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Olivier Destaing, Emmanuelle Planus, Daniel Bouvard, Christiane I. Oddou, Cedric Badowski, et al..  $\beta$ 1A integrin is a master regulator of invadosome organization and function.:  $\beta$ 1 integrin control of invadosomes. *Molecular Biology of the Cell*, 2010, 21 (23), pp.4108-19. 10.1091/mbc.E10-07-0580 . inserm-00529654

**HAL Id: inserm-00529654**

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Submitted on 26 Oct 2010

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MBoC manuscript : E10-07-0580R in press

## **$\beta$ 1A integrin is a master regulator of invadosome organization and function**

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**Running title:**  $\beta$ 1 integrin control of invadosomes

**Keywords:** ECM degradation/integrins/invadopodia//PKC/podosomes

**ABSTRACT**

Invadosomes are adhesion structures involved in tissue invasion, characterized by an intense actin polymerization/depolymerization associated with  $\beta 1$  and  $\beta 3$  integrins and coupled to extracellular matrix degradation (ECM) activity. We induced the formation of invadosomes by expressing the constitutive active form of Src, SrcYF, in different cell types. Use of ECM surfaces micropatterned at the subcellular scale clearly showed that in mesenchymal cells, integrin signaling controls invadosome activity. Using  $\beta 1^{-/-}$  or  $\beta 3^{-/-}$  cells, it appeared that  $\beta 1A$  but not  $\beta 3$  integrins are essential for initiation of invadosome formation. PKC activity was shown to regulate auto-assembly of invadosomes into a ring-like meta-structure (rosette), likely by phosphorylation of S785 on the  $\beta 1A$  tail. Moreover, our study clearly showed that  $\beta 1A$  links actin dynamics and ECM degradation in invadosomes. Finally, a new strategy based on fusion of the photosensitizer KillerRed to the  $\beta 1A$  cytoplasmic domain allowed specific and immediate loss of function of  $\beta 1A$ , resulting in disorganization and disassembly of invadosomes and formation of focal adhesions.

## INTRODUCTION

Invadosome is a general term for structures implicated in tissue invasion processes that share similarities in organization, composition, dynamics, or function with podosomes, present in non-transformed cells (such as macrophages, osteoclasts, dendritic cells, endothelial cells, and smooth muscle cells), or invadopodia, present in cancer cells. This class of structure can be simply defined as an adhesion structure centered on an actin column, where intense actin activity takes place, and linked with localized extracellular matrix (ECM) degradation activity. Invadosomes can form isolated dot-like structures centered on a rapidly polymerizing actin column associated with actin regulators (such as cortactin, WASP, Rho GTPases, and fascin), adhesion molecules (such as paxillin, talin, and integrins), regulators of membrane dynamics (such as Tsk5, IQGAP, and VAMP7), metalloproteases, and regulatory kinases (such as FAK/Pyk2, PAK, and Src) (Linder and Aepfelbacher, 2003; Weaver, 2006; Ory *et al.*, 2008; Vignjevic and Montagnac, 2008; Albiges-Rizo *et al.*, 2009; Poincloux *et al.*, 2009). Moreover, like podosomes, invadosomes have the capacity to self-assemble into round meta-structures known as rosettes or rings, which can expand in diameter and fuse with each other. This treadmilling behavior is based on the coordinated assembly of new, individual actin columns, connected to each other by a “cloud” of F-actin at the outer rim, with disassembly of the original structure occurring at the inner rim of the rosette (Destaing *et al.*, 2003; Destaing *et al.*, 2005; Jurdic *et al.*, 2006; Badowski *et al.*, 2008).

Invadosomes were originally described in cells expressing the oncogene v-Src and have been reported in many subsequent studies (Marchisio *et al.*, 1984; Tarone *et al.*, 1985; Mueller *et al.*, 1992; Linder and Aepfelbacher, 2003; Bowden *et al.*, 2006). The essential role of the non-receptor tyrosine kinase c-Src in podosomes has been shown in Src<sup>-/-</sup> osteoclasts, where reduced bone resorption is associated with poorly functioning podosomes (Yoneda *et al.*, 1993; Hall *et al.*, 1994). The action of c-Src in podosomes is complex and essential for

initiation of podosome assembly, intensity of the actin flux, and architecture and disassembly of the structure (Luxenburg *et al.*, 2006; Ayala *et al.*, 2008; Destaing *et al.*, 2008). These adhesion structures can also be induced by activation of PKCs by Phorbol ester treatment, suggesting a synergistic activity of this pathway with the tyrosine kinase Src (Hai *et al.*, 2002; Tatin *et al.*, 2006).

Thus, it appears that both invadosome formation and self-assembly involve an inside-out signaling process. The question of which specific stimuli from the external environment (those participating in outside-in signaling) are able to induce invadosome formation remains unanswered. This led us to explore the functions of the integrin receptor families in the regulation of invadosome activity since these receptors integrate the composition, concentration, and compliance of the ECM. Integrins are heterodimers that oscillate between conformations having low and high affinity for the ECM. This switch corresponds to integrin activation and is favored by the disruption of the salt bridge between the  $\alpha$  and  $\beta$  subunits induced by talin interaction with the  $\beta$  cytosolic domain of the integrin molecules (Shattil *et al.*, 2010). Moreover, this class of proteins has a strong link with ECM degradation, interacting directly with the membrane-associated metalloprotease MT1-MMP (also known as MMP14; (Galvez *et al.*, 2002). Although numerous studies have localized different integrins in podosomes and invadosomes, the specific functions of integrins in invadosomes have been poorly described. Indeed,  $\alpha\nu\beta3$  is found in osteoclast podosomes and in invadosomes/invadopodia in many cancer cells (Zambonin-Zallone *et al.*, 1989);  $\alpha3\beta1$  in 804G carcinoma cells (Spinardi *et al.*, 2004);  $\alpha4\beta1$  in monocyte podosomes and  $\beta2$  integrins in macrophage podosomes (Duong and Rodan, 2000); and  $\beta1$  integrins in osteoclast podosomes (Helfrich *et al.*, 1996). Due to the role of podosomes in bone resorption by osteoclasts, a major role was assigned to  $\alpha\nu\beta3$  integrin in this process based on the correlation between the strong increase in the expression of  $\alpha\nu\beta3$  and the formation of podosomes during

osteoclast differentiation (Mimura *et al.*, 1994; Pfaff and Jurdic, 2001; Destaing *et al.*, 2003; Jurdic *et al.*, 2006). Moreover, perturbation of  $\alpha v\beta 3$  integrin by disintegrin modulates osteoclast migration and podosome formation (Nakamura *et al.*, 1999; Blair *et al.*, 2009). However,  $\beta 3^{-/-}$  mice show only a slight increase in bone mass in comparison to  $\text{Src}^{-/-}$  osteoclasts, which are only associated with a disorganization of podosomes belts (McHugh *et al.*, 2000; Faccio *et al.*, 2003). In macrophages, Rho B inactivation results in decreased surface expression of integrins  $\beta 2$  and  $\beta 3$ , while  $\beta 1$  surface expression remains constant. However, modification of this integrin pattern does not affect podosome formation (Wheeler and Ridley, 2007). On the other hand, the importance of  $\beta 1$  in invadopodia was suggested by activation of these integrins by soluble antibody, which leads to an increase in ECM degradation (Nakahara *et al.*, 1998).

To clarify the role of integrins in invadosome formation, auto-assembly, and organization, we have induced them by the expression of a constitutively active Src mutant, SrcYF, in cells in which either the  $\beta 1$  or  $\beta 3$  gene has been deleted, and performed reverse genetic analysis by expression of exogenous wild-type or mutant human integrin chains. Surprisingly, invadosome initiation and auto-assembly into rings were found to be strictly dependent on ECM signaling through  $\beta 1$  and not  $\beta 3$  integrins despite the high concentration of  $\beta 3$  in these structures. Invadosome auto-assembly likely involves the phosphorylation of Ser785 on the  $\beta 1A$  cytosolic tail by PKC activity since PKC stimulation can be mimicked by the phosphomimetic mutants S785D or S785E. In addition, the modulation of  $\beta 1A$  affinity by expression of  $\beta 1A$  mutant in a genetic null background uncouples actin dynamics and the ECM-degradative activity of invadosomes. Finally, a new method to induce quick loss of function of  $\beta 1A$  by photo-inactivation revealed that this integrin also plays a key role in invadosome metastructure stabilization. Thus, it appears that  $\beta 1A$  is a key modulator of invadosome function in invasion processes.

## MATERIALS AND METHODS

### *Antibodies and reagents*

Antibodies for immunoblotting and immunofluorescence were obtained from the following commercial sources: rabbit anti-PhosphoTyr 418 Src and anti-phosphoTyr397 FAK (Invitrogen, Carlsbad, CA), mouse anti-Src (GD11, Millipore, Billerica, MA), mouse anti-actin (Sigma Aldrich, St. Louis, MO), mouse anti-paxillin (BD, Franklin Lakes, NJ), mouse anti-human  $\beta 1$  integrin (clone 4B7R, Beckton Dickinson, le Pont de Claix, France), and rat anti-mouse  $\beta 1$  integrin (MB1.2, Millipore, Fremont, CA), and rat anti-mouse  $\beta 3$  integrin (clone LucA5, Emfret Analytics, Würzburg, Germany).

Alexa 546-phalloidin, as well as Alexa 488, gelatin-Oregon green, and Alexa 488-, 546-, and 633-conjugated secondary antibodies were from Invitrogen.

### *Plasmids*

pEGFP-actin vector was from Clontech (Palo Alto, CA). pBabe GFP-paxillin was provided by Dr. M. Hiraishi (Department of Molecular Biology, Osaka Bioscience Institute, Suita, Osaka, Japan), pBabe RFP-cortactin was engineered from the initial constructs, pDsRed-N1-cortactin from Dr P. Jurdic (ENS Lyon, France) and pcDNA3-mRFP (Addgen, Cambridge, MA).

Plasmids pFB-Neo-human  $\beta 1$ -GFP, VASP-RFP, and pBabe-Src Y527F were the generous gifts of Dr Humphries (University of Manchester, Manchester, UK), Prof. Gertler (The David H. Koch Institute for Integrative Cancer Research, Massachusetts Institute of Technology, Cambridge, MA), and Dr K. Gil-Henn (Yale University, New Haven, CT), respectively.

For the pTRFP™ or KillerRed™-tagged human  $\beta 1$  construct, the pTRFP or KillerRed coding sequences were PCR-amplified from the original pTagRFP-N or pKillerRed-N vectors (Evrogen, Moscow, Russia) and used to replace GFP of pFB-Neo-human  $\beta 1$ -GFP to generate an in-frame C-terminal fusion. pCLMGF-human  $\beta 1$  WT, pCLMGF-human  $\beta 1$  L747R, pCLMGF-human  $\beta 1$  D759A, pCLMGF-human  $\beta 1$  S785A, and pCLMGF-human  $\beta 1$  S785E constructs were made using the QuikChange XL site-directed mutagenesis kit (Stratagene, La Jolla, CA, USA) using the following primer pairs:

D759A:            forward,            5'-gcttttaatgataattcatGCCagaagggagtttgc-3';            reverse,  
5'gcaaacctccttctGGCatgaattatcattaaaagc-3';  
S785D:            forward,            5'cgggtgaaaatcctatttataagGATgccgtaacaactgtgg-3';            reverse,  
5'ccacagttgttacggcATCcttataaataggattttcaccgc-3';  
S785E:            forward,            5'cgggtgaaaatcctatttataagGAGgccgtaacaactgtgg-3';            reverse,  
5'ccacagttgttacggcCTCcttataaataggattttcaccgc-3';

S785A: forward, 5'cgggtgaaaatcctatttataagGCTgccgtaacaactgtgg-3'; reverse, 5'ccacagtgttacggcAGCcttataaataggattttcacccg-3'

#### *Cell culture and infection*

MEF  $\beta 3^{+/+}$  and  $\beta 3^{-/-}$  cells were the generous gift of Dr. Richard Hynes (The David H. Koch Institute for Integrative Cancer Research, Massachusetts Institute of Technology, Cambridge, MA). Mouse embryonic fibroblasts (MEF) isolated from  $\beta 1^{\text{loxP/loxP}}$  mice between embryonic day 12 and postnatal day 1, as described recently (Ferguson *et al.*, 2009), were the generous gift of Prof. Reinhard Fässler (Max Planck Institute of Biochemistry, Martinsreid, Germany).

A population of primary, mouse osteoblast-enriched cells was isolated from newborn mouse calvaria using a mixture of 0.3 mg/ml collagenase type I (Sigma-Aldrich, St. Louis, MO) and 0.25% trypsin (Invitrogen), as described previously (Bellows *et al.*, 1986; Bouvard *et al.*, 2007). Cells were grown in  $\alpha$ -MEM containing 10% fetal calf serum (FCS). Primary osteoblasts (passage 2) were immortalized by transduction with a retrovirus expressing the large SV40 T antigen (Fassler *et al.*, 1995), cloned, and tested for their ability to express alkaline phosphatase upon differentiation (Mansukhani *et al.*, 2000), as previously described (Bouvard *et al.*, 2007). At least five clones from floxed mice were isolated. Rescue of  $\beta 1A$  integrin expression in cells was performed via retroviral infection using the pCLMFG- $\beta 1$  vectors, as previously described (Bouvard *et al.*, 2007; Millon-Fremillon *et al.*, 2008). Cells were grown in DMEM containing glutamine and supplemented with 10% FCS and 1% penicillin/streptomycin. Cre adenovirus was purchased from the University of Iowa Gene Transfer Vector Core (Iowa City, IA). Maximal  $\beta 1$  depletion was achieved within 4 d. Cells were generally used for experiments between 6 and 9 days after Cre recombinase delivery. In most experiments, cDNAs were delivered via retroviral transduction following packaging in Phoenix-Eco or Phoenix-Ampho cells (American Type Culture Collection, Manassas, VA). Supernatant containing viral particles from transduced cells was harvested, filtered, and, following addition of 8  $\mu\text{g/ml}$  polybrene (Sigma-Aldrich), was used to infect fibroblasts. For rescue experiments, cells were infected with exogenous  $\beta 1$  constructs, before addition of the CRE recombinase, to remove endogenous integrin. Before use, the cells were either serum-starved for 14 h in order or treated for 1 h with 2  $\mu\text{M}$  phorbol myristyl acetate (PMA) to have SrcYF activity as the main signaling pathway in the cells. Either treatment allowed the development of a number of invadosomes and rosettes.

### *Micropatterning and functionalization*

Patterned protein glass cover slips were performed according to (Guillou *et al.*, 2008) with slight modifications. Glass cover slips (22 × 22 mm) were washed in a solution of sulfuric acid and hydrogen peroxide (7:3, vol:vol) for 30 min, dried, and then dipped for 1 h in a solution of octadecyltrimethoxysilane and aminopropyltrimethoxy silane (3:1, mol:mol) (Sigma-Aldrich) in toluene. Positive photoresist resin (Shipley, S1805, Rhom & Haas Electronic Materials, Villeurbanne, France) was spin-coated and cured according to the manufacturer's protocol to form a uniform, UV-sensitive film 0.5- $\mu\text{m}$  thick. The coated cover slips were then insolated with UV light using a Karl Süss aligner (MJB3, SUSS MicroTec, Saint-Jeoire, France) at 436 nm and 15 mJ/cm<sup>2</sup> through a chromium mask. The irradiated pattern was revealed with microposit developer concentrate in deionized water (1:1, vol:vol) (Shipley, MF CD-26, Rhom & Haas Electronic Materials). The patterned cover slips were incubated for 1 h at 37°C in a solution of gelatin-RITC and 10  $\mu\text{g}/\text{ml}$  vitronectin in phosphate-buffered saline (PBS). Substrates were rinsed in PBS and then in absolute ethanol in an ultrasonic water bath to dissolve the photoresist resin. Finally, either antiadhesive triblock copolymer Pluronic F127™ (Sigma-Aldrich) at a concentration of 4% in water for 1 h 30 min at 37°C, or a solution of FN7–10-FITC (Fibronectin type III domains 7-10 conjugated to FITC) at 5-15  $\mu\text{g}/\text{ml}$  in PBS was adsorbed to the complementary pattern revealed after resin dissolution by ethanol for 1 hour at 37°C. Following a last rinse in PBS, 155 cells/mm<sup>2</sup> were seeded and incubated overnight, prior to fixation and staining.

### *Degradation assays*

Coverslips were coated with 1 mg/ml gelatin-Oregon green, fixed with 4% (wt/vol) paraformaldehyde/0.5% glutaraldehyde for 30 min at 4°C, washed with 30 mg/ml sodium borohydride in PBS, sterilized with 70% ethanol, and rinsed once with PBS. Cells were seeded on the coverslips in culture medium for 2 h before being imaged for 14 h with a Zeiss Axiovert 200M equipped with a MicroMax 5MHz, 10× (NA 0.25) LDplan objective.

### *Microscopy and photoinactivation*

For immunofluorescence analysis, cells were fixed with 4% paraformaldehyde in PBS, pH 7.4, and imaged with a Zeiss Axiovert 200M equipped with CoolSNAP HQ2, 63× (NA 1.4) Plan Apochromat and 100X (NA 1.4) Plan Apochromat objectives and a filter set to specifically detect Alexa488/GFP or Alexa546/pTRFP/KillerRed. At least 700 podosome structures were analyzed for each condition; representative data from 3-5 independent experiments is presented.

For live imaging, cells were seeded at subconfluent densities in serum-coated, 35-mm, glass-bottom, 1.5mm-thick dishes (Mattek, Ashland, MA) and allowed to grow for 12 to 48 h prior to imaging. DMEM was replaced by a CO<sub>2</sub>-independent medium (Invitrogen), placed on a heated 37°C stage (Carl Zeiss Microimaging, Inc., Thornwood, NY), and imaged with the same Zeiss Axiovert 200M microscope set-up as previously described. Total internal reflection fluorescence (TIRF) microscopy was carried out with the same set-up as previously described and equipped with the TIRF 1 slider (Carl Zeiss microimaging GmbH, Gottingen, Germany).

For photoinactivation experiments, a Zeiss Axiovert 200M microscope equipped with a 63× (NA 1.4) Plan Apochromat objective and triple-filter set 25HE (excitation, TBP 405 + 495 + 575 [HE]; beam splitter, TFT 435 + 510 + 600 [HE], and emission, TBP 460 + 530 + 625 [HE]) (Carl Zeiss microimaging GmbH) was used for illumination. Cells were imaged as for live imaging, followed by a pause to allow illumination of the whole field of observation for 40-50 s (average, 45 s) with a 100W HBO mercury lamp at 100% power.

For fluorescence recovery after photobleaching (FRAP) experiments, an LSM510 ConfoCor microscope equipped with a 40× (NA 1.2) Plan apochromat objective (Carl Zeiss Microimaging GmbH) was used. The fluorescence recovery after bleaching time (3.2 s) was observed primarily in actin spots that persisted throughout the entire recovery time.

Imaging Series 7.0 (Universal Imaging, Downingtown, PA) software was used to mount .avi movies from image stacks. Images extracted from stacks were processed with Adobe Photoshop CS2 (Adobe Systems, San Jose, CA) and Image J (<http://rsb.info.nih.gov/ij/>). Significance of the differences between standard deviations was analyzed in Microsoft Excel with a F-test.

## RESULTS

### The ECM controls the assembly of invadosomes

To determine the role of ECM signaling on invadosome activity, we plated MEF transformed with constitutively active SrcYF on a layer of ECM micropatterned at the subcellular scale. Cells were seeded on alternate stripes of adhesive (gelatin-RITC mixed with vitronectin, red areas) and non-adhesive areas (Pluronic F127<sup>TM</sup>, black areas), 5 and 10  $\mu\text{m}$  in width, respectively. The invadosome rosettes were present on the adhesive stripes 95% of the time and continued to expand along the axis of these stripes (Figure 1A). These rosette formations suggested that the initiation of invadosome assembly is promoted by ECM signaling. Since integrins are the major actors in matrix sensing, we wanted to precisely define the roles played by specific subclasses of this receptor family. Therefore, we plated MEF-SrcYF onto patterned surfaces composed of alternating 5- $\mu\text{m}$  stripes of RITC-vitronectin, which preferentially binds  $\beta 3$  integrins, and unlabelled fibronectin, which preferentially binds  $\beta 1$  integrins. Rosettes were more abundant on vitronectin, although the cells spread on both adhesive surfaces. In contrast, individual podosomes were seen on both surfaces (Figure 1B). However, on glass coverslips homogeneously coated with fibronectin or vitronectin, MEF-SrcYF generated similar individual invadosomes and rosettes (data not shown). This result was reproduced with double patterned coverslips with either laminin and vitronectin, or collagen and vitronectin (Supplementary Figure S1B, C). These data indicated that invadosomes have a preference for vitronectin coated areas, suggesting an essential role of  $\beta 3$  integrin in invadosome activity (Figure 1B). However, most of the time, rosettes were initiated at the boundary of fibronectin and vitronectin areas (Supplementary Figure S1A). This peculiar location suggested that, despite their location on vitronectin, some outside-in signaling from fibronectin, possibly through  $\beta 1$  integrins, was necessary to initiate invadosome self-organization.

To determine the importance of  $\beta 1$  and  $\beta 3$  integrins in invadosome activity we analyzed the locations of these molecules and compared them with those of  $\beta 1$  integrins after spreading of the cells on endogenous matrix (48-h culture on glass coverslips). Since F-actin was found to be a reliable marker of nascent and mature invadosomes (Badowski *et al.*, 2008), double staining with either  $\beta 1$  and paxillin, or  $\beta 3$  antibodies and phalloidin, was carried out. Confocal scanning microscopy showed colocalization of  $\beta 3$  and F-actin, while  $\beta 1$  integrins were mostly excluded from the rosettes and accumulated at the outer rim, suggesting a possible function in newly formed invadosomes (Figure 1C). The early assembled invadosomes contain mostly the actin core, including cortactin. Detection of the active conformation of  $\beta 1A$  was carried out after external addition in the medium of 9FG7 antibody directly-conjugated to FITC and visualized by TIRF microscopy on living cells expressing cortactin-mRFP. This analysis revealed that  $\beta 1$  integrins did not colocalize with cortactin and, rather, were in close proximity to the rim of the invadosome rosette (Figure 1D). Although  $\beta 1$  integrins accumulate around rosettes, our results did not support a structural role for them, in contrast to  $\beta 3$  integrins, which mediate adhesion and are a component of the mature invadosome.

### **$\beta 1$ integrins are key regulators of invadosome formation**

To investigate the involvement of  $\beta 3$  integrins in invadosome assembly, we induced these structures in  $\beta 3^{+/+}$  and  $\beta 3^{-/-}$  MEF by expressing the constitutively active form of Src. Surprisingly, MEF-SrcYF  $\beta 3^{-/-}$  cells displayed invadosome rosettes, although these structures were narrower and exhibited less intense actin staining than those observed in MEF-SrcYF  $\beta 3^{+/+}$  cells (Figure 2A). In line with these findings, MEF-YFSrc established invadosomes rosettes on the  $\beta 1$  specific substrates laminin111 and collagen (not shown). Conversely,  $\beta 1$  depletion in MEF SrcYF  $\beta 1^{\text{loxP/loxP}}$  cells, generated by adenoviral delivery of Cre

recombinase, resulted in invadosome formation in less than 5% of cells (Figure 2B top panel, 2C). The invadosomes observed in this small percentage of cells were likely due to a lack of Cre expression in some uninfected cells, as shown by quantitative PCR (Figure 2D).  $\beta 1$  depletion in MEF-SrcYF  $\beta 1^{\text{loxP/loxP}}$  was characterized by an increase in cell spreading and reorganization of F-actin into more abundant stress fibers (Figure 2B, bottom panel).

To confirm this unexpected and dramatic effect of removal of  $\beta 1$  and generalize this finding to other cell types, we applied the same strategy of inducing invadosomes through SrcYF expression in selected pre-osteoblastic pOBL  $\beta 1^{\text{loxP/loxP}}$  cells purified after Cre treatment. As for MEFs, the expression of SrcYF induced the formation of individual invadosomes and rosettes in  $\beta 1^{+/+}$  preosteoblasts, but not in their  $\beta 1^{-/-}$  counterparts. This loss of  $\beta 1$  was also accompanied by an increase in stress fibers within the cell bodies (Figure 3A and D). These modifications suggested some impairment of Src activity. However, Western analysis of cell lysates did not reveal significant changes in either Y416 phosphorylation, which characterizes Src activation, or in total Src expression (Figure 3B). Thus, our data suggested that  $\beta 1$  integrins have an essential role in the initiation of invadosome assembly.

### **Activation of $\beta 1$ integrins stimulates invadosome auto-assembly into rosettes**

Most of the  $\beta 1$  integrins around the rosettes were stained with the 9EG7 monoclonal antibody, indicating that these receptors were bound to their ECM ligands and therefore likely in their high-affinity state (Figure 1D). To test the role of integrin activation in invadopodia dynamics, we carried out a structure-function study and re-expressed exogenous human  $\beta 1$  chains bearing the point mutation D759A, which is known to modulate  $\beta 1$  activation state, in  $\beta 1^{-/-}$  pOBL-SrcYF cells (Figure 3C). This mutation promotes the integrin high-affinity state by breaking the saline bridge to the nearby arginine residue on the  $\alpha$  chain (Shattil *et al.*, 2010). This mutant showed a dramatic increase in rosette number compared to wild-type cells (Figure 3D). In conclusion, in addition to the involvement of  $\beta 1A$  in the initiation of assembly

of individual podosomes, the activation of  $\beta$ 1A integrins appears to potentiate invadosome auto-assembly.

### **PKC directly targets $\beta$ 1A integrin to control invadosome auto-assembly**

Previous studies in the literature show that in addition to Src signaling, the activation of conventional PKCs promotes invadosome formation in a variety of cell types (Hai *et al.*, 2002; Tatin *et al.*, 2006). Indeed, under standard cell culture conditions, PMA treatment stimulated invadosome auto-assembly into rosettes in a manner similar to conditions of serum starvation (Figure 4A) Based on the treadmilling process in invadosome turnover (Badowski *et al.*, 2008), the increase in invadosome auto-assembly could be due to an increase in either rosette stability or dynamics. To address this question, live-cell imaging was carried out on pOBL-SrcYF cells stably expressing GFP-actin and grown in serum-supplemented DMEM in the presence or absence of PMA. In the absence of PMA the few rosettes that could be detected were quite stable over 30 min. Conversely, activation of PKCs largely decreased invadosome life-span to under 10 min, resulting in a dramatic increase in rosette expansion and turnover (Figure 4B). On the other hand, inhibition of PKCs by the general inhibitor BIM resulted in rapid dissociation of rosettes, while the formation of individual invadosomes was still observed (Figure 4B). In the cytosolic domain of the  $\beta$ 1A integrin subunit, a number of serine and threonine residues have been shown to be potential PKC phosphorylation sites modulating integrin function (Stroeken *et al.*, 2000; Mulrooney *et al.*, 2001) (Figure 4C). Among those residues, S785 was previously shown to be strongly phosphorylated upon Src overexpression (Sakai *et al.*, 2001). To investigate the importance of the PKC-dependent signaling pathway on  $\beta$ 1A in the invadosome auto-assembly process, we expressed the  $\beta$ 1 integrin mutants S785A, or S785D or S785E (nonphosphorylatable or phosphomimetic forms, respectively), in a null genetic background and modulated PKC activity with an activator (PMA) or inhibitor (BIM). Consistent with the view that S785 is a direct target of PKC, only

the phosphomimetic mutants S785D and S785E were able to stimulate invadosome auto-assembly into rosettes in the absence of PMA (Figure 4D). The same phosphomimetic mutants were partly resistant to BIM inhibition as compared to wild type and the nonphosphorylatable S785A mutant (Figure 4E). In addition, the S785A mutant poorly rescued rosette assembly following PMA treatment (supplementary Figure S2). Taken together, these data support the view that S785 on the  $\beta 1$  subunit is one of the primary targets of PKC in the regulatory pathway of invadosome rosette auto-assembly in cells.

### **$\beta 1$ integrin downstream signaling links invadosome formation and ECM degradation properties**

Since invadosomes are major sites of ECM degradation, we investigated the involvement of  $\beta 1$  integrins in this crucial invadosome function by quantifying gelatin-Oregon green surface degradation, normalized per cell, over time. Even in the absence of invadosomes, pOBL-SrcYF  $\beta 1^{-/-}$  cells showed very low, but significant, ECM degradation activity 4 h after plating on gelatin (Figure 5A, C). Quantification of the average fluorescence intensity of the digested area is an efficient way to determine the extent or the depth of digestion. It was clearly shown that surfaces degraded by pOBL-SrcYF  $\beta 1^{-/-}$  cells were poorly digested (Figure 5B) as compared with rescued cells. The same results were obtained for MEF-SrcYF cells (data not shown). As shown previously, this structure-function study allowed exploration of the function of  $\beta 1A$  in the ECM degradative activity of invadosomes. Re-expression of wild-type human  $\beta 1A$  integrin rescued the degradation phenotype of pOBL-SrcYF  $\beta 1^{-/-}$  cells in terms of extent and depth of the ECM digestion (Figure 5A, B). On the other hand, the rescue of pOBL-SrcYF  $\beta 1^{-/-}$  cells with human  $\beta 1A$  D759A, a mutant that pre-activates the integrin, led to the formation of numerous invadosomes, but which poorly digested ECM. Since wild-type integrin cycles between low- and high-affinity states, this loss

of function when the high-affinity state is promoted suggests the importance of the cycle of  $\beta 1$  activation/inactivation in this process. Thus, modulation of the  $\beta 1A$  integrin activation state allowed, for the first time, the uncoupling of invadosome formation and ECM degradation activity. Moreover, regulation of invadosomes by PKC through phosphorylation of Ser785 was shown to be an essential step in activating invadosome ECM degradation properties. Indeed, the nonphosphorylatable mutant S785A of  $\beta 1A$  strongly reduced the average surface area digested per cell, without affecting the depth of the degradation (Figure 5B). Conversely, the phosphomimetic  $\beta 1A$  mutant S785D dramatically increased invadosome ECM degradation activity. Thus, not only the affinity state of  $\beta 1$ , but also signaling pathways downstream of  $\beta 1A$ S785 phosphorylation (likely by PKC) control the coupling of invadosome assembly and ECM degradation activity.

### **$\beta 1$ integrins stabilizes both rosettes and individual invadosomes**

Having established that  $\beta 1A$  integrins are important in initiating formation of individual invadosomes in the auto-assembly of rosettes, and to invadosome degradative function, we wanted to determine next whether signaling from  $\beta 1A$  integrins located at the rosette periphery was required to simply initiate or to maintain rosette structure and dynamics. To address this question, we developed an improved photo-inactivation strategy based on the use of the photosensitizer KillerRed™ to achieve inducible loss of the  $\beta 1A$  integrin chain. Briefly, we fused KillerRed™ to  $\beta 1A$  in place of GFP and expressed it in MEF-SrcYF  $\beta 1^{\text{loxP/loxP}}$  cells. The endogenous  $\beta 1$  gene was deleted in almost 100% of the cells 7 d post-Cre expression, as monitored by qPCR analysis of mouse  $\beta 1$  mRNA (data not shown). In this genetic null background, the  $\beta 1$ -KillerRed™ was functional since it allowed the assembly of rosettes and was correctly localized at their periphery. GFP-actin dynamics were followed after 45-s irradiation with red light in the KillerRed™ excitation spectrum (585 nm-615 nm).

KillerRed™ locally produces reactive oxygen species (ROS), resulting in the rapid inactivation of the protein to which it is fused. Indeed, photo-inactivation of  $\beta$ 1-KillerRed™ resulted in a 95% decrease in red fluorescence, which was not recovered over the time of the observation (a maximum of 40 min after irradiation). This loss of  $\beta$ 1A function led to the massive disorganization of the rosettes in under 20 min (Figure 6A, D).

ROS production in the cells could potentially have multiple indirect effects. To clearly show the specificity of this strategy, we first confirmed that the 45-s excitation with red light that resulted in KillerRed™ inactivation had no effect on invadosome structure, organization, and dynamics in cells expressing KillerRed™ alone in the cytosol (data not shown). Thus, non-localized ROS production after KillerRed™ irradiation had no effect on invadosomes or focal adhesions. To evaluate the potential toxicity of the 45-s red light irradiation and adsorption, KillerRed™ was replaced in the  $\beta$ 1A fusion protein by TagRFP™, another photostable fluorescent molecule with an excitation/emission spectra similar to that of KillerRed™ (Supplementary Movie 2). Indeed, 45-s red light excitation of  $\beta$ 1A-TagRFP™ had no effect on invadosomes, which remained stable for more than 40 min post-irradiation (Figure 6B, D). Finally, the nonspecific effects of ROS production on proteins and membranes in the vicinity of  $\beta$ 1 after KillerRed™ excitation were investigated by simultaneous expression of  $\beta$ 1A-GFP and  $\beta$ 1A-KillerRed™ in a  $\beta$ 1<sup>-/-</sup> background, since the two proteins were likely located in close proximity to each other (Supplementary Movie 3). In this environment, photo-inactivation of  $\beta$ 1-KillerRed™ had no effect on  $\beta$ 1A-GFP, which still allowed the formation of characteristic invadosome rings, as seen in non treated invadosome visualized by  $\beta$ 1A-GFP and cortactin-TagRFP™ (bottom panel Figure 6C, Supplementary movie 8). These data clearly show that ROS produced by photoinactivation of KillerRed™ act only on the KillerRed™-tagged protein and not on surrounding macromolecules (Figure 6C, D).

This photo-inactivation strategy allowed us to monitor the specific effects of loss of  $\beta$ 1A on pre-existing rosettes on a time scale of minutes. It is noteworthy that despite its specific localization around invadosome rings and its role in their initiation, inducible  $\beta$ 1A depletion did not lead to progressive dissociation of the actin cytoskeleton from the inside to the outside of the rosettes, as would be expected because new actin structures are formed at the outer rim of the ring while older parts of the structure are disassembled at its inner rim) (Figure 6A). Soon after photo-inactivation, the polymerization of GFP-actin was not blocked, but rather formed unstable waves inside the rosette before the disorganization of these structures (Supplementary Movies 1, 7). Instability in the actin-polymerization domains within the rosette was followed by the complete collapse of the structure and increased cell spreading associated with the rapid formation of stress fibers (Supplementary Movie 1). Occasionally, GFP-actin signals reminiscent of the localization of invadosomes remained (Figure 6A).

### **Photo-inactivation of $\beta$ 1A integrins reveals the integrin functions in invadosome organization**

To understand the mechanism underlying the GFP-actin-polymerization defect seen after loss of  $\beta$ 1A function, the dynamics of the activity of the actin regulator cortactin fused to GFP was monitored (Supplementary movie 4).  $\beta$ 1 photo-inactivation was rapidly followed by the dissociation of cortactin from invadosomes, explaining the perturbation of actin dynamics (Figure 7A). Similarly, the dynamics of adhesion molecules such as paxillin and  $\beta$ 3-GFP integrins were analyzed (Supplementary Movies 5 and 6). In particular, the induction of  $\beta$ 1 loss of function led to paxillin disorganization in invadosomes, although a fraction of this GFP-tagged protein remained localized at the previous site in the rosette (Figure 7B). This was also the case for  $\beta$ 3-GFP but with this specific marker, it was clearer that invadosome

disorganization was associated with massive new formation or growth of focal adhesions (Figure 7C, red arrows). This rapid reorganization of the cellular adhesive structures was consistent with our observations of the formation of multiple stress fibers in response to  $\beta 1$  photo-inactivation (Supplementary Movie 1). In conclusion, despite its peripheral localization in the rosette,  $\beta 1A$  integrin is a master regulator of invadosome assembly, organization, and stability.

## DISCUSSION

Based on their high content and variety of integrins, invadosomes are integrin dependent adhesive structures associated with intense actin dynamics and responsible for local ECM degradation. The role of a specific integrin type in invadosome regulation is unclear, due to trans-dominant activities among the integrin classes and the lack of specificity of the tools used such as specific inhibitors or antibodies. Herein, we used the power of genetic to understand the role of two major integrins classes (those pairing with  $\beta 1A$  and  $\beta 3$  chains) in the formation and dynamics of invadosomes. This strategy is based on the induction of invadosomes by SrcYF expression in a  $\beta 1$  or  $\beta 3$  null genetic background. Thus we are coupling the historical experiment by Tarone *et al.*, 1985 with the re-expression of wild type or mutant  $\beta$  chains allowing a straightforward reverse genetic analysis of  $\beta 1A$  or  $\beta 3$  integrins functions in invadosomes.

Although the rosette assembly associated with the colocalization of  $\beta 3$  and F-actin on patterned surfaces has clearly shown preferential invadosome localization on vitronectin, MEF SrcYF  $\beta 3^{-/-}$  cells form invadosome rosettes, indicating that other integrin types can compensate the loss of  $\beta 3$ . This finding confirms previous data showing that  $\beta 3^{-/-}$  osteoclasts are able to form podosomes (Faccio *et al.*, 2003).

On the contrary, the specific role of the  $\beta 1$  chain in initiating invadosome assembly is highlighted by the fact that the loss of  $\beta 1$  resulted in the complete disappearance of both individual and self-assembled invadopodia in primary cells and cell lines. These data do not fit with an earlier study reporting the presence of invadosome rosettes in the  $\beta 1$  null cell lines G $\beta 11$  and GD25 transformed with SrcYF. In that case however, the re-expression of the  $\beta 1A$  double mutant (Y783F, Y795F) that poorly respond to Src transformation (Sakai *et al.*, 2001) clearly showed a trans dominant negative effect on invadosome formation, pointing to a major role of this integrin chain in invadosome formation (Huvneers *et al.*, 2008). Since these studies were using immortalized cells lines from knockout embryonic cells, one may assume that other compensatory mechanisms may have been at work. Indeed, in our hands, isolated clones of pOBL SrcYF  $\beta 1^{-/-}$  cells which normally do not form invadosomes, can form few invadosome rosettes after numerous passages in culture, suggesting that these immortalized cells lines start to set up compensatory mechanisms that rescue the formation of these adhesion structures (data not shown). At a first glance, and despite its localization around the rosette, the importance of  $\beta 1$  integrin is surprising since this integrin class appeared in wild type cells to be excluded from invadosomes, which contain mostly  $\beta 3$  integrin chains. However, immunostaining revealed an increased concentration of  $\beta 1$  at the outer rim of the rosettes. Since no colocalization with cortactin, a marker of nascent and mature invadopodia and invadosomes (Artym *et al.*, 2006; Badowski *et al.*, 2008) was observed, it is likely that  $\beta 1$  integrins do not belong to the F-actin architecture composing invadosomes, but rather form a signaling platform to initiate invadosome assembly. In order to test this hypothesis, we developed a new approach to inactivate integrins at the minute time scale. The specific photo-inactivation of  $\beta 1$ - KillerRed<sup>TM</sup> showed that this integrin loss induced a rapid collapse of the whole structure, indicating that the  $\beta 1$  chain is required not only to initiate invadosome assembly, but also to control the stability of the structure during the entire life span of the

rosette. This  $\beta 1$  functional ablation allowed us also to observe the rosette collapse from the outside to the inside. Thus, it appears that  $\beta 1A$  integrins can signal at distance to control the disassembly processes occurring at the inner rim of invadosomes (Badowski *et al.*, 2008). Moreover, some residual F-actin, not associated with GFP-cortactin, forms an imprint after F-actin disassembly following photo-inactivation corresponding to the initial rosette. This strongly suggests the presence of two distinct actin network in the rosette: the actin cores with high cortactin content that depend on  $\beta 1$  signaling, and a more stable actin cloud around individual podosomes that is reminiscent of the radial actin arrays observed in macrophage or in the sealing zone of osteoclasts (Evans *et al.*, 2003; Luxenburg *et al.*, 2007). Finally, photo-inactivation of  $\beta 1A$ -KillerRed™ is followed by the formation of focal adhesions, providing another example of the well described competition between focal adhesions and invadosomes. In order to explore the  $\beta 1A$  dependent control mechanisms of invadosomes, we focus our attention on PKC which is in addition to Src, a major inducer of invadosomes or podosomes (Hai *et al.*, 2002; Tatin *et al.*, 2006). Indeed, under standard cell culture conditions, PKC activity induced by PMA treatment greatly stimulated invadosome and rosette formation. The precise role of PKC activity in invadosomes is unclear. PKC $\alpha$  and PKC $\delta$  were shown to allow  $\beta 1$  integrin activation (Brenner *et al.*, 2008). This latter finding could be indirect since another PKC, PKC $\theta$  was shown to regulate the integrin activator Rap1 (Letschka *et al.*, 2008). The other possibility is that PKC phosphorylate directly integrins. Indeed, serine 785 and threonine 788 and 789 on the cytoplasmic tail of this integrin are potential targets of PKC. Since it was previously shown that S785 phosphorylation alters cell spreading (Mulrooney *et al.*, 2001) and that this particular residue was over-phosphorylated upon Src over expression (Sakai *et al.*, 2001), phosphomimetic and the non-phosphorylable  $\beta 1A$  mutants S785E and S785D or S785A, respectively, were expressed in  $\beta 1A^{-/-}$  SrcYF MEF and pre-osteoblasts cells. Phosphomimetic mutant expression strongly stimulated invadosome self-assembly in the

absence of PMA and the mutant became partially resistant to the general PKC inhibitor BIM. These results strongly suggest that the direct phosphorylation of  $\beta$ 1A on serine785 by PKC is an important event in the regulation of in invadosome assembly. However, the partial inhibition of phosphomimetic  $\beta$ 1A mutants by BIM treatment also suggests that in addition to the direct phosphorylation of the  $\beta$ 1A chain, PKC stimulation by PMA acts at other different levels of invadosome assembly. This view is also confirmed by the fact that, BIM treatment does not fully mimic the collapse of the rosette after  $\beta$ 1-KillerRed™ photo-inactivation, but rather leads to the dissociation of the rosette into individual invadosomes.

The characterization of the ECM degradation by the multiple cell lines that we generated allowed us to determine the involvement of  $\beta$ 1 integrins in this process and in invasion. This integrin is essential for proteolytic function of invadosomes. We observed a dramatic decrease in ECM degradation in pOBL  $\beta$ 1<sup>-/-</sup> SrcYF cells. This result was expected since despite the transformation of the cells by SrcYF, the loss of the integrin chain was accompanied by an almost complete loss of invadosomes. More surprisingly, the level of ECM degradation did not correlate with the increase in rosette assembly. Indeed, the expression of the pre-activated  $\beta$ 1A mutant D759A in a  $\beta$ 1null genetic background resulted in a 2- to 3-fold increase in the rosette number, which was associated with a significant decrease in the ECM degradation. To our knowledge, this is the first report the uncoupling of invadosome formation and matrix degradation. This could be due to the property of  $\beta$ 1A integrin to interact with the plasma membrane-associated metalloprotease MT1-MMP (also called MMP14), which localized to invadosomes and is essential for the ECM degradation (Galvez *et al.*, 2002; Steffen *et al.*, 2008). Interference with MT1-MMP trafficking at the plasma membrane revealed that MT1-MMP activation and cell invasiveness are tightly coupled (Uekita *et al.*, 2001; Steffen *et al.*, 2008). Several lines of evidence have now established that in addition to being endosomal passengers, an important function of

integrins is to direct the trafficking of other receptors and cargos (for review see (Caswell *et al.*, 2009)). One can hypothesize that the affinity state of  $\beta$ 1A integrin could modulate MT1-MMP trafficking at the plasma membrane and therefore impair its activity at the cell surface. This hypothesis is supported by the fact that PKC $\alpha$  increase integrin trafficking (Ng *et al.*, 1999) and that expression of  $\beta$ 1A S785D or S785E, which mimic PKC activation, results in increased ECM degradation.

In conclusion, our results support a central role of  $\beta$ 1 integrin-dependent outside-in signaling pathways in the regulation of the multiple cell compartments involved in invadosome functions.

## ACKNOWLEDGMENTS

We thank Mrs. Manaa Wafa for technical assistance and interest, Dr Richard Hynes and Dr R. Fässler for providing us with  $\beta$ 1<sup>-/-</sup> MEFs and  $\beta$ 1 knock out conditional mice, respectively, This work was supported in part by the NanoFab micro fabrication facility of Louis Neel Institute (CNRS UPR 5051), the Association pour la Recherche contre le Cancer, the Ligne Nationale Contre le Cancer (équipe labellisée), the Agence Nationale pour la Recherche program PIRIBIO, and the fond d'intervention du Pôle Chimie Sciences du Vivant of Université J. Fourier.

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## FIGURE LEGENDS

### Figure 1: Extracellular matrix sensing by $\beta 1$ and $\beta 3$ integrins controls invadosome formation and localization.

A) Most SrcYF-expressing cells formed invadosome rosettes (visualized by F-actin staining, in green) only on the adhesive surface (gelatin-TRITC, in red, mixed with vitronectin) and not on anti-adhesive areas (Pluronic F127<sup>TM</sup>, black areas). B) Invadosome rosettes stained by phalloidin-TRITC show higher affinity for vitronectin-FITC (light gray bands), sensed by members of the  $\beta 3$  integrin family, than for fibronectin (black bands), sensed by members of both the  $\beta 1$  and  $\beta 3$  integrin families. C)  $\beta 1$  and  $\beta 3$  integrins show distinct patterns of localization, observed in MEF-SrcYF cells.  $\beta 3$  (in green in merge) highly colocalized with F-actin while  $\beta 1$  staining is limited to the rosette periphery. D) 9EG7 antibody  $\beta 1$  staining is specific of the activated form of the integrin. Antibody against activated form of  $\beta 1$  directly conjugated to FITC (9EG7-FITC) was added externally and localized around the invadosome visualized by cortactin-mRFP (in red in merge) expressed in live MEF-SrcYF cells. Bars represent 5  $\mu\text{m}$  (A, B), 4  $\mu\text{m}$  (C), and 2  $\mu\text{m}$  (D).

### Figure 2: $\beta 1A$ , and not $\beta 3$ , integrin is essential for invadosome formation.

A)  $\beta 3$  is not essential for invadosome formation and self-assembly into rosettes, visualized by F-actin (in red in merge) and phospho-Y397-FAK (in blue in merge) staining, which occurs in both MEF-SrcYF  $\beta 3$   $+/+$  or  $-/-$  cells. B) In contrast,  $\beta 1$  depletion in MEF-SrcYF  $\beta 1^{\text{LoxP/LoxP}}$  expressing the CRE recombinase for 96 h resulted in the disappearance of isolated invadosomes or in rosettes probed by phalloidin staining. C) Quantification of the percentage of cells forming invadosomes reveals that almost 95% of MEF-SrcYF  $\beta 1^{\text{LoxP/LoxP}}$  treated with CRE recombinase did not form this structure 4 d post infection (n = 650 counted cells per condition). D) Quantification by qPCR shows an average decrease of 95% in the level of  $\beta 1$  mRNA 96 h post-CRE treatment. Bars represents 3  $\mu\text{m}$  (A) and 10  $\mu\text{m}$  (B).

### Figure 3: Activation of $\beta 1$ stimulates invadosome auto-assembly.

A)  $\beta 1$  depletion in pOBL-SrcYF induced the disappearance of invadosomes, shown by phalloidin staining of F-actin. Bar represents 5  $\mu\text{m}$ . B)  $\beta 1$  depletion does not affect Src activation. Lysates of pOBL-SrcYF  $\beta 1^{+/+}$  and  $-/-$  were probed by Western blotting for phospho-SrcY416, a marker of Src activation, total Src, and actin. C) Amino-acyl sequence of the cytoplasmic domain of  $\beta 1A$  integrin and the location of the main mutation that activates this integrin. D) Expression of the preactivated mutants of  $\beta 1$  ( $\beta 1$  D759A) in pOBL-SrcYF  $\beta 1^{-/-}$  cells dramatically increases the number of invadosome rosettes per air unit, while  $\beta 1\text{WT}$  mutant rescue the rosette number up to the control level.

**Figure 4: PKC regulates invadosome auto-assembly by phosphorylating S785 of  $\beta$ 1A integrins.**

A) PKC activation by a 60-min treatment of pOBL-SrcYF cells with 2  $\mu$ M PMA induces a massive increase in invadosome rosette autoassembly, visualized by phalloidin staining. B) Extracted images from time series (in minutes) from representative observations of pOBL-SrcYF cells expressing GFP-actin and treated with either DMSO (control), the PKC activator PMA (2  $\mu$ M), and the PKC inhibitor Bim (5 mM). PKC activity regulates the dynamics and maintenance of the invadosome autoassembly state. C) Amino-acyl sequence of the cytoplasmic domain of  $\beta$ 1A integrin and the location of the main PKC targets. D) Quantification of invadosomes per Airy unit (AU) shows that a mutation mimicking a constitutive phosphorylated form of Ser 785 (Asp or Glu) dramatically increases the formation of rosettes in pOBL-SrcYF  $\beta$ 1<sup>-/-</sup> cells. The non-phosphorylatable mutant of  $\beta$ 1 at this site (S785A) has no effect on rosette formation. E) The number of rosettes/AU was quantified in pOBL-SrcYF cells treated with 2  $\mu$ M PMA or simultaneously with PMA and 5 mM BIM for 60 min. The inhibitory effect of BIM was determined by calculating the percent inhibition of invadosome rosette formation. Mutants mimicking a constitutively phosphorylated Ser785 (S785D and S785E) show only 50% inhibition after BIM treatment, indicating that this residue on  $\beta$ 1 is a major target of PKC in the regulation of invadosome autoassembly. Bars represent 20  $\mu$ m (A) and 5  $\mu$ m (B).

**Figure 5:  $\beta$ 1 activity and signaling control invadosome ECM degradation activity.**

A) Quantification of the degraded surface of gelatin-Oregon Green per cell reveals that  $\beta$ 1 has an essential function in this invadosome function. Surprisingly, expression of the activated mutant of  $\beta$ 1 (D759A) induces numerous invadosome rosettes associated with poor degradation activity. Moreover, constitutive activation of the signaling pathway downstream of phosphorylation of Ser 785 strongly stimulates ECM degradation. B)  $\beta$ 1 also controls the quality of the degradation, as revealed by quantification of the average intensity of the resorbed areas. The few areas degraded in the pOBL-SrcYF  $\beta$ 1<sup>-/-</sup> cells are poorly digested since they are close to the maximal fluorescence intensity of a non-digested surface (255) in comparison to pOBL-SrcYF  $\beta$ 1<sup>+/+</sup> cells (values closer to 0 indicate a totally black, completely digested area). Between 600 and 1050 cells were counted per condition. C) Representative images extracted from the time series of pOBL-SrcYF  $\beta$ 1<sup>-/-</sup> cells expressing or not expressing either human  $\beta$ 1 WT, D759A, S785A, or S785D spread on a layer of degradable gelatin-Oregon green. Bar represents 10  $\mu$ m.

**Figure 6: Photo-inactivation revealed role of  $\beta$ 1 in maintaining invadosome self-assembly.**

A) Representative images extracted from time series of MEF-SrcYF  $\beta$ 1<sup>-/-</sup> cells expressing human  $\beta$ 1-KillerRed<sup>TM</sup> and GFP-actin. Exogenous human  $\beta$ 1-KillerRed<sup>TM</sup> is functional in rescuing invadosome formation and its proper localization at the periphery. Exposure of KillerRed<sup>TM</sup> to light for 45 s is followed by fluctuations in intensity and disorganization of GFP-actin in the invadosome rosette. B) Representative images extracted from time series of MEF-SrcYF  $\beta$ 1<sup>-/-</sup> cells expressing human  $\beta$ 1-pTagRFP<sup>TM</sup>, which has the same excitation/emission spectrum but is much more photostable than KillerRed, and GFP-actin. Light irradiation without ROS production is not sufficient to dissociate invadosomes. C) Representative images extracted from time series of MEF-SrcYF  $\beta$ 1<sup>-/-</sup> cells expressing human  $\beta$ 1-KillerRed<sup>TM</sup> and human  $\beta$ 1-GFP. These two proteins colocalized, but ROS production at this level of  $\beta$ 1-KillerRed<sup>TM</sup> has no effect on either  $\beta$ 1-GFP stability or on any other important proteins for invadosome integrity because invadosomes are still present when  $\beta$ 1-KillerRed<sup>TM</sup>

is photo-inactivated. Moreover,  $\beta 1$ -KillerRed<sup>TM</sup> depletion did not affect  $\beta 1$ -GFP behaviour in comparison to  $\beta 1$ -GFP present in untreated invadosome visualized by cortactin-pTRFP.

D) Photo-inactivation of  $\beta 1$ -KillerRed leads to rapid and specific disorganization of invadosomes. Histograms, show the distribution of the percentage of cells where invadosomes are disorganized at various times after light irradiation. X-axis shows time in minutes. Twelve to thirty-nine cells per condition were monitored. Bars represents 3  $\mu\text{m}$  (A,B,C).

**Figure 7:  $\beta 1$  photo-inactivation leads to the loss of cortactin, disorganization of adhesion molecules within the invadosome metastructures, and induction of large,  $\beta 3$ -rich focal adhesions.**

A) Representative images extracted from time series of MEF-SrcYF  $\beta 1^{-/-}$  cells expressing human  $\beta 1$ -KillerRed<sup>TM</sup> and GFP-cortactin. Photo-inactivation of  $\beta 1$ -KillerRed<sup>TM</sup> is followed by a slow decrease in GFP-cortactin fluorescence and its complete disappearance. B) Representative images extracted from time series of MEF-SrcYF  $\beta 1^{-/-}$  cells expressing both human  $\beta 1$ -KillerRed<sup>TM</sup> and GFP-paxillin.  $\beta 1$  photo-inactivation leads to GFP-paxillin disorganization and decrease in intensity but, in contrast to what is observed with GFP-cortactin, GFP-paxillin remains associated with the invadosome. C) Representative images extracted from time series of MEF-SrcYF  $\beta 1^{-/-}$  cells expressing human  $\beta 1$ -KillerRed<sup>TM</sup> and  $\beta 3$ -GFP.  $\beta 1$  photo-inactivation leads to slow dissociation of invadosomes and the massive formation of  $\beta 3$ -rich focal adhesions (red arrows). Bars represents 3  $\mu\text{m}$  (A, B, C).

## SUPPLEMENTARY INFORMATION

### SUPPLEMENTARY FIGURE LEGEND

**Figure S1:** A MEF-YFSrc adhesion on micropatterned stripes of FITC-vitronectin (green fluorescence) and fibronectin (unlabeled). Actin is stained by TRITC-phalloïdin. The invadosome rosette is localized at the interface between vitronectin and fibronectin. Bar is 10  $\mu\text{m}$ . B MEF-YFSrc adhesion on micro-patterned stripes of FITC-vitronectin (green fluorescence) width 10  $\mu\text{m}$ , and either unlabeled laminins (right panel) or laminins (left panel) (unlabeled). Actin is stained by TRITC-phalloïdin. C Quantification of the localization of invadosome rosettes on double patterned substrates.

**Figure S2:** The number of rosettes/AU was quantified in pOBL-SrcYF cells treated with 2  $\mu\text{M}$  PMA or simultaneously with PMA and 5 mM BIM for 60 min. The inhibitory effect of BIM was determined by calculating the percent inhibition of invadosome rosette formation. Mutants mimicking a constitutively phosphorylated Ser785 (S785D and S785E) show only 50% inhibition after BIM treatment, indicating that this residue on  $\beta 1$  is a major target of PKC in the regulation of invadosome autoassembly.

### SUPPLEMENTARY MOVIE LEGENDS

**Supplementary Movie 1:** Live imaging (0,05Hz) of invadosome rosette visualized by GFP-actin (TIRF microscopy) and  $\beta 1$ -KillerRed<sup>TM</sup> (epifluorescence microscopy), followed by 50 s of red light irradiation to photo-inactivate  $\beta 1$ -KillerRed<sup>TM</sup>.

**Supplementary Movie 2:** Live imaging (0,05Hz) of invadosome rosette visualized by GFP-actin (TIRF microscopy) and  $\beta 1$ -TagRFP<sup>TM</sup> (epifluorescence microscopy), followed by 45 s of red light irradiation, which does not photo-inactivate, but just bleaches,  $\beta 1$ -TagRFP<sup>TM</sup>.

**Supplementary Movie 3:** Live imaging (0,025Hz) of invadosome rosette visualized by peripheral signals of  $\beta 1$ -GFP (TIRF microscopy) and  $\beta 1$ -KillerRed<sup>TM</sup> (epifluorescence microscopy), followed by 45 s of red light irradiation to photo-inactivate  $\beta 1$ -KillerRed<sup>TM</sup>.

**Supplementary Movie 4:** Live imaging (0,05Hz) of invadosome rosette visualized by cortactin-GFP (TIRF microscopy) and  $\beta 1$ -KillerRed<sup>TM</sup> (epifluorescence microscopy), followed by 50 s of red light irradiation to photo-inactivate  $\beta 1$ -KillerRed<sup>TM</sup>.

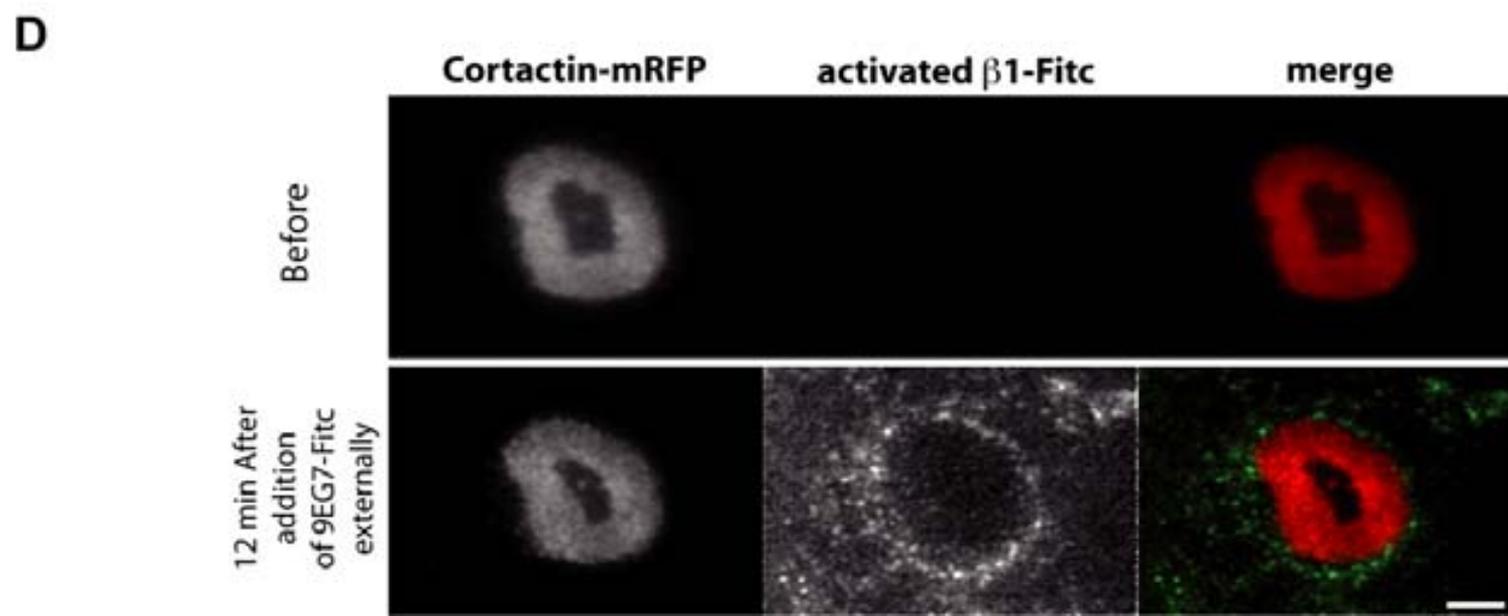
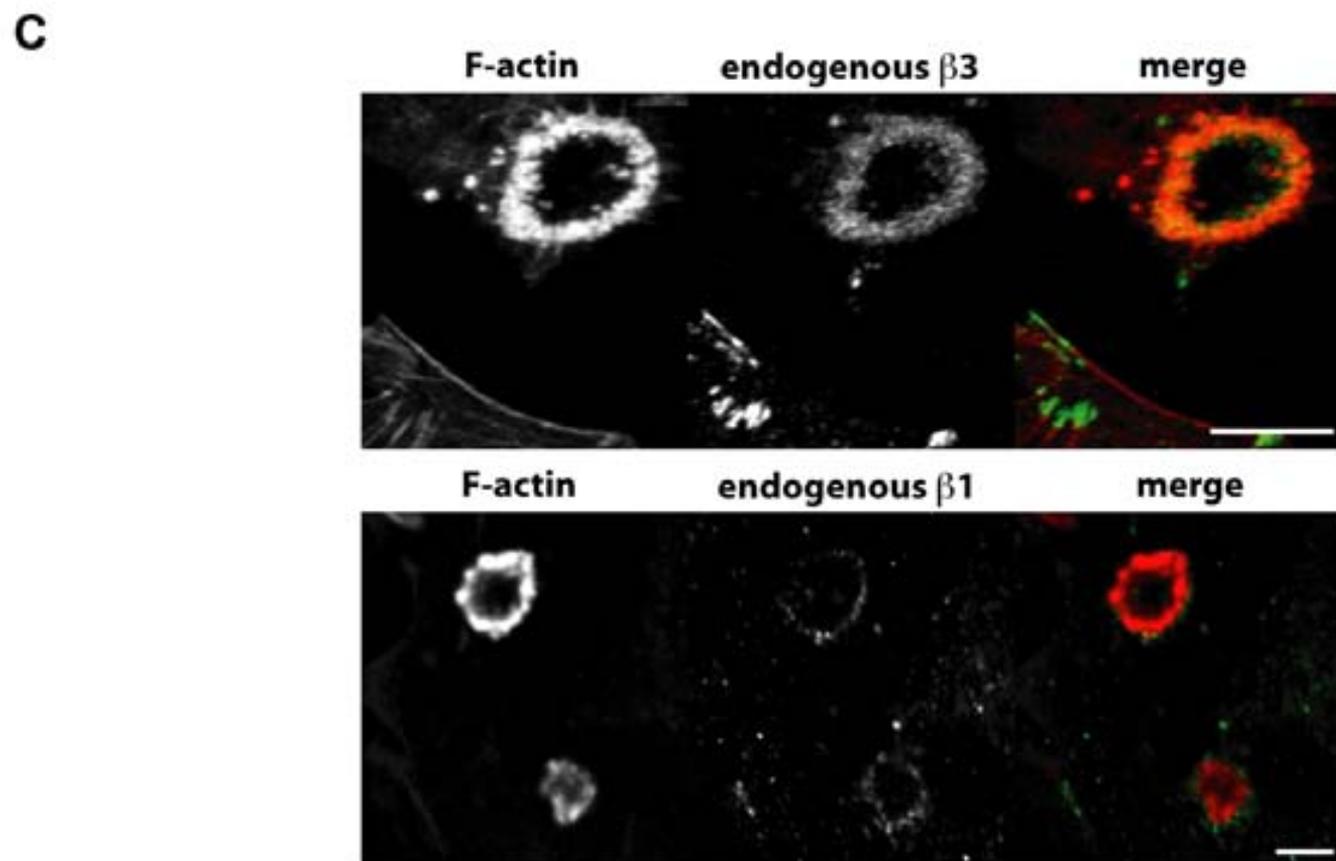
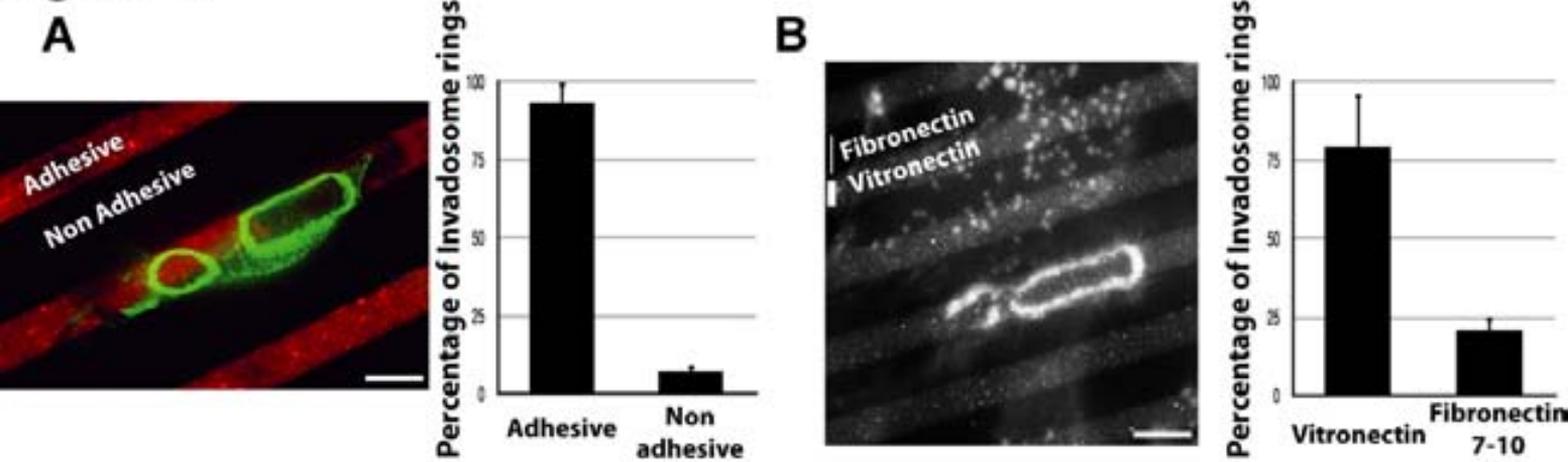
**Supplementary Movie 5:** Live imaging (0,05Hz) of invadosome rosette visualized by paxillin-GFP (TIRF microscopy) and  $\beta 1$ -KillerRed<sup>TM</sup> (epifluorescence microscopy), followed by 45 s of red light irradiation to photo-inactivate  $\beta 1$ -KillerRed<sup>TM</sup>.

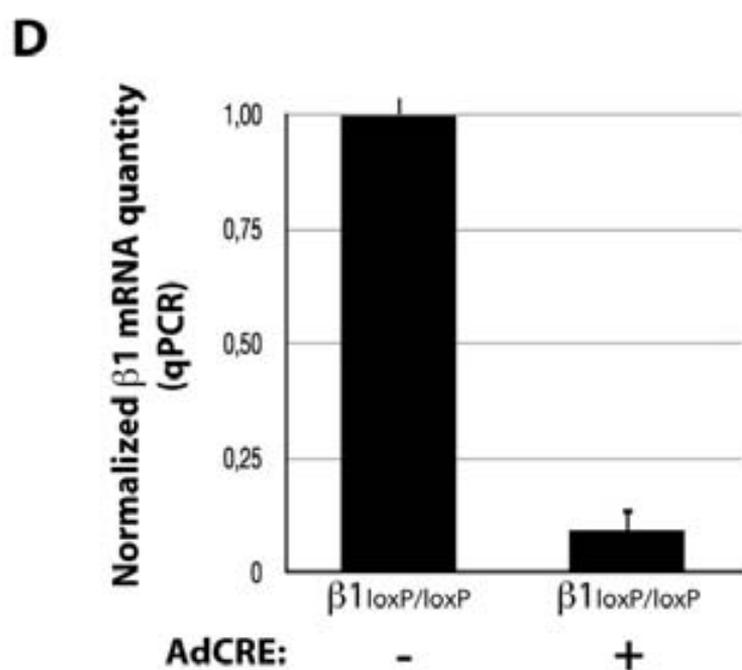
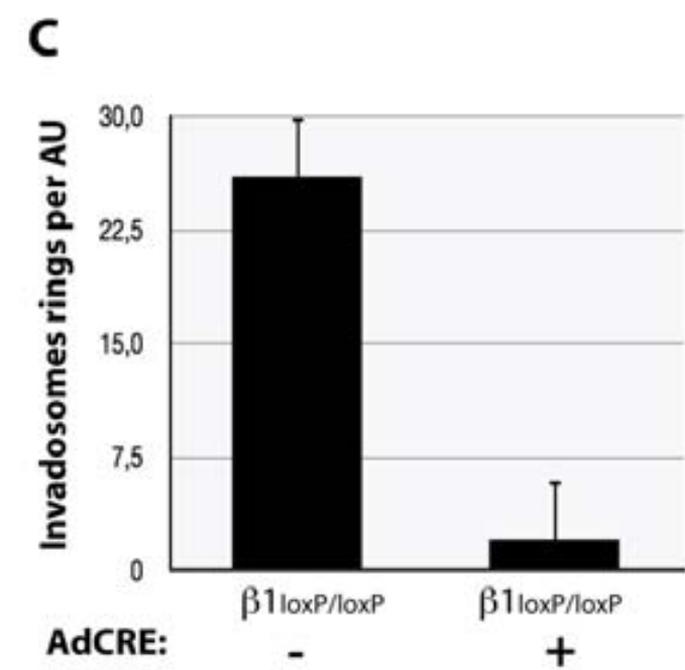
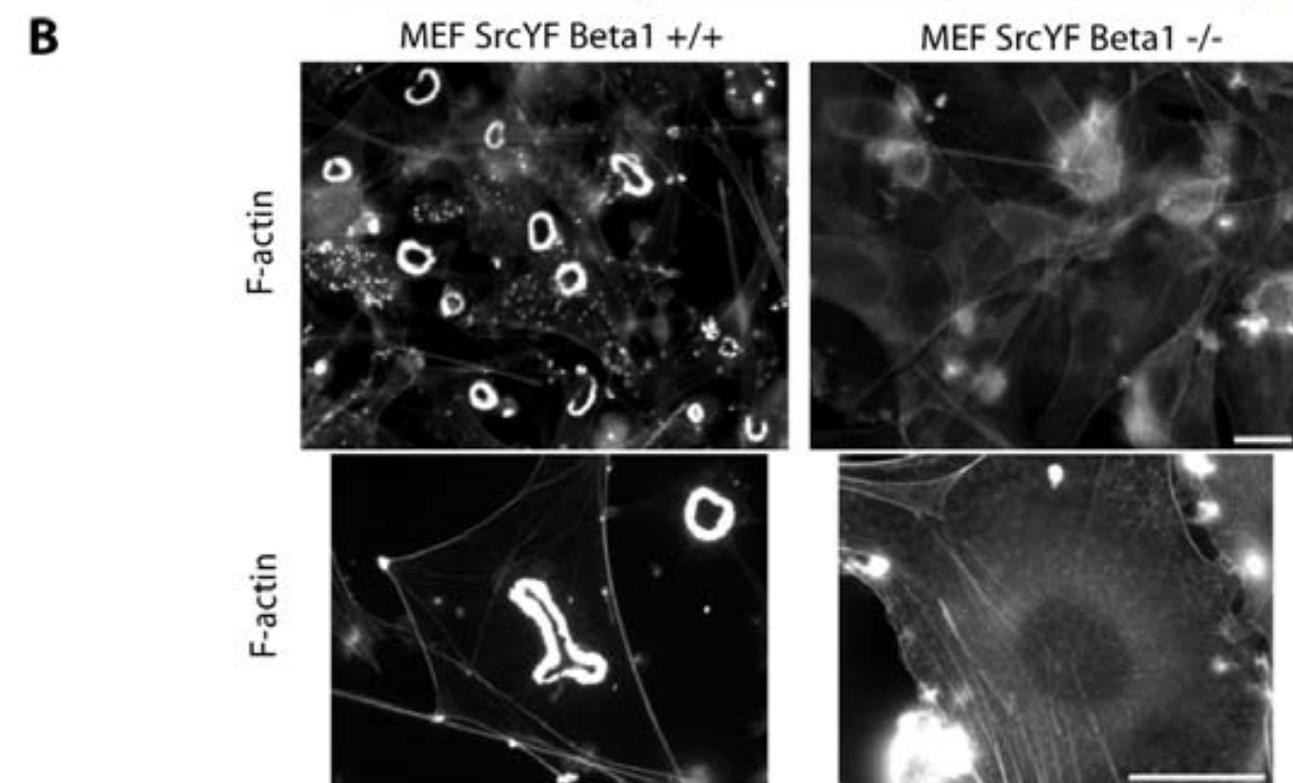
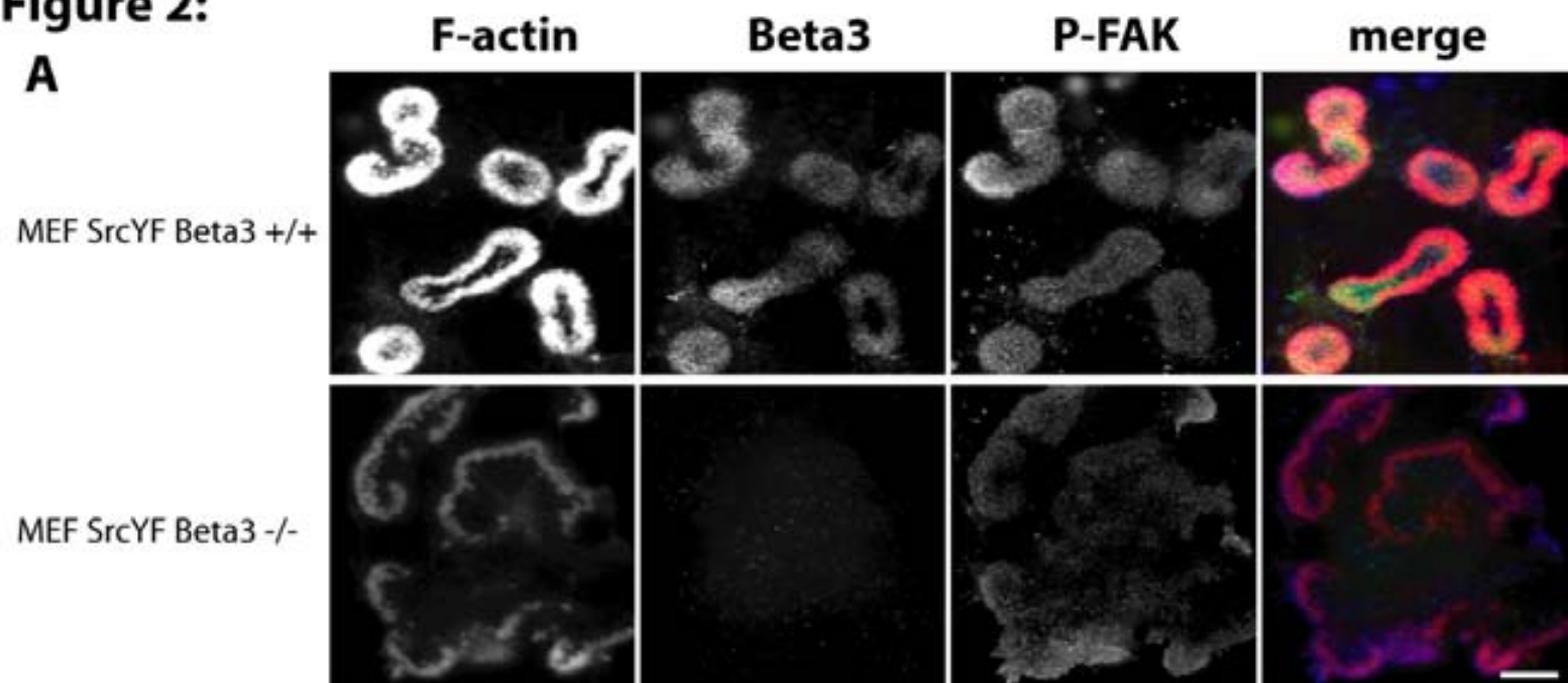
**Supplementary Movie 6:** Live imaging (0,016Hz) of invadosome rosette visualized by  $\beta 3$ -GFP (TIRF microscopy) and  $\beta 1$ -KillerRed<sup>TM</sup> (epifluorescence microscopy), followed by 45 s of red light irradiation to photo-inactivate  $\beta 1$ -KillerRed<sup>TM</sup>.

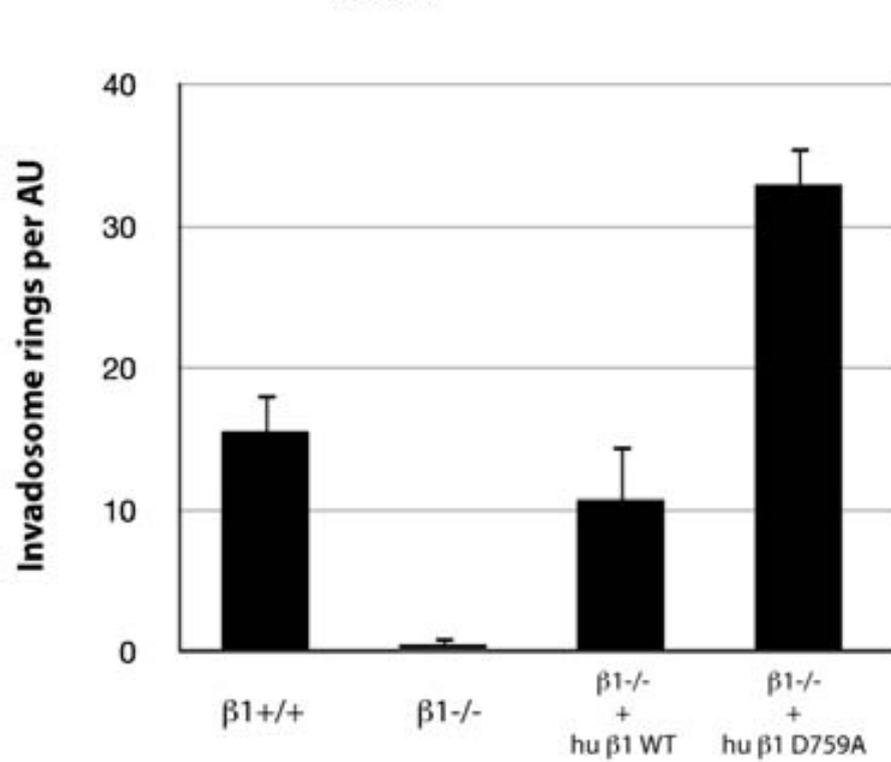
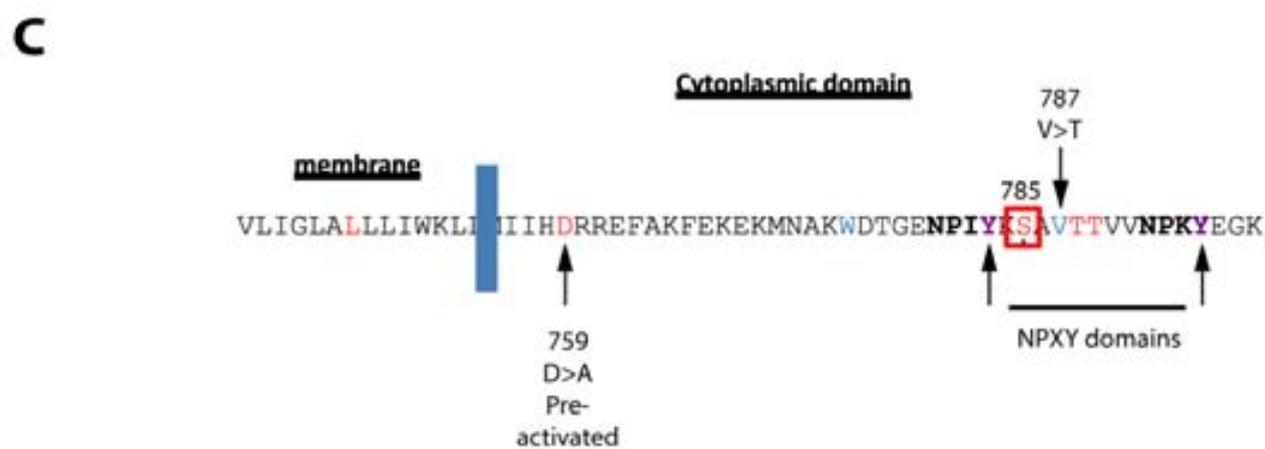
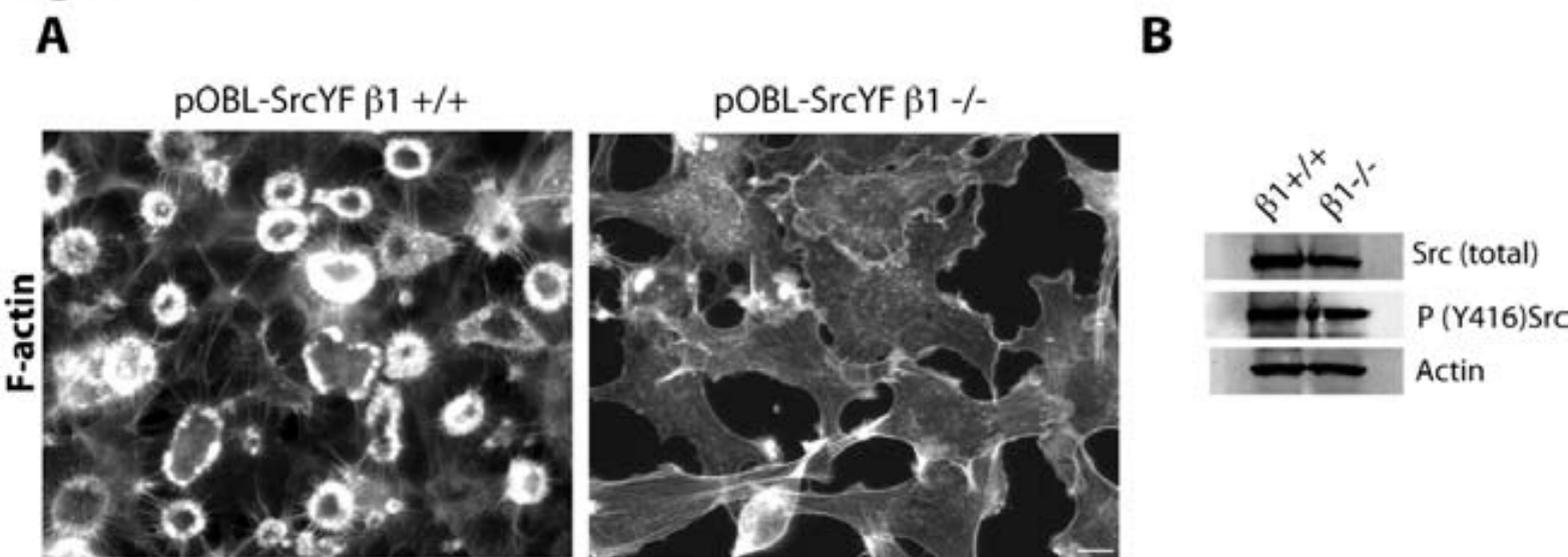
**Supplementary Movie 7:** Live imaging (0,1Hz) of invadosome rosette visualized by GFP-actin (TIRF microscopy) and  $\beta 1$ -KillerRed<sup>TM</sup> (epifluorescence microscopy), followed by 45 s of red light irradiation to photo-inactivate  $\beta 1$ -KillerRed<sup>TM</sup>.

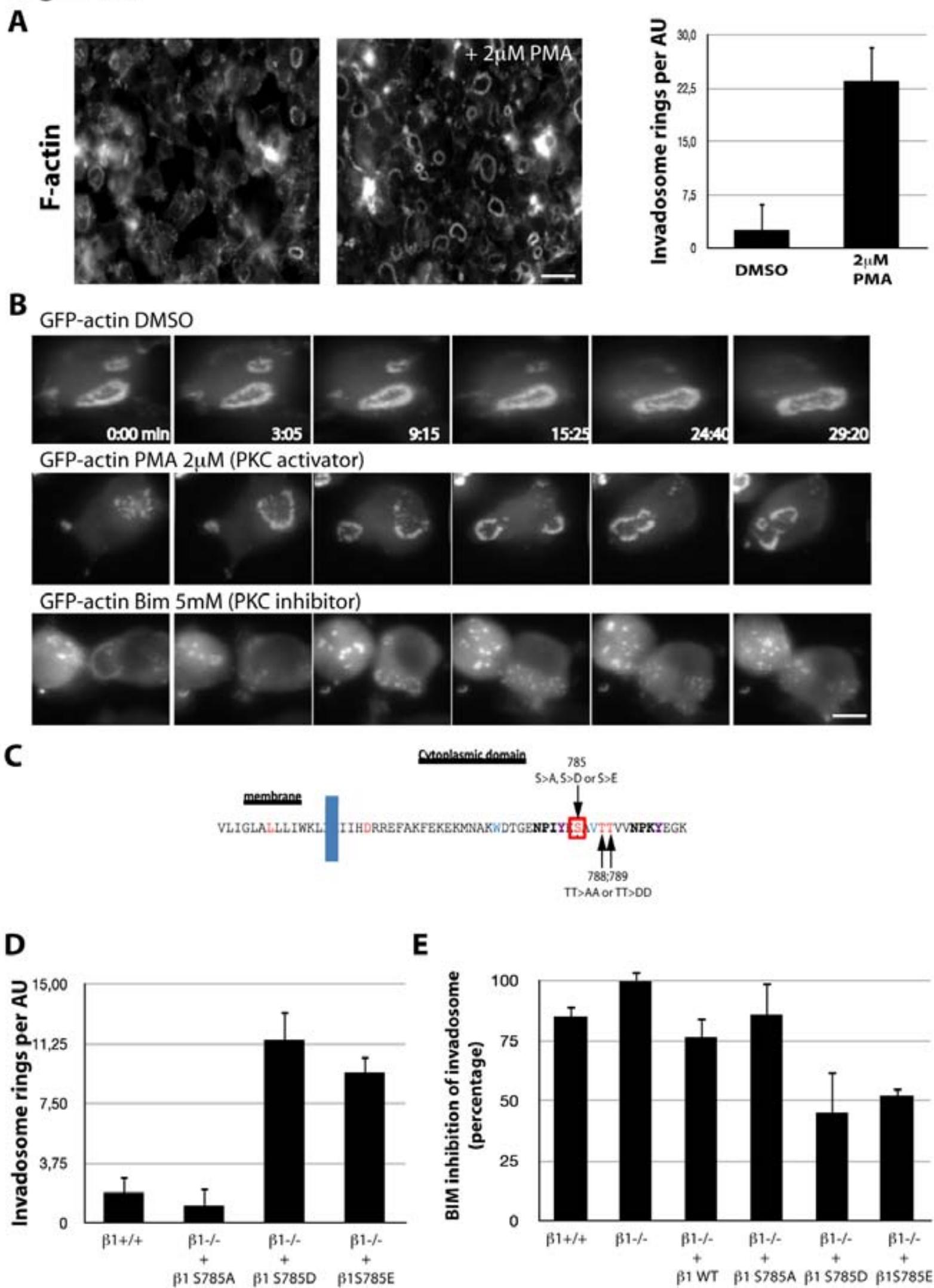
**Supplementary Movie 8:** Live imaging (0,0083Hz) of invadosome rosette visualized by  $\beta$ 1-GFP (TIRF microscopy) and cortactin-pTRFP (epifluorescence microscopy) under normal conditions.

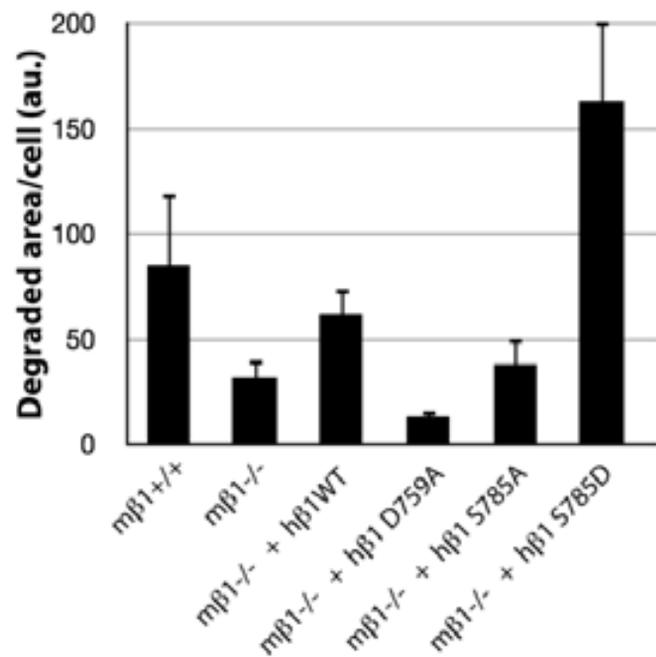
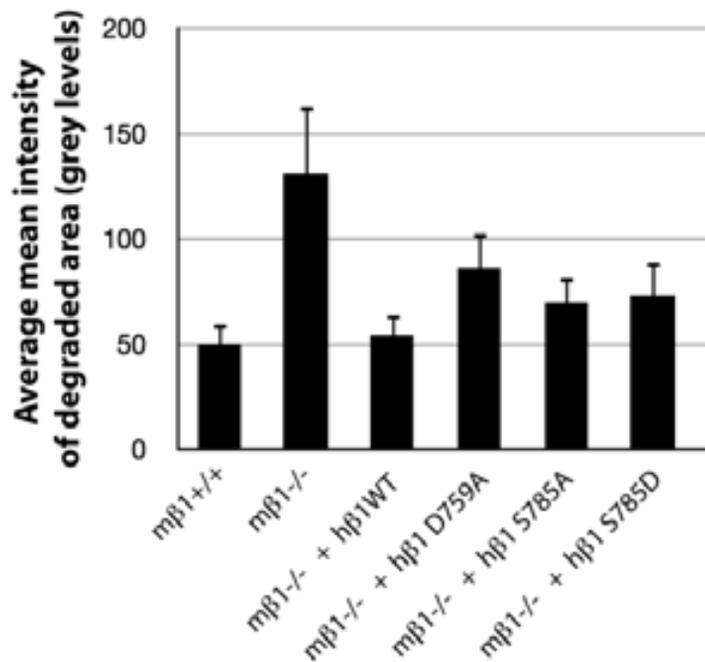
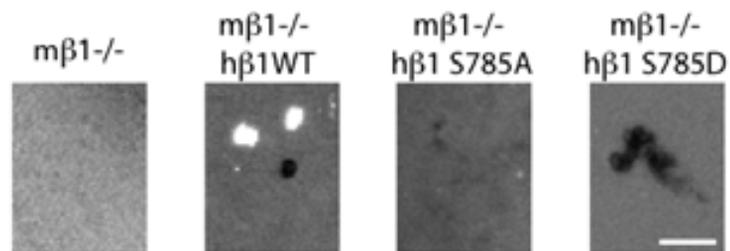
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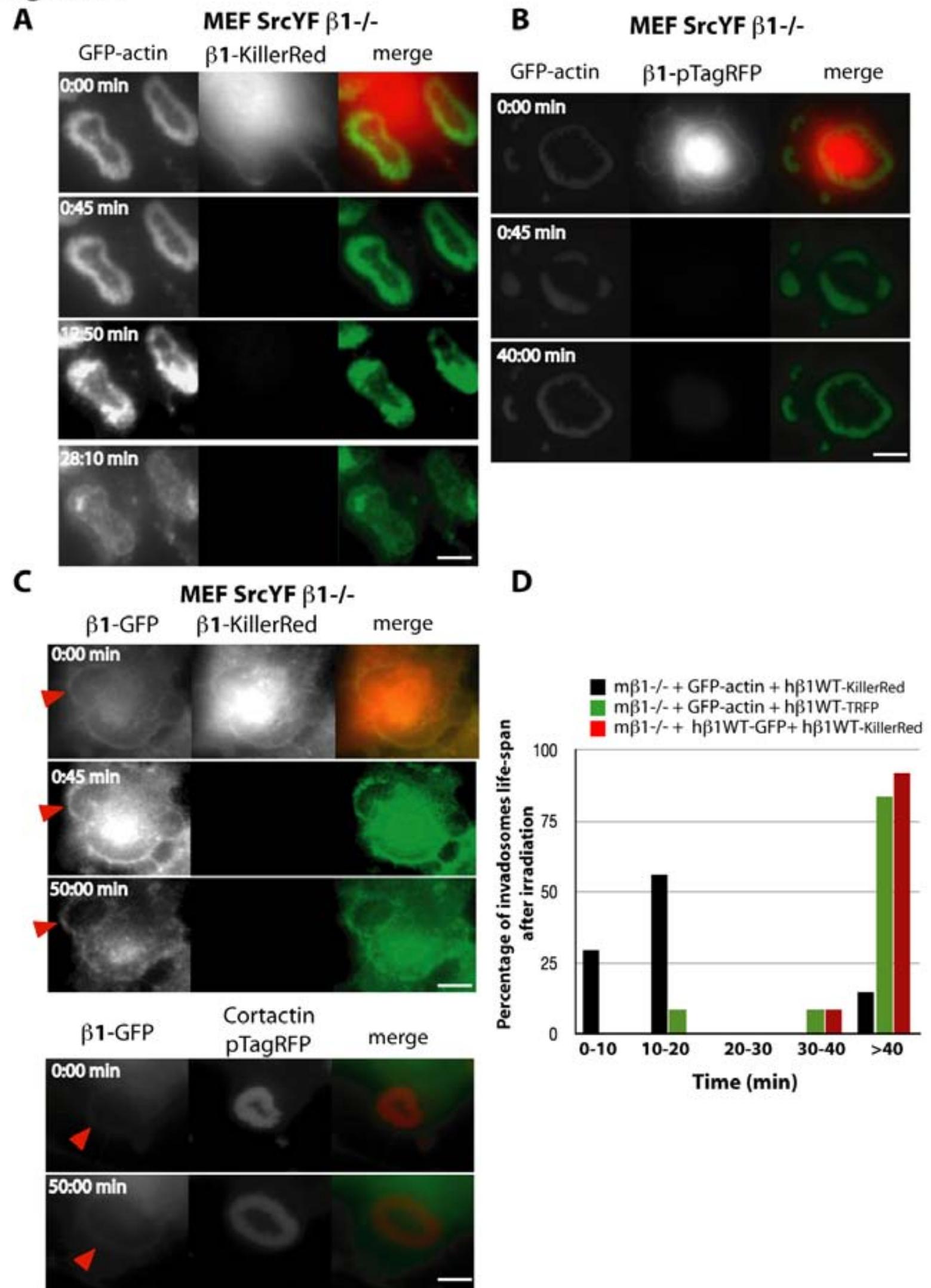


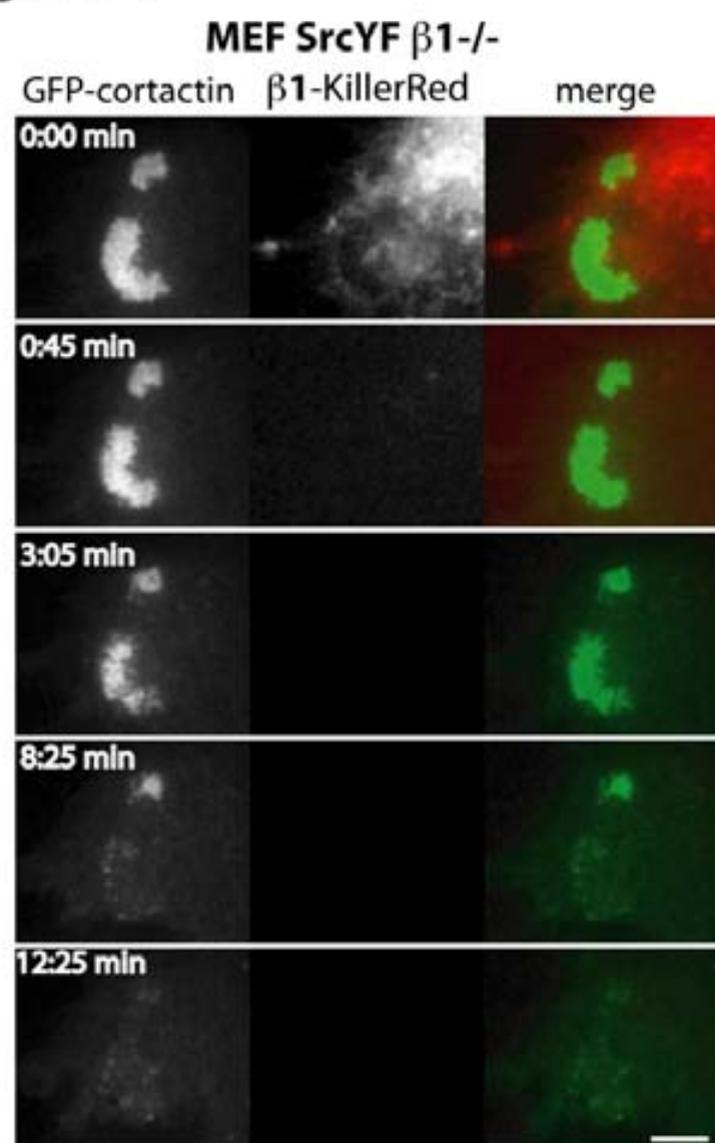
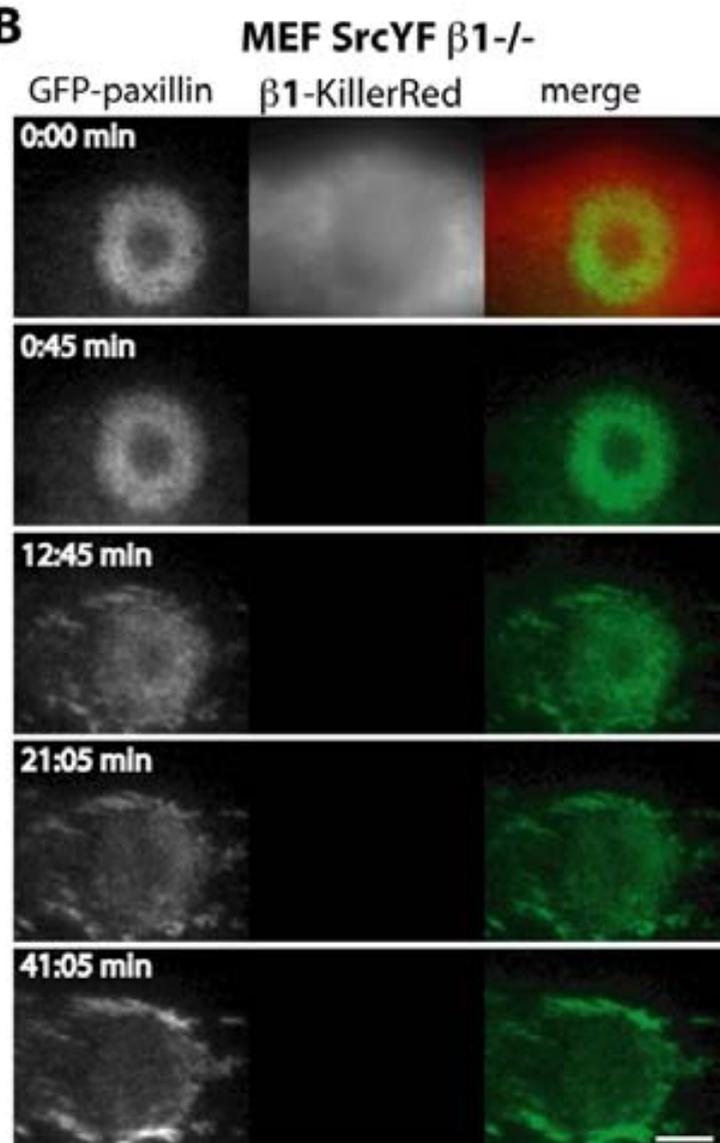
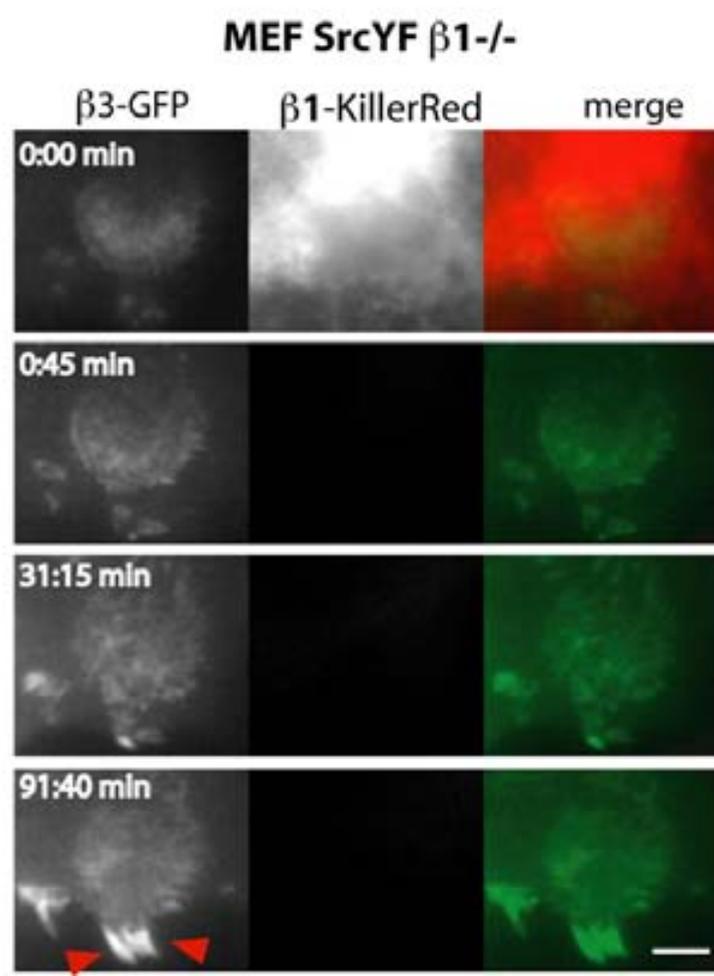
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**Figure 3:**

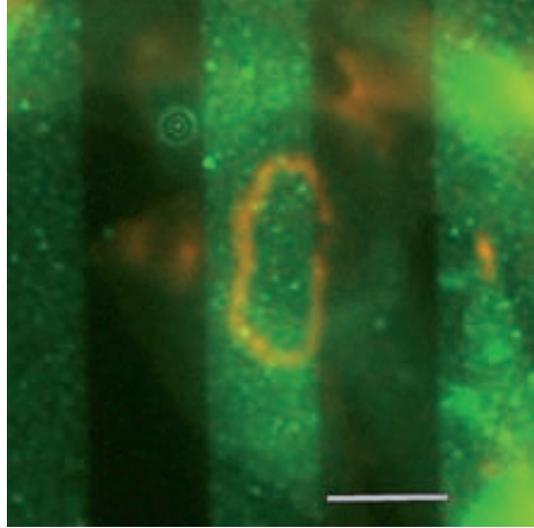
**Figure 4:**

**Figure 5:****A****B****C****Gelatin-Oregon green**

**Figure 6:**

**Figure 7:****A****B****C**

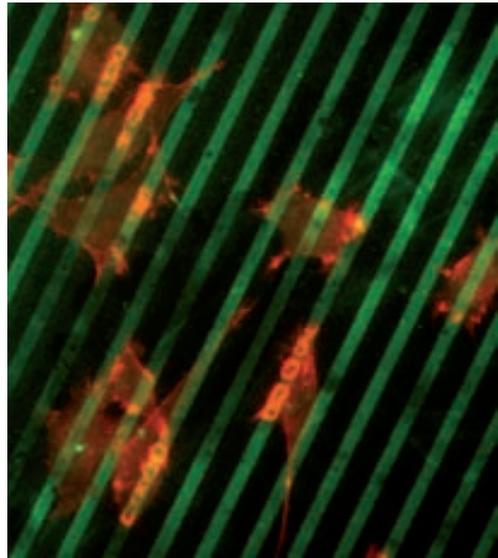
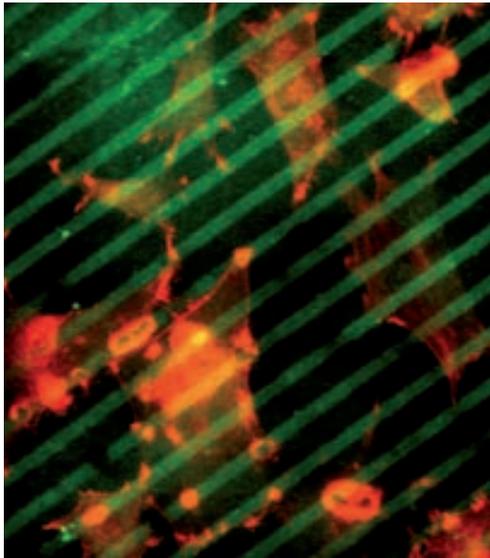
**A**



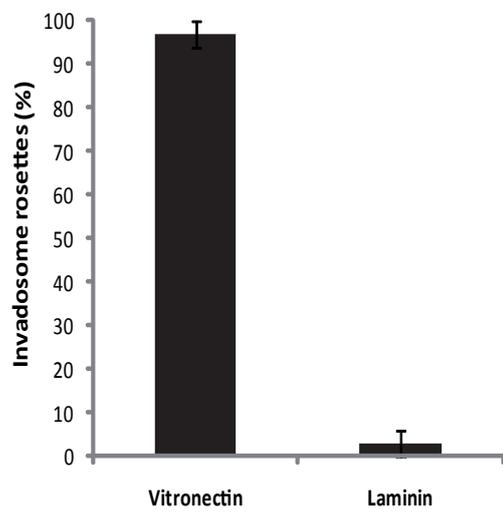
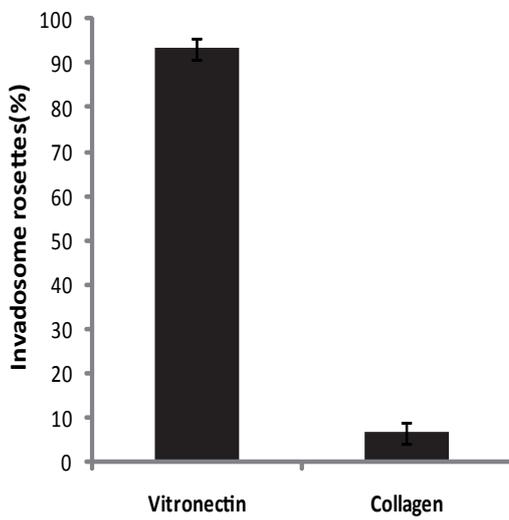
**Collagen/Vitronectin**

**Laminin/Vitronectin**

**B**



**C**



**Figure S1**

**Figure S2:**

**Invadosome rings per AU  
after PMA treatment**

