The effect of plate boundary geometry on the evolution of crustal structures in the Norwegian continental margin.
An analogue modelling study

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1. Abstract

The Norwegian continental margin was formed during the early Cenozoic continental breakup and opening of the Norwegian-Greenland Sea. The plate boundary is not straight, but made up of multiple segments with different orientation giving it a very irregular appearance.

A series of analogue models was run to study the evolution of structures near the plate boundary as a function of the geometry of the plate boundary and the obliquity of convergence. Quartz sand was used to make brittle models with different amounts of deformation and different plate geometry.

It was found that the wedge that forms during deformation is wider in the models with the irregular plate boundary than in those with a straight boundary. Also, the larger strike-slip faults occur sooner than with a straight plate boundary. Transtension occurs in the transpressional area of the irregular plate boundary models, whereas this does not occur in the straight boundary models. These differences are due to the fact that the models with an irregular plate boundary have a domain of nearly pure strike-slip. The models also showed that the rift in the transtensional area of the models with the irregular boundary is wider with a smaller convergence angle. The wedge however is broader with a larger convergence angle. Localized transtension in the transpressional area of the model occurs sooner with a larger convergence angle.

Also, the analogue models were compared to the situation in nature. On large scale, the models are very similar to nature. On smaller scale, the basic structures of the cross-sections through the transition domain have significant similarities to nature, such as the shape of the wedge and the thrust faults forming this wedge. The results from this research compare very well to the results from Leever et al. (2011). The same structures are present in the cross-sections from both studies.
2. Introduction

The Norwegian continental margin was formed during the early Cenozoic continental breakup and opening of the Norwegian-Greenland Sea. The plate boundary is not straight, but made up of multiple segments with different orientation giving it a very irregular appearance (Fig. 1). The segment west of Svalbard is a straight segment, as is the most southern segment along the western Barents Sea (also known as the Senja Shear Margin). The segment in between, the Vestbakken Volcanic Province (VVP) has a more irregular shape. The direction of plate movement is to the NNW, more or less parallel to the two straight segments (Faleide, et al., 2008). Due to this, the Svalbard segment and the Senja Shear Margin are dominantly sheared margin segments. The VVP is a releasing bend, making it a dominantly rifted segment.

![Image of Norwegian plate boundary and continental margin](image)

The Norwegian margin is made up of two segments, each of which is divided into smaller segments, based on shape and orientation of the margin.

The mid-Norwegian margin is from Møre to the Lofoten in the north of Norway. The western Barents Sea-Svalbard margin is from the north of Norway to Svalbard (fig. 1).

2.2. Characteristics of the Norwegian Continental Margin

The mid-Norwegian margin consists of the Møre, Vøring and Lofoten-Vesterålen segments. During the latest Cretaceous lithospheric extension led to the breakup of the continent between
Greenland and Scandinavia. Here was increased igneous activity and central rift uplift, followed by a lot of basaltic lavaflows in the early Eocene. From the middle Eocene to now, the lavaflows became less voluminous and the continental margin subsided (Eldholm et al., 2002).

The Møre margin has a narrow shelf and a wide slope (figures 2 & 3, profile 1) and is underlain by the Møre basin, which consists of Cretaceous rocks. The structural relief, formed during Late Jurassic-Early Cretaceous rifting, was mostly filled in by middle Cretaceous strata. Sill intrusions, associated with the increased igneous activity, are found throughout the basin. The most western part of the basin is covered by lavaflows from the Early Eocene. Most of the basin is underlain by a lower crustal body which has been interpreted as breakup-related magmatic underplating (Olafsson et al., 1992; Raum, 2000).

![Figure 2: Structural map of the NE Atlantic region, with the locations of the margin transects in figures 3 and 4. (from Faleide et al., 2008)](image)

The Vøring margin, north of the Møre margin, consists (from SE to NW) of the Trøndelag Platform, the Halten and Dønna terraces, the Vøringer Basin and the Vøring Marginal High (figure 3, profiles 2, 3 and 4). The Trøndelag Platform is made up of deep basins which are filled by sediments from Triassic and Upper Paleozoic time. The Vøring Basin is a series of sub-basins and highs, which reflect the differential vertical movements during the rifting in the late Jurassic – early Cretaceous. The Vøring Marginal High consists of a thick oceanic crust, covered by basalts and underlain by mafic intrusions.
The Lofoten-Vesterålen margin is narrower than the Møre and Vøringer margins and the basin is shallower (figure 3, profile 5 and 6). The sedimentary basins in the shelf form asymmetric half-graben structures. A sedimentary basin beneath the slope is covered by break-up related lavas (Tsikalas et al., 2001). The continental crust on this margin seems to have experienced less pre-breakup extension than the Møre and especially the Vøringer Margin.

Figure 3: Crustal transects across the Norwegian continental margin. The locations can be found in figure 2. (from Faleide et al., 2002)

The Western Barents Sea-Svalbard margin is a dominantly sheared margin along the western Barents Sea. It consists of two sheared segments and a rifted margin segment. The most southern segments is the Senja Shear Margin (figure 4, profile 7). In the east, 18 to 20 km of sediment covers the crystalline continental crust. More to the north is the Vestbakken Volcanic Province (figure 4, profile 8), which is the rifted margin segment, associated with volcanism. It is found to the
southwest of Bjørnøya. The basin formed as a result of a pull-apart setting in a releasing bend during rifting. There are extensional structures as well as some transpressional structures. Also, prominent volcanoes and sill intrusions are observed (Jebsen and Faleide, 1998).

North of Bjørnøya is another sheared segment of the Western Barents Sea-Svalbard margin. This one can be further subdivided into three smaller segments: a sheared segment from Bjørnøya to Sørkapp (Spitsbergen), a first sheared and later rifted segment west of Svalbard and a complex sheared and rifted margin northwest of Svalbard (figure 4, profiles 9-12).

The sheared segment is dominated by two rotated down-faulted blocks, which formed during the development of the transform margin (Breivik et al., 2003). The northern two segments together are the Spitsbergen Fold-and-Thrust Belt. It formed between a restraining and releasing bend during the late Paleocene and Eocene. This is also the area of interest during this research. The continental crust thins very quickly west of the fold-and-thrust belt (Ritzmann et al., 2002). The Hovgård Ridge is a piece of continental crust which has been separated from the rest of the continental crust during rifting (Ritzmann et al., 2004).

Earlier research, by Leever et al. (2011), was done on the effect of the convergence angle on the kinematic evolution of strain partitioning in transpressional brittle wedges. The Spitsbergen fold and

Figure 4: Crustal transects across the western Barents Sea-Svalbard margin. The locations can be found in figure 2.
thrust belt, in the north of the Norwegian continental margin, was among others used as an example. The study showed, that in the case of a straight plate boundary, with a 15 degrees convergence angle, there are three main structures: the retroshear, the central shear zone and proshears. The wedge is asymmetric and the pro wedge and retrowedge are separated by the central shear zone. The retrowedge is significantly smaller than the pro wedge. Strike-slip faults dissect the pro wedge. This research builds upon the results of Leever et al. (2011). While her research only focused on a straight boundary, this research studies the evolution of structures near the plate boundary as a function of the geometry of the plate boundary. The evolution of structures throughout deformation is compared with the results from a reference model with a straight boundary. The model results will also be compared to the situation in nature, the Norwegian continental margin.
3. Modelling strategy

A series of analogue models was run at the Tectonic Laboratory (TecLab) at the VU University in Amsterdam to study the difference in structures between a straight boundary and an irregular one. Quartz sand was used to make brittle models with different amounts of deformation and different plate geometry. At the end of a model run, the developed structures were covered with sand and saturated with water. Then, cross sections were cut perpendicular to the structures.

3.1 Model setup

Two 1 mm thick plastic sheets were placed on top of each other, with a thin layer of glass bits in between to reduce friction. The upper sheet was cut in the shape of the plate boundary and fixed on the table. Plastic straps were fixed onto the mobile lower plate, so that it could be pulled. The models were pulled by hand, one centimeter at a time. Three different model setups were used. The first with the upper plate straight and at an angle of 15 degrees to the lower plate (fig. 5).

![Fig. 5: Model setups. (a) Top view of the first model setup, with D the total displacement of the lower plate. (b) Cross section of the sand pack, showing the different layers. (c) Top view of the second and third model setup, with \( \alpha \) the angle between the upper and lower plate.](image)

The second model setup with the shape of the irregular plate boundary cut out in the upper plate had
the same angle of obliquity as the first setup. The irregular boundary forms a releasing bend in the southern part of the model and a restraining bend in the northern part of the model. The last model setup was also with an irregular plate boundary, but at an angle of 5 degrees to the lower plate. With the first two setups, the lower plate was pulled for 4, 8, 12 and 22 centimeters, to study the evolution of the structures. With the last setup, only a model with 22 centimeters of shortening was run. Three centimeters of sand were sieved onto the plates, covering an area of 45 by 90 centimeter for the first model setup and 60 by 90 cm for the second and third setup. The sand pack was layered with different colours, so the deformation would be visible.

3.2 Model scaling and rheology
Quartz sand was used as an analog for brittle rheology. This obeys the scaling rules of dynamic similarity (Hubbert, 1937), which say that if a scaled model is to be representative of its analog in nature, you require similar distributions of stresses, rheologies and densities. The scale used is 1:1000.000, so 1 cm in the model corresponds to 10 km in nature. The sieved quartz that was used has a grain size of 300 μm, a density of 1510 kg/m³, cohesion of 30-70 Pa and an angle of internal friction of 31°. The ratio of the densities of model and prototype (granite, 2700 kg/m³) is approximately 1,6, resulting in a scaling factor of 1,25 x 10⁻⁶ for the brittle strength (for details see Leever et al., 2011).

3.3 Model limitations
Analogue modelling is only an approximation of nature. There are several natural factors that the models do not take into account. First of all, the models that were run were completely made up of quartz sand as an analog for brittle rheology. The 3 cm of sand that the model consists of, corresponds to the first 30 kilometer of the crust. In nature, the crust does not only consist of brittle rheology. Also, it is not homogenous, whereas the models were. In this research, only the brittle structures will be studied. The borders of the model influence the structures at the northern and southern edges of the model. As deformation progresses, this effect gets more significant. Furthermore, the deformation in nature is not continuous and not in the exact same direction at all times (Faleide et al., 2008). This is however the case in the models that were run. Finally, erosion and isostasy were not taken into account. These parameters are difficult to integrate in the models and do not significantly affect the structures that will form in the models.
4. Model results

In this section, the results of the analogue models are discussed and interpreted. The geographical coordinate system will be used to describe and compare the models (fig. 6a). In the top views and cross-sections of the models, thrust faults will be showed as black lines, normal faults as red lines and strike-slip faults as green lines. The normal and thrust faults are not pure dip-slip, they all also have a strike-slip component and the strike-slip faults also have a small dip-slip component. The abbreviations R, N and S, as used in the interpreted cross-sections, stand for reverse fault, normal fault and strike-slip fault respectively.

4.1. Model 1

For the first model, a straight upper plate at an angle of 15 degrees to the lower plate was used. The lower plate was pulled for 4 centimeters, corresponding to 40 km of convergence in nature.

![Fig. 6: Geometry of the first model. (a) Top view. The scale bar represents 5 cm. The grey line is the location of the cross-section. The arrow represents the direction of deformation. The black lines are thrust faults and the green lines are strike-slip faults. (b) Uninterpreted cross-section. (c) Interpreted cross-section.](image)

During the first centimeter of plate convergence, a pop-up developed, with a NNW-SSE orientation, parallel to the boundary of the upper plate (fig. 6). The wedge is bounded by two thrust faults (r1 and r2). Those faults developed further during the rest of deformation. During the final centimeter of
deformation, multiple strike-slip faults formed along the western side of the pop-up (fig. 6a). These are however not visible in the cross-sections.

In the cross-section it can be seen that the wedge is bounded by the two thrust faults. R1 and r2 have an orthogonal offset of 1,2 and 0,8 cm respectively. R1 has a dip angle of approximately 45 degrees. R2 is 10 degrees steeper. The wedge is 7,6 cm wide, measured from the point where the surface becomes higher than the initial height of 3 cm to the point where it is back at its initial height again (A and B in fig. 6c).

4.2. Model 2

For the second model, the first model setup was used, with a straight upper plate at an angle of 15 degrees to the lower plate. The lower plate was pulled for 8 centimeters, corresponding to 80 km in nature.

In addition to the two thrust faults (r1 and r2) that were also visible in the first model after 4 cm of shortening, a third thrust fault (r3) formed in the pro-wedge at about six centimeter of shortening. The earlier formed strike-slip faults propagated and two larger strike-slip faults (s1 and s2) formed parallel to the thrust faults. The earlier formed strike-slip faults are now branches of s2 with a Riedel shear orientation.

The cross-section in fig. 7 shows the three thrust faults that formed the wedge. R2 moved up the ramp of r1 during deformation. The dip angle of r2 and r3 is approximately the same. Also, the two larger strike-slip faults are visible. At 1,5 cm from the surface, they connect to the thrust faults r1 and r2. The offset of the thrust faults r1, r2 and r3 is 1,4 cm, 0,4 cm and 0,3 cm respectively. The wedge is now 10,8
cm wide.

### 4.3. Model 3

For the third model, the first model setup was used, with a straight upper plate at an angle of 15 degrees to the lower plate. The lower plate was pulled for 12 centimeters, corresponding to 120 km in nature.

![Cross-section A](image)

![Cross-section B](image)

Fig. 8: Geometry of the third model. (a) Top view. (b) Uninterpreted cross-section A. (c).Interpreted cross-section A. (d) Uninterpreted cross-section B. (e) Interpreted cross-section B.

In model 3, a third thrust fault in the pro-wedge began to form during the ninth centimeter of
shortening (fig. 8a). S1 is less visible in this top view, because it formed closer to thrust fault r1 than in model 2 and the eastern slope collapsed after 7 centimeters of deformation.

In cross-section A, the four thrust faults are visible (fig. 8c) The offset of these faults is shown in table I. All the thrust faults have the same dip angle of 45 degrees. Strike-slip fault s2 connects to r2 at 1 cm below the surface. The wedge is more asymmetrical than in the previous models. It is now 11,4 cm wide.

<table>
<thead>
<tr>
<th>Fault</th>
<th>Offset (cm) section A</th>
<th>Offset (cm) section B</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>2</td>
<td>2,1</td>
</tr>
<tr>
<td>R2</td>
<td>0,4</td>
<td>0,8</td>
</tr>
<tr>
<td>R3</td>
<td>0,6</td>
<td>0,2</td>
</tr>
<tr>
<td>R4</td>
<td>0,2</td>
<td>0,5</td>
</tr>
</tbody>
</table>

*Table I: Offset of thrust faults in cross-section A and B*

In cross-section B, there are three reverse faults (r1, r2 and r4). R3 ended on r2 before this cross-section (fig. 8e). The offset is discussed in table I. The width of the wedge is 11,5 cm.

### 4.4. Model 4

For the fourth model, the first model setup was used, with a straight upper plate at an angle of 15 degrees to the lower plate. The lower plate was pulled for 22 centimeters, corresponding to 220 km in nature.

The development of the model until the 12th centimeter was the same as in model 3. During the 13th centimeter, a central shear zone (CSZ) formed through the middle of the wedge (fig. 9a). This zone got wider during the rest of the deformation. It has a NNW-SSE orientation, but in the south the orientation is more N-S. In addition, more branches of strike-slip fault s2 formed, with a more or less N-S orientation, connecting s2 with the central shear zone. Several not continuous thrust faults formed in the pro-wedge. Also, the eastern side of the wedge collapsed further.

In cross-section A, five thrust faults are visible (fig. 9c), one in the retro-wedge and four in the pro-wedge. The dip angle of r1 and r5 is 45 and 35 degrees respectively. The angle of the other thrust faults in the pro-wedge becomes smaller closer to the surface, because they move up the R1-ramp during deformation. The upper two thrust faults are cut off by the central shear zone. The CSZ also has an strike-slip as well as an orthogonal component. The offset of the thrust faults is shown in table II. The wedge is 12,7 cm wide.

<table>
<thead>
<tr>
<th>Fault</th>
<th>Offset (cm) section A</th>
<th>Offset (cm) section B</th>
<th>Offset (cm) section C</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>2,2</td>
<td>3,6</td>
<td>3,2</td>
</tr>
<tr>
<td>R2</td>
<td>0,5</td>
<td>0,6</td>
<td>0,3</td>
</tr>
<tr>
<td>R3</td>
<td>0,4</td>
<td>1,2</td>
<td>0,2</td>
</tr>
<tr>
<td>R4</td>
<td>0,5</td>
<td>-</td>
<td>0,4</td>
</tr>
<tr>
<td>R5</td>
<td>0,4</td>
<td>0,7</td>
<td>0,7</td>
</tr>
</tbody>
</table>

*Table II: Offset of thrust faults in cross-section A, B and C.*
In cross-section B, there is one thrust fault in the retro-wedge and three (r2-r4) in the pro-wedge (fig. 9e). R2 crosses the strike-slip fault s2. The offset of the thrust faults is discussed in table II. In addition, there is another strike-slip fault with a normal component in the section. This fault is part of the central shear zone. Due to collapse of the eastern side of the formed orogen, part of the central shear zone is destroyed. The width of the wedge in this cross-section is 13.7 cm.

In cross-section C, there are four thrust faults in the pro-wedge and one in the retro-wedge (fig. 9g). Also, there are three normal faults. The two eastern strike-slip faults are part of the central shear zone. They both also have a normal component. The western strike-slip fault is a branch of the earlier formed strike-slip fault s2. The offset of the thrust faults is discussed in table II. The width of the wedge is this cross-section is also 13.7 cm.
4.5. Model 5
For the fifth model, the second model setup was used, with an irregular upper plate at an angle of 15 degrees to the lower plate. The lower plate was pulled for 5 centimeters, corresponding to 50 km in nature. The formed rift was filled with black sand after deformation.
Fig. 10: Geometry of the fifth model. (a) Top view, with the locations of the cross-sections. (b) Uninterpreted cross-section A. (c) Interpreted cross-section A. (d) Uninterpreted cross-section B. (e) Interpreted cross-section B. (f) Uninterpreted cross-section C. (g) Interpreted cross-section C. (h) Uninterpreted cross-section D. (i) Interpreted cross-section D.
As can be seen in fig. 10a, in this model there was an area of extension as well as compression. In both domains there was also a strike-slip component. This caused a oblique rift to form in the south of the model and a mountain belt in the north. The mountain belt has a NNE-SSW orientation, whereas the oblique rift strikes NE-SW. The rift is 7,5 cm at its broadest. In the transition from extension to compression, the offset of the normal faults gets smaller until they become thrust faults. In this domain, the faults are almost pure strike-slip. This is visible in the top view by the large lateral offset of the black marker line, and the lack of developed topography. Some of the thrust faults progress into the extensional area. Smaller thrust faults develop close to thrust fault R2. Moreover, in the compressional area, during the 4th centimeter of deformation, two strike-slip faults (s1 and s2) formed.

Cross-section A displays an asymmetric rift, 7,5 centimeters wide, with one large normal fault (n1) on one side and five smaller faults (n2 to n6) on the other (fig. 10c). The offset of n1 got larger after every centimeter of deformation and after 5 centimeters the offset was 3 centimeters. The dip angle is 60 degrees. On the other side of the rift, an extra fault formed after every centimeter of deformation. The offset of every one of these faults is approximately 0,5 centimeter. They all have a dip angle of approximately 70 degrees.

Cross-section B is a cut through the transition area between extension and compression (fig. 10e). It is still an asymmetric rift, but it is much narrower (4,6 cm) than in cross-section A. Also, a thrust fault (r1) developed in the middle of the rift, cutting of normal fault n1. The offset of n1 in this cross-section is 0,5 centimeter. The faults on the other side of the rift (n2 and n4) have an offset of respectively 1 centimeter and 0,5 centimeter. The thrust fault also has an offset of 0,5 centimeter. N1 has a dip angle of 60 degrees, the rest is between 70 and 75 degrees.

Cross-section C was cut north of the transition area. There are no more normal faults in this cross-section (fig. 10g). On the eastern side of the section, there is a thrust fault (r1), with an offset of 0,5 centimeter. To the west there are two thrust faults (r2 and r3). R2 has an offset of 0,25 centimeters. R3 is a very small thrust fault that developed in the last centimeter of shortening and has an offset of 1 millimeter.

Between r1 and r2 there is a strike-slip fault. The wedge has a width of 7,5 centimeters. R1 has a dip angle of 60 degrees, the angles of r2 and r3 are 55 and 45 degrees.

Cross-section D is a cut through the compressional area. Two thrust faults (r1 and r2) are visible (fig. 10i). R1 has an offset of 1 cm. The strike-slip fault s2 ends on r1. R2 has an offset of 0,5 cm. The wedge is a lot wider than in cross-section C, it is now 10,6 centimeters wide. The dip angle is less steep than in the previous cross-sections, r1 and r2 have a dip angle of 45 and 35 degrees respectively.

4.6. Model 6
For the sixth model, the second model setup was used, with an irregular upper plate at an angle of 15 degrees to the lower plate. The lower plate was then pulled for 8 centimeters, corresponding to 90 km in nature. The rift that formed during deformation was filled after every centimeter with quartz sand, as syn-tectonic sedimentation.
Fig. 11: Geometry of the sixth model. (a) Top view, with the locations of the cross-sections. (b) Uninterpreted cross-section A. (c) Interpreted cross-section A. (d) Uninterpreted cross-section B. (e) Interpreted cross-section B. (f) Uninterpreted cross-section C. (g) Interpreted cross-section C. (h) Uninterpreted cross-section D. (i) Interpreted cross-section D.
In the models where the rift was filled with sand during deformation (models 6 -9), only the faults that developed in the oblique rift area during the last centimeter of deformation are visible in the top view. Earlier faults in this area are however visible in the cross-sections. It is possible to measure the width of the rift, as it is filled with sand. In this model, the rift is 11 cm at its broadest (fig. 11a). Just as in the fifth model, the offset of the normal faults gets smaller in the transition area, until they become thrust faults. During the third centimeter of deformation, one of the normal faults (n7) progresses into the compressional area. In this domain however, the fault does not have a significant orthogonal offset. During the fifth centimeter, two strike-slip faults developed in the compressional area and a second thrust fault forms on the western side of the pop-up. A small transtensional area formed along strike-slip fault s2 after seven centimeter of shortening (fig. 11a).

In cross-section A an asymmetrical rift, 8,3 centimeters wide and filled with syn-tectonic sediments can be seen (fig. 11c). The layers are numbered, to show the order of deposition. Layers 2, 3 and 4 are syn-tectonic. There are six normal faults. Fault n1 formed during the first centimeter of deformation and developed more offset during the rest of the deformation. The offset got larger after every increment of deformation. The offset after eight centimeters is larger than 2 centimeter. Faults n2 and n3 were formed during the first centimeter of deformation, because they do not affect the layers of syn-tectonic sediments. They both have 1 centimeter offset. N4 formed during the second centimeter of deformation and has 1,3 centimeter offset. N5 also affects the pink layer, so this fault formed during the fourth centimeter of deformation. Its offset is 0,3 centimeter. N6 affects all layers of sand and is also visible in the top view after the eighth centimeter of deformation, so this formed during the last centimeter of deformation. It has an offset of 1 centimeter. N1 has a dip angle of 60 degrees, the rest of the faults have a dip angle of around 70 degrees.

Cross-section B is a cut through the area of transition from extension to compression. Thrust faults as well as strike-slip faults are visible (fig. 11e). Since the cut is made through the beginning of the transpressional area, the offset of the thrust faults is still small. Thrust faults r1, r2 and r3 have an offset of 4, 1 and 2 millimeter respectively. The strike-slip faults both have an orthogonal offset of 3 millimeters. The wedge is 8,3 centimeters wide. R1 and r2 both have a dip angle of 60 degrees. R3 is less steep with an angle of 35 degrees.

Cross-section C is another cut through the transition area. There are two strike-slip faults present, next to three thrust faults (fig. 11g). R1 has an offset of 1,2 centimeter and r3 has an offset of 0,2 centimeter. Thrust fault r2 splits up into two faults. The main fault has an offset of 1,2 centimeter and the smaller one has an offset of 0,2 centimeter. Strike-slip fault s1 has a significant orthogonal component with an offset of 0,7 centimeter. The wedge is 11,5 centimeters wide. The dip angle of the thrust faults is smaller than in cross-section B, all three faults have an angle of around 40 degrees.

Cross-section D is a cut through the local transtensional area on the crest of the pop-up defined by thrusts r1 and r3 along the overall compressional area. The transtension is visible as a small basin in the upper yellow layer of sand (fig. 11i). The normal fault in this area has an offset of 0,2 centimeter. The strike-slip fault has a small dip-slip component of 0,1 centimeter. Besides the transtension, there are three thrust faults in this cross-section. Thrust fault r1 has an offset of 2,5 centimeters. R3 and r2 have offsets of 0,6 and 0,4 centimeter respectively. The wedge is 12,5 centimeters wide. The dip angle of the faults becomes smaller more to the north, because the faults in this cross-section have an angle of around 35 degrees.
4.7. Model 7
For the seventh model, the second model setup was used, with an irregular upper plate at an angle of 15 degrees to the lower plate. The lower plate was then pulled for 12 centimeters, corresponding to 120 km in nature. The rift that formed during deformation was filled after every centimeter with quartz sand, functioning as syn-tectonic sediments.

Fig. 12: Geometry of the seventh model. (a) Top view, with the locations of the cross-sections. (b) Uninterpreted cross-section A. (c) Interpreted cross-section A. (d) Uninterpreted cross-section B. (e) Interpreted cross-section B. (f) Uninterpreted cross-section C. (g) Interpreted cross-section C. (h) Uninterpreted cross-section D. (i) Interpreted cross-section D.
The oblique rift is 13 cm at its broadest and narrows towards the transition zone with the compressional domain (fig. 12a). Just as in the fifth and sixth model, the offset of the normal faults gets smaller in the transition area, until they become thrust faults. The normal fault segments in the rift are connected by relay ramps. Until the seventh centimeter, the development of the model is the same as the previous model. After seven centimeters, a third strike-slip fault formed in the northwest of the model. Also a third thrust fault on the western edge formed and after ten centimeters, a fourth thrust fault occurred. Also a series of small strike-slip faults developed at the eastern edge near s2.

Cross-section A is a cut through the oblique rift domain. The rift is asymmetrical and 11 cm wide (fig. 12c). Nine normal faults are visible. The fault on the east side of the rift formed after the first centimeter of deformation and developed further during the rest of the deformation. Its total offset after deformation is larger than 4 cm. The west side of the rift had a different development. After every centimeter of deformation a new fault formed. These are not all continuous along the whole extensional area, so they are not all visible in this cross-section. N1 has a dip angle of 60 degrees, the faults in the west side of the rift have a dip angle between 65 and 70 degrees.

<table>
<thead>
<tr>
<th>Fault</th>
<th>Offset (cm)</th>
<th>Formed during (cm of deformation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N9</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>N8</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>N7</td>
<td>0,6</td>
<td>2</td>
</tr>
<tr>
<td>N6</td>
<td>0,6</td>
<td>3</td>
</tr>
<tr>
<td>N5</td>
<td>0,5</td>
<td>4</td>
</tr>
<tr>
<td>N4</td>
<td>1,4</td>
<td>5-9</td>
</tr>
<tr>
<td>N3</td>
<td>1,1</td>
<td>10-12</td>
</tr>
<tr>
<td>N2</td>
<td>1,2</td>
<td>10-12</td>
</tr>
</tbody>
</table>

Table III: Development of the western side of the rift.

Table III shows the development of the western side of the rift. Fault n4 formed during the fifth centimeter of deformation and stayed active to the ninth centimeter. The older layers have larger offset than the younger ones. Faults n3 and n2 were also active during multiple phases of rifting.

Cross-section B was cut through the compressional area of the model. Three reverse faults form a small wedge (fig. 12e). On the retro-side of the wedge there is a reverse faults (r1) with an offset of 0,1 centimeter. On the pro-side the two reverse faults both have an offset of 0,5 centimeter. The width of the wedge is 8,3 centimeters. In the middle of the wedge are two strike-slip faults (s1 and n10). S1 does not have a significant orthogonal component while n10 has a orthogonal offset of 0,4 centimeter. R1 and r3 have a dip angle of 50 degrees and r2 has an angle of 65 degrees.

In cross-section C, there are four thrust faults, one in the retro-wedge and three in the pro-wedge (fig. 12g). In the retro-wedge, one thrust fault have an offset of 1,7. The offset of the faults in the pro-wedge (from east to west) is 0,7 cm, 0,8 cm and 0,2 cm respectively. The width of the wedge in this cross-section is 14,7 centimeters. In addition to the thrust faults there are three strike-slip faults. S1 has a orthogonal component with 0,4 cm offset. S2 and 3 cut through the thrust faults in the pro-wedge and do not have an orthogonal component. The lateral offset can be clearly seen in the top view. The dip angle of r1 is 35
degrees and the other thrust faults are less steep with an angle of around 30 degrees.
In addition to a thrust fault in the retro-wedge and three thrust faults in the pro-wedge, cross-section D also shows two strike-slip faults (fig. 12i). These are visible as basins in the sand layers. S2 cuts through thrust faults r2 and r3. The thrust fault in the retro-wedge has an offset of 3,4 centimeters. The three other thrust faults, from east to west, have an offset of 0,8 cm, 0,5 cm and 0,7 cm respectively. The dip of the thrust faults in the pro-wedge is less steep than in the cross-section through the transition domain. The faults have an angle of around 30 degrees. The wedge is 14,1 centimeters wide.

4.8. Model 8
For the eighth model, the second model setup was used, with an irregular upper plate at an angle of 15 degrees to the lower plate. The lower plate was then pulled for 22 centimeters, corresponding to 220 km in nature. The rift that formed during deformation was filled after every centimeter with quartz sand, functioning as syn-tectonic sediments.

The rift is 15 cm at its broadest (fig. 13a). Just as in the previous model with the second model setup, the offset of the normal faults gets smaller in the transition area, until they become thrust faults. In the top view it can also be seen that the upper part of the rift domain, which is filled with syn-tectonic sediments, is now part of the orogen. The central shear zone that was also visible in the previous model, developed further and more branches formed. The last seven centimeters, there was only formation of new small strike-slip faults and collapsing of the edges of the model.

Cross-section A is a cut through the oblique rift area. The rift that formed is asymmetrical and at the point of the cut 15 centimeter wide (fig. 13c). The normal fault on the east side of the rift formed during the first centimeter of deformation and the offset got larger with every centimeter of deformation. The offset at the end of deformation is more than 3,5 centimeters. On the west side of the rift a new normal fault formed during every centimeter of deformation. These faults are not continuous throughout the whole transtensional area, so they are not all visible in this cross-section. In this section there are 15 normal faults. All faults have a dip angle between 55 and 65 degrees.

<table>
<thead>
<tr>
<th>Normal fault</th>
<th>Formed during (cm of deformation)</th>
<th>Offset (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0,4</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0,4</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>0,8</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>0,8</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>0,6</td>
</tr>
<tr>
<td>6</td>
<td>4,5,6,7</td>
<td>1 - 1,3</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>0,6</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>1,1</td>
</tr>
<tr>
<td>9</td>
<td>10,11</td>
<td>0,8 – 1</td>
</tr>
<tr>
<td>10</td>
<td>12</td>
<td>0,8</td>
</tr>
<tr>
<td>11</td>
<td>13</td>
<td>0,4</td>
</tr>
<tr>
<td>12</td>
<td>14</td>
<td>1,1</td>
</tr>
<tr>
<td>13</td>
<td>15,16,17</td>
<td>0,2 - 0,8</td>
</tr>
<tr>
<td>14</td>
<td>18</td>
<td>0,3</td>
</tr>
</tbody>
</table>
Table IV shows the development of the western side of the rift. Fault 6 formed during the fourth centimeter of deformation and developed further from the fifth to the seventh centimeter. The older layers have larger offset than the younger ones. The same goes for fault 9, 13 and 15.

Fig. 13: Geometry of the eighth model. (a) Top view, with the locations of the cross-sections. (b) Uninterpreted cross-section A. (c) Interpreted cross-section A. (d) Uninterpreted cross-section B. (e) Interpreted cross-section B. (f) Uninterpreted cross-section C. (g) Interpreted cross-section C. (h) Uninterpreted cross-section D. (i) Interpreted cross-section D.
Cross-section B was cut through the transition area between extension and compression. As can be seen in fig. 13e, the syn-tectonic sediments are now part of the western side of the orogen. The western side of this cross-section consists mainly of normal faults and the eastern side is mainly thrust faults. There is one thrust fault through the western part, which lifts up the syn-tectonic sediments. This fault has an offset of 1.2 centimeters. West of this fault, there is also uplift, caused by reactivation of the normal faults into compressional structures. The four other thrust faults, from east to west have an offset of 3 mm, 7 mm, 1 mm and at least 1.6 cm respectively. The wedge is 11.1 centimeters wide. R1 has a dip angle of 70 degrees, the faults in the pro-wedge have an angle of around 60 degrees.

Cross-section C shows a wedge, with one thrust fault in the retro-wedge and four thrust faults in the pro-wedge (fig. 13g). In addition, in the pro-wedge there is also a normal fault and a strike-slip fault. The thrust fault in the retro-wedge has an offset of 2.2 cm. The thrust faults in the pro-wedge, from west to east, have an offset of 1.3 cm, 1.2 cm, 3 mm and 4 mm. The last fault ends on the strike-slip fault. The strike-slip faults s2 cuts through thrust fault s3. The normal fault has an offset of 1 mm and also ends on a thrust fault. The width of the wedge in the cross-section is 13.2 centimeters. The dip angle of r1 and r2 is 40 degrees. The dip of the other thrust faults gets smaller closer to the surface.

Just as in cross-section C, in cross-section D there is a thrust fault in the retro-wedge and four thrust faults in the pro-wedge (fig. 13i). Two normal faults and two strike-slip faults are also visible. The fault in the retro-wedge has an offset of 4.2 cm. The thrust faults in the pro-wedge have an offset of 1 cm, 0.3 cm, 0.6 cm and 0.7 cm. The upper thrust fault ends on the most western strike-slip fault. The western normal fault also ends on this strike-slip fault. The normal fault has an offset of 0.3 cm. The eastern normal fault has an offset of 0.4 cm and ends on the thrust fault in the retro-wedge. The width of the wedge is 16 centimeters. The dip of the faults becomes less steep, further away from the transition zone. In this cross-section, r1 has a dip angle of 40 degrees. The dip thrust faults in the pro-wedge becomes smaller towards the surface. The upper fault r2 has an angle of 10 degrees.

4.9. Model 9

For the ninth model, the third model setup was used, with an irregular plate at an angle of 5 degrees to the lower plate. The lower plate was then pulled for 22 centimeters, corresponding to 220 km in nature. The rift that formed during deformation was filled after every centimeter with quartz sand, functioning as syn-tectonic sediments.

Just as in the previous model with the second model setup, the offset of the normal faults gets smaller in the transition area, until they become thrust faults.

During the first centimeter, a oblique rift forms in the south and a pop-up in the north (fig. 14a). These develop further during the next 3 centimeters. After 4 centimeters, two strike-slip faults develop in the southern part of the pop-up. The two centimeters after that, multiple small strike-slip faults form along the western edge of the pop-up and a second thrust fault forms in the pro-wedge. During the next ten centimeters, multiple small branches of the strike-slip faults form and a narrow rift opens along s2. After 18 centimeters, another thrust fault forms along the western edge.
Cross-section A is a cut through the rifted area. The rift that formed is asymmetrical and at the point of the cut 16.5 centimeter wide (fig. 14c). The normal fault on the east side of the rift formed during the first centimeter of deformation and the offset got larger with every centimeter of deformation. The
offset at the end of deformation is more than 3,5 centimeters. On the west side of the rift a new normal fault formed during every centimeter of deformation. These faults are not continuous throughout the whole transtensional area, so they are not all visible in this cross-section. In this section there are 14 normal faults. These are numbered 1 to 14 from west to east. The dip angle of the faults is between 65 and 70 degrees.

<table>
<thead>
<tr>
<th>Normal fault</th>
<th>Formed during (cm of deformation)</th>
<th>Offset (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0,9</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0,7</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>3,4,5</td>
<td>0,6 - 0,9</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>0,7</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>0,9</td>
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<tr>
<td>7</td>
<td>8</td>
<td>0,8</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>1,2</td>
</tr>
<tr>
<td>9</td>
<td>10,11</td>
<td>0,7 - 1,1</td>
</tr>
<tr>
<td>10</td>
<td>12</td>
<td>0,8</td>
</tr>
<tr>
<td>11</td>
<td>13,14,15</td>
<td>0,7 - 0,9</td>
</tr>
<tr>
<td>12</td>
<td>16</td>
<td>1,3</td>
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<tr>
<td>13</td>
<td>17,18</td>
<td>1</td>
</tr>
<tr>
<td>14</td>
<td>19,20</td>
<td>0,7</td>
</tr>
</tbody>
</table>

Table V: Development of the western side of the rift.

Table II shows the development of the western side of the rift. Fault 4 formed during the third centimeter of deformation and developed further from during the fourth and fifth centimeter. The older layers have larger offset than the younger ones. The same goes for fault 9, 11, 13 and 14.

Cross-section B was cut through the transition area between the rift and the mountain belt. As can be seen in fig. 14e, the syn-tectonic sediments are now part of the western side of the orogen. The western side of the wedge consists mainly of syn-tectonic sediments and the eastern side consists only of the initial layers. The sides are separated by a thrust fault with an offset of 4 cm. In the western side there are two thrust faults and two normal faults. In the eastern side there is a strike-slip zone, a normal fault and a thrust fault. The wedge is 10,9 centimeters wide. The faults are steeper than in the previous cross-sections. All faults have an angle steeper than 70 degrees, accept for r1, with an angle of 45 degrees. The offset of the faults is discussed in table VI.

<table>
<thead>
<tr>
<th>Fault</th>
<th>Offset (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>r1</td>
<td>0,3</td>
</tr>
<tr>
<td>n1</td>
<td>1,2</td>
</tr>
<tr>
<td>r2</td>
<td>4</td>
</tr>
<tr>
<td>r3</td>
<td>1,5</td>
</tr>
<tr>
<td>r4</td>
<td>0,1</td>
</tr>
</tbody>
</table>

Table VI: Offset of the faults in the cross-section in fig. 33.

In cross-section C, there are four thrust faults, one in the retro-wedge and three in the pro-wedge (fig. 33).
14g). In addition, there are three strike-slip faults with an orthogonal component in the pro-wedge. The wedge is 12,7 centimeters wide. R1 has an offset of 2,2 centimeter. The three other thrust faults, from east to west, have an offset of 8, 9 and 4 millimeter. The faults are a lot less steep than in the transition zone. All the faults have dip angles around the 40 degrees.

As can be seen in fig. 14i, there are four nearly horizontal thrust faults in the pro-wedge of cross-section D. The angle gets smaller closer to the surface. The most eastern fault has a branch going down. They all end on the thrust fault of the retro-wedge and on the strike-slip fault separating the two sides of the wedge. R2 has an offset of 0,8 centimeter, the offset of r3 is 0,2 centimeter and r4 has an offset of 1,4 centimeter. In the pro-wedge there is also a normal fault and a strike-slip fault. The normal fault has an offset of 0,3 centimeter. In the retro-wedge there are two more strike-slip faults. The thrust fault in the retro-wedge, r1, has an offset of 3,2 centimeter. The upper yellow layer of sand breaches the surface on the eastern slope of the wedge, due to collapsing of the slope. The wedge is 13,5 centimeters wide.

4.10. Summary of modelling results for setup 1

In the models that used the first model setup, with a straight plate boundary at an angle of 15 degrees to the lower plate, the following development of structures was seen:

First, a pop-up occurred with a NNE-SSW orientation, parallel to the boundary of the upper plate of the model. Then, small strike-faults started to form along the western side of the pop-up. These faults connected to form a continuous strike-slip fault along the western edge of the pop-up. A second strike-slip fault along the eastern edge formed. At the same time, a second thrust fault formed in the pro-wedge. After that, a third thrust fault in the pro-wedge formed and the eastern slope of the formed orogen collapsed. Along the western strike-slip fault, branches towards the east began to form. A central shear zone formed through the middle of the wedge. This zone got wider during the rest of the deformation. After the formation of the central shear zone, part of the western slope of the orogen collapsed because it got too steep and a fourth thrust fault developed in the pro-wedge. Finally, the western strike-slip fault developed more branches, connecting it to the central shear zone in the middle.

<table>
<thead>
<tr>
<th>Model</th>
<th>Deformation (cm)</th>
<th>Width of wedge (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>10,8</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>22</td>
<td>13,7</td>
</tr>
</tbody>
</table>

Table VII: Development of the wedge in model 1-4.

Table VII shows the relationship between the amount of convergence and wedge growth (in terms of its width).

4.11. Summary of modelling results for setup 2

In the models with a irregular plate boundary at an angle of 15 degrees to the lower plate, the following development of structures was seen:
First, a rift with a NE-SW orientation formed in the south and a pop-up with a NNW-SSE orientation in
the north. The rift deepened at the eastern side and widened at the western side, so it became
asymmetric. One of the normal faults of the rift area progressed into the compressional area in the
north. A strike-slip fault started to develop in the southeast of the extensional area during and af
after that a second strike-slip fault formed in the west. Also at that time, a second thrust fault formed at the
western edge of the pop-up. Then, a small transtensional basin formed along the western strike-slip
fault. Also a third strike-slip fault formed in the northwest of the model and a third thrust fault on the
western edge formed. A fourth thrust fault formed and at the same time a series of small strike-slip
faults developed at the eastern edge. This formed a central shear zone. This zone developed further
during the last centimeters of deformation. During these final stages of deformation, there was also
formation of small strike-slip faults and collapsing of the edges of the structures. The dip of the faults
got steeper towards the transition zone and were nearly pure strike-slip in this domain.

<table>
<thead>
<tr>
<th>Model</th>
<th>Deformation (cm)</th>
<th>Width of wedge (cm)</th>
<th>Width of rift (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
<td>11</td>
<td>7,5</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>12,5</td>
<td>11</td>
</tr>
<tr>
<td>7</td>
<td>12</td>
<td>14,7</td>
<td>13</td>
</tr>
<tr>
<td>8</td>
<td>22</td>
<td>16</td>
<td>15</td>
</tr>
</tbody>
</table>

*Table VIII: Development of the wedge and rift in models 5-8.*

Table VIII summarizes the width of the wedge and the rift throughout deformation.
5. Discussion

5.1. Comparison of the models

5.1.1 Models 1-4 with models 5-8
Besides the obvious difference that model setup 1 only results in a compressional area and model setup 2 also has an oblique rift area, there is also a difference in structures and the development of them. As can be seen in tables VII and VIII, the wedge is about 3 centimeters wider in models 5-8. Also the maximum height is different;

In model setup 2, the larger strike-slip faults occur sooner than in model setup 1 (fig. 16). Also, a second thrust fault in the pro-wedge forms sooner in model setup 2. In the models with the straight boundary, the first larger strike-slip faults develop parallel to the boundary, whereas in models with the irregular boundary, the larger strike-slip faults form parallel to the deformation direction (fig. 16). In addition, after 22 centimeter of deformation, model 4 shows a clear central shear zone, whereas model 8 does not. It has multiple larger strike-slip faults throughout the whole compressional area. There is however a zone of transtension in the compressional area. This does not occur in the straight boundary models. These differences occur because in model setup 2, there is a transition from a rift domain to a domain that is mainly compressional. In this transition zone, the faults are almost pure strike-slip. This causes the strike-slip faults to occur sooner than in model setup 1. This also explains why the strike-slip faults form mainly parallel to the deformation direction in model setup 2. In the transition zone, where the pure strike-slip faults form, the plate boundary is parallel to the deformation direction. Later in the deformation, also strike-slip faults parallel to the boundary form in the compressional domain. These cut through the earlier formed strike-slip faults, preventing a central shear zone to form. In model setup 1, the strike-slip faults are in the same direction, making it easier to form a central shear zone.

5.1.2. Model 8 with model 9
Models 8 and 9 have the same upper plate boundary, but at a different angle to the lower plate. Model 8 has an angle of 15 degrees and model 9 an angle of 5 degrees.

Fig. 15: Top views of models 8 and 9 after 22 cm of deformation.
Both models have an transtensional and transpressional area. However, in model 9, the rift in the transtensional area is a wider than in model 8. At the broadest point, the rift in model 8 is 15 cm wide whereas the rift in model 9 is 17 cm at its broadest. The wedge however is broader in model 8. It is 16 cm wide in model 9 and 13,5 in model 8. The major strike-slip faults formed earlier in the deformation in model 9. However, localized transtension occurs sooner in model 8 than model 9. Also, the central shear zone that is present in model 8, does not occur in model 9, as well as a fourth thrust fault in the pro-wedge.

These differences can be explained by the angle of the upper plate to the lower plate. In model 9, the plate boundary is almost parallel to the deformation direction. This causes the major strike-slip faults to form earlier, because the faults have a larger lateral offset. Since the orthogonal component of the faults in the compressional domain is larger in model 8 than in model 9, the wedge of model 8 is broader. The rift however is broader in model 9, because the larger lateral offset causes new normal faults to form with every increment of deformation, instead of reactivating old ones.
Fig. 16: Top-views of models 1-8.
5.2. Comparison to nature

When compared to nature, there are a few differences and similarities between the models and the real structures along the Norwegian margin.

Just as in nature (fig. 17), the models with model setup 2 have a releasing and a restraining bend, causing a rift and mountain belt to form. This rift is at the place of the Vestbakken Volcanic Province (VVP) and the mountain belt is the Spitsbergen Fold and Thrust belt.
Fig. 18: Regional structural map. Location of transects are shown. (after Faleide et al., 2008)

Fig. 18 shows the area of the Norwegian margin that is comparable to the irregular boundary used for the analogue models. Cross-sections 9 will be compared to the cross-section of the models with the irregular plate boundary. For the comparison, cross-sections from model 9 will be used, because its amount of deformation is closest to nature.

Fig. 19: Cross-sections 8, 9 and 10, as showed in fig. 38. (after Faleide et al., 2008)

In the cross-sections, the yellow layers are deposited during the deformation, so they are comparable to the layers of sand that the rift of models 5-9 was filled with.
The location of the cross-section in fig. 20 is comparable to the location of cross-section 9 in fig. 18. In this cross-sections, the syn-tectonic sediments were uplifted and became part of the orogen of the northern part of the model. Three major thrust faults in the west, middle and east of the wedge, caused the sediments to be uplifted and form a wedge with low profile. The wedge is around 10 cm wide, which compares to 100 km in nature. In cross-section 9 from fig. 18, there is also a wide wedge with low profile. The wedge is around 150 km wide. West of the wedge is a shallow basin. This basin is not visible in the cross-section from the analogue model, but it can be interpreted from the top view that a basin was present a few centimeter south of the location of the cross-section.

There are however no cross-sections of the model at exactly that location. The thrust faults visible in the wedge in cross-section 9 do have similarities with the thrust faults in the model. The angle of the faults however is smaller in the model. In general, the basic structures of the analogue model at this location are comparable to the situation in nature.

5.3. Comparison to the results of Leever et al.

To compare the results to the results of the research by Leever, the reference model of 15 degrees is used and compared to a cross-section of model 4.

Fig. 21 shows a cross-section from the model from Leever. The model is comparable to model 4, it has a straight plate boundary and the lower plate at an angle of 15 degrees to the upper plate.
As can be seen in figures 21 and 22, the results from this and Leevers research compare very well. One main thrust fault in the retro-wedge and four thrust faults in the pro-wedge with a very small dip angle. Also the central shear zone is present in both cross-sections.
6. Conclusion

During this research, the effect of an irregular plate boundary on the evolution of structures close to the plate boundary under oblique convergence was studied. The irregular plate boundary is characterized by two straight segments, which are connected by a releasing bend. It was found that the orogenic wedge that forms during deformation is wider with the irregular plate boundary. Also, the larger strike-slip faults occur sooner than with a straight plate boundary. The strike-slip faults in the straight boundary models follow the boundary, whereas the strike-slip faults in the irregular boundary models mainly follow the deformation direction. Local transtension occurs in the transpressional area of the irregular plate boundary models. This does not occur in the straight boundary models. These differences occur because there is a domain in the irregular boundary models where the faults are almost pure strike-slip.

Also a comparison was made between two models, both with an irregular plate boundary, but at a different convergence angle. Comparison of the models shows that the rift in the transtensional area is wider with a smaller convergence angle. The wedge however is broader with a larger convergence angle. This is because in model 9 the plate boundary is almost parallel to the deformation direction. Therefore the lateral component of the faults in the compressional domain is larger, causing the wedge to be narrower.

The analogue models were also compared to the situation in nature at the Norwegian continental margin. On large scale, the models are very similar to nature. The releasing and restraining bend in the models compare to the Vestbakken Volcanic Province and the Spitsbergen Fold and Thrust belt. From the cross-sections through the transition domain the basic structures in the model are comparable to the structures in nature.

When the results are compared to the research of Leever et al. (2011), it is founded that they compare very well. The same structures are present in both cross-sections.

Future research

In the future, more research can be done on this subject, by eliminating some of the limitations and taking more parameters into account. For example, by adding silicon putty to the models, the effect of a ductile lower crust can be studied. In that way, the limitation of rheology would be of less effect than in this research. Larger models can be used to lessen the effect of the boundaries on the structures. Also, more shortening could be used, to get closer to the situation in nature. Furthermore, the effect of convergence angle on the structures can be further studied with an irregular plate boundary by using model setup 2 with different convergence angles.
7. References


