, M., Kirchhausen, T., Takenawa, T., and Kirschner, M. (1999). The interaction between N-WASP, and the Arp2/3 complex links Cdc42-dependent signals to actin assembly. *Cell* 97, 221–231.
- Sambrook, J., Fritsch, E.F., and Maniatis, T. (1989). *Molecular Cloning: A Laboratory Manual*, Cold Spring Harbor, NY: Cold Spring Harbor Laboratory.
- Schiestl, R.H., and Gietz, R.D. (1989). High efficiency transformation of intact yeast cells using single stranded nucleic acids as a carrier. *Curr. Genet.* 16, 339–346.
- Sikorski, R.S., and Hieter, P. (1989). A system of shuttle vectors and yeast host strains designed for efficient manipulation of DNA in *S. cerevisiae*. *Genetics*. 122, 19–27.

- Singer, B., and Riezman, H. (1990). Detection of an intermediate compartment involved in transport of alpha-factor from the plasma membrane to the vacuole in yeast. *J. Cell Biol.* *110*, 1911–1922.
- Sivadon, P., Bauer, F., Aigle, M., and Crouzet, M. (1995). Actin cytoskeleton and budding pattern are altered in the yeast *rvs161* mutant: the Rvs161 protein shares common domains with the brain protein amphiphysin. *Mol. Gen. Genet.* *246*, 485–495.
- Symons, M., Derry, J.M.J., Karlak, B., Jiang, S., Lemahieu, V., McCormick, F., Francke, U., and Abo, A. (1996). Wiskott–Aldrich syndrome protein, a novel effector for the GTPase CDC42Hs, is implicated in actin polymerization. *Cell* *84*, 723–734.
- Vaduva, G., Martin, N.C., and Hopper, A. (1997). Actin-binding verprolin is a polarity development protein required for the morphogenesis and function of the yeast actin cytoskeleton. *J. Cell Biol.* *139*, 1821–1833.
- Vida, T.A., and Emr, S. (1995). A new vital stain for visualizing vacuolar membrane dynamics and endocytosis in yeast. *J. Cell Biol.* *128*, 779–792.
- Wach, A., Brachat, A., Alberti-Segui, C., Rebischung, C., and Philippsen, P. (1997). Heterologous *HIS3* marker and GFP reporter modules for PCR-targeting in *Saccharomyces cerevisiae*. *Yeast*, *13*, 1065–1075.
- Wach, A., Brachat, A., Pöhlmann, R., and Philippsen, P. (1994). New heterologous modules for classical or PCR-based disruptions in *Saccharomyces cerevisiae*. *Yeast* *10*, 1793–1808.
- Wang, W.Y., Nishikawa, T., and Isono, K. (1997). Isolation and characterization of *Saccharomyces cerevisiae* genes: differential expression under different growth conditions. *J. Gen. Appl. Microbiol.* *43*, 217–224.
- Welch, M.D., Iwamatsu, A., and Mitchison, T. (1997a). Actin polymerization is induced by the Arp2/3 complex at the surface of *Listeria monocytogenes*. *Nature* *385*, 265–269.
- Welch, M.D., DePace, A.H., Verma, S., Iwamatsu, A., and Mitchison, T. (1997b). The human Arp2/3 complex is composed of evolutionarily conserved subunits and is localized to cellular regions of dynamic actin filament assembly. *J. Cell Biol.* *138*, 375–384.
- Welch, M.D., Rosenblatt, J., Scoble, J., Portnoy, D.A., and Mitchison, T.J. (1998). Interaction of human Arp2/3 complex and the *Listeria monocytogenes* ActA protein in actin filament nucleation. *Science* *281*, 105–108.
- Winter, D., Lechler, T., and Li, R. (1999). Activation of the yeast Arp2/3 complex by bee1p, a WASP-family protein. *Curr. Biol.* *9*, 501–504.
- Winter, D., Podteljnikov, A.V., Mann, M., and Li, R. (1997). The complex containing actin-related proteins Arp2 and Arp3 is required for the motility and integrity of yeast actin patches. *Curr. Biol.* *7*, 519–529.
- Yang, S., Ayscough, K.R., and Drubin, D.G. (1997). A role for the actin cytoskeleton of *Saccharomyces cerevisiae* in bipolar bud-site selection. *J. Cell Biol.* *136*, 111–123.
- Yarar, D., To, W., Abo, A., and Welch, M.D. (1999). The Wiskott–Aldrich syndrome protein directs actin-based motility by stimulating actin nucleation with the Arp2/3 complex. *Curr. Biol.* *20*, 555–558.
- Zanolari, B., and Riezman, H. (1991). Quantitation of alpha-factor internalization and response during the *Saccharomyces cerevisiae* cell cycle. *Mol. Cell. Biol.* *11*, 5251–5258.
- Zigmond, S.H., Joyce, M., Yang, C., Brown, K., Huang, M., and Pring, M. (1998). Mechanism of Cdc42-induced actin polymerization in neutrophil extracts. *J. Cell Biol.* *142*, 1001–10012.