Brittle Ductile coupling in symmetrical extension
Analogue modeling at a crustal scale

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Abstract

Analogue models made of sand simulate the frictional/brittle behaviour of the crust or overburden. Silicon putty simulates the viscous/ductile behaviour of the crust or salt. Extensional structures are dependant on the mechanical coupling between the ductile and brittle part of the upper crust. Coupling depends on the strength ratio between the upper brittle layer and the lower ductile layer. The strength of a brittle layer is directly depending of its thickness, the strength of the ductile layer, for a given thickness, depends directly on the strain rate. We ran a set of 9 experiments with different brittle thicknesses and strain rates. Under strong coupling rollovers and localised deformation are dominant. At weak coupling half grabens dominate the regime. Localised rifting occurs in a normal crustal thickness. Wide spread extension occurs in a thickened crust, but also in a normal crustal thickness. The strain rate or the ductile strength is the controlling factor.

Introduction

Rifting often seems to be asymmetric, though it may be resulting from asymmetric simple shear or it may be the result of symmetric pure shear. Analogue models made of sand simulate the frictional/brittle behaviour of the crust or overburden. Silicon putty simulates the viscous/ductile behaviour of the crust or salt. This project is a follow up of analogue experiments realised in asymmetric extension and currently in press. With asymmetric extension, we have been able to demonstrate that:

Continental lithosphere extension occurs in various plate tectonic environments leading to localised rifting when the brittle crust has a normal thickness and widespread extension where the brittle crust is thicker.

Localised extension results from weak brittle ductile coupling, strong brittle strength and/or low ductile strength.

Stronger coupling results in transitions from horst and graben to tilted blocks.

Thin skinned extension occurs on most of the passive margins and result from the gliding of a brittle sedimentary cover of variable thickness over a ductile decollement layer.

These crustal or basin scale structures are highly dependant on the mechanical coupling between the ductile and brittle part of the upper crust. This project is designed to study the effects of the coupling existing between brittle and ductile layers in a symmetrical extensional regime. According to Brun, 1999 coupling depends on the strength ratio between the upper brittle layer and the lower ductile layer. After Brun, 1999, Michon and Merle, 2000, 2003. Strength of a brittle layer is directly depending of its thickness, the strength of the ductile layer, for a given thickness, depends directly on the strain rate. To understand the coupling between the ductile and the brittle layer, these parameters need to be changed. Thus various brittle thicknesses were used, to change the strength of the brittle layer. To change the strain rate of the ductile layer, various strain rates were used. In these experiments we took in account the crustal scale and basin scale.

To cover a wide range of brittle ductile coupling in symmetrical extension we performed 9 experiments with 3 different velocities and 3 different brittle thicknesses. 9 syn-kinematic layers are deposited during the experiments to simulate sedimentation.
Velocity

Brittle Thickness

<table>
<thead>
<tr>
<th></th>
<th>1 cm/h</th>
<th>5 cm/h</th>
<th>10 cm/h</th>
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<tbody>
<tr>
<td>(5 cm extension each side)</td>
<td>(5 cm extension each side)</td>
<td>(5 cm extension each side)</td>
<td></td>
</tr>
<tr>
<td>2 cm</td>
<td>SE 1</td>
<td>SE 2</td>
<td>SE 3</td>
</tr>
<tr>
<td>4 cm</td>
<td>SE 4</td>
<td>SE 5</td>
<td>SE 6</td>
</tr>
<tr>
<td>6 cm</td>
<td>SE 7</td>
<td>SE 8</td>
<td>SE 9</td>
</tr>
<tr>
<td>Duration experiment</td>
<td>10 hours</td>
<td>2 hours</td>
<td>1 hour</td>
</tr>
</tbody>
</table>

Table 1: The experiments, and their boundary conditions

The experiments were done under supervision of Thomas Mauduit. These experiments are part of his research on coupling to understand the rifting at lithospheric scale. All experiments have been done at the ISES Tectonic Laboratory of the Institute of Earth and Life Sciences, Vrije Universiteit, Amsterdam. The article is further subdivided in the following chapters:
- Analogue modelling, consisting of: model scaling, materials, construction, deformation and limitations.
- Results, consisting of: deformation width and description of the structures in terms of brittle strength and ductile strength.
- Comparison with natural examples
- Discussion
- Conclusions

Analogue modelling

scaling

Scaling relations between the natural prototype and the model are obtained by keeping the average strength of the ductile layers correctly scaled with respect to the strength of the brittle layers and gravity forces. In the equation of dynamics:

\[ \delta \sigma_{ij} / \delta x_{ij} + \rho ( g - ( \delta^2 \sigma_{ij} / \delta t^2 )) = 0 \]

where \( \sigma_{ij} \) are the components of stress, \( \epsilon_{ij} \) are the components of deformation, \( x_{ij} \) the space coordinates, \( \rho \) density, \( g \) gravity acceleration and \( t \) time (Brun, 1999). To scale the model properly we need the equation and we also have to keep in account the ratios:

\[ \sigma^* = \rho^* g^* L^* \]
\[ \epsilon^* = g^* (t^*)^2 \]

Where \( L \) is the length. The exponent * refers to the ratios between natural prototype and model. In geological processes inertial processes can be neglected (Hubert, 1937), there for we are only interested in the first equation: \( \sigma^* = \rho^* g^* L^* \). The ratio for gravity in natural and experimental environments is 1. The density in the model is 1560 kg/m\(^3\), in nature the density of the rocks is 2300 to 3000 kg/m\(^3\). These densities are in the same order of magnitude, the ratio can be considered to be 1. (Smit, 2005) The equation can be simplified to:

\[ \sigma^* \sim L^* \]

The ratio of stresses becomes nearly equal to the ratio’s of lengths (Brun, 1999).

Model materials

For these experiments silicon putty for the lower ductile crust, and sand for the upper brittle crust was used. The sand can be compared to crustal rocks because of the same brittle behaviour (Mohr Coulomb and Beyerlee). The failure of brittle rocks can be given in the following equation, the friction law:

\[ \tau = C + (\tan \Phi) \sigma \]

Where \( \tau \) is the shear stress, \( C \) the cohesion, \( \Phi \) the angle of inertial friction and \( \sigma \) the normal stress. (earth structures)

The Mohr-Coulomb criterion states that the confining pressure increases with increasing depth independent of strain rate. At each of these confining pressures a critical Mohr circle can be drawn, representing the failure envelope. Beyerlee states that \( \Phi = 30^\circ \) for rocks, the sand used in the experiments has an internal friction of: \( 42^\circ \). This dry sand is similar to the internal friction of cover rocks in the upper crust (van Mechelen, 2004). The sand used as an analogue for the upper crust comes from Fontainebleau (France) and consists of 99.8% quartz. The cohesion \( C \) of crustal rocks is 50 MPa, knowing that the length scale ratio is \( 10^{-6} \) (Michon and Merle, 2000), the cohesion of the model is negligible. The vertical normal stress \( \sigma \) is given by:

\[ \sigma = \rho g h \]

These equations can be rewritten to the deviatoric stress (maximum minus the minimum stress): \( \sigma_{13} - \sigma_{33} \). Where in extension \( \sigma = \sigma_{13} \) gives:

\[ \sigma_{13} - \sigma_{33} = 2/3 \rho g h \]


The silicon putty was used as an analogue for the ductile crustal rocks. The viscosity of natural ductile rocks is difficult to measure and various over a wide range of strain rates. The silicon putty used in this experiment has a density of: 1200 kg/m\(^3\) and has a viscosity of 1.18·10\(^4\) Pa s. The stress exponent of this silicon putty is 0.93; which
is nearly Newtonian. In nature stress exponents are in a range of 1-4. Although silicon putty’s with stress exponents higher than 2 exists, other modelling advantages become lost (Davy and Cobbold, 1991). The ductile strength can be calculated from the ratio between the extension rate (the velocity) and the thickness of the ductile layer (Michon and Merle, 2000):

$$\sigma = \mu \frac{v}{z}$$

where $\sigma$ is the strength, $\mu$ is the viscosity, $v$ the velocity of deformation and $z$ the depth (thickness) of the ductile layer.

Knowing that the strain rate is considered to be $v/z$. The equation can be rewritten as:

$$\sigma_1 - \sigma_3 = \mu \varepsilon$$

where $\sigma_1 - \sigma_3$ is the deviatoric stress (maximum minus the minimum stress: $\sigma_1 - \sigma_3$), $\mu$ is the viscosity, $\varepsilon$ is the strain rate.

These equations gives the following strength profiles presented in figures 1, 2, 3 and 4 for experiments SE1-SE9:

For further details on the mathematics see appendix A.

Figure 1: Strength profiles for models SE1, SE2, SE3, where the brittle strength is 203.84 Pa and the ductile strength is 1.6 Pa at 1 cm/h, 8.2 Pa at 5 cm/h, 16.4 Pa at 10 cm/h.

Figure 2: Strength profiles for models SE4, SE5, SE6, where the brittle strength is 407.68 Pa and the ductile strength is 1.6 Pa at 1 cm/h, 8.2 Pa at 5 cm/h, 16.4 Pa at 10 cm/h.

Figure 3: Strength profiles for models SE7, SE8, SE9, where the brittle strength is 611.52 Pa and the ductile strength is 1.6 Pa at 1 cm/h, 8.2 Pa at 5 cm/h, 16.4 Pa at 10 cm/h.

Figure 4: Strength profiles for models SE10 - SE14, where the brittle strength is given by the maximum stress on the profile.
In order to put the experiments in a proper natural environment, we need as mentioned before a length scale ratio, being $10^6$ (Michon and Merle, 2000). That means 1 cm in the model represents 10 km in nature. Table 2 shows the results of this scaling. According to Michon and Merle, 2003: in nature the brittle crust (BC) is 15-18 km thick, and the ductile crust (DC) is 12-15 km thick. This means that in nature the BC/DC ratio is 1-1.5. In our experiments the DC seems rather too thick, but is still suitable to represent the crust. SE1,2,3 have a ratio of 1 and are perfect for resembling a normal crust in nature. SE4,5,6 have a ratio of 2, in this case the thickness of the BC would represent an older and colder lithosphere with higher brittle strength. Crusts with thicknesses up to 60 km are common when thickened. SE7,8,9, have a ratio of 3 and seem out of crustal scale. In the case of SE7,8,9 this situation can be related to basin scale, with an overburden of sedimentary cover on a decollement (salt) layer. In that case the scale is not 60 km, but more in the range of 6 km.

![Figure 4: Strength profiles of all models.](image)

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Table 2: Scaling of the model, natural thicknesses.

<table>
<thead>
<tr>
<th>BC</th>
<th>DC</th>
<th>scaling</th>
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</thead>
<tbody>
<tr>
<td>18 km</td>
<td>15 km</td>
<td>1.2</td>
</tr>
<tr>
<td>2 cm</td>
<td>2 cm</td>
<td>1</td>
</tr>
<tr>
<td>4 cm</td>
<td>2 cm</td>
<td>2</td>
</tr>
<tr>
<td>6 cm</td>
<td>2 cm</td>
<td>3</td>
</tr>
<tr>
<td>18 km</td>
<td>20 km</td>
<td>18 km</td>
</tr>
<tr>
<td>20 km</td>
<td>20 km</td>
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<tr>
<td>40 km</td>
<td>20 km</td>
<td>40 km</td>
</tr>
<tr>
<td>60 km</td>
<td>20 km</td>
<td>60 km</td>
</tr>
</tbody>
</table>

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Table 3: Scaling of the model, deformation velocities.

<table>
<thead>
<tr>
<th>General (Bonini et al, 2000)</th>
<th>Model m/s</th>
<th>Nature m/s</th>
<th>Ratio M/N</th>
<th>Trivial Mm/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE 3,6,9</td>
<td>5*10^-6</td>
<td>8,3*10^-11</td>
<td>6*10^4</td>
<td>2,6</td>
</tr>
<tr>
<td>SE 2,5,8</td>
<td>2,7*10^-5</td>
<td>1,4*10^-5</td>
<td>2,3*10^-10</td>
<td>14</td>
</tr>
<tr>
<td>SE 1,4,7</td>
<td>2,7*10^-6</td>
<td>4,5*10^-11</td>
<td>6*10^4</td>
<td>1,4</td>
</tr>
</tbody>
</table>

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Model construction

Symmetrical extension was obtained by two moving walls, driven by a motor. Each wall has its own motor set at the same speed. The model was pulled apart by plastic attached to the moving walls. The deformation apparatus used was placed on two tables, the apparatus and the tables were placed in a way, that the plastic sheet could fit in between, in the middle of the model. This is clearly pointed out in figure 5 and 6 (the model set up). The plastic sheet in the middle gives a fixed velocity discontinuity. This velocity discontinuity resembles the brittle mantle rupture, which is considered to govern crustal deformation (Brun, 1999. Michon and Merle, 2000). This plastic also has a role of a decoupling layer. The lower ductile crust and the upper brittle mantle form a distinct boundary. To prevent the plastic from deforming within the model, a 5 kg weight was placed at the base. A 2 cm thick, 28 cm long and 20 cm wide silicon putty layer was placed on the plastic. The walls were placed 30 cm apart from each other, the 1 cm gap between the silicon putty and the walls were filled with sand. The sides were also filled with sand, two bars at the sides constrained the models. Above the silicon putty, sand with 2, 4 and 6 cm in thickness was placed. The apparatus deformed the model by moving each wall 5 cm from the model in 1,2 and 10 hours. Recall table 1: the experiments and their boundary conditions. Thus creating 10 cm of extension : 33% deformation. At the end of the experiment the walls are 40 cm apart.
Deformation

The 2 cm thick silicon layer and the 2.4 or 6 cm thick sand layer are the pre-kinematic layer. In pictures the silicon is pink and the pre-kinematics are recognizable as stratified white and blue sand. A thin layer of blue sand is added to represent the original topography. 9 syn-kinematic layers are deposited in these experiments. These layers resemble sedimentation, each layer has its own colour. Before each sedimentation a picture was made from above. Figures 7 and 8 show 2 of these top views. In SE 1,4,7 the sedimentation layers were added every 6 minutes. For SE 2,5,8 the sedimentation layers were added every 12 minutes. For SE 3,6,9 the sedimentation layers were added every hour. The sedimentations were only put in the deformed zone, where accommodation space was created. After the 9th sedimentation the experiment ran for another 6, 12 or 60 minutes, then the experiment was stopped. A layer of white sand was added to protect the new topography; the post-kinematic. The model is wetted and cut in serial cross sections perpendicular to the extension direction to visualize the deformation, pictures of these sections were made. Figure 9 shows a cross section of SE 4. Fault interpretations were made on
the middle of the cross sections, where side effects are negligible.

**Figure 7:** Top view of SE5 before the 8th sedimentation layer.

**Figure 8:** Top view of SE5 before the 9th sedimentation layer.

**Figure 9:** Pre/syn-and post-kinematics and extensional structures.

**Results**

With asymmetric extension, we have been able to demonstrate that: Continental lithosphere extension occurs in various plate tectonic environments leading to localised rifting when the brittle crust has a normal thickness and widespread extension where the brittle crust is thicker. Localised extension results from weak brittle ductile coupling, strong brittle strength and/or low ductile strength. Stronger coupling leads to transitions from horst and graben to tilted blocks. Thin skinned extension occurs on most of the passive margins and result from the gliding of a brittle sedimentary cover of variable thickness over a ductile decollement layer. Under the discussed conditions, the following structures: rotation, conjugate faulting, tilted blocks, normal faulting developed. First we will discuss the deformation width as a function of brittle thickness and deformation velocity. In the second part of this chapter pictures of the experiments are presented with their interpretation and strength profiles. We will demonstrate how coupling between the brittle and the ductile layer controls structural features.

**Deformation width**

“Localised rifting occurs when the brittle crust has a normal thickness and widespread extension where the brittle crust is thicker.” (Brun & Choukroune, 1983 and Buck, 1991). Table 4 presents the deformation width of the SE experiments. To understand what feature controls the deformation width (further referred to Wd), it is discussed as a function of brittle thickness (further referred to as Tb) and as a function of deformation velocity (further referred to as velocity). As explained in the chapter; “results”. The walls of the deformation apparatus are 30 cm apart. The extension is 10 cm (33 %), the final state is 40 cm. When table 4 states 29,2 cm deformation, this is 29,2 cm of 40 cm of the whole model. In the sub chapter; “description of the structures” the Wd in the models is visualised in an overview.

**Limitations**

The complexity of nature can not be simulated in even the best Tectonic lab. For example erosion was not taken into account in our experiment. During extension the crust thins, the moho moves upward and therefore, the thermal gradient changes. The heating of the crust was also not taken into account. The plastic pulled apart by the two moving walls deforms the model at the base (decoupling layer) only, this creates simple shear. On a mechanical point of view, the study of symmetric extension is very interesting. However such cylindrical boundary conditions are of course unlikely to occur in nature.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Tb (cm)</th>
<th>Deformation velocity (cm/h)</th>
<th>Width of deformation (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE1</td>
<td>2</td>
<td>1</td>
<td>18.5</td>
</tr>
<tr>
<td>SE2</td>
<td>2</td>
<td>5</td>
<td>32</td>
</tr>
<tr>
<td>SE3</td>
<td>2</td>
<td>10</td>
<td>29.2</td>
</tr>
<tr>
<td>SE4</td>
<td>4</td>
<td>1</td>
<td>25.8</td>
</tr>
<tr>
<td>SE5</td>
<td>4</td>
<td>5</td>
<td>26.8</td>
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<td>SE6</td>
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<td>10</td>
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<td>SE7</td>
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<td>1</td>
<td>27</td>
</tr>
<tr>
<td>SE8</td>
<td>6</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>SE9</td>
<td>6</td>
<td>10</td>
<td>22.8</td>
</tr>
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</table>

*Table 4: Wd of the SE experiments.*
Figure 10 presents $W_d$ as a function of the $T_b$. SE 1, 4, 7 have the same deformation velocity: 1 cm/h, the slowest velocity. At a $T_b$ of 2 cm (SE1) the $W_d$ is 18.5 cm, the smallest width of this set, but it is also the smallest width of all the 9 experiments. At a $T_b$ of 4 cm (SE4) the $W_d$ is 25.8 cm. At a $T_b$ of 6 cm (SE7) the $W_d$ is 27 cm. The $W_d$ increases, but the difference between SE4 and SE7 is small in perspective with SE 1: 18.5 cm. In short: at a slow velocity the $W_d$ increases with increasing $T_b$. SE 2, 5, 8 have the same velocity: 5 cm/h, the medium fast velocity. At a $T_b$ of 2 cm (SE2) the $W_d$ is 32 cm, the widest of this set, but it also the widest width of all 9 experiments. At a $T_b$ of 4 cm (SE5) the $W_d$ is 26.8 cm. At a $T_b$ of 6 cm (SE8) the $W_d$ is 30 cm. The $W_d$ decreases and increases again, but not as high as the $T_b$ of SE2. SE2 and SE8 do not differ much in perspective of SE5. In short: at a medium velocity the $W_d$ decreases and then increases, with increasing brittle strength. SE 3, 6, 9 have the same velocity: 10 cm/h, the fastest velocity. At a $T_b$ of 2 cm (SE3) the $W_d$ is 29.2 cm this is the widest width of this set. At a $T_b$ of 4 cm (SE6) the $W_d$ is 27.5 cm. At a $T_b$ of 6 cm (SE9) the $W_d$ is 22.8 cm. In perspective with SE9, SE3 and SE6 do not differ much in $W_d$. In short: at a fast velocity the $W_d$ decreases with increasing $T_b$.

$W_d$ as a function of $T_b$ as explained above, therefore shows no simple relation ship between $W_d$ and $T_b$. We have shown that:

- At a fast velocity $W_d$ decreases and increases again with increasing $T_b$.
- At a medium fast velocity $W_d$ decreases and increases again with increasing $T_b$.
- At a medium velocity $W_d$ stays consistent with increasing velocity. SE 3, 6, 9 have the same $T_b$: 6 cm, the thickest $T_b$. At a velocity of 1 cm/h (SE3) the $W_d$ is 29.2 cm, the widest width of this set. At a velocity of 5 cm/h (SE6) the $W_d$ is 27.5 cm. At a velocity of 10 cm/h (SE9) the $W_d$ is 22.8 cm. The $W_d$ increases slightly with increasing velocity, and increases again. In perspective of SE9, SE3 and SE6 do not differ significantly. In short: at a thick $T_b$ the $W_d$ increases slightly with increasing velocity and then decreases significantly.

$W_d$ as a function of velocity as explained above, therefore shows no simple relation ship between $W_d$ and $T_b$. We have shown that:

- At a thin $T_b$ the $W_d$ increases significantly with increasing velocity and then decreases slightly. SE 4, 5, 6 have the same $T_b$: 4 cm, the medium $T_b$. At a deformation velocity of 1 cm/h (SE4) the $W_d$ is 25.8 cm. At a velocity of 5 cm/h (SE5) the $W_d$ is 26.8 cm, At a velocity of 10 cm/h (SE6) the $W_d$ is 27.5 cm. The $W_d$ increases slightly with increasing velocity. But the difference in $W_d$ of this set do not differ significantly. In short: at a medium $T_b$ the $W_d$ stays consistent with increasing velocity. SE 7, 8, 9 have the same $T_b$: 6 cm, the thickest $T_b$. At a velocity of 1 cm/h (SE7) the $W_d$ is 27 cm. At a velocity of 5 cm/h (SE8) the $W_d$ is 30 cm. At a velocity of 10 cm/h (SE9) the $W_d$ is 22.8 cm. The $W_d$ increases with increasing velocity, and increases again. In perspective of SE9, SE 7 and SE8 do not differ significantly. In short: at a thick $T_b$ the $W_d$ increases slightly with increasing velocity and then decreases significantly.

$W_d$ as a function of velocity as explained above, therefore shows no simple relation ship between $W_d$ and $T_b$. We have shown that:

- At a thin $T_b$ the $W_d$ increases significantly with increasing velocity and then decreases slightly, at a thin $T_b$. At a thick $T_b$, the $W_d$ increases slightly with increasing velocity an then decreases significantly. At a medium $T_b$, the $W_d$ stays consistent with increasing velocity.

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**Figure 10:** $W_d$ as a function of $T_b$.  

![Deformation width as a function of brittle thickness](image)

**Figure 11:** $W_d$ as a function of velocity.  

![Deformation width as a function of velocity](image)
To come back at an earlier stated conclusion: “localised rifting occurs when the brittle crust has a normal thickness and widespread extension where the brittle crust is thicker.” In this case if we state that Wd above 28 cm is wide spread extension. Figures 10 and 11 show that most Wd’s lay in a range of 25 to 28 cm. SE4, 5, 6, 7 lay in this range, the exact Wd’s are 25.8 to 27.5 this gives that 72% to 76% of the model is deformed. Then contain the experiments SE2, SE3 and SE8 wide spread extension. 29.2 to 32 cm deformation gives that 81% up to 89% of the model is deformed. SE1 and SE9 have the thinnest Wd’s: 18.5 to 22, 8 cm deformation gives that 51% to 63% of the model is deformed. SE4,5,6 have a medium Tb of 4 cm, SE7 has a thick Tb of 6 cm. The experiments with a thin deformation zone; SE1 and SE9 have very different Tb; SE1 has a Tb of 2 cm and SE 9 has a Tb of 6 cm. At the wide spread extension SE2 and SE3 have the same Tb: 2 cm. SE 8 on the other hand has a Tb of 6 cm. Figure 12 presents an overview of these Wd distributions.

Wd is not only dependent on Tb, but also on velocity. At a thin Tb velocity has a great influence, especially from slow velocity to medium velocity. Lets call it a positive influence as the deformed zone gets wider. At a thick Tb velocity has a influence, especially from medium velocity to fast velocity. Lets call it a negative influence as the deformed zone gets smaller. At a medium Tb deformation velocity has no influence on the Wd.

Our experiments have shown that narrow rifting occurs in thin Tb at a slow velocity, and in a thickened area at a fast velocity. Wide spread deformation occurs in a thin crust at a medium to fast velocity, and in a thickened crust at a medium velocity. At a normal thickness of the crust, the velocity has no influence.

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Localised rifting was not taken into account when measuring the Wd. In the next subchapter: “Description of the structures” this will be explained further.

**Description of the structures**

In this section pictures of the experiments are presented with interpretation and strength profiles. The interpretation is described in terms of rotation, conjugate faulting, tilted blocks, normal faults, Wd and horst width.

Note that the pictures are not similar in their size.
Figure 13: SE experiments with thin brittle cover.
Brittle strength

Figure 13 presents SE1 through SE3 with the same brittle strength, i.e. 203.84 Pa for 2 cm. The velocities are: for SE1 1 cm/h, for SE2 5 cm/h and for SE 3 10 cm/h. This changes the ductile strength (σ*) from 1.6 to 8.2 until 16.4 Pa. This means the difference in strength between the ductile and the brittle layer is 202 – 187 Pa and is thus the set with the strongest coupling. In this succession SE1 has the weakest coupling and SE3 has the strongest coupling. In SE1 the Wd is 18.5 cm. SE2 and SE3 have a Wd of 29.2 and 32 cm.

SE1 shows a Wd of 18.5 cm with a horst and 2 graben structures. The whole model gives a strong symmetric pattern. At the velocity discontinuity (further referred to as VD) the horst is located between 2 graben. The 2 sets of transient grabens have migrated from the VD. Looking at the right graben one can see that the left transient fault, was active after the fourth sedimentation (after 4 hours), because the graben is not filled with this pink sedimentation layer. This transient fault became active before the eighth sedimentation (before 8 hours), because it is filled with the purple sedimentation layer. In the left graben one can see that the graben is filled with this eighth sedimentation layer. This means that the other transient faults were not active anymore when, after 8 hours, the eighth sedimentation layer was put on. The right fault of the left graben became active before the eighth sedimentation, it is the last transient fault to be active. Looking at the sedimentations and the faults you will notice that the faults near the VD were the first to be active, died out and other faults further away from the VD became active. The normal faults, which mark the deformation zone, have been active from the beginning of the deformation. The top view pictures show no sign of propagating synthetic normal faults. That means the grabens migrated away from the VD by activating new antithetic/transient normal faults. The whole model gives a rather symmetrical structure.

SE2 shows a Wd of 32 cm with a horst and graben structure. The horsts and grabens are not well developed and tilted blocks and rotation appears. Instead of a graben on the left side of the VD a rollover appears. This rollover is in the direction of the shear and therefore called synthetic. This synthetic rollover is growing on a tilted block. The rollover is controlled by planar antithetic conjugate faults and gives a fishbone structure. The graben at the left of the rollover starts to rotate in the opposite of the shear direction. This might result in an antithetic rollover. At the right side of the model there is little rotation. This graben looks like the migrating graben in SE1. The left side of the VD is very different from the right side of the VD. Apparently with this strength profile; rotation, rollover, conjugate faulting as well as migrating grabens appear. On the left side of the VD localised deformation can be noticed at the tilted block.

SE3 shows a Wd of 29.2 cm with a horst and graben structure. The horst in the middle is cut by faults and the model shows little rotation and no tilted blocks. In the graben right of the VD a conjugate fault sets appear. 2 horsts are developing at each side of the VD, while at the VD a graben appears. In this experiment the deformation is much more localised than in the other 2. Horst and grabens appear through the whole model. 3 grabens appear on the right side and 1 appears on the left side. Furthermore there are 2 grabens on each side of the VD just as the other 2 experiments. A little rotation can be seen in one of these grabens on the right side of the VD. As in experiment SE2 the left side is also more developed than the right side of the model.

Conclusion: In this set of experiments the horsts at the VD are not distinctly developed. Where the strength of the ductile layer is the weakest; SE1 the horst is best developed and wide. Where the ductile layer has medium strength; SE2 the horst is not noticeable. Where the strength of the ductile layer is the strongest; SE3 there is no horst and a graben appeared. SE1 has migrating grabens. SE2 has rotation, rollovers (antithetic and synthetic), a tilted block and migrating grabens, SE3 has localised deformation and conjugating faulting.
Figure 14: SE experiment with medium brittle cover.
Figure 14 presents SE4 through SE6 with the same brittle strength, i.e. 407,68 Pa for 4 cm. The velocities are: for SE4 1 cm/h, for SE5 5 cm/h and for SE 6 10 cm/h. This changes the ductile strength ($\sigma_1 - \sigma_3$) from 1,6 to 8,2 until 16,4 Pa. This means the difference in strength between the ductile and the brittle layer is 406 – 389 Pa and is thus the set wit the intermediate coupling. In this succession SE4 has the weakest coupling and SE6 has the strongest coupling. In SE4 the Wd is 25.8 cm, SE5 has a Wd of 26.8 cm and SE6 has a Wd of 27.5 cm.

SE4 shows a Wd of 25.8 cm with a horst and graben structure. The horst has a width of 4.6 cm and the whole model is little symmetric. The right side of the VD displays a tilted block with rotation. On the left side of the VD, there is a graben with little rotation. The rotation of the tilted block and the graben are in the direction of the shear and are therefore synthetic. The right side of the VD shows 2 grabens with little rotation and a horst in between. This experiment consist of: a tilted block, horsts and grabens and rotation.

SE5 shows a Wd of 26.8 cm with a horst and graben structure. The horst has a width of 7.1 cm. The model is symmetric. The left side of the VD shows the 2 grabens are effected by a set of conjugate faulting. This conjugate fault set is more developed at the right side of the VD.

SE6 shows a Wd of 27.5 cm with a horst and graben structure. The horst is not as well developed as in the other 2 experiments in this set. The horst is only 1.9 cm wide and is rotated. The model is symmetric. The right side as well as the left side of the VD show a graben with rotation. The right side shows more rotated faults than the left side. The rotation is synthetic as well as antithetic. Rotation leads to listric conjugate faulting. This structure of two grabens and conjugate faulting is similar to SE5.

Conclusion: In this set of intermediate strength profiles the horsts at the VD are well developed. Where the strength of the ductile layer is the weakest; SE4 the horst is medium wide with a width of 4.6 cm. Where the ductile layer has medium strength; SE5 the horst is wide and has a width of 7.1 cm. Where the strength of the ductile layer is the strongest; SE6 the horst is narrow, and has a width of 1.9 cm and begins to rotate. SE4 has a tilted block and rotation on both sides of the VD, SE5 has conjugate faulting on both sides of the VD and SE6 has rotation and conjugate listric normal faults on both sides of the VD.
Figure 15: SE experiments with thick brittle cover.
Figures 15 and 16 presents SE7 through SE9 with the same brittle strength i.e. 611.52 Pa for 6 cm. The velocities are: for SE7 1 cm/h, for SE8 5 cm/h and for SE9 10 cm/h. This changes the ductile strength (\(\sigma_1 - \sigma_3\)) from 1.6 to 8.2 until 16.4 Pa. This means the difference in strength between the ductile and the brittle layer is 609 - 595 Pa and is thus the set wit the weakest coupling. In this succession SE7 has the weakest coupling and SE9 has the strongest coupling. In SE7 the WD is 27 cm. The WD in SE8 is 30 cm and SE9 has a WD of 22.8 cm. This set of experiments seems to be the most symmetric.

SE7 shows a WD of 27 cm with a horst and graben structure. The horst has a width of 6.6 cm. The horst is bounded by two grabens. The grabens have no rotation. The graben at the left of the VD is affected by a later normal fault, which creates a half graben.

SE8 shows a WD of 30 cm with a horst and graben structure. The has a width of: 6.4 cm. This is similar to SE7 (6.6 cm). The horst is bounded by two grabens. Both are affected by later synthetic normal faults, which creates half grabens on each side of the VD. No rotation and no tilted blocks have formed in this model.

SE9 shows a WD of 22.8 cm with a horst and graben structure. The horst is covered with the last two sedimentation layers and is very narrow. The two grabens are effected by conjugate faulting creating a new graben in the middle. The two faults bounding the grabens at the end of the deformation zone show little rotation.

Conclusion: In this set of weakest strength profiles the horsts at the VD are good developed. Where the strength of the ductile layer is the weakest; SE7 the horst is wide, with a width of 6.6 cm. Where the ductile layer has medium strength; SE8 the horst is similar in width as SE7. Where the strength of the ductile layer is the strongest; SE9 the horst is narrow and buried in sedimentation layers. SE7 has two grabens and a normal fault, SE8 has two grabens en normal faults, SE9 has two grabens, conjugate faulting and little rotation.
Ductile strength
The previous set was described from the perspective of the brittle strength. On the next two pages figure 17 gives an overview of all the experiments from the perspective of the ductile strength.

SE3, SE6 and SE9 have the same ductile strength, with a velocity of 10 cm/h the ductile strength \((\sigma_1 - \sigma_3)\) is 16.39 Pa. The Tb are: for SE3 2 cm, for SE6 4 cm and for SE9 6 cm. This changes the brittle strength \((\sigma_1 - \sigma_3)\) from 203 to 407 until 611 Pa. This means the difference in strength between the ductile and the brittle layer is 187 – 595 Pa and is thus the set with the strongest coupling. In this succession SE9 has the weakest coupling and SE3 has the strongest coupling.

In SE9 the Wd is 22.8 cm.
In SE6 the Wd is 27.5 cm.
In SE3 the Wd is 29.2 cm.

SE3 has a Wd of 29.2 cm with a horst and graben structure. In this experiment the deformation is much more localised than in the other 2 of this set. Horst and grabens effect the whole model. 3 grabens appear on the right side and 1 appears on the left side. The experiment shows a little rotation. In the graben right of the VD a conjugate fault set appears.

SE6 has a Wd of 27.5 cm with a horst and graben structure. The horst is narrow, only 1.9 cm and rotated. The model is symmetric. Both sides show a graben with rotation. The rotation is in each graben synthetic as antithetic. Rotation leads to listric conjugate faulting.

SE9 has a Wd of 22.8 cm with a horst and graben structure. The horst is covered with sedimentation layers. The two grabens are effected by conjugate faulting. The two faults bounding the grabens at the end of the deformation zone show little rotation.

Conclusion: In this set of strongest coupling the horsts are narrow. SE3 has the strongest coupling, here the horst is a graben. SE6 has the intermediate coupling, here the horst is small and rotated. SE9 has the weakest coupling, here the horst is buried in sedimentation layers. SE3 has localised deformation and conjugating faulting. SE6 has rotation and conjugate faulting. SE9 has conjugate faulting and little rotation. An increase in Tb leads to wider grabens and less rotation

SE2, SE5 and SE8 have the same ductile strength, with a velocity of 5 cm/h the ductile strength \((\sigma_1 - \sigma_3)\) is 8.19 Pa. The Tb are: for SE2 2 cm, for SE5 4 cm and for SE8 6 cm. This changes the brittle strength \((\sigma_1 - \sigma_3)\) from 203 to 407 until 611 Pa.

This means the difference in strength between the ductile and the brittle layer is 195 – 603 Pa and is thus the set with the intermediate coupling. In this succession SE8 has the weakest coupling and SE2 has the strongest coupling.

In SE5 the Wd is 26.8 cm.
In SE2 the Wd is 32 cm.
In SE8 the Wd is 30 cm.

SE2 has a Wd of 32 cm with a horsts and grabens structure. The horst is wide. On the left side of the VD a rollover appears on a tilted block. The rollover is controlled by planar antithetic conjugate faults and gives a fishbone structure. The graben at the left has little rotation. Rotation, rollover, conjugate faulting as well as migrating grabens appear.

SE5 has a Wd of 26.8 cm with a horst and graben structure. The horst is wide; 7.1 cm. The model is symmetric. The left side of the VD shows the 2 grabens are effected by a set of conjugate faulting. This conjugate fault set is more developed at the right side of the VD.

SE8 has a Wd of 30 cm with a horst and graben structure. The horst is wide; 6.4 cm. The horst is bounded by two grabens. Both are affected by later synthetic normal faults, which creates half grabens.

Conclusion: In this set of intermediate coupling the horsts are wide and similar in width. SE2 has the strongest coupling and has rotation, rollovers, migrating grabens and a tilted block. SE5 has two grabens with conjugate faulting. SE8 has the weakest coupling and has two grabens en normal faults creating half grabens. An increase in Tb leads to wider grabens, lesser rotation and less complex structures

SE1, SE4 and SE7 have the same ductile strength, with a velocity of 1 cm/h the ductile strength \((\sigma_1 - \sigma_3)\) is 1.64 Pa. The Tb are: for SE1 2 cm, for SE4 4 cm and for SE7 6 cm. This changes the brittle strength \((\sigma_1 - \sigma_3)\) from 203 to 407 until 611 Pa. This means the difference in strength between the ductile and the brittle layer is 201 – 609 Pa and is thus the set with the weakest coupling. In this succession SE7 has the weakest coupling and SE1 has the strongest coupling.

In SE1 the Wd is 18.5 cm.
In SE4 the Wd is 25.8 cm.
In SE7 the Wd is 27 cm.
Figure 17: Overview of all the experiments.
SE1 has a Wd of 18.5 cm with a horst and grabens structure. The model is symmetric. The horst is wide. The 2 grabens appear on each side of the VD. The faults near the VD were the first to be active, died out and other faults further away from the VD became active. The normal faults, which mark the deformation zone, have been active from the beginning of the deformation. So the grabens migrated away from the VD by activation of new antithetic normal faults. There is no rotation and no tilted blocks in this model.

SE4 has a Wd of 25.8 cm with a horst and graben structure. The horst is wide; 4.6 cm. The model is symmetric. The right side of the VD shows a tilted block with rotation. On the left side of the VD is a graben with little rotation.

SE7 has a Wd of 27 cm with a horst and graben structure. The horst has a width of 6.6 cm. The horst is bounded by two grabens. The graben at the left of the VD is affected by a normal fault creating a half graben.

Conclusion: In this set of weakest coupling the horsts are wide and similar in width. SE1 has the strongest coupling, here the horst is covered. SE4 has intermediate coupling, here the horst is wide. SE7 has the weakest coupling, here the horst is wider than SE4. SE1 has a migrating grabens. SE4 has a tilted block and rotation on both sides of the VD. SE7 has two grabens and one normal fault. An increase in Tb leads to wider grabens, lesser rotation and less complex structures.

Conclusions:

From the perspective of brittle strength the weakest brittle strength (SE1, SE2 and SE3), but the strongest coupling gives underdeveloped horsts. The stronger the coupling the less obvious the horst gets, at the strongest coupling it is covered and cut by normal faults. The Wd gets wider as the coupling gets stronger. The structures appearing at strong coupling are: migrating grabens, rollovers (antithetic and synthetic), localised deformation, conjugate faulting and tilted blocks.

At intermediate brittle strength (SE4, SE5 and SE6), and also the intermediate coupling gives well developed horsts. The stronger the coupling the horsts width increases and decreases, at the strongest coupling the horst gets rotated. The Wd is consistent in this set. The structures appearing at intermediate coupling are: tilted blocks, rotation, grabens and conjugate faulting.

The strongest brittle strength (SE7, SE8 and SE9), but the weakest coupling gives developed horsts. The stronger the coupling gets the smaller the horst, at the strongest coupling of this set the horst is covered with sedimentation layers. The Wd gets smaller as the coupling gets stronger. The structures appearing at weak coupling are: grabens, half grabens, normal faults, and conjugate faulting.

From the perspective of ductile strength the strongest ductile strength (SE9, SE6 and SE3), and also the strongest coupling gives narrow horsts. When the coupling is high the horsts evolve from covered under sedimentation layers to a rotated horst, to a horst cut by normal faults. The Wd gets wider as coupling gets stronger. The structures appearing at strong coupling are: grabens, conjugate faulting, rotation and localised deformation.

At intermediate ductile strength (SE8, SE5 and SE2), and also the intermediate coupling gives wide horsts. The stronger the coupling the wider the horst, at the strongest the coupling the horst is covered. The Wd decreases and increases with increasing coupling. The structures appearing at intermediate coupling are: grabens, half grabens, conjugate faulting, rollovers (antithetic and synthetic) and migrating grabens.

At the weakest ductile strength (SE7, SE4 and SE1), and also the weakest coupling gives wide horsts. The stronger the coupling the smaller the horsts, At SE1 the horst is covered and cut by normal faults. The Wd gets smaller as the coupling gets stronger. The structures appearing at weak coupling are: half grabens, tilted blocks, rotation migrating grabens.

Comparison with natural examples

To evaluate the influence of coupling in symmetrical extension experiments, we need to compare the models with natural examples. This experimental set up can be compared with natural examples as the West European Cenozoic rift: Rhine graben, Eger graben and Massif Central grabens. The Rhine graben consist of simple shear at a slow velocity (Michon and Merle, 2003) and is comparable with SE1,4,7. Although the strain rate of the Rhine graben is even slower: 10^-6 (Brun, 1999). The Eger graben consists of necking at a slow velocity (Michon and Merle, 2003) and is comparable with SE1. The massif central graben consists of necking at a high velocity (Michon and Merle, 2003) and is comparable with SE9.

Discussion

Where earlier conclusions stated that localised extension results from weak brittle ductile coupling, In our experiments localised extension occurs under strong coupling. Stronger coupling is believed to result in transitions from horst and graben to tilted blocks. In our experiments the
transition from grabens to tilted blocks occurred in intermediate to strong coupling. Localised rifting should occur when the brittle crust has a normal thickness and widespread extension where the brittle crust is thicker. Where our experiments prove that localised rifting occurs in a normal crustal thickness. Wide spread extension occurs in a thickened crust, but also in a normal crustal thickness. The velocity or the ductile strength is the controlling factor.

Differences in conclusions may lay in the scaling of the models. The model to nature ratio’s in these experiments are 1,2 and 3. Where 1-1,5 is a normal ratio (Michon and Merle, 2003). Therefore SE1, SE2 and SE3 with the ratio 1 are considered to have a normal crustal thickness. Experiments with ratio 1 or 1,5 could differ in their results. The same applies to the conclusions that state a strong coupling, one can not quantify strong and weak.

Our conclusions are based on only 9 experiments. Of each coupling just one experiment was conducted. To confirm my conclusions more experiments are needed.

Conclusions

The crustal structures are highly dependant on the mechanical coupling between the ductile and brittle part of the upper crust. This project was designed to study the effects of the coupling existing between brittle and ductile layers in a symmetrical extensional regime. According to Brun, 1999 coupling depends on the strength ratio between the upper brittle layer and the lower ductile layer. This means that weak brittle ductile coupling results from strong brittle strength and/or low ductile strength. And strong brittle viscous coupling results from weak brittle strength and/or high ductile strength. When looking at figure 4, the strongest coupling occurs where the difference in strength between the brittle part and the ductile part is the smallest. And weak coupling occurs where the difference between the brittle part and the ductile part is biggest. In our experiments the strongest coupling occurs in the set with Tb: 2cm. The weakest coupling in the set with Tb: 6 cm. The intermediate coupling in the set with Tb: 4 cm.

“Localised extension results from weak brittle ductile coupling. Stronger coupling results in transitions from horst and graben to tilted blocks. Thin skinned extension occurs on most of the passive margins and result from the gliding of a brittle sedimentary cover of variable thickness over a ductile decollement layer. Localised rifting occurs when the brittle crust has a normal thickness and widespread extension where the brittle crust is thicker.”

In our experiments rollovers, localised deformation, and migrating grabens only appear at strong coupling. Tilted blocks, rotation and listric faults are typically structures to appear at strong to intermediate coupling. Half grabens appear at weak coupling. Conjugate faulting is coupling independent and appear in almost every experiment. Localised extension occurs under strong coupling in a thin brittle crust. The horst width is not dependant on coupling but on a certain brittle strength and a certain ductile strength. At weak brittle strength the horsts over the VD are covered and wide. With increasing ductile strength, the horst gets more narrow. At strong ductile strength the horsts at the VD are narrow. With increasing brittle strength, the horst get covered. Necking occurs in areas with thin Tb at a slow velocity, and in a thickened area at a fast velocity. Wide spread extension occurs in a thin crust at a medium to fast velocity, and in a thickened crust at a medium velocity. At a normal crustal thickness, the velocity has no influence on the width of the deformation zone.
Appendix A: mathematics of the strength profiles

crustal properties

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lower crust

|                         | density silicon putty | kg/m³   | ρ        |        | 1200  | 1200  | 1200  | 1200  | 1200  | 1200  | 1200  | 1200  | 1200  |
| viscosity silicon putty | Pa·s        | μ        | 11802  | 11802  | 11802 | 11802 | 11802 | 11802 | 11802 | 11802 | 11802 | 11802 | 11802 |
| thickness               | cm          | t        | 2      | 2      | 2     | 2     | 2     | 2     | 2     | 2     | 2     | 2     | 2     |
| velocity                | cm/s        | v        | 2.7×10⁻⁴ | 1.4×10⁻³ | 2.7×10⁻⁴ | 1.4×10⁻³ | 2.7×10⁻⁴ | 1.4×10⁻³ | 2.7×10⁻⁴ | 1.4×10⁻³ | 2.7×10⁻⁴ | 1.4×10⁻³ | 2.7×10⁻³ |
| strain rate             | v / t       | s⁻¹  | 1.38×10⁻⁴ | 6.95×10⁻⁴ | 1.38×10⁻³ | 6.95×10⁻⁴ | 1.38×10⁻³ | 6.95×10⁻⁴ | 1.38×10⁻³ | 6.95×10⁻⁴ | 1.38×10⁻³ | 6.95×10⁻⁴ | 1.38×10⁻³ |

strength brittle 2/3 x ρ x g x h σ1 - σ3 (Pa) σ 203.84 203.84 203.84 407.68 407.68 407.68 611.52 611.52 611.52

(P) Pa = N/m²
(F) N = m g
m = ρ V
N = kg/m³ m³ m/s²
Pa = (kg/m³ m³ m/s²) / m² = ρ h g
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