Floral stem cell termination involves the direct regulation of AGAMOUS by PERIANTHIA

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In Arabidopsis, the population of stem cells present in young flower buds is lost after the production of a fixed number of floral organs. The precisely timed repression of the stem cell identity gene WUSCHEL (WUS) by the floral homeotic protein AGAMOUS (AG) is a key part of this process. In this study, we report on the identification of a novel input into the process of floral stem cell regulation. We use genetics and chromatin immunoprecipitation assays to demonstrate that the bZIP transcription factor PERIANTHIA (PAN) plays a role in regulating stem cell fate by directly controlling AG expression and suggest that this activity is spatially restricted to the centermost region of the AG expression domain. These results suggest that the termination of floral stem cell fate is a multiply redundant process involving loci with unrelated floral patterning functions.

KEY WORDS: AGAMOUS, Flower development, Stem cells, Arabidopsis

INTRODUCTION

In Arabidopsis, the indeterminate shoot apical meristem (SAM) produces organs such as leaves and flowers throughout the life of the plant. By contrast, the determinate floral meristem (FM), from which flowers are derived, produces a stereotypical number of floral organs: four sepals, four petals, six stamens and two carpels. Underlying the different behaviors of these two meristematic tissues are the different properties of their respective stem cell populations. In the SAM, as well as in the FM, the expression of the homeodomain gene WUSCHEL (WUS) in a small group of cells at the center of the structures, the so-called stem cell organizing center, is essential for maintaining the pool of stem cells. In the FM, once the correct numbers of floral organs have formed, WUS is quickly downregulated and the stem cells lost (Laux et al., 1996; Mayer et al., 1998).

The floral identity regulator LEAFY (LFY) (Schultz and Haughn, 1991; Weigel et al., 1992) activates the expression of the homeotic gene AGAMOUS (AG) in the center of young flower buds, and the AG gene product then acts to downregulate WUS, leading to a loss of stem cell activity (Busch et al., 1999; Lenhard et al., 2001; Lohmann et al., 2001; Parcy et al., 1998). However, loss of LFY function only leads to a delay in the onset of AG expression, and not to its absence (Weigel and Meyerowitz, 1993), suggesting that other factors also play a role in the early activation of AG. One of these factors was recently shown to be WUS itself, which directly binds AG regulatory sequences in combination with LFY (Lohmann et al., 2001). Flowers mutant for AG display stem cell maintenance phenotypes, resulting in the formation of flowers within flowers, and also show hemicmbiotic transformations of stamens to petals (Bowman et al., 1989). It has been suggested that these are functionally distinct activities of AG (Mizukami and Ma, 1995; Sieburth et al., 1995), yet not much is known about how this is regulated: whether AG is regulated at the RNA level, for example, via the regulation of AG expression in specific floral domains, or at the protein level, through interactions between AG and other spatially restricted molecules. Furthermore, it is unclear how AG shuts down WUS expression and thus the floral stem cell population (Laux et al., 1996; Mayer et al., 1998).

In this study, we report on the identification of a novel input into the process of floral stem cell arrest and suggest that this activity is spatially restricted to the centermost region of the AG expression domain.

MATERIALS AND METHODS

Mutagenesis

pan-3 seeds (10,000–15,000; in the L-er accession) were treated with a 0.3% (v/v) aqueous solution of ethyl methanesulfonate (Sigma) in a volume of 15 ml for 10 hours, then washed with water for 8 hours (with hourly changes) before being resuspended in a 0.15% (v/v) agar solution and sown on soil 1 cm apart. Seeds from M1 plants were harvested individually and 20-30 M2 plants per M1 line (~1000) were screened for altered floral phenotypes, which were reconfirmed in the M3 generation. Ten putative modifiers were retained after re-screening. To identify the mutation in the novel lfvy allele, the genomic coding region was amplified in two fragments of 1.3 kb and 1.4 kb by PCR (using Ex Taq, Takara) and sequenced. The mutation was found to be a nonsense mutation (Q162Stop), similar to all published null alleles.

Plasmid constructs and sequences

Details of primers available upon request. All PCR amplifications were carried out using the Phusion high fidelity polymerase (Finnzymes). All constructs were sequenced. To construct the pan repressor domain chimeric fusion, we first annealed complementary oligonucleotides carrying the enhanced SUPERMAN repressor domain motif flanked by BamHI and BglII sites, and ligated this to the pGEM-T EZ cloning vector (Promega), to yield pGEM-SDRX. The pan cDNA was PCR-amplified, digested with KpnI and BglII and cloned into the KpnI and BamHI sites of pGEM-SDRX to yield pPD64.1. The Pan-SDRX fragment was extracted with BamHI and BglII, and cloned into pJ36 (Gleave, 1992) carrying either the p35S, pPAN or pAP1(1.7-kb) promoters to yield pP66.1, pPD199.2 or pPD143.1 respectively. The Pan promoter was PCR-amplified from the L-er accession and cloned into pB36 using the SalI and KpnI sites. pAP1(1.7-kb) was a kind gift of Dr Marty Yanofsky (University of California, San Diego, CA, USA). The promoter-Pan-SDRX fragments were then extracted from pB36 using NotI and ligated to the plant transformation vector pM L BART (Eshed et al., 2001) yielding pPD74.1, pPD218.1 or pPD171.20, respectively.

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For the ethanol-inducible version of PAN-RD under the control of the PAN promoter, we used the MultiSite Gateway Three-Fragment Vector Construction Kit (Invitrogen) to generate a single plasmid harboring the two components. We PCR-amplified a fragment of the LFY::alcR–alcA::ER-GFP pGreen binary vector (gift of Patrick Laufs; INRA, Versailles, France); the alcR gene harboring a 3’ nos terminator, followed by a 3SS terminator in an inverted orientation. This fragment was recombined with the pDONR 221 vector to generate pENTR-alcR-2xT. We also modified a destination vector (pGreen 0229; gift of Philip Benfey; Duke University, Durham, NC, USA) by inserting the chimeric promoter alcA immediately after, and oriented towards, the attR3 recombination sequence. To do so, the alcA promoter was PCR-amplified from the LFY::alcR–alcA::ER-GFP pGreen vector, digested with SpeI and HnnIII and ligated to the pGreen 0229 binary vector, to yield the dpGreenBar-alcA binary vector. The PAN promoter was PCR-amplified from Col-0 and recombined with pDONR P4-P1R to yield pPD277. The PAN-RD fragment was amplified from pPD269 and recombined with pDONR P2R-P3 to yield pPD317. Finally, the three pENTR vectors (pPD277, pENTR-alcR-2xT and pPD317) were recombined into dpGreenBar-alcR, to yield the PAN::alcR–alcA::PAN-RD binary vector.

The putative bZIP binding sites in the second AGtron inton were identified based on the presence of ‘ACGT’ core sequences (Jakoby et al., 2002). The six observed sites are (5’-3’): ACTTATACGT, AGTCCCTACGTT, TGTACCGTACCATCAG, TGTAATACGTATTTG, TTGAAAGCTTGTGAT and TCTACTCATCGTTAAAT.

For the p35S::PAN-VF16 construct, VF16 was PCR-amplified, digested with BamH1 and BglII, and ligated to pB336. The PAN-VF16 fragment was then PCR-amplified and cloned into the pDONR 221 vector (Invitrogen). The triple gateway system was then used to generate the final p35S::PAN-VF16 plastid in pdpGreen-BaRT. The reporter construct used in the particle bombardment assays, pGii-3’, is published as KB31 (Busch et al., 1999).

Plant lines, transgenics and plant growth conditions
All plants were grown at either 16°C or 22°C with continuous white light, except the pan-3 and L-er plants shown in Fig. S6, which were grown at long days (22°C) under a combination of white and gro-lux light. Photos of flowers were taken using either a Zeiss Steami SV 11 stereoendoscope fitted with a Zeiss Axioscan or a Leica MZ12 stereomicroscope with a Leica DFC320 camera. Some images were adjusted for clarity by altering the brightness or contrast but any changes were applied evenly, across the entirety of the picture, without exception.

In situ hybridizations were performed according to published protocols. The WUS antisense RNA probe corresponds to the entire cDNA. Photos were taken on a Nikon Optiphot-2 equipped with a Zeiss Axioscan. Transgenic plants were generated using standard floral dipping methods. Transformant lines were selected on soil for resistance to the herbicide Basta. To determine the copy number of the PAN-RD transgene, T2 seeds were plated on petri dishes containing 10 μg/ml ammonium glutinose (Basta) and the ratio of resistant to sensitive seedlings determined (~75% resistant seedlings indicates the parent had a single insertion). The sterile 2×PAN-RD and 1×PAN-RD pan-2 plants were used as pollen donors to fertilize emasculated wild type flowers, and the F1 seeds were tested as above.

pAP1(1.7-6b)-driven expression patterns were assayed in inflorescences of ethanol-induced pAP1(1.7-6b)::alcR–alcA::ER-GFP lines treated with the water soluble lipophilic dye FM4-64 and imaged on a Zeiss 510 confocal microscope.

Chromatin immunoprecipitation
Chromatin immunoprecipitation (ChIP) experiments were performed according to published protocols (Ito et al., 1997). Inflorescences from plants mutant for the redundant APETALA1 and CAULIFLOWER genes, and expressing the dexamethasone-inducible 35S::APETALA-GR transgene (p35S::AP1-GR ap1-1 cal-1), were used. Plants were induced as described (Wellmer et al., 2006) and tissue were collected 5-7 days later for a synchronized population of flowers. Inflorescences were ground in liquid nitrogen, resuspended in buffer M1 (10 mM phosphate buffer 0.1 M NaCl, 10 mM β-mercaptoethanol, 1 M hexylene glycol), fixed with 1% formaldehyde for 10 minutes, washed in buffers M2 (buffer M1 containing 10 mM MgCl2, 0.5% (v/v) Triton X-100) and M3 (10 mM phosphate buffer, 0.1 M NaCl, 10 mM β-mercaptoethanol) and centrifuged to collect nuclei. Chromatin was isolated by resuspending the pellet in lysis buffer [1% SDS (w/v), 10 mM EDTA, 50 mM Tris-HCl pH 8.1] containing protease inhibitors (1 μg/ml Leupeptin, 15 μg/ml Aprotinin), incubating on ice for 10 minutes before adding ChIP dilution buffer (Upstate) supplemented with protease inhibitors. This purified, antibody-bound DNA (B) was used to determine enrichment using quantitative real-time PCR on an ABI 7900HT system (Applied Biosystems) with a MUTATOR-LIKE (ML) locus (At4g03870) serving as control. Relative enrichment levels were calculated by determining the ratio of the ‘mean quantity’ (calculated by the ABI software) of antibody-bound DNA (B) to total input DNA (I) for the control primers (BCTRL/ICTRL) as well as for each experimental primer pair (BEXP/IEXP), and then normalizing the ratio of the experimental value to the control value ([BEXP/IEXP]/[BCTRL/ICTRL]).

Particle bombardments
Three milligrams of one micron gold microcarrier particles were coated with 2.5 μg of the p35S::AP1 reporter construct alone (for the control) or with an additional 2.5 μg of the p35S::PAN-VF16 (for the co-bombardments). DNA was premixed prior to each coating. Equal aliquots of the coated particles were then placed onto macrocarriers and bombarded onto onion epidermal cells using a PDS-1000/He Biolistic Particle Delivery System (Bio-Rad) and 1100-psi rupture discs. The onion cells were incubated at 25°C for 2-3 days and then visualized for GUS staining using standard protocols.

RESULTS AND DISCUSSION
A genetic screen uncovers a combined role for LEAFY and PERIANTHIA in floral stem cell regulation
In a mutagenesis experiment designed to identify modifiers of the floral organ number regulator PERNIANTHIA (PAN) (Chuang et al., 1999; Running and Meyerowitz, 1996), we isolated a new lfy allele (see Materials and methods), which we named lfy-31. When compared with wild-type flowers (Fig. 1A), lfy single mutant flowers (of either lfy-31 or the well-described lfy-6 allele) bear organs that resemble leaf-like or sepal-like structures instead of sepals, petals or stamens; and sepalloid organs with stigmatic papillae instead of carpels (Fig. 1B,C). However, flowers of pan-3 mutants, which we used in the mutagenesis experiment, show no defects in floral identity, but rather bear increased numbers of sepals and petals, and reduced numbers of stamens (Fig. 1D). Flowers of the pan-3 lfy-31 double mutant line bear several notable differences from flowers of either single mutant. First, the overall number of primary organs is slightly increased with respect to lfy flowers (Table 1). Second, whereas the carpelloid structures of lfy mutant flowers are fully or partially fused (Fig. 1B,C), those of pan lfy flowers remain unfused (Fig. 1E,F). Third, ovule-like structures are often visible within carpels of lfy mutants (Fig. 1G) but only very rarely in the pan lfy double mutant (Fig. 1F). Finally, whereas all lfy flowers produce a determinate number of organs (Weigel et al., 1992), 89% (n=38) of pan lfy flowers are indeterminate, such that ectopic floral structures continue to develop interior to the fourth whorl organs (Table 1; Fig. 1F). As a further test of this interaction, we generated lines doubly mutant for pan-3 and the weak lfy-5 allele
by the continued expression of are associated with the persistence of the stem cell pool, as revealed results indicate that the indeterminacy phenotypes of arise (Fig. 1M; see Fig. S4 in the supplementary material). These flower from where the organs of the interior floral structures will detectable within the broad expanse of tissue at the center of the older see Figs S2 and S3 in the supplementary material). By contrast, in flowers, (Mayer et al., 1998). Similarly, in approximately stage 7, when the carpel primordia first appear the case of wild-type flowers (Mayer et al., 1998), WUS center is essential for floral determinacy (Mayer et al., 1998). As in clearly detectable in the center of very early flower buds of double mutant flowers, we performed in situ hybridization transcript, as the downregulation of lfy double mutant flowers, we performed in situ hybridization experiments to determine the expression dynamics of the WUS transcript, as the downregulation of WUS in the stem cell organizing center is essential for floral determinacy (Mayer et al., 1998). As in the case of wild-type flowers (Mayer et al., 1998), WUS mRNA is clearly detectable in the center of very early flower buds of pan-3 and lfy-6 single mutants, as well as in pan-3 lfy-31 double mutants (Fig. 1H-J). In the wild type, WUS mRNA becomes undetectable by approximately stage 7, when the carpel primordia first appear (Mayer et al., 1998). Similarly, in pan-3 and lfy-6 single mutant flowers, WUS expression is absent in later-stage flowers (Fig. 1K,L; see Figs S2 and S3 in the supplementary material). By contrast, in older pan lfy double mutant flowers, WUS expression is clearly detectable within the broad expanse of tissue at the center of the flower from where the organs of the interior floral structures will arise (Fig. 1M; see Fig. S4 in the supplementary material). These results indicate that the indeterminacy phenotypes of pan lfy flowers are associated with the persistence of the stem cell pool, as revealed by the continued expression of WUS in the stem cell organizing center.

The role of LFY in the center of the floral meristem, via the activation of AG expression, has been well studied. In addition, three lines of evidence suggest that PAN might also be active in this region. First, when certain alleles of pan (such as pan-3) are grown under specific culture conditions (see Materials and methods), some flowers (13%, n=84) show slight indeterminacy (see Fig. S5 in the supplementary material). Second, flowers from plants doubly mutant for pan and crabs claw (the carpel patterning gene) are indeterminate, with a reiteration of carpel structures in internal whorls (see Fig. S6C-F in the supplementary material; Y. Eshed and J. Bowman, personal communication). Third, pan mutations restore fourth-whorl carpels to flowers of the superman-1 (sup-1) single mutant that normally either lack carpels or have staminoid carpels, also suggesting a role in this domain (see Fig. S6G-I in the supplementary material) (Running and Meyerowitz, 1996). Because these data reveal a function for PAN in the presumptive fourth whorl, we hypothesized that the determinacy defects apparent in lfy pan double mutant flowers were due to a hidden role for PAN in regulating the floral stem cell population, which lies within the fourth whorl.

A dominant-negative pan allele induces floral indeterminacy by suppressing AG expression One explanation for the absence of floral indeterminacy phenotypes in most pan mutant flowers is that this activity of PAN might be masked by functional redundancy with other factors. To overcome

<p>| Table 1. Identities and numbers of organs in lfy and pan mutant flowers* |
|-----------------|-----------------|----------------|-----------------|-------------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Mutant</th>
<th>Sepals/sepal-like</th>
<th>Petals</th>
<th>Stamens</th>
<th>Carpels/sepaloid-carpels</th>
<th>Flowers with interior organs (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pan-3</td>
<td>5.1±0.7</td>
<td>5.1±0.6</td>
<td>5.3±0.7</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>lfy-6</td>
<td>9.8±0.5</td>
<td>0</td>
<td>0</td>
<td>3.5±0.5</td>
<td>0</td>
</tr>
<tr>
<td>lfy-31 pan-3</td>
<td>11.2±1.9</td>
<td>0</td>
<td>0</td>
<td>6.9±1.1</td>
<td>89</td>
</tr>
</tbody>
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*lfy-6 and lfy-31 pan-3 flowers were later-arising structures with floral and secondary inflorescence characteristics.
Fig. 2. A dominant-negative PAN chimera induces floral determinacy phenotypes. (A) pAP1(1.7-kb)::alcR--alcA::ER-GFP expression in an inflorescence meristem. GFP signal (green) is observed in the central domes (arrowheads) of all visible flowers after induction with ethanol vapors. Autofluorescence from the shoot apical meristem is visible (red). (B-H) Floral phenotypes of PAN wild-type or mutant plants harboring one or more copies of PAN-RD under the control of the AP1(1.7-kb) promoter. Red and green bars indicate the number of copies of PAN-RD or wild-type PAN, respectively. Open bar indicates no copies, half-filled indicates one copy and filled indicates two copies (see key, bottom right). (B) pan-2 mutant flower. (C) pan flower harboring one copy of PAN-RD displaying amplified pan-like phenotypes, as well as additional phenotypes such as extra carpels (arrow) and severe floral indeterminacy. (D) Side view of the flower in C with some organs removed to reveal ectopic floral structures (arrow) developing interior to the fourth whorl (demarcated by a dashed line). (E) A pan-like phenotype is observed in flowers arising from a cross of genotype C to wild type. This flower harbors one copy of PAN-RD and is heterozygous at the PAN locus. (F) Wild-type flower. (G) Wild-type flower harboring one copy of PAN-RD displaying a pan-like phenotype. (H) Flower from progeny of the plant in G harboring two copies of PAN-RD presenting strong indeterminacy defects, similar to PAN-RD/+ pan plants (C). (I-K) In situ localizations of AG transcript in stage 5-6 flowers of pan-2 (l) or PAN-RD/+ pan-2 (l,K) plants. AG localization appears unperturbed in pan flowers (l), but in PAN-RD/+ pan-2 flowers a central region within the AG domain shows diminished signal intensity. Also marked are sepals (dashed arrow) that do not express AG and early stamen primordia (arrowhead) that do. (K) Magnified view of the dashed box in J. Scale bars: 10 μm.

such redundancy, we generated a constitutively repressing form of PAN by fusing it to the SUPERMAN repressor domain motif (Hiratsu et al., 2003). Such constructions have been used to study bZIP factors in several model systems (Fukazawa et al., 2000; Rieping et al., 1994) and, in Arabidopsis, SUPERMAN repressor domain (RD) fusions of several transcription factors have been shown to phenocopy their corresponding loss-of-function mutants (Baudry et al., 2006; Hiratsu et al., 2003; Xu et al., 2006). The expression of such a PAN fusion, either ubiquitously or from the endogenous promoter, yielded plants with severe growth defects, thereby masking any floral phenotypes (data not shown). In order to assay its effects on floral patterning, we thus used the flower-specific APETALA1 (AP1) promoter (Hempel et al., 1997). A 1.7 kb upstream fragment of the AP1 locus drives expression throughout the early flower; in addition, and at variance with the normal AP1 expression pattern, it remains active in the entire flower, presumably due to the absence of additional regulatory elements (Fig. 2A; see Fig. S7 in the supplementary material; M. Yanofsky, personal communication).

In order to remove the effects of competition between PAN-RD and endogenous PAN, we introduced the pAP1(1.7-kb)::alcR--alcA::ER construct (hereafter referred to as PAN-RD) into pan-2 mutant plants (Fig. 2B). The majority (82%) of these PAN-RD/+ pan pan primary transformants bore flowers with increased numbers of petals and stamens (6.3±0.6 and 5.8±0.4 respectively, n=20), secondary flowers in the axils of first-whorl organs (2.8±0.6 versus 0 in the wild type and pan), extra carpels in the fourth whorl (3.5±0.5) and severe indeterminacy (Fig. 2C,D). The other 18% (n=85) of transformants showed a slight enhancement of the pan organ number phenotypes without any determinacy defects (data not shown). To eliminate the possibility that the indeterminacy phenotypes were caused by the use of the AP1(1.7-kb) promoter fragment, we used an ethanol-inducible two component system (Devaux et al., 2003; Maizel and Weigel, 2004) to drive PAN-RD expression under the endogenous PAN promoter. In the absence of induction, pan-2 plants bearing this construct show no fourth-whorl phenotypes (see Fig. S8A in the supplementary material). However, after induction with ethanol, we observe flowers bearing unfused gynoecia and ectopic internal carpel structures (see Fig. S8B in the supplementary material). Thus, expression of a PAN-repressor domain fusion protein in the flower leads to the loss of floral determinacy, a phenotype observed at low frequency in pan mutant plants grown in specific culture conditions (see above).

A caveat to the use of dominant-negative alleles is that they may act as neomorphs, altering the expression of ectopic, rather than genuine, downstream targets of the protein under study. We decided to study this by varying the ratio of chimeric to wild-type protein. If PAN-RD behaves as a true dominant-negative allele, increasing doses of it should yield increasingly stronger phenotypes, whereas increasing doses of unmodified PAN should attenuate the phenotypes. We first
used pollen from the PAN-RD+/+; pan/pan flowers described above in a cross to wild type and examined the phenotypes of F1 plants selected for the presence of the transgene. We found that these flowers (PAN-RD+/+; pan/+) had phenotypes similar to the pan mutant (compare Fig. 2E with 2B). Thus the same PAN-RD insertion that confers strong indeterminacy phenotypes on pan flowers does not do so on pan/+ heterozygotes (instead yielding only the more sensitive organ number defect), showing that PAN-RD expression does not ectopically induce floral indeterminacy. Next we examined primary transformants in wild-type plants, thus with two additional wild-type copies of PAN (Fig. 2F). Approximately 20% (n=60) of these plants (genotypically PAN-RD+/; PAN/PAN) phenocopied the pan mutant (Fig. 2G; 4.3±0.5 sepals, 4.9±0.3 petals and 4.7±0.5 stamens; n=20), whereas the rest showed no discernable phenotypes. We then examined the progeny of these plants, to determine the phenotypes of plants harboring two copies of the transgene (see Materials and methods). These flowers (PAN-RD/PAN-RD; PAN/PAN) displayed strong phenotypes, including extra carpels and floral indeterminacy (Fig. 2H), and closely resembled PAN-RD+/+; pan/pan flowers (Fig. 2C,D). Taken together, these data show that the effects of the PAN-RD fusion protein are modified by wild-type PAN in a dosage sensitive manner. This suggests that PAN-RD and endogenous PAN compete for the same targets and that the PAN-RD phenotypes are due to the repression of genuine PAN targets.

To characterize the molecular basis of the PAN-RD phenotype, we performed in situ hybridizations to determine whether the PAN-RD transgene induced changes in AG expression patterns. We observed that, as in the wild type, AG is expressed uniformly throughout the third and fourth whorls of stage 5-6 pan-2 flowers (Fig. 2I). However, in similarly staged PAN-RD+/+; pan/pan flowers, AG expression is patchy, with the central region of the floral meristem showing reduced expression (Fig. 2J,K). Since pAP1(1.7-kb) drives expression throughout the central dome of the flower during these stages, these results indicate that the PAN-RD chimera might exert an unequal influence on different cells within the AG-expressing region.

Thus our results show that expression of a PAN-RD fusion protein in the flower is sufficient to mimic pan loss-of-function phenotypes and to produce floral indeterminacy. Since the indeterminacy phenotype occurs more stably in pan-RD plants than in pan simple mutants, this role possibly requires other spatially or temporally restricted factors. Taken together with the phenotypes of the double mutant flowers described above, this suggests that PAN plays a role in the development of the fourth whorl, specifically in the proper regulation of the floral stem cell population, and that this role is achieved through the regulation of AG. Furthermore, as the effects of PAN-RD were similar to the loss-of-function phenotypes of pan mutant alleles, the role of PAN in floral determinacy is likely to be that of an activator of a gene involved in the process.

PAN binds AG regulatory sequences in vivo

We next sought to determine the precise mechanism by which PAN affects floral stem cell fate. As discussed above, AG is a key regulator of this process, by itself acting to repress WUS expression. Because AG expression is perturbed in PAN-RD flowers and because PAN is a predicted transcriptional activator, we reasoned that its role might be to positively regulate AG expression. To test whether PAN directly associates with the AG promoter, we used chromatin immunoprecipitation (ChIP) assays, which examine the in vivo binding of transcription factors to DNA. We maximized the sensitivity of our assays by using a synchronized population of flowers at stages 5-7 (Wellmer et al., 2006) (see Materials and methods), as the stem cell organizing activity is known to be terminated during this time. In addition, we used a characterized PAN-specific polyclonal antibody that, when used in immunohistochemical analyses, detects protein signals closely resembling PAN mRNA expression patterns, but showing no signal in mutant flowers (Chuang et al., 1999). We further pre-cleared this antibody against tissue from pan-2 plants prior to immunoprecipitating intact protein-DNA complexes. We then performed quantitative real-time RT-PCR to assay for the enrichment of sequences within the 3 kb second intron of the AG locus with respect to input DNA, where important cis regulatory sequences are located (Fig. 3A) (Busch et al., 1999; Deyholos and Sieburth, 2000; Hong et al., 2003; Lohmann et al., 2001; Parcy et al., 1998). Black triangles, LFY/WUS binding sites; white triangle, predicted LFY binding site; stars, CARG boxes; circles, CCAAT boxes; diamond, AAGAAT motif; green squares, predicted core bZIP binding sites; vertical tick marks: 200 bp intervals. (B) Results of chromatin immunoprecipitation experiments from stage 5-7 flowers. Anti-PAN antiserum was used to isolate protein-DNA complexes and DNA enrichment levels were measured by quantitative real-time RT-PCR (see Materials and methods). Enrichment was calculated for antibody-bound DNA relative to total input DNA and was then normalized against an internal genomic control. Vertical bars show mean enrichment levels from duplicate experiments for amplicons distributed along the intron (shown in 3A). The scale for amplicon ‘H’ is different and is shown in red. Results are shown only for amplicons with a coefficient of correlation (r²)>0.98. (C) Results of particle bombardment experiments in onion epidermal cells. Vertical bars represent mean values from duplicate experiments for numbers of cells stained for GUS enzymatic activity. The pAGi-3::GUS reporter, which recapitulates most facets of AG expression in vivo, shows some background activity (left bar) in onion epidermal cells. When co-bombarded with p35S::PAN-p16 (right bar), the ‘numbers of cells’ stained for GUS activity is 4- to 5-fold greater. Error bars represent standard deviation from the mean.
normalized relative to internal genomic controls. These data demonstrate that PAN, either alone or in a complex, binds AG regulatory sequences in vivo.

Because of the nature of ChIP assays, not every enriched fragment necessarily contains a PAN binding site. Four of the five ChIP-enriched amplicons (B, C, F and H) map to regions previously described as being very highly conserved (Hong et al., 2003). Of these, amplicon C contains binding sites for LFY and WUS (Lohmann et al., 2001; Parcy et al., 1998); whereas predicted bZIP core binding sites (Jakoby et al., 2002) are located within or close to two others (F and H). Hong et al. (Hong et al., 2003) have shown that an AG reporter containing a deletion within amplicon H loses expression at later floral stages, suggesting that it plays a role in the maintenance of AG expression. In an accompanying article (Maier et al., 2009), the authors use one-hybrid assays to show that amplicon F contains PAN binding sites. Furthermore, they show that mutations in this bZIP motif disrupt binding in vitro and eliminate in vivo expression in the context of an AG reporter. Given the very high enrichment of amplicon H in our ChIP assays, we were interested in determining whether this region might also contain PAN binding sites. To this end, we made use of a published 3' AG reporter construct that reproduces the normal AG expression pattern in vivo (Busch et al., 1999). In this reporter, an 800 bp 3' pAG fragment (Fig. 3A) drives expression of the uidA gene, which encodes the β-glucuronidase (GUS) enzyme (Busch et al., 1999).

We performed particle co-bombardment experiments in onion epidermal cells with a putative constitutively activated form of PAN (p35S::PAN-VP16). Although the reporter alone presents basal reporter activity in onion cells (44±5±4.6 cells; Fig. 3C; see Fig. S9A,C in the supplementary material), perhaps due to the presence of minimal p35S sequences, 4- to 5-fold greater numbers of cells (157±11.3; Fig. 3C; see Fig. S9B,D in the supplementary material) show GUS activity when co-bombarded with p35S::PAN-VP16. It is thus possible that PAN has two or more target sites within the AG promoter, to which it might bind with different affinities or different partners.

Flowers mutant for AG display stem cell overproliferation phenotypes and, in addition, also show homeotic transformations of stamens to petals (Bowman et al., 1989). Since PAN-RD disrupts floral stem cell regulation without inducing the homeotic transformations associated with the loss of AG function, we asked whether PAN might function as a general regulator of AG, or only to modify its activity in the fourth whorl. To this end, we used the weak ag-4 allele, which produces flowers with reduced numbers of stamens and with fourth whorl organs replaced by another flower (Fig. 4A) (Sieburth et al., 1995). Mutations in several loci, including HUA1 and HUA2, REBELOTE (RBL) or ULTRAPETALA1 (ULT1) enhance the ag-4 allele by fully or partially converting stamens to petals (Chen and Meyerowitz, 1999; Fletcher, 2001; Prunet et al., 2008). We reasoned that if PAN plays a general role in regulating AG expression, a pan allele might similarly enhance the weak ag phenotype. Conversely, if PAN participates primarily in the floral determinacy aspects of AG, the double mutant might not be significantly enhanced. In fact, we observe that pan-2 ag-4 double mutant flowers (Fig. 4B) differ from ag-4 single mutants only in that they present an additional pan-like phenotype: extra perianth organs (4.8±0.5 sepal and 4.8±0.5 petals compared with four each in ag-4; n=20 for both genotypes), as is the case for double mutants of pan and the strong ag-1 allele (Running and Meyerowitz, 1996). The third-whorl stamens of pan-2 ag-4 flowers appear morphologically normal, although they are reduced in number (5.5±0.5 compared with 5.8±0.4 in ag-4). This suggests either that the stamen identity functions of the mutant protein encoded by the ag-4 allele are robust and are not perturbed by the absence of PAN, or that PAN regulates AG expression only in the fourth whorl.

Prunet et al. (Prunet et al., 2008) have recently proposed the existence of a distinct subdomain within the floral fourth whorl, in which a decrease in AG expression is sufficient to disrupt the specification of floral determinacy. Two observations indicate that the effects of PAN on the AG promoter might be spatially restricted, perhaps to this subdomain. First, in PAN-RD flowers, there is a marked reduction in the accumulation of AG transcript at the very center of the dome of the floral meristem. Second, unlike many other AG interactors (Chen and Meyerowitz, 1999; Fletcher, 2001; Prunet et al., 2008), pan mutations have no effect on the third whorl phenotypes of a weak ag allele. A restricted effect of PAN on AG expression might explain why mutations in PAN attenuate the fourth whorl phenotype of sup mutants (Running and Meyerowitz, 1996), which produce reduced or masculinized carpels (see Fig. S6H in the supplementary material) (Bowman et al., 1992). One model is that in the center of the fourth whorl of pan sup double mutant flowers (see Fig. S6I in the supplementary material), even the mild reduction in AG expression caused by the absence of PAN could lead to increased or prolonged WUS expression, and thus to an increase in the size of this region. Since the stamen identity genes AP3 and PI are excluded from the very center of sup flowers (Bowman et al., 1992; Goto and Meyerowitz, 1994), the corresponding, but enlarged, region in pan sup flowers could now become specified into a functional carpel.

Like PAN, the broadly expressed APETALA2 (AP2) gene, the absence of which causes only specific floral phenotypes (a change in sepal and petal identities), was recently shown, through the characterization of a semi-dominant allele, to play a role in the control of stem cells in the shoot (Würschum et al., 2006). Thus both PAN and AP2 have primary roles in specific aspects of floral patterning, but also have masked functions in stem cell regulation that are likely to require interactions with other domain- and/or stage-specific factors. Identifying these interactors through genetic screens or other methods could prove invaluable in gaining a full understanding of the complex regulatory mechanisms that control stem cell fate.

As the main function of AG in floral determinacy appears to be to downregulate WUS expression in a narrow temporal window, AG expression must be quickly upregulated in order to ensure the complete arrest of stem cell fate, and thereby ensure proper floral development.
patterning. We suggest that plants have evolved a complex, multiply redundant system to ensure the proper regulation of AG, and furthermore, that many of the factors involved in the regulation of floral stem cells probably also perform unrelated patterning functions.

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Supplementary material

Supplementary material available online at http://dev.biologists.org/cgi/content/full/136/10/1605/DC1

References


