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"Towards a nappe theory: Thermo-mechanical simulations of nappe detachment, transport and stacking in the Helvetic Nappe System, Switzerland" by Kiss and col- leagues is an interesting paper that investigate the thermo-mechanical processes of nappe formation. Overall, the paper is quite short, but well-written, pretty balanced, and the illustrations are to the point. It provides a modern and clear perspective on the topic. As soon as the authors consider the comments below, I will be happy to recommend this work for publication in EGU Solid Earth. I think with some improvements this review paper will be ready to have a big impact and long shelf-life.

GENERAL COMMENTS:

- I found the title "Towards a nappe theory" and the first part of the introduction a bit far from the aim of this study. This study is definitely a step towards a better theory of tectonic nappes; however, it is focused on a specific case (Helvetic Nappe System) and the model setup is also made for it. Based on my comment, I suggest to remove "Towards a nappe theory" from the title and rephrase the first part of the introduction (see my next comment).

We agree, therefore we modified the title accordingly.

- The introduction is very detailed. The authors provide a very broad overview. I would recommend to make it shorter. Also, the authors go back and forth between the general knowledge on the topic and what is addressed in the study. I suggest to separate this parts and improve the transition between the two; for examples, I would add some lines to highlight how numerical simulations can help to overcome the uncertainties from e.g., geological interpretation and/or typical limitation of analogue models.

We have shortened the introduction.

SPECIFIC COMMENTS:

Page 1:

#5: "of a thrust nappe and stacking of this thrust nappe" - remove "of this thrust nappe"?

We reformulated it.

#10: "and the resulting brittle-plastic shear band formation" - shear band (bands?) cutting through the cover layer?

We reformulated the sentence to make it clearer.

#10: "weak sediments" - décollement?

We extended the sentence to make it clearer.

Page 2: #5 ", for example, a basic definition" - ; for example...

We modified the sentence accordingly.

Page 5:

#15 "We assume slow, incompressible deformation" - please be more specific with the term "slow". Maybe long-term tectonic deformation?

We added the information that slow means here: no inertial forces.

#25 "With ongoing deformation, this marker chain needs to be locally remeshed which is achieved by adding marker points in the deficient chain segments." - The term remesh is odd, as it refers to the "Lagrangian" markers. Please specify whether this criterion assumes a minimum number of markers per cell. If so, please clarify how these markers are added and how the physical properties are interpolated from the nodes.

We reformulated the sentence. The marker chain is actually a contour line defined by marker points, and these marker points are different to the markers that carry information on material properties.

Page 6:

#20 "ambient pressure and temperature"?

We reformulated the sentence to make it clearer.

#25 "The top boundary is a free surface, using the algorithm of Duretz et al. (2016)". I recommend to spend a few more lines to specify how this algorithm works and that this is not "the usual" pseudo free-surface used in many geodynamic models.

The algorithm is explained in a bit more detail in the mathematical model section. p.5. #25

#25 I suppose the velocity discontinuity at the bottom right corner introduces a stress singularity - how do you treat this issue in the boundary conditions?

The velocity around the discontinuity is linearly decreased to zero within a small distance to minimize and smooth the effect of the discontinuity. The presented stress fields show that the stress perturbation around the discontinuity are minor.

Page 7:

#20 "deviatoric stresses reach ca 250 MPa". This values seems pretty high. In section 4.4 the authors discuss the effects of softening mechanisms - e.g., lower effective friction to mimic the presence of pore fluid-pressure. I was wondering what is level of deviatoric stresses when the model is under hydrostatic conditions.

Deviatoric stresses for hydrostatic conditions can also be around 200 to 250 MPa (see e.g. Kohlstedt et al., JGR, 1995; their figure 10). However, the maximal stress at the brittle-ductile transition in the cover units is not of first-order importance for our simulations, because the important deformation takes place around the basement-cover contact far below the brittle-ductile transition.

Figure 1: could you please add a small inset to locate the region of the cross-section?

We added a small inset.

I hope my comments contribute the authors to improve the manuscript.
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The paper presents a set of high-resolution thermo-mechanical simulations aiming to- wards a "nappe theory". The simulations focus strongly on reproducing as many features and attributes documented in the Helvetic nappe system, which guides the choice of input parameters, geometry, and boundary conditions. From a reference simulation, a set of key parameters are varied to test their influence on the simulation outcome. âĂ̆c′ First, the viscosity of each material is tested in turn by (i) dropping the viscosity of the basement, (ii) increasing the viscosity of the cover sequence, and (iii) increasing the viscosity of the stronger syn-rift unit capping the rift basins. âĂ̆c′ Then the stronger syn-rift unit is replaced by a 4- or 5-layer system involving 2 stronger layers and 2 or 3 weaker units. Three simulations test various thicknesses and configurations. âĂ̆c′ Two strain weakening mechanisms (i.e. shear heating and accumulated plastic strain) are tested at various extensional velocities (1 cm/yr and 5 cm/yr). The simulation outcomes are then compared to the Helvetic nappe system.

The paper will be of great interest to geologists interested in nappe tectonics and in particular those interested in the Helvetic nappe system. The paper is well organized, relatively easy to follow, and the figures serve their purpose reasonably well.

The study is an attempt to learn about nappe tectonics from reproducing via numerical simulations the well-documented Helvetic nappe system. However, it remains to be seen whether an all-encompassing "nappe theory" can be extracted from such an approach, for two reasons: âĂ̆c′ I would first question in the present context the use of the word "theory". In

natural science, a theory is a very robust model established over decades of data collection and analysis and explaining a very large range of unrelated observations. Plate tectonics and biological evolution are two theories. For this reason, I think that the concept of "nappe theory" could safely be replaced by the concept of "nappe model". âĂ˘ cˊ In addition, I think it is pretty safe to state that there is probably more than one way for nappes to develop. Hence, the proposed model is only strictly relevant to the Helvetic nappe system that develops as the result of the inversion of an extended continental margin, and the extrusion of its syn-rift sedimentary infilling. Hence, I think that modifying slightly the title and introduction, to bring a stronger focus on the "Helvetic style" of nappe tectonics, would be beneficial to the paper.

Perhaps the main missing ingredient in the numerical experiments presented here is isostasy and the absence of flexure despite up to 10 km of topography due to crust thickening and nappe stacking. I acknowledge that this issue is touch upon in section 5.2, but it is important to stress that the outcome of this set of simulation will change should the basement be allowed to subside under the weight of the nappe stack.

We added a sentence that the impact of flexure and isostasy on our model results can be tested eventually with larger scale models including flexure and isostasy.

The paper would also benefit from being leaner. I found at places the paper to be unnecessarily wordy, and the description on the simulation lengthy and tedious to read. Rather than describing the evolution of each experiment in great detail (perhaps you can point toward movies or animations instead), it would be best to highlight key differences. The conclusion needs to be rewritten and shortened. A conclusion goes beyond merely repeating what was said before.

We have added one animation as a supplementary material.

We rewrote and shortened the conclusion and focused on the results relevant for the tectonic interpretation of the Helvetic nappe system.

The supplementary section needs some editing, there are too many spelling mistakes.

We considered and implemented all corrections, from the supplementary pdf. We considered all suggestions and implemented most of them.

Finally, either a code is made freely available, or it is not. Having to ask permission to the author to access the code is, in my view, not sufficient. Codes which are accessible are available online (e.g. underworldcode.org). Chances are that in ten years Underworld will still be available like it was ten years ago.

The code is planned to make publicly available in the near future once the paper describing it is published. The data is not publicly available because of its massive size.

Kind regards, Patrice Rey

~~Towards a~~ Tectonic inheritance controls nappe ~~theory: Thermo-mechanical simulations of nappe~~ detachment, transport and stacking in the Helvetic Nappe System, Switzerland: insights from thermo-mechanical simulations

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Abstract.

Tectonic nappes ~~are observed~~ have been investigated for more than a hundred years. Although geological studies often refer to a "nappe theory", the physical mechanisms of nappe formation are still ~~incompletely understood~~disputed. We apply two-dimensional numerical simulations of shortening of a passive margin, to investigate the thermo-mechanical processes of detachment (or shearing off), transport and stacking of nappes. We use a visco-elasto-plastic model with standard creep flow laws~~and~~, Drucker-Prager ~~yield criterion~~and von Mises yield criteria. We consider tectonic inheritance with two initial mechanical heterogeneities: (1) lateral heterogeneity of the basement-cover interface due to half-grabens and horsts and (2) vertical heterogeneities due to layering of mechanically strong and weak sedimentary units. The model shows detachment and horizontal transport of a thrust nappe ~~and stacking of this thrust nappe above~~ that gets stacked on a fold nappe. The detachment of the thrust sheet is triggered by stress concentrations around the sediment-basement contact and the resulting brittle-plastic shear band ~~formation. The horizontal~~ that shears off the sedimentary units from the sediment-basement contact. Horizontal transport is facilitated by a basal shear zone just above the basement-cover contact, composed of thin, weak sediments that act as a décollement. Fold nappe formation occurs by a dominantly ductile closure of a half-graben and the associated extrusion of the half-graben fill. We apply our model to the Helvetic nappe system in Western Switzerland, which is characterized by stacking of the Wildhorn thrust nappe above the Morcles fold nappe. The modeled structures~~and~~, the deformation rates and the temperature field agree with data from the Helvetic nappe system. ~~The mechanical heterogeneities must generate contrasts in effective viscosity~~ Mechanical heterogeneities must locally generate effective viscosity contrast (i.e. ratio of stress to visco-plastic strain rate) of ~~four~~ about three orders of magnitude to model nappe structures similar to the ones of the Helvetic nappe system. Our results indicate that the structural evolution of the Helvetic nappe system was controlled by tectonic inheritance and that material softening mechanisms are not essential to reproduce the first order nappe structures.

1 Introduction

Tectonic nappes were discovered more than a hundred years ago and are considered as typical tectonic features of orogenic belts (e.g. Price and McClay, 1981), particularly in the Alps (e.g. Lugeon, 1902; Termier, 1906; Argand, 1916; Tollmann, 1973; Trümpy, 1980; Escher et al., 1993; Pfiffner, 2014). Several definitions of a nappe have been proposed (see discussion in Price and McClay, 1981), for example, ~~a basic definition modified after Termier (1922)is~~ after Termier (1922): "A nappe is a rock packet not in its place, resting on a substratum that is not its original one". Two end-member types of nappes are commonly distinguished, namely fold nappes and thrust nappes, or thrust sheets (e.g. Termier, 1906; Price and McClay, 1981; Epard and Escher, 1996). Fold nappes are recumbent folds exhibiting large-scale stratigraphic inversion, typically with amplitudes that are exceeding several kilometers. In contrast, thrust sheets are allochtonous sheets with a prominent shear zone or thrust at their base, but without a prominent overturned limb. The importance of tectonic nappes for orogeny, especially for collisional orogens, is nowadays well established~~and many geological studies refer to a "nappe theory" when mentioning tectonic nappes. However,~~, however, the physical mechanisms of nappe detachment (or shearing off), transport and stacking are still ~~incompletely understood~~ disputed.

We focus here on the Helvetic nappe system in Western Switzerland (see next section for a geological overview), which is one of the birthplaces of the concept of tectonic nappes. In 1841, Arnold Escher mentioned a nappe (he used "Decke" in german) and a colossal overthrust ("colossale Überschiebung") ~~in 1841~~ during the presentation of a geological map of the canton Glarus, Eastern Switzerland (Escher von der Linth, 1841). Escher did not dare to publish his interpretation, but explained it in the field to Roderick Murchinson, who published the overthrust interpretation in 1849 (Murchison, 1849), crediting Escher for the original observation. Bertrand (1884) argued also convincingly for an overthrust nappe (he used "masse de recouvrement" and "lambeaux de recouvrement" instead of nappe) in the Glarus region so that finally also Heim (1906) accepted the overthrust interpretation instead of the earlier preferred double-fold interpretation ("Überschiebungsfalte" instead of "Doppelfalte"). Although the important controversies and observations supporting tectonic nappes are related to the Glarus region, which is part of the Helvetic nappe system, the true birth date of the nappe concept in the Alps, according to Trümpy (1991), is the publication by Schardt (1893) who worked in the Prealps, belonging to the Penninic domain (e.g. Escher et al., 1993). Schardt (1893) realized that Jurassic breccias have been thrust over Tertiary flysch and that large regions of the Prealps have been actually emplaced as a major overthrust. After decades of controversy, the existence of nappes ~~got~~ was generally accepted approximately a century ago, revolutionizing Tectonics, Alpine Geology and orogeny in general (for historical reviews see Bailey 1935; Masson 1976; Merle 1998; Trümpy 1991; Dal Piaz 2001; Schaer 2010).

Since then, a considerable effort has been made in mapping the present-day structure of the Helvetic nappe system (e.g. Steck, 1999; Pfiffner et al., 2011). Structural and paleogeographic reconstructions have provided a valuable insight into the kinematics of nappe formation (e.g. Gillcrist et al., 1987; Epard and Escher, 1996; Herwegh and Pfiffner, 2005; Bellahsen et al., 2012; Boutoux et al., 2014). Therefore, the geometrical structure and kinematic evolution of the Helvetic nappe system is reasonably well understood. There are also theoretical and analogue modeling studies investigating the formation of fold-and-thrust belts and nappes (e.g. Bucher, 1956; Rubey and King Hubbert, 1959; Dietrich and Casey, 1989; Merle, 1989; Casey

and Dietrich, 1997; Wissing and Pfiffner, 2003; Bauville et al., 2013; Poulet et al., 2014; Erdős et al., 2014; Jaquet et al., 2014; Ruh et al., 2014; Bauville and Schmalholz, 2017). However, the controlling physical processes of nappe detachment, transport and stacking, and the associated dominant rock deformation mechanism are still ~~incompletely understood and , therefore, the frequently mentioned "nappe theory" is not complete~~disputed. An overview of suggested driving forces and

5 deformation mechanisms for nappe formation is given in Merle (1998, his chapter 3). For example, for fold nappes, many interpretations favor distributed shearing and dominantly ductile deformation mechanisms, such as dislocation or grain-size sensitive diffusion creep (e.g. Ramsay et al., 1983; Gillcrist et al., 1987; Ebert et al., 2008; Bauville et al., 2013). However, there are also interpretations arguing for localized thrusting and dominantly brittle-plastic deformation mechanisms, such as fracturing related to fluid pressure (e.g. Boyer and Elliott, 1982; Granado and Ruh, 2019). Furthermore, the presumed driving

10 forces of nappe transport are either external surface forces, due to tectonic compression, or internal body forces, due to gravity. Heterogeneous shearing due to buttressing in a general compressional regime is an example of deformation driven by external forces (e.g. Ramsay et al., 1983; Epard, 1990; Bauville et al., 2013; Boutoux et al., 2014). Gravity gliding and spreading is an example of deformation driven by body forces (e.g. Durney, 1982; Merle, 1989; Merle and Guillier, 1989).

For thrust sheets, the ~~variety of the proposed emplacement mechanisms is even larger than for fold nappes (see for an overview Merle, 199~~

15 ~~. The apparently straightforward interpretation that thrust sheet transport is controlled by frictional sliding is problematic, because stresses required to move a long sheet over a frictional surface exceed the strength of the rock sheet so that the sheet would break into smaller pieces (e.g. Smoluchowski, 1909; King Hubbert and Rubey, 1959; Price and Cosgrove, 1990). This problem is known as the overthrust paradox (e.g. Smoluchowski, 1909; King Hubbert and Rubey, 1959). Several solutions for this paradox were proposed~~ prominent low-angle thrust planes are likely controlled by mechanical heterogeneities, such as the

20 orientation of the basement-cover interface and of mechanically weak shale-rich or evaporite layers, as has been suggested for the Helvetic nappe system (e.g. Pfiffner, 1993; Steck, 1999; Pfiffner et al., 2011; Bauville and Schmalholz, 2017). Several softening mechanisms have been proposed to localize deformation at the base of the thrust sheet, such as ~~(1)~~reduction of the effective stress due to pore fluid pressure causing a reduction of the effective friction angle (e.g. King Hubbert and Rubey, 1959; Rubey and King Hubbert, 1959) or ~~(2)~~a dominantly ductile deformation mechanism (e.g. Smoluchowski, 1909; Goguel, 1948;

25 Voight, 1976), presumably in combination with thermally-, chemically- or mechanically-activated softening mechanisms (e.g. Poirier, 1980; Ebert et al., 2008; Poulet et al., 2014). ~~Another problem of purely brittle-frictional interpretations, assuming homogeneous material properties, is that thrust sheets have often been displaced over tens of kilometers on sub-horizontal thrust planes or shear zones. However, according to Anderson's theory of faulting (e.g. Turcotte and Schubert, 2014) thrust planes for friction angles of ca 30 degrees should dip with ca 30 degrees with respect to the horizontal, if the smallest principal~~

30 ~~stress, σ_3, is approximately vertical. Smaller friction angles would increase the dip angle. For example, for zero friction angle, corresponding to a constant, pressure-insensitive yield stress, the dip angle would be 45 degrees. Therefore, prominent low-angle thrust planes are likely controlled by mechanical heterogeneities, such as the orientation of the basement-cover interface and of mechanically weak shale-rich or evaporite layers, as has been suggested for the Hevetic nappe system (e.g. Pfiffner, 1993; Steck, 1999; Pfiffner et al., 2011; Bauville and Schmalholz, 2017).~~

To make another step towards ~~a "nappe theory" that explains~~ understanding the physical process of nappe formation, we investigate the detachment, transport and stacking of nappes with two-dimensional (2D) numerical simulations based on continuum mechanics. To keep the model relatively simple ~~and transparent~~, we focus here on thermo-mechanical processes on the macro-scale, larger than the typical size of mineral grains. Hence, we do not consider hydro-chemical couplings, such as fluid release by carbonate decomposition (e.g. Poulet et al., 2014), and micro-scale processes, such as micro-structural grain size evolution with secondary phases (e.g. Herwegh et al., 2011). The numerical algorithm is based on the finite difference method. We consider a standard visco-elasto-plastic deformation behavior, heat transfer and thermo-mechanical coupling by shear heating and temperature-dependent viscosities. We also apply velocity boundary conditions that are standard for modeling accretionary or orogenic wedges (e.g. Buiter et al., 2006). For the comparison between model results and natural observations, we consider a geological section across the Helvetic Nappe System in Western Switzerland. This section is characterized by two deformed basement massifs, the Aiguilles-Rouges and Mont-Blanc massifs, a fold nappe, the Morcles nappe, and a thrust nappe, the Wildhorn super-nappe, that has been overthrust, or stacked, above the underlying fold nappe (Fig. 1). In our models, we consider the tectonic inheritance of the Mesozoic passive margin formation in the form of simple half-grabens and horsts, because the Helvetic nappe system resulted from the inversion of the pre-Alpine European passive margin (e.g. Trümpy, 1980). We consider two main orientations of inherited mechanical heterogeneities: (1) a lateral variation of mechanical strength due to the lateral alternation of basement and sediments associated with the half-graben structure and (2) a vertical variation of strength due to (i) the basement-cover interface, (ii) the alternation of strong carbonate with weak shale-rich units (so-called mechanical stratigraphy after Pfiffner (1993)) and (iii) the pressure and temperature sensitivity of rock strength and effective viscosity, respectively.

The main aim of this study is to show that a thermo-mechanical model based on the theory of continuum mechanics (i) with a well established visco-elasto-plastic ~~deformation behaviour using~~ rheology based on standard flow laws, (ii) with mechanical heterogeneities mimicking pre-Alpine extensional heritage and stratigraphic layering and (iii) with a wedge-type compressional configuration can self-consistently explain the first-order features of nappe detachment, transport and stacking in the Helvetic nappe system.

2   Short overview of the Helvetic Nappe System in Western Switzerland

The Helvetic nappe system is commonly subdivided into Infrahelvetic, Helvetic and Ultrahelvetic units (Fig. 1c) (e.g. Masson et al., 1980; Escher et al., 1993; Pfiffner et al., 2011). The nappes consist mainly of Jurrasic to Paleogen sediments that were deposited on the Mesozoic European passive margin before the Alpine orogeny (Fig. 1a). This passive margin inherited half-grabens and horsts from the Mesozoic, pre-Alpine extensional phase (e.g. Masson et al., 1980; Escher et al., 1993). The stratigraphy of the nappes is generally characterized by shale-rich units, totaling several kilometers in thickness, and two major units of massive platform carbonates, the so-called Quinten (Malm) and Urgonian (Lower Cretaceous) limestones, with a thickness of several hundred meters (e.g. Masson et al., 1980; Pfiffner, 1993; Pfiffner et al., 2011).

In the studied section, along the Rhone-valley near Martigny (Switzerland), the Infrahelvetic units form the Morcles fold nappe (e.g. Steck, 1999). This recumbent fold nappe is strongly deformed, but is still connected to its original position of deposition, the Mesozoic half-graben between the Aiguilles-Rouges and the Mont-Blanc massifs (Fig. 1a). Therefore, the Morcles nappe is considered as a parautochtonous unit and its root zone, ~~between the Aiguilles-Rouges and the Mont-Blanc~~

5 ~~massifs,~~ is termed the Chamonix zone (Fig. 1c). The sediments forming the Helvetic nappes have been deposited on more distal regions of the European passive margin than the units forming the Morcles nappe. The original regions of deposition of the Infrahelvetic and the Helvetic units have been <u>presumably</u> separated by a horst, or basement high (Fig. 1a). The Helvetic nappes have been thrust above the Infrahelvetic units. In the studied region, the Helvetic nappe is termed the Wildhorn super-nappe~~that~~<u>, because it</u> can be subdivided into the Diablerets, Mont Gond and Sublage nappes (Fig. 1c; Escher et al. (1993)).

10 Due to the Rhone valley associated with the Rhone-Simplon fault, the Helvetic nappes cannot be continuously traced back to their original position of deposition (Fig. 1c). The Ultrahelvetic units have been depositied on more distal regions than the Helvetic units (Fig. 1a). Today, the Ultrahelvetic units are found in front and between the Morcles and Wildhorn nappes (Fig. 1c).

During the Alpine continental collision, the Ultrahevetic units and the Penninic nappes, originating from more distal posi-

15 tions, have been thrust above the original deposition regions of the sediments forming today the Morcles and Wildhorn nappes (Fig. 1b) (e.g. Epard and Escher, 1996). These sediments were subsequently sheared off from their original position of deposition and were transported several tens of kilometers towards the foreland, ~~i.e. top to the~~ <u>along a</u> northwest transport direction (e.g. Epard and Escher, 1996; Ebert et al., 2007). The present day nappe structure represents a thick-skinned tectonic style because the crystalline basement of the Aiguilles-Rouges and Mont-Blanc massifs exhibits significant deformation (Fig. 1c).

20 The above tectonic scenario is supported by peak metamorphic temperatures of the Helvetic nappe system, which range between 250-385 °C (Kirschner et al., 1996, 1995; Ebert et al., 2007, 2008) increasing ~~structurally~~ downwards and towards the root zone. The maximal depth of burial of the Morcles nappe has most likely exceeded 10 km and was achieved between 29 Ma and 24 Ma (Fig. 1b) (Kirschner et al., 1996, 1995). In the studied section, the carbonate layers are strongly folded indicating significant internal <u>ductile</u> deformation of the nappes (Fig. 1c). The Morcles fold nappe is characterized by strong

25 parasitic folding in its frontal part and by a ca. 20 km long, highly stretched inverse limb. The Wildhorn super-nappe also exhibits significant internal deformation, such as the isoclinal fold separating the Diablerets and Mont Gond nappes (Fig. 1c). These observations indicate that in the studied region ductile deformation was significant during formation of the nappes.

3 Methods

3.1 Mathematical model

30 Our mathematical model is based on the concept of continuum mechanics (e.g. Mase and Mase, 1970; Turcotte and Schubert, 2014). We assume slow <u>(no inertial forces),</u> incompressible deformation under gravity~~so that inertial forces are negligible.~~ ~~Heat~~<u>.</u> <u>Heat production and</u> transfer by conduction ~~, advection and production is considered. Heat transfer~~ and <u>advection are</u> <u>considered. Thermal evolution and</u> deformation are coupled by <u>temperature dependent viscosities and</u> shear heating, that is,

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dissipative deformation is converted into heat to conserve energy. The governing system of partial differential equations is solved numerically. The applied equations are described in detail in Schmalholz et al. (2019). The applied numerical algorithm is based on the finite-difference/marker-in-cell method (e.g. Gerya and Yuen, 2003). The diffusive terms in the force balance and heat transfer equations are discretized on an Eulerian staggered grid~~while advection~~, with a resolution of 3001×1001 (width$\times$height). Advection and rotation terms are treated explicitly using a set of Lagrangian markers and a 4th order in space / 1st order in time Runge-Kutta scheme. The topography in the model is a material interface defined by a ~~Lagrangian marker chain and this interface is displaced with the numerically calculated~~ contour line with Lagrangian coordinate points, which is advected with the computed velocity field (Duretz et al., 2016). With ongoing deformation, ~~this marker chain needs to be locally remeshed which is achieved by adding marker~~ the distance between neighboring points can increase and achieve the size of the numerical finite difference cells. In such case this contour line is locally remeshed by adding additional points in the deficient ~~chain~~ contour line segments.

We consider a visco-elasto-plastic deformation behavior and assume a Maxwell viscoelastic model and Drucker-Prager ~~yield criterion~~ and von Mises yield criteria (see details in Schmalholz et al., 2019). In the applied creep flow laws, we add a constant pre-factor f to ~~vary the effective viscosities in order to test the impact of different effective viscosities on the model results. The effective viscosity is defined by the ratio of stress to (viscous) strain rate and has the form~~ the dislocation creep flow laws

$$\eta_{\text{eff dis}}(\dot{\epsilon}_{\text{disII}}, T) = f F A^{-\frac{1}{n}} (\dot{\epsilon}_{\text{II disII}})^{\frac{1}{n}-1} \exp\left(\frac{Q}{nRT}\right), \tag{1}$$

where the expression to the right of f corresponds to the effective viscosity from standard dislocation creep flow laws determined by rock deformation experiments. ~~Material parameters, such as effective viscosities, must be indepenent on the chosen coordinate system and, therefore, the dependence on strain rate is expressed by the quantity $\dot{\epsilon}_{\text{II}}$, which is the~~ In equation (1), $\dot{\epsilon}_{\text{disII}}$ is the square root of the second invariant of the ~~(viscous) strain rate tensor. The equation for η_{eff} is given above because the magnitude and distribution of η_{eff} will be displayed for the performed simulations in the next section~~dislocation creep strain rate [s^{-1}], and T is temperature [K]. All other parameters are explained and listed in Table 1.

3.2 Model configuration

The applied model configuration mimics a 200 km long section of the upper crustal region of a simplified passive margin (Fig. 2). We consider four model units with distinct mechanical properties, namely basement, cover, strong layer and weak unit. The basement unit represents the crystalline basement, the cover unit represents the Ultrahelvetic and Penninic nappes, the strong layer represents the ~~major~~ main carbonate layers (Malm and Urgonian) and the weak unit represents the shale-rich units. The initial geometry of the basement unit represents the crystalline upper crust of a passive continental margin with 15 km thickness, tapering down to 5 km thickness (Fig. 2). The Infrahelvetic basin is represented by an idealized half-graben that is 5 km deep and 25 km wide. The Infrahelvetic and the more distal (right ~~model side~~ side of the model) Helvetic basin are separated by an idealized horst structure. We cover the entire passive margin structure with sediments, to obtain a total (basement + sediments) model thickness of 25 km. The model stratigraphy ~~is consisting~~ consits of three units (cover, strong layer and weak units) and each unit has homogenous material parameters. Both the half-graben and the basin are filled with weak units up to a depth of

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13.5 km. On top of the weak units we place a 1.5 km thick strong layer. Our initial geometry represents the stage during the Alpine orogeny, when the proximal passive margin~~region~~, including the Infrahelvetic and Helvetic basins, ~~is~~ was still relatively undeformed, but the Ultrahelvetic and Penninic units have been already thrust on top of it (Fig. 1b). We consider the overthrust units by adding a 10 km thick, homogenous unit of cover sediments (without distinction between the Ultrahelvetic and Penninic

5 units) on top of the model basement and basins (Fig. 2). Adding this 10 km thick unit is important to ~~consider appropriately the ambient~~ achieve pressure and temperature ~~, which~~ conditions that are close to the recorded ones, because those control the brittle-plastic yield strength and the ~~temperature dependent~~ temperature-dependent effective viscosities.

We apply boundary conditions that are similar to sandbox experiments of fold-and-thrust belts and orogenic wedges (Fig. 2). The left lateral model boundary moves to the right with a constant horizontal velocity of 1 cm.yr^{-1}, while the right lateral

10 boundary does not move horizontally. There are no shear stresses at the vertical model boundaries (i.e. free slip boundary conditions). The bottom boundary also moves with a horizontal velocity of 1 cm.yr^{-1}, but does not move vertically. This velocity boundary condition generates a velocity discontinuity at the bottom right corner of the model, which is typical for sandbox experiments and numerical simulations of accretionary wedges (e.g. Buiter et al., 2006). The top boundary is a free surface, using the algorithm of Duretz et al. (2016). We apply constant temperature boundary conditions of 10 °C at the top and

15 420 °C at the bottom of the model. There is no heat flux across the lateral model boundaries. We apply an initially equilibrated temperature field which results in a ca. 16 °C.km^{-1} initial geothermal gradient. Applied parameters are listed in Table 1.

4 Results

~~We present first~~ First, we present the main results of a reference simulation, for the configuration described above, and then results of simulations in which some parameters are varied. All simulations show some common, general features: With in-

20 creasing bulk shortening, the initially flat topography is increasing~~most~~, mostly around the right model boundary, representing a "back-stop" (Fig. 3). The models develop a wedge shape with a topography tilting towards the left ~~model side~~ side of the model. With progressive shortening, the increasing topography reaches the left model boundary and the topographic slope ~~reduces~~diminishes, generating again a ~~more horizontal~~ flatter topography. Also, ~~initially the~~ basement deformation occurs initially around the bottom right corner and progressively propagates towards the left (Fig. 3). With progressive shortening,

25 the model thickens and the ~~models become generally thicker but the~~ sedimentary units above the basement become relatively thicker than the underlying basement because the sediments are thrust above the basement. The thickened sedimentary cover results in increasing basement temperatures, hence decreasing its ~~teperature-dependent~~ viscosity. The temperature increase ~~of~~ at the top of the basement is ~~visible by the vertical~~ documented in figure (3) by the position of the 300 °C isotherm~~in figure (3)~~. Such basement temperature increase and the related shift to ~~a~~ thick-skinned deformation was also reported by Bauville and

30 Schmalholz (2015) in their numerical models of fold-and-thrust belts. Basement deformation results in the partial or total closure of the half-graben and associated extrusion of the basin fill. The specific model evolution, however, depends on the applied flow laws and model stratigraphy, which will be discussed in ~~the following in~~ comparison with the reference simulation.

4.1 Reference model

We apply the configuration and parameters described in the previous section and displayed in figure 2 to generate a reference simulation ~~for later comparison~~ (Figs. 3 and 4). Initially, elastic stress builds up during a few hundred thousand years until the brittle-plastic yield stress and the steady-state ductile creep stress are reached. ~~For the applied model configuration, the~~ The brittle-ductile transition occurs at about 6-8 km depth. We quantify deviatoric stress magnitudes with the square root of the second invariant of the deviatoric stress tensor, τ_{II}, and maximal deviatoric stresses reach ca. 250 MPa at the brittle-ductile transition (Fig. 4). Maximal strain rates in the developing shear zones are between 10^{-13} and 10^{-12} s^{-1}, in broad agreement with strain rate estimates for natural shear zones (e.g. Pfiffner and Ramsay, 1982; Boutonnet et al., 2013; Fagereng and Biggs, 2018). The largest stresses ~~occur~~ develop around the brittle-ductile transition in the cover, whereas stresses in the basement and in the strong layer are significantly smaller (Fig. 4).

The model shows several key phases of ~~the~~ formation of a nappe stack: (1) Detachment of ~~a sedimentary unit of the right basin , mimicking~~ sedimentary units from their substratum as observed on the basin on the right, which mimicks the Helvetic basin ~~, from their original substratum~~ (Figs. 3a and b, and 4a and c). (2) Significant horizontal transport of ca. 30 km with little internal deformation indicated by the relatively undeformed strong layer in the detached unit (Figs. 3b to d, and 4b to c). (3) Formation of a fold nappe due to ~~ductile closure~~ the closure and ductile drag of the left half-graben, mimicking the Infrahelvetic basin, and associate extrusion of the sedimentary half-graben fill (Figs. 3c to e). (4) ~~Stacking of the nappe originating from the right basin above the fold nappe from the left half-graben~~ A major thurst nappe stacked on top of a fold nappe (Figs. 3d and e).

During the initial stages of deformation, the strong layer of the right basin is gently folding, or buckling (Fig. 3a). Stress becomes concentrated around the contact of this strong layer and around the basement horst (Fig. 5m) causing increased strain rates in this region. With progressive deformation, a localized shear zone ~~,~~ dominated by brittle-plastic deformation ~~,~~ develops across the strong layer, eventually detaching it from the basement (Fig. 5j to l). This shear zone develops within the strong layer so that a small piece of the strong layer remains attached to the basement (Fig. 5t). The detachment of the strong layer causes a significant stress drop in the strong layer and the basement (Fig. 5m to p). Once detached, the strong layer and parts of the underlying weak unit passively move sub-horizontally over the horst initiating the horizontal nappe transport. Quantification of elastic strain rates shows that elastic deformation is active during the detachment process and that, hence, elastic stresses are not completely relaxed ~~visco-plastically~~ through visco-plastic deformation (Fig. 5e to h).

During the detachment, some parts of the weak cover, originally residing above the strong layer, are dragged below the detaching strong layer (Fig. 5). During the horizontal transport, the detached unit, consisting of the strong layer and some weak units, is displaced above the cover material. Significant horizontal transport is facilitated because the underlying basement and the strong layer of the left half-graben are significantly more competent than the weak units at the base of the overthrusting nappe.

While the detached unit from the ~~right basin~~ basin on the right is overthrusting the fill of the ~~left~~ half-graben left, this fill is also sheared out of the half-graben due to (i) shear stresses generated by the overthrusting unit and (ii) closure of the half-graben due to ductile deformation of basement units. During overthrusting, some parts of the cover units are incorporated between

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the overthrusting unit and the fill of the left half-graben. Finally, a nappe consisting of the fill from the ~~right basin~~ basin on the right has been stacked above a fold nappe made of ~~fill~~ materials from the left half-graben. The entire process of nappe detachment, transport and stacking occurs during ca. 8 Myr for the applied bulk shortening velocity of 1 cm.yr^{-1}. At the end of the simulation, the ~~temperatures~~ temperature of the strong layer range between 250 °C at the ~~topmost position~~ top and 350 °C in the root zone of the fold nappe. The final bulk shortening was ca. 38 % after ca. 8 Myr.

4.2 Impact of varying strength contrast

We performed three simulations with the same initial geometry and final bulk shortening as the reference simulation, but with modified pre-factors, f, in the applied flow laws. ~~All simulations are terminated after a bulk shortening of ca 38 %, corresponding to the one of the reference simulation.~~ In a first simulation, we used a smaller effective viscosity ~~only~~ for the basement only ($f = 0.33$). Here, the basement is weak enough to deform significantly from the ~~beginning~~ onset of shortening. Yield stresses are not reached at the contact of the basement horst with the strong layer (Fig. 6a). The strong layer does ~~, hence,~~ not detach from the basement and overthrusting does not take place. Instead, a several km large fold nappe develops in the strong layer of the ~~right basin~~ basin on the right. Due to the highly distributed basement deformation, the half-graben closes only partially, resulting in a moderate buckling of the strong layer, but not in ~~fold nappe formation~~ the formation of a fold nappe. Also, a nappe stack does not form in ~~the~~ this simulation.

In a second simulation, we used a stronger cover ($f = 0.5$ instead of $f = 0.1$). The effective viscosities of basement and cover are similar, ~~hence, a~~ as a result a mostly evenly distributed thick-skinned deformation ~~is present from the beginning of shortening~~ takes place (Fig. 6c and d). A large scale fold develops above the horst, but the overturned limb ~~made of the strong layer~~ eventually detaches from the basement by necking. Although the overthrusting stage results in a significant horizontal displacement, this displacement is only half ~~of the one~~ that observed in the reference simulation and not ~~enough~~ sufficient to form a nappe stack. Due to the stronger shear drag from the top, the strong layer of the ~~left~~ half-graben on the left is almost entirely sheared out ~~from the half-graben~~. The strong layer of the left half-graben forms an overthrust nappe with significant horizontal displacement and with significant internal extension.

In a third simulation, we used weaker strong layers ($f = 0.33$). The development of the sediment units of the basin is largely similar to that in the reference model (Fig. 6). The only notable difference is that before the strong layer is detached from the basement, it forms a shear fold that is on the scale of a few km. The development of the units of the left half-graben is largely different compared to the reference simulation. Since the strong layer is weaker, the drag from the overriding units is sufficient to detach the strong layer from its left contact with the basement and displace it several tens of km to the left. ~~During this displacement, the strong layer from the left half-graben is highly stretched and almost necking at its tail.~~ Due to significant horizontal displacements, a nappe stack forms with two thrust sheets on ~~the~~ top of each other. However, the strong layer from the left half-graben is displaced considerably further towards the left than the strong layer from the ~~right basin~~ basin on the right.

The final result of the three simulations ~~, especially with respect to nappe detachment, transport and stacking,~~ differs significantly from the result of the reference simulation, although the effective viscosities of individual model units have been

modified by factors of only three to five (Fig. 6). The results indicate that the effective viscosity contrast between the model units has a first-order impact on the results.

At the onset of nappe formation, after ca. 5% bulk shortening, the reference simulation and the three simulations with different f factors exhibit different distributions and magnitudes of effective viscosity (Fig. 7). The ~~maximal viscosity contrast in the reference simulation is up to five orders of magnitude inside the model domain, mainly between weak units in the basin and the uppermost cover (Fig. 7a). The~~ effective viscosity at the top of the basement is in the order of 10^{24} Pa.s and the viscosity of the cover directly above the basement is at least one order of magnitude smaller. The strong layers have locally similar maximal effective viscosities than the top basement in the order of 10^{24} Pa.s. The effective viscosity contrast between strong layer and weak units in the ~~right basin is ca~~ basin on the right is ca. three orders of magnitude (Fig. 7a). The above mentioned viscosity ratios between model units are required to generate the nappe detachment, transport and stacking in the reference simulation. In the three models with different f factors in some model units, one of these viscosity ratios is different and, hence, the final result differs from the one of the reference simulation (Fig. 7). In other terms, slight changes in effective viscosity distribution leads to different outcomes.

4.3 Impact of stress limiters in the basement

To test the impact of the vertical strength distribution in the basement, we performed four simulations with the same configuration as the reference model, but we limit the deviatoric stress in the basement to 25, 50, 75 and 100 MPa, respectively (Fig. 8a-d). The stress limitation is achieved by setting, in the basement only, the cohesion (C) to the stress limit and the friction angle to zero. A zero friction angle simulates effectively a pressure-insensitive von Mises yield criterion, which can mimic low temperature plasticity, such as Peierls creep. In all four simulations, the detachment of the strong layers from the basement in the distal basin is caused by a plastic shear zone that cuts through the edge of the horst and shears off a small basement sliver (Fig. 8a-d). At the half-graben, however, the deformational style depends on the value of the cohesion (C). For $C = 25$ MPa, the strong layer in the half-graben is scratching off the top of the left basement and forms a thrust nappe (Fig. 8a). For $C = 50$ MPa, the strong layer still scratches off a bit of the basement top, but forms now a fold nappe. For increasing values of C, the amount of strain in the basement is decreasing, hence the shape of the nappe from the half-graben is becoming more similar to the shape in the reference simulation (Fig. 8b-d).

4.4 Impact of multilayers

We also run simulations in which we replaced the single strong layer in the reference model with two thinner ones that are separated by weak units. We run three simulations with different initial thickness distributions of the two strong layers and alternating weak units. The initial thickness configuration is displayed on the right of the three panels in Fig. 9. The material parameters of every unit are the same as in the reference model. The basement deformation agrees with the one in the reference model. The deformation of the strong layers is different. ~~Initially~~

On the right side, the strong layers ~~of the right basin form more intense,~~ form initially shorter wavelength (due to their smaller thickness) buckle folds, in agreement with the dominant wavelength theory (e.g. Biot, 1961; Schmalholz and Mancktelow, 2016).

In the simulations, where the upper strong layer rests directly below the cover (Fig. 9b, c), the top layer is being detached and transported in a similar fashion as in the reference model. The lower layer, on the other hand, forms a fold nappe first, with an extremely thinned inverse limb. Eventually this inverse limb develops boudinage, and once necking takes place it detaches from the basement. In the simulation, in which a weak unit is located between the upper strong layer and the cover (Fig. 9a), both layers form folds and detach from the basement horst by necking in the inverse limb. ~~After the detachment, the internal~~ Around the half-graben on the left, the deformation of the ~~strong layers is negligible.~~

~~The deformation of the units of the left half-graben~~ units is similar to the reference model, when weak units are located between the upper strong layer and the cover (Fig. 9a). The main difference to the reference simulation is that the weak unit located on top of the half-graben is sheared out, and both strong layers form a fold nappe with a more intensely stretched inverse limb. In the models, in which the upper strong layer is in direct contact with the cover (Fig. 9b, c), the ~~deformation of the strong layers in the half-graben is considerably different than it is in the reference model. Because the strong layer on the top of the left half-graben is much thinner, the~~ drag from the overriding unit is sufficient to displace this layer considerably horizontally. ~~The drag~~ Drag from the top shears the upper strong layer of the left half-graben above the basement to the left and it detaches the layer from the half-graben. As a result, buckle and shear folds form around the left tip of the layer (Fig. 9b). The upper strong layer starts moving sub-horizontally without considerable internal deformation, and eventually forms a rootless nappe. The lower strong layer of the half-graben stays mostly in place, until the weak units are extruded from the half-graben due to its closure. Then, the lower strong layer forms a fold nappe, with a highly stretched inverse limb (Fig. 9b, c).

4.5 Impact of softening mechanisms

We also test the impact of two different softening mechanisms, activated in the reference simulation, that can enhance strain localization (Fig. 10). The first mechanism is thermal softening by shear heating due to the conversion of mechanical work into heat and the resulting decrease of the ~~temperature dependent~~ temperature-dependent viscosity (e.g. Yuen et al., 1978; Kaus and Podladchikov, 2006; Jaquet and Schmalholz, 2017; Kiss et al., 2019). Although this mechanism is activated in all simulations, for the applied $1 \ \mathrm{cm.yr}^{-1}$ convergence velocity its impact on structure development is negligible. However, ~~for faster bulk shortening,~~ with $5 \ \mathrm{cm.yr}^{-1}$ convergence velocity, thermal softening is sufficient to cause spontaneous shear zone formation (Kiss et al., 2019). ~~For the simulation with 5 convergence velocity , all other parameters are identical to the ones in the reference simulation. There are two striking differences between the two simulations. First, in the high velocity simulation~~ In the higher velocity simulation, prominent ductile shear zones are formed in the cover that also promote ~~the appearance of~~ more localized brittle deformation zones (Fig. 10a). ~~Second, heat~~ Heat production in the ductile shear zone raises the temperature of the units close to the "back-stop" on the right ~~model side~~ side of the model. Thus, at this location, the basement deformation ~~in the right model domain~~ is more intense, whereas the left half-graben in the basement is not being closed and the sediment fill is not being squeezed out (Fig. 10a).

The other considered softening mechanism is ~~plastic~~ frictional-plastic strain softening. Such softening is frequently applied in numerical models of crustal deformation in order to enforce highly-localized brittle deformation by decreasing the friction angle as a function of accumulated plastic strain (e.g. Buiter et al., 2006). Such softening algorithm ~~generates mesh-dependent results~~induces mesh dependence of load bearing capacities, but we apply it here for comparison ~~, because such strain softening~~

5 ~~is applied in many numerical models of fold-and-thrust belts~~ (e.g. Buiter et al., 2006; Erdős et al., 2014; Ruh et al., 2014). We used two different parameter sets to model strain softening. In the first case (Fig. 10b), we start with a friction angle of 30° that we linearly decrease to 5° between an accumulated plastic strain of 0.5 and 1.5, which is a strain interval typically considered in geodynamic models with frictional strain softening (e.g. Erdős et al., 2014). Compared to the reference simulation, we observe strongly localized brittle deformation that is characterized by high angle ($\gg$ 0° from horizontal) and small displacement (< 10

10 km) overthrusts. This is the only simulation, where a strong back-thrust forms over the right basin that also deforms the strong layer. In the second case (Fig. 10c), we start with a friction angle of 15° that we linearly decrease to 5° between accumulated plastic strain of 0.5 and 1.5. Such initially lower friction angle is often suggested to mimic fluid-pressure reduced effective friction angles (e.g. Erdős et al., 2014). In this simulation, the detachment mechanism of the ~~right,~~ strong layer from the right side of the horst is different ~~, as the~~ than in the reference simulation. The initial buckling and folding phase is entirely missing,

15 and plastic yielding dominates from the beginning of deformation. Initially, the angle of thrusting is ca. 35° from the horizontal. Once a sufficient amount of weak units are sheared on top of the horst, the transport direction is sub-horizontal. Similarly to the other simulations with significant softening mechanisms, the basement around the half-graben is only deformed to a small degree and the half-graben is not closed.

5 Discussion

20 ### 5.1 Numerical robustness

We investigated the impact of different numerical resolutions on the model results to test the robustness of these results. Such ~~resolution~~ test is important~~for the presented simulations, because weak material, such as cover and weak units, is entrapped along thin regions between stronger model units, such as strong layer and basement. Entrapment of weak~~, because of weak and thin material between strong material can cause mechanical decoupling ~~if~~but only when resolved numerically. We compare the

25 reference model with an original resolution of 3001×1001 (width×height) numerical grid points (initially 66×25 m grid spacing) with two simulations having identical configuration and parameters, but with smaller resolutions of 1501×501 (initially 133×50 m) and 751×251 (initially 267×100 m). The resulting structures after 38% of bulk shortening are essentially identical (Fig. 11). Similarly, the strain rate fields below the brittle-ductile transition are similar too. However, the strain rate distribution in the brittle part and around the brittle-ductile transition is resolution dependent (Fig. 11). This is typical for the applied

30 non-associated plasticity scheme with the Drucker-Prager yield criterion, that is merely a stress limiter, inhibiting the stresses to exceed the failure limit. Thus the exact geometry of the brittle-plastic shear bands is resolution dependent, but the effective load bearing capacity of the brittle layer converges with increasing resolution (Yamato et al., 2019, their appendix). Keeping in mind these limitations regarding the brittle-plastic deformation, the results in our main area of interest, that is the ductile

nappe stacking, are essentially independent on the resolution within the studied range. Hence, our results are numerically robust concerning the detachment, transport and stacking of nappes under dominantly ductile deformation.

5.2 Comparison of the model results with the geological observations

There are several features of the Helvetic Nappe System that we could successfully reproduce in our thermo-mechanical model. Similarly to Bauville and Schmalholz (2015), a structure resembling a fold nappe has been formed by the extrusion of the sedimentary fill from a half-graben. During formation of this fold nappe, the half-graben has been closed and the sediments squeezed between the two basements resemble the structure of the Chamonix zone located between the Aiguilles-Rouges and Mont-Blanc massifs (Fig. 1c). Hence, our model generated the first-order structural features ~~of~~ (i.e. features larger than the applied numerical resolution of 66×25 m) of the Infrahelvetic complex in W-Switzerland, namely a recumbent fold nappe with a root located between two deformed basement massifs. Additionally, our model reproduced the detachment and sub-horizontal transport of sedimentray units from a ~~model passive marginstructure~~ passive margin. The thrust nappe, which originates from the ~~rigth basin~~ basin on the right in our model, resembles the Wildhorn super-nappe. The horizontal transport of this thrust nappe is in the order of 30 km in the model. Furthermore, in the model this thrust sheet is stacked above the fold nappe and the final model structure resembles a thrust nappe that is stacked above a fold nappe, as observed in the Helvetic nappe system. Moreover, there is a considerable amount of cover units entrapped between the fold nappe and the thrust sheet. The entrapped lower region of the cover unit resembles the Ultrahelvetic units so that our model can explain how these Ultrahelvetic units have been entrapped between the Morcles fold nappe and the Wildhorn super-nappe (Fig. 1c). At the end of the simulated formation of the nappe system, the maximum temperature in the nappe system ranges between 250 °C and 350 °C. The Wildhorn nappe exhibits peak temperatures between 250 °C and 300 °C and the underlying Morcles nappe hotter peak temperatures between 290 °C and 350 °C, which is in broad agreement with the metamorphic peak temperatures of the Helvetic nappe system reported by Kirschner et al. (1996) and Ebert et al. (2007). In the simulations, the nappe stack is formed within ca. 8 Myr, which is also in broad agreement with the estimated time span of main formation of the Morcles fold nappe from ca. 28 to 17 Ma (Kirschner et al., 1995). The simulations with two thin strong layers, separated by weak units, can explain the significant parasitic, or second order, folding of the two main carbonate units (Quinten and Urgonian limestone formations) which is observed in the Wildhorn super-nappe.

Some features of the Helvetic Nappe System are not reproduced by the simulations. In the frontal part of the fold nappe, originating from the left half-graben, the front is first thrust out of the half-graben and the overturned limb develops subsequently. This deformation generates a "nose-like" structure in the frontal part of the fold nappe, which is not observed. However, a stress limiter in the basement favours the formation of a fold nappe without the "nose-like" structure, indicating that the stress contrast between the basement top and the strong layer has a first-order control on the developing fold nappe geometry. Also, in all simulations the fold nappe has only a minor second order folding, in contrast with the prominent parasitic folds of the Morcles nappe. ~~Reproducing these natural, second-order parasitic folds with their correct scale with respect to the first-order fold nappe would require an even higher numerical resolution.~~ In the numerical models, we ~~also~~ likely overestimated the amount of shale-rich sediments in the ~~right basin~~ basin on the right, mimicking the Helvetic basin, as the total volume of the

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Wildhorn super-nappe south of the Morcles nappes is much thinner than in the simulations. There was also ~~likely a~~ a likely significant amount of vertical flattening, and presumably pressure solution related volume decrease, after the main phase of nappe formation and during the exhumation of the nappe system, which is not modelled in our simulations. Moreover, several basement shear zones have been mapped in the Aiguilles-Rouges and in the Mont-Blanc massifs, which are not present

5 in the simulations. This is likely because (i) the straight bottom boundary of the model may prohibit any significant vertical displacement of the basement units and hence inhibit significant shear zone formation, (ii) the model basement is mechanically homogeneous and there are no heterogeneities that can trigger shear zone localization and (iii) the amount of brittle-plastic deformation is underestimated in the basement. We considered a horizontal model base while during natural nappe formation the overall basement-cover interface was likely dipping, or tilting, in the direction of subduction (i.e. direction of basal veloc-

10 ity), so that a model ~~bottom inclinded~~ base gently dipping towards the subduction direction ~~would~~ zone be more realistic. The deformation at ~~our model bottom~~ the base of our model is viscous and the surface slope for evolving crustal wedges with a viscous base depends on the viscous shear stress at the base, whereby larger shear stresses are related to higher surface slopes (e.g. Ruh et al., 2012). Keeping the basal viscous shear stress the same, a tilting of the model base towards the subduction ~~direction~~ zone would reduce the surface slope. Therefore, in our models the surface slopes towards the foreland (left) region

15 represent high end-member surface slopes so that effects of gravity-related forces directed towards the foreland region are on the higher end.

Finally, the applied "numerical sandbox" model configuration and velocity boundary conditions constrain the deformation in the model domain. During the large-scale dynamics of Alpine orogenic wedge formation, the straight bottom and right model boundaries do not exist. Processes such as laterally-varying vertical isostatic adjustment, flexure due to subduction and back-

20 thrusting, or back-folding, generate geodynamic conditions for the formation of the Helvetic nappe system which are clearly more dynamic and complex than implied by the considered model configuration. Lithospheric scale numerical models can self-consistently model the generation of orogenic wedges and major crustal shear zones, including effects of isostasy, flexure and back-folding (e.g. Erdős et al., 2014; Jaquet et al., 2018; Jourdon et al., 2019; Erdős et al., 2019). With higher numerical resolution such lithosphere models may eventually be able to resolve the upper crustal deformation with a resolution as applied

25 in our model. Hence, the impact of isostasy and flexure on the presented results and the formation of the Helvetic nappe system can be tested eventually with larger scale models.

5.3 Tectonic inheritance, mechanical heterogeneities and potential softening mechanisms

Geological reconstructions of the Helvetic nappe system showed the correlation of the nappes with their original positions along the pre-Alpine European passive margin, which was characterized by half-grabens and horsts (e.g. Epard, 1990; Boutoux et al.,

30 2014). In agreement with previous modelling studies (e.g. Beaumont et al., 2000; Wissing and Pfiffner, 2003; Bellahsen et al., 2012; Lafosse et al., 2016; Bauville and Schmalholz, 2017), our results suggest that tectonic inheritance in the ~~crust in the~~ form of half-grabens and horsts has a strong impact on the development of fold and thrust nappes during crustal deformation. Our results indicate that two ~~features of the~~ types of tectonic inheritance are important, namely the geometry and the magnitude of mechanical heterogeneities. The geometry of half-grabens and horsts controls the location of nappe initiation (Bauville and

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Schmalholz, 2017). The basement and sediments must, of course, have different mechanical strength, otherwise the geometry of the basement would be unimportant. Our results suggest that tectonic inheritance ~~is necessary to model~~ was necessary to the evolution of the Helvetic nappe system, but not sufficient. The results show that specific ~~strength, or effective viscosity, contrast~~ strength-contrast between basement and sediments and within the sediments are required to model nappe structures resembling those of the Helvetic nappe system (Figs. 6 and 7). The reference simulation exhibits ~~a~~ an effective viscosity contrast between weak units and strong layer and basement in the order of three to four orders of magnitude (Fig. 7a). Although the effective viscosity in the basement and strong layer is in the order of 10^{24} Pa.s, the stresses in the basement and strong layer are far below the brittle-plastic yield stress and typically smaller than 100 MPa (Fig. 4). If the effective viscosity contrast between strong layer and basement is not large enough, then the sediments of the ~~right basin~~ basin on the right side are not detached in the manner of a thrust sheet ~~from their original position~~ (Fig. 6a). One possibility to enforce detachment ~~also~~ for smaller viscosity contrasts is the application of plastic strain softening and/or initially reduced friction angles (Fig. 10b and c). Application of strain softening favors the formation of thrust sheets in the models, but prohibits the formation of fold nappes (Fig. 10b and c). The importance of tectonic inheritance and the pre-Alpine configuration on the nappe formation ~~during Alpine orogeny~~ underlines the importance of considering geological field work and associated geological reconstructions for the model configuration, because only such field based reconstructions can provide estimates for the pre-Alpine configurations. Our results are consistent with those of Duretz et al. (2011) which showed that inherited mechanical heterogeneities, promoting large lateral strength contrast, are essential to trigger exhumation of lower crustal granulites as observed in the Bohemian Massif. Generally, our results are consistent with a variety of studies, which show the importance of structural inversion of extensional systems during compressional deformation and are based on geological field observation, analogue deformation experiments and numerical models (e.g. Gillcrist et al., 1987; Buiter and Adrian Pfiffner, 2003; Buiter et al., 2009; Bellahsen et al., 2012; Bonini et al., 2012; Lafosse et al., 2016; Granado and Ruh, 2019).

For the ~~applied~~ model configuration, a significant localization due to thermal softening does not occur for a convergence velocity of 1 cm.yr^{-1}, but it does for 5 cm.yr^{-1}. Average convergence velocities during the Alpine orogeny are typically estimated to be in the order of 1 cm.yr^{-1} (Schmid et al., 1996). However, some short periods with higher convergence velocities cannot be excluded. So if there were short periods during the formation of the Helvetic nappe system with convergence velocities larger than ca. 5 cm.yr^{-1}, then thermal softening might have been important.

There is field evidence for grain size reduction associated with mylonitic shear zones at the base of nappes in the Helvetic nappe system (e.g. Ebert et al., 2007, 2008). We did not consider the microscale grain size reduction in our models for several reasons: First, the major mylonitic shear zones with significant grain size reduction have a thickness in the order of 10 m. Although we use high resolution models we have a numerical grid size of ca. 66×25 m, hence, this resolution is still not large enough to resolve the internal deformation within shear zones having thickness of 10 m. Second, recent numerical simulations including grain size reduction and combined diffusion and dislocation creep flow laws suggest that grain size reduction does not have a dramatic impact on strain localization (Schmalholz and Duretz, 2017), which is in agreement with theoretical results of Montési and Zuber (2002). The reason is that a piezometer-type stress to grain size relation, when subsituted into a grain-size-sensitive diffusion creep flow law, generates a power-law type flow law with stress exponents similar to the one

of the corresponding dislocation creep flow law (e.g. Montési and Zuber, 2002). However, other studies argue that microscale processes such as coupled grain evolution and damage mechanisms can generate significant strain localization and that these mechanisms have been responsible for generating subduction and plate tectonics (e.g. Bercovici and Ricard, 2014). Therefore, future simulations should consider such coupled microscale processes in order to quantify their importance on the first order

5   tectonic nappe detachment, overthrusting and stacking.

6   Conclusions

~~The presented~~ Our 2D thermo-mechanical simulations ~~of shortening of the upper crustal region of a passive margin consider initial mechanical heterogeneitiesand can explain key aspects of tectonic~~ support geological interpretations arguing that tectonic and structural inheritance controlled the tectonic evolution and resulting first order structures in the Helvetic nappe system. We

10   show that both the geometry and magnitude of mechanical heterogeneities, representing the tectonic and structural inheritance, control the nappe formation. ~~Two types of heterogeneities are considered: (1) a lateral heterogeneity due to the~~ The two main heterogeneities are caused by the laterally varying basement-cover interface, that is characterized by half-grabens and horsts, and ~~(2) a vertical heterogeneity due to alternating~~ by the vertical alternation of sedimentary layers with different mechanical strength. ~~The simulations can model the detachment and sub-horizontal transport of a nappe and the stacking of two nappes.~~

15   ~~Detachment of sedimentary units occurs due to stress concentrations in strong sediment layers around the basement-sediment contact, which result in a localized brittle-plastic shear band that detaches the strong layer from the basement. Horizontal transport is controlled by basement-cover geometry and occurs by moving relatively stronger sediment units above thinner and weaker units. The detached and horizontally transported units resemble a thrust nappe. Structures resembling fold nappes form by the ductile closure of a half-graben and the associated extrusion of the sedimentary half-graben fill; in agreement with~~

20   ~~previous modelling studies. In the simulations, the thrust nappe initiates before the fold nappe, because it is located closer to the "back-stop" of the applied model configuration. The thrust nappe exhibits a larger horizontal displacement than the fold nappe so that the thrust nappe can be stacked above the fold nappe.~~

~~The considered lateral variation of the basement-cover interface and associated mechanical heterogeneity is necessary to model nappe formation and stacking , but it is not sufficient. Additionally, a specific effective viscosity contrast between~~

25   ~~basement and strong and weak sediments is required. For our model configuration~~If these heterogeneities are included in numerical simulations, based on continuum thermo-mechanics, with standard creep flow laws and with Drucker-Prager and von Mises yield criteria, then the simulations can produce the first order features of nappe detachment, transport and stacking in the Helvetic nappe system. In our models, an effective viscosity contrast of approximately three to four orders of magnitude between weak sediments and strong sediments and basement is ~~required. Simulations with smaller viscosity contrasts did not~~

30   ~~generate the detachment and transport of thrust nappes. Nappe detachment and transport are modeled with standard creep flow laws and a Drucker-Prager yield criterion, without the application of strain softening algorithms. Considering several strong layers in the models can explain the second-order internal folding observed within some thrust nappes.~~ essential to reproduce the first order tectonic features. Furthermore, our results suggest that it is not essential to consider additional rock

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mechanic processes, in addition to the applied creep and brittle-plastic deformation, such as grain size evolution, frictional strain softening or pore fluid pressurization in order to explain these first order features, although all these additional processes most likely occured during the formation of the Helvetic nappe system. Therefore, our model requires likely the least amount of assumptions concerning rock deformation mechanisms for the explanation of the first order features of the Helvetic nappe

5   system.

Based on the first-order agreement between our model results and natural data, we propose a ~~macroscale "nappe theory" for the~~ thermo-mechanics based interpretation for the tectonic evolution of the Helvetic nappe system of Western Switzerland. ~~Our "nappe theory" can be self-consistently calculated and reproduced with a well-established continuum mechanics thermo-mechanical theory and with standard creep flow laws and a Drucker-Prager yield criterion, which are based on rock~~

10 ~~deformation experiments. We propose that the~~ : The pre-Alpine ~~configuration of the~~ European passive margin was characterized by ~~important mechanical heterogeneities resulting from (i)~~ significant mechanical heterogeneities due to a basement-cover contact with half-grabens and horst, and ~~(ii)~~ due to the alternation of mechanically strong and weak sediment units. During the ~~Alpine~~ continental collision, the passive margin ~~is shortened and sheared due to~~ was deformed by external compressive stresses. During ~~margin~~ deformation, mechanical heterogeneities, and not material softening mechanisms, control the detach-

15 ment, transport and stacking of nappes. ~~The~~ Detachment of sedimentary units of the Wildhorn super-nappe ~~are detached due to the existence of horsts, or basement highs, causing stress concentrations and brittle-plastic shear bands. The~~ is caused by stress concentrations around the contact between basement and sediments. The transport of the Wildhorn super-nappe was ~~transported mainly above~~ facilitated by weak shale-rich units and weak Ultrahelvetic units, which have been entrapped from above to below the Wildhorn super-nappe. Formation of the Morcles fold nappe ~~occured by dominantly ductile~~ is associated to the closing of

20 a half-graben, bounded by basement massifs that form now the Aiguilles-Rouges and Mont-Blanc massifs, and the associated squeezing-out of sediments from this half-graben. Closing of the half-graben occurred by an overall distributed deformation without major reactivation of earlier half-graben normal faults and without major localized thrusting in the basement.

Code availability. Not publicly available.

Data availability. Not publicly available.

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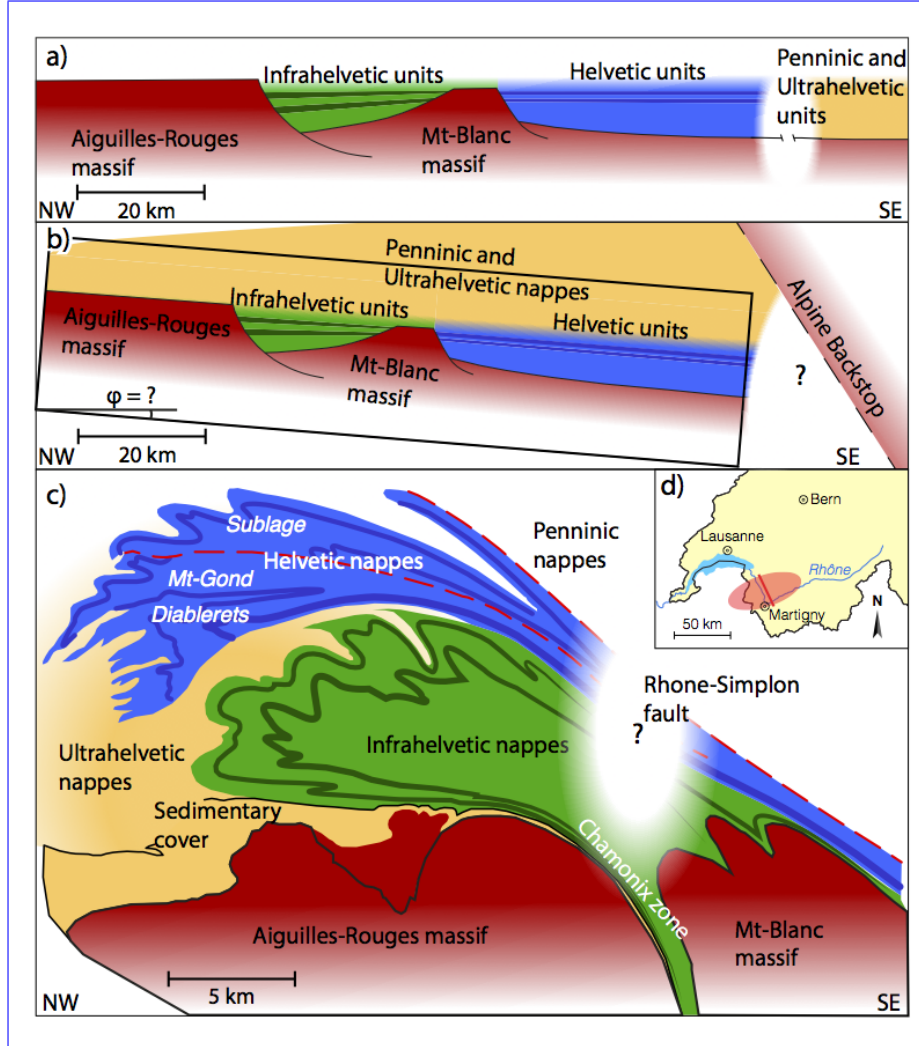
Figure 1. a) Simplified geological reconstruction of the Mesozoic, pre-Alpine European passive margin. b) Simplified geological reconstruction of the Alpine orogenic wedge, after emplacement of the Penninic and Ultrahelvetic units and before the Helvetic nappe stacking. The black rectangle represents the model domain of the numerical simulations. c) Simplified geological reconstruction of the present day structure of the Helvetic Nappe System. d) The location of the study area (red ellipse) and the cross section (red line) are indicated on the map of Switzerland.
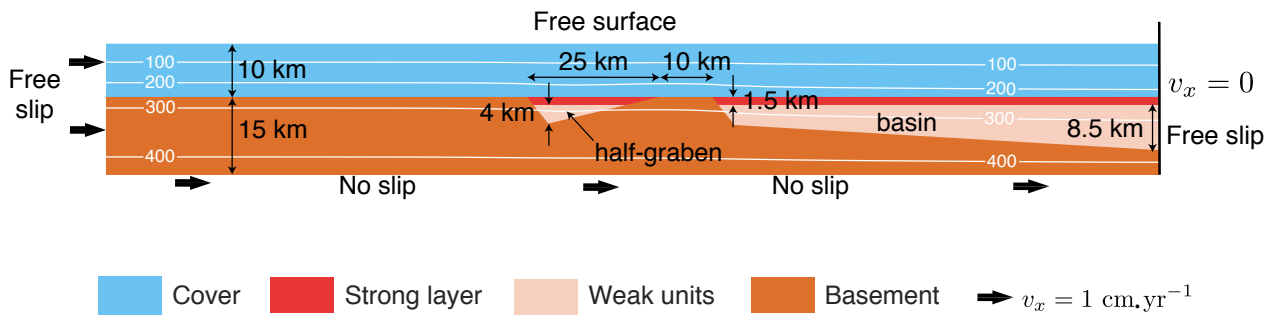
Figure 2. Reference model configuration. The white contours show isotherms and the labels are the corresponding temperatures in °C.
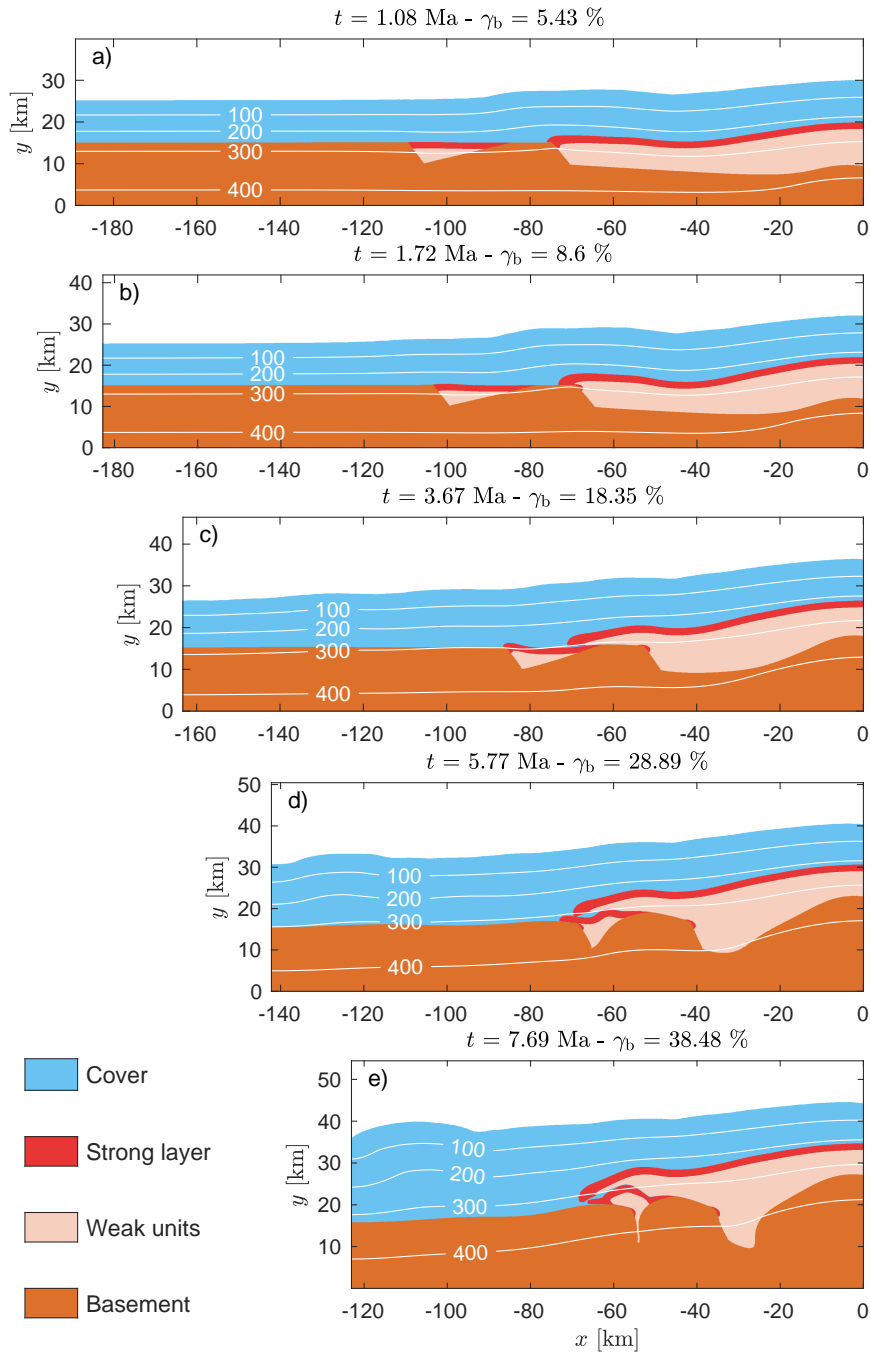
Figure 3. Structural and thermal evolution of the reference model for different times, t, and bulk shortening, γ_b. The white contours show isotherms and the labels are the corresponding temperatures in $^{\circ}$C. An animation, showing the full time evolution of the reference model, can be found as a supplementary material.
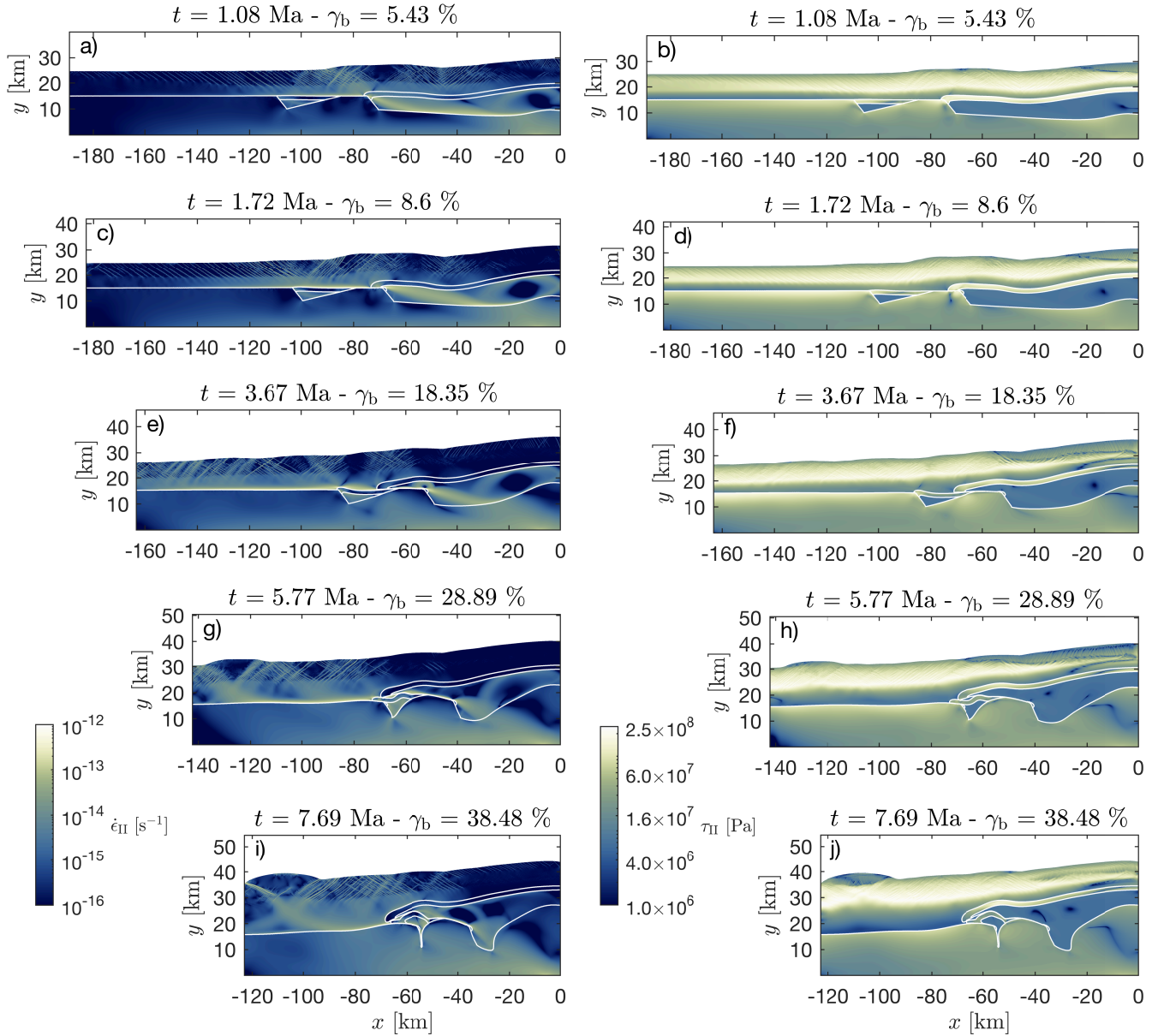
Figure 4. Evolution of the strain rate (left column) and deviatoric stress (right column) fields of the reference model for different times, t, and bulk shortening, γ_b. Strain rate and deviatoric stress are quantified with the square root of the second invariant of the strain rate, $\dot{\epsilon}_{II}$, and deviatoric stress, τ_{II}, tensor, respectively. Magnitudes of $\dot{\epsilon}_{II}$ and τ_{II} are displayed with logarithmic colorscale. Colormaps are from Crameri (2018).
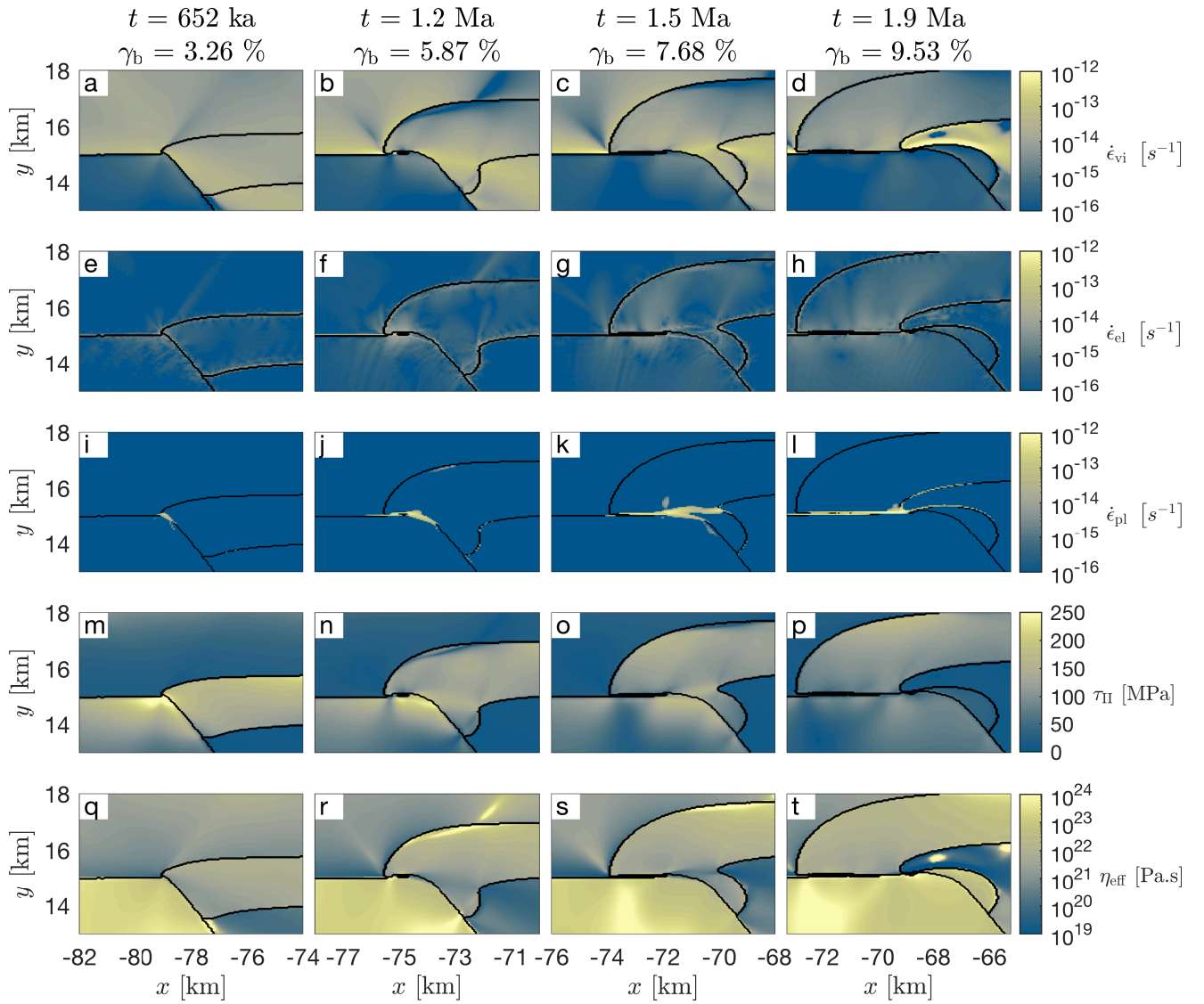
Figure 5. Enlargement of different stages of the detachment of the strong layer from the basement horst for different times, t, and bulk shortening, γ_b (see figure 4 for entire model domain). Colorplots of viscous strain rates (a-d), elastic strain rates (e-h), plastic strain rates (i-l), deviatoric stresses (m-p) and effective viscosities (q-t) are displayed. For all strain rate and stress tensor quantities we display their corresponding square root of the second invariants.
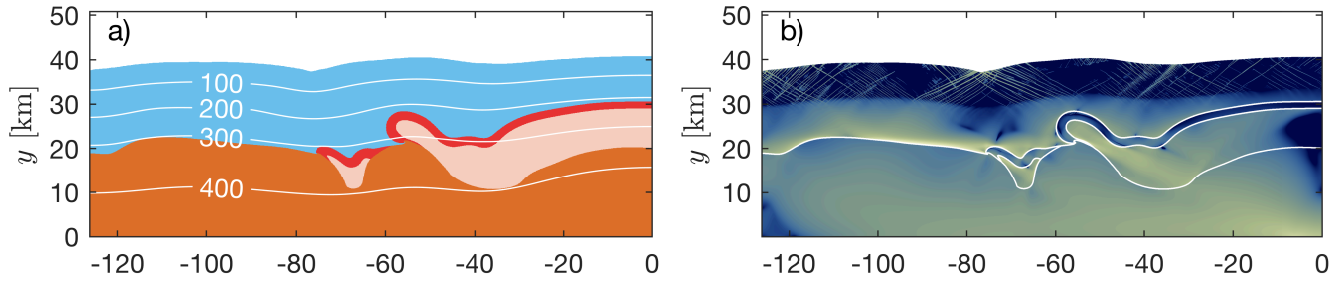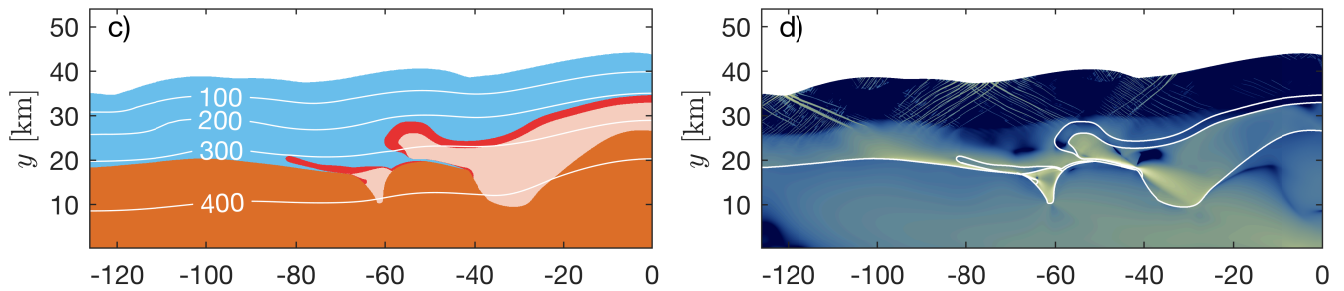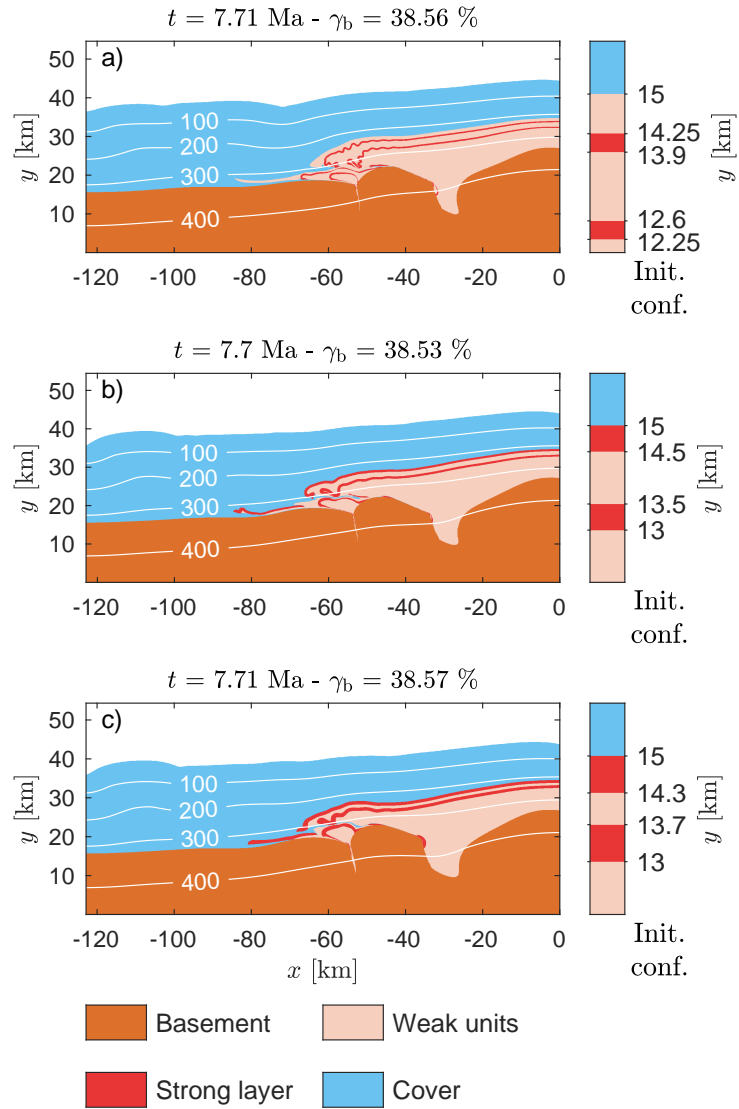
Figure 6. The final geometry, temperature and viscosity fields of three simulations with different f factor for certain model units (see ~~text~~figure titles).

Reference simulation
$t = 1.08$ Ma - $\gamma_b = 5.43$ %

Weaker basement $(f = 0.33)$
$t = 1.08$ Ma - $\gamma_b = 5.4$ %

Stronger cover $(f = 0.5$, instead of $f = 0.1)$
$t = 1.09$ Ma - $\gamma_b = 5.44$ %

Weaker strong layer $(f = 0.33)$
$t = 1.09$ Ma - $\gamma_b = 5.43$ %

η_{eff} [Pa.s]
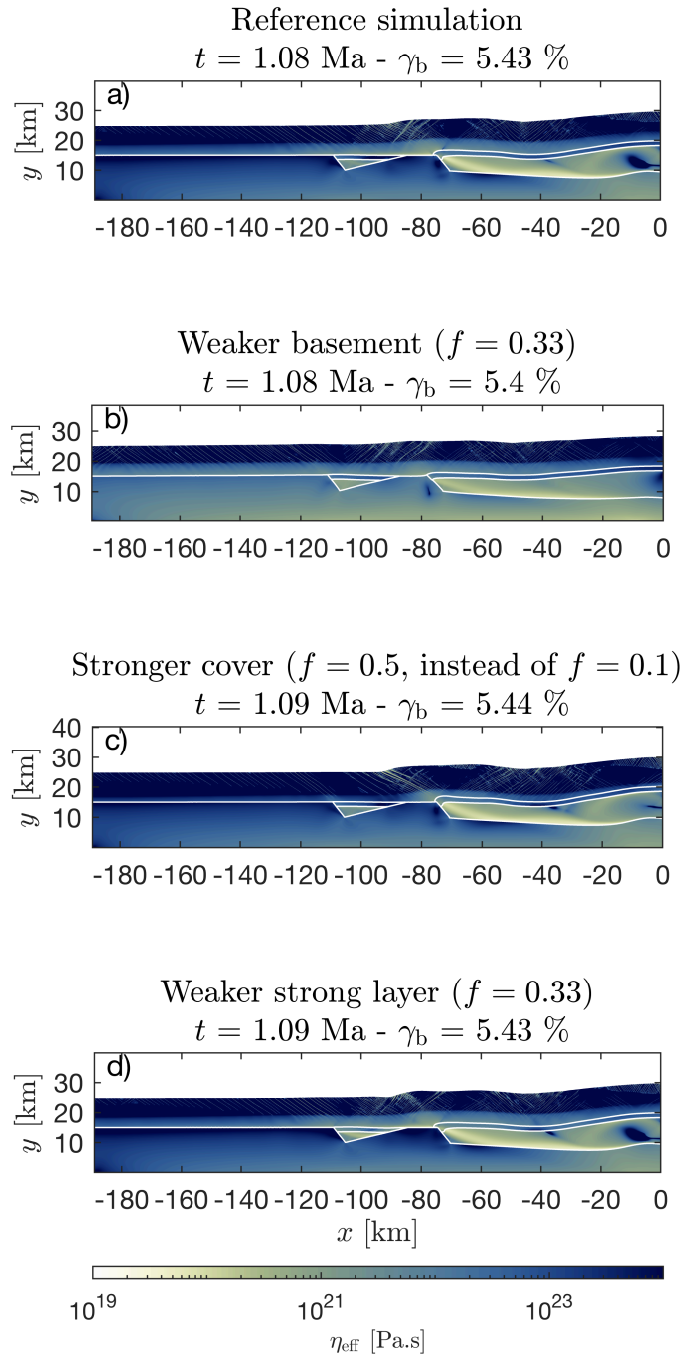
Figure 7. Effective viscosity for four simulations with different f factor for certain model units after a bulk shortening of ca. 5.4%. Below the brittle-ductile transition the effective viscosity (i.e. ratio of stress and visco-elastic strain rate) essentially equals the viscosity calculated from the dislocation creep flow law (eq. 1). Panel a) displays the reference simulation and panels b) to d) displays the three simulations shown in figure 6.
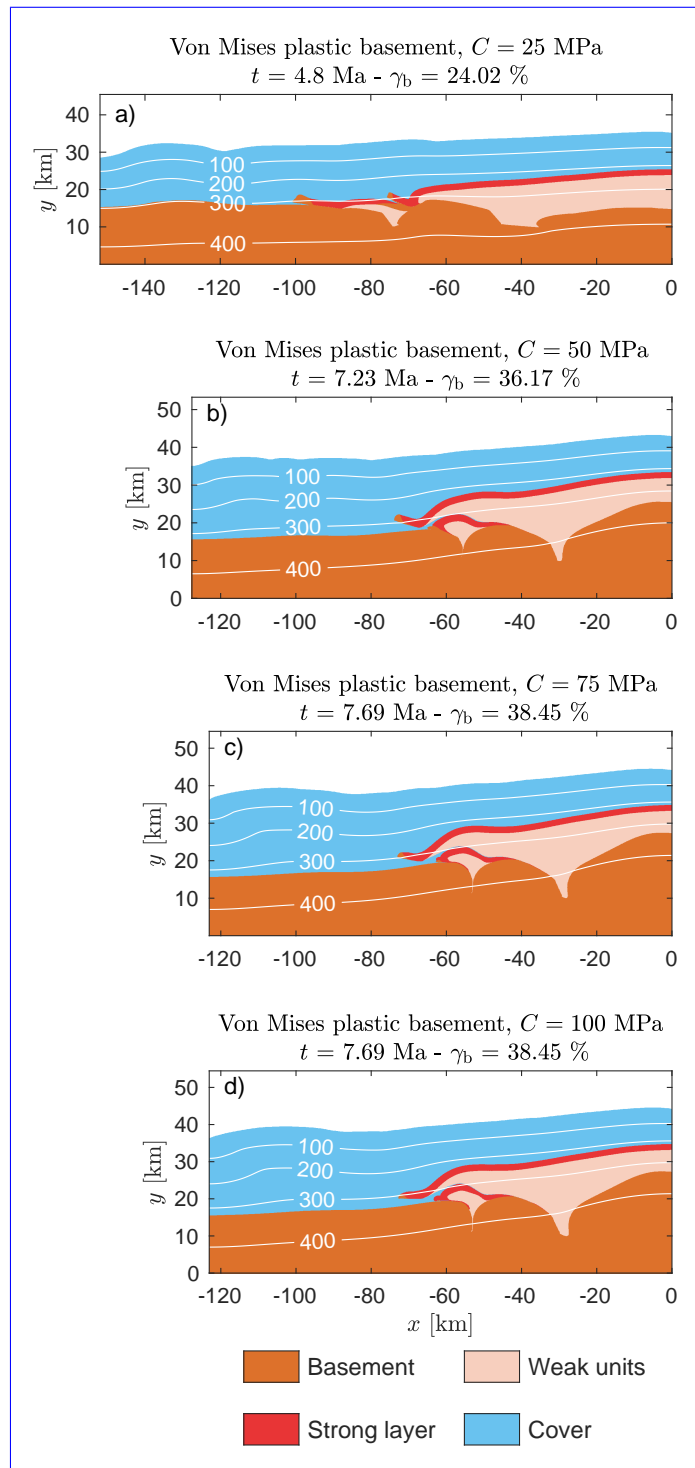
Figure 8. The final geometry and temperature fields of three simulations with different Von Mises yield criteria (see figure titles). The simulation with $C = 25$ MPa has been terminated earlier, as the results (the sedimentary units are bulldozing off huge pieces of the crystalline basement) are totally different from geological observations.

Figure 9. The final geometry of three simulations with two strong layers with the isotherms of the corresponding temperature field. The initial model stratigraphy around the upper region of the half-graben and basin is displayed on the right of each panel. The model stratigraphy is laterally homogenous, so the overall initial configuration is similar to that in Figure (2).
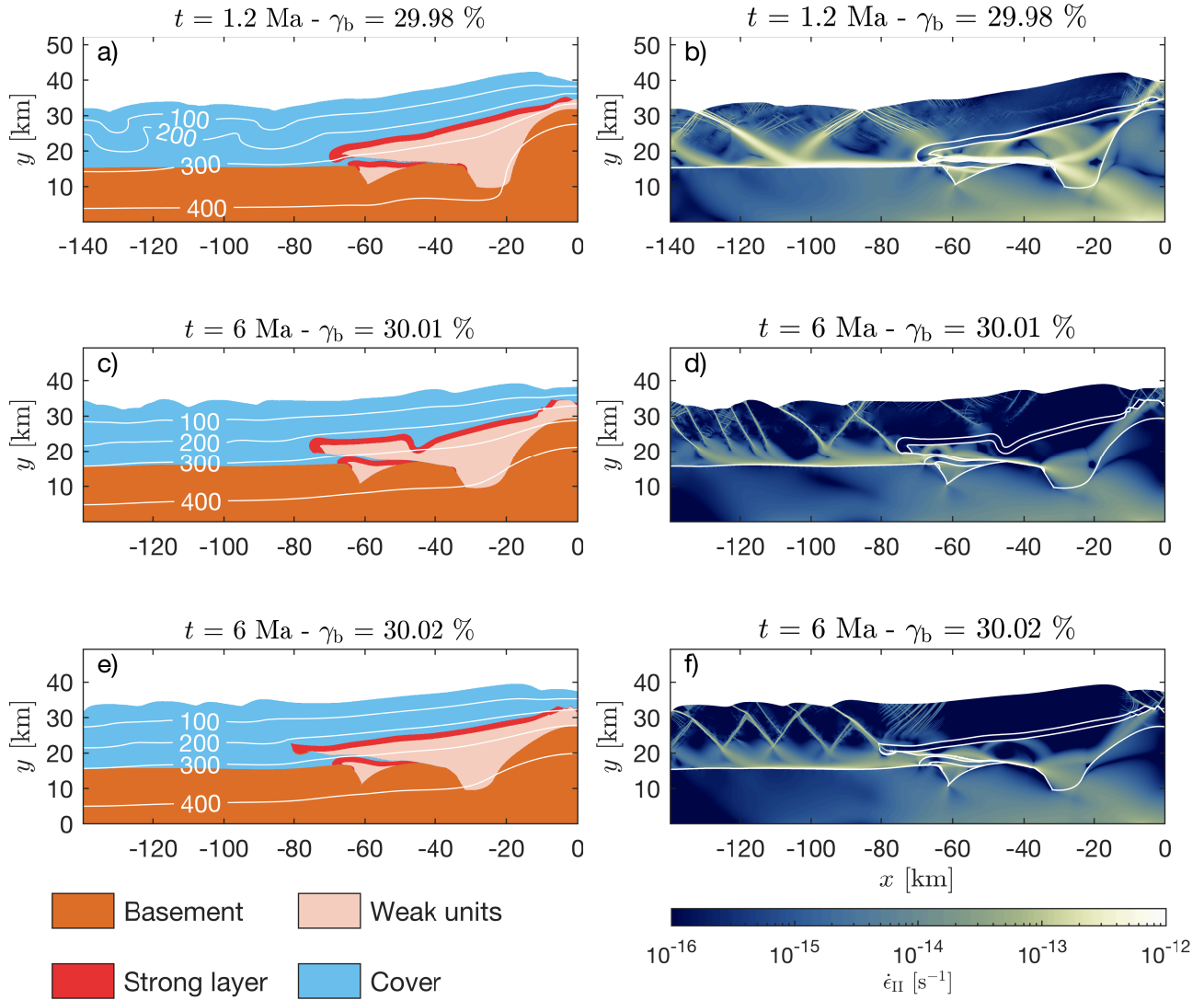
Figure 10. The geometry and the strain-rate field of three simulations after ca. 30% bulk shortening, with various softening mechanisms. Panels a) and b) show results of a simulation with a convergence rate of 5 cm.yr^{-1}, in which thermal softening has a significant impact. Panels c) and d) show results of a simulation with strain softening that reduces friction angle from the initial 30 degrees to 5 degrees. Panels e) and f) show results of a simulation with strain softening that reduces friction angle from the initial 15 degrees to 5 degrees.
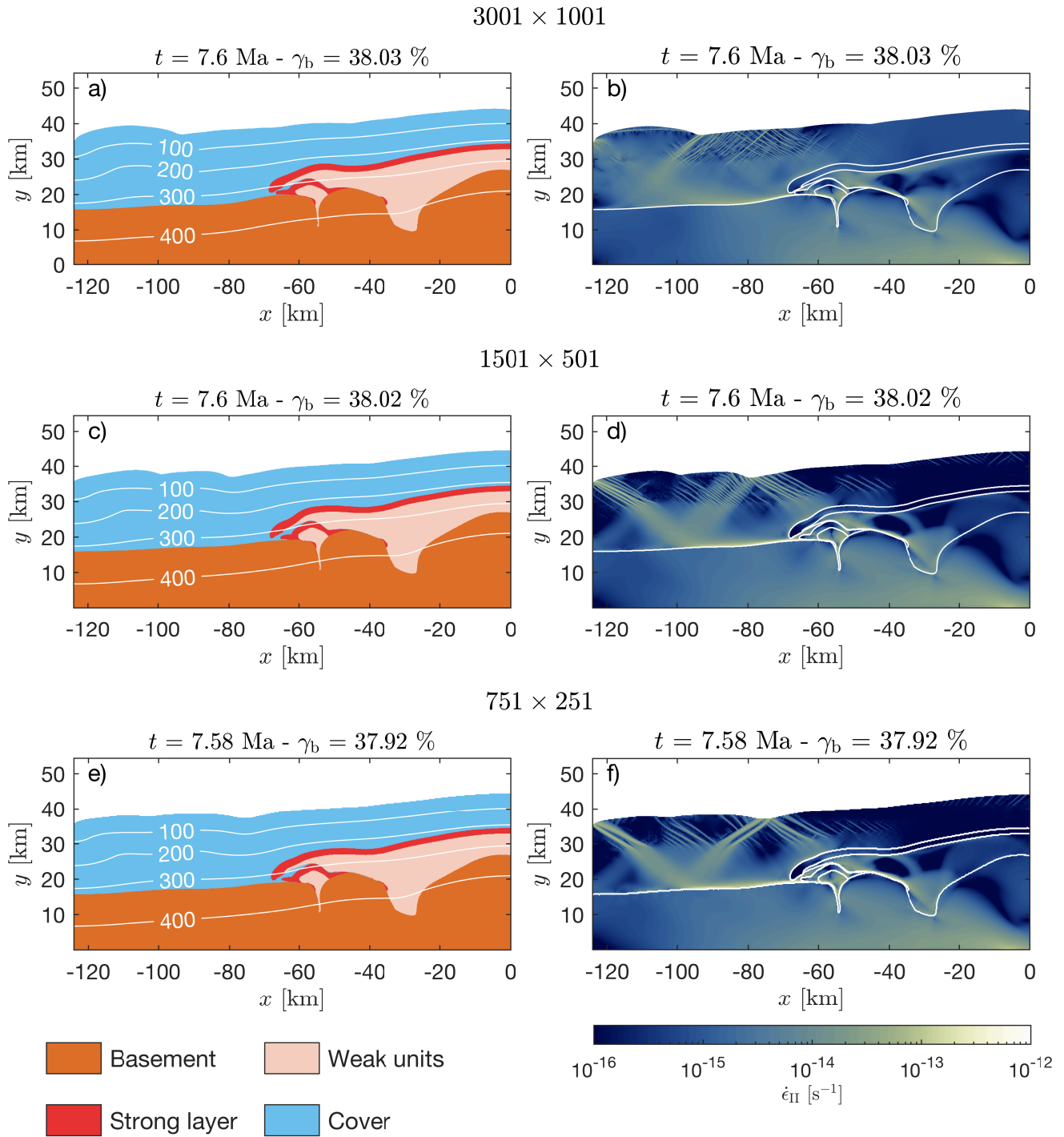
Figure 11. The geometry and the strain-rate field of three simulations after ca. 38% bulk shortening for different numerical resolutions.

Table 1. The list of the reference model parameters, where f is a custom pre-factor, A is the pre-exponential factor, n is the power-law exponent, Q is the activation energy, λ is the thermal conductivity, ρ_{ref} is the density at reference pressure ($P_{\text{ref}} = 0$ Pa) and temperature ($T_{\text{ref}} = 0$ °C), Q_r is the radioactive heat production, C is the cohesion and ϕ is the friction angle. Some parameters have constant values: $C_p = 1050$ J.K^{-1} is the heat capacity, $G = 10^{10}$ Pa is the shear modulus, $\alpha = 3 \times 10^5$ K^{-1} is the thermal expansion coefficient, $\beta = 10^{-11}$ Pa^{-1} is the compressibility and $F = 2^{(1-n)/n}3^{-(n+1)/(2n)}$ is a geometry factor (needed to convert flow law parameters from axial compression experiments into an invariant form). The creep flow law parameters (A, n and Q) are: [1]Westerly granite (Hansen et al., 1983), [2]calcite (Schmid et al., 1977) and [3]mica (Kronenberg et al., 1990).

Lithology	f	A [Pa^{-n}s^{-1}]	n	Q [J.mol^{-1}]	λ [W.m^{-1}K^{-1}]	ρ_{ref} [kg.m^{-3}]	Q_r [W.m^{-3}]	C [Pa]	ϕ [°]
Basement[1]	1.0	3.16×10^{-26}	3.3	1.87×10^5	3.0	2800	2.5×10^{-6}	10^7	30
Cover[2]	0.1	1.58×10^{-25}	4.2	4.45×10^5	2.5	2700	5×10^{-7}	10^7	30
Strong layer[2]	1.0	1.58×10^{-25}	4.2	4.45×10^5	2.5	2750	5×10^{-7}	10^7	30
Weak units[3]	1.0	1.00×10^{-138}	18.0	5.10×10^4	2.0	2700	1×10^{-6}	10^6	5