

# 1 **Mechanical stress driven by rigidity sensing governs epithelial stability**

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30 **Abstract**

31

32 Epithelia act as a barrier against environmental stress and abrasion and *in vivo* they are  
33 continuously exposed to environments of various mechanical properties. The impact of this  
34 environment on epithelial integrity remains elusive. By culturing epithelial cells on 2D  
35 hydrogels, we observe a loss of epithelial monolayer integrity through spontaneous hole  
36 formation when grown on soft substrates. Substrate stiffness triggers an unanticipated  
37 mechanical switch of epithelial monolayers from tensile on soft to compressive on stiff  
38 substrates. Through active nematic modelling, we find unique patterns of cell shape texture  
39 called nematic topological defects that underpin large isotropic stress fluctuations at certain  
40 locations thereby triggering mechanical failure of the monolayer and hole opening. Our results  
41 show that substrate stiffness provides feedback on monolayer mechanical state and that  
42 topological defects can trigger stochastic mechanical failure, with potential application towards  
43 a mechanistic understanding of compromised epithelial integrity in bacterial infection, tumor  
44 progression and morphogenesis.

45

46

47 **Keywords: rigidity, epithelium, MDCK cells, hole formation, polyacrylamide gels, tissue**  
48 **stress and tension**

49

50 The plasticity of epithelial tissue is crucial during animal ontogenesis, and wound healing<sup>1-4</sup>.  
51 Epithelia are cell sheets that act as a covering for most of the internal and external surfaces of  
52 the body, playing an important role as protective barriers. As such, epithelial cells are  
53 constantly challenged by the environment assaults. In response to these challenging  
54 environments, epithelia are subject to constant cell renewal and cell extrusions, whose balance  
55 is key for epithelia homeostasis but also modify their shapes<sup>5</sup>. These morphological changes  
56 include the formation of holes between cells which are crucial for tissue development<sup>6,7</sup> but  
57 also in macrophage infiltration<sup>8</sup> or diseases such as diabetes<sup>9</sup>, asthma<sup>10</sup> and cancer<sup>11</sup>.

58 Epithelial integrity is maintained under the guidance of long range and coordinated mechanical  
59 forces<sup>1</sup>. These force patterns give rise to tissue scale stresses that assist in the maintenance of  
60 tissue homeostasis by controlling cell division<sup>2</sup>, cell intercalation<sup>3</sup>, cell extrusion<sup>12</sup> and cell  
61 migration<sup>13</sup>. While local compression contributes to cell extrusion<sup>14</sup>, cell division<sup>2</sup> and  
62 migration<sup>13</sup> occur in a tension dependent manner. *In vitro*, migrating epithelial cells display a  
63 tensile stress gradient that increases as one moves from the front to the middle of the migrating  
64 sheet<sup>13,15</sup> mediated through E-cadherin based adhesions<sup>16</sup>. However, excess stress buildup can  
65 result in tissue fracture. *In vitro* studies have shown that tension build up results in tearing of  
66 suspended proliferative epithelial monolayers indicating that tensile stresses can contribute to  
67 hole formation in growing epithelia<sup>17,18</sup>. *In vivo* studies across various organisms such as  
68 *Drosophila melanogaster*, *Trichoplax adhaerens* and *Hydra*<sup>19-22</sup> have shown hole formation to  
69 be an important developmental feature necessary for growth. This occurs through a build-up of  
70 force and stress within the developing epithelia leading to subsequent loss of cell-substrate  
71 adhesions<sup>21</sup>. The rupture is either initiated through tension build-up at cell-cell contacts as in  
72 chick lung epithelia<sup>23</sup>, or tissue level tension as in the peripodial epithelium in *Drosophila* leg<sup>18</sup>.  
73 In other studies, the loss of cell-cell junctions in *Drosophila*<sup>24</sup> or reduction of junctional  
74 contractility in *Tribolium castaneum*<sup>25</sup> leads to temporary hole formation and loss of epithelial  
75 integrity. During mouse embryogenesis, cracks at cell-cell contacts gives rise to eventual  
76 opening up of the lumen and blastocyst formation in a tension dependent manner<sup>7</sup>. All these  
77 results across various model organisms show that hole formation possibly occurs in a tension  
78 dependent manner and can be related to the strength of cell-cell and cell-substrate adhesions.

79 However, the impact of cellular and tissular mechanical forces and stresses on epithelial  
80 integrity remains unclear. These mechanical stresses can be modulated by parameters such as  
81 substrate geometry and adhesiveness and rigidity<sup>26-28</sup>. Rigidity is known to impact a large

82 variety of biological processes including cell adhesion, migration and differentiation<sup>27,29–34</sup> and  
83 stiffness mechanosensing relies on the cross-talk between cell-cell and cell-substrate  
84 adhesion<sup>35–37</sup>. Here, we used substrates of various stiffness on which we cultured epithelial  
85 cells as a tool to modulate tissue mechanics. We revealed that substrate stiffness induced a  
86 switch from a tensile state on soft to compressive on stiff substrates. Furthermore, this tensile  
87 state observed on softer substrates favors the formation of spontaneous holes within epithelial  
88 monolayers at nematic topological defects, further confirmed by our modeling approaches  
89 combining cell-based simulations and continuum hydrodynamic theory.

### 90 **Hole formation in epithelial monolayers is rigidity-dependent**

91 We first cultured MDCK epithelial cells on polyacrylamide (PA) gels of distinct stiffnesses,  
92 2.3 and 55 kPa (hereafter referred to as unconfined condition). Surprisingly, we observed the  
93 spontaneous formation of holes within intact monolayers on 2.3 kPa gels (**Figure 1a**,  
94 **Supplementary movie S1**) during their expansion but not on 55 kPa (**Figure 1a**,  
95 **Supplementary movie S1**). To better control culture conditions, we thus used PA gels with  
96 circular micropatterns (1mm diameter) using deep UV patterning (hereafter referred to as  
97 confined condition) (**Figure 1b**), in combination with live cell imaging to study the response  
98 of cell monolayers to substrate stiffness (**Figure 1c**, **Supplementary movie S2**). We noted a  
99 significant increase in the density of holes upon confining the monolayers (**Extended Figure**  
100 **1a**) on 2.3kPa gels to  $\sim 18 \pm 9$  holes/mm<sup>2</sup>. On 2.3kPa gels holes formed at the rate of  $3.4 \pm 1.5$   
101 holes/mm<sup>2</sup>/h (n = 15 circles in 2 independent experiments). Similar to the unconfined  
102 conditions, MDCK monolayers formed holes in a rigidity-dependent manner and the  
103 prevalence of holes monotonically decreased with the increase in gel stiffness (**Figure 1d**,  
104 **Supplementary movie S2**). Hence the most stable holes were observed on gels of stiffness 2.3  
105 kPa (**Figure 1c, d**) and thus, we continued to study hole growth and dynamics on 2.3 kPa gels.  
106 Using live imaging of Cy5-tagged fibronectin coated gels, we verified that hole initiation was  
107 not associated to any pre-existing inhomogeneity nor progressive loss of fibronectin coating  
108 over the time scale of our experiments (**Extended Figure 1b**, **Supplementary movie S3**).

109 A closer examination revealed two types of cellular events prior to hole initiation:  $\sim 10\%$  of  
110 holes were associated to breakage of junctions between stretched cell (**Extended Figure 1c**,  
111 **Supplementary movies S1 and S4**) while  $\sim 90\%$  (n=30 holes, 2 independent experiments)  
112 were formed in the immediate vicinity of a figure of cell division at the time of cytokinesis (or  
113 of abscission of the intercellular bridge<sup>38</sup>) (**Extended Figure 1d**, **Supplementary movie S4**),

114 with the hole major axis aligned with the division axis, (**Extended Figure 1d,e**). Within the  
115 preceding 50min to a hole detection event, the nearest cell division formed at a mean distance  
116 of  $14 \pm 4 \mu\text{m}$ , against  $36 \mu\text{m}$  if cell division were randomly distributed, see **Extended Figure 1f**  
117 **and Supplementary movie S4**.

118 Only in very few instances we observed the formation of holes on stiff substrates and only at  
119 higher densities. However, the prevalence of hole formation on 2.3 kPa (soft) gels increased as  
120 a function of cell density (**Figure 1e**) and these holes continue to grow as the density increases  
121 (**Supplementary Movie S2**). As suggested above, hole formation may be induced through two  
122 different mechanisms associated to cell stretching and cell division, respectively. Interestingly,  
123 when comparing cell proliferation on soft and stiff, we found a significant decrease in cell  
124 proliferation on stiff substrates (**Extended figures 1g, h**).

125 To delineate the role of cell division we blocked DNA synthesis by mitomycin C treatment.  
126 Upon mitomycin C treatment on 2.3kPa gels we obtained a significant reduction in the number  
127 of holes formed per unit surface (**Figure 1f**), indicating that when cell division is blocked, hole  
128 formation is largely blocked as well, but cell stretching events can still lead to hole formation.

129 We generalize our findings by performing complementary experiments on the colorectal  
130 adenocarcinoma epithelial cell line Caco2, which displayed a similar behavior as MDCK cells  
131 leading to hole formation on soft (2.3 kPa) substrates (**Extended Figure 1i, Supplementary**  
132 **movie S5**). Altogether, these observations point towards hole formation in epithelial  
133 monolayers due to altered cell-cell interactions mediated by substrate stiffness.

134

### 135 **Dynamics of hole initiation and growth**

136 Tracking the dynamics of hole opening through a side view angle and imaging MDCK  
137 monolayers tagged with actin-GFP showed differences in the curvature formed by the cell edge  
138 at the hole periphery during and after hole opening. At early stage of hole initiation, cells spread  
139 on the substrate and the cell front formed a contact angle with the substrate lower than  $90^\circ$ ,  
140 suggesting that rupture first occurs on the apical side (**Figure 2a(i), b**). During hole opening,  
141 the local curvature of the cell front changes, evidenced by an increase in contact angle between  
142 the cell front and substrate (greater than  $90^\circ$ ) (**Figure 2a(ii), b**). The change in curvature of the  
143 cell front and the radial speed of hole growth are reminiscent of an active dewetting process,  
144 previously described during cell spreading<sup>39,40</sup> as a result of low interactions with the  
145 underlying surface or increased tension. In addition, at high cell density, a side-view of nuclei-

146 labelled monolayers revealed a preference to form multilayered epithelia at the hole boundary  
147 (**Figure 2c, d**). This shows that cells at high densities prefer to pile up around the hole instead  
148 of closing it, pointing towards reduced substrate adhesion.

149 Along this line, tracking the dynamics of holes revealed two distinct lifetimes: short-lived holes  
150 that tend to close in less than 5 hours (**Figure 2e, Extended Figure 1j, Supplementary movie**  
151 **S6**) and long-lived holes that stayed open for a longer duration (at least during the time course  
152 of our experiments) (**Figure 2f, Extended Figure 1k, Supplementary movie S6**). Computing  
153 the area of these short- and long-lived holes, revealed a threshold area, around  $4000\mu\text{m}^2$   
154 (corresponding to approx.  $36\mu\text{m}$  in radius) beyond which the holes tended to be long-lived  
155 (**Figure 2g**). These long-term holes occasionally grew through the fusion of two holes forming  
156 a larger one while in other cases, fission of large holes results in the formation of two small  
157 holes (**Supplementary movie S2**).

158

### 159 **Reduced substrate adhesion triggers hole formation**

160 Previous studies have shown that substrate stiffness has a strong impact on focal adhesion (FA)  
161 mechanosensing at single and collective cell levels<sup>41-45</sup> while its role in regulating cell-cell  
162 adhesion remains less clear<sup>37,46</sup>. We first looked at the role of substrate adhesions during hole  
163 formation.

164 To this end, we decreased the fibronectin concentration from  $20\mu\text{g/ml}$  to  $5\mu\text{g/ml}$  (see  
165 Methods). On  $2.3\text{ kPa}$  gels varying fibronectin concentration did not significantly affect hole  
166 formation. On stiff ( $55\text{ kPa}$ ) gels the hole formation further diminished to zero on  $5\mu\text{g/ml}$   
167 compared to close to zero at  $20\mu\text{g/ml}$  (**Extended Figure 2a**). However, when soft ( $2.3\text{ kPa}$ )  
168 gels were patterned with different amounts of fibronectin simultaneously (see Methods), holes  
169 preferentially formed on regions of low fibronectin coating (**Figure 3a, Supplementary movie**  
170 **S7**), with 60% probability. No holes were formed in the other cases ( $n=10$  samples in 2  
171 independent experiments). We then stained for cell-substrate adhesion marker (paxillin), where  
172 we noted a marked increase in the length and area of focal adhesions on  $55\text{ kPa}$  gels in  
173 comparison to  $2.3\text{ kPa}$  gels (**Extended Figure 2b-d**). In agreement with<sup>45</sup>, we also showed that  
174 both the number and length of substrate adhesions reduced as cell density increases (**Extended**  
175 **Figures 2e-g**) which may explain the higher propensity of holes to remain open at high density  
176 (**Supplementary movie S2**). Altogether, these results point toward a major contribution of  
177 stiffness sensing over purely substrate adhesion mechanisms on hole formation.

178 Mechanical failure of monolayers grown on soft substrates is unlikely to be explained by a  
179 lower strength of cell-cell adhesion as no difference in junctional E-cadherin intensity within  
180 MDCK monolayers was observed whether grown on 2.3kPa or 55kPa gels, nor did E-cadherin  
181 intensity change prior to hole formation on 2.3kPa (**Extended Figure 2h-k**). Yet, we observed  
182 an increase in the junctional intensity of vinculin on soft substrates, as compared to the stiff  
183 ones (**Extended Figures 2l, m**). This increase in junctional vinculin, a mechanosensitive  
184 protein - known to shuttle between cell-cell contacts and cell-substrate adhesions in a force  
185 dependent manner<sup>47,48</sup>, accompanied by reduced substrate adhesion point towards a build-up in  
186 junctional stresses leading to hole formation on soft (2.3kPa) gels.

187 We tested this interpretation through an *in silico* vertex model of epithelial tissues (see  
188 Methods)<sup>49</sup>. In such framework, the dynamics the contacts between cell-cell junctions  
189 (*vertices*) results from a balance between a drag friction to the substrate and internal stresses  
190 generated within cells; constant tissue flows were achieved through an active stress mechanism  
191 (see **Methods** and next paragraph). Modulating surface friction in our simulations resulted in  
192 higher cellular stresses within regions of low substrate friction (**Extended Figure 3a, b**), in  
193 agreement with our experimental observation of hole formation at low fibronectin density  
194 (**Figure 3a**).

195 Importantly, these results can be recapitulated by considering a minimal Kelvin-Voigt  
196 rheological model for cells which accounts for the role of cell-substrate friction. In such model,  
197 the stress load imposed by the tissue on an individual cell is shared between the viscous drag  
198 on the substrate (damper) and a bulk cell or cell-cell elastic moduli (spring). In regions of  
199 reduced adhesion molecule density or low substrate elastic modulus<sup>50</sup>, a lower viscous drag on  
200 the substrate is expected<sup>51</sup>. In a Kelvin-Voigt model, a weaker damper (low adhesion) results  
201 in a higher stress load within cells (spring). Since higher stresses within epithelial monolayers  
202 has been attributed to mechanical failure of cell-cell junctions<sup>17</sup>, our Kelvin-Voigt model  
203 explains why hole formation is favored by a lower adhesion at the cell-substrate interface in  
204 both experiments and simulations.

### 205 **Monolayer tension on soft gels drives hole formation**

206 Our results thus far, point towards an increase in junctional tension on soft (2.3kPa) substrates.  
207 To assess the contributions of tension during hole formation, we measured traction forces and  
208 inferred stress within the monolayer using Traction Force Microscopy (TFM) and Bayesian

209 Inversion Stress Microscopy<sup>52</sup> (BISM), respectively (**Figure 3b**). In these experiments, we  
210 used 30 kPa as stiff substrates instead of 55 kPa due to limitations of TFM use at higher  
211 stiffnesses. We first confirmed that cells exerted higher traction forces on stiffer substrates both  
212 under confined and unconfined conditions (**Figure 3c, Extended figure 3c**). Additionally, in  
213 confined MDCK monolayers the direction of traction forces along the diameter of the circle  
214 changed from soft to stiff substrates, i.e., traction forces pointed inward on soft and outward  
215 on stiff substrates (**Figure 3d, Extended figure 3d**), revealing a potential change in stress  
216 patterns within the monolayer. Computing monolayer stresses, we observed a change in the  
217 sign of averaged monolayer isotropic stress from positive values ( $\sim 50 \text{ Pa}\cdot\mu\text{m}$ ) (negative  
218 pressure) on soft substrates to a negative values ( $\sim -60 \text{ Pa}\cdot\mu\text{m}$ ) (positive pressure) on stiff  
219 substrates under both confined and unconfined conditions (**Figure 3e, Extended figure 3e**).  
220 Our results are in agreement with previous studies that described cellular monolayers to be  
221 tensile on soft substrates<sup>13,52</sup>, but unveiled an unanticipated switch from a tensile to a  
222 compressive state upon increase in substrate stiffness (**Figure 3e**). We further confirmed our  
223 stress inference results using laser ablation on cellular monolayers plated on 2.3 kPa and 30  
224 kPa gels (**Supplementary movie S8**). The recoil velocity (noise level  $\sim 0.6 \mu\text{m}/\text{sec}$ ) of  
225 monolayers was negligible on 30 kPa gels but significant around  $2.5\mu\text{m}/\text{s}$  on 2.3 kPa gels  
226 (**Figure 3f**) confirming the tensile nature of the epithelial monolayers on soft gels.

227 We then investigated the changes of cell movement and monolayer tension in the vicinity of  
228 the hole over time. About 30-50 minutes prior to hole initiation in a region of about 5 cell radii,  
229 cells showed outward movement combined by high velocity vectors pointing outwards and  
230 positive divergence (**Figure 3g top, Extended Figure 3f**). Traction force vectors demonstrated  
231 a similar pattern, where cells exerted outward forces before hole initiation (**Extended Figure**  
232 **3g**). The isotropic stress exhibited a local buildup of tensile stress which relaxed prior to hole  
233 initiation (**Figure 3g bottom, h, Extended Figure 3h**) and about 14% of all tensile regions  
234 give rise to hole formation. This local spike in stress prior to hole formation was in striking  
235 contrast to the overall monolayer stress that remained unchanged (**Figure 3h**). We quantified  
236 the straightness of E-cadherin junctions, a direct indicator of the local stress in the tissue<sup>53</sup> and  
237 found an increased straightness around the hole in comparison to the regions far away from the  
238 hole (**Extended Figure 3i, j**) confirming the implication of local tensile stresses in the process  
239 of hole initiation.



240 To understand the origin of this difference in tissue stresses with substrate stiffness, we turned  
241 to a vertex model approach where cell-adhesion energy can be modulated. Beyond the  
242 individual cell shape energy function (Method), we expect substrate interactions to modify the  
243 cell-substrate adhesion energy<sup>54</sup> through a contribution  $\delta U = -\gamma_b A$ , where  $A$  is the cell area;  
244 this results in a modulated spreading area  $A_0^* = A_0 + \gamma_b/K_A$ , where  $K_A$  is the standard area  
245 elasticity (SI). Thus, having constant cell divisions with a constant spreading area of each  
246 daughter cell  $A_0^*$  leads to a simulated tissue under compression (**Figure S5**). However, a  
247 reduced spreading area of daughter cells upon cell division gives rise to a simulated tensile  
248 tissue (**Figure S5**). Such interpretation is consistent with our experimental observations of  
249 tensile monolayers on soft substrates with reduced size of focal adhesions.

### 250 Nematic ordering of cells initiates hole opening

251 To understand the origin of this increase in local stress, we looked at local organization of cells  
252 since nematic ordering and defects (trefoils or comet shapes, corresponding to  $-1/2$  and  $+1/2$   
253 topological defects) (**Figure 4a**), with either extensile<sup>14,55,56</sup> or contractile<sup>56,57</sup> active stresses  
254 give rise to characteristic stress profiles around these defects. In particular, isotropic stress  
255 exhibits distinct patterns between  $-1/2$  and  $+1/2$  defects as it is tensile around  $-1/2$  defects  
256 (**Figure 4a left**) and compressive at the head portion and tensile at the tail end of a  $+1/2$  defect  
257 (**Figure 4a right**)<sup>14</sup>. Topological defects are found on both soft and stiff substrates with  
258 comparable number of defects formed on soft and stiff substrates as shown in **Extended Figure**  
259 **4a**. Tracking the movement of  $+1/2$  (comet) defects revealed monolayers to be extensile on  
260 both soft and stiff substrates. (**Extended Figure 4b**) in agreement with our previous work<sup>14,56</sup>.

261 Upon calculating the MSD of defects, we found the lifetime of  $+1/2$  defects to be  $129 \pm 49$  mins  
262 on soft substrates and  $92 \pm 90$  mins on stiff substrates (**Extended Figure 4c**), although,  $-1/2$   
263 defects were slower than  $+1/2$  defects on both substrates as shown previously<sup>55,56</sup>. We then  
264 compared this to the persistence of tensile hotspots in a region of  $51 \times 51 \mu\text{m}$  at random locations  
265 and we find that tensile regions are persistent for a longer period on soft substrates in  
266 comparison to stiff substrates. The mean lifetime of tensile regions on soft substrates was  
267  $97.5 \pm 39$  min while the mean lifetime of  $+1/2$  defects on soft substrates was  $129 \pm 49$  min thereby  
268 showing a strong correlation with the lifetime of  $+1/2$  defects. However, the persistence of  
269 tensile regions on stiff substrates was  $53 \pm 21$  min and is lower than the lifetime of  $+1/2$  defects  
270 (**Extended Figure 4d**).

271 The stress pattern around defects on soft and stiff substrates seem to be different. +1/2 defects  
272 have compressive stresses at the head of the defect and tensile stresses around the tail on soft  
273 substrates, whereas stresses are overall compressive on stiff substrates at +1/2 defects but less  
274 at the tail (**Extended Figure 4e, f**). Moreover, the cores of -1/2 defects on soft substrates exhibit  
275 tensile stresses (**Extended Figure 4g**) on the contrary the core of -1/2 defects are compressive  
276 on stiff substrates.

277 Upon correlating the location of hole formation with the defect location, we find that the holes  
278 form at specific locations around topological defects on soft substrates, with ~70% of holes  
279 initiated at locations near -1/2 nematic defects which are under tensile stress prior to hole  
280 initiation (**Figure 4b left**) while the remaining ~30% holes were initiated close to the tensile  
281 tail region of a +1/2 defect (**Figure 4b right**). Altogether, these results show that the formation  
282 of holes is favored on soft surfaces (i) due to the overall tensile nature of the monolayer and  
283 (ii) near -1/2 defects or tail region of +1/2 defects due to a local amplification of tensile stresses.  
284 However, dividing these holes into different groups based on their origin (cell division or cell  
285 stretching) and correlating them to the formation of topological defects showed no correlation  
286 between topological defect shape and either event of hole formation. In our experiments ~50%  
287 of hole formation driven by cell division was related to a +1/2 defect and ~50% of holes driven  
288 by cell stretching were driven by +1/2 defect formation. (**Extended Figure 4h**).

289  
290 We used our cell-based vertex model to explore whether topological defects could underpin  
291 the large stresses needed to trigger hole opening. Indeed, as visible in **Figure 4a**, the mean  
292 stress around the topological defect is at a maximum of 60 Pa.μm, significantly lower than the  
293 range of stresses observed to trigger hole opening (200-500 Pa.μm, **Extended Figure 3d**). We  
294 utilized a recent method to generate cell-based nematic stresses<sup>58,59</sup> that were oriented by the  
295 cell shape<sup>56,60,61</sup> (**SI I**). We show that such cell-based active stresses lead to spontaneous tissue  
296 flows (**Supplementary movie S9**) with spontaneous generation of ±1/2 topological defects  
297 with average stress patterns that match those observed in experiments (**Figure 4c, d**). We  
298 further found that the 95<sup>th</sup> upper percentile (**Methods**) of the isotropic stress, is in that range of  
299 values of stresses needed to create holes. Importantly, it exhibited the same pattern as mean  
300 stress both in simulations (**Figure 4d, e**) and experiments (**Figure 4b, f**). Together, both  
301 experimental and numerical results show that hole formation on soft surfaces emerge in areas  
302 of high tension associated to specific location around topological defects.

303

304 To further identify the mode of stress-mediated fracture we validated our model prediction that  
305 regions of large shear stresses (as quantified through the Von-Mises criterium, **Methods**) were  
306 anti-correlated to the location of hole opening (**Extended Figure 5**). Hole opening is therefore  
307 a mode I (tension mediated) process according to classical terminology in material science<sup>62</sup>.

308 Here, the measured stress maps were obtained through coarse-graining over a few cell sizes.  
309 We utilized our cell-based simulation framework to test whether we could test hypothesis at  
310 the single cell-cell junction scale. Initiating holes by splitting a vertex into three, we  
311 investigated whether cell-cell junction ruptures could either be mediated (i) through normal  
312 stresses applied to cell-cell junction or (ii) by the junction elongation rate (**Extended Figure**  
313 **6a, b**). We found that only the normal stress hypothesis is consistent with holes forming in  
314 regions of extreme isotropic stresses (**Extended Figure 6c-f**).

315 Reducing the level of active stress level led to a lower amplitude of stress fluctuations thereby  
316 suppressing hole formation in our simulations (**SI**). This is in qualitative agreement with our  
317 experiments where 50 $\mu$ M CK666 (inhibitor of actin polymerization) led to abrogation of hole  
318 formation (**Extended Figure 7a, b**) and treatment with 20  $\mu$ M blebbistatin (Myosin IIA  
319 inhibitor) led to reduced number of holes (**Extended Figure 7b, c**), in spite of both  
320 blebbistatin<sup>14</sup> and CK666 treatment maintaining extensile activity (**Extended Figure 7d, e**).

### 321 **Hole dynamics**

322 We then evaluated the dynamics of holes in our simulations using the same parameter set as in  
323 **Figure 4 and Extended figure 8a**. As in experiments, we identified short-lived holes with a  
324 lifetime < 5 hours (**Figure 2e, Extended figure 8a, Supplementary movie S10**) and long-  
325 lived holes that stayed open for a longer duration (**Figure 2f, Extended figure 8b,**  
326 **Supplementary movie S10**). On short times, hole growth was linear with a radial speed of  $(6.1$   
327  $\pm 0.1) \times 10^{-3} \mu\text{m/s}$  (**Extended figure 8c**), leading to similar values as those reported by Beaune  
328 *et al*<sup>40</sup> for spreading sarcoma cell aggregates  $(9 \pm 0.5) \times 10^{-3} \mu\text{m/s}$ .

329

330 As holes grew and opened, they evolved from a circular to an irregular shape featuring finger-  
331 like structures (**Figure 5a, Extended figures 8a, e and Supplementary movie S10**) both in  
332 simulations and experiments. Occasionally, such fingers could reach the other side of the hole  
333 and drive fission of a large hole into two smaller ones (**Extended figures 8a, e and**  
334 **Supplementary movie S10**) both in simulations and experiments. In addition, during the phase  
335 of opening, cells at the periphery of hole became increasingly elongated and organized

336 themselves tangentially at the margin of the hole both in simulations and experiments (**Figures**  
337 **5b, c**). This tangential organization continued until the hole reached its maximal area (**Figure**  
338 **5c, Extended Figure 8f**). In contrast, closure of these holes was associated to a loss of  
339 tangential organization in both experiments and simulations (**Extended figures 8a, e**).

340

341 We propose a simplified coarse-grained model to fit the hole dynamics and the existence of  
342 short and long-lived holes (**SI**). The hole opening rate is determined by a mechanical balance  
343 between (i) the local tissue tension around the hole  $\sigma$ , (ii) a resisting line tension, denoted by  $\gamma$   
344 (amount of mechanical work required to create a new free interface within the tissue), along  
345 with stresses associated to cell elongation around the hole, denoted by  $\zeta\Delta q$  where  $\Delta q$  quantifies  
346 the local elongation field within a nematic layer of width  $\lambda$  around the hole and (iii) a bulk  
347 viscous dynamic within the monolayer hole. Our analytical prediction for hole opening rate (**SI**  
348 **II**) reads

349 
$$\tilde{\xi}r \frac{dr}{dt} \approx -\frac{\gamma}{r} + \zeta\Delta q \ln\left(\frac{r+\lambda}{r}\right) + \sigma \sim -\frac{\tilde{\gamma}}{r} + \sigma \quad (\text{Equation 1})$$

350 with  $\tilde{\gamma} \approx \gamma - \lambda\zeta\Delta q$  a renormalized tension and  $\tilde{\xi} = \xi \ln(2l/r)$ , where  $l = \sqrt{\eta/\xi}$  a  
351 hydrodynamic length expressed in terms of the cell-substrate friction  $\xi$  and the monolayer  
352 viscosity  $\eta$ . Equation (1) leads to a typical nucleation size  $R_c \approx \tilde{\gamma}/\sigma$ ; for  $r < R_c$ , holes  
353 spontaneously close while for a hole of radius  $r > R_c$  holes would tend to grow in agreement  
354 with the observation of small (resp. large) holes being short-lived (resp. long-lived). Fits of the  
355 control experiments based on Eq. (1) are consistent with  $\sigma = 500 \text{ Pa}\cdot\mu\text{m}$ ,  $\tilde{\gamma} \approx 1.5 \text{ kPa}\cdot\mu\text{m}^2$   
356 and  $\xi = 50 \text{ Pa}\cdot\mu\text{m}^{-1}\cdot\text{min}$  (with  $l = 1000 \mu\text{m}$ ), **Figure 5d**. We also compare our vertex model  
357 result with Eq. (1) and find an increase of the hole opening rate with the exerted activity stress,  
358 see **SI**. We recapitulated the key features of our model in **Figure 5e**.

359

360

## 361 **Conclusion**

362 *In vivo* failure in adherens junctions<sup>24,63</sup>, increased mechanical load<sup>23</sup> and post-apoptotic failure  
363 in sealing<sup>64,65</sup> leads to hole formation in tissues. During morphogenesis, hole formation is not  
364 only essential for *Drosophila* peripodium elongation<sup>21</sup>, mouse embryogenesis<sup>7</sup> but is also  
365 crucial for macrophage invasion during *Drosophila* development<sup>8</sup>. In addition loss of epithelial  
366 integrity has been reported under pathophysiological conditions<sup>66,67</sup>, immune cell<sup>68</sup> and tumor  
367 extravasation<sup>69</sup>. Since tissue integrity and barrier function<sup>70,71</sup> are known to be altered by  
368 substrate stiffness, our study shows distinct mechanical states of epithelial tissues are triggered

369 by substrate stiffness which in turn modify tissue integrity. Epithelial monolayers grown on  
370 soft substrates exhibit the formation of holes in the bulk of the tissues at locations of high  
371 tensile stresses.

372 The emergence of holes within these monolayers relies on an unanticipated behavior of cellular  
373 monolayers, being under tension on soft and compression on stiff substrates. Tension has been  
374 attributed to tissue tear in suspended monolayers<sup>17</sup>, stretched monolayer<sup>72</sup>, peripodium  
375 elongation<sup>21</sup>, gaps in monolayer of neural progenitor cells<sup>73</sup> and in migrating organisms<sup>19</sup>. Our  
376 results so far show that reduced substrate adhesion in combination with tensile nature of  
377 monolayers on soft substrates make them sensitive to local increase in tension, resulting in  
378 spontaneous hole formations. These tensile stresses arise from the formation of topological  
379 defects and hole formation is initiated within the tensile regions of those defects. Theoretical  
380 approaches, corroborated by experiments, predict that hole formation relies on the formation  
381 of topological defects where cells experience high tensile normal stresses along cell-cell  
382 junctions. We anticipate that our mechanistic *in vitro* study will bring new perspectives to  
383 understand morphological changes of epithelial tissues as well as the maintenance of their  
384 integrity during development and morphogenetic events.

## 385 **Material and Methods**

### 386 **Patterned surfaces on polyacrylamide (PA) gels**

387 Glass coverslips were plasma activated and coated with 0.1mg/ml PLL-g-PEG (SuSoS  
388 Technology). Using a quartz mask, circles of 1mm diameter were patterned on the passivated  
389 glass coverslips and incubated with 5 or 20 $\mu$ g/ml fibronectin for 30 min. After incubation, glass  
390 coverslips were rinsed in 1x PBS to remove excess protein. Simultaneously, silanization of  
391 another set of glass coverslips were performed by plasma activation of clean coverslips and  
392 then incubated with an ethanol solution containing 2% (v/v) 3-(trimethoxysilyl) propyl  
393 methacrylate (Sigma-Aldrich, St Louis, Missouri, USA) and 1% (v/v) acetic acid. The silanised  
394 coverslips were then heated at 120°C. Freshly made Polyacrylamide (PA) mix was sandwiched  
395 between the patterned glass coverslip and silanized coverslip. Polyacrylamide mix was made  
396 as suggested in Plotnikov *et al*<sup>74</sup>. After polymerization, the patterned coverslips were peeled  
397 off to reveal the patterns of protein on PA gels. Samples were kept hydrated with 1x PBS until  
398 cell seeding.

### 399 **Cell culture and reagents used**

400 MDCK WT (ATCC CCL-34), stably transfected actin GFP and E-cadherin GFP MDCK cells  
401 (kind gift from James Nelson's lab) and Caco2 cells were cultured in 4.5 gl<sup>-1</sup> DMEM containing  
402 10% FBS (20% for Caco2) and 1% Penicillin-Streptavidin (Gibco, Thermo Fischer Scientific,  
403 Waltham, MA, USA). 100 $\mu$ l cell culture media containing 100,000 cells was seeded on the  
404 PA gels for 1 hour. 2 ml fresh media was added into the sample without washing to prevent  
405 detachment of loosely attached cells. Samples were imaged the following day once they spread  
406 and reached confluency. In some experiments to study the effect of blocking cell division, cells  
407 were treated with 10 $\mu$ g/ml of mitomycin-C (Sigma-Aldrich, St Louis, Missouri, USA) for 1  
408 hour and washed prior to imaging. 100 $\mu$ M CK666 (Sigma Aldrich) was added prior to imaging  
409 for Arp 2/3 inhibition experiments.

### 410 **Immunostaining and antibodies used**

411 Samples were fixed with 4% paraformaldehyde (Thermo Fischer Scientific, Waltham, MA,  
412 USA) for 10 mins and permeabilized with 0.5% Triton-X for 5 mins. Cells were then blocked  
413 with 1% BSA/PBS and incubated with primary antibody overnight. Cells were incubated in  
414 secondary antibody for 1 hour and then mounted on another glass coverslip using Mowiol 40-  
415 88 (Sigma-Aldrich). For immunostaining, the following primary antibodies were used, E-

416 cadherin (24E10- Cell Signaling Technology; DECMA1- Sigma Aldrich, ECCD2, Takara Bio)  
417 (1:100)and paxillin (Abcam, Ab32084) (1:100) vinculin was a gift from Glukhova lab (1:2).  
418 Anti-mouse, anti-rat, and anti-rabbit secondary antibodies conjugated with Alexa (488 or 568)  
419 (used at 1:200 dilution), phalloidin (1:20) were purchased from Life Technologies and Hoechst  
420 (Thermo Fisher, 1:10000). The fixation was slightly altered to stain vinculin at cell–cell  
421 junctions and focal adhesions. Cells were fixed with a mix of 4% PFA and 0.5% Triton-X 100  
422 for 90 seconds, followed by fixation with 4% PFA for 10 min.

### 423 **Traction force microscopy**

424 PA gels were embedded with 200nm fluorescent beads (Life Technologies, Paisley, UK)  
425 during polymerization. The samples were imaged on Biostation IM-Q (Nikon) for 24 hours  
426 after which 1ml of 10x SDS was added to the sample in order to obtain the resting position of  
427 beads.

### 428 **Differential fibronectin coating on PA gels**

429 Differential coating of fibronectin was performed using Primo® (Alveole). Glass coverslips  
430 were passivated with double coating of 0.1% w/v poly-L-Lysine (PLL) for 30 min and  
431 100mg/ml poly (ethylene glycol) succinimidyl valerate (PEG-SVA) for 1 hour. After washing  
432 the glass coverslip carefully with water, they were patterned with evenly spaced grey  
433 circular patterns (100µm diameter, 500µm apart) using a UV beam with an energy dosage of  
434 600mJ/mm in presence of a photoinitiator, PLPP (Alveole). After patterning, the sample was  
435 washed with 1x PBS and incubated with 20µg/ml fibronectin for 10 min. Excess protein was  
436 washed away with 1x PBS and the rest of the unpatterned space (while covering the patterned  
437 area with black masks) was exposed to UV beam with an energy of 600mJ/mm using a white  
438 pattern. Newly exposed surface was incubated with 50µg/ml fibronectin (Sigma Aldrich) and  
439 1µg/ml cy3-conjugated fibronectin for 10 min. PA gel was casted after washing off excess  
440 protein. As mentioned previously, patterned glass coverslip was removed from the sandwich  
441 to reveal the patterns on PA gels.

### 442 **Imaging**

443 Phase contrast long-term imaging of samples was performed with 10x objective on Olympus  
444 inverted microscope (IX81). Traction force microscopy was performed on Biostation IM-Q  
445 (Nikon) with a 10x objective. Imaging was done for 24 hours with frame rate of 0.2frames/min.  
446 Fluorescent cells were imaged on Zeiss spinning disk confocal (CSU X1) using 40x water

447 objective. To follow the actin dynamics, Actin-GFP MDCK cells were imaged at a frame rate  
448 of 0.5frames/min for 12 hours. Fixed samples were imaged with 63x Oil objective on Zeiss  
449 Confocal microscope (LSM 710).

#### 450 **Laser ablation experiments**

451 Wound induction (by ablating a cell) on monolayer tissue of density of about 3000-3500 cells  
452 per mm<sup>2</sup> was done on a Nikon A1R MP laser scanning confocal microscope with Nikon CFI  
453 Apo LWD Lambda S 40XC WI/1.15 water-immersion objective. After about 10 s of imaging  
454 at 1 s interval for a total duration of 5 minutes, an ultraviolet laser (355 nm, 3-5 ns pulse  
455 duration, 1-15 Hz repetition rate, Minilite II, High Energy Nd:YAG, Amplitude Laser) was  
456 focused on the center of the monolayer within the region of interest for 1 s at a laser power of  
457 450 nW at the back aperture of the objective. The recoil velocity was measured by manually  
458 detecting cell edges over time and plotting the change in perimeter of the ablated region.

#### 459 **Data analysis**

460 Images were prepared using ImageJ and analysis was done with the plugins and home-written  
461 macros on ImageJ and MATLAB. Cross-sectional views of the tissue were represented by  
462 Imaris. E-cadherin and vinculin intensities were measured by manually drawing a line over the  
463 junction and measuring the intensity at cell-cell contacts. Similarly, paxillin size was measured  
464 by manual segmenting paxillin molecules obtained from immunostaining and size  
465 determination on ImageJ.

466 Junctional straightness was calculated as a ratio between Euclidean length (measured by  
467 drawing a straight line from one end to another) and actual length of cell-cell junctions  
468 identified by the E-cadherin staining.

#### 469 Cell segmentation

470 Cell segmentation and division tracking shown in Supplementary Movie 4 was manually  
471 corrected using Cellpose<sup>75</sup> with an erosion with a 3x3 square pixel kernel applied to each mask;  
472 we used btrack<sup>76</sup> for the cell tracking. Manual corrections were performed using the Napari  
473 software (46 lineage for the soft case, 42 for the stiff case)<sup>77</sup>. Figure 1f is obtained through a  
474 standard method in spatial statistics<sup>78</sup>: if the nearest division (with the 50min time window  
475 prior to the hole initiation date) is located further away from the hole than the boundary of the  
476 image, the hole is not considered in the statistics of **Figure 1f**. Comparison to the random case



477 if achieved by considering a Poisson process of parameters matching the total number of cell  
478 division observed during the movie.

#### 479 Nematic analysis

480 In our experiments, nematic detection analysis was done on both untreated and mitomycin-C-  
481 treated samples at low density as cells tend to be more isotropic at higher densities and form  
482 3D structures making it hard to identify the cell shape. Orientation field and defect detection  
483 was carried out as previously described<sup>14</sup>. Briefly, the orientation of cells was obtained using  
484 the OrientationJ plugin on ImageJ<sup>79</sup> where the largest eigenvector of the structure tensor was  
485 obtained for each pixel thereby giving us the orientation. The local nematic order parameter  
486 tensor  $Q$  (averaged over 1-2 cells) ( $52 \mu\text{m}$ ) was then calculated. The largest eigenvalue of  $Q$   
487 was taken to the orientation of 2-3 cells and overlaid over phase contrast images as a red line.  
488 Based on this orientation, winding number parameter<sup>80,81</sup>, was used to identify  $+1/2$  and  $-1/2$   
489 defects. In order to reduce noise, we only identify defects that stable over 60min, we obtain the  
490 orientation of 1-2 cells. Defect detection was compared against previous studies<sup>57</sup>. The MSD  
491 and lifetime of defects were obtained by using TrackMate plugin in ImageJ<sup>82</sup>. In the  
492 Supplementary Material, we show the robustness of our topological defect analysis. The 95th  
493 percentile is the value below which 95% of scores in the isotropic stress (or the von Mises  
494 stress) field frequency distribution falls.

#### 495 Velocity measurements, strain rate, traction force and stress analysis

496 Velocities of the monolayer were obtained through Particle Image Velocimetry (PIV) analysis  
497 using PIVlab<sup>83</sup> on MATLAB. Interrogation window of size  $41 \times 41 \mu\text{m}$  (strain rate) and  $21 \times 21$   
498  $\mu\text{m}$  (monolayer) with an overlap of 50% was used for analysis and the outlier vectors were  
499 manually removed. Having identified the location of defects, we obtain the average velocity  
500 field around defects identified by realigning these defects. The strain rate around these defects  
501 was calculated from the gradient of the velocity field as  $\dot{\epsilon} = \nabla v$ . By plotting the velocity around  
502  $+1/2$  defect, we can characterize the system as an extensile or contractile system.

503 For force measurements, firstly the reference bead image was concatenated with the bead  
504 images containing cells such that the reference frame precedes the bead image with cells. The  
505 images were then stabilized using Image Stabilizer plugin in ImageJ (written by Kang Li,  
506 CMU) to correct with xy drift following which the intensity correction was applied on these  
507 images. The velocities of bead movement were obtained using PIV analysis. Using the FTTC

508 plugin<sup>84</sup>, we obtain traction force fields from bead velocities using a regularization parameter  
509 of  $9 \times 10^{-9}$ . Using the traction force fields, stress in the monolayer is obtained using Bayesian  
510 Inversion Stress Microscopy (BISM)<sup>52</sup> where an unconfined boundary condition was used to  
511 obtain stresses. The isotropic stress is defined as half of the stress tensor trace  $((\sigma_{xx} + \sigma_{yy})/2)$ .  
512 Besides the isotropic stress, we also checked the von Mises stress, which is a scalar invariant  
513 value of a stress tensor and defined as  $\sigma_{VM} = \sqrt{\sigma_{xx}^2 - \sigma_{xx}\sigma_{yy} + \sigma_{yy}^2 + 3\sigma_{xy}^2}$ . Using the traction  
514 force fields, stress in the monolayer is obtained using Bayesian Inversion Stress Microscopy  
515 (BISM)<sup>52</sup> where an unconfined boundary condition was used to obtain stresses<sup>14</sup>. As a  
516 consequence, we systematically ignored stress values obtained close to the domain boundaries,  
517 and considered only stresses in the central part of the domain (previously validated using  
518 numerical data<sup>14</sup>). The heatmaps obtained for strain rate and stress were smoothed through  
519 linear interpolation. Tensile hotspots detection was based on the time needed for the stress to  
520 change sign over an interrogation window of  $51 \times 51 \mu\text{m}$ .

521

## 522 **Vertex-based active nematic model**

523 Please refer to Supplementary Information I

## 524 **Statistics**

525 Statistical analysis of all the data sets were performed by the student t-tests.

526

## 527 **References**

528

- 529 1. Ladoux, B. & Mège, R.-M. Mechanobiology of collective cell behaviours. *Nature*  
530 *Reviews Molecular Cell Biology* **18**, 743–757 (2017).
- 531 2. Campinho, P. *et al.* Tension-oriented cell divisions limit anisotropic tissue tension in  
532 epithelial spreading during zebrafish epiboly. *Nat. Cell Biol.* **15**, 1405–1414 (2013).
- 533 3. Heisenberg, C. P. & Bellaïche, Y. Forces in tissue morphogenesis and patterning. *Cell*  
534 **153**, 948 (2013).
- 535 4. Yu, J. C. & Fernandez-Gonzalez, R. Local mechanical forces promote polarized  
536 junctional assembly and axis elongation in *Drosophila*. *eLife* **5**, e10757 (2016).
- 537 5. Lecuit, T. & Lenne, P.-F. Cell surface mechanics and the control of cell shape, tissue  
538 patterns and morphogenesis. *Nature Reviews Molecular Cell Biology* **8**, 633–644 (2007).
- 539 6. Low, I. I. C. *et al.* Morphogenesis of neurons and glia within an epithelium. *Development*  
540 **146**, (2019).
- 541 7. Dumortier, J. G. *et al.* Hydraulic fracturing and active coarsening position the lumen of  
542 the mouse blastocyst. *Science* **365**, 465–468 (2019).
- 543 8. Akhmanova, M. *et al.* Cell division in tissues enables macrophage infiltration. *bioRxiv* 31  
544 (2021) doi:<https://doi.org/10.1101/2021.04.19.438995>.
- 545 9. Damms-Machado, A. *et al.* Gut permeability is related to body weight, fatty liver disease,  
546 and insulin resistance in obese individuals undergoing weight reduction. *Am J Clin Nutr*  
547 **105**, 127–135 (2017).
- 548 10. Xiao, C. *et al.* Defective epithelial barrier function in asthma. *Journal of Allergy and*  
549 *Clinical Immunology* **128**, 549-556.e12 (2011).
- 550 11. Soler, A. P. *et al.* Increased tight junctional permeability is associated with the  
551 development of colon cancer. *Carcinogenesis* **20**, 1425–1432 (1999).

- 552 12. Eisenhoffer, G. T. *et al.* Crowding induces live cell extrusion to maintain homeostatic  
553 cell numbers in epithelia. *Nature* **484**, 546–549 (2012).
- 554 13. Trepap, X. *et al.* Physical forces during collective cell migration. *Nature Phys* **5**, 426–430  
555 (2009).
- 556 14. Saw, T. B. *et al.* Topological defects in epithelia govern cell death and extrusion. *Nature*  
557 **544**, 212–216 (2017).
- 558 15. Serra-Picamal, X. *et al.* Mechanical waves during tissue expansion. *Nature Physics* **8**,  
559 628–634 (2012).
- 560 16. Gayraud, C., Bernaudin, C., Déjardin, T., Seiler, C. & Borghi, N. Src- and confinement-  
561 dependent FAK activation causes E-cadherin relaxation and  $\beta$ -catenin activity. *Journal of*  
562 *Cell Biology* **217**, 1063–1077 (2018).
- 563 17. Harris, A. R. *et al.* Characterizing the mechanics of cultured cell monolayers. *PNAS* **109**,  
564 16449–16454 (2012).
- 565 18. Fouchard, J. *et al.* Curling of epithelial monolayers reveals coupling between active  
566 bending and tissue tension. *PNAS* **117**, 9377–9383 (2020).
- 567 19. Prakash, V. N., Bull, M. S. & Prakash, M. Motility-induced fracture reveals a ductile-to-  
568 brittle crossover in a simple animal’s epithelia. *Nat. Phys.* **17**, 504–511 (2021).
- 569 20. Bull, M. S. & Prakash, M. Mobile defects born from an energy cascade shape the  
570 locomotive behavior of a headless animal. *arXiv:2107.02940 [physics]* (2021).
- 571 21. Proag, A., Monier, B. & Suzanne, M. Physical and functional cell-matrix uncoupling in a  
572 developing tissue under tension. *Development* **146**, (2019).
- 573 22. Carter, J. A., Hyland, C., Steele, R. E. & Collins, E.-M. S. Dynamics of Mouth Opening  
574 in Hydra. *Biophys J* **110**, 1191–1201 (2016).
- 575 23. Maina, J. N. & Jimoh, S. A. Structural failures of the blood-gas barrier and the epithelial-  
576 epithelial cell connections in the different vascular regions of the lung of the domestic

- 577 fowl, *Gallus gallus* variant domesticus, at rest and during exercise. *Biology Open* **2**, 267–  
578 276 (2013).
- 579 24. Martin, A. C., Gelbart, M., Fernandez-Gonzalez, R., Kaschube, M. & Wieschaus, E. F.  
580 Integration of contractile forces during tissue invagination. *Journal of Cell Biology* **188**,  
581 735–749 (2010).
- 582 25. Benton, M. A. *et al.* Fog signaling has diverse roles in epithelial morphogenesis in  
583 insects. *eLife* **8**, e47346 (2019).
- 584 26. Sunyer, R. *et al.* Collective cell durotaxis emerges from long-range intercellular force  
585 transmission. *Science* **353**, 1157 LP – 1161 (2016).
- 586 27. Balcioglu, H. E. *et al.* A subtle relationship between substrate stiffness and collective  
587 migration of cell clusters. *Soft Matter* **16**, 1825–1839 (2020).
- 588 28. Chen, T. *et al.* Large-scale curvature sensing by directional actin flow drives cellular  
589 migration mode switching. *Nat. Phys.* **15**, 393–402 (2019).
- 590 29. Lo, C.-M., Wang, H.-B., Dembo, M. & Wang, Y. Cell Movement Is Guided by the  
591 Rigidity of the Substrate. *Biophysical Journal* **79**, 144–152 (2000).
- 592 30. Nasrollahi, S. *et al.* Past matrix stiffness primes epithelial cells and regulates their future  
593 collective migration through a mechanical memory. *Biomaterials* **146**, 146–155 (2017).
- 594 31. Barriga, E. H., Franze, K., Charras, G. & Mayor, R. Tissue stiffening coordinates  
595 morphogenesis by triggering collective cell migration in vivo. *Nature* **554**, 523–527  
596 (2018).
- 597 32. Trichet, L. *et al.* Evidence of a large-scale mechanosensing mechanism for cellular  
598 adaptation to substrate stiffness. *Proceedings of the National Academy of Sciences* **109**,  
599 6933–6938 (2012).
- 600 33. Hadden, W. J. *et al.* Stem cell migration and mechanotransduction on linear stiffness  
601 gradient hydrogels. *PNAS* **114**, 5647–5652 (2017).

- 602 34. Shellard, A. & Mayor, R. Collective durotaxis along a self-generated stiffness gradient in  
603 vivo. *Nature* **600**, 690–694 (2021).
- 604 35. Guo, W., Frey, M. T., Burnham, N. A. & Wang, Y. Substrate Rigidity Regulates the  
605 Formation and Maintenance of Tissues. *Biophysical Journal* **90**, 2213–2220 (2006).
- 606 36. Matte, B. F. *et al.* Matrix stiffness mechanically conditions EMT and migratory behavior  
607 of oral squamous cell carcinoma. *J Cell Sci* **132**, (2019).
- 608 37. Seddiki, R. *et al.* Force-dependent binding of vinculin to  $\alpha$ -catenin regulates cell–cell  
609 contact stability and collective cell behavior. *Molecular Biology of the Cell* **29**, 380–388  
610 (2018).
- 611 38. Lafaurie-Janvore, J. *et al.* ESCRT-III Assembly and Cytokinetic Abcission Are Induced  
612 by Tension Release in the Intercellular Bridge. *Science* **339**, 1625–1629 (2013).
- 613 39. Douezan, S. *et al.* Spreading dynamics and wetting transition of cellular aggregates.  
614 *Proceedings of the National Academy of Sciences of the United States of America* **108**,  
615 7315–7320 (2011).
- 616 40. Beaune, G. *et al.* How cells flow in the spreading of cellular aggregates. *PNAS* **111**,  
617 8055–8060 (2014).
- 618 41. Pelham, R. J. & Wang, Y. Cell locomotion and focal adhesions are regulated by substrate  
619 flexibility. *PNAS* **94**, 13661–13665 (1997).
- 620 42. Saez, A., Buguin, A., Silberzan, P. & Ladoux, B. Is the Mechanical Activity of Epithelial  
621 Cells Controlled by Deformations or Forces? *Biophys J* **89**, L52–L54 (2005).
- 622 43. de Rooij, J., Kerstens, A., Danuser, G., Schwartz, M. A. & Waterman-Storer, C. M.  
623 Integrin-dependent actomyosin contraction regulates epithelial cell scattering. *J Cell Biol*  
624 **171**, 153–164 (2005).

- 625 44. Plotnikov, S. V., Pasapera, A. M., Sabass, B. & Waterman, C. M. Force Fluctuations  
626 within Focal Adhesions Mediate ECM-Rigidity Sensing to Guide Directed Cell  
627 Migration. *Cell* **151**, 1513–1527 (2012).
- 628 45. Kocgozlu, L. *et al.* Epithelial cell packing induces distinct modes of cell extrusions. *Curr*  
629 *Biol* **26**, 2942–2950 (2016).
- 630 46. Andresen Eguiluz, R. C., Kaylan, K. B., Underhill, G. H. & Leckband, D. E. Substrate  
631 stiffness and VE-cadherin mechano-transduction coordinate to regulate endothelial  
632 monolayer integrity. *Biomaterials* **140**, 45–57 (2017).
- 633 47. Yonemura, S., Wada, Y., Watanabe, T., Nagafuchi, A. & Shibata, M.  $\alpha$ -Catenin as a  
634 tension transducer that induces adherens junction development. *Nat Cell Biol* **12**, 533–  
635 542 (2010).
- 636 48. Bays, J. L. & DeMali, K. A. Vinculin in cell–cell and cell–matrix adhesions. *Cell Mol*  
637 *Life Sci* **74**, 2999–3009 (2017).
- 638 49. Alt, S., Ganguly, P. & Salbreux, G. Vertex models: From cell mechanics to tissue  
639 morphogenesis. *Philosophical Transactions of the Royal Society B: Biological Sciences*  
640 **372**, (2017).
- 641 50. Walcott, S. & Sun, S. X. A mechanical model of actin stress fiber formation and substrate  
642 elasticity sensing in adherent cells. *PNAS* **107**, 7757–7762 (2010).
- 643 51. Tawada, K. & Sekimoto, K. Protein friction exerted by motor enzymes through a weak-  
644 binding interaction. *J Theor Biol* **150**, 193–200 (1991).
- 645 52. Nier, V. *et al.* Inference of Internal Stress in a Cell Monolayer. *Biophysical Journal* **110**,  
646 1625–1635 (2016).
- 647 53. Hara, Y., Shagirov, M. & Toyama, Y. Cell Boundary Elongation by Non-autonomous  
648 Contractility in Cell Oscillation. *Current Biology* **26**, 2388–2396 (2016).

- 649 54. Hannezo, E., Prost, J. & Joanny, J.-F. Theory of epithelial sheet morphology in three  
650 dimensions. *Proceedings of the National Academy of Sciences* **111**, 27–32 (2014).
- 651 55. Blanch-Mercader, C. *et al.* Turbulent Dynamics of Epithelial Cell Cultures. *Phys. Rev.*  
652 *Lett.* **120**, 208101 (2018).
- 653 56. Balasubramaniam, L. *et al.* Investigating the nature of active forces in tissues reveals how  
654 contractile cells can form extensile monolayers. *Nature Materials* **20**, 1156–1166 (2021).
- 655 57. Duclos, G., Erenkämper, C., Joanny, J.-F. & Silberzan, P. Topological defects in  
656 confined populations of spindle-shaped cells. *Nature Physics* **13**, 58–62 (2017).
- 657 58. Tlili, S. *et al.* Shaping the zebrafish myotome by intertissue friction and active stress.  
658 *PNAS* **116**, 25430–25439 (2019).
- 659 59. Lin, S.-Z., Merkel, M. & Rupprecht, J.-F. Implementation of cellular bulk stresses in  
660 vertex models of biological tissues. *Eur. Phys. J. E* **45**, 4 (2022).
- 661 60. Mueller, R., Yeomans, J. M. & Doostmohammadi, A. Emergence of Active Nematic  
662 Behavior in Monolayers of Isotropic Cells. *Phys. Rev. Lett.* **122**, 048004 (2019).
- 663 61. Comelles, J. *et al.* Epithelial colonies in vitro elongate through collective effects. *eLife*  
664 **10**, e57730 (2021).
- 665 62. Anderson, T. L. *Fracture Mechanics: Fundamentals and Applications*. (CRC Press,  
666 2017). doi:10.1201/9781315370293.
- 667 63. Classen, A. K., Anderson, K. I., Marois, E. & Eaton, S. Hexagonal packing of *Drosophila*  
668 wing epithelial cells by the planar cell polarity pathway. *Developmental Cell* **9**, 805–817  
669 (2005).
- 670 64. Watson, A. J. M., Duckworth, C. A., Guan, Y. & Montrose, M. H. Mechanisms of  
671 Epithelial Cell Shedding in the Mammalian Intestine and Maintenance of Barrier  
672 Function. *Annals of the New York Academy of Sciences* **1165**, 135–142 (2009).



- 673 65. Bullen, T. F. *et al.* Characterization of epithelial cell shedding from human small  
674 intestine. *Laboratory Investigation* **86**, 1052–1063 (2006).
- 675 66. Weiss, L. & Ward, P. M. Cell detachment and metastasis. *Cancer Metast Rev* **2**, 111–127  
676 (1983).
- 677 67. Gelman, R., Stevenson, W., Prospero Ponce, C., Agarwal, D. & Christoforidis, J. B.  
678 Retinal damage induced by internal limiting membrane removal. *Journal of*  
679 *Ophthalmology* **2015**, (2015).
- 680 68. Escribano, J. *et al.* Balance of mechanical forces drives endothelial gap formation and  
681 may facilitate cancer and immune-cell extravasation. *PLOS Computational Biology* **15**,  
682 e1006395 (2019).
- 683 69. Chen, M. B., Whisler, J. A., Jeon, J. S. & Kamm, R. D. Mechanisms of tumor cell  
684 extravasation in an in vitro microvascular network platform. *Integr Biol (Camb)* **5**, 1262–  
685 1271 (2013).
- 686 70. Wang, W., Lollis, E. M., Bordeleau, F. & Reinhart-King, C. A. Matrix stiffness regulates  
687 vascular integrity through focal adhesion kinase activity. *The FASEB Journal* **33**, 1199–  
688 1208 (2018).
- 689 71. Mammoto, A. *et al.* Control of lung vascular permeability and endotoxin-induced  
690 pulmonary oedema by changes in extracellular matrix mechanics. *Nature*  
691 *Communications* **4**, 1759 (2013).
- 692 72. Casares, L. *et al.* Hydraulic fracture during epithelial stretching. *Nature materials* **14**,  
693 343–351 (2015).
- 694 73. Kawaguchi, K., Kageyama, R. & Sano, M. Topological defects control collective  
695 dynamics in neural progenitor cell cultures. *Nature* **545**, 327–331 (2017).
- 696 74. Plotnikov, S. V, Sabass, B., Schwarz, U. S. & Waterman, C. M. High-Resolution  
697 Traction Force Microscopy. *Methods in Cell Biology* **123**, 367–394 (2014).

- 698 75. Stringer, C., Wang, T., Michaelos, M. & Pachitariu, M. Cellpose: a generalist algorithm  
699 for cellular segmentation. *Nat Methods* **18**, 100–106 (2021).
- 700 76. Bove, A. *et al.* Local cellular neighborhood controls proliferation in cell competition.  
701 *MBoC* **28**, 3215–3228 (2017).
- 702 77. Sofroniew, N. *et al.* *napari/napari: 0.3.1rc0*. (Zenodo, 2020).  
703 doi:10.5281/zenodo.3823467.
- 704 78. Baddeley, A., Rubak, E. & Turner, R. *Spatial Point Patterns: Methodology and*  
705 *Applications with R*. (Chapman and Hall/CRC, 2015). doi:10.1201/b19708.
- 706 79. Püspöki, Z., Storath, M., Sage, D. & Unser, M. Transforms and Operators for Directional  
707 Bioimage Analysis: A Survey. *Adv Anat Embryol Cell Biol* **219**, 69–93 (2016).
- 708 80. Vromans, A. J. & Giomi, L. Orientational properties of nematic disclinations. *Soft Matter*  
709 **12**, 6490–6495 (2016).
- 710 81. DeCamp, S. J., Redner, G. S., Baskaran, A., Hagan, M. F. & Dogic, Z. Orientational  
711 Order of Motile Defects in Active Nematics. *Nat Mater* **14**, 1110–1115 (2015).
- 712 82. Tinevez, J.-Y. *et al.* TrackMate: An open and extensible platform for single-particle  
713 tracking. *Methods* **115**, 80–90 (2017).
- 714 83. Thielicke, W. PIVlab – Towards User-friendly, Affordable and Accurate Digital Particle  
715 Image Velocimetry in MATLAB. *Journal of Open Research Software* **2**, 30 (2014).
- 716 84. Tseng, Q. *et al.* Spatial organization of the extracellular matrix regulates cell–cell  
717 junction positioning. *PNAS* **109**, 1506–1511 (2012).

718

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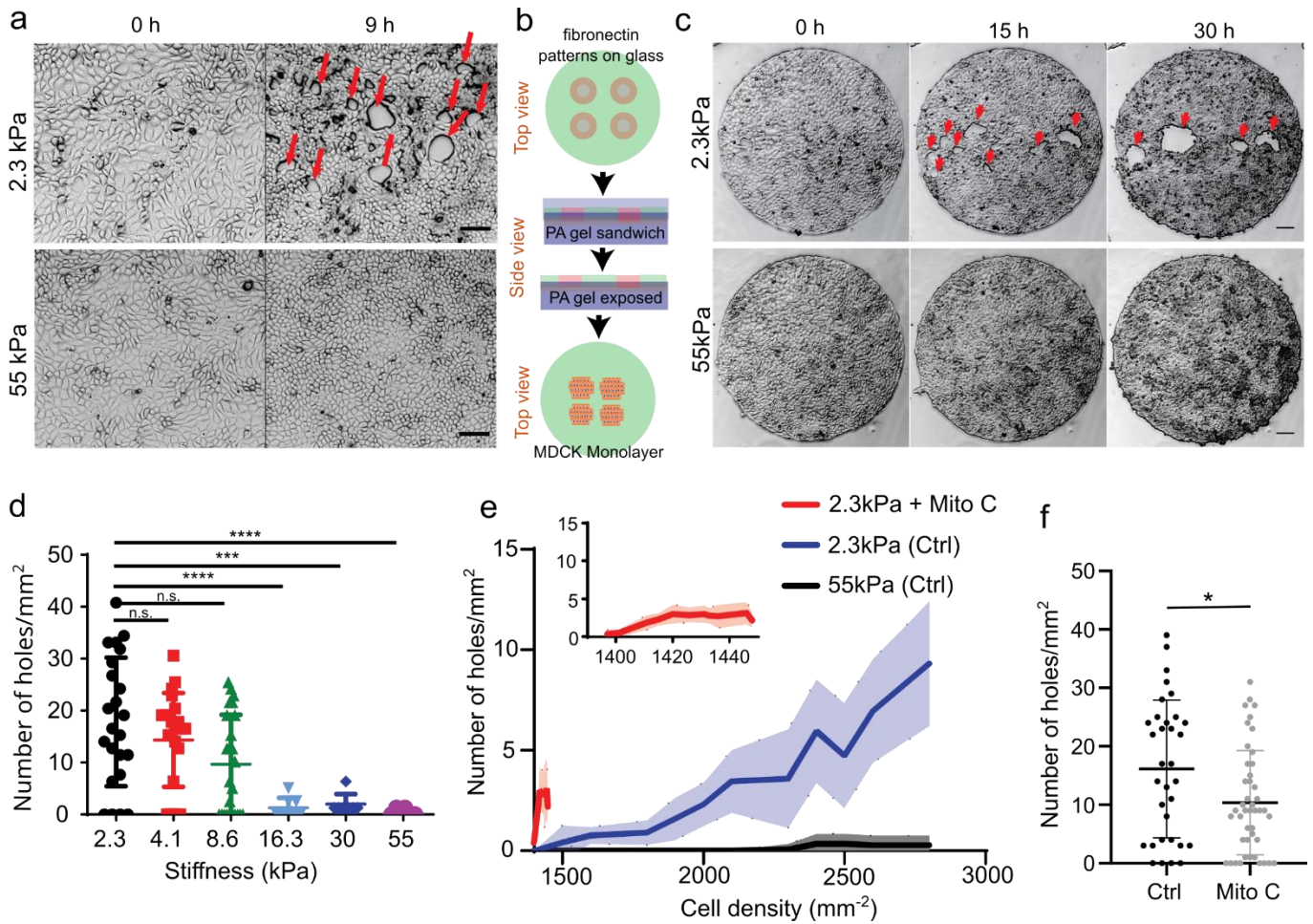
### 732 **Author Contributions**

733 S.S., L.B., R.M.M. and B.L. designed the research, S.S., L.B., Y.M.Y.I. and C.J. performed  
734 experiments, S.Z.L., J.F.R. and J.P. developed the theoretical vertex and analytical model, S.S.,  
735 L.B. analysed data with help from I.P.J, M. K. helped with segmentation, Y.T. participated in  
736 discussions, P.M. provided the BISM code and helped with the analysis, S.S., L.B., S.Z.L.,  
737 J.F.R., R.M.M. and B.L wrote the paper, J.F.R., R.M.M. and B.L. oversaw the project. All  
738 authors read the manuscript and commented on it.  
739

### 740 **Code Availability Statement**

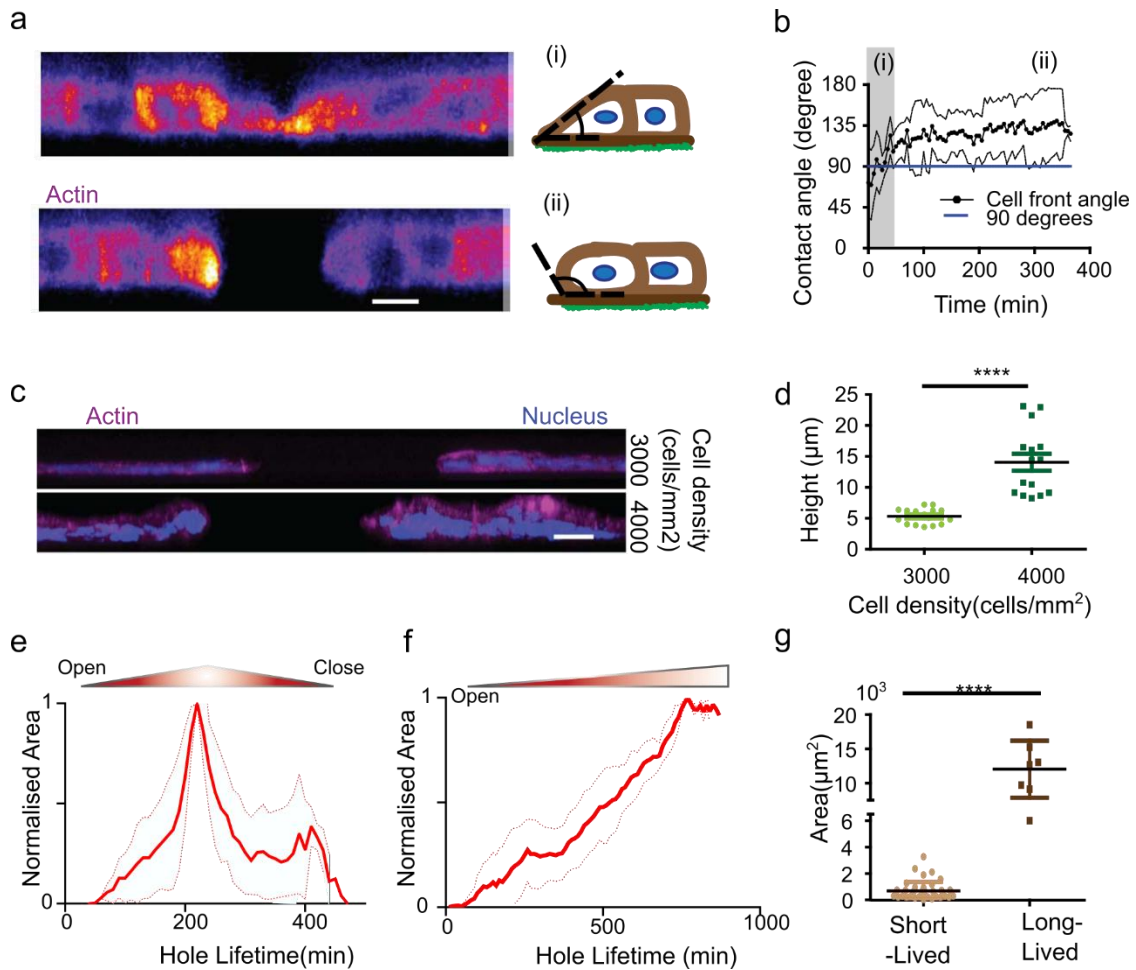
741 Codes used in this manuscript will be available upon request.

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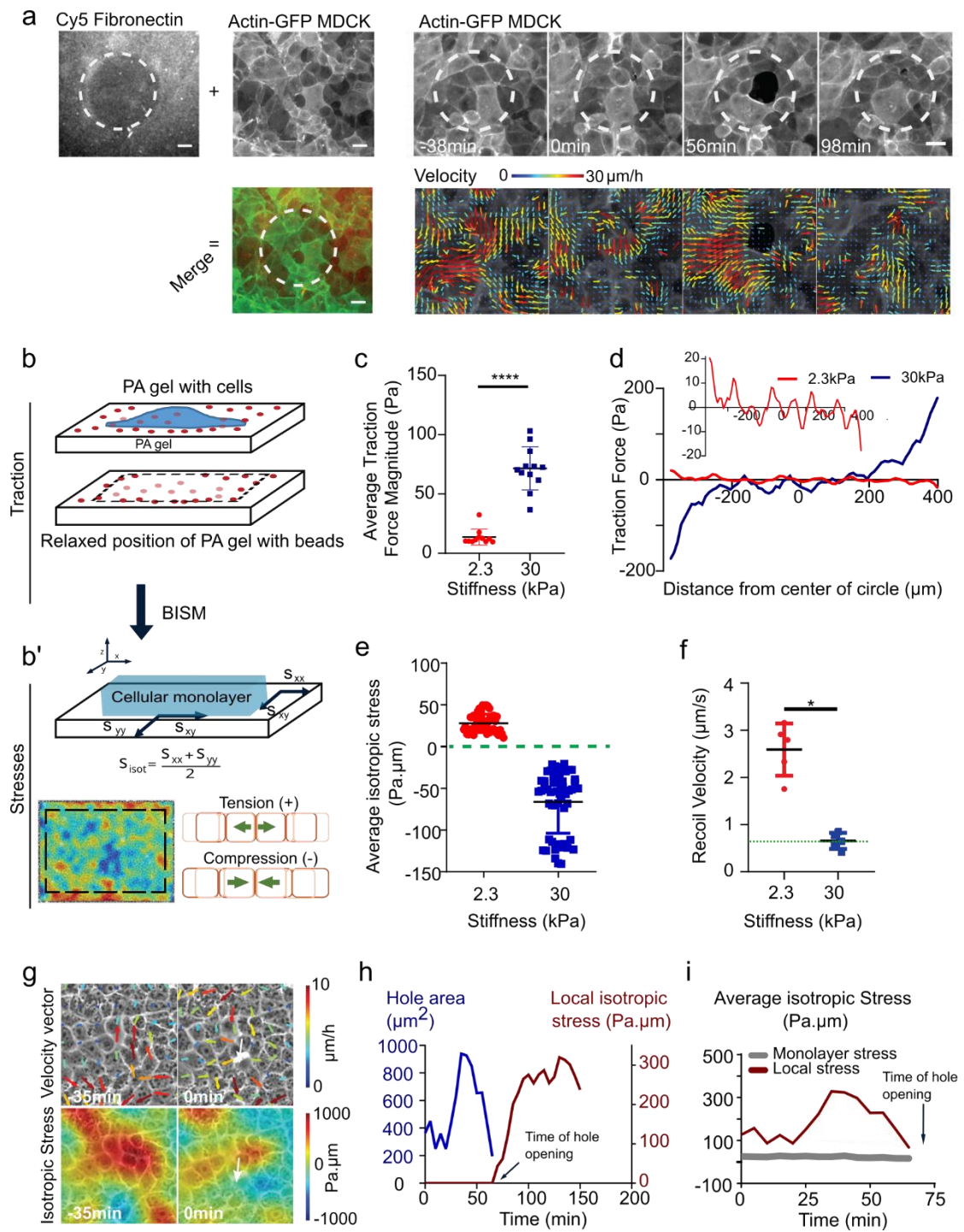
**Figure 1| Rigidity based hole formation within MDCK monolayers.** (a) Time course of hole formation in an unconfined MDCK monolayer on 2.3kPa and 55kPa PA gels. Red arrows show the holes formed within the monolayer (Scale: 50 $\mu$ m) (b) Schematic of the process of fibronectin patterning on PA gels; top: fibronectin coating on coverslips patterned through deep UV; middle: PA gel is placed between patterned and silanized coverslips; bottom: MDCK cells are seeded on patterned PA gel. (c) Time based montage of MDCK cells forming holes on 2.3kPa PA gels (top panel) and intact monolayers on 55kPa gels (bottom panel). Red arrows show the holes formed in the monolayer (Scale: 100 $\mu$ m). (d) Likelihood of hole formation as a function of PA gel stiffness ( $n_{2.3} = 23$ ,  $n_{4.1\text{kPa}} = 23$ ,  $n_{8.6\text{kPa}} = 24$ ,  $n_{16.3\text{kPa}} = 8$ ,  $n_{30\text{kPa}} = 7$  and  $n_{55\text{kPa}} = 15$  different circles; \*\*\*\* $p < 0.001$ , \*\*\*\* $p < 0.0001$ ) (e) The number of holes formed as a function of cell density on untreated and mitomycin C treated monolayers on soft (2.3kPa) substrates and monolayers on stiff (55kPa) substrates averaged over  $n = 22$  circles and  $n = 10$  circles for untreated and mitomycin treated samples on 2.3kPa and  $n = 14$  circles for 55kPa. (f) The number of holes formed within untreated and mitomycin-c treated circles on soft (2.3kPa) gels. ( $n_{\text{ctrl}} = 33$ ,  $n_{\text{mito}} = 44$ , \* $p < 0.05$ ). All results were obtained from 2 independent experiments and solid bars represent mean and error bars standard deviation.

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**Figure 2| Hole characteristics.** (a) Cross-sectional view of actin-GFP MDCK cells before (top panel) and after (bottom panel) hole formation on soft (2.3kPa) substrates (Scale: 10 μm) (b) Change of contact angle over time ( $t_0$  = initiation of hole) as the hole grows. Blue line represents 90° on the y-axis. ( $n = 6$  different circles) where (i) and (ii) illustrate the regions (i) and (ii) in panel a (c) Illustration of cell density change around the hole periphery on soft (2.3kPa) substrates (d) Post-hole formation, increase in cell density does not contribute to hole closure ( $n_{3000} = 16$  different circles and  $n_{4000} = 15$  different circles; \*\*\*\* $p < 0.0001$ ). (Scale: 20 μm) (e, f) Time dependent change in hole area normalized over maximum area of the hole for experiment and simulation of (e) short-lived holes (<5hr) ( $n = 36$  different circles) and (f) long-lived hole (>5hr) ( $n = 9$  different circles in experiment) on soft (2.3kPa) substrates from 2 independent experiments. (g) Maximal hole opening area for short-lived ( $n = 42$  different circles) and long-lived holes ( $n = 7$  different circles) from 2 independent experiments (\*\*\*\* $p < 0.0001$ ). Solid lines represent mean and error bars represent standard deviation.

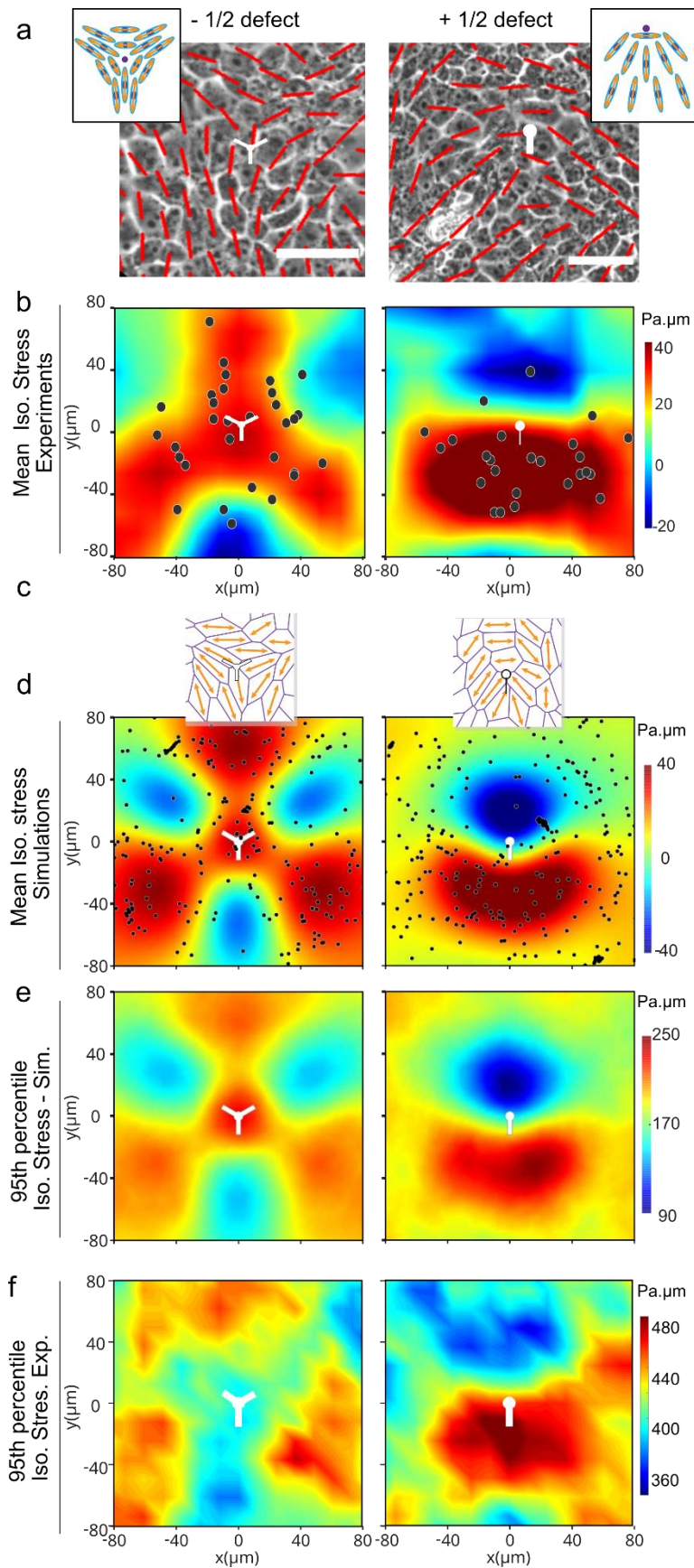
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**Figure 3| Substrate stiffness modulates tissue stress within MDCK monolayers.** (a) Actin GFP monolayer on a soft (2.3kPa) substrate with differential coating of fibronectin with 100  $\mu\text{m}$  circular islands of 50 $\mu\text{g/ml}$  and surroundings with 200 $\mu\text{g/ml}$  allows holes formation in regions of low fibronectin coating. Velocity maps show movement of cells towards the high fibronectin coated spaces. (scale: 20 $\mu\text{m}$ ) (b) Schematic showing the method of measurement of traction forces and inferred stress (c) Average traction force magnitude increases in MDCK monolayer on soft (2.3kPa) and stiff (30kPa) substrates ( $n = 114$  time averaged for  $n_{2.3\text{kPa}} = 11$  different circles, 3 independent experiments &  $n = 183$  time averaged for  $n_{30\text{kPa}} = 12$  different circles, 2 independent experiments; \*\*\*\* $p < 0.0001$ ) (d) Representative graph of a confined monolayer shows that traction forces are oppositely directed on soft (2.3kPa) and stiff (30kPa) gels along the diameter of the circle (e) Average isotropic stress for no-hole regions of confined monolayers on 2.3kPa and 30kPa substrates. Green dashed line represents 0 Pa. $\mu\text{m}$  on the y-axis ( $n = 50$  time averaged for  $n_{2.3\text{kPa}} = 10$  different circles, 3 independent experiments &  $n = 52$  time averaged for  $n_{30\text{kPa}} = 8$  different circles, 2 independent experiments; \*\*\*\* $p < 0.0001$ , \*\*\*\* $p < 0.0001$ ) (f) Recoil velocity after laser ablation of the MDCK monolayers grown on substrates of different stiffnesses. Green dashed line indicated the noise in the recoil velocity measurements ( $\sim 0.6 \mu\text{m/sec}$ ) ( $n_{2.3\text{kPa}} = 5$  &  $n_{55\text{kPa}} = 5$  different circles; \* $p < 0.05$ ) (g) Velocity vectors (top) and isotropic stress (bottom) before and during hole formation in a local region obtained from experiments on 2.3kPa PA gels. Color bar represents the respective scale bar for the values of the particular measurement and white arrow indicates the location of hole formation. (h) Change in isotropic stress (blue) in a local region near a hole and the change in area of a hole (red) as a function of time (additional trajectories are provided in Extended Figure 3). (i) Isotropic stress of the entire monolayer (grey) and isotropic stress in a local region (red) containing the hole as a function of time until the hole is formed on soft (2.3kPa substrates). Solid lines indicate mean values and error bars the standard deviation.

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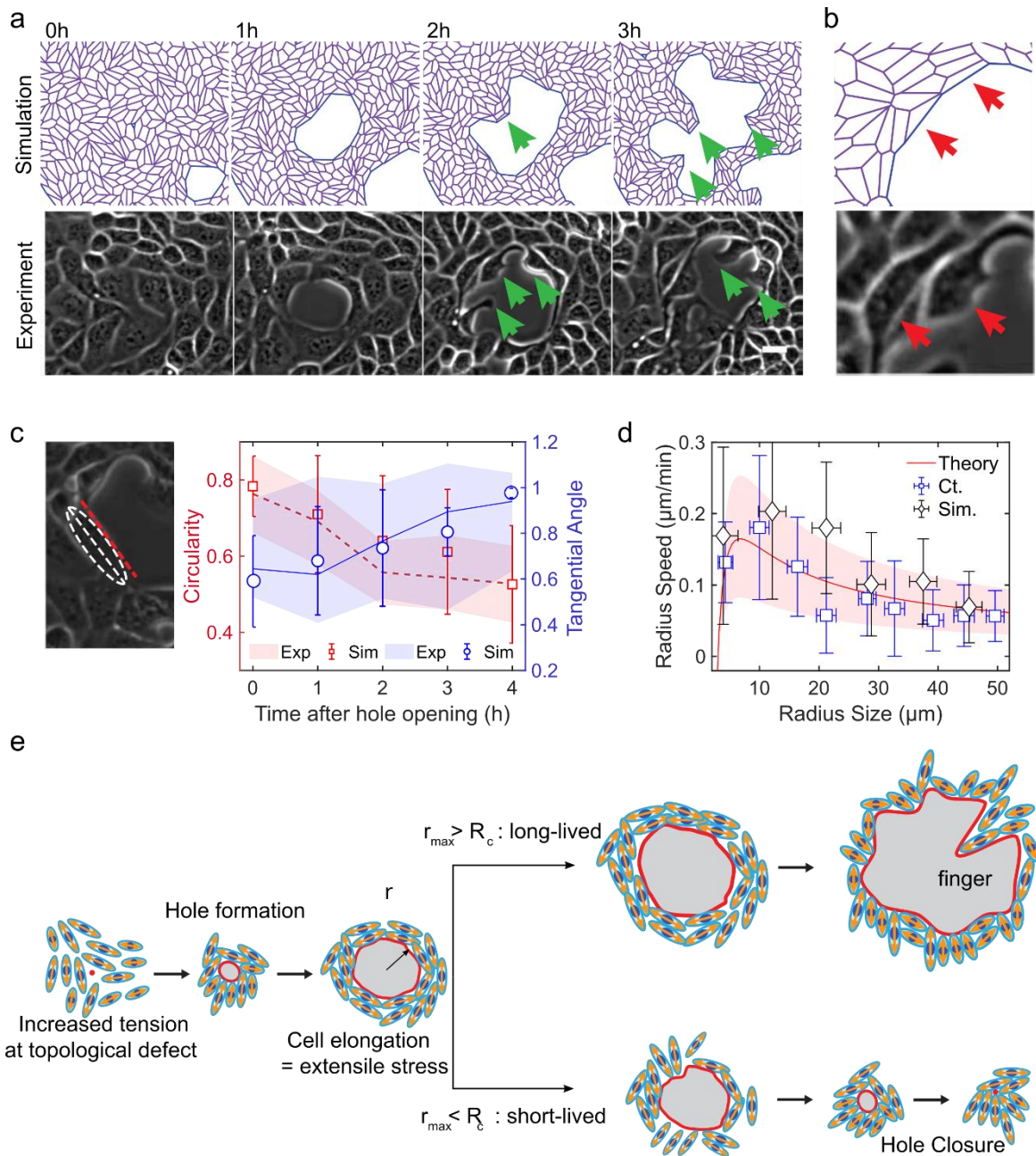


**Figure 4| Hole formation is triggered by tensile stresses around topological defects.**

**(a)** Orientation field overlaid over phase contrast images obtained from experiments on soft ( $2.3\text{kPa}$ ) substrates representing  $-1/2$  defect (left column) and  $+1/2$  defect (right column). Scale bar:  $50\mu\text{m}$ . **(b)** Averaged isotropic stress overlaid with location of hole initiation events with respect to the defect for (left)  $-1/2$  defects ( $n=2810$  defects and  $n=35$  holes) (right)  $+1/2$  defects ( $n=2924$  defects and  $n=20$  holes) obtained from experiments. **(c)** Typical cell orientation and topological defect detected in our vertex model simulation **(d)** Averaged isotropic stress overlaid with location of hole initiation events with respect to the defect for (left)  $-1/2$  defects ( $n=8555$  defects and  $n=1302$  holes) (right)  $+1/2$  defects ( $n=8553$  defects and  $n=1371$  holes) obtained from vertex model. **(e, f)** 95<sup>th</sup> percentile of isotropic stress around  $-1/2$  defects (left) and  $+1/2$  defects (right) obtained from vertex simulations **(e)** and experiments **(f)**. Experimental results were obtained on soft ( $2.3\text{kPa}$ ) substrates. White dots represent center of the defect and scale bars represent limits of stress values in Pa. $\mu\text{m}$

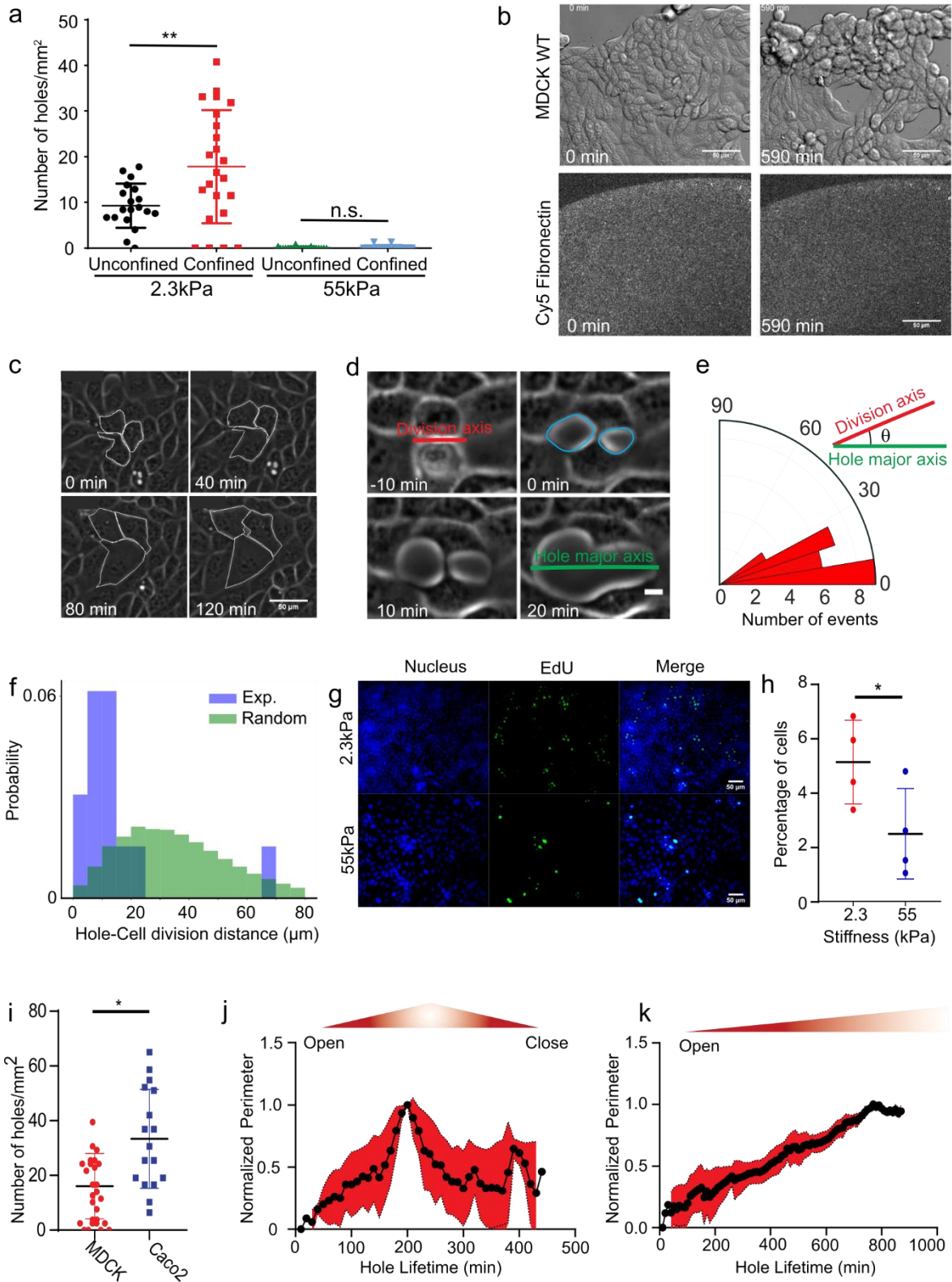


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**Figure 5 | Characterization of hole dynamics and cells around the hole.** (a) Finger-like projections (green arrows) formed along the hole periphery both in simulations (top) and experiments (bottom). (b) Elongation of cells around the hole obtained from simulations (top) and experiments (bottom) on soft (2.3kPa) substrates (c) Morphometrics of cells along the hole periphery: circularity (red, defined as  $C = 4\pi AP^2$ , where  $A$  = area and  $P$  = perimeter;  $C = 1$  for a circle) and tangential orientation (blue; cosine of the angle between the cell major axis and the tangent direction to the hole; 1 if parallel to the local hole tangent) obtained from experiments ( $n=14$  circles from 2 independent experiments) and simulations (dashed/solid lines for the mean circularity/tangential direction. Shaded areas represent standard deviation,  $n = 10$ ). (d) Rate of hole opening as a function of the hole size defined as  $R = \sqrt{A/\pi}$  in control experiments on soft 2.3kPa substrates (mean: blue square; ; errorbar: half-variance;  $n_{\text{expt}} = 10$  holes) and simulations (black diamond; errorbar: half-variance;  $n_{\text{sim}} = 10$  holes; soft case parameters, see SI) and the analytical expression Eq. (1) (solid red line for  $\xi = 50 \text{ Pa}\cdot\mu\text{m}^{-1}\cdot\text{min}$ ; shaded red area in between  $\xi = 30$  and  $\xi = 200 \text{ Pa}\cdot\mu\text{m}^{-1}\cdot\text{min}$ ) (e) Schematic representing the process of hole opening. Orange arrows represent extensile activity of each particle, red spots the location of hole opening and red line represents hole boundary.

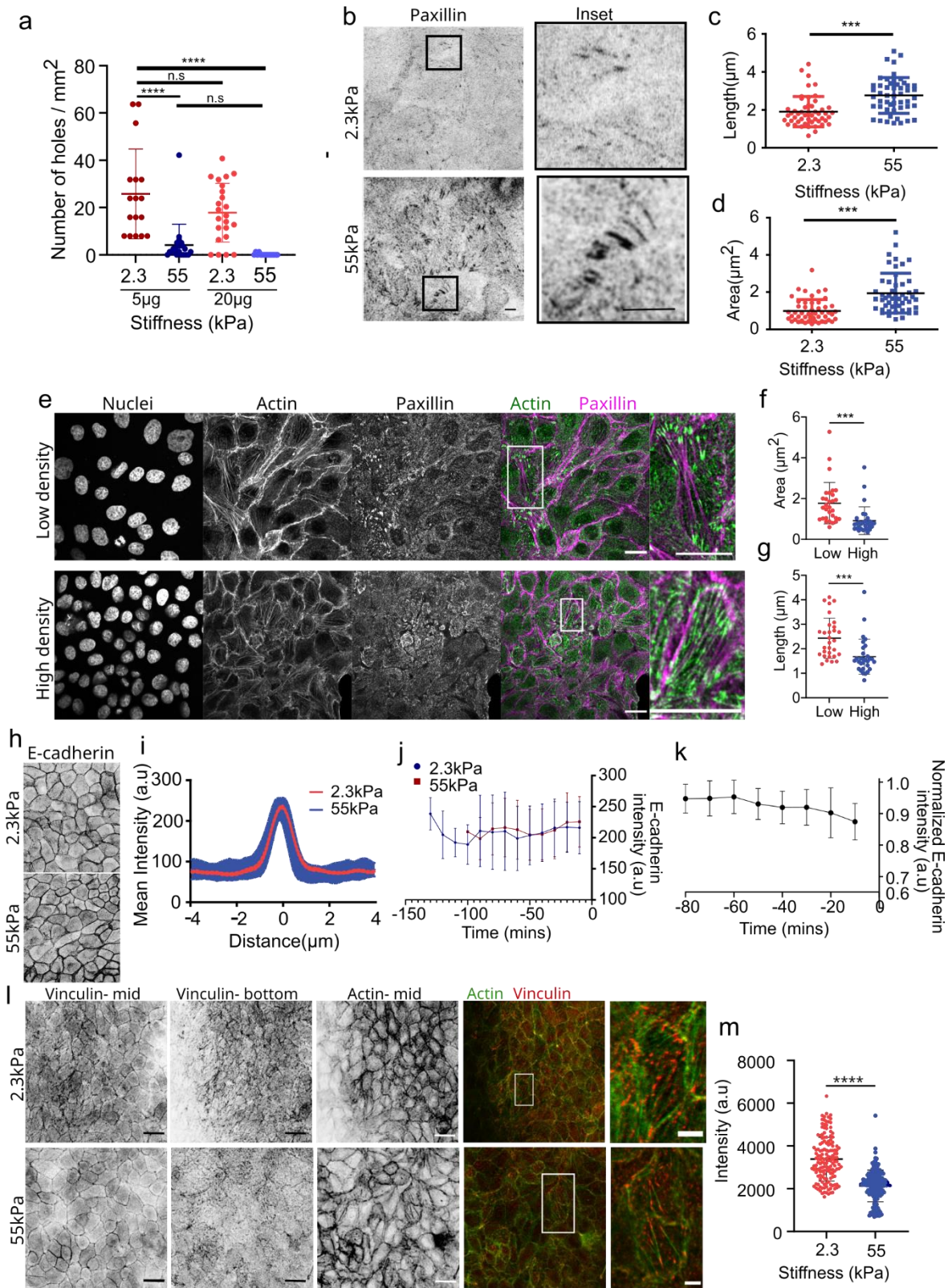
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**Extended Figure 1| Hole formation is a dynamic process influenced by cell division.** (a) Number of holes formed on unconfined and confined monolayers on 2.3kPa and 55kPa gels. (For confined,  $n_{2.3kPa} = 23$  and  $n_{55kPa} = 15$ . For unconfined  $n_{2.3kPa} = 19$  and  $n_{55kPa} = 19$ , \*\*\*\* $p < 0.0001$ ) (b) Hole formation in PA gels (2.3kPa) evenly coated with fibronectin. Fibronectin coating before and after the hole formation does not change. (Scale: 50  $\mu\text{m}$ ) (c) Representative image of hole formation due to cell stretching on soft (2.3kPa) substrates (Scale: 10  $\mu\text{m}$ ) (d) Illustration of hole formation after a cell division event (Scale: 5  $\mu\text{m}$ ). Red line represents the division axis, green line, hole major axis and yellow dots the location of hole formation. (e) Angle of division axis in degree with respect to the hole major axis ( $n = 20$  holes from 3 independent experiments) on soft (2.3kPa) substrates. Green line represents major axis of the hole and red line the division axis. (f) Probability distribution as a function of distance from a newly nucleated hole to the nearest cell division within 25mins of hole nucleation on soft (2.3kPa) substrates, blue, experiments ( $n = 14$  holes), green, simulation with cell divisions at random locations (identical number of divisions as in experiments). (g) Representative immunostaining images of EdU positive cells on 2.3 kPa and 55 kPa substrates. (h) Percentage of cells stained positive for EdU (marker of proliferation) on 2.3 kPa and 55kPa substrates ( $n_{2.3kPa} = 4$  and  $n_{55kPa} = 4$  on 2 independent experiments, \* $p < 0.05$ ) (i) Number of holes formed in a circular monolayer of MDCK ( $n = 33$  different circles) and Caco2 ( $n = 17$  different circles, \* $p < 0.05$ ) on soft (2.3kPa) substrates from 2 independent experiments. (j, k) Change in perimeter as a function of time for (j) short-lived ( $n = 35$  holes from 3 independent experiments) and (k) long-lived holes ( $n = 9$  holes from 3 independent experiments) on soft (2.3kPa) substrates. Solid lines represent mean and error bars the standard deviation.

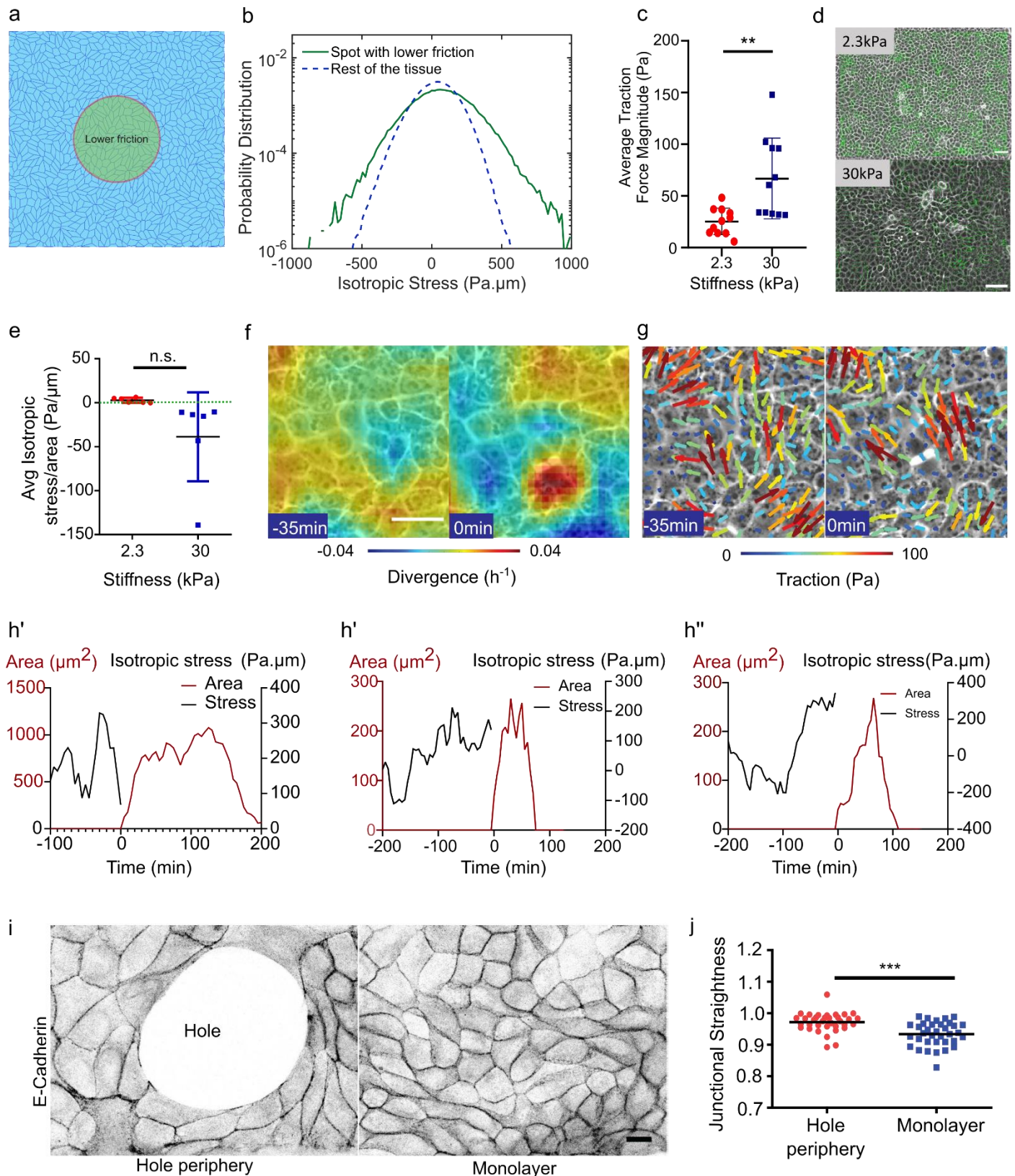
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**Extended Figure 2| Rigidity alters focal adhesions but not cell-cell adhesions.** (a) Number of holes formed/mm<sup>2</sup> on different concentration of fibronectin coated samples ( $n_{2.3kPa-5\mu g}=17$ ,  $n_{55kPa-5\mu g}=23$ ,  $n_{2.3kPa-20\mu g}=23$ ,  $n_{55kPa-20\mu g}=15$ ). (b) Paxillin staining for focal adhesions formed within a MDCK monolayer on 2.3kPa (top) and 55kPa (bottom). Inset shows the zoomed image of the representative focal adhesions. (Scale: 5  $\mu$ m) (c) Length ( $n = 69$  from 2 independent experiments circles; \*\*\* $p < 0.001$ ) and (d) area ( $n = 50$  from 2 independent experiments; \*\*\* $p < 0.001$ ) of focal adhesion on 2.3kPa and 55kPa gels. (e, f, g) Immunostaining of actin (green) and paxillin (magenta) on monolayers grown on glass at low (top) and high (bottom) density and the (f, g) quantification of area (f) and length (g) of paxillin at these two different densities for  $n=30$  focal adhesions. Scale: 20 $\mu$ m (h) E-cadherin localization at junctions on 2.3kPa and 55kPa gels. (Scale: 10 $\mu$ m) (i) Mean intensity plot of E-cadherin localization at junctions ( $n = 30$  from 2 independent experiments) (j) Averaged E-cadherin intensity of new junctions formed after a cell division event on soft (2.3kPa) and stiff (55kPa) substrates for  $n=33$  division events from 2 independent samples for each condition. (k) Averaged E-cadherin intensity over time just before hole formation on soft (2.3kPa) substrates ( $n=12$  junctions from 2 independent experiments). (l) Immunostaining of vinculin (red) and actin (green) of monolayers grown on soft (2.3kPa) and stiff (50kPa) substrates. (m) Quantification of vinculin intensity at cell junctions obtained from  $n_{2.3kPa}=151$  and  $n_{55kPa}=166$  junctions from 2 independent experiments. Solid lines represent mean and error bars standard deviation.

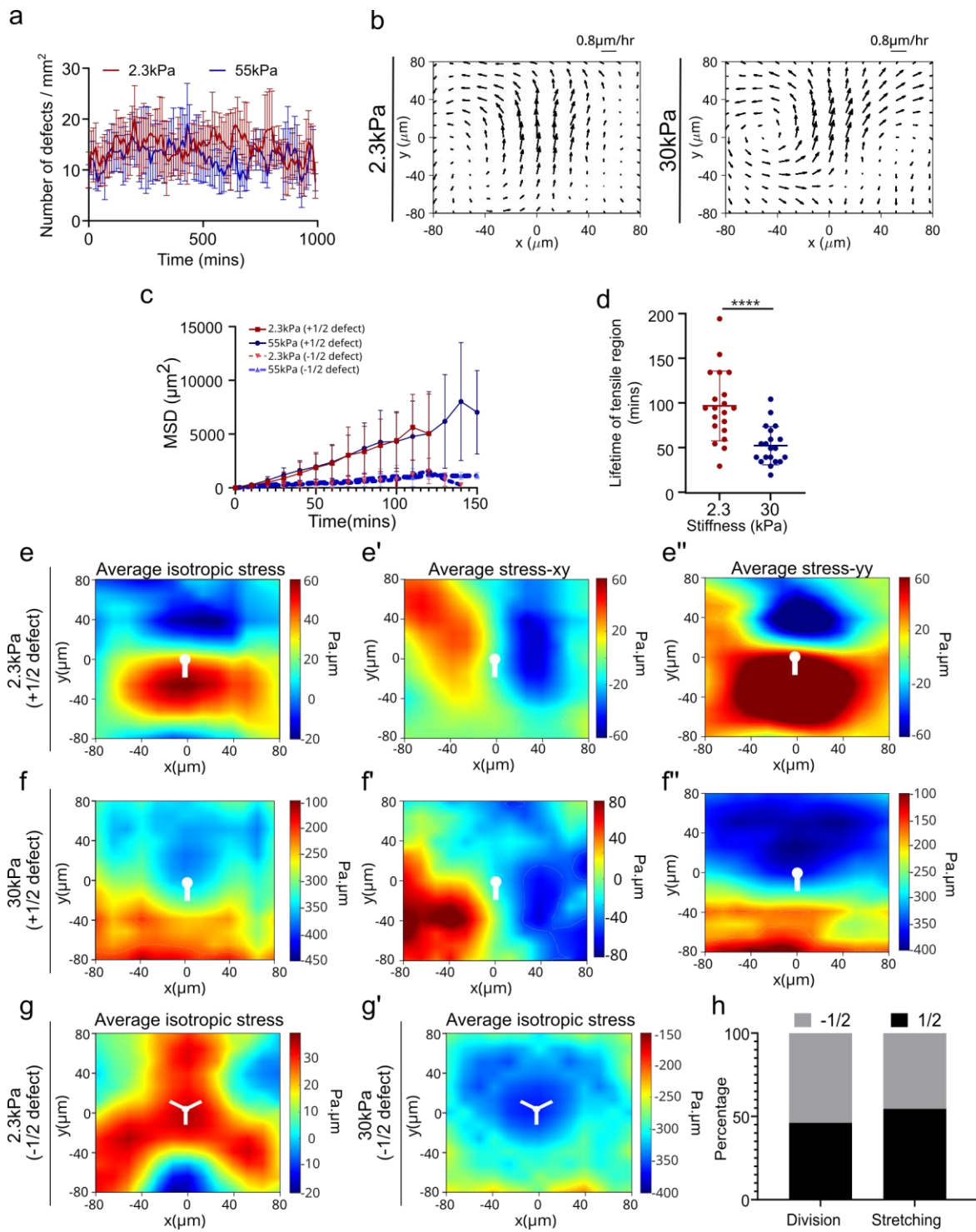
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**Extended Figure 3| Cell-substrate adhesion and tissue stress contributions in hole lifetime.** (a) Vertex-model for the differential fibronectin experiment (as Figure 3a), where a circular spot with a lower friction (green) region (10% of the friction in the rest of the tissue) mimics an area of low fibronectin concentration. (b) Probability distribution of isotropic stress per cell in the low friction region (green) as compared to rest of the tissue region (blue). Value of the isotropic stress in the spot with respect to rest of the tissue: mean = 87 Pa.μm (resp. 37 Pa.μm). 95th percentile value = 397 Pa.μm (resp. 240 Pa.μm) obtained from 10 independent simulations,  $n = 85,715$  cells within the spot and  $n = 422,347$  cells in the rest of the tissue. Simulation parameters are specified in Table 1, SI. (c) Average traction force magnitude in MDCK unconfined monolayers ( $n = 102$  time averaged for  $n_{2.3kPa} = 11$  different circles &  $n = 112$  time averaged for  $n_{30kPa} = 11$  different circles;  $**p < 0.05$  from 2 independent experiments). (d) Traction force quiver overlaid on phase contrast images for soft (2.3kPa, top) and stiff (30kPa, bottom) substrates. Scale: 100μm (e) Average isotropic stress for no-hole regions of unconfined monolayer on 2.3kPa and 30kPa PA gels. Green dashed line represents 0 Pa.μm on the y-axis (For unconfined,  $n_{2.3} = 12$  &  $n_{30} = 12$  different circles obtained from 2 independent experiments) (f-g) Divergence of the velocity field and traction forces overlaid on phase contrast images on 2.3kPa substrate prior to hole formation where white dot indicates location of hole formation. (h) Representative graphs of evolution in the hole area (red) and averaged local isotropic stress (black) around the hole initiation site as a function of the time where  $t=0$  indicates hole initiation on soft (2.3kPa) substrates. (i) E-cadherin localization at junctions around the hole and within the monolayer. (Scale: 10 μm) (j) Junctional straightness (ratio between Euclidean and actual lengths) around the holes and within the monolayer ( $n=35$  different circles;  $***p < 0.001$ ) on soft (2.3kPa) substrates. Error bars represent standard deviation.

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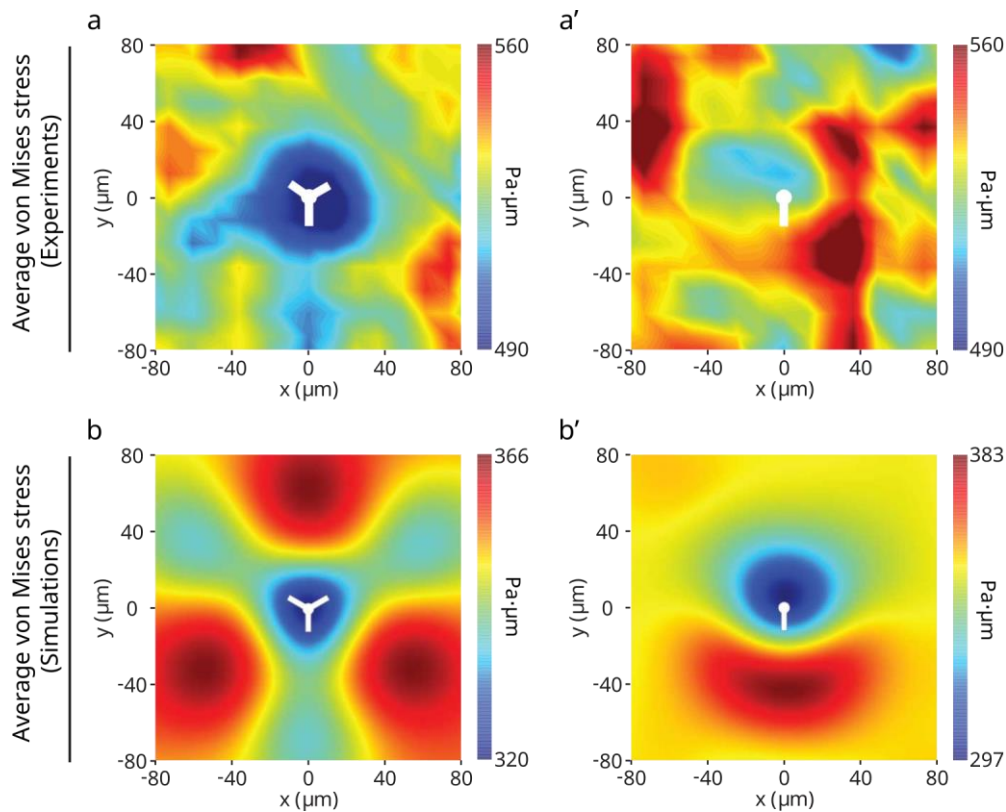




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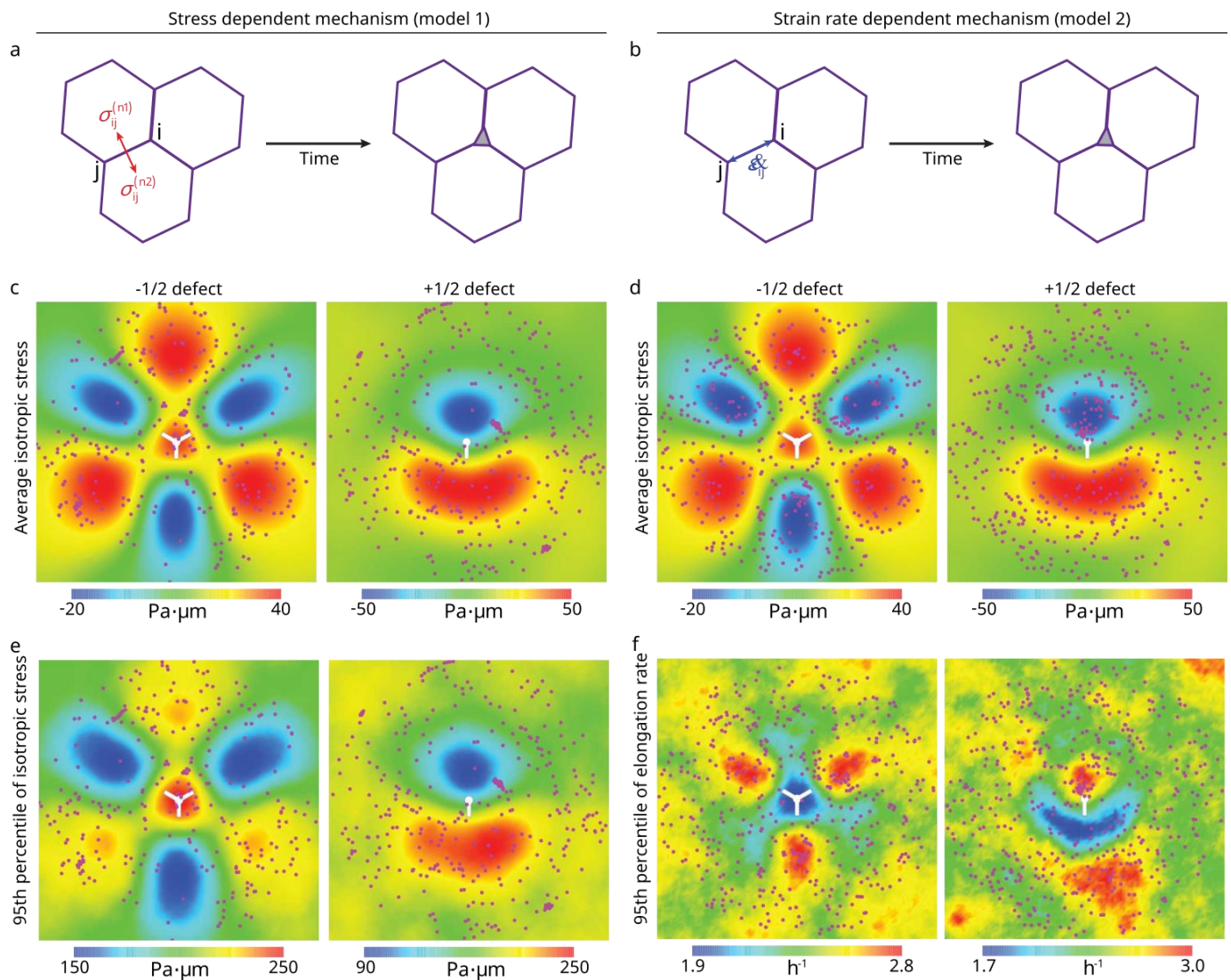
**Extended Figure 4| Hole formation around defects from experiments.** (a) Averaged number of defects on soft and stiff substrates obtained from  $n_{2.3kPa} = 6$  circles for soft (2.3kPa) substrates and  $n_{55kPa} = 5$  circles for stiff (55kPa) substrates. (b) Average velocity flow field around +1/2 defects demonstrating the extensile nature of MDCK monolayers on soft (2.3kPa) substrates ( $n=2646$  defects) and stiff (30kPa) substrates ( $n=2765$  defects) obtained from experiments. (c) MSD of +1/2 and -1/2 defects on both soft and stiff substrates ( $n=15$  defects for -1/2 defects and +1/2 defects on 55kPa and  $n=17$  defects for +1/2 defects on 2.3kPa substrates). (d) Lifetime of random tensile regions on both soft (2.3kPa) and stiff (30kPa) regions obtained from TFM for  $n=30$  regions (e, f) Averaged isotropic stress, averaged stress  $\sigma_{xy}$  (e', f') and averaged stress  $\sigma_{yy}$  (e'', f'') around +1/2 defects on soft (2.3kPa) substrates (e, e', e'') ( $n = 2924$  defects) and stiff (30kPa) substrates (f, f', f'') ( $n = 3632$  defects) from 2 independent experiments. (g, g') Averaged isotropic stress around -1/2 defects on (g) soft (2.3kPa) substrate ( $n = 2810$  defects) and (g') stiff (30kPa) substrates ( $n = 3716$  defects) from 2 independent experiments. White dots indicate the location of the defect core. (h) Percentage of +/- 1/2 linked division and stretched cell linked hole formation on 2.3kPa gels ( $n_{-1/2(\text{cell division})}=7$ ,  $n_{+1/2(\text{cell division})}=6$ ,  $n_{-1/2(\text{stretching})}=5$ ,  $n_{+1/2(\text{stretching})}=6$ ). All results were obtained from 2 independent experiments and error bars represent standard deviation.

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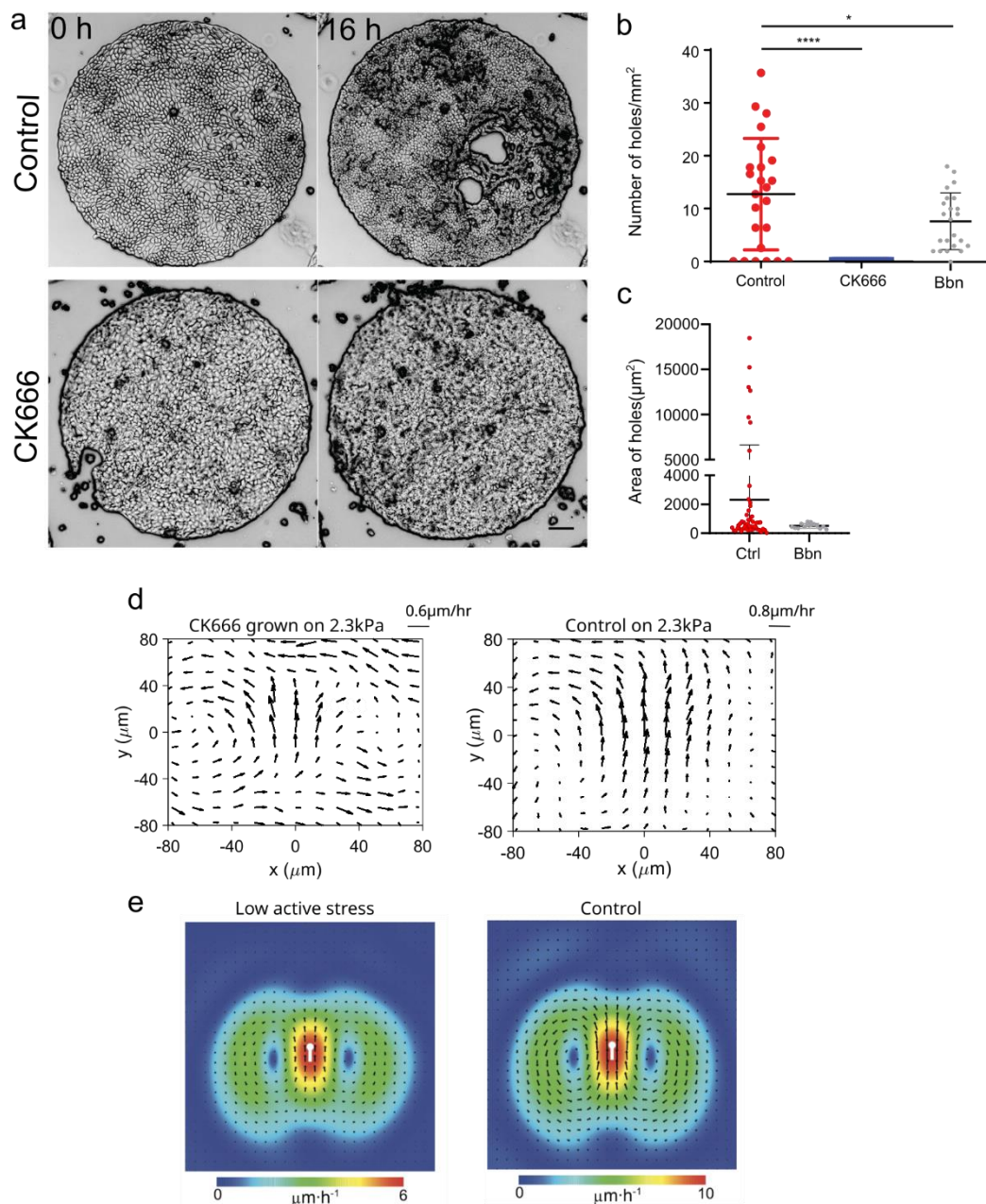
**Extended Figure 5 | Maps of the average von Mises stress near half-integer topological defects. (a, a')** Experiments: (a)  $-1/2$  defects ( $n = 2810$ ); (a')  $+1/2$  defects ( $n = 2924$ ). (b, b') Simulations: (b)  $-1/2$  defects ( $n = 8555$ ); (b')  $+1/2$  defects ( $n = 8553$ ) obtained from 2 independent experiments. White dots represent centre of the defects.

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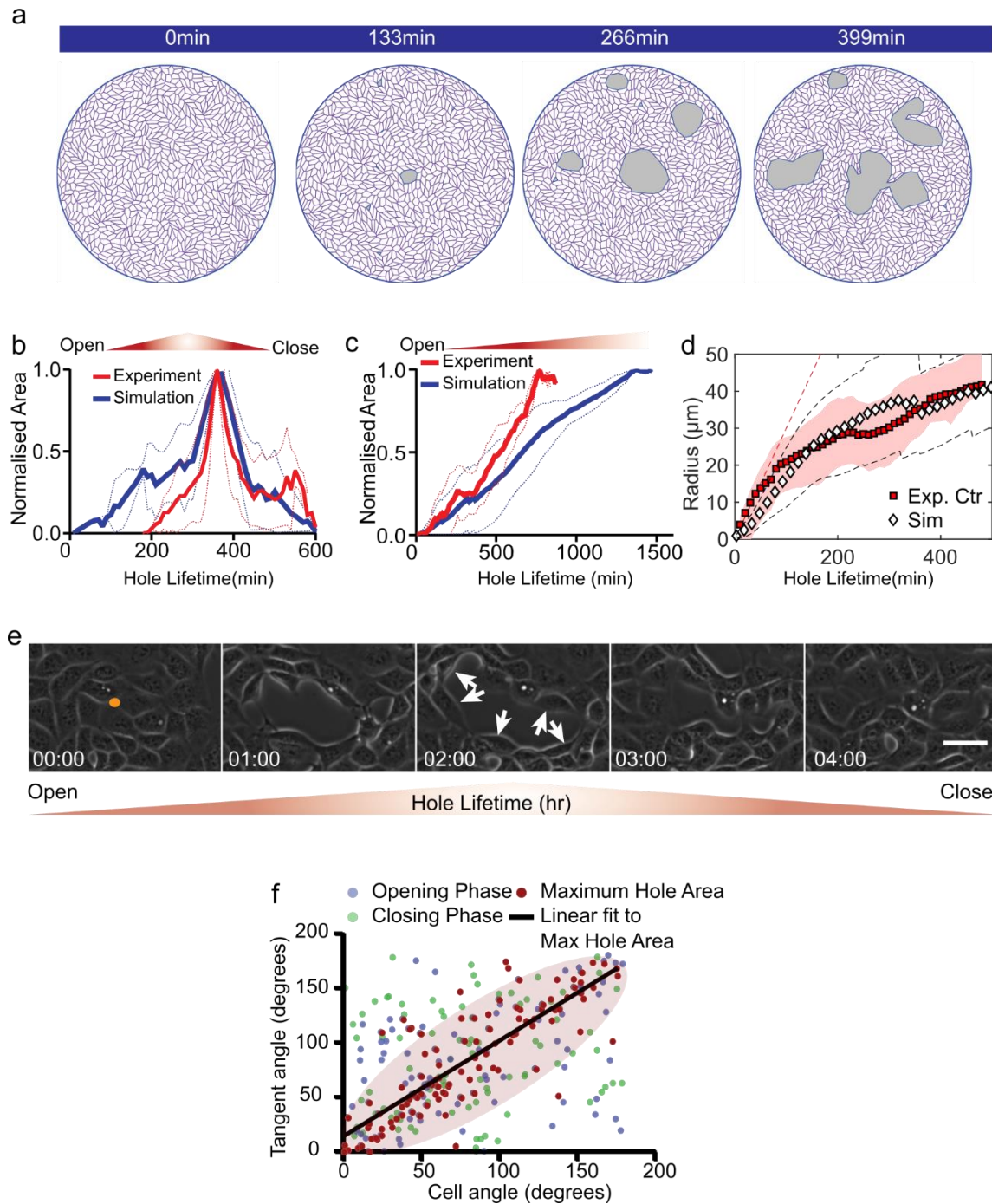
**Extended Figure 6 | Stress maps and hole opening locations near topological defects.** (a, b) Sketches of the two mechanisms of hole initiation: (a) stress dependent mechanism (model 1) and (b) strain rate dependent mechanism (model 2). (c-f) Comparisons of maps of hole opening locations near half-integer topological defects: (c, e) model 1 and (d, f) model 2. The magenta spots indicate the locations of opening holes. The 95th percentile is the value below 95% of cellular isotropic stress (or the junctional elongation rate) field frequency distribution falls. Domain size = 200 $\mu\text{m}$ . These simulations were generated for tension initial conditions (soft gel case, see Table 1 SI).

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**Extended Figure 7 | Activity and tension drives hole formation.** (a) Inhibition of arp2/3 by 100 μM CK666 treatment prevents hole formation on 2.3 kPa gels (Scale: 100 μm) (b) Number of holes/mm<sup>2</sup> under control, CK666 and blebbistatin (5μM) treated samples averaged over n=33 for control, n = 24 for CK666 and n=23 for blebbistatin (\*\*\*\*p < 0.0001) (c) Area of holes formed under control (n=49) and 5μM blebbistatin treated (n=14) samples (d) Averaged velocity profile around +1/2 defects with CK666 treatment (left) (n<sub>CK666</sub>=2294) and WT (right) (n<sub>WT</sub>=2646) monolayers on soft (2.3kPa) substrates (e) Simulations with a lower active stress (left; n = 4750 defects) as compared to the control case (right; n = 8553 defects).

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**Extended Figure 8 | Lifetime of holes and cell organization around hole periphery** (a) Time-lapse of a typical tissue-scale vertex model simulation (b,c) Time dependent change in hole area normalized over maximum area of the hole for simulation of (b) short-lived holes (<5hr) ( $n = 9$  different simulations) and (c) long-lived holes ( $n = 9$  different simulations) (d) Evolution in the estimated hole radii in experiments, mean (red squares)  $\pm$  standard deviation (red shaded area) and simulations, mean (black diamonds)  $\pm$  standard deviation (black dashed lines);  $n=14$  in experiments and  $n=10$  in simulations. (e) Time-lapse of a typical opening and closing process on soft (2.3kPa) substrates. (f) Cell alignment along the tangent of the hole obtained from experiments is highly co-related during the maximum hole area. Scatter plot between cell angle and tangent angle shows the distribution during hole opening phase (blue dots), maximum hole area (red dots) and hole closing phase (green dots). A linear line (black line) fits to the maximum hole area distribution with a Pearson's co-efficient,  $r = 0.83$  and slope = 0.877. Majority of the maximum hole area data falls inside the pink ellipsoid area showing the small spread of their distribution.

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