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The development of bone-shaped structures in initially segmented layers during layer-parallel extension: numerical modelling and parameter sensitivity analysis

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Abstract

In orogenic zones the geometric occurrence of specific tectonic structures can often be related to contrasting rheological properties of rock materials. One of such tectonic structures is layer-perpendicular naturally fractured layers with vein infill that underwent subsequent deformation. Internal deformation by coaxial extension of these segmented layers, with host-rock material less competent than the vein material, gives rise to the development of bone-shaped structures (i.e. dogbones). In this paper, the formation of such dogbones is modelled using finite element techniques. A parameter sensitivity analysis of the model demonstrates that the degree of extension of the host-rock segments, their initial aspect ratio and the competence contrast between vein material and host-rock are the controlling parameters for the final shape of the dogbones during coaxial extension. The results, moreover, suggest that the specific geometry of the dogbones can serve to quantify competence contrasts between the host-rock and vein material during flow at geological strain rates.

Keywords: Dogbones; Vein material; Finite elements; Competence contrast; Rheology

1. Introduction

Orogenic zones are comprised of crustal materials with continental and oceanic origin. The geometric occurrence of the tectonic structures we observe in these zones can often be related to contrasting rheological properties of these materials (Ramsay, 1982). One of such tectonic structures is layer-perpendicular naturally fractured layers with vein infill that underwent subsequent deformation. The layer-perpendicular veins can develop due to the consequence of brittle boudinage (i.e. mechanical stretching of the layers; cf. Ramsay, 1982; Price and Cosgrove, 1990; Goscombe et al., 2004) or due to the process of hydraulic fracturing (e.g. Cosgrove, 1997; Urai et al., 2001; Kenis et al., 2002; Kenis, 2004). Both processes can result in rectangular, block-shaped segmentation of the host-rock layer. In the case of the process of boudinage, we are dealing with torn boudins according to the classification of Goscombe et al. (2004).

As recognized in the literature, the rectangular blocks can be reworked and modified to varying degrees by subsequent deformation (Ramsay, 1982; Malavieille and Lacassin, 1988; Urai et al., 2001; Kenis et al., 2002; Goscombe et al., 2004; Kenis, 2004). This modification is due to a difference in competence between the vein material and host-rock. The final geometry of these segmented layers highly depends on the type and degree of the subsequent deformation and on the rheological properties of the materials (Fig. 1). Kenis et al. (2004) developed a numerical model, which allows modelling of the subsequent deformation of single layers that are segmented by layer-perpendicular veins (whether formed by the process of boudinage or by the process of hydraulic fracturing). More specifically the model focuses on deformation by coaxial shortening of segmented layers where the vein material is more competent than the host-rock material, resulting in the formation of cuspate–lobate structures at the interfaces of the host-rock and comprising layers (Figs. 1a and 2). These cuspate–lobate structures can be termed 'shortened torn boudins' or 'mullions' depending on the initial process that was responsible for the formation of the veins, i.e. boudinage or hydraulic fracturing, respectively. A parameter

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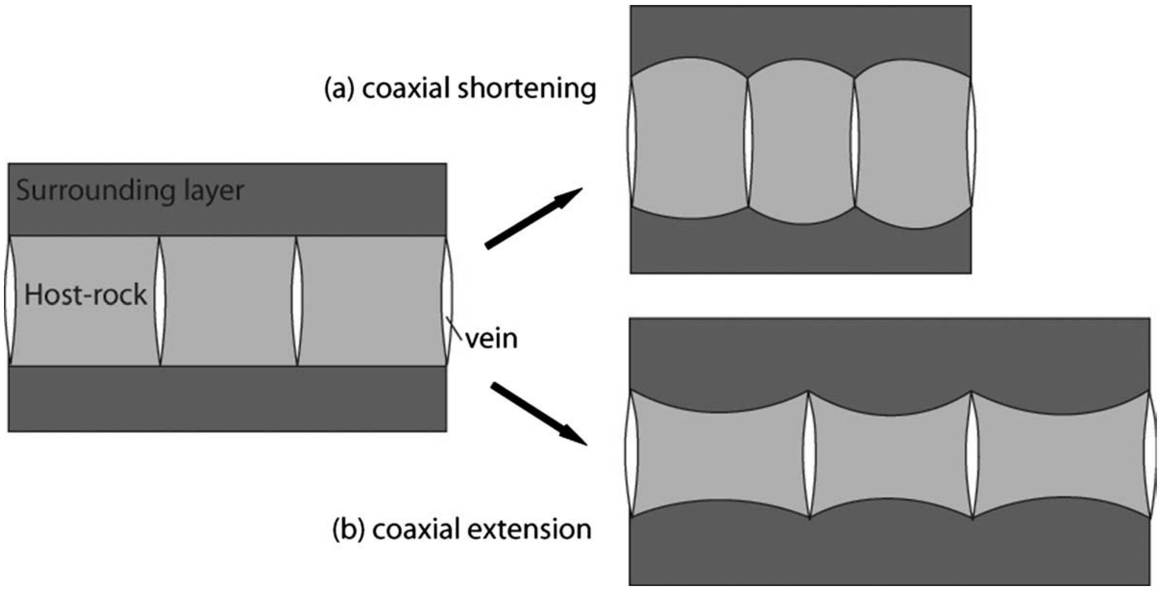

Fig. 1. Subsequent deformation of initially fractured layer. (a) Formation of mullions or 'shortened torn boudins' due to co-axial shortening; (b) formation of dogbones due to co-axial extension.

sensitivity analysis of the formation of these cuspate–lobate structures demonstrated that the final morphology of the interfaces of the host-rock and comprising material can be used to constrain the rheology of the host-rock (Kenis et al., 2004, 2005). This implies that outcrops including these structures can be used as natural laboratories to quantify the rheology of natural rocks during flow at geological strain rates (Kenis et al., 2005). In addition to this quantification, the parameter sensitivity analysis illustrated the range of layer-parallel shortening/extension structures that form in nature during subsequent deformation in associating with these layer-perpendicular veins.

Internal deformation by coaxial extension of the segmented host-rock, with host-rock material less competent than the vein material, gives rise to the development of bone-shaped structures (i.e. dogbones) such as described by Ramsay (1982) and Malavieille and Lacassin (1988) (Figs. 1b and 3). Although the formation of bone-shaped structures is possible with the numerical model of Kenis et al. (2004), the potential of dogbones as paleorheological gauges has never been investigated.

The aim of this paper is to explore this ability and thus to find out whether bone-shaped structures formed in layer-perpendicular segmented layers due to the consequence of

Fig. 2. Photograph of mullions in the High-Ardenne slate belt (Bastogne). The mullions formed due to layer-parallel shortening after formation of the layer-perpendicular quartz veins.

Fig. 3. Dogbones formed due to layer-parallel extension of initially fractured layers (Dinorwic, North Wales, UK; after Ramsay, 1982).

coaxial extension can be used to say something about the rheology of the host-rock material in which the veins are formed. To satisfy this aim, we present a parameter sensitivity analysis of the numerical 'dogbone' model, which will demonstrate the effect of the different geological parameters on the resulting shape of the structures. This will be used to evaluate the use of dogbones as a gauge to constrain the in-situ rheology of polymineralic material in nature.

2. Numerical model

The simple geometry of dogbones provides an unusually well constrained set of initial geometries and boundary conditions. This allows the construction of a plane strain geomechanical model using finite element techniques, which is capable of producing dogbones due to coaxial extension (Fig. 4). More specifically, the numerical model used in this paper starts from the 'deformable vein model' described by Kenis et al. (2004). In this model, a time-hardening power law creep formulation is used in which the strain-rate potential can be written as a function of equivalent stress, as implemented in the ABAQUS software package (Hibbitt et al., 2002).

The model implements three materials in its geometry: (1) the vein material, (2) the host-rock and (3) the surrounding layers of the host-rock (Fig. 4). In the model, a volume-constant steady-state power-law creep rheology is assumed for all these materials. In order to produce the bone-shaped structures due to co-axial extension of the segmented layer, Kenis et al. (2004) demonstrated that the host-rock should be less competent than the vein material, no matter what their composition is.

3. Parameter sensitivity analysis

The aim of the parameter sensitivity analysis is to investigate the effect of different geological parameters that have an effect on the strain, stresses and morphology of the bone-shaped structures in the model. The results of the parameter sensitivity analysis will be used to evaluate the potential of dogbones as a gauge to constrain the in-situ rheology of polymineralic rocks in nature (i.e. the host-rock).

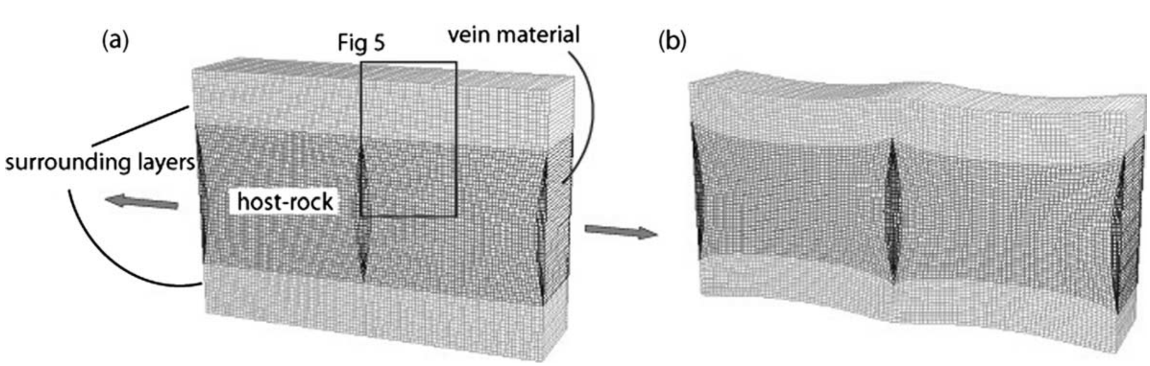

Fig. 4. Numerical 'dogbone' model. (a) Mesh of initially fractured layer. (b) Mesh of the same layer after layer-parallel extension, giving rise to the formation of bone-shaped structures (i.e. dogbones).

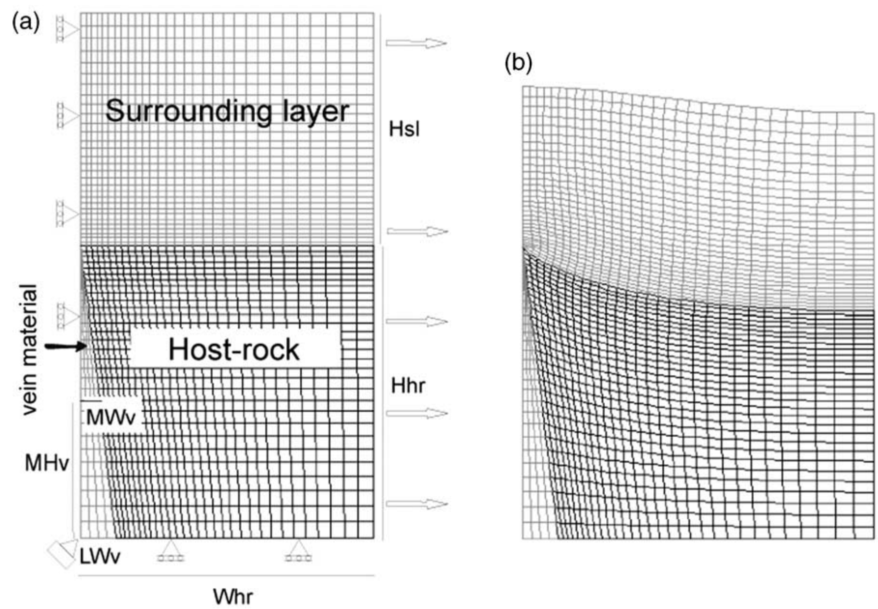

Fig. 5. Mesh of simplified dogbone model before (a) and after (b) deformation. The triangles give a representation of the boundary conditions imposed on the model. H sl—height surrounding layer, W hr—width host-rock, H hr—height host-rock, MH v—mid-height vein, MW v—mid-width vein, LW v—lower-width vein.

For the formation of the dogbones, we simplify modelling based on the near-orthorhombic symmetry of the structures. Therefore in the parameter sensitivity analysis only 1/4th of the dogbones is modelled, reducing computation time (Fig. 5).

The reference model of the parameter sensitivity analysis (model extension in Table 1), to which other models will be compared assumes the formation of dogbones formed in a siliciclastic sedimentary basin at deformation temperatures of 390 °C. More specifically, the vein material, host-rock and surrounding material correspond to wet quartz, psammite and pelite, respectively. This material choice is not aiming to reproduce a particular natural example but is rather to match with the Kenis et al. (2004, 2005) papers and because psammite and pelite are sufficiently general and likely for a variety of geological settings.

For all three materials we use a volume-constant steady state power law creep rheology ($\mathrm{d}\varepsilon/\mathrm{d}t = A\Delta\sigma^n$) characterized by the corresponding parameters A_{pe}, n_{pe}, A_{ps}, n_{ps}, A_{q} and n_{q} (Table 1). Here, ($\mathrm{d}\varepsilon/\mathrm{d}t$) is strain rate ($\mathrm{s}^{-1}$), $\Delta\sigma$ differential stress (MPa) and n the stress exponent. For vein quartz we use the relatively well constrained wet quartz flow law of Hirth et al. (2001). For psammite we use the corresponding rheological flow law as determined by Kenis et al. (2005). In agreement with results of earlier work (Treagus, 1999, 2002; Treagus and Treagus, 2002) we assume a viscosity ratio of 5 between psammite and pelite ($A_{\mathrm{pe}} = 5A_{\mathrm{ps}}$, and $n_{\mathrm{pe}} = n_{\mathrm{ps}}$). The reference model is extended with 20% during a deformation time of 1 Ma. These boundary conditions imply a constant displacement rate of 6.3×10^{-15}/s, which are believed to be within the limits of realistic geological strain rates (e.g. Twiss and Moores, 1992).

The following parameters are investigated:

(1) total extension;
(2) original geometry of the undeformed segmented layer:
    (a) thickness of the comprising material;
    (b) aspect ratio of host-rock segments between two veins;
(3) competence contrast of the host-rock and surrounding material;
(4) stress exponent of the host-rock;
(5) competence contrast of the vein material and host-rock.

The input parameters of the different simulations used for this parameter sensitivity analysis are listed in Table 1. Numerical convergence of the dogbone model for all parameters was robust and stable.

3.1. Total extension

The effect of the degree of coaxial extension on the dogbone model is illustrated in Fig. 6. The model is extended at a constant displacement rate. Different shapes of dogbones can be observed for extensions of, respectively, 10, 20 and 50% (Fig. 6). The higher the degree of extension, the thinner the centre of the fractured segments becomes with respect to the thickness of the layer adjacent to the veins. The dependence of the concavity of the shape of the dogbones on the degree of extension demonstrates the importance of constraining this parameter.

3.2. Original geometry of the undeformed segmented layer

The layer thickness of the host-rock and surrounding layers and the spacing between the veins is represented by the aspect

Table 1
Table of input parameters for the different simulations used in the parameter sensitivity analysis

Label inputfile	W hr	H hr	H cl	LW v	MW v	MH v	*E* ps	ν ps	A ps	*n* ps	*E* pel	ν pel	A pel	*n* pel	*E* qtz	ν qtz	A qtz	*n* qtz	t.o.d.	Displ.
Extension	50	50	90	6	4	25	1E+05	0.28	7.00E−15	1	1E+05	0.29	3.50E−14	1	1E+05	0.27	5.50E−21	4	3.15E+13	10
10%	50	50	90	6	4	25	1E+05	0.28	7.00E−15	1	1E+05	0.29	3.50E−14	1	1E+05	0.27	5.50E−21	4	3.15E+13	5
20% = extension	50	50	90	6	4	25	1E+05	0.28	7.00E−15	1	1E+05	0.29	3.50E−14	1	1E+05	0.27	5.50E−21	4	3.15E+13	10
50%	50	50	90	6	4	25	1E+05	0.28	7.00E−15	1	1E+05	0.29	3.50E−14	1	1E+05	0.27	5.50E−21	4	3.15E+13	25
pelratio 4/5 = extension	50	50	90	6	4	25	1E+05	0.28	7.00E−15	1	1E+05	0.29	3.50E−14	1	1E+05	0.27	5.50E−21	4	3.15E+13	10
pelratio 8/5	50	50	130	6	4	25	1E+05	0.28	7.00E−15	1	1E+05	0.29	3.50E−14	1	1E+05	0.27	5.50E−21	4	3.15E+13	10
psamratio 1/2	50	25	65	6	4	12.5	1E+05	0.28	7.00E−15	1	1E+05	0.29	3.50E−14	1	1E+05	0.27	5.50E−21	4	3.15E+13	10
psamratio 1/1 = extension	50	50	90	6	4	25	1E+05	0.28	7.00E−15	1	1E+05	0.29	3.50E−14	1	1E+05	0.27	5.50E−21	4	3.15E+13	10
psamratio 3/2	50	75	115	6	4	37.5	1E+05	0.28	7.00E−15	1	1E+05	0.29	3.50E−14	1	1E+05	0.27	5.50E−21	4	3.15E+13	10
psam/pel 0	50	50	90	6	4	25	1E+05	0.28	7.00E−15	1	1E+05	0.29	7.00E−15	1	1E+05	0.27	5.50E−21	4	3.15E+13	10
psam/pel 5	50	50	90	6	4	25	1E+05	0.28	7.00E−15	1	1E+05	0.29	3.50E−14	1	1E+05	0.27	5.50E−21	4	3.15E+13	10
psam/pel 1000	50	50	90	6	4	25	1E+05	0.28	7.00E−15	1	1E+05	0.29	7.00E−12	1	1E+05	0.27	5.50E−21	4	3.15E+13	10
quartz/psam 0	50	50	90	6	4	25	1E+05	0.28	5.50E−21	4	1E+05	0.29	2.75E−20	4	1E+05	0.27	5.50E−21	4	3.15E+13	10
quartz/psam 1000	50	50	90	6	4	25	1E+05	0.28	5.50E−18	4	1E+05	0.29	2.75E−17	4	1E+05	0.27	5.50E−21	4	3.15E+13	10
quartz/ psam1000000	50	50	90	6	4	25	1E+05	0.28	5.50E−15	4	1E+05	0.29	2.75E−14	4	1E+05	0.27	5.50E−21	4	3.15E+13	10
n1	50	50	90	6	4	25	1E+05	0.28	7.00E−15	1	1E+05	0.29	3.50E−14	1	1E+05	0.27	5.50E−21	4	3.15E+13	10
n2	50	50	90	6	4	25	1E+05	0.28	7.00E−15	2	1E+05	0.29	3.85E−14	2	1E+05	0.27	5.50E−21	4	3.15E+13	10
n3	50	50	90	6	4	25	1E+05	0.28	8.50E−15	3	1E+05	0.29	4.25E−14	3	1E+05	0.27	5.50E−21	4	3.15E+13	10
n4	50	50	90	6	4	25	1E+05	0.28	9.40E−15	4	1E+05	0.29	4.70E−14	4	1E+05	0.27	5.50E−21	4	3.15E+13	10
n6	50	50	90	6	4	25	1E+05	0.28	1.14E−14	6	1E+05	0.29	5.70E−14	6	1E+05	0.27	5.50E−21	4	3.15E+13	10

W—width; H—height; MW—middle width; LW—lower width; MH—middle height; hr—host-rock; sl—surrounding layer; v—vein material; ps—psammite; pel—pelite; qtz—quartz; t.o.d.—time of deformation; displ—displacement; *n*—stress exponent of power law equation; A—power law multiplier; *E*—Young's modulus; ν—Possion's ratio. See also Fig. 5.

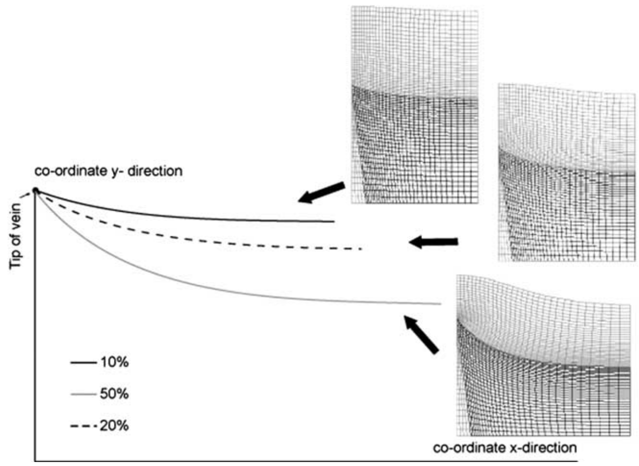

Fig. 6. Diagram showing half a dogbone curve (host-rock/surrounding layer interface) at different degrees of extension (10, 20 and 50%) of the geodynamic model. The input parameters of the different simulations represented are reported in Table 1. The scale of the diagram is 1/1.

ratio (H/W) of the undeformed mesh of both the host-rock and surrounding layers. These aspect ratios were varied with respect to the reference model to evaluate their effect on the shape of the dogbones (Figs. 7 and 8, Table 1).

The aspect ratio of the psammites (H hr/W hr in Fig. 5) clearly is important for the concavity of the final shape of the dogbones (Fig. 7), while the aspect ratio of the pelite (H sl/W hr in Fig. 5) has very little influence compared with this first (Fig. 8). The dependence of the shape of the dogbones on the original aspect ratio of the host-rock segments shows that the wider the vein spacing in the host-rock with respect to the layer thickness the less concave the shape of the dogbones will be. The result of the effect of the original geometry of the dogbones demonstrates that a strain analysis of the host-rock is not only necessary to determine the degree of extension of this material, but also to reconstruct the original shape of the undeformed fractured layer. This undeformed shape will have a significant effect on the final geometry of the dogbones formed during deformation of the segmented layer.

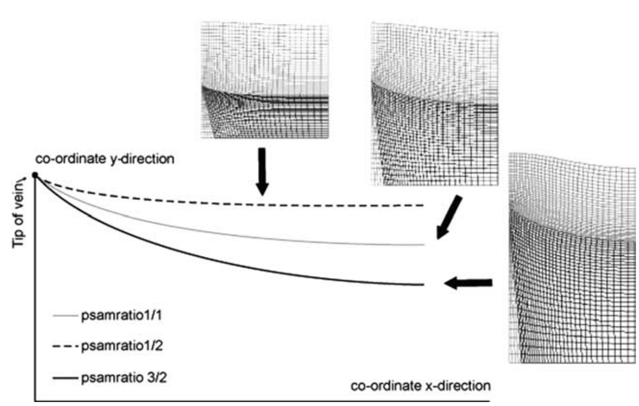

Fig. 7. Diagram showing the influence of the aspect ratio of the undeformed host-rock segment between the veins. The input parameters of the different simulations represented are reported in Table 1. The scale of the diagram is 1/1. psamratio 1/1, 1/2 and 3/2 refer to an initial aspect ratio (height–width) of the host-rock segments of 1/1, 1/2 and 3/2, respectively.

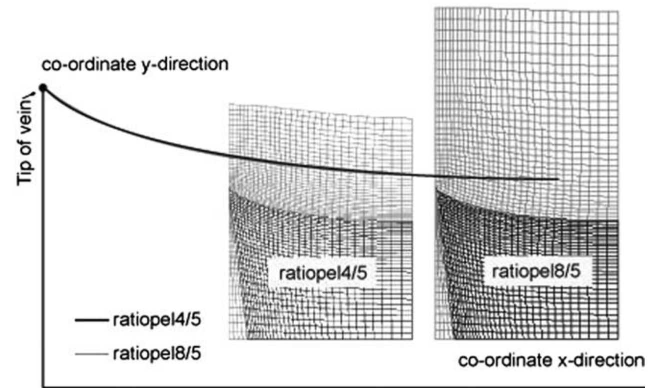

Fig. 8. Diagram showing the influence of the aspect ratio of the surrounding layers of the host-rock. The input parameters of the different simulations represented are reported in Table 1. The scale of the diagram is 1/1. ratiopel 4/5 and 8/5 refer to an initial aspect ratio (height–width) of the surrounding layer of 4/5 and 8/5, respectively.

An example of a similar strain analysis has been published in Kenis et al. (2005).

3.3. Competence contrast of the host-rock and surrounding material

In order to investigate the effect of the competence contrast of the host-rock and its surrounding material, the A-value of the surrounding material (i.e. pelite in the reference model) has been increased stepwise while keeping the A-value of host-rock material constant (Fig. 9, Table 1). Keeping the values of the stress exponent and the strain rate constant for all simulations in Fig. 9, an increase in A-value for the surrounding material directly corresponds to a reduction in competence. Considering the results of this part of the parameter sensitivity analysis, it has to be kept in mind that the vein material here is modelled as a relatively rigid body with respect to the host-rock and its surrounding material.

Results of the different simulations show only a small effect of the competence contrast of the host-rock and its surrounding material on the final shape of the dogbones. Since the competence

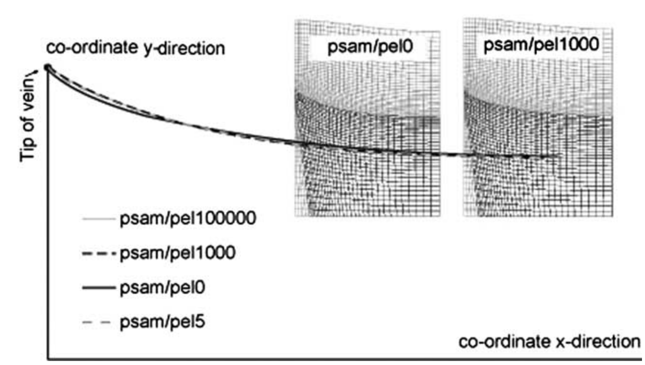

Fig. 9. Diagram showing the influence of the difference in competence between the host-rock and surrounding layer. The input parameters of the different simulations represented are reported in Table 1. The scale of the diagram is 1/1. psam/pel0-no competence contrast between the host-rock (psammite) and surrounding layer (pelite), psam/pel5-surrounding layer 5× weaker than host-rock, etc.

contrast between pelite and psammite has almost no influence on the shape of a dogbone, we conclude that the effect of the rheology of the pelites on the shape of dogbones is negligible. A similar conclusion has been drawn for the influence of the rheology of the surrounding layer on the development of mullions due to coaxial shortening of the segmented host-rock layer (see Kenis et al., 2004). From literature, realistic viscosity contrasts of quartzite relative to pelite are estimated to be less than 10–5 (Treagus, 1999, 2002; Treagus and Treagus, 2002).

3.4. Stress exponent of the host-rock

Next, the influence of the stress exponent of the host-rock on the shape of the dogbones is investigated (Table 1, Fig. 10). To make sure that the competence of the host-rock material remains similar for all simulations, the equation $\delta\varepsilon/\delta t = A(\sigma_1 - \sigma_3)^n$ was used to calculate corresponding A-value starting with the power law for psammite at 390 °C (Kenis et al., 2005), an extension of 20% and a deformation time of 1 Ma. As a consequence, the differential stress in the different simulations of Fig. 10 remain in the same order of magnitude.

In contrast to what is found for the influence of the stress exponent on the final shape of mullions that develop during coaxial shortening of segmented layers (Kenis et al., 2004), the stress exponent of the host-rock has very little effect on the final shape of dogbones formed due to coaxial extension of such segmented layers (Fig. 10). Although a small influence can be observed, it is clear from Fig. 10 that this difference in shape will not be convincing enough to quantify n values for the host-rock from the natural shape of dogbones as is the case with mullions (Kenis et al., 2004, 2005). Especially when keeping in mind that dogbones observed in the field can show more irregularities than the ones observed in the model.

3.5. Competence contrast of vein material and host-rock

The last step in the parameter sensitivity analysis involves the effect of the competence contrast of the vein material and host-rock on the shape of the dogbones (Fig. 11). For this part of the parameter sensitivity analysis a different reference model is used (i.e. model psam/quartz 0 in Table 1). For this reference model the vein material is the most competent material and is

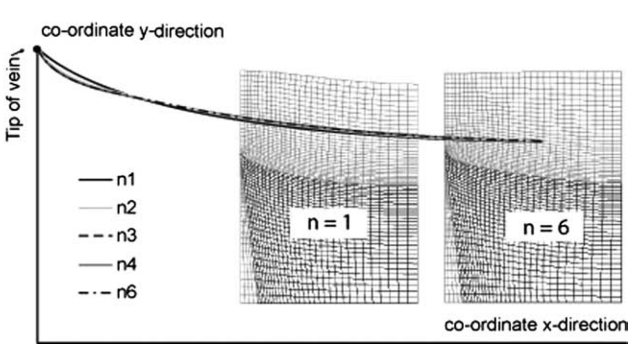

Fig. 10. Diagram showing the influence of the stress exponent of the host-rock between the veins. The input parameters of the different simulations represented are reported in Table 1.

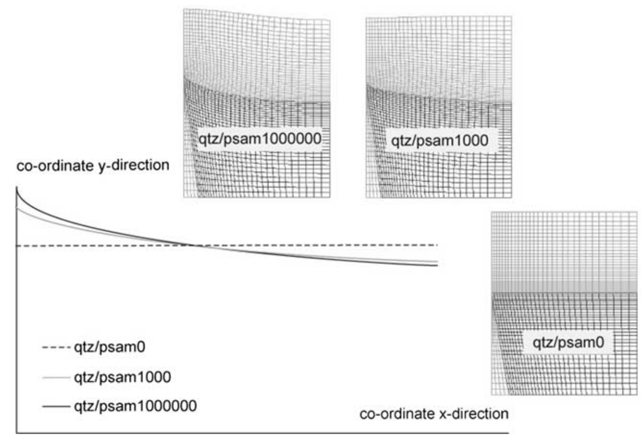

Fig. 11. Diagram showing the influence of the difference in competence between the host-rock and vein material. The input parameters of the different simulations represented are reported in Table 1. The scale of the diagram is 1/1. qtz/psam0-no competence contrast between the host-rock (psammite) and vein material (quartz), qtz/psam1000-host-rock 1000× weaker than vein material; qtz/psam1000000-host-rock 1000000× weaker than vein material, etc.

assigned the wet-quartz rheology of Hirth et al. (2001) deforming at temperatures of 390 °C. To evaluate the competence contrast of vein material and host-rock, the stress exponent of 4 (Hirth et al., 2001) was used for all three materials and only A-values of the host-rock have been varied to reflect a difference in competence. A competence contrast of host-rock/comprising layer of 5 is retained for all the simulations (cf. Treagus, 1999, 2002).

The results show that the shape of the dogbones is a strong function of the competence contrast of the vein material versus the host-rock (Fig. 11, Table 1). At a very high competence contrast the deformation of the vein material reduces to zero while the deformation in the host-rock remains relatively high (Fig. 12). With decreasing competence contrast, the deformation of the host-rock and vein material becomes more and more similar, evolving to a homogeneous extension at a competence ratio of 1 (Figs. 11 and 12).

The development of a pronounced concave shape of the dogbones in the field only occurs when a relatively large competence contrast between the vein material and host-rock exists. This pronounced shape is the consequence of a relatively large difference in strain between the host-rock and vein material resulting in a large difference in strain rate. This difference in strain rate is due to a competence contrast, which promotes strain

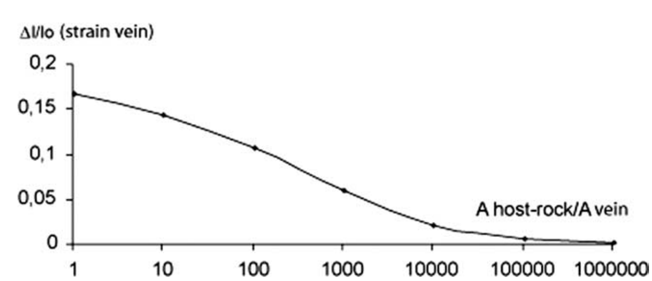

Fig. 12. Diagram representing the difference in strain of the vein corresponding to different competence ratios vein/host-rock. The more competent the vein becomes with respect to the host-rock the less strain occurs in the veins. A host-rock/A vein = 1000: vein 1000× stronger than host-rock.

partitioning between compositional bands (cf. Ramsay and Lisle, 2000). The development of dogbones due to coaxial extension therefore does not occur if the competence of the vein material and host-rock was similar during layer-parallel extension.

4. Discussion

Based on the parameter sensitivity analysis, three main controlling parameters were identified for the development of the specific shape of dogbones due to coaxial extension (Fig. 13):

1. the total extension
2. the initial shape of the host-rock segments and
3. the competence contrast of the vein material versus the host-rock.

For the development of mullions due to coaxial shortening of a segmented layer, a fourth parameter could be found, i.e. the stress exponent of the power-law equation of the host-rock (Kenis et al., 2004). This fourth parameter mainly expressed itself in the convexity of the shape of the mullions while the competence contrast between the host-rock and vein material mainly expressed itself in a difference in strain between both materials. Once this difference in strain could be determined from quantitative strain analysis, it was possible to determine the stress exponent of the host-rock during the development of mullions in nature. This determination allows outcrops including mullions to be used as natural laboratories to quantify rheological flow laws for polyphase materials deforming under natural geological conditions.

For dogbones, the stress exponent is not a controlling parameter for the final shape of the structures. This implies that

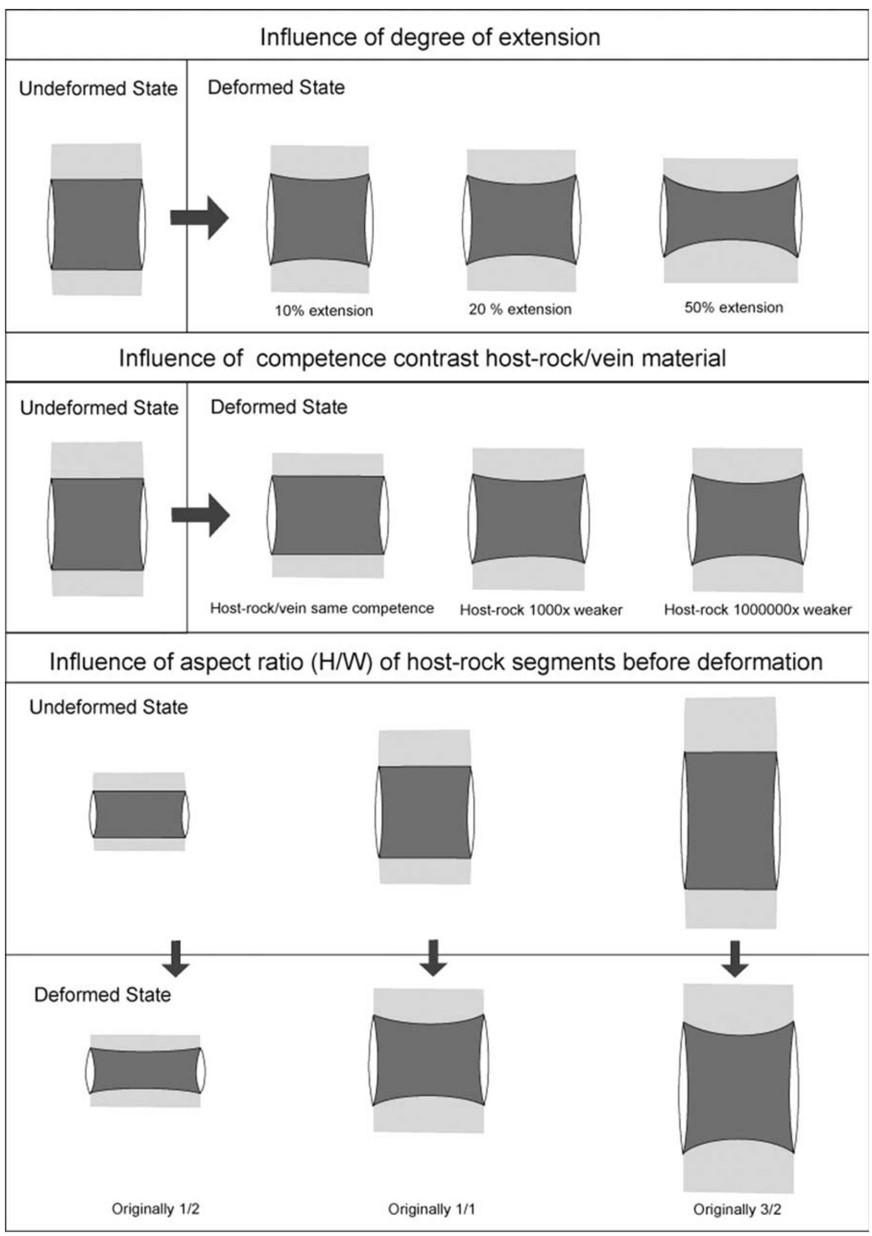

Fig. 13. Schematic drawing showing the influence of the three main controlling parameters on the shape of the dogbones. All dogbone drawings are on scale 1/1.

dogbones cannot be used to quantify the rheological parameters of the flow law for the host-rock during in-situ deformation. However, this conclusion does not mean that dogbones are worthless for rheologic estimates. When studying dogbones in the field much can be constrained from structural, mineralogical and geochemical work (e.g. differential stresses, strains, deformation temperatures, rheological properties for the vein material from monomineral experimental flow laws in literature …). More specifically, a strain analysis of the different lithologies can be used to constrain the total degree of extension and to reconstruct the original shape of the segments before ductile extension. Taking into account the three controlling parameters on the shape as reported above, this leaves the competence contrast between the vein material and host-rock as the only unknown parameter determining the shape of the dogbones. Using the structural constraints in the numerical model, the best-fit solution of the model allows for determining the competence contrast between the vein material and the host-rock. This makes the dogbones good examples of structures that can teach us something about competence contrasts between different rock materials in nature (see also studies of Treagus, 1983, 1999; Lan and Hudleston, 1991, 1996; Hudleston and Lan, 1994; Biot, 1961; Treagus and Treagus, 2002). Moreover, vein material is often composed of monomineralic material. For these monomineralic materials experimental flow laws are deduced in laboratory and extrapolated to geological conditions. When using such monomineralic flow laws and calculating the absolute competence of the vein material during deformation of the fractured layers, an absolute competence for the host-rock of the dogbones can also be constrained. This possibility implies that in some cases dogbones do not only serve to estimate the competence contrast between vein material and host-rock but also teach us something about the absolute competence of the host-rock.

It is clear from the parameter sensitivity analysis that dogbones are important rheology indicators. With this study we hope that in the future these structures therefore get more attention in structural studies. To our knowledge dogbones have only been clearly reported by Ramsay (1982) and Malavieille and Lacassin (1988). These studies report dogbones occurring worldwide (from Wales to the Basin and Range province) and in different geological settings (flyschoid series, shales and limestones, dolorite dykes and argillaceous slates) demonstrating that most probably these structures are more common than expected from examples in literature.

5. Conclusion

A parameter sensitivity analysis has been performed on a geomechanical segmented layer model using the ABAQUS package in order to qualify the controlling parameters on the development of the specific shape of dogbones due to coaxial extension of this segmented layer (Fig. 12). On the one hand, the parameter sensitivity analysis shows that the competence contrast between host-rock and surrounding material, the dimension of the surrounding material before deformation and the stress exponent of the host-rock are relatively of no importance for the shape of dogbones. On the other hand, the analysis demonstrates that the degree of extension of the host-rock segments, their initial aspect ratio and the competence contrast between vein material and host-rock are the important controlling parameters for the final shape of the dogbones during coaxial extension.

From strain analysis it is possible to constrain the first two controlling parameters. This means that the best-fit solution of the numerical ‘dogbone’ model allows the determination of the specific competence contrast of the host-rock and vein material of the dogbones. If an appropriate flow law can be obtained from literature for the often monomineralic material of the veins, it is even possible to quantify the absolute competence of the host-rock during deformation. This application allows outcrops including dogbones to be used as natural laboratories to quantify relative, and sometimes absolute, competences of polyphase materials deforming under natural geological conditions and implies that dogbones can be considered as new important rheological indicators for polymineralic rocks.

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