Oriented basement membrane fibrils provide a memory for F-actin planar polarization via the Dystrophin-Dystroglycan complex during tissue elongation

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Summary

The elongation of the fly ovarian follicle is a model of tissue morphogenesis involving the extracellular matrix. It has been proposed that after Fat2-dependent planar polarization of the follicle cell basal domain, oriented basement membrane (BM) fibrils and F-actin stress fibers constrain follicle growth, promoting its axial elongation. However, the relationship between BM fibrils and stress fibers and their respective impact on elongation are unclear. We found that Dystroglycan (Dg) and Dystrophin (Dys) are involved in BM fibril deposition. Moreover, they orient stress fibers, by acting locally and in parallel to Fat2. Nonetheless, Dg-Dys complex-mediated cell autonomous control of F-actin orientation relies on the previous BM fibril deposition, indicating two distinct but interdependent functions. Thus, the Dg-Dys complex works as a critical organizer of the epithelial basal domain, regulating both F-actin and BM. Furthermore, BM fibrils act as a persistent cue for the orientation of stress fibers that are the main effector of elongation.

Keywords: morphogenesis, ECM, Drosophila, tissue elongation, planar cell polarity, Dystrophin, Dystroglycan, basement membrane

Introduction

Deciphering the mechanisms underlying tissue morphogenesis is crucial for our fundamental understanding development and also for regenerative medicine. Building organs generally requires the precise modeling of a basement membrane extracellular matrix (ECM), which in turn can influence tissue shape (Dzamba and DeSimone, 2018; Sekiguchi and Yamada, 2018; Isabella and Horne-Badovinac, 2015). However, the mechanisms driving the assembly of a specific basement membrane (BM)and how this BM then feeds forward on morphogenesis are still poorly understood. *Drosophila* oogenesis offers one of the best tractable examples in which such a morphogenetic process. Each ovarian follicle, which is composed of a germline cyst surrounded by the somatic follicular epithelium. Follicles undergo a dramatic growth, associated with tissue elongation, starting from a little sphere and ending with an egg in which the anteroposterior (AP) axis is 3-fold longer than the mediolateral (ML) axis (Fig. 1A). This elongation is roughly linear from the early to the late stages, but can be separated in at least two mechanistically distinct phases (Alégot et al., 2018; Aurich and Dahmann, 2016). The first phase (from stage 3 to stage 8) requires a double gradient of JAK-STAT pathway activity that emanates from each pole and that controls myosin II-dependent apical pulsations (Alégot et al., 2018). In the second phase, from stage 7-8, elongation depends on the atypical cadherin Fat2 that is part of a planar cell polarity (pcp) pathway orienting the basal domain of epithelial follicle cells (Gutzeit et al., 1991; Barlan et al., 2017; Chen et al., 2016; Viktorinová et al., 2009). Earlier during oogenesis, Fat2 gives a chirality to the basal domain cytoskeleton in the germarium, the structure from which new follicles bud (Chen et al., 2016). This chirality is required to set up a process of oriented collective cell migration perpendicularly to the elongation axis that induces follicle revolutions (Chen et al., 2016; Viktorinová and Dahmann, 2013). From each migrating cell, Fat2 also induces, in the rear adjacent cell, the formation of planar polarized protrusions that are required for rotation (Cetera et al., 2014, Barlan et al., 2017). These rotations end at late stage 8, and allow the polarized deposition of BM fibrils, via a secretion route to the lateral domain of the cells that persists until late developmental stages (Haigo and Bilder, 2011; Isabella and Horne-Badovinac, 2016). Follicle rotation also contributes to the planar cell polarization of integrin-dependent basal stress fibers that are oriented perpendicularly to the AP axis (Cetera et al., 2014). Moreover, at stage 7-8, a gradient of matrix stiffness controlled by the JAK-STAT pathway and Fat2 contributes to elongation (Crest et al., 2017). Then, from stage 9, the epithelial cell basal domain undergoes anisotropic oscillations, due to the periodic contraction of the oriented stress fibers, which also contributes

to follicle elongation (He et al., 2010; Qin et al., 2017). To explain the impact of *fat2* mutations on tissue elongation, it is generally accepted that oriented stress fibers and BM fibrils acts as a molecular corset that constrains follicle growth in the ML axis and promotes its elongation along the AP axis. However, the exact contribution of F-actin versus BM to this corset is still unclear, as is whether the orientations of stress fibers and of BM fibrils are causally linked.

Here, we analyzed the function of Dystrophin (Dys) and Dystroglycan (Dg) during follicle elongation. Dys and Dg are the two main components of the Dystrophin-Associated Protein Complex (DAPC), an evolutionarily conserved transmembrane complex that links the ECM (via Dg) to the F-actin cytoskeleton (via Dys) (Barresi and Campbell, 2006). This complex is expressed in a large variety of tissues and is implicated in many congenital degenerative disorders. Loss of function studies in model organisms have revealed an important morphogenetic role for Dg during development, usually linked to defects in ECM secretion, assembly or remodeling (Clements et al., 2017; Henry and Campbell, 1998; Satz et al., 2010; Bello et al., 2008; Buisson et al., 2014; Naegeli et al., 2017; Yatsenko and Shcherbata, 2014). A developmental role for Dys is less clear, possibly due to the existence of several paralogs in vertebrates. As *Drosophila* has only one *Dg* and one *Dys* gene, it is a promising model for their functional study during development and morphogenesis.

We found that *Dg* and *Dys* are required for follicle elongation and proper BM fibril formation early in fly oogenesis. During these early stages, DAPC loss and hypomorphic *fat2* conditions similarly delay stress fiber orientation. However, DAPC promotes this alignment more locally than Fat2. Moreover, DAPC genetically interacts with *fat2* in different tissues, suggesting that they belong to a common morphogenetic network. Later in oogenesis, Dg and Dys are required for stress fiber orientation in a cell autonomous manner. This is the period when the main elongation defect is seen in these mutants, arguing for a predominant role for stress fibers in the elongation process. Nonetheless, this latter function depends on the earlier DAPC function in BM fibril deposition. We propose that BM fibrils serve as a pcp memory for the late stages, and are used as a template by the DAPC for F-actin stress fiber alignment.

Results

Dys and *Dg* mutants reveal a new phase of follicle elongation

As in *Drosophila* follicle elongation requires many proteins that function at the basal side of the follicular epithelium, we checked whether the DAPC could be involved in this process. Both *Drosophila Dg* and *Dys* null mutants are viable and we used combinations of two different null alleles for each of them (Christoforou et al., 2008). Mature eggs from mutant females were significantly shorter and wider (Fig. 1B-F) with an aspect ratio (AR) around 2.3 compared with 2.9 in wild type (WT) follicles (Fig. 1G). Importantly, such a phenotype can be rescued by restoring expression in the follicle cells, confirming that it is associated with these mutations, and indicating that the DAPC is required for elongation in the follicle cells (see below). Comparison of the elongation kinetics in mutant and WT follicles showed that such morphological differences appeared mainly during the later stages of oogenesis (stages 12 to 14), although a slight, but significant defect was present around stage 8 (Fig. 1H). The *Dg* and *Dys* null mutants'elongation kinetic curves were clearly different from those of *fat2* mutants in which elongation is strongly affected from stages 7-8 (Alégot et al., 2018; Aurich and Dahmann, 2016). Thus, the DAPC is involved in follicle morphogenesis, and its specific temporal requirement suggests the existence of an elongation phase that is mechanistically different from the Fat2-dependent one.

Then, to determine how the DAPC contributes to follicle elongation, we first checked the collective cell migration that induces rotation during the early stages because it is upstream of many subsequent events that are potentially important for elongation. Both *Dys* and *Dg* null mutant follicles rotate and the migration velocity is not significantly different from that of WT follicles (Fig. 1I-L). Thus, the DAPC is not involved in the collective cell migration and the initial PCP established by Fat2, confirming that it acts through a distinct mechanism. We then focused our phenotypic analysis on the two events induced by follicle rotation: BM fibril deposition and stress fiber orientation.

The DAPC is important for BM fibril deposition

The follicle cell BM contains two ECM types, a planar BM without a specific organization visible by confocal microscopy, and BM fibrils that are oriented perpendicular to the follicle AP axis. BM fibrils are deposited during follicle rotation via a secretory route targeted to the cell lateral domain, and can be observed by monitoring the expression of the main ECM components: Collagen IV (ColIV), Perlecan (Pcan) and Laminin (LanA) , the two latter being

direct Dg ligands (Gutzeit et al., 1991; Haigo and Bilder, 2011; Isabella and Horne-Badovinac, 2016). Collagen IV and Pcan can be visualized using the Viking- and Trol-GFP protein traps, respectively (Morin et al., 2001). Moreover, a fosmid containing the whole *laminin A* gene tagged with GFP has also been generated (LanA-GFP) (Sarov et al., 2016). We also employed the MiMIC system to generate RFP-tagged Pcan (Venken et al., 2011). This line gives an identical pattern to Pcan-GFP and is homozygous viable and fertile, indicating that it does not disrupt Pcan function (not shown). Comparison of the fibril composition using these different tagged proteins (Fig. 2A-B) showed that in WT follicles, Pcan-RFP co-localized exactly with ColIV-GFP and LanA-GFP. This indicates that BM fibrils are uniformly composed of these three proteins, as previously shown by immunostaining (Isabella and Horne-Badovinac, 2016). We then wondered whether BM fibril deposition is affected in *Dys* and *Dg* mutants. In these two mutants, the general targeting of BM secretion towards the basal domain is normal, with no visible apical secretion as it has been observed in different mutants affecting BM secretion (Fig. S2A-C) (Denef et al., 2008; Devergne et al., 2014; Lerner et al., 2013; Devergne et al., 2017). However, images in the focal plane of the BM reveal a very strong decrease of the Collagen IV-positive BM fibrils both in *Dys* and *Dg* null mutants (Fig. 2D). This observation is also true for LanA and Pcan (Fig. 2C and E). Quantification of the fibril fraction on stage 8 follicles indicates that it corresponds to about 13% in the WT situation, but it drops to 4% in *Dys* and *Dg* mutants (Fig. 2F). Loss of the DAPC seems to affect both the number and length of the fibrils. As a result of this defect some fibrils are still visible in stage 12 WT follicles but not in *Dys* and *Dg* mutant ones (Fig. S2D-G). It has been previously reported that Laminin accumulates between follicle cells overexpressing Dg (Yatsenko and Shcherbata, 2014). We therefore overexpressed Dg in these cells and examined the BM. Under such conditions, the fibril fraction is also increased (Fig. S2H,I), confirming the key role of Dg in this process. Thus, the DAPC is involved in BM fibril deposition.

Fibril deposition depends on the lateral secretion of ECM proteins while the rotation facilitates their deposition and orientation in the BM (Isabella and Horne-Badovinac, 2016). The lateral secretion of BM proteins can be visualized by immunostaining on non-permeabilized follicle cells to detect only the protein localized between the cells. Such an approach on *Dys* mutant clones show that some ColIV is detected, as between WT cells (Fig. 2 G,H). This suggests that Dys does not directly interfere with the lateral targeting of BM secretion. In a mutant blocking rotation, such as *fat2*, BM proteins accumulate in the lateral space between cells, whereas no massive accumulation is observed in a *Dys* mutant, suggesting that the fibril defect associated with DAPC loss of function cannot be explained by a failure of the latest step of fibril deposition

(Isabella and Horne-Badovinac, 2016) (Fig. 2G,I). Moreover, in a *fat2, Dys* double mutant we observed the same lateral accumulation of ECM protein as in a *fat2* mutant, confirming that lateral secretion is not affected by DAPC loss of function (Fig. 2 I, J). It is therefore unclear by which mechanism the DAPC contributes to fibril formation. Nonetheless, these mutants are the first examples of mutations that specifically reduce BM fibril formation without any defect in the general targeting of basal secretion or in rotation, offering a unique opportunity to address the functional relevance of the fibrils.

The DAPC contributes to stress fiber orientation during early stages

In parallel to the analysis of BM fibrils, we also studied the impact of the loss of the DAPC on basal F-actin organization. This alignment is still weak at stage 4 and then increases to reach a maximum around stage 8 (Fig. 3A-F)(Cetera et al., 2014). Both in *Dys* and *Dg* null mutants, although the stress fibers are globally oriented perpendicular to the AP axis in mutant follicles, quantification of the angular distribution reveals a delay in their proper orientation at stage 4 and 6 to reach a normal level at stage 8 (Fig. 3A-R). Stress fiber orientation can be also analysed by the determination of the Tissue Order Parameter (TOP) based on a method previously described (Cetera et al., 2014). A complete random orientation TOP value will tend to 0, whereas a perfect alignment between the cells will tend to 1 (Fig. 3S). This method confirms that *Dys* and *Dg* mutants behave similarly, with a delay in the proper stress fiber alignment (Fig. 3T). Although rotation is required for stress fiber orientation, this motion is not affected by DAPC loss of function. Thus, this complex likely acts downstream of or in parallel to rotation to orient stress fibers.

The DAPC and Fat2 have partially redundant functions.

We found that the DAPC has only a minor impact on the early phase of stress fiber orientation, with a delayed orientation of actin fibers that is however achieved at stage 8, suggesting alternative mechanisms to orient fibers at these stages (4-8). Similarly, deletion of the intracellular part of Fat2, (*fat2-DeltaICD)* induces a hypomorphic defect with only a slight delay of stress fiber orientation, despite a slower rotation (Aurich and Dahmann, 2016; Barlan et al., 2017; Chen et al., 2017). We therefore wondered what could be the relationship between these two genetic backgrounds. We generated a double mutant background for *fat2/ fat2-DeltaICD* and *Dys* null alleles *(Dys, fat2-DeltaICD)* and compared stress fiber alignment for these different genotypes (Fig 4A-D). TOP analysis shows that single mutants are quite similar

and that they have an additive effect (Fig. 4E,I), an additivity that is also observed on follicle elongation (Fig. 4Q). Thus, Dys and Fat2 probably work in parallel for stress fiber orientation once Fat2 as initiated follicle rotation.

To get a better understanding of this additivity we performed a deeper analysis of stress fiber orientation. First, we wondered whether the alignment robustness was the same in each cell and we therefore analyzed the Cell Order Parameter (COP) (Fig. 4F). This clearly shows that the mutants behave in a different manner, with *fat2-DeltaICD* behaving quite similarly to WT whereas *Dys* and *Dys, fat2-DeltaICD* giving an identical weaker COP (Fig. 4J). This result is confirmed by the close observation of *Dys* single cells in which more divergent stress fibers are seen than in *fat2-DeltaICD* cells (Fig. S4C-D). This indicates that *Dys* promotes stress fiber alignment in each cell, a process that does not seem to involve *fat2*. We also calculated a Local Order Parameter (LOP), determined for each cell on a cluster including this cell and its neighbor cells included in a given radius (Fig. 4G). Globally, for all mutant genotypes that we analyzed, LOP values decrease when increasing the radius and are therefore higher than the TOP ones, which are identical to the value obtained for a large radius (Fig S4E). Moreover, the additivity of *Dys* and *fat2* can be also observed on this parameter (Fig 4K and S4E). Finally, we looked at the difference between LOP and TOP (Fig 4H). Interestingly, we noticed a stronger LOP-TOP difference for *fat2-DeltaICD* than for *Dys* mutants, a difference culminating at stage 6 (Fig 4L and S4F). This difference can be also directly observed on images of F-Actin orientation (Fig S4A-B). For *fat2-DeltaICD*, several patches of neighbor cells with a same orientation but changing from a patch to another can be observed. For *Dys,* we did not observe these patches but changes in orientation from one cell to another. Altogether, these data indicate that *Dys* promotes stress fiber planar polarization at a cellular and local scale whereas *fat2*, or at least its intracellular domain, acts at a more global scale.

These results indicate an additive effect of the loss of the DAPC and of this hypomorphic condition for *fat2* and that they are partially redundant to orient stress fibers during early stages. They further suggest that Fat2 and the DAPC are part of a same functional network during follicle elongation, although they probably work in parallel once BM fibrils are deposited.

Intriguingly, *Dys, Dg* and *fat2* mutants show a very specific defect in the wing, with a partial absence of the posterior crossvein, although the cellular basis for this defect is unknown (Christoforou et al., 2008; Viktorinová et al., 2009) (Fig. 4M, N, R). However, this defect is not observed in a *fat2 / fat2-DeltaICD* hypomorphic background (Fig. 4O, R). In the double mutant *Dys, fat2-DeltaICD* flies, the posterior crossvein is usually completely absent or limited to a dot and the anterior crossvein, which is never affected in *Dys* mutant flies, is incomplete (Fig.

4P, R). These defects indicate a strong genetic interaction in the wings as observed in follicles. Thus, these results suggest that Fat2 and the DAPC work in parallel in the same network, which might be involved in many contexts.

The DAPC is required for stress fiber orientation during late stages

Elongation curves of *Dys* and *Dg* mutants indicate that the major elongation defect appears around stage 12 (Fig. 1H). Of note, for unknown reasons, stress fibers lose their planar polarization at stage 10B/11 but regain their proper orientation around stage 12 (Delon and Brown, 2009; Wahlström et al., 2006) (Fig. 5A,B). In WT follicles, this transition can be observed by the change in angular distribution between stage 11 and stage 13 (Fig. 5C,D). F-actin staining of *Dys* and *Dg* null mutant follicles indicates that the stress fibers lose their orientation at stage 11 as in WT, but fail to regain their proper orientation at stage 13 (Fig. 5E,F,I,J). Angular distribution quantification even indicates a tendency of the stress fibers to be aligned parallel to the AP axis at stage 13 (Fig. 5G,H,K,L). Despite their misorientation, these fibers appear normal in structure with, for instance, a correct localization of integrins at their extremities (Fig. S5A-C). Importantly, mitotic recombination to generate mosaic tissues indicates that this function is cell autonomous for both *Dys* (not shown) and *Dg* (Fig. 5M,N) with stress fibers being misaligned only in the mutant cells. The defect is strictly cell autonomous as it is also observed in mutant cells that are adjacent to WT cells. Moreover, WT cells that are adjacent to mutant cells have stress fibers properly oriented (Fig. 5M). Importantly, this cannot be a consequence of a primary effect on BM fibril deposition because follicle rotation has moved the position of the clone with respect to the BM. It reveals, therefore, another function of the DAPC during follicle development. Given the known link of the DAPC with F-actin, it suggests a direct role in stress fiber orientation, sensing and transmitting a cue defining this planar polarization.

Late DAPC function relies on both early and late activities

Since *Dys* and *Dg* mutants affect BM fibril deposition and stress fiber orientation, we aimed to determine which of these defects is the main contributor to the follicle elongation phenotype. To address this question, we took advantage of the temporality of the DAPC function during oogenesis, being required for BM fibril deposition during early stages and for stress fiber orientation mainly during later stages. Importantly, these three defects, follicle elongation, BM fibril deposition and stress fiber orientation are recapitulated when RNAi against Dg is induced in follicle cells during all stages using tj:Gal4 (Fig. 6J-N). We also used Cy2:Gal4 which is

only expressed in follicle cells from stage 9 (Fig. S6V). The expression of *Dg* RNAi with this driver knocks it down after the correct BM fibril deposition (Fig. S6A,B), but before the second phase of stress fiber orientation. As expected, the stress fiber orientation is disrupted, confirming that this DAPC function is distinct from the one influencing the BM (Fig. S6C,D). Importantly, egg elongation is also affected (Fig. S6E). Thus, BM fibrils are not sufficient to drive late follicle elongation and stress fiber orientation is necessary for it.

We also performed the reverse experiment by trying to rescue the late stress fiber orientation defect in a *Dg* mutant using a UAS:Dg. Expression of Dg during the whole oogenesis in the follicle cells, using tj:Gal4 in a mutant background, rescues the elongation defect, the BM fibril deposition and stress fiber orientation (Fig. S6F,H,I,J,M). We then tried to rescue *Dg* mutant using the Cy2:Gal4 driver. As expected, such follicles show BM defects associated with *Dg* mutation (Fig. S6G,H). However, surprisingly, this genetic combination also fails to rescue stress fiber orientation (Fig. S6K,L). Moreover, egg elongation is only poorly rescued (Fig. S6M). Together these results indicate that late expression of Dg is not sufficient to restore its late functions, and, thus, that they also rely on a previous role of Dg during oogenesis.

To confirm these important observations we set up an alternative method to control the timing of Dg inhibition by RNAi, using Tj:Gal4 and Tub:Gal80^{ts}, which is a thermosensitive Gal4 inhibitor allowing a temporal control of its activity. We defined two conditions allowing Gal4 activity during early stages (switch from 30 to 18°C, "Early *Dg* RNAi") or late stages (switch from 18 to 30°C, "Late *Dg* RNAi") (Fig. 6A). The best timing for the temperature switches was determined using a UAS fluorescent reporter to separate expression during stages 1 to 8 from stages 10 to 14 (Fig. S6N-U). Moreover, positive and negative controls were performed at 18°C and 30°C (Fig. 6). For each condition, an internal negative control (driver line) with the same temperature was performed. *Dg* RNAi at 18°C is similar to control (Fig. 6 B-F) whereas at 30°C it recapitulates all the defects observed in *Dg* mutants, as previously mentioned (Fig. 6 J-N). We observed that F-actin orientation at late stages and follicle elongation are affected in both late (Fig. 6G-I) and early (Fig5 O-Q) *Dg* RNAi conditions, confirming our previous results. Thus, the DAPC is required at two different time windows and its second function is dependent on the first one.

BM fibril deposition provides a persistent cue for F-actin orientation

Overexpression of Rab10 increases the BM fibril fraction and enhances follicle elongation, a phenotype similar to *Dg* overexpression and opposite to the loss of function of the DAPC

(Isabella and Horne-Badovinac, 2016). We therefore decided to perform an epistasis test between these two conditions. Concomitant overexpression of Rab10 and knock-down of *Dg* or *Dys* in follicle cells with Tj:Gal4 increases the amount of fibrils to a higher level than the WT control and thus fully compensates for the absence of Dg (not shown) or Dys (Fig. S7A). Classical interpretation of such a test would indicate that Rab10 acts downstream (or in parallel) of the DAPC. These experiments were performed at optimal temperature for Gal4-induced expression (30°C). However, in such context Rab10 overexpression disrupts follicle elongation (Isabella and Horne-Badovinac, 2016), and it is also associated with the abnormal targeting of ColIV containing vesicles to the apical side of the cells (Fig. S7B). Therefore, these conditions did not allow us to determine whether it could also rescue follicle elongation. Thus, we repeated these experiments at 25°C and observed a partial rescue of BM fibril fraction (Fig 7A). However, mature egg elongation is still disrupted, as in DAPC loss of function (Fig. 7B). Thus, for elongation, Dys should be placed downstream of Rab10. Taken together, these results are consistent with the proposal that the DAPC has two separate functions, one upstream and one downstream of Rab10. Moreover, it also confirms that, in absence of the DAPC, BM fibrils are not sufficient for elongation.

We also analyzed in this context stress fiber orientation in late stages. Angular distribution for *Dys* RNAi (Fig S7C), compared to the one of null mutants (Fig. 5H), indicates that it corresponds to hypomorphic conditions. This result prompted us to also analyze the different order parameters and the three were strongly affected (Fig 7C-E). When Rab10 is overexpressed at the same time we observed a partial rescue of this defect on the angular distribution, the TOP, the LOP but not the COP (Fig S7C, Fig 7C-E). These observations could be explained by the rescue of the early function of the DAPC by Rab10 and the hypomorphic nature of *Dys* RNAi. Nonetheless, this approach offers a unique opportunity to test whether the DAPC's first function in BM fibril deposition is required for its later function in stress fiber orientation. We repeated the experiments but allowing *Dys* expression during late stages by a temperature switch (25-18°C condition). Strikingly, the late expression of Dys promoted correct stress fiber orientation on all the parameters that we analyzed only if the BM fibrils have been restored by Rab10 overexpression (Fig 7C-E, Fig S7C). Moreover, this condition also restores egg elongation (Fig. 7B). These experiments demonstrate the double function of the DAPC, with the latter in F-actin organization depending on the first one in BM structure. It also shows that the BM fibrils are required for F-actin orientation long after their deposition and that this function explains their contribution to follicle elongation.

Discussion

In this article, we show that the DAPC contributes to follicle elongation by two distinct functions in which the second relies on the output of the first one. These results are important for understanding the activity of this key complex and the morphogenetic mechanisms involving the ECM.

Follicle elongation relies on multiple mechanisms

Genetic data already showed that follicle elongation relies on at least two different and successive mechanisms. The first one is controlled by JAK-STAT and involves the follicle cell apical domain, whereas the second one is controlled by Fat2 and involves their basal domain and the BM (Alégot et al., 2018; Aurich and Dahmann, 2016). Between these phases, around stage 7-8, JAK-STAT and Fat2 seem to be integrated in a third mechanism based on a BM stiffness gradient (Crest et al., 2017). Here, we show that the DAPC influences elongation mainly at very late stages, suggesting the existence of a fourth mechanistic elongation phase. Of note, elongation at these late stages is also defective in *fat2* mutants (Alégot et al., 2018; Aurich and Dahmann, 2016). This is consistent with the fact that rotation is required for polarized BM fibril deposition, and that this deposition depends on and is required for DAPC function. The existence of multiple and interconnected mechanisms to induce elongation, a process that initially appeared to be very simple, highlights the true complexity of morphogenesis, and the necessity to explore it in simple models.

BM fibrils act as a planar polarity cue and F-actin as a molecular corset

Fat2 is clearly part of the upstream signal governing the basal planar polarization. However, how this polarization leads to tissue elongation is still debated. It has been proposed that elongation relies on a molecular corset that could be formed, non-exclusively, by BM fibrils or F-actin stress fibers (Gutzeit, 1990; Gutzeit et al., 1991; Haigo and Bilder, 2011; Frydman and Spradling, 2001; Bateman et al., 2001; Viktorinová et al., 2009; Cetera et al., 2014). The initial observation that rotation is required for both elongation and BM fibrils favored a direct mechanical role for these structures (Haigo and Bilder, 2011). Recent data showing that BM fibrils are stiffer than the surrounding ECM supports this view (Chlasta et al., 2017). Moreover, increasing the fibril number and size can lead to hyper-elongation (Isabella and Horne-Badovinac, 2016). Finally, addition of collagenase induces follicle rounding, at least at some stages, and genetic manipulation of the ECM protein levels also influences elongation (Haigo

and Bilder, 2011; Isabella and Horne-Badovinac, 2015; Chlasta et al., 2017). However, these experiments did not discriminate between the function of the fibril fraction and a general BM effect. Moreover, they do not allow to discriminate whether their impact on elongation is direct and mechanic or indirect, by a specific response of the epithelial cells. Fat2 and rotation are also required for the proper orientation of the stress fibers. The F-actin molecular corset is dynamic with follicle cells undergoing basal pulsations, and perturbation of both these oscillations and of the stress fiber structure affect elongation (Bateman et al., 2001; He et al., 2010). In the DAPC mutants we observed a faint but significant elongation defect during mid-oogenesis and a stronger one from stage 12. These defects are clearly correlated with the stress fiber orientation defects observed in the same mutants, both temporally and in terms of intensity. Moreover, rescuing the BM fibrils in a *Dys* loss of function by the overexpression of Rab10 does not rescue elongation indicating that stress fiber orientation is instrumental.

Thus, if the role of the BM fibrils as a direct mechanical corset seems limited, what is their function? One possibility could have been that they promote rotation, acting in a positive feed-back and explaining speed increase over time. However, the rotation reaches the same speed in WT and DAPC mutants, excluding this possibility. Similarly, increasing the fibrillary fraction also has no effect on rotation speed (Isabella and Horne-Badovinac, 2016).

Our results strongly argue that BM fibrils act as a cue for the orientation of stress fibers, which then generate the mechanical strain for elongation. This appears clear in late stages where the function of the DAPC for stress fiber orientation is dependent on the previous BM fibril deposition. Whereas it is unknown why the cells lose their orientation from stages 10 to 12, these stages are associated with a strong remodeling of the follicular epithelium. The BM fibrils provide the long-term memory of the initial PCP of the tissue, allowing their reorientation (Figure 8). Such mechanism appears as a very efficient way to memorize positional cues, and could represent a general BM function in many developmental processes.

How BM fibrils contribute to stress fiber orientation remains to be elucidated. Nevertheless, we can hypothesize that it involves their higher stiffness or a higher density in binding sites for ECM receptors. Our data indicates that the DAPC might be such a receptor. This hypothesis is supported by our findings that the DAPC acts in a cell autonomous manner and promotes stress fiber orientation in each cell and rather locally than at a tissue scale. Of note, this kind of pcp is unusual because it does not require signal transmission between neighboring cells, usually through heterophilic protein-protein interactions. However, an interesting parallel with the pcp established by Fat/Dachsous and the core pcp pathways could be drawn. In many tissues these two pathways work in parallel and their cooperation is required for proper pcp establishment at

the apical domain of epithelial cells (Hale and Strutt, 2015). The genetic interaction that we revealed between Fat2 and the DAPC suggests that robust basal pcp establishment also requires the integration of two independent mechanisms. Importantly this genetic interaction applies to at least two tissues suggesting a general functional link between them.

The DAPC acts as an organizer of the basal domain of epithelial cells

We found that the DAPC impacts the two key actors at the basal domain of the follicle cells: the BM and the stress fibers linked to the BM. All the defects of *Dg* null mutants were also observed in *Dys* mutants, demonstrating a developmental and morphogenetic role for this gene. In vertebrates, at least in some tissues, Dg presence seems essential for BMassembly(Henry and Campbell, 1998; Satz et al., 2010; Bello et al., 2008; Buisson et al., 2014). However, BM formation on the follicular epithelium does not require Dg, suggesting the existence of alternative platforms for its general assembly. Our genetic data suggest that Rab10 is epistatic to Dg for BM fibril deposition. The usual interpretation of such a result would be that Dg is involved in the targeting of ECM secretion upstream of Rab10 rather than in ECM assembly in the extracellular space. In *C. elegans,* Dg acts as a diffusion barrier to define a precise subcellular domain for ECM remodeling (Naegeli et al., 2017). One could imagine that the DAPC has a similar function in follicle cells, by defining the position where the Rab10 secretory route is targeted. However, in DAPC loss of function, some ECM is still secreted between cells, suggesting that the lateral Rab10 route is not affected. Moreover, ECM proteins do not abnormally accumulate between cells in such mutants, suggesting that they are able to leave this localization but without forming fibrils. Therefore, the functional interplay between Rab10 and the DAPC is still unclear.

As mentioned before, Dg has often been proposed to act as a scaffold to promote BM assembly in mice. Deletion of the Dg intracellular domain is only sub-lethal in mice, whereas complete loss of this protein is lethal very early during development, indicating that the abolishment of Dg's interaction with Dys affects only partially its function (Henry and Campbell, 1998; Satz et al., 2009). In these mice, laminin assembly can still be observed, for instance in the brain and retina (Satz et al., 2010; Clements et al., 2017). Similar results were also obtained in cultured mammary epithelial cells (Weir et al., 2006). Thus, despite the existence of Dys paralogs that could mask some effects on ECM and the fact that we observed the same ECM alteration in *Dg* or *Dys* mutant fly follicles, not all the Dg functions related to ECM assembly or secretion involve Dys. It is possible that Dys is required when Dg needs a very specific subcellular targeting for its function, whereas a more general role in ECM assembly would be Dys-independent. Our results suggest that some specific Dys effects on ECM could have been

underestimated and this could help to explain the impact of its loss of function on tissue integrity maintenance. For instance, as it has been reported that Dg influences ECM organization in fly embryonic muscles, it would be interesting to determine whether this also involves Dys (Yatsenko and Shcherbata, 2014).

The DAPC is involved in the planar polarization of the basal stress fibers and its ability to read ECM structure to orchestrate integrin-dependent adhesion could play a role in many developmental and physiological contexts. The link between ECM and F-actin provided by this complex is likely required for this function, although it remains to be formally demonstrated. BM fibrils could provide local and oriented higher density of binding sites for Dg, and the alignment could then be transmitted to the actin cytoskeleton. Alternatively, DAPC function could rely on sensing the mechanical ECM properties. The hypothesis that the DAPC could act as a mechanosensor is a long standing proposal, partly due to the presence of spectrin repeats in Dys (Brown and Lucy, 1993; Garbincius and Michele, 2015). The basal domain of the follicle cells may offer an amenable model to combine genetics and cell biology approaches to decipher such function.

Altogether, this work provides important insights on BM role during morphogenesis, by acting as a static pcp cue retaining spatial information while cells are highly dynamic. It also reveals important functions of the DAPC, including Dys, that may be broadly involved during animal development and physiology.

Methods

Genetics

The detailed genotypes, temperature and heat-shock conditions are given in supplementary table 1.

Live imaging and rotation speed analysis

For live imaging, ovaries were dissected, as described previously (Alégot *et al*, 2018), and stained with the membrane dye FM464. Samples were cultured for less than 1 hour before imaging. Damaged follicles (identified on the basis of abnormal FM4-64 incorporation) were not analyzed. Rotation speed analysis was performed using a Fiji Manual Tracking plug-in. For each follicle, speed was measured at three independent positions during 30min.

Dissection and immunostaining

Dissection and immunostaining were performed as described previously (Vachias et al., 2014) with the following changes: ovaries were dissected in supplemented Schneider medium, and ovarioles were separated before fixation to obtain undistorted follicles. Stage was determined using unambiguous reference criteria that are follicle shape-independent (Spradling et al., 1993). For quantification of stress fiber orientation, ovaries were fixed with 8% paraformaldehyde (PFA) containing phalloidin-TRITC or phalloidin Atto-488. They were then permeabilized with PBS-Triton at 0.02% and incubated again with phalloidin-TRITC (or Atto-488). Images were taken using a Leica SP8 or Zeiss LSM800 Airyscan confocal microscope.

Immunostaining of pericellular ECM was performed as described by Isabella and Horne-Badovinac, 2016, using antibodies against GFP (ColIV-GFP-expressing flies) or against LanA (a gift from Volk's laboratory).

Aspect Ratio determination

The length of the long and short axes of each follicle were directly measured by transmitted light microscopy and used to determine the aspect ratio.

BM fraction, pericellular matrix and F-actin orientation quantification

BM fibril fraction was determined using a homemade Fiji macro, using the principles developed by Isabella and Horne-Badovinac, 2016. The pericellular matrix was quantified using the Fiji tool to measure the "meangray value" of a 1.32µm wide line drawn on the cell walls (about 100 line for each genotype - 20 cells).

Stress fiber orientation and Tissue Order Parameter (TOP) analysis were performed as described in Cetera et al., 2014 after manual segmentation. Analyses were performed on 40 and 96 μm^2 images for the early and late stages, respectively. The Cell Order Parameter (COP) was

determined in the same way, by analyzing the alignment robustness at the cellular scale. For Local Order Parameter (LOP), the average cell radius of each image was determined. Then, we analyzed the cells with their barycenter being in 3.5 radiuses from the considered cell, this value fitting with an average of 6 neighbors. This value included on average six neighboring cells. Clusters with less than four cells were excluded. Then, the radius was progressively increased from 3.5 to 25. At 25, all the cells of the image were included, and thus the LOP value corresponded to the TOP value. Therefore, this approach was used to observe the tendency from LOP to TOP and to calculate for each cell the difference between LOP and TOP.

Statistical analysis

For all experiments, the minimal sample size is indicated in the figure legends. Results were obtained from at least two independent experiments, and for each experiment multiple females were dissected. Randomization or blinding was not performed. The normality of the samples was calculated using the D'Agostino & Pearson normality test. The unpaired t-test was used to compare samples with normal distribution, and the unpaired Mann-Whitney test for samples without normal distribution.

Concerning the stress fiber angular distribution, the circular mean orientation of the fibers was computed for each cell and then used for the Rao's test of homogeneity. For each stage, a pairwise comparison of genotypes was performed to determine whether the polar vectors or the dispersions were equal. These tests were performed in R using the "circular" package.

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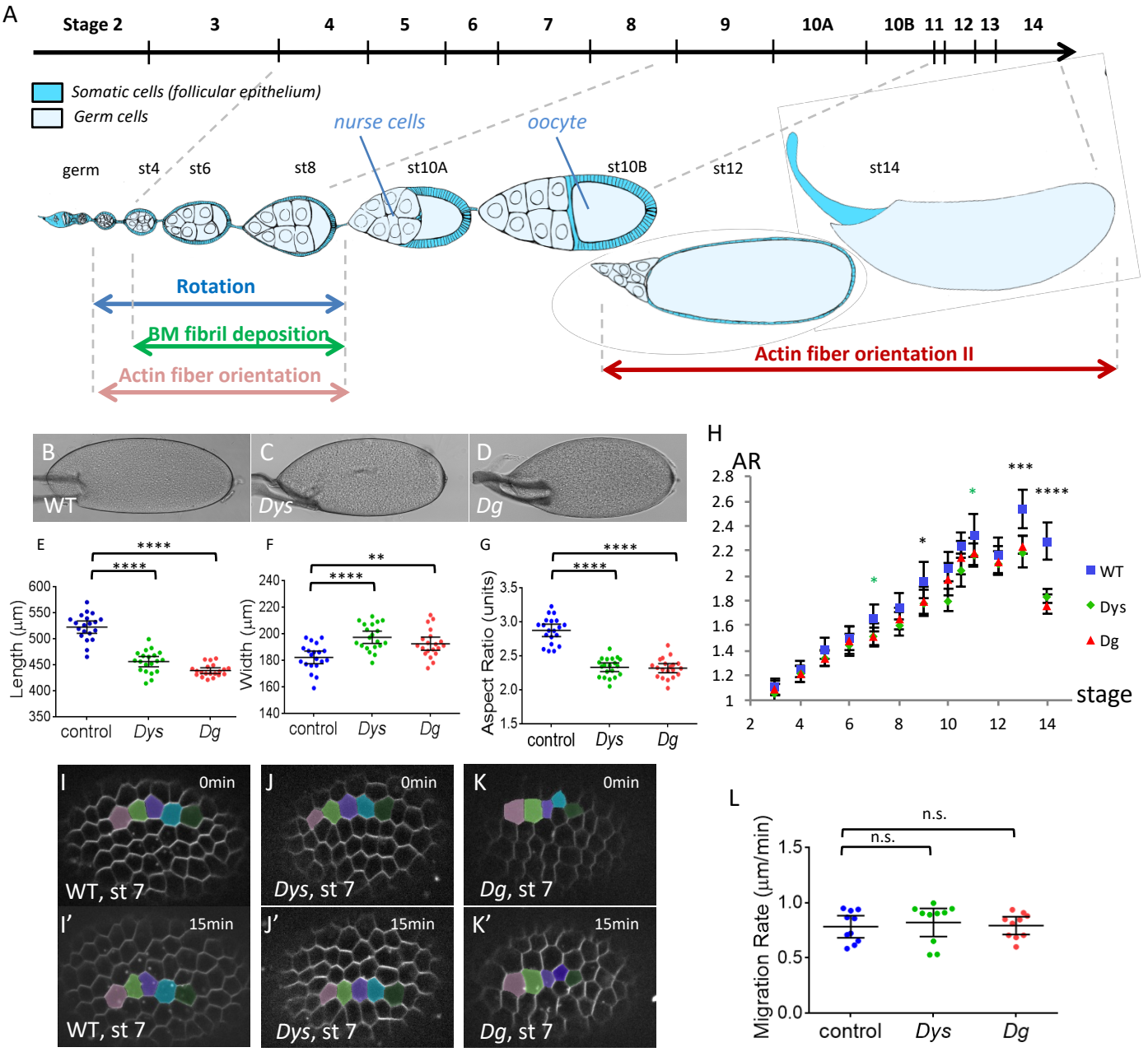
A
Stage 2
3
4
5
6
7
8
9
10A
10B
11
12
13
14
Somatic cells (follicular epithelium)
Germ cells
nurse cells
oocyte
germ
st4
st6
st8
st10A
st10B
st12
st14
Rotation
BM fibril deposition
Actin fiber orientation
Actin fiber orientation II
B
WT
C
Dys
D
Dg
E
Length (µm)
control
Dys
Dg
F
Width (µm)
G
Aspect Ratio (units)
H
AR
stage
WT
Dys
Dg
I
0min
WT, st 7
I'
15min
J
Dys, st 7
J'
K
Dg, st 7
K'
L
Migration Rate (µm/min)
n.s.

Figure 1

Figure 1: The DAPC is involved in follicle elongation but not rotation.

A) Scheme of an ovariole with the main events involved in follicle elongation.

The above line indicates the time scale of the different developmental stages. The ovariole is oriented anterior to posterior (germ: germarium)**.** Each follicle is composed of a germline cyst surrounded by the follicular epithelium. Rotation occurs from very early to stage 8. It promotes F-actin fiber orientation and allows polarized BM fibril deposition, both perpendicularly to the elongation axis. At stage 11, actin fibers lose their orientation and then progressively reorient (orientation II).

B,C,D) Representative mature eggs from B) WT, C) $Dys^{E17/Exel6184}$ and D) $Dg^{O46/O83}$ females.

E,F,G) quantification of E) the length, F) the width, and G) the aspect-ratio for mature eggs from WT, $Dys^{E17/Exel6184}$ and $Dg^{O46/O83}$ mutant females (n=20 eggs).

H) Elongation kinetics of WT, *Dys* and *Dg* mutant follicles (n>6 follicles for each point, green stars for *Dys*, Black stars for *Dys* and *Dg)*. There are two series of value for stage 10, corresponding to stage 10A and 10B.

I,J,K) images of rotation movies of stage 7 I) WT, J) $Dys^{E17/Exel6184}$ and K) $Dg^{O46/O83}$ mutant follicles.

L) Rotation velocity of WT, *Dys* and *Dg* mutant stage 7 follicles (n>8 follicles).

(For all panels error bars represent s.d.; p *< 0.01, **<0.005, ***<0.001, ****<0.0001)

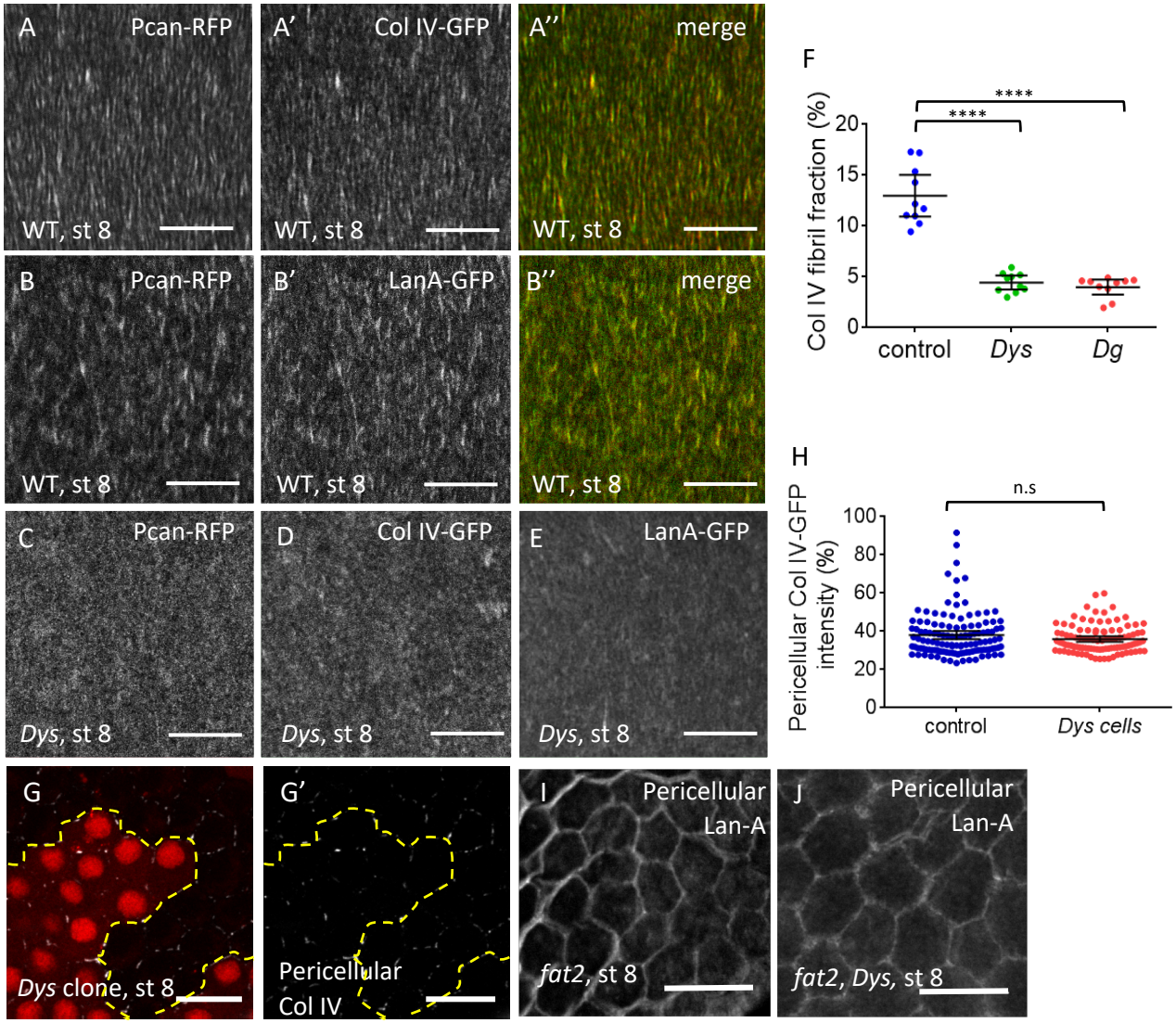
A
Pcan-RFP
WT, st 8
A'
Col IV-GFP
WT, st 8
A''
merge
WT, st 8
B
Pcan-RFP
WT, st 8
B'
LanA-GFP
WT, st 8
B''
merge
WT, st 8
C
Pcan-RFP
Dys, st 8
D
Col IV-GFP
Dys, st 8
E
LanA-GFP
Dys, st 8
F
Col IV fibril fraction (%)
****
****
control
Dys
Dg
H
Pericellular Col IV-GFP intensity (%)
n.s
control
Dys cells
G
Dys clone, st 8
G'
Pericellular Col IV
I
Pericellular Lan-A
fat2, st 8
J
Pericellular Lan-A
fat2, Dys, st 8

Figure 2

Figure 2: The DAPC is important for BM fibril deposition

A-B) Basal view of wild-type follicle ECM at stage 8 visualized with A) Pcan-RFP and ColIV-GFP and B) Pcan-RFP and LanA-GFP

C) Basal view of $Dys^{E17}/Dys^{Exel8164}$ follicles expressing C) Pcan-RFP D) ColIV-GFP E) LanA-GFP. F) Quantification of the fibril fraction at stage 8 in WT, $Dys^{E17}/Dys^{Exel8164}$ and Dg^{O86}/Dg^{O43} mutant follicles (n> 10 follicles).

G) Mutant clones for $Dys^{Exel8164}$ marked by the absence of RFP and stained to detect pericellular colIV H) quantification of pericellular ColIV intensity around WT and *Dys* mutant cells (n> 20 cells).

IJ) Accumulation of pericellular LanA in I) *fat2* and J) *fat2, Dys* mutant follicles.

For all panels error bars represent s.d.; p *< 0.01, **<0.005, ***<0.001, ****<0.0001. Scale bar 10µm

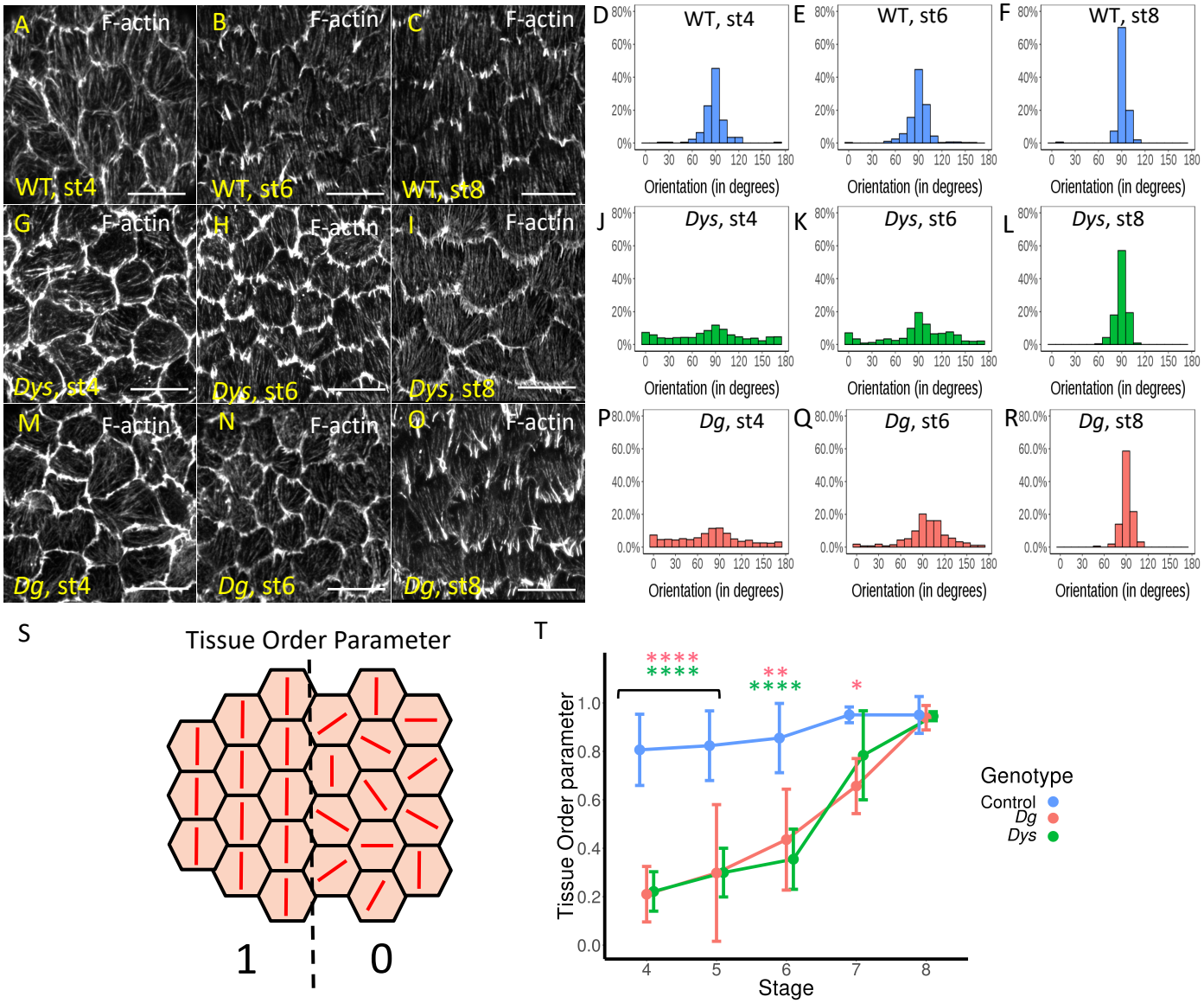
A
F-actin
WT, st4
B
F-actin
WT, st6
C
F-actin
WT, st8
G
F-actin
Dys, st4
H
F-actin
Dys, st6
I
F-actin
Dys, st8
M
F-actin
Dg, st4
N
F-actin
Dg, st6
O
F-actin
Dg, st8
D
WT, st4
E
WT, st6
F
WT, st8
J
Dys, st4
K
Dys, st6
L
Dys, st8
P
Dg, st4
Q
Dg, st6
R
Dg, st8
Orientation (in degrees)
S
Tissue Order Parameter
1
0
T
Tissue Order parameter
Stage
Genotype
Control
Dg
Dys

Figure 3

Figure 3: Stress fiber orientation delay in DAPC mutants during early stages

Representative images of basal F-actin in A,B,C) WT (w^{1118}), G,H,I) $Dys^{E17}/Dys^{Exel8164}$ and M,N,O) Dg^{O86}/Dg^{O43} follicles at stage 4, 6 and 8 and D,E,F,J,K,L,P,Q,R) quantification of the corresponding angular distribution S) illustration of Tissue Order Parameter (TOP) : if all the cells have the same orientation TOP is equal to one, if orientation is random TOP is equal to zero. T) TOP analysis of control, *Dys* and *Dg* follicles. Error bars represent s.d (n> 7 follicles for each stage and each genotype). p *< 0.01, **<0.005, ***<0.001, ****<0.0001. Scale bar 10µm

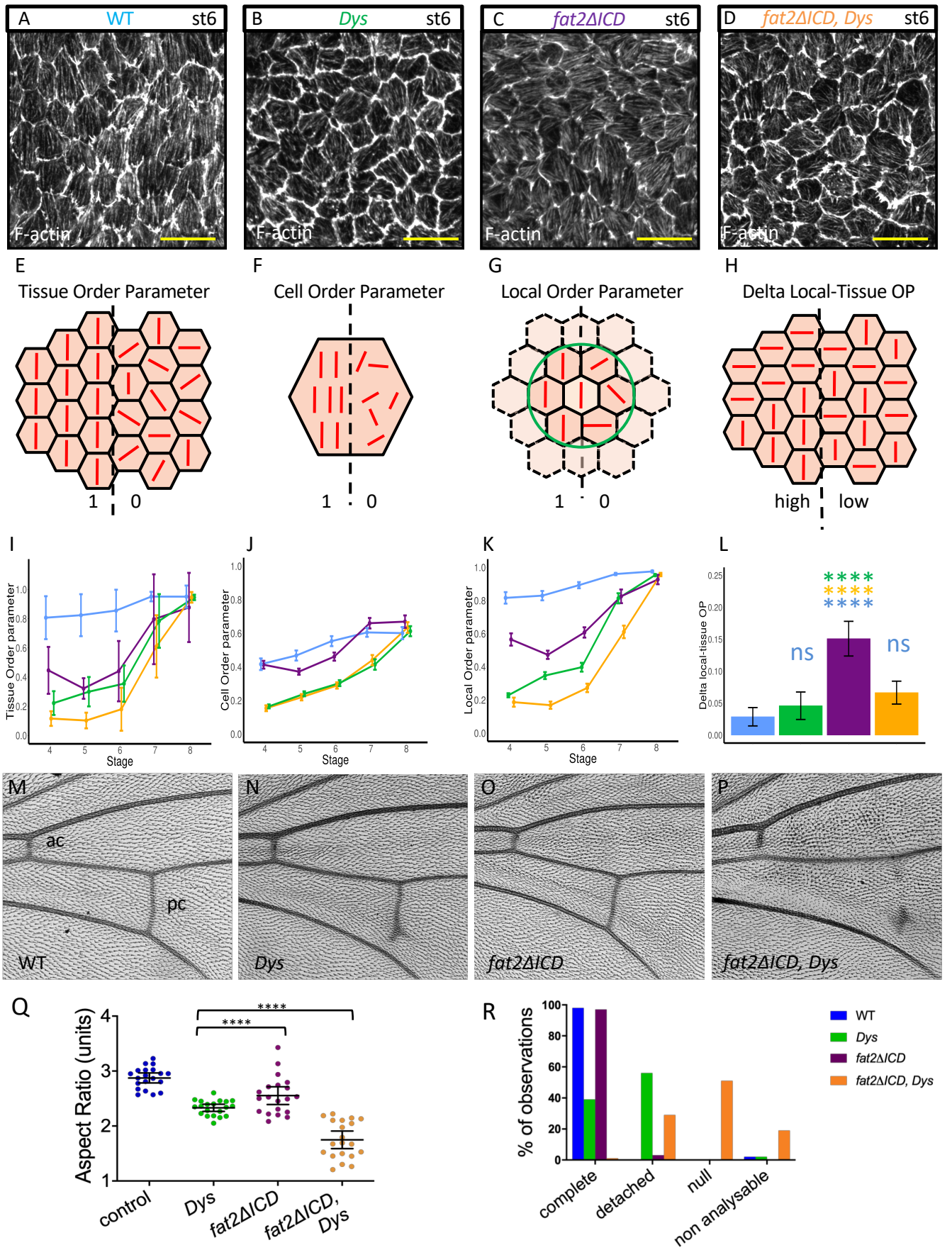
A
WT
st6
F-actin
B
Dys
st6
F-actin
C
fat2ΔICD
st6
F-actin
D
fat2ΔICD, Dys
st6
F-actin
E
Tissue Order Parameter
1
0
F
Cell Order Parameter
1
0
G
Local Order Parameter
1
0
H
Delta Local-Tissue OP
high
low
I
Tissue Order parameter
Stage
J
Cell Order parameter
Stage
K
Local Order parameter
Stage
L
Delta local-tissue OP
****
****
****
ns
ns
M
ac
pc
WT
N
Dys
O
fat2ΔICD
P
fat2ΔICD, Dys
Q
Aspect Ratio (units)
****
****
control
Dys
fat2ΔICD
fat2ΔICD, Dys
R
% of observations
WT
Dys
fat2ΔICD
fat2ΔICD, Dys
complete
detached
null
non analysable

Figure 4

Figure 4: Genetic interaction between *fat2* and *Dys*

A-D) Representative images of stress fibers at stage 6 of A) WT, B) *Dys* mutant, C) *fat2-DeltaICD* mutant and D) *Dys, fat2-DeltaICD* double mutant . Genotype color code is conserved on all panels. E-H) Schemes explaining the different parameters that are analyzed in I-L) : E,I) Tissue Order parameter (n > 7 follicles for each stage and each genotype): F, J) Cell Order Parameter, G,K) Local Order Parameter H,L) difference between local and tissue order parameter (n > 171 cells for each stage and each genotype). P-values between the different genotypes for I,J,K are indicated table S2.

M-P) Representative images of wing veins of M) WT, N) *Dys* mutant, O) *fat2-DeltaICD* mutant and P) *Dys, fat2-DeltaICD* double mutant (pc: posterior crossvein, ac: anterior crossvein).

Q) quantification of egg elongation for the indicated genotypes (n>20 eggs for each genotype).

R) Quantification of the wing defect observed in the different genotypes on the pc. Non analysable corresponds to wrinkled or misfolded wings for which crossveins cannot be observed (n=40 wings).

For all panels error bars represent s.d.; p *< 0.01, **<0.005, ***<0.001, ****<0.0001. Scale

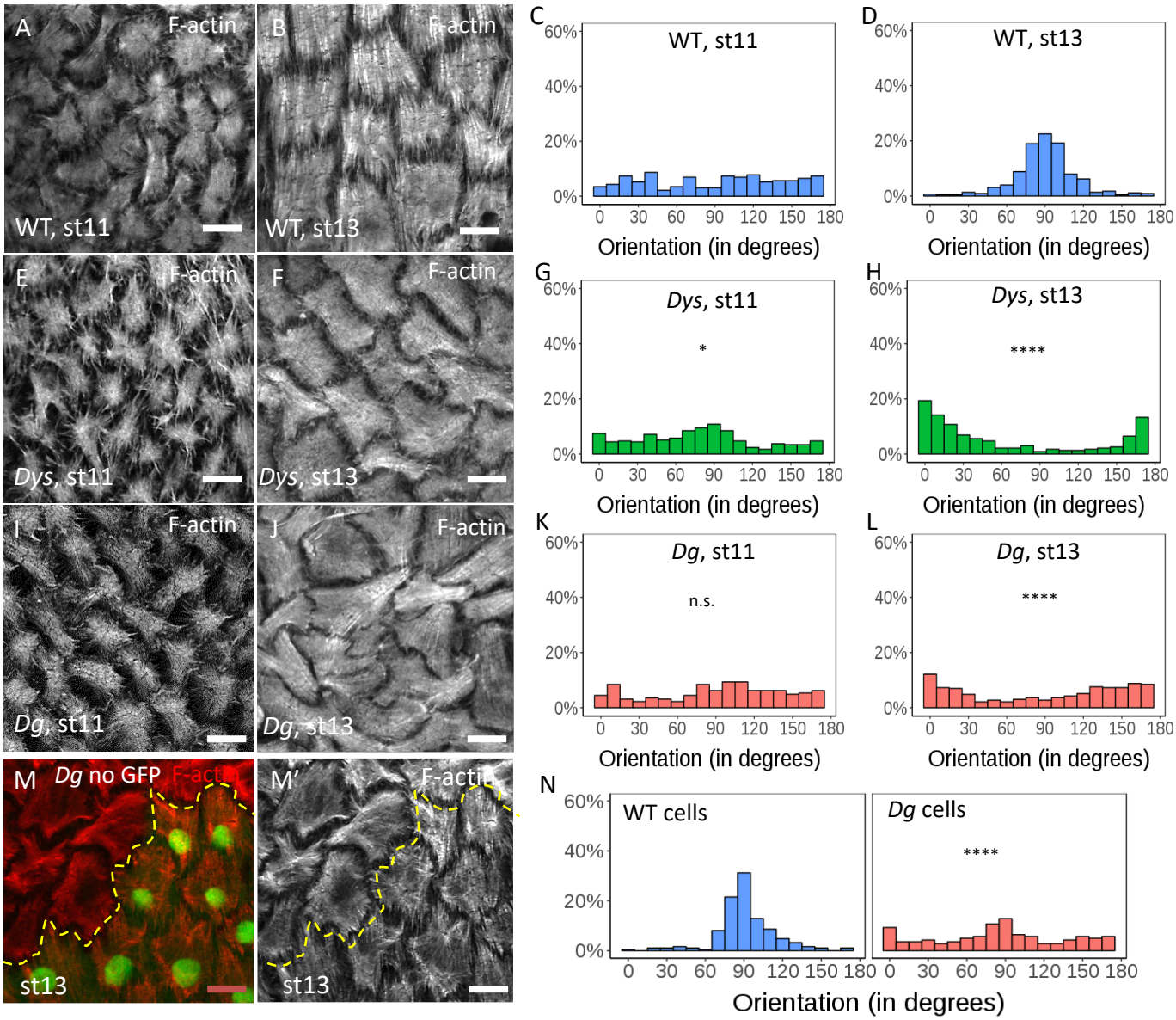
A
F-actin
WT, st11
B
F-actin
WT, st13
C
WT, st11
D
WT, st13
E
F-actin
Dys, st11
F
F-actin
Dys, st13
G
Dys, st11
*
H
Dys, st13
****
I
F-actin
Dg, st11
J
F-actin
Dg, st13
K
Dg, st11
n.s.
L
Dg, st13
****
M
Dg no GFP
F-actin
st13
M'
F-actin
st13
N
WT cells
Dg cells
****
60%
40%
20%
0%
0 30 60 90 120 150 180
Orientation (in degrees)

Figure 5

Figure 5: Stress fiber orientation defect in DAPC mutants during late stages

Representative images of basal F-actin in A,B) WT, E,F) $Dys^{E17}/Dys^{Exel8164}$ and I,J) Dg^{O86}/Dg^{O43} follicles at stage 11 and 13 and C,D,G,H,K,L) Quantification of the corresponding angular distribution (n> 5 follicles).

M) Representative image of basal F-actin in *Dg* mutant clone marked by the absence of GFP and N) Quantification of the corresponding angular distribution of the mutant cells and the neighbouring WT cells (n> 5 clones).

Angular distribution was statistically compared to the WT one of the same stage; p *< 0.01, **<0.005, ***<0.001, ****<0.0001. Scale bar 10µm

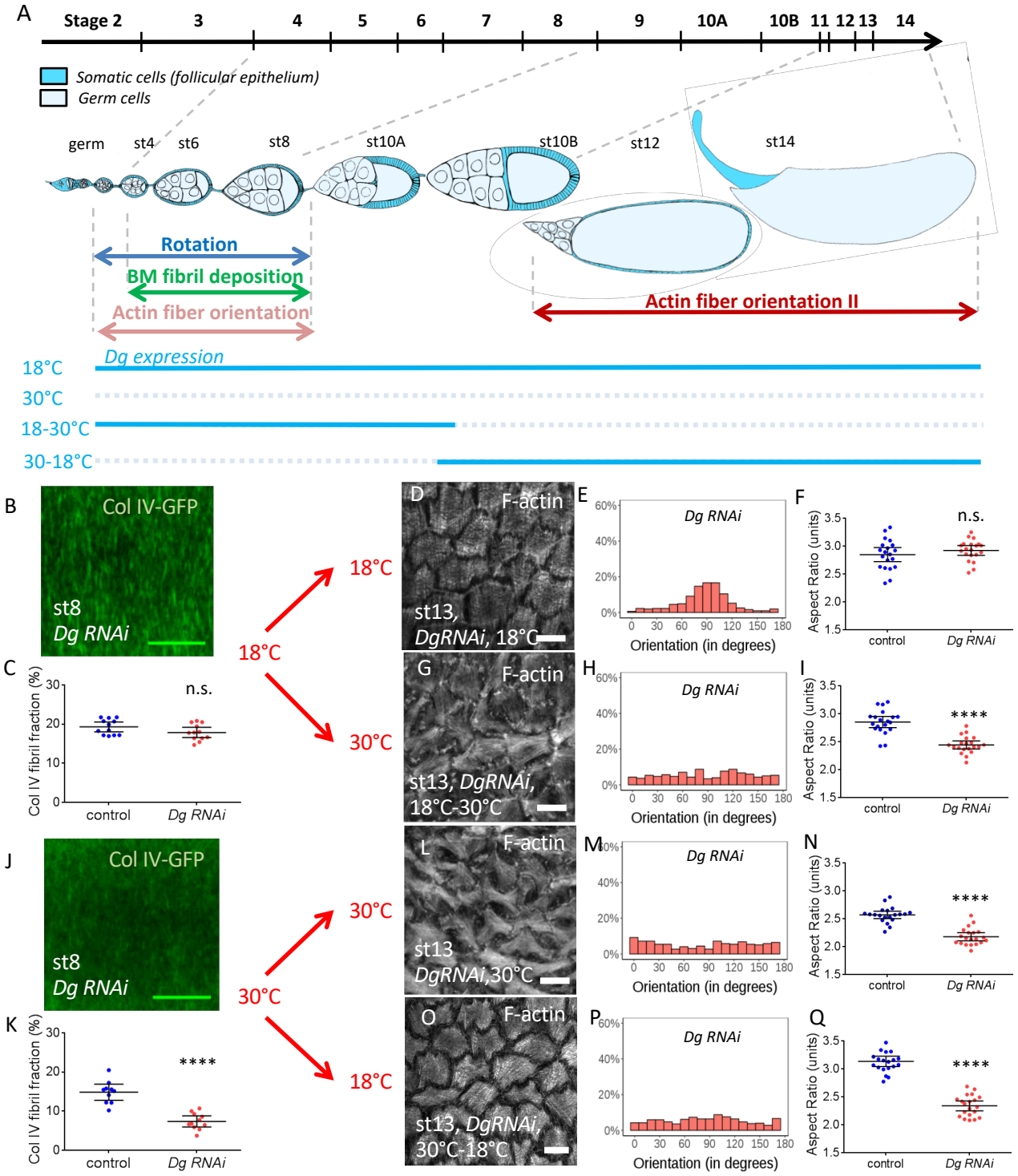
A
Stage 2
3
4
5
6
7
8
9
10A
10B
11
12
13
14
Somatic cells (follicular epithelium)
Germ cells
germ
st4
st6
st8
st10A
st10B
st12
st14
Rotation
BM fibril deposition
Actin fiber orientation
Actin fiber orientation II
Dg expression
18°C
30°C
18-30°C
30-18°C
B
Col IV-GFP
st8
Dg RNAi
18°C
30°C
C
Col IV fibril fraction (%)
n.s.
control
Dg RNAi
D
F-actin
st13,
DgRNAi, 18°C
E
Dg RNAi
Orientation (in degrees)
F
Aspect Ratio (units)
n.s.
control
Dg RNAi
G
F-actin
st13, DgRNAi,
18°C-30°C
H
Dg RNAi
Orientation (in degrees)
I
Aspect Ratio (units)
****
control
Dg RNAi
J
Col IV-GFP
st8
Dg RNAi
30°C
18°C
K
Col IV fibril fraction (%)
****
control
Dg RNAi
L
F-actin
st13
DgRNAi,30°C
M
Dg RNAi
Orientation (in degrees)
N
Aspect Ratio (units)
****
control
Dg RNAi
O
F-actin
st13, DgRNAi,
30°C-18°C
P
Dg RNAi
Orientation (in degrees)
Q
Aspect Ratio (units)
****
control
Dg RNAi

Figure 6

Figure 6: The DAPC is required at two time frames for follicle elongation

A) Scheme of an ovariole with the main events involved in follicle elongation.

The above line indicates the time scale of the different developmental stages. The ovariole is oriented anterior to posterior (germ: germarium)**.** Level on endogenous Dg is temporally controlled by the temperature (blue lines).

B,J) Basal view of *Dg* RNAi stage 8 follicles expressing ColIV-GFP in the indicated condition and C,K) quantification of the corresponding fibril fraction compared to control performed in the same temperature condition (n=10 follicles).

D,G,L,O) Representative images of basal F-actin of *Dg* RNAi stage 13 follicles in the indicated condition and E,H,M,P) quantification of the corresponding angular distribution (n>5 follicles) F,I,N,Q) Aspect-Ratio quantification of Dg RNAi mature eggs in the indicated condition compared to control performed in the same temperature condition (n>20 eggs).

(For all panels error bars represent s.d.; p *< 0.01, **<0.005, ***<0.001, ****<0.0001)

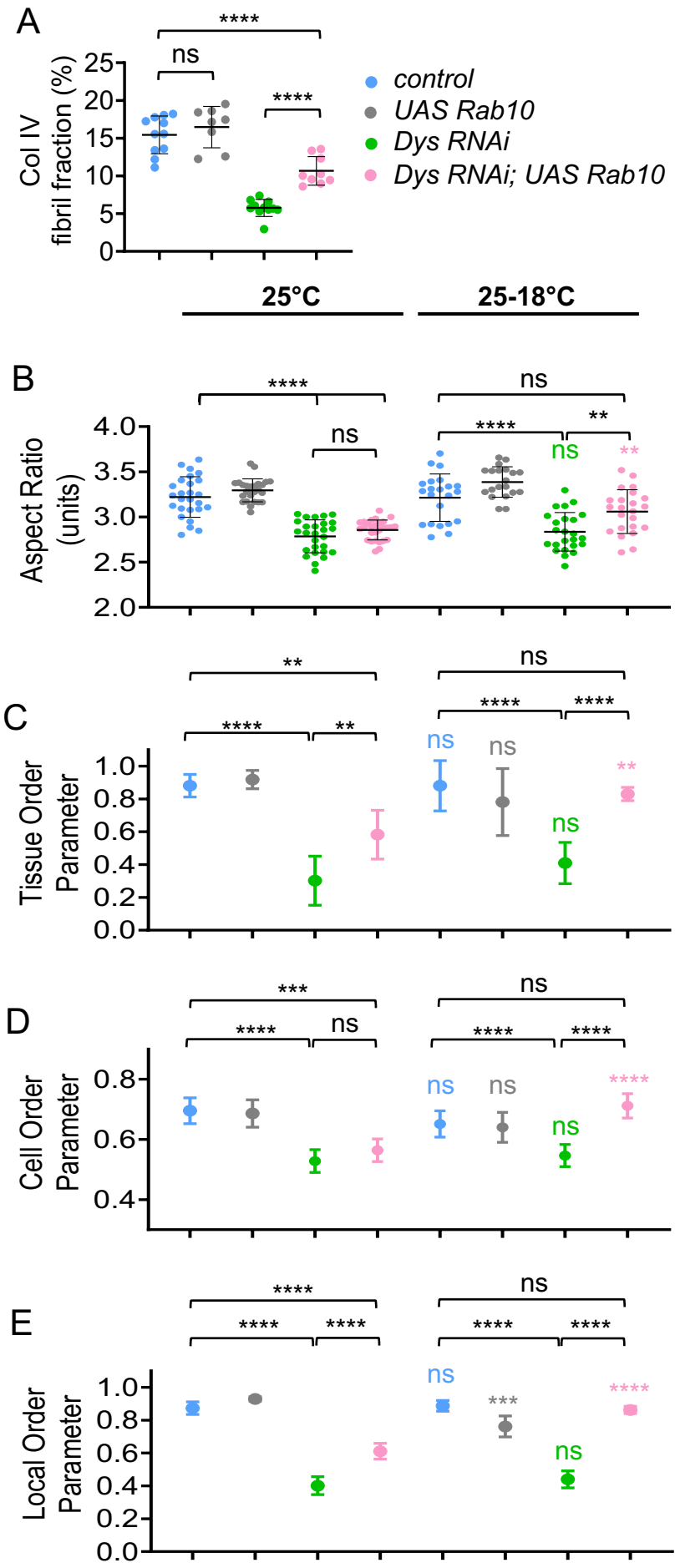
A
Col IV fibril fraction (%)
control
UAS Rab10
Dys RNAi
Dys RNAi; UAS Rab10
25°C
25-18°C
B
Aspect Ratio (units)
C
Tissue Order Parameter
D
Cell Order Parameter
E
Local Order Parameter

Figure 7

Figure 7: BM fibrils provide a cue for DAPC dependent F-actin orientation

A) Quantification of the fibril fraction at stage 8 for the indicated genotypes at 25°C (n>8) .

B-E) For the indicated genotypes without (25°C) or with (25-18°C) a switch to non permissive temperature, were quantified B) the Aspect-Ratio for mature eggs C) the Tissue Order parameter (n > 7 follicles) D) Cell Order Parameter , E) Local Order Parameter at stage 13 (n > 45 cells).

For all panels error bars represent s.d.; p *< 0.01, **<0.005, ***<0.001, ****<0.0001. Coloured stars (or ns) correspond to the statistical test for a same genotype between 25°C and 25-18°C conditions.

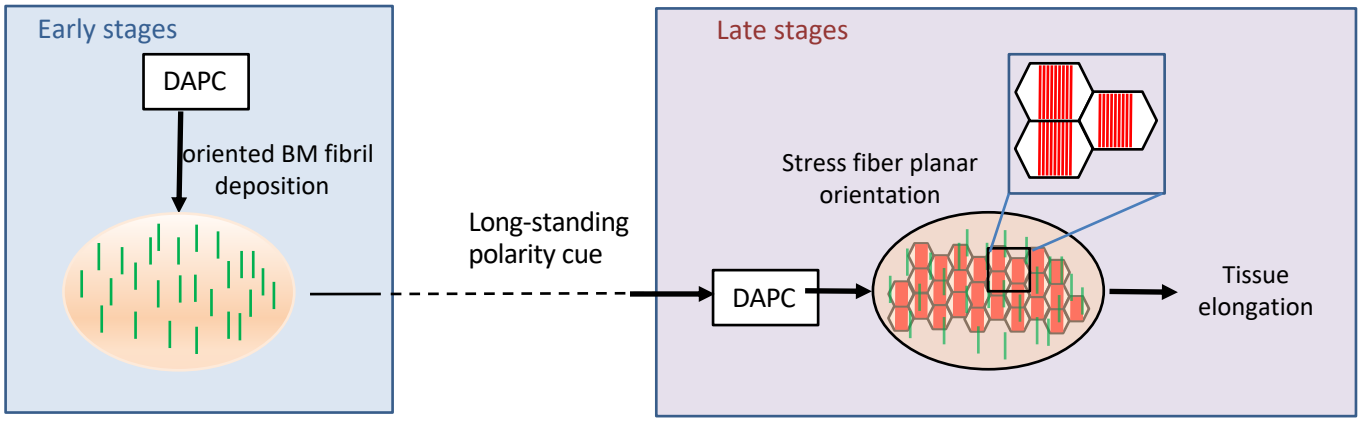
Early stages
DAPC
oriented BM fibril deposition
Long-standing polarity cue
Late stages
Stress fiber planar orientation
DAPC
Tissue elongation

Figure 8

Figure 8: Dual function of the DAPC during elongation revealing that BM fibrils work as a persistent planar polarity cue

During the early stages (4-8) the DAPC participates to the formation of oriented BM fibrils perpendicular to the follicle elongation axis. These fibrils are maintained during follicle development including stages with intense morphogenetic processes unrelated to elongation (stages 9-11). At late stages, cells use the persistent BM fibrils as a signal to guide the planar orientation of the stress fibers. This event depends on a distinct second function of the DAPC. The stress fibers are the main mechanical effector of follicle elongation.

elongation.

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Antibodies		
Anti-GFP, goat	Abcam	5450
Laminin, Guinea Pig	(Harpaz and Volk 2012) (Volk lab)	N/A
Beta integrin, mouse	Developmental Studies Hybridoma Bank	CF.6G11
Chemicals, Peptides, and Recombinant Proteins		
FM4-64	Invitrogen	T13320
Phalloidin Alexa568 or Alexa 488	invitrogen	A12380 or A12379
Experimental Models: Organisms/Strains		
w^{1118}	Bloomington Drosophila Stock Center	FlyBase ID: FBal0018186 BDSC:3605
Dg^{O86}	{Christoforou 2008} (Rob Ray)	FlyBase ID: FBal0218114
Dg^{O43}	Christoforou 2008} (Rob Ray)	FlyBase ID: FBal0218112
Dys^{E17}	Christoforou 2008} (Rob Ray)	FlyBase ID: FBal0241311
$Dys^{Exel6184}$: FRT 82B, Df(3R)Exel6184	Bloomington Drosophila Stock Center	BDSC: 7663; FlyBase ID: FBab0038239
RNAi Dg: UAS:Dg(KK100828)	Vienna Drosophila Resource Center	FBal0230939 VDRC: v107029
RNAI Dys : UAS :Dys(KK101285)	Vienna Drosophila Resource Center	FBal0231174 VDRC: v108006
Pcan-GFP : P{PTT-un1}$trol^{1973}$	Kyoto Stock Center (DGRC)	FlyBase ID: FBal0191079 : DGRC : 110836
colIV-GFP : P{PTT-un1}$ColIV^{G205}$	Kyoto Stock Center (DGRC)	FlyBase ID: FBti0074199; DGRC: 110626
LanA-GFP : LanA(fTRG00574.sfGFP-TVPTBF)	Vienna Drosophila Resource Center	VDRC: v318155 FlyBase ID: FBal0339089
Pcan-mCherry	This paper	based on MI03800
UAS:Rab10-RFP	Isabella and Horne-Badovinac, 2016	
Tj:Gal4 : P{w+mW.hs=GawB}NP1624	Kyoto Stock Center	DGRC: 104055 FlyBase ID: FBti0034540
Cy2:Gal4 : w; P{GawB}CY2	{Queenan 1997} (St Johnston lab)	FlyBase ID: FBti0007266
Tub:Gal80ts : w[*]; sna[Sco]/CyO; P{w[+mC]=tubP-GAL80[ts]}7	Bloomington Drosophila Stock Center	BDSC: 67071; FlyBase ID: FBti0027798

Fat2^{N103-2}	{HorneBadovinac 2012}	FlyBase ID: FBal0267777
Fat2^{58D}	{Viktorinová 2009} (Dhamann	FlyBase ID: FBal0241216
UAS:Dg-C	(Deng et al, 2003) (Ruhola-Baker lab)	FlyBase ID: FBal0145088
FRTG13, Ubi:GFP^{nls} : w[1118]; P{w[+mW.hs]=FRT(w[hs])}G13 P{w[+mC]=Ubi-GFP.nls}2R1 P{Ubi-GFP.nls}2R2	Bloomington Drosophila Stock Center	BDSC: 5826
Fat2-DeltaICD-3xGFP	(Barlan et al, 2017)	FlyBase ID: FBal0326665
y,w, hs:flp : P{ry[+t7.2]=hsFLP}22, w[*]	Bloomington Drosophila Stock Center	BDSC: 8862; FlyBase ID: FBst0008862
Software and Algorithms		
Fiji	(Schindelin et al, 2012)	
R		
Prism		