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Impact of Inherited Geometries on Syn-orogenic Foreland Basin Architecture

Benjamin Gérard¹, Delphine Rouby¹, Ritske Sipke Huismans², Cécile Robin³, Charlotte Fillon⁴ and Jean Braun^{5,6}

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- ⁶ ¹GET, Université de Toulouse, CNRS, IRD, UPS, Toulouse, France
- ⁷ ²Department of Earth Sciences, Bergen University, Norway
- ⁸ ³CNRS, Géosciences Rennes, UMR6118, University of Rennes, Rennes, 35042, France
- ⁹ ⁴TotalEnergies, Centre Scientifique et Technique Jean Féger, Avenue Larribau, 64018 Pau
- 10 Cédex, France
- ¹¹ ⁵Helmholtz Centre Potsdam, German Research Centre for Geosciences, Potsdam, Germany
- ⁶Institute of Geosciences, University of Potsdam, Potsdam, Germany
- 13
- 14 Corresponding author: Benjamin Gérard (<u>benjamin.gerard.alpes@gmail.com</u>)
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16 Key Points:

- An initially elevated foreland domain produces a thinner flexural basin than a low-lying
 foreland domain as more sediments are exported.
- An initially deep foreland produces a thicker basin than a flat-lying foreland domain
 because of the extra load of the initial space infill.
- An initially deep foreland domain is required to preserve a significant proportion deep
 marine deposits in the foreland basin.

23 Abstract

24 We use a Landscape Evolution Model (FastScape S2S) to explore the impact of inherited topography in the foreland domain of a rising mountain range on its stratigraphic architecture 25 26 and sediment accumulation history, inspired by the northern Pyrenean foreland. We simulate an uplifting half mountain range, its foreland basin and forebulge, and beyond, an open marine 27 domain. We ran models with 4 different initial reliefs in the foreland domain: an initially flat 28 foreland domain at sea-level, an elevated flat continental foreland (+300 m), a pre-existing 1 km-29 30 deep and 100 km-wide bathymetry at the location of the future foreland basin associated with a forebulge domain either at sea-level or elevated at +300m. 31

32

All models show a prograding mega-sequence associated with building of mountain topography and development of the flexural foreland basin and forebulge, coalescence of alluvial fans at the foot of the range, progressive continentalization of the foreland domain, and burial of the forebulge. An initially elevated foreland domain ultimately produces a thinner foreland basin while an initially deep foreland basin produces a thicker one.

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After 10-13 Myr, the initial relief of foreland domain is smoothed out and the landscape does not exhibit a record of pre-existing relief. In contrast, the stratigraphic architecture of the foreland basin allows to trace inherited relief with deep marine sediments in the initially deep foreland basin, marine sediments onlapping and then burying the forebulge initially at sea-level, and continental sediments onlapping and burying the initially elevated foreland domain. We compare these interpretations to the Pyrenean retro-foreland.

45

46 Plain Language Summary

Rising mountain ranges thicken earth crust and, the extra load generates lateral 47 48 depressions where sediments eroded in the mountain range are stored. This forms foreland sedimentary basins that record the growth of the mountain range. We simulated the landscape of 49 a mountain range to test the impact of different initial relief of its foreland domain, before the 50 mountain range build-up: initially low lying (0m), elevated (+300 m) or deep (-1000m) at the 51 foot of the mountain range. We show that an initially elevated foreland will preserve less 52 sediments and produce a thinner sedimentary basin than a low lying or deep forelands. The 53 54 landscape smooth out inherited relief after ~10-13 Myr and cannot be used to infer it afterwards. As a difference, the geometry of the sediment strata in the basin are discriminant: with marine 55 sediments covering the initially low lying and deep foreland and only continental sediments 56 57 covering the initially elevated foreland.

58

59 **1 Introduction**

Foreland basins are unique archives of the evolution of orogenic mountain ranges as they 60 preserve and recycle the products of their erosion. They often develop in previously rifted 61 domain (Erdos et al., 2014) and while the impact of rifting on the deformation sequence has been 62 widely studied (e.g. Molnar & Buiter, 2022; Wolf et al., 2021), its direct influence on the 63 evolution of foreland basins in terms of sedimentary architecture remains poorly documented. 64 The first-order stratigraphic architecture of foreland basins consists in most cases in a prograding 65 and coarsening-up mega-sequence initiating with deep to shallow marine conditions, followed by 66 continental fluvial plain and eventually alluvial fan deposits (DeCelles & Giles, 1996; Heller et 67 al., 1988). This mega-sequence is controlled by the variation of the ratio of accommodation 68

69 space creation (A) and sediment supply (S) (Allen & Allen, 2005; Beaumont, 1981; Clevis et al., 70 2004; Dickinson, 1974), which are driven by tectonic growth of the mountain range, climatic variability and eustasy. The sedimentary mega-sequence in foreland basins exhibits three 71 72 characteristic phases (Catuneanu, 2004; DeCelles, 2012). The "underfilled phase 1" is associated with deep marine depositional environments and an [A/S] ratio larger than 1. The filled phase 2 73 74 is associated with shallow marine and coastal fluvial plain depositional environments and an [A/S] ratio close or equal to 1. The overfilled phase 3 is associated with fluvial plain and alluvial 75 fan depositional environments during which the [A/S] ratio is lower than 1. 76

77

78 Uplift and subsidence in foreland domains mainly result from the flexural isostasy response to the load of the topography of the growing mountain range forming a foreland basin 79 at its foot and a distal forebulge. Sediment accumulation in the foreland basin further amplifies 80 the flexural isostatic response, creating additional accommodation space in the foreland basin 81 and uplift of the forebulge (Beaumont, 1981; DeCelles & Giles, 1996; Garcia-Castellanos & 82 Cloetingh, 2012; Figure 1). Surface processes, as part of the sediment routing systems, 83 84 constantly alter the topographic and sediment loads by producing sediments by erosion of the mountain range that are deposited in the foreland basins (Simpson, 2006). These mountain 85 range-foreland basins systems are therefore complex source-to-sink systems controlled not only 86 by mountain range tectonic uplift and foreland flexural subsidence but also by changes in 87 climate, base-level and eustasy impacting erosion, sediment transport and deposition (Flemings 88 & Jordan, 1989; Jordan & Flemings, 1991). Because these controlling factors are coupled, 89 flexural isostatic numerical modelling including mass conserving diffusion-based erosion, 90 sediment transport and deposition, has been commonly used to unravel their respective 91 contributions on the stratigraphic evolution in foreland basins (see Paola, 2000 and Garcia-92 Castellanos & Cloetingh, 2012 for review). These studies have thoroughly analyzed, among 93 others, the impact of erosional and depositional transport coefficients, effective elastic thickness, 94 rate of thrust advance or sediment supply cycles on the development of the either long-term or 95 short-term sequences and unconformities. For example, Flemings & Jordan (1989) showed that 96 the transition from the underfilled to overfilled phases can be solely driven by surface processes 97 (*i.e.* erosion, sediment transport and deposition efficiency) without other lithospheric processes 98 in addition to the flexural isostasy. Sinclair et al (1991) showed that unconformities can develop 99 in response to changes in thrusting and associated loading, the sediment transport coefficient, or 100 the surface slope of the orogenic wedge without eustasy or complex viscoelastic lithosphere 101 rheology. Flemings & Jordan (1990) demonstrated that thrusting events are recorded by transient 102 retrogradations associated with deepening initiated at the onset of a thrust cycle within an overall 103 progradation sequence. In addition to orogenic crustal thickening and sediment loading, an 104 increase in displacement of the orogenic frontal fault combined with efficient erosion can 105 produce a deeper foreland basin (Simpson, 2014). Finally, Naylor & Sinclair (2008) show that 106 retro-foreland basins are stratigraphically more stable than pro-foreland basins as they exhibit a 107 steady tectonic subsidence that allows recording the entire growth of the mountain range. Self-108 consistent thermo-mechanical models of mountain belt formation show similarly that shortening 109 and outward growth predominantly occur in the pro-wedge, whereas the retro-wedge is largely 110 stable (Erdos et al., 2014; Grool et al., 2019; Willett et al., 1993; Wolf et al., 2021). 111 112

113 Despite these numerous studies, the effect of inherited topography or bathymetry in the 114 foreland domain on stratigraphic architecture has not yet been addressed. Mountain ranges often

develop in previously rifted domains, as for instance in Tethyan orogenic systems such as the 115 116 Pyrenees and the Alps (Desegaulx et al., 1991; Erdos et al., 2014; Schlunegger et al., 1997; Vacherat et al., 2017). This suggests that these foreland domains may not correspond to flat 117 continental surfaces and exhibit pre-orogenic relief corresponding to remnants of the previous 118 extensional phase. In this work, we explore the effect of varying foreland paleo-topography and 119 paleo-bathymetry on foreland basin syn-orogenic stratigraphic architecture. To do this, we use a 120 Landscape Evolution Model taking into account both marine and continental sedimentary 121 processes and allowing to assess the relationships between stratigraphic architecture, flexural 122 isostasy, and landscape evolution in 3D (FastScape S2S; Yuan et al., 2019a; Yuan et al., 2019b). 123 We focus on the stratigraphic architecture of the retro-wedge foredeep, between the frontal tip of 124 the orogenic wedge and the forebulge (DeCelles & Giles, 1996). This allows us to simulate the 125 syn-orogenic landscape and foreland basin evolution with only vertical motion (uplift and 126 flexural isostasy) as retro-wedge systems of small to intermediate size orogens are relatively 127 stable and less affected by horizontal advection related to thrusting (Grool et al., 2018; Naylor & 128 Sinclair, 2008; Wolf et al., 2021). This generic approach, is inspired and compared to the 129 Pyrenean retro-foreland system in order to understand the potential effect of inherited 130 topography and/or bathymetry on the northern Pyrenean evolution and the build-up of its retro-131 foreland. 132 133



- **Figure 1**. a) Top view of the model setup and associated landscape domains. Lateral open
- boundaries imply that sediments exiting the model on one side enter it back on the opposite side.
- b) Cross section (location in a) with (1) the uplifted domain, (2) the foreland domain (foreland
- basin and forebulge) and (3) the open marine domain. c) Perspective view of the model showingthe location of the foredeep and forebulge sections.

141 **2 Materials and Methods**

We use the numerical Landscape Evolution Model FastScape (Bovy, 2021; Braun & Willett, 2013; Guerit et al., 2019; Yuan et al., 2019a; Yuan et al., 2019b). The model simulates the evolution of a fluvial landscape including sediment production, transport, continental and marine deposition, as well as the flexural isostatic response of the lithosphere to associated loading and unloading (Braun & Willett, 2013; Guerit et al., 2019; Yuan et al., 2019a; Yuan et al., 2019b; see details in Text S1).

148

Our model setup consists of a half mountain range $(150 \times 400 \text{ km})$ uplifting at a constant rate (0.5 mm/yr; Figure 1; Table 1) for 25 Myr. Eroded material produced in the uplifted area is transported to a foreland domain $(350 \times 400 \text{ km})$ and, beyond, to a distal open marine domain (200×400 km; Figure 1; Table 1). The foreland domain includes the foreland basin and the forebulge formed by flexural isostasy (Figure 1). The dimensions of the models are consistent with small-orogen retro wedge systems.

155

We present four models with varying initial topography and bathymetry in the foreland 156 (Figure 2): Reference model M1 with a foreland domain initially at sea-level (Figure 2a); Model 157 M2 with a foreland domain elevated at +300 m (Figure 2b); Model M3 with a 100 km-wide and 158 1000 m-deep water filled foreland basin and a 250 km-wide forebulge area at sea-level (Figure 159 2c); Model M4 with a 100 km-wide and 1000-m deep water filled foreland basin and an elevated 160 161 foreland area 300 m above sea level (Figure 2d). Model M1 is a reference model to allow comparisons. Initial bathymetries in models M3 and M4 are comparable to rift remnants as often 162 encountered in natural orogenic systems such as the Pyrenees (e.g., Desegaulx et al., 1991). The 163 initially elevated foreland domain in models M2 and M4 represents stable Phanerozoic 164 continents that have an average elevation of ~400 m +/- 400 m (e.g., Theunissen et al., in 165 review). The initial bathymetry in models M3 and M4 represents pre-existing rift related 166 167 topography. To initiate river grading toward the foreland domain, we impose a small initial tilt of the uplifted domain ($\alpha = 0.076^\circ$; Figure 2). 168

169

170 In the four models, we use parameter values generally admitted in the literature (Table 1). 171 A constant and homogenous precipitation rate P = 0.5 m/yr, an effective elastic thickness, EET = 15 km, fluvial erodibility $K_f = 2.5 \times 10^5 \text{ m}^{0.2}/\text{yr}$ (Whipple & Tucker, 1999), hillslope diffusion 172 $K_h = 1.0 \times 10^{-2} \text{ m}^2/\text{yr}$ (Armitage et al., 2013; Densmore et al., 2007), continental deposition 173 coefficient G = 0.4 (Davy & Lague, 2009; Guerit et al., 2019), and a marine diffusion coefficient 174 $K_d = 2.0 \times 10^2 \text{ m}^2/\text{yr}$ (Jordan & Flemings, 1991; Rouby et al., 2013; Yuan et al., 2019b; Table 1). 175 For marine diffusion, we use value representative for a silty grain-size (Rouby et al., 2013; 176 177 Simon et al., in review). Sediment compaction is not included.



Figure 2. Setup for models M1-M4. a) M1, foreland domain at sea-level. b) M2, elevated foreland domain (+ 300 m). c) M3, the foreland domain is composed of a water filled foreland basin (100 km wide; 1000 m deep) and forebulge at sea-level (250 km wide). d) M4, the foreland domain is composed of a water filled foreland basin (100 km wide; 1000 m deep) and an elevated forebulge at sea-level (250 km wide; + 300 m). Initial slopes of the uplifted domains (red box) are identical ($\alpha = 0.076^{\circ}$).

Parameter	Value	Unit
Size of the model domain	400×700	km
Size of the cell (d_x, d_y)	1000	m
Time step (d_t)	1000	yr
Total duration	25×10^{6}	yr
Uplift rate (U)	0.5	mm/yr
Precipitation rate (P) - homogeneous and constant	0.5	m/yr
Effective Elastic thickness (EET)	15 ^a	km
Erodibility (K _f)	$2.5 \times 10^{-5 \text{ b}}$	$m^{0.2}/yr$
Hillslope diffusion coefficient (K _h)	1.0×10^{-2} c;d	m ² /yr
Deposition coefficient (G)	$0.4^{e;f}$	-
Erosion law coefficients (m, n)	$0.4^{\rm g}, 1^{\rm h}$	-
Sea-level elevation	0	m
Marine diffusion coefficient (K _d)	2.0×10^{2} i;j;k;l	m ² /yr
Porosity (Ø) - proxy for compaction	0	%

186 **Table 1**. Common Parameters for the Different Models

187 Note. The erodibility value (K_f) was chosen to reach a mean mountain range elevation of ~1.7

188 km after 25 Myr. Parameters from ^aGarcia-Castellanos & Cloetingh (2012⁾; ^bWhipple & Tucker 189 (1999); ^cDensmore et al. (2007); ^dArmitage et al. (2013); ^eDavy & Lague (2009); ^fGuerit et al.

(2019); ^gStock & Montgomery (1999); ^hBraun & Willett (2013); ⁱJordan & Flemings (1991);
 ^jRouby et al. (2013); ^kYuan et al. (2019b); ^lSimon et al. (in review).

193 **3 Results**

194**3.1 Reference model M1**

During the first 1 Myr of the reference model M1, initial mountain belt grows to an 195 196 average topography of 1.7 km elevation at 25 Myr (Figures 3a and 4a). The basement of the flexural foreland basin subsides progressively under the load of the mountain range topography 197 and of the deposited sediments. The depositional environments are largely shallow marine and 198 the forebulge is partly submerged (Figures 3b and 4a). Part of the sediments produced by erosion 199 of the mountain belt fills the flexural foreland basin while the remainder is exported to the 200 marine domain ([A/S] ratio less than, but nearly equal to, 1; Figures 3a and 4a). Initially isolated 201 and progressively coalescing alluvial fans (sediment deposited at a slope $> 0.4^{\circ}$; Bull, 1964; 202 Milana & Ruzycki, 1999) form at the foot of the mountain range (Figures 3b and 4a). At 6 Myr, 203 204 continental deposits migrate from the foot of the mountain range to the forebulge as the foreland basin evolves toward an overfilled stage ([A/S]<1; Figures 3b and 4a). At 15 Myr, continental 205 deposits reach the forebulge (Figures 3c and 4a). At 25 Myr, the foreland domain is completely 206 continentalized and the forebulge area is emerged (Figures 3d and 4a). 207



Figure 3. Evolution of model M1 at (a) 1 Myr; (b) 6 Myr, (c) 15 Myr and (d) 25 Myr. The

surface of the model is coloured according to the topography and bathymetry. The section of the model is coloured according to the depositional bathymetry. Black arrows represent sediment transport directions.



Figure 4. Top view of the topography of models (a) M1, (b) M2, (c) M3 and (d) M4 at 0.3, 1, 5, 10 and 25 Myr. Topography below sea-level is shown in grey.

3.2 Models M2 to M4 with inherited topography/bathymetry in the foreland domain
Models with inherited topography and/or bathymetry in the foreland domain follow a
general first order evolution similar to the reference model: initial building of mountain range
topography, development of the flexural foreland basin, formation of alluvial fans at the foot of
the mountain range, and the progressive continentalization of the foreland domain (Figures 4, S1,
S2 and S3). Inherited topography and/or bathymetry in the foreland domain does nevertheless
have a significant impact on the surface evolution of the models (Figures 4, S1, S2 and S3).

224

Model M2, that has a continental foreland domain initially elevated at 300 m (Figure 2b), develops a drainage network that incises the foreland domain and connects the mountain range to the open marine domain within the first 5 Myr (Figures 4b and S1). Throughout the model evolution, the subsiding foreland basin preserves part of the sediments deposited in a continental environment, while the remaining sediments are exported to the open marine domain. In contrast with the reference model M1, the initially open marine domain is entirely continentalized after 25 Myr (Figures 4b and S1).

232

Model M3 includes an initial water filled foreland basin (1000 m deep) at the foot of the uplifting mountain range (Figure 2c). During the first 5 Myr, sediments produced in the mountain range are fully stored in the initial deep basin under marine depositional conditions (Figures 4c and S2). At this stage the foreland basin is underfilled ([A/S]>1). The export of sediments toward the open marine domain and the transition to an overfilled stage ([A/S]<1) are delayed compared to the reference model M1 (Figures 4a, 4c and S2).

239

240 Model M4 combines an initial water filled foreland basin at the foot of the uplifting mountain range with a continental forebulge initially elevated at 300 m (Figure 2d). During the 241 first 5 Myr, sediments are fully stored in the initial deep basin, under marine depositional 242 environments, similarly to model M3 (underfilled stage; [A/S]>1). Additional sediments are, 243 however, produced by erosion of the elevated forebulge area and deposited in the foreland and in 244 the marine domain (Figures 4d and S3). Similarly, to M3, sediment export toward the open 245 marine domain is delayed compared to the reference model M1 (Figures 4a, 4d and S3). The 246 foreland basin reaches the overfilled stage with continental depositional environments by 5 Myr, 247 earlier than in the reference model M1 (Figures 4a, 4d and S3). After 10 Myr, erosion affects the 248 continental foreland domain, remobilizing and exporting previously deposited sediments towards 249 the open marine domain. The entire foreland domain is continentalized at 25 Myr (Figure 4d). 250

251 252

3.3 General characteristics of mountain range and foreland basin evolution

We next evaluate the evolution of mean elevation, mean erosion rate, foreland basin 253 depth, and sediment volume in the models (Figure 5). The evolution of the mean elevation of the 254 uplifted domain is very similar in the four models and shows a progressive build-up to ~ 1.7 km 255 after 25 Myr, without reaching steady state (Figure 5a). Associated mean erosion rates in the 256 mountain range follow a similar build-up to $3.5 - 4.0 \times 10^{-4}$ m/yr at 25 Myr (Figure 5b). During 257 this build up however, all models undergo drops in mean erosion rates (ca. two-fold decrease; 258 Figure 5b). The timing of the drops in erosion rate varies from one model to the other (5.2, 4.9 259 and 3 Myr in Models 1, 2 and 3 respectively). Model M4 shows a more complex behavior with a 260 261 first drop at 4.6 Myr and a second one at 11.9 Myr associated with a few oscillations. After the drops, all models return to a trend of increasing mean erosion rates over time (Figure 5b). This 262

particular behavior is further discussed below. Supplementary Figure S4 provides a top view of
 the erosion and deposition rates above sea-level through time.

265

The maximum basement depths of the foreland basins of M1 to M4 exhibit similar deepening trends but reach different final depths at 25 Myr (e.g., 2.7 km for M1, 2.3 km for M2, 3.6 km and 3.4 km for M4; Figure 5c). The total volume of sediments produced in the mountain range is similar in the four models (4 to 4.5×10^{14} m³). However, the volume of sediment accumulated in the foreland is quite different between the models $(1.30 \times 10^{14}, 0.95 \times 10^{14},$ 2.20×10¹⁴ and 1.80×10^{14} m³ for M1, M2, M3 and M4 respectively; Figure 5d). This is mirrored by different proportions of sediments exported to the open marine domain.





3.4 Foreland basin stratigraphic architecture

For each model, we show the stratigraphic architecture of the foreland basin along a longitudinal cross-section as well as the corresponding Wheeler diagram of the depositional bathymetry/elevation through time (Figures 6a-h; Sections location in figure 4). We highlight the transition from alluvial fan to fluvial plain deposits for sediments with a depositional slope > 0.4° (Figures 6 and S5; Bull, 1964; Milana & Ruzycki, 1999).

290

291 In reference model M1, the foreland basin has a maximum thickness of 2.6 km at the mountain front (Figure 6a). It shows continuous accumulation, first in a shallow marine 292 depositional environment with a water depth <100 m and an [A/S] ratio >1, evolving to 293 continental conditions with a [A/S] ratio <1 (Figures 6a and 6e). Marine foreland basin deposits 294 first onlap the forebulge before burying it by 12 Myr (Figures 6a and 6e). Continental deposits 295 emplaced at the foot of the mountain range from 5-7 Myr and then progressively propagate 296 through the foreland domain to reach the open marine domain by 25 Myr. Alluvial fans 297 propagate up to 40 km within the foreland basin (Figures 6a and 6e). 298

299

In model M2, sediments in the foreland basin are significantly thinner than in reference 300 model M1, reaching a maximum thickness of 2.0 km of only continental deposits (Figure 6b and 301 6f). Significant regressive erosion affects the elevated foreland until 10 Myr (Figure 4b and 6f). 302 Continental sediments bury the forebulge by 11 Myr (Figures 6b and 6f). The foreland shows 303 several local incisions, especially after 16 Myr (Figure 6f). The erosion patterns of fluvial 304 incision (channels of a few kilometers) or larger eroding areas (~80 km) develop particularly 305 above the buried forebulge, remobilizing previously deposited sediments (Figure 6f). Alluvial 306 fans propagate up to ~ 100 km within the foreland basin (Figures 6b and 6f). 307

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In model M3, the foreland basin reaches a maximum thickness of 4.5 km (Figure 6c). Sediments produced in the mountain range are initially fully deposited in the deep foreland basin under marine environments with water depths >300 m and an [A/S] ratio >1 (Figure 6c). The marine sediments progressively onlap the forebulge before burying it by 10 Myr (Figure 6c and 6g). Subsequently, the shoreline propagates across the foreland domain similarly to model M1 (Figure 6g). Alluvial fans then propagate up to ~80 km within the foreland basin (Figures 6c and 6g).

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In model M4, the maximum thickness of the foreland basin is 4.4 km, similar to model 317 M3 (Figure 6d). The initial deep foreland basin is under marine depositional environments until 318 5 Myr, with deposition depth >300 m (Figure 6d). The transition to overfilled conditions ([A/S] 319 ratio <1) occurs earlier than in reference model M1. At 13 Myr the forebulge is buried by 320 continental deposits (Figure 6h). Similar to Model M2, the elevated forebulge undergoes 321 significant regressive erosion until 10 Myr (Figures 4d and 6h), and shows more local incisions 322 afterwards, at 12 and 22-23 Myr (Figure 6h). Subsequently, alluvial fans propagate for more than 323 100 km in the foreland basin (Figures 6d and 6h). 324



Figure 6. Stratigraphic architecture of the foreland basins of (a) M1, (b) M2, (c) M3 and (d) M4 models along the sections located in Figure 4. Sediments are coloured according to their depositional bathymetry or elevation. Associates Wheeler diagrams of (e) M1, (f) M2, (g) M3 and (h) M4 models. The limit between fluvial plains and alluvial fans is extracted for portions, longer than 10 km, associated to depositional slopes $>0.4^{\circ}$ (Figure S5).

332 3.5 Erosion and accumulation dynamics

Our models show peculiar erosion and accumulation features. In reference model M1, erosion rates in the mountain range reduce sharply at 5.2 Myr. Subsequently the rate of erosion increases again steadily with time (Figures 5b and 7). The reduction in erosion rate is coeval with the coalescence of alluvial fans at the foot of the mountain range (Figure 7b). Models M2-M4 exhibit similar behavior with one or more short time scale reductions of erosion rate that are also correlated to changes in continentalization or alluvial fan dynamics (Figure 5b, S6, S7 and S8).

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Figure 8 shows the co-evolution of depositional environments and bathymetry/elevation 340 at the foot of the mountain range. In models M1, M3 and M4, transition from marine to 341 continental depositional environments occurs between 3.0 and 4.6 Myr. In model M1, M2 and 342 M3, alluvial fan build-up occurs between 4.9 and 6.0 Myr. Model M4 presents specific features 343 in comparison to other models. Transition from marine to continental depositional environments 344 corresponds to a first alluvial fan build-up (i.e., without preceding fluvial plain deposits) and a 345 second phase of alluvial fan build-up occurs at 11.9 Myr (Figure 8d). The shoreline migration 346 rates across the foreland are 23 and 17 km/Myr for M1 and M3, respectively (Figures 8a and 8c). 347 For all models, the maximum elevation of the alluvial fan varies from 600 to 800 m at 25 Myr 348 (Figures 8). 349

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Interestingly, reductions in erosion rates in the mountain range are coeval with the transition from the underfilled to the overfilled phase, that is with the transition from marine to continental depositional environments and/or with alluvial fan coalescence in the foreland basin (Figures 5b, 7, 8, S6, S7 and S8).









Figure 8. Evolution of depositional bathymetry / elevation of sediments at time of deposition along the foreland section (solid line) and forebulge section (dashed line; see location of sections in Figure 1c) for models M1 to M4 (Figure 2). These curves represent the mean elevation values integrated along the sections (Figure 1c).

367 4 Discussion

368 4.1 Stratigraphic evolution trends of reference model M1

Model M1 produces a long-term prograding mega-sequence that is characteristic of 369 370 foreland basin stratigraphic architecture (Figure 9a; DeCelles & Giles, 1996). During the first stage, the topographic load of the rising mountain range creates accommodation in the foreland 371 basin by flexural isostasy allowing storage of sediments at the foot of the mountain range 372 (Figures 5a, 5b, 3 and 6a). The load of these sediments amplifies the flexural subsidence of the 373 foreland basin. At the same time, sediments in excess of accommodation space available in the 374 foreland basin are exported across the forebulge to the open marine domain (Figure 3a). The 375 foreland basin at the foot of the mountain range is characterized by marine depositional 376 environments between 0-3.6 Myr corresponding to the underfilled phase ([A/S]>1; Figures 3a 377 and 8). From 3.6 Myr onward, the foreland basin stores progressively less sediments showing 378 that creation of accommodation space by flexure is lower than sediment production in the 379 mountain range (Figure 5d). The progressive continentalization of the foreland domain initiated 380 at 3.6 Myr marks the transition of the foreland basin from underfilled to filled-overfilled 381 $([A/S] \le 1;$ Figures 3 and 8a). This transition is slightly diachronous longitudinally, depending on 382 the local relief of the mountain range, and migrates across the foreland basin at a mean rate of 23 383 km/Myr (Figures 3, 6a, 6e and 8a). Models M2 to M4 display this long-term trend as well, 384 although the timing of continentalization and sediments export to the marine domain are 385 different (Figures 6 and 9). 386

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Along with the continentalization, alluvial fans form at the foot of the range and show 388 alternating build-up and retreat away and toward the mountain range (Figures 6a and 6e; 389 Catuneanu, 2019). These oscillations are driven by local lateral migration of alluvial fans (i.e., in 390 and out of the cross-section). These lateral migrations are driven by the competition between 391 local erosion and the space available for deposition, which is controlled by the deposition of the 392 previous fans, local reliefs and individual drain dynamic (Movie S1). These short-term 393 oscillations provide only minor perturbations within the general long-term prograding mega-394 sequence in which alluvial fans migrate from the mountain range towards the open marine 395 domain (Figure 9). 396

All our models are based on identical mountain range uplift rate, erodibility, and effective 398 399 elastic thickness. To test the robustness of the mega-sequence described above, we performed a sensitivity analysis of model M1 to varying uplift rate, erodibility, and effective elastic thickness. 400 Varying these parameters modifies the timing of the characteristic stages of the mega-sequence 401 (Table S1; Figures S9 to S11). Supplementary model SM1 shows that higher uplift rate results in 402 higher mountain range topography and accordingly topographic load, which result in a larger 403 flexural isostatic response of the foreland and ultimately in thicker foreland basin deposits 404 (Figure S9). Supplementary model SM4 shows that higher erodibility reduces mountain range 405 topography and the associated flexural controlled accommodation space creation in the foreland 406 basin (Figure S10). Finally, supplementary model SM5 shows that higher effective elastic 407 thickness results in higher amplitude and longer wavelength of foreland basin deepening, 408 resulting in a thicker foreland basin (Figure S11). However, the long-term stratigraphic mega-409 sequence of the foreland basins described above is similar in all our models irrespective of the 410 411 uplift rate, erodibility, and effective elastic thickness (Text S2; Table S1; Figures S9 to S11).



Figure 9. Schematic stratigraphic architecture for models (a) M1, (b) M2 and (c) M3. Upper panels show schematic cross-sections of the initial setups. Middle panels show schematic crosssections of the depositional environments in the foreland basin. Bottom panels show associated schematic Wheeler diagrams.

4.2 Influence of inherited foreland domain topography and bathymetry

The landscape evolution of models M1 to M4 is significantly different within the first 10 420 Myr as a result of the inherited foreland domain bathymetry and topography (Figure 4). For 421 instance, in cases with a pre-existing foredeep (e.g., M3 and M4), sediment export to the open 422 marine domain is delayed with respect to reference model M1 because the initial deep basin first 423 fills-up during the first 4 - 7 Myr (Figure 4 and 5d; Movies S3 and S4). In models with an 424 elevated foreland (M2 and M4), regressive erosion remobilizes sediments previously deposited 425 in the foreland domain (Figures 4b and 4d; Movies S2 and S4). The forebulge is buried by 426 continental sediments in models with an elevated foreland while it is buried by marine sediments 427 when the foreland domain is initially at sea-level (models M1 and M3; Figures 6 and 9; Movies 428 S1 and S3). However, the influence of the initial relief largely disappears after $\sim 10-13$ Myr and 429 all models show similar landscapes with a continentalized foreland domain developing 430 longitudinal hydrographic networks (Figure 4). Nonetheless, at 25 Myr, the location of the 431 shoreline in the various cases provides a memory of the initial foreland basin setting. An initial 432 elevated foreland leads to further migration of the shoreline compared to the reference case. 433 Thus, in our models, the landscape after 10-13 Myr contains only indirect clues regarding the 434 initial foreland geometry (Figure 6). 435

Once the foreland basin is continentalized, the sedimentary load is more evenly 437 distributed over the entire accumulation area (foreland basin, forebulge, and open marine 438 domain). Its influence on the flexure and the differential subsidence/uplift in the foreland basin 439 and forebulge decreases (Figure 5). On the other hand, the increasing topographic load of the 440 mountain range continues to deepen the basement of the foreland basin. Over time the 441 importance of local flexural isostatic subsidence decreases, especially when the forebulge is 442 permanently buried by sediments (between 10 and 13 Myr in the models shown here; Figures 6 443 and 9). This stage corresponds to the period when the initial topography and bathymetry are no 444 longer visible in the landscape. 445

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The initial relief of the foreland does not significantly influence the topographic evolution 447 of the mountain range and, accordingly, mean elevation histories are similar in the four models 448 (Figure 5a). As the mean elevation of the uplifted domain and sediment production are similar 449 between the models, the topographic load of the mountain range cannot explain the differences 450 in the depth of the foreland basin basement in the four models (Figure 5c). The differences in 451 foreland basin geometry are consequently directly linked to the load of the sediments stored in 452 the foreland basin and to variations in accommodation space creation resulting from different 453 initial topography and bathymetry of the foreland domain. 454

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4.3 Influence of the initial elevation of the foreland domain on its stratigraphic evolution

The initial elevation of the foreland domain directly controls its storage capacity for sediments. 458 In models with an initial foreland domain at sea-level (M1 and M3), the foreland basin basement 459 is ultimately 600 m deeper and has a thicker infill with a large proportion of marine to 460 continental sediments than in models that have a foreland domain that is initially elevated (M2 461 and M4; Figures 5c and 6). The initially elevated foreland domain (300 m above marine base-462 level) is rapidly incised by regressive erosion that connects the mountain range to the open 463 marine domain (Figures 4b and 4d). These river networks, not only export sediments exiting the 464 mountain range to the marine domain, but also remobilize sediments previously stored in the 465 foreland basin (Figures 4b, 4d, 6 and 9). 466

The initial elevation of the foreland domain also influences the build-up of alluvial fans at 468 the foot of the mountain range. Alluvial fans form at higher elevation and are more widely 469 spread out at the foot of the mountain range in models with an initially elevated foreland domain 470 (~100 km for M2 and M4) than in models with a foreland domain at sea level (< 80 km for M1 471 and M3; Figures 6, 8 and 9). We interpret this to result from reduced accommodation space 472 available in the case of an initial elevated foreland domain that allows less material to be stored 473 at the foot of the mountain range in comparison with cases with a foreland domain at sea level. 474 The lower amount of sediment stored in the foreland basin for these cases results in less 475 accommodation space creation by flexure. As a result, alluvial fans form at higher elevation in an 476 initially elevated foreland and spread further out than in cases with a foreland domain that is 477 initially at sea level. 478

4.4 Influence of an initially deep foreland basin on its stratigraphic evolution 480

In models M3 and M4 with an initially deep foreland basin (1000 m), the basement is 481 twice deeper and sediments are twice thicker than in models with a foreland initially elevated or 482

at sea-level (M1 and M2; Figures 5c, 6 and 9). The initially deep foreland basin forms a large 483 484 additional accommodation space. Sediments exiting the mountain range that are initially stored in the inherited deep foreland basin increase the load induced flexural response and the creation 485 of accommodation space with respect to the models without a deep basin (M1 and M2; Figures 486 4, 5c and 6). Sediment export to the open marine domain is accordingly delayed and the foreland 487 domain is less incised when it emerges (Figure 6). Accordingly, shoreline migration across the 488 foreland domain and continentalization are slower for model M3 (17 km/Myr) than for reference 489 model M1 (23 km/Myr; Figure 8). In addition, our models suggest that an initially deep foreland 490 basin is required to preserve a significant proportion of marine deposits in foreland basins. 491

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The initially deep foreland basin also leads the formation of alluvial fans at lower 493 elevation than in other models (Figures 6 and 8). In the cases with an initial deep foreland basin, 494 the additional load of sediments filling in the basin enhances the flexural response and the 495 creation of accommodation space (Figures 5c, 6 and 9). As a result, the continentalization rate is 496 slower and alluvial fans form at lower elevations than in the reference model. 497

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As discussed by Simpson (2014), increased displacement of the mountain range-fault 499 front leads to a deeper foreland basin. We show here that an inherited bathymetry, which can be 500 considered as a rift remnant, provides an alternative mechanism to produce a deep foreland 501 502 basin.

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4.5 Accumulation feedback on erosion rates

We show above that the inherited foreland domain topography and bathymetry exert a 505 control on the sediment accumulation history in foreland basins in a syn-orogeny context. 506 However, the filling dynamics of the foreland basin also exerts a feedback on erosion of the 507 mountain range. Indeed, abrupt drops in erosion rates in the uplifted domain (Figures 5b and 7) 508 are synchronous with changes in the depositional systems at the foot of the mountain range in the 509 foreland domain. These systematically correspond to a transition from marine to continental 510 depositional environments or from fluvial to alluvial fan deposits (Figures 7, 8, S6, S7 and S8). 511 512

- Continentalization of the foreland domain, as well as build-up and coalescence of alluvial 513 fans, is associated with a raise of the base-level at the foot of the mountain range resulting in a 514 decrease of the erosive potential of the mountain range (Babault et al., 2005; Carretier & 515 Lucazeau, 2005). These events are responsible for the transient drops of erosion rates observed in 516 the mountain range (Figures 5b and 7). Afterwards, the hydrographic network returns to its 517 previous base level and erosion rates in the mountain range gradually return to similar but lower 518 trends (Figure 5b). This autogenic feedback has previously been documented using both 519 analogue (Babault et al., 2005) and numerical modelling studies (Carretier & Lucazeau, 2005). 520 The high-frequency transient oscillations in erosion rates shown in models M1 and M4 521 correspond to short time scale coalescence and dispersal events of alluvial fans (< 500 kyr; e.g., 522 Figure 5b). However, these short-term oscillations do not impact the long-term erosion dynamics 523 of the mountain range. 524
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4.6 Comparison with the Pyrenean retro-foreland system

527 We next consider the northern retro-foreland system of the Pyrenees (Figure 10). The northern Pyrenees and the Aquitaine basin - Bay of Biscay system is a classic example of retro-528

529 wedge flexural foreland basin (Angrand et al., 2018; Bernard et al., 2019; Ortiz et al., 2020). The 530 northern Pyrenean retro-foreland developed through inversion of an inherited rifted domain. Vacherat et al. (2017) and Desegaulx et al., (1991) show that inherited bathymetry in the 531 532 Pyrenean proto-foreland significantly affects the record of vertical motion and the stratigraphy of the foreland. The Pyrenean retro-foreland basin exhibits a classical prograding coarsening 533 upward megasequence (Ortiz et al., 2020). Several features of the Pyrenean system are, however, 534 not included in our model setup such as: horizontal displacement of thrusts, thermal post-rift 535 subsidence (Vacherat et al., 2014), basement heterogeneities in the retro-foreland basin (Angrand 536 et al., 2018), geological and geometric complexities during mountain building (Vacherat et al., 537 2017), and lateral variations in exhumation and uplift of the mountain range (Curry et al., 2021; 538 Fillon & van der Beek, 2012; Fitzgerald et al., 1999). However, several first order features of our 539 models are useful to provide understanding of retro-foreland basins systems such as in the 540 northern Pyrenees. 541

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In our models, mean mountain range elevation after 25 Myr is in the order of 1.5–2 km 543 (Figure 5a), similar to the reconstructed mean elevation of the Pyrenean mountain range at the 544 end of the syn-orogenic phase (e.g., Curry et al., 2019; Huyghe et al., 2012). The maximum total 545 subsidence at the deepest part of the Pyrenean retro-foreland (Central Pyrenees; close to ECORS 546 line; Roure et al., 1989) ranges between 4 and 5 km-depth (Ford et al., 2016), which is to first 547 order consistent with models presented here that include an initially deep foreland basin (models 548 M3 and M4; Figures 6 and 9). The inherited bathymetry included here in models M3 and M4 549 represents pre-existing rift structure characteristic of many foreland basins worldwide including 550 the Pyrenean retro-foreland (Desegaulx et al., 1991; Erdos et al., 2014; Vacherat et al., 2017). 551

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A pre-existing deep foreland basin also explains some features of the retro-foreland basin 553 of the northern Pyrenees, in particular the initially deep depositional environment in the foreland 554 basin (flysch; Puigdefabregas & Souquet, 1986) with a significant marine sedimentary section 555 (Serrano et al., 2006; Figure 10b). Models without an initially deep foreland reach basement 556 depths shallower than the present-day basement in the Pyrenean retro-foreland (Figure 10c; 557 Angrand et al., 2018). Reference model M1 produces a foreland basin thinner than in the North 558 Pyrenean case and is filled only by shallow marine sediments during the underfilled phase (< 100 559 m-depth at time of deposition; Figure 6a). Model M2 does not preserve any marine sediments 560 while the Pyrenean retro-foreland does (Figures 10b and 10c). In model M3, with an initially 561 deep foreland basin, the basement is about 1 km deeper than in the Pyrenean case (Figure 10c), 562 but, the stratigraphic architecture is consistent with the main trends of the present-day Pyrenean 563 retro-foreland basin of Serrano et al. (2006) (Figure 10b and 10c). The initially deep basin in 564 model M3, could be interpreted as a rift remnant, required to preserve a significant proportion of 565 marine sediments in the foreland basin, and, more specifically deep marine sediments (> 300 m-566 depth at time of deposition; Figure 6c). These are consistent with the northern Pyrenean flysch, 567 deposited during the late-Cretaceous, at the onset of the orogenic phase (Puigdefabregas & 568 Souquet, 1986). We quantitatively show here that inherited bathymetry in foreland basins is 569 critical to explain preservation of deep-marine sediments in small-scale orogen retro-foreland 570 (Figures 9 and 10). 571 572



Figure 10. a) Pyrenees and cross-section locations (from Angrand et al. (2018) and Serrano et al. 574 (2006). The inset shows Pyrenees and its associated Aquitaine foreland basin location (red 575 square) at the scale of western Europe. b) Cross-section of the Pyrenean retro-foreland 576 stratigraphy modified after Serrano et al. (2006). The transition from marine to continental 577 depositional environment is deduced from Rougier et al. (2016). c) Cross-sections of foreland 578 basin stratigraphic architectures and basement depth in models M1 to M3. We plotted the 579 580 present-day smoothed base of the Pyrenean retro-foreland from Angrand et al. (2018). NPFT: Northern Pyrenean Frontal Thrust. 581

582 **4.6 Model limitations**

Thrust front propagation may affect the syn-orogenic dynamics of foreland basins 583 (Simpson, 2006), in particular by remobilizing previously deposited sediments at the foot of the 584 mountain range as well as inducing retrogradation phases in the foreland basin at the onset of 585 thrusting events (Flemings & Jordan, 1990). These effects of thrust propagation are significant in 586 pro-foreland systems where thrust front migration can exceed 100 km as for instance in the 587 southern Pyrenean pro-wedge (Grool et al., 2018). Our models do not include horizontal 588 deformation and cannot be used as an analogue for pro-wedge systems. However, they are useful 589 for understanding retro-foreland systems of small to intermediate size orogens in which the 590 maximum propagation of the deformation front is limited and less than 100 km. The northern 591 Pyrenees are characterized by a shortening about 60 km (Grool et al., 2018). In retro-foreland 592 basins, the stratigraphic architecture is mostly controlled by the load of mountain range 593 topography and the associated flexural isostatic subsidence of the foreland the limited, whereas 594 horizontal thrust propagation plays a subordinate role (Naylor & Sinclair, 2008). 595

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597 Natural examples of mountain range-foreland systems may also display lateral variations in the degree of shortening, amount of erosion and corresponding sediment delivery to the 598 foreland. In the case of the Pyrenees, the basement depth varies from 1-3 km in the east to > 5599 km in the west. This variation has been mainly related to variations in extensional inheritance in 600 601 the foreland (Angrand et al., 2018). The asymmetric and diachronous onset of the orogenic phase from east to west (Vacherat et al., 2017) is also responsible for along strike varying sediment 602 supply range which impact the foreland basin filling and the stratigraphic architecture (Michael 603 et al., 2014; Ortiz et al., 2022; Verges, 2007). Our cylindrical modelling setup does not allow to 604 test for these lateral variations, that may be investigated in future work using a non-cylindrical 605 model setup. 606

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For sake of simplicity, in our models, global sea-level, precipitation rate, and continental transport coefficient (K_f) are constant through time and homogenous in space. Furthermore, we do not include a multi-grain size distribution of the marine deposition and marine diffusion of sediments (e.g., sand vs. silt; Rouby et al., 2013; Yuan et al., 2019b). Investigation of climatedriven variations of sediment flux is beyond the scope of our study. We focus on the long-term stratigraphic architecture of the foreland basin and the detailed stratigraphic architecture of the open-marine domain is beyond the scope of our study.

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Finally, although our setup is cylindrical, the Fastscape S2S models result in three dimensional depositional systems at high-resolution and in lateral variations of deltas or alluvial fans at small-scale (Figure 4; Movies S1 to S4). However, these local sediment migrations along strike do not affect the long-term trends in the sedimentary filling and stratigraphic architecture.

620 621 **5 Conclusions**

We investigate the influence of inherited foreland relief on the stratigraphic evolution of the foreland domain during the building of a mountain range using a landscape evolution model that couples continental and marine surface processes with flexural isostasy. We show models with four characteristically different initial relief in the foreland domain: an initially foreland domain at sea-level, an initially +300 m high continental foreland, a pre-existing 1 km-deep and 100 km-wide foreland basin associated with either a forebulge at sea-level or elevated at +300 m.

629 The models show that after 25 Myr an initially elevated foreland domain produces a thinner foreland basin than a low-lying foreland domain because a larger proportion of sediments 630 is exported out of the foreland domain to the open marine domain, which reduces the 631 sedimentary load, the flexure and accommodation space creation in the foreland basin. In 632 contrast, an initially deep foreland basin, produces a thicker foreland basin than an initial flat 633 foreland domain because the sediments filling the initial space increase the load, the flexure and 634 accommodation space in the foreland basin. In our model, an initially deep foreland basin is 635 required to preserve a significant proportion of deep marine deposits in the foreland basin. 636 Comparison with the Pyrenean retro-foreland basin shows that inherited bathymetry related to 637 pre-orogenic rift structure, is required to preserve a significant amount of deep marine deposits 638 often encountered in orogenic systems worldwide. 639

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The results presented here illustrate how changes in the dynamics of the depositional system at the foot of the mountain range (fluvial deposits and alluvial fans) exert a feedback on the erosion of the mountain range. A transient drop of erosion rates occurs when continentalization and/or alluvial fan coalescence at the foot of the mountain range raise its local base level.

646 647 The models show that the influence of the inherited relief largely disappears after ~10-13 Myr and all models show similar landscapes with a continentalized foreland domain developing 648 longitudinal hydrographic networks. However, even at 25 Myr the location of the shoreline 649 provides a memory of the initial foreland basin setting. Flexural isostasy appears to become less 650 important in the foreland stratigraphic evolution with time, when the forebulge is permanently 651 buried by marine or continental sediments. However, the stratigraphic architecture of the 652 653 foreland basin does provide information on the initial geometry, with the occurrence of deep marine sediments resulting from an initially deep foreland basin. 654

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661 **Open Research**

We use in this study a Landscape Evolution Model (FastScape S2S; Yuan et al., 2019a; Yuan et al., 2019b; <u>https://fastscape.org</u>); The version of the program we use is the one published online on April 26th 2021 (release v0.1.0beta3; fastscapelib-fortran; public access) available on GitHub: <u>https://github.com/fastscape-lem</u>.

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