Flanking structures of the Ugab and Goantagab valley, Namibia: Natural observations and comparison with new analogue experiments.

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1. Introduction.

1.1 What are flanking structures?

The planar fabric of a rock (e.g. foliation or lithological layering) often contains crosscutting elements like faults or veins. Occasionally, the fabric is deflected near the margin of the crosscutting element. For this deflection, Passchier (2001) introduced the term **flanking structure**. The fabric of a rock (referred to as the host element, HE) can be a foliation or compositional layering. Occasionally, it can be an isolated layer or vein in a non-foliated rock. The crosscutting element (CE) is a planar feature that represents a fault, vein or a dyke.

Flanking structures develop by the rotation of the CE during ductile deformation of the host element. Different geometries of flanking structures can occur, depending on the sense of offset along the CE, rheological differences between the CE and the HE, initial orientation of the CE relative to the HE and the type of ductile flow. Four main types of flanking structures have been distinguished (N-, S-, A-types flanking folds and shear bands (Figure 1.1 and 1.2)). We speak of an **N-type** flanking fold if there is no offset of a marker horizon along the CE (Passchier, 2001). A schematic drawing of an example of an N-type flanking fold is given in figure 1.1. If the CE acts as a slip surface, we use the terminology that was recently proposed by Grasemann et al. (2003). If the sense of shear along the CE is the same as the bulk shear, the slip surface is co-shearing. If the sense of shear along the CE is opposite to that of the bulk shear, the CE is counter-shearing. **S-type** flanking folds are co-shearing with a contractional offset (figure 1.2a). **A-type** flanking folds are counter-shearing (figure 1.2b). **Shear bands** are co-shearing with an extensional offset along the CE. S-flanking folds, A-type flanking folds and shear band structures can be further subdivided into normal and reverse drag structures, defined by the concave or convex deflection of the marker line in the direction of the shear along CE (indicated in figure 1.2).

![Figure 1.1](image)

Figure 1.1: Schematic example of an N-type flanking structure. The host element (HE) is deflected close to the crosscutting element (CE). The HE further away from the CE is undisturbed.

Flanking structures have been found in different geological settings, with a variety scale ranging from millimeter up to at least meter scale. The axial plane of the fold train that has developed along the CE is often found to be orientated sub-parallel to the CE. The folds can be open as well as isoclinal. If the CE is continuous, the flanking of the HE usually dies out in the wall rock beyond the tips of the CE or, less commonly, before the tip is reached. If the CE is boudinaged, a different type of flanking geometry occurs (boudin-related flanking structures (Passchier, 2001)), where the deflection of the HE shows a switch in the vergence of folding along the sides of each individual boudin (figure 1.3). Boudin-related flanking folds were not included in this report.
Figure 1.2: Terminology of flanking structures. HE: Host element, containing markers parallel to the shear zone boundaries; CE: Crosscutting element, i.e. a planar slip surface embedded in the HE. The convex or concave deflection of the marker line in the direction of shear along the CE defines normal or reverse drag. (a) S-type flanking folds are co-shearing with a contractional offset. (b) A-type flanking folds are counter-shearing. (c) Shear bands are co-shearing with an extensional offset. (Grasemann et al., 2003)

Figure 1.3: Three types of boudin-related flaking structures around a boudinaged vein. (a) Flanking folds central to each boudin. (b) No deflection of the HE central to each boudin, but folds associated with boudin necks on both sides. (c) Flanking shear band geometry central to each boudin. (Passchier, 2001)
1.2 What do we already know about flanking structures?

Gayer (1978) described folds that have been developed against meta-dolerite dykes in the Caledonides of Finmark, Norway. The axial planes of the folds were found to be parallel to the dykes and the folds were symmetrical about their axial surfaces. Gayer proved that the dykes intruded before folding and he proposed two models for the development of the folds: by frictional slip along the margin of rigid, un-rotated dykes, or by rotation of the dykes together with shear parallel to the dyke margins.

Hudleston (1989) referred to what we now call flanking folds as pair hooked folds. He studied the folds in glaciers (Reverse A-type according to the classification of figure 1.2) and emphasized that the folding was a consequence of fracturing and vein formation, not visa versa. Hudleston did some modeling with plasticene in which he made cuts to simulate veins. Shear was induced on the plasticene by shearing the edges with the help of wooden blocks. It was concluded that the folds were a consequence of the strain in the host material and the perturbation of flow by the presence of an open, partly healed or filled fracture. Hudleston also concluded that the folds were shear sense indicators and that they indicated non-coaxial flow, provided that the vein formed in the same deformational event as the folds. Extensional veins open normal to \( \sigma_3 \) (the least compressive stress) and such veins will not rotate after formation if strain is coaxial. The amount of shear stain was responsible for the amplification of the folds. With higher shear strain, the folds became more isoclinal. Hudleston also concluded that folds did not develop if the fracture healed shortly after formation or if there was no good foliation to become folded.

Drugeut et al. (1997) described folded foliation against pegmatite veins in a complex high-strain zone at Cap de Creus, Spain. The pegmatite veins contain tourmaline rims that are more competent than the surrounding mica schist is. The veins were rotated during non-coaxial shear. Initially, the veins were at high angle relative to the foliation. This initially high angle was largely preserved at the contact of the folded foliation with the veins. They also described complex folding structures around rotated and boudinaged pegmatite veins with folds of opposite vergence facing each other across a boudin neck.

Grasemann et al. (1999) referred to flanking fold as fringes folds. These authors studied rotated, quartz filled tension gashes in the Main Central Thrust Zone in the NW-Himalaya. Brittle failure during ductile flow opened the tension gashes that rotated during bulk shear deformation. During rotation, the tension gashes did not show a shear component parallel to the vein margin as described by Hudleston (1989). Therefore, they are N-type flanking folds following the classification of figure 1.1.

Grasemann and Stüwe (2001) preformed numerical modeling in a non-linear viscous medium during ideal simple shear conditions. They showed that A-type flanking folds develop if the vein is less viscous than the host material due to counter shear slip along the vein. If the vein is more viscous than the host material, the vein does not deform and N-type flanking folds develop. The interlimb angle of the folds decrease (i.e. folds get more isoclinal) with increasing shear strain. Increasing viscosity of the vein with respect to the host material also results in a decrease of the interlimb angle of the folds. Therefore, Grasemann and Stüwe emphasize that care must be taken to derive the amount of shear strain only based on the interlimb angles of the folds.

Passchier (2001) described five different mechanisms for the development of flanking folds (figure 1.4):

I: Intrusion or in situ formation of veins that bisect existing fold trains or shear bands along the axis of the structure because of a plane of weakness.
II: Flow partitioning alongside an active fault in a ductile deforming rock.
III: Passive rotation of a vein with attached narrow rim of wall rock formed by alteration of the wall rock during intrusion of the vein.
IV: Development of a shear zone in or along a pre-existing vein.
V: Passive amplification of small deflections alongside a vein.

He concluded that flanking structures can be used as shear sense indicators only if the mechanism that is responsible for the structure is known.

Figure 1.4: Schematic representation of several mechanisms by which flanking structures can develop. All structures are shown in a section normal to planar CE (gray) and HE (black). The top of the diagram shows deformation of a CE and HE that act as passive markers. (Ia) Development of a fold train and later passive development of a vein in the mica-rich core of the structure caused by preferential partial melting. (Ib) Development of a fold train followed by generation of a fault or shear zone in the core of the structure. This fault or shear zone is passively erased by a local melt vein. (Ic) Development of a fold train, and concentration of melt in the core of the structure in a early stage. Both Ib and Ic can show synthetic displacement along the melt vein-CE (S-type flanking folds). (II) Development of a flanking fold by slip of an active fault which rotates in bulk ductile coaxial flow. Caused by flow partitioning, deformation alongside the fault is close to pure shear, leading to development of an internal HE with deviant orientation from the external HE. (III) Development of an N-type flanking fold caused by passive rotation of a vein-CE with attached narrow strip of wall rock (insets) caused by alteration of the wall rock during intrusion of the vein. The rotated strip of wall rock develops into the internal HE. (III') Development of an A- and S-type flanking fold by mechanism (III) from pre-existing offset on conjugate sets of veins. (IV) Development of flanking folds by preferential non-coaxial flow along a CE. Insets show two possible types, with flow in the entire CE (IVa) or in a chilled margin and/ or altered wall rock rim (IVb). (V) Development of flanking folds by passive amplification of asymmetric deflection in the HE close to the CE. (V') Development of a flanking fold and shear band pair by passive amplification of a symmetric deflection along a CE. (Passchier, 2001)

A follow-up of the study by Grasemann and Stüwe (2001) was done by Grasemann et al. (2003). They did numerical modeling on flanking structures in which they simulated flow around a slip surface in a linear viscous medium. They only modeled linear viscous material because non-linear rheologies generated topologically equivalent structures (Grasemann and Stüwe, 2001). There work resulted in the subdivision of the different flanking structures.
presented in figure 1.2. Grasemann et al. showed that the geometry of a flanking fold is a function of the initial orientation of the vein and the flow field. For the model, they did not change the rheology of the vein. It was assumed to be a pinned CE (no propagation of the CE during deformation) with zero shear stress along the sides. They concluded that a Normal shear band is very similar to a Normal A-type, and that a Reverse shear band is very similar to a Reverse A-type. Failing to consider this may lead to wrong interpretations of the shear sense of the bulk deformation. The only criteria to distinguish them are that the shear band has to have a sigmoidal shaped CE and that the orientation with respect to the shear zone always has to be less than 25-30 degrees. Above this, the shear band is unstable.

1.3 Aim of the study.

The above overview of previous studies on flanking structures shows that, except for some early descriptions of deflection and folding against dykes and veins (Gayer, 1978; Hudleston, 1989), the importance of flanking structures as kinematic indicators has been appreciated only since 1997 (Drugeut et al., 1997; Grasemann et al., 1999; Grasemann and Stüwe, 2001; Passchier, 2001; Grasemann et al., 2003). Detailed analysis of field examples and limited numerical modeling improved the understanding of flanking structures. The present study focuses on flanking structures in the Ugab and Goantagab valley, Namibia. Our main aim was to apply the state-of-the-art knowledge coming from the previous studies to interpret the geometry and significance of these natural flanking structures. In particular, I concentrated on shear sense, shear strain and type of ductile flow. During the study, however, several questions came up that could not be solved with the existing understanding of flanking structures. These questions were:

1) How can we get sinistrally as well as dextrally rotated veins that show N-type flanking structures next to each other in the same structural setting?
2) How can we get A-, S- and N-type flanking folds next to each other in the same volume of rock (under the same rheological conditions with respect to the CE and the HE)?
3) How are differences in the interlimb angles of the folds, thickening of the HE at the fold hinges and different grades of deflection inside a flanking structure generated?
4) Is the classification of figure 1.1 and 1.2 sufficient to characterize all natural flanking structures?

We may speculate about the answers of these questions using the results of the numerical model of Grasemann et al. (2003). In that model, flanking structures were developed as a function of ductile flow and initial position of the CE, where the CE consisted of an active but pinned free-slipping surface embedded in a viscous medium. I hypothesize that, in addition to type of ductile flow and initial position, also the rheological properties of the CE will play a role in the development of different types of flanking structures. I tested this hypothesis by manufacturing flanking structures with the help of analogue modeling, in which I could not only vary the type of ductile flow and the initial position of the CE, but also to some degree the rheological properties of the CE. With the knowledge of previous studies and the additional knowledge that is derived from the new analogue experiments, I will try to answer the above questions regarding the natural examples from the Ugab and Goantagab valley, Namibia.

This report will start with discussing the typical natural examples of flanking structures that were studied in the Ugab and Goantagab valley, Namibia. The questions that remained open and that could not be solved with the previous studies will be outlined. Next, I will explain the method that was used to manufacture analogue flanking structures and introduce the apparatus and materials that were used in the experiments. The geometry of the results of the experiments will be analyzed. From these result I will try to answer the above questions
regarding the natural examples from the Ugab and Goantagab valley, Namibia. Finally, I will discuss the reliability of flanking structures as kinematic indicators in field analysis and discuss if they can be used to predict the type of flow in the rock. Attached to this report is a CD that contains the movies of the analogue experiments (attachment 1) and three appendixes. An appendix of suggestions for improvement of the apparatus that was used for the experiments (appendix 1), an appendix that contains the settings of the configuration files for the PC-program PIVSleuth (appendix 2) and an appendix with the flow patterns that were derived with help of this program (appendix 3).

2. Natural examples.

2.1 Geological setting of the fieldwork area.

Natural examples of flanking structures were studied in the Ugab and Goantagab Valley in Namibia, which is located at the junction of two related Pan African mobile belts: the Kaoko belt (trending NW-SE along the coastline) and the Inland Damara Belt (the inland branch of the Damara Orogen, trending NE-SW). In the Ugab and Goantagab Valley, exposed rocks are predominantly siliciclastic and carbonate successions of the Neoproterozoic Zerrissene turbidite system. The rocks have been metamorphosed to biotite zone conditions of the greenschist facies (Passchier et al., 2002). A schematic map of the fieldwork area is given in figure 2.1. Two main tectonic events were responsible for the development of structures in the turbidite layers. The first tectonic event generated two folding phases (D1 and D2) and was associated with shortening due to the collision across both the Kaoko and the Damara belts. D1 resulted from dominant E-W shortening and caused kilometer scale upright folds with well-developed axial planar cleavage, N-S trending axial planes, and sub-horizontal fold axes. D1 progressively graded into D2, which is a phase of shear movement to the north, combined with continued minor E-W shortening. D2 was responsible for refolding of the D1 folds. The second younger tectonic event was responsible for the third folding phase (D3) and is related to final adjustments in the Damara belt associated with the collision between the Congo Craton (North of the Damara Belt) and the Kalahari Craton (south of the Damara Belt). D3 was significantly different from D1 and D2 because of its deviant orientation (NW-SE shortening relative to the E-W shortening of D1 and D2) and activity under lower metamorphic grade. It is of apparent sinistral transpression and caused localized fold trains on a meter to kilometer scale with NE to NNE trending sub vertical axial planes (Passchier et al., 2002). In the area, two intrusions crop out: the Doros Pluton in the NW of the fieldwork area and the Voetspoor Pluton more to the SE. The Doros intrusion (of hornblende-syenite and younger biotite granite) is of post-D1 to pre-D3 age. The Voetspoor intrusion (equally composed of hornblende-syenite and younger biotite granite) is of post-D1 and syn-D3 age (Passchier et al., 2002). A detailed map of the fieldwork area is given in figure 2.2. Flanking structures were studied in the Aims River Formation and the Upper and Lower Gemsbok Formation of the Zerrissene Turbidite System at different sites. In the Aims River Formation, flanking structures are well developed just NE of the contact against the Doros Pluton and they occur against small pegmatite veins inside the meta-sediments. In the Gemsbok formation, flanking structures occur against quartz veins within marbles. Markers are formed by quartzitic layers inside these marbles.
Figure 2.1: Schematic map of N-Namibia showing the fieldwork area that was located in the Ugab River Turbidite domain.

Figure 2.2: Detailed map of the fieldwork area of the Ugab and Goantagab area in Namibia.
2.2 Typical natural flanking structures of the Ugab and Goantagab valley, Namibia.

2.2.1 Aims River Formation, NE of the contact with the Doros Pluton.

The Aims River Formation, NE of the contact with the Doros Pluton, consists of a well-foliated mica schist (HE). Inside the schist, thin pegmatite veins (with a thickness of 1-5 mm) are present with an orientation of 5-20° relative to the foliation. Figure 2.3 shows that the deflection of the HE occurs only at the veins that contain alteration rims with the wall rock [1]. Other veins do not show flanking fold development, despite their identical orientation relative to the foliation [4]. An anticlinal fold train is developed above the CE (hanging wall). A synclinal fold train is developed below the CE (footwall). Maximum deflection of the foliation of the hanging wall occurs just above the centre of CE [3]. The deflection dies out towards the tip of the vein and does not continue beyond the tip. The maximum deflection of the footwall is occupied near the centre of CE [2] and dies out at the tip of the CE. No individual markers could be traced from the footwall to the hanging wall in the example of Figure 2.3, but in all veins where markers were present, there was no sign of displacement along the vein. Therefore, the flanking folds are interpreted as N-type and the vein rotation is interpreted as being dextral.

Figure 2.3: N-type flanking fold in the Aims River Formation, NE of the Doros crater, Namibia. 1: Pegmatite vein with alteration rim 2: Maximum flanking of the footwall. 3: Maximum flanking of the hanging wall 4: Veins with the same orientation that do not show flanking folds and contain no alteration rim.

Figure 2.4 shows another example of a flanking fold against a pegmatite vein in the mica schist. The vein shows a very small alteration rim at the contact with the HE, in the central part of the vein. At the tips of the veins, no alteration rim was detected. The markers do not show any displacement along the CE and therefore this structure was interpreted as being an N-type flanking fold. The hanging wall contains an anticlinal fold train, where the footwall contains a synclinal fold train. In order to create this structure, the vein must have been
rotated sinistrally during shear. Note the difference in structure with respect to the previous example. The thickness of the foliation planes increases towards the CE, which was not the case in figure 2.3. This indicates extension in the fold hinges along the axial planes of the fold trains. The extension is largest where maximum deflection occurs (in the centre of the vein) [2]. The folding dies out into the wall rock, beyond the tips of the vein [3].

Figure 2.4: N-type flanking fold in the Aims River Formation, NE of the Doros crater, Namibia. 1: Pegmatite vein with small alteration rim in the centre. 2: Most intense folding around the centre of the CE. Note that the extension in the fold hinges is maximum where maximum flanking occurs. 3: Deflection goes on beyond the tip of the CE and gradually dies out into the wall rock.

Figure 2.5 shows a 3-dimensional view of an N-type flanking fold that also developed in the mica schist of the Aims River Formation. Although the tips of the pegmatite vein are not exposed, we can clearly see a zone in which the deflection of the foliation is strongest [2]. In this zone, we also see maximum thickness of the foliation planes due to extension in the fold hinges along the axial planes of the fold train. The deflections as well as the thickness of the foliation planes near the vein tend do die out away from this zone (towards the tips of the CE) [3].
The flanking folds in the Ains River Formation, NE of the contact with the Doros Pluton, all were interpreted as being N-type flanking folds because no displacement along the vein was found. Although I found dextrally rotated veins as well as sinistrally rotated veins, all veins were orientated 5-20° with respect to the foliation. The only difference between the flanking folds of the sinistrally and the dextrally rotated veins is that all sinistrally rotated veins show extension in the fold hinges along the axial planes. No indication for this was found in the folds associated with the dextrally rotated veins. The sinistrally rotated veins also seem to have smaller alteration rims than the dextrally rotated veins. Along both veins, I found open folds as well as isoclinal folds.

2.2.2 Lower Gemsbok Formation.

Flanking structures were also found in the Lower Gemsbok Formation of the Zerrissene Turbidite System. These structures have been formed inside marbles against straight quartz veins. Although the quartz veins are extended, no boudin-related flanking structures were developed. The veins vary in thickness from 0.5 to 2.5 cm. The orientation of the veins with respect to the marble bedding was always found to be between 40 and 55°. Quartzitic layers inside the marbles form good markers for the offset along the veins. The bulk shear in the marble is of sinistral sense. Veins that do not show any development of flanking structures, despite of there identical orientation with veins that do, did not differ geometrically or structurally from other veins.

Figure 2.6 shows an example of the flanking structures inside the Lower Gemsbok Formation. The vein at the right of the photo [1] shows a contractional offset along the vein that is co-shearing. The drag of the marker (quartzitic) layer is normal with respect to the displacement along the vein and therefore this structure was interpreted as being a Normal S-type flanking fold. The vein more to the left [2] only shows counter shearing offset of the marker. The layer
is not deflected near the vein. The two veins at the left of the photo [3] [4] show counter shearing offset along the veins with respect to the bulk shear. The quartzitic layer shows a reverse drag with respect to the displacement along the vein. Therefore, these structures were interpreted as being Reverse A-type flanking folds. Note that the offset along the vein that is occupied on the left of the photo [4] is larger than the offset along the other veins. The marker becomes very thin towards the vein. The tips of the veins are not exposed and due to the lack of more markers, it was impossible to infer how the structures were developed along each individual vein.

Figure 2.6: Different flanking folds inside a marble against straight quartz veins, Lower Gemsbok Formation, Namibia. 1: Co-shearing vein with contractional offset. Drag of the quartzitic marker layer is normal (Normal S-type flanking fold). 2: Counter shearing vein. Offset along the vein (no development of flanking fold). 3: Counter shearing vein with reverse drag of the quartzitic layer (Reverse A-type flanking fold). 4: Counter shearing vein with reverse drag of the quartzitic layer (Reverse A-type flanking fold).

Figure 2.7 shows an example of an N-type flanking fold inside the marbles of the Lower Gemsbok Formation. The quartzitic layer [1] shows an anticlinal fold in the hanging wall together with a synclinal fold in the footwall. No displacement of this marker was found along the vein. Note that the vergence of the quartzitic layer above [2] is opposite to the vergence of the folds at [1]. It is possible that this is an effect that occurs around the tip of CE. The upper part of the vein decreases in thickness, which might indicate that the tip of the vein is near, but because the tips are not exposed, the dimensions of the vein are unknown. Note also that the deflection at [2] is larger at the hanging wall than it is at the footwall.
Inside the marbles of the Lower Gemsbok Formation, N-type as well as Reverse A- and Normal S-type flanking folds occur in the same volume of rock and even next to each other. Between these different flanking structures, no difference in orientation or composition of the CE was found.

2.2.3 Upper Gemsbok Formation.

Flanking structures were also studied in the Upper Gemsbok Formation. This formation contains a blue/white/grey banded marble. These beds provide good markers to study flanking structures. The CE’s in these marbles are thin faults that sometimes branch into each other or start running parallel to the beds at their ends. The orientation of the faults with respect to the HE has always been found to be between 10 and 45°. Not all faults show development of flanking structures, but they all show dextral displacement of the marble beds. The bulk shear in the marbles is sinistral.

An example of flanking structures inside these marbles is given in figure 2.8. All faults show counter shearing offset of the marble beds with respect to the bulk shear. Only the lower tips of the faults are exposed. In the hanging walls, anticlinal fold trains are present were in the footwalls synclinal fold trains occur. Note that the amount of displacement as well as the deflection of the marble beds against the fault decreases towards the lower tips and that the deflection continues beyond the tip [1]. Also, note that the deflection beyond the tip is of opposite sense than the folds in the fold trains, away from the tip. The deflection as well as the displacement increases away from the tips [2] but we cannot tell if this is at the centre of the CE, because the upper tips of the CE are not exposed and therefore the dimensions of the veins are unknown. These structures were interpreted as being Reverse A-Type flanking folds.
Another example of Reverse A-type flanking folds is given in figure 2.9. The marble contains thin quartzitic beds that, together with the blue, grey and white metamorphic limestone beds, are good markers. The thin faults that crosscut the marble are all counter shearing with respect to the bulk shear. Against most faults, flanking folds develop. All hanging walls show anticlinal fold trains that are dextrally displaced with respect to the synclinal fold trains that are formed in the footwalls. Note that some folds show thickening of the beds inside the fold hinges [1] and that the tightness of folding varies. Most intense folding occurs largely around the centre of the faults [1] and dies out towards the tips. The deflection does not continue beyond the tips of the CE [2]. Also, note the opposite vergence of the HE at the tip of a fault [2], with respect to the folding of the fold trains at the centre of the CE. The grade of deflection of the hanging wall with respect to the footwall sometimes varies. At some sites, deflection is less pronounced [3] and at other sites, deflection is more pronounced [1].
The Reverse A-type flanking folds of the Upper Gemsbok Formation are the only flanking structures that were found in the discussed volume of rock. In all cases, the deflection did not continue beyond the tip of the fault. Open as well as tight folding occurs along the faults. No relationship between the tightness of folding and orientation of the fault with respect of the HE was found. Some of the folds show thickening of the HE at the fold hinges. The grade of deflection between the hanging and the footwall sometimes differs.

2.2.4 Gemsbok Formation, more to the North, near the Phanerozoic cover.

A very different type of flanking structure was studied in the Gemsbok formation, more to the North, near the Phanerozoic cover (mainly basalts of the Cretaceous Etendeka Group). The flanking structures occur in marbles that show an alteration of thin quartzitic beds and thin marble beds. The foliation developed parallel to the layering. The beds show isoclinal folding with axial planes parallel to the foliation. The marble contains quartz veins with a thickness of a few mm, which run almost parallel to the foliation and the layering. The veins are boudinaged in the direction of the foliation. No development of flanking structures along these veins was observed. Another set of quartz veins run through the marble. These make an angle with the foliation of 60° and are just a few mm thick. Along these veins, flanking structures were observed. The bedding as well as the boudinaged veins are deflected, indicating that the flanking structures are the youngest structure in the rock. The bulk shear of the rock was interpreted as being sinistral, based on the asymmetry of sigma-clasts found throughout the whole area.

An example of these flanking structures is given in figure 2.10. The example shows two veins. Near the tip of the left vein we see an anticlinal fold train in the hanging wall, together with a synclinal fold train in the footwall. The folding goes on beyond the tip of the vein and
continues inside the wall rock [2]. Away from the tip, the vergence of deflection of both the hanging wall and the footwall is of opposite sense. Along the vein to the right, we see the same structure: at the tip of the CE, we see development of anticlinal fold trains in the hanging wall and synclinal fold train in the footwall. Folding continues beyond the tip and dies out inside the wall rock [1]. Displacement along CE is dextral and maximal in the centre [3]. The displacement decreases towards the tips of the CE. Note that the deflection at the centre of the vein (were displacement is maximal) is of reverse drag with respect to the dextral shear movement along the vein [3] and that the deflection gradually goes into normal drag near the tips of the vein [4]. Also, note the fold train at [2]. The deflection goes on beyond the tip of the left vein and interferes with the deflection of the right vein, to form fold trains of anti- and synclinal folds.

Another example of this structure is given in figure 2.11. Both veins show dextral displacement of the marker beds, and displacement along the veins is maximal in the centre of the vein [3]. The displacement decreases towards the tips of the CE. The deflection at the tips is of normal drag with respect to the dextral displacement along the vein [2] and deflection goes on beyond the tips to die out inside the wall rock [1]. The deflection around the centre of the veins shows reverse drag [3]. Note the quartz vein [4] that makes a small angle with the beds and that is deflected against the CE.
Figure 2.11: Flanking structure against quartz veins inside the marbles of the Gemsbok Formation, Namibia. 1: Folding continues beyond the tip of the veins and dies out inside the wall rock. 2: Displacement along the vein gets less towards the tip and the deflection shows normal drag with respect to the dextral displacement. 3: Maximum displacement of the HE is occupied at the centre of the vein. Deflection is of reverse drag with respect to the dextral shear along the vein. 4: Deflection of a quartz vein.

All flanking structures in this volume of rock show counter-rotation veins in the sinistral bulk shear. All veins show dextral displacement (counter-shearing) and make large angles with the foliation (60°). The veins sometimes show jogs that are formed due to compression of the vein. Around these jogs, a disturbance of the deflection was recognized which means that the jogs must have formed during rotation of the vein. An example of such a jog is given in figure 2.12. Exposed here is a lower part of a flanking structure, probably near the lower tip of the vein. Again, the vein shows dextral displacement [1]. From the opening of the jog, we can conclude that the vein is shortened and that this strain is compensated with dextral movement along the vein. Note the deflection below the jog, where the fold trains consist of both an anticlinal and a synclinal fold with the fold planes parallel to the vein. The deflection disturbance dies out away from the jog.
Figure 2.12: Jog forming inside the veins along which flanking structure occurs inside the marbles of the Gemsbok Formation, Namibia. Exposed here is the lower part of the structure, almost near the tip of the vein. 1: Dextral displacement along the CE with normal drag of the HE. 2: Deflection due to the presence of the jog, creating a fold train of anti- and synclinal folds. The deflection dies out away from the jog.

The question that arises is how these structures fit in the classification of figure 1.2. The veins are counter shearing (suggesting A-type) but there position inside the foliation is highly unfavorable for sinistral shear. In this position, they would fit inside the classification of shear bands (see figure 1.2), but with compressional offset (counter-shearing) instead of the extensional offset (co-shearing). Another possibility is that the bulk shear is not sinistral any more during the formation of these flanking structures. The flanking folds are the youngest structures found in these rocks and therefore postdate the asymmetrical sigma-clasts, indicating sinistral shear. The youngest tectonic event in this geological setting was found to be of sinistral transpression resulting in the D3 folding phase (Passchier et al, 2003). If the rock has experienced some later stage dextral shear in which these flanking structures developed, then the orientation of the veins better fits into a history that is more acceptable and we deal with a third tectonic event, that has not been described yet, post dating the second tectonic event. The vein would be co-shearing and co-rotating, forming a Reverse S-type flanking fold. However, no evidence was found inside the rocks for an overprint of sinistral shear sense indicators with younger dextral indicators and throughout the whole area, no evidence was found for a third tectonic event, post dating the second tectonic event.

2.3 What does it help us to know more about flanking structures?

Above, an overview was presented of observations on flanking structures in the Ugab and Goantagab Valley, Namibia. Previous work on flanking structures helped in the interpretation of the geometry and kinematics of these structures. For some structures, the sense of shear could be established by comparing the geometry of the natural flanking structure with the geometries derived from the numerical modeling of Grasemann et al. (2003) (figure 1.2). This mostly resulted in sinistral non-coaxial flow for the rocks in the Ugab and Goantagab Valley. The presence of flanking structures against veins or faults indicates that there must have been
a transition between a brittle phase (in which the vein or fault developed) and a ductile phase (in which the vein rotated and the flanking structure developed). However, in spite of the knowledge derived from previous studies, several questions remained open in the interpretation of the geometry and kinematics of the natural flanking structures in the Ugab and Goantagab Valley. These have already been introduced in chapter 1.3, but the precise reasons for posing these questions will be summarized below.

In the mica schist of the Aims River Formation NE of the contact with the Doros Pluton, I found N-type flanking folds only against veins that contain alteration rims. I found flanking folds developed against sinistrally as well as dextrally rotated veins in the same volume of rock. The folds against the sinistrally rotated veins show extension in the fold hinges (parallel to the axial planes). The folds against the dextrally rotated veins do not show this extension. Difference between the timing of the formation of both sets of veins might be a reason for the different orientations of the veins. However, no crosscutting relationships were found between the formation of the dextrally and the sinistrally rotated veins. If the veins formed at the same time, the following question comes up: What processes are responsible for folds against sinistrally rotated veins (with extension in the fold hinges) next to folds against dextrally rotated veins (without extension in the fold hinges)?

Inside the marbles of the Lower Gemsbok Formation, I found Reverse A-type, Normal S-type and N-type flanking folds next to each other. N-type flanking folds are produced if the viscosity of the CE is higher than that of the HE. A- and S-types are produced when the viscosity of the CE is lower than that of the HE (Grasemann and Stüwe, 2001). No difference in timing between the formations of the veins was found. The veins in these marbles all consist of the same rheology and all veins are in the same orientation. What mechanism can produce three types of flanking structures (under the same rheological conditions with respect to the CE and the HE) in the same volume of rock?

In the marbles of the Upper Gemsbok Formation, I found Reverse A-type flanking folds. These flanking folds showed small differences that could not be explained from the field data. Independent of the finite orientation of the CE with respect to the HE, I found open as well as isoclinal folds developed along the CE. Some of these folds showed thickening of the HE at the fold hinges and the grade of deflection between the hanging wall and the footwall sometimes differed. How are the differences in the interlimb angles of the folds, thickening of the HE at the fold hinges and grade of deflection inside Reverse A-type flanking folds generated?

In the Gemsbok Formation, a flanking structure was found that does not fit inside the classification proposed by Grasemann et al. (2003) (figure 1.2). Either, the structure is a shear band with compressional offset (counter-shearing) inside a sinistral bulk shear, or the structure formed during a younger phase of dextral shear. This structure has never been described before and it does not fit inside the classification of figure 1.1 and 1.2. Is the classification of figure 1.1 and 1.2 sufficient to characterize all natural flanking structures? Analogue experiments were carried out in an attempt to answer the above questions.


3.1 Apparatus.

The apparatus used for the analog experiments consists of the four-sided deformation box (figure 3.1) described by Piazolo et al. (2001). The walls of the deformation box are made of small Plexiglas segments, which connect to each other with flexible plastic in order to construct walls of wrinkled pistons. Each second Plexiglas segment is at its outer part connected to two metal springs with the help of some tape. This construction is responsible for homogeneous contraction and extension of the walls. The corners of the springs are
connected to four aluminum plates (indicated in figure 3.1 with P). Each plate is attached to a
sliding carriage (C1). These carriages are arranged two by two and attached on two PVC
boards (B1). The walls of the box parallel to the PVC boards are parallel to the x-direction.
Therefore, these carriages control the movement in the x-direction. The PVC boards connect
to four other sliding carriages (C2) which are orientated perpendicular to the PVC boards and
are responsible for the movement in the y-direction. These four carriages connect to a wooden
basal plate (B2). The maximum extension of the walls parallel to the x-direction is
approximately 35 cm and of the walls parallel to the y-direction, approximately 25 cm. Six
different motors (M) charge the deformation inside the box. Four of these motors drive the
corners of the box in the x-direction via shafts and connect to the PVC boards (M1, M2, M3,
and M4). Two motors, attached to the basal plate, are responsible for the movement in the y-
direction (M5 and M6). In Piazolo et al. (2001), the bottom of the box was made of a 0.35
mm thick sheet of elastic latex. This sheet, attached to the four aluminum plates, served to
reduce the friction of the box and the matrix material with the basal plate. However, during
deformation the sheet got folded or came loose and therefore had influence on the
homogeneity of the deformation. In addition, reparation of the connection of the sheet was
necessary after each experiment, which was very time consuming. To solve these problems, I
built a Plexiglas plate with small upstanding edges, so that it was possible to fill the plate with
a fluid acting as a thin film underneath the material used in the deformation box. In this way,
the friction of the material and the basal plate was very low. The top of the box is open.
The PC-program LabView controls the six motors. This program was set up such that 5
different regimes of transpression are defined (figure 3.2), in which the movement of each
motor is calculated for each time step depending on the current dimensions of the deformation
box and using dextral shear along the x-direction. For each of the five regimes of
transpression, the user can define different parameters as kinematic vorticity number, strain
rate along a specific axis and duration of the experiment. During the experiments, I only used
the transpression programs A (simple shear) and D (Plane strain; No extension along the Z-
axis). The maximum shear strain that is possible to reach with the apparatus is in the order of
two and depends strongly on the initial geometry of the box. A digital camera, placed above
the deformation box with help of a tripod, captured images during the experiments. Figure 3.3
indicates the general setup of the apparatus. The construction of the box is such that the centre
of the box remains in one place during deformation and thus that objects of interest inside the
deforming material do not move with respect of the camera.
A large area of the deformation box deforms homogeneously, except for the edges of the
defformation box. The width of the zone that deforms inhomogeneous is independent of the
kinematic vorticity number and strain rate but depends on the viscosity of the matrix material
(Piazolo et al., 2001). Therefore, the zone of inhomogeneous deformation needs to be
established for each material before experiments are carried out.
Figure 3.1: A. Schematic drawing of deformation apparatus (view from the top) where x and y are along symmetric axes of apparatus. B1 are PVC boards, B2 is base plate, C1 is set of 4 sliding carriages parallel to x-direction, C2 is a set of 4 sliding carriages parallel to the y-direction, P is connecting aluminum plates, and M1-M6 are motors. B. Close up of deformation box with flexible walls (view from top). Angle $\psi$ is angle between sides of deformation box. (Piazolo et al., 2001)

Figure 3.2: Schematic illustration of the 5 different types of transpressional regimes for which LabView programs exist. (Piazolo et al., 2001)
3.2 Materials.

The matrix material used in the deformation box is polydimethyl-siloxane (PDMS, trade name SMG 36) which is a polymer manufactured by Dow Corning, Great Brittan. It is a transparent polymer with a density of 0.965 g/cm$^3$ and a viscosity (at room temperature) of $5.0\times10^4$ Pa s. The material shows Newtonian viscous flow behavior for strain rates $<5\times10^4$ s$^{-1}$ (Weijermars, 1986). The strength of the motors of the deformation box and leakage problems at the bottom limits the choice of matrix materials to ones with a viscosity between $10^3$ and $10^6$ Pa s (Piazolo et al., 2001). PDMS has a viscosity that fits within this range and earlier experiments with PDMS in the deformation box revealed the advantages of the use of PDMS above other polymers, like its transparency and non-toxicity. In addition, PDMS is relatively cheap.

In order to reduce the friction of the PDMS with the basal plate of the deformation box, I used a tin layer of glycerin acting as a lubricant. The glycerin has a lower viscosity ($1.55\times10^2$ Pa s) and a higher density (1.17 g/cm$^3$) than the PDMS and does not react with PDMS. Therefore, it is a good lubricant for these experiments.

During the experiments, materials with different rheological properties were used to represent the cross cutting element. I used pieces of carton with a thickness of 1mm, which represent a rigid CE that cannot be deformed. I also used small pieces of transparent overhead-projector paper, which are much thinner than the carton. Silicone gel (which has trade name 200/12.500 CS Fluid, manufactured by Dow Corning, Great Brittan) was used to represent a CE along which slip could occur. At room temperature, the silicone fluid has a viscosity of $1.25\times10^4$ Pa s, which is about 40 times lower than that of the PDMS. I also used soap (LUX kitchen soap), which has a much lower viscosity than the silicone fluid. Furthermore, combinations of pieces of transparent overhead-projector paper and silicone gel were used, like silicone gel with a piece of transparent overhead-projector paper in between and two pieces of transparent overhead-projector paper at the edges of the PDMS with silicone gel in between. These combinations represent a CE in which there is still fluid or melt available for slip but also some crystalline material, in the centre of the CE or at the rims, which is very hard to deform with respect to the HE (for example chilled margins). I also used a mixture of PDMS and a filler material (33.3 wt% BaSO$_4$). An increase in BaSO$_4$ means an increase of the viscosity. PDMS + 33.3 wt% BaSO$_4$ behaves linear viscoelastic (rheological properties are not influenced by finite strain) with a dominant elastic component (ten Grotenhuis et al., 2002). In addition, mixtures of Rhodorsil Gomme (pinkish opaque bouncing putty; trade name: Silbione Gomme 70009, Société des Chemiques Rhône-Poulenc (France)) + 32 wt% Plastilina and
Rhodorsil Gomme + 25 wt% Plastilina were used. These mixtures are nonlinear viscoelastic (rheological properties are not constant with finite shear, hence a function of deformation history). These mixtures were used to represent a deformable CE with higher viscosities than the HE.

### 3.3 Experimental Procedure.

To start the experiments, the deformation box had to be set in the preferred initial orientation while still empty. After this, the basal plate was filled with a thin layer of glycerin. The deformation box was filled with PDMS. Large pieces of PDMS are preferred (if possible one piece, to fill the whole box) because many small pieces will result in air bubbles that are trapped inside the PDMS. After filling the box, the PDMS had to settle two or three hours to distribute itself throughout the box, to let air bubbles rise out of the PDMS and to get a flat surface. A cut of about 3 to 4 cm was made in the centre of the box and the material that forms the CE (the carton, the glycerin, etc) was put inside. Now the PDMS had to settle for one to two more hours, until the surface was smooth again. A grid was made by using a copy-machine without the heating element, leaving the ink powder loose on the paper surface. By putting the paper on the surface of the PDMS, the ink came off the paper and stack onto the PDMS. The grid was build up by squares of 0.5cm by 0.5cm. After this, the PDMS had to settle again for about one hour before the experiment could get started.

Experiments in program A of LabView (simple shear) always had initial box dimensions of X and Y between 210 and 211 mm and between 177 and 183 mm, respectively. The displacement of M1, M2, and M3 was always set at 150 mm with a velocity of 0.02 mm/s. Each experiment took 7500 second. At the end of each experiment the shear strain (γ) and the shear strain rate (φ) were calculated between 1.60 and 1.65 and between 2.12*10⁻⁴ s⁻¹ and 2.20*10⁻⁴ s⁻¹ respectively.

For the experiments in program D of LabView (plane strain), the initial box dimensions were set at X between 172 and 173 mm and Y between 258 and 261 mm. The shortening rate was set at 0.04/sec., the vorticity (Wk) at 0.7 and the end value of x at 250 mm. Each experiment took 9200 seconds. The calculated γ and φ at the end of each experiment varied between 0.595 and 0.615 and between 6.46*10⁻⁵ s⁻¹ and 6.68*10⁻⁵ s⁻¹ respectively.

All experiments were carried out at room temperature. A digital camera that was hanging above the centre of the deformation box (with the help of a tripod) captured images during the experiments. Light for the camera was given from underneath the box, through the transparent basal plate and the PDMS. Images were captured every 300 seconds and saved as high-resolution JPEG files in Photoshop. These images were converted to TIF files that were laid on top of each other with the help of the program Canvas. From this, a Canvas movie was made which was than converted into a QuickTime movie. After the experiment, the top of the PDMS (with the grid on it) was removed from the deformation box and a little bit of new PDMS was put in for new experiments. After a few experiments, the PDMS got dirty and had to be removed completely. The whole box was cleaned and the tapes that are responsible for the connection between the metal springs and the plastic segments of the deformation box were checked. The PDMS slowly dissolves the glue of the tapes. These have to be repaired, because this has influence on the homogeneity of the deformation.

### 3.4 Analysis Procedure.

The flanking structures that were produced with help of the deformation box were described following the classification of figure 1.1 and 1.2. Every characteristic element of each different flanking structure during its formation needs to be qualified in order to be able to
recognize these structures in the field. It is necessary to look at the behavior of the marker lines not only at the final state, but also during the deformation in order to understand the processes that are responsible for the formation of the final state of a flanking structure. To learn more about the geometrical characteristics, I looked at the heterogeneity of the deformation grid in such a way that the deflection around each structure was subtracted from the deformation incase there was no CE present. I also looked at the flow patterns of the flanking structures that were made in the deformation box, in order to find out if different structures have different flow patterns. Can we find systematics in these flow patterns in such a way that we can derive the type of flow from flanking structures that are analyzed in the field? These patterns might change during deformation due to the rotation of the CE. Therefore, flow patterns were made for a few incremental deformation steps of each experiment. Details of the analyzing techniques that were used to derive the heterogeneity patterns and the flow patterns of the experiments are given below.

3.4.1 Heterogeneity patterns.
In order to get the heterogeneity patterns from the images of an experiment, I distracted the grid that should have formed at the same conditions incase no CE was added to the HE. This was done by overlaying an image from the experiment with a grid that represents the deformation at the same \( \gamma \), without a CE. With help of illustrator, a grid of equal squares was made. This overlay-grid was sheared until the squares of the grid fit onto the squares of the experimental-grid, away from the CE. The grid away from the CE is not affected by the CE and therefore deforms close to homogeneous. Each grid point of the overlay-grid was then connected to its corresponding grid point from the image by arrows. An example of the overlay-grid and the arrows that connect the grid points is given in figure 3.4. The arrows indicate the position of the grid point with respect to its position if no CE was added to the experiment (homogeneous deformation). The pattern that is created indicates the directions and magnitudes of heterogeneity of each grid point. Note that these patterns are no flow patterns.

Figure 3.4: Example of the overlay-grid on top of the image that was used to construct the heterogeneity patterns of the experiments. The arrows indicate the position of the grid point with respect to its position if no CE was added to the experiment (homogeneous deformation).
3.4.2 Flow patterns.

Flow patterns of incremental deformation steps of an experiment were made with help of the program PivSleuth (free software at http://ltcf.tam.uiuc.edu/downloads.html). This program is a Particle Image Velocimetry measurement tool. It relies on the image of tracer particles embedded within a flow of two distinct times and is capable of recognizing pixel group’s trough time. The image field of $t_1$ is divided into small sub domains referred to as interrogation spots. These sub domains can be recognized on the image field of $t_2$ if the displacement between these two domains is not too large (i.e. if the deformation step is small). The result is the velocity of the interrogation spot as a function of the average displacement of the particles inside the interrogation spot Christensen et al. (2001).

Two consecutive images of an experiment were opened in PIVSleuth. A configuration file (necessary for the dimensions and manner of correlation) was created for a first stage, coarse interrogation. The settings of this coarse configuration file are given in appendix 2. A Two Frame Cross Correlation with FFT (Fast Fourier Transform) size 64x64 was applied on these two images. The result of the Two Frame Cross Correlation is a field of first order vectors (vectors of first choice). Vectors with orientations that deviated from the general trend were manually removed or replaced by second or third order vectors, provided by the program itself. After this correction, the file was validated. A new configuration file was made for the second, fine phase of interrogation. The settings of the fine configuration file are given in appendix 2. A Two Frame Cross Correlation with FFT (Fast Fourier Transform) size 16x16 was applied on the images with the validated file used as reference in the iterative interrogation of this section. Again, corrections for vectors with orientations that deviated from the general trend were applied and the file was validated. With help of the program File Format Converter (free software that can be downloaded from http://ltcf.tam.uiuc.edu/downloads.html), the .v2f- file (validated file) was converted into a .txt file. This text file contains four columns. The first two are the x and y-coordinates of the starting points of the vectors and the last two represent the direction and size of the vectors from the starting point. Because of the very small deformation step between the images, the vectors are very small and therefore I multiplied them to enhance the size of the vectors. This was done in Microsoft Excel by multiplying the last two columns of the text file with a factor 10. The file was than converted to its original layout by replacing characters in Microsoft Word. In order to get an image out of this text file, I used the program PIV2PS (a MS-DOS executable code, making postscript files out of text files, made by Jessell, M.). This postscript file was than opened in Adobe Illustrator to create an image of the vector field.

4. Results.

4.1 Movies from the experiments and their geometries.

The movies that resulted from the images of the experiments are presented on the CD that is attached to this report (Attachment 1). On this CD, a subdivision was made between the experiments in simple shear ($W_k = 1.0$) and experiments in general shear ($W_k = 0.7$). The finite structures of the experiments are classified following the classification of figure 1.1 and 1.2. The numbers behind this classification represent the initial starting orientation of the CE with respect to the shear zone boundaries. The angle between the CE and the shear zone boundaries ($\alpha$) is defined as illustrated in figure 4.1. Each movie has the name of the material that was used for the CE.
4.1.1 $W_k = 1.0 / \text{No CE}$

The experiment that was carried out in simple shear without a CE shows that the PDMS in the centre of the box deforms homogeneous $Attachment 1/W_k = 1.0/\text{No CE}$. Towards the edges of the box, the deformation becomes more and more inhomogeneous.

4.1.2 $W_k = 1.0 / \text{CE (no slip)}$

Experiments that contained a piece of carton in the centre of the deformation box (representing a rigid CE that cannot be deformed) were carried out under different initial starting orientations of the CE with respect to the shear zone boundaries.

**N165/Carton:**

$Attachment 1/W_k = 1.0/\text{CE (No slip)/N165/carton}$ shows that deflection of the HE against the CE increases during rotation of the CE. At the tips of the CE, the squares of the grid are being compressed, resulting in a buckling structure of the HE around the CE. The deflection goes on beyond the tips of the carton and gradually dies out away from the tips. The centre of the CE shows elongated squares indicating extension at the centre of the CE. Note that the axial planes of the folds are not parallel to the CE. Because of the low initial angle of the CE with respect to the shear zone, there are just a few markers deflecting against the CE and therefore, it is hard to tell were most intense folding occurs. Also, note that for left side of the CE as well as for the right side, the vergence of folding at the upper tip of the CE is of opposite sense than the folding at the lower tip.

**N135/Carton:**

$Attachment 1/W_k = 1.0/\text{CE (No slip)/N135/carton}$ shows the same characteristics as N165/carton until 3300 sec, but the folding is less pronounced. At 3300 sec., the carton has a position of 90° with respect to the shear zone boundaries. The markers above and below the CE, start to show a necking structure. Along the left side of the CE (hanging wall), an anticlinal fold train was created. Along the right side of the CE (footwall), a synclinal fold train was created. Folding dies out beyond the tips of the CE. Note that the marker at the lower tip of the CE of the hanging wall shows different vergence of folding compared to the fold trains along the CE and that the marker above shows most intense folding. The marker at the upper tip of the footwall shows different vergence of folding than the fold trains along the CE and the marker below shows most intense folding at the footwall. The axial planes of the fold trains are parallel to the CE.

**N90/Carton:**

$Attachment 1/W_k = 1.0/\text{CE (No slip)/N90/carton}$ shows necking structures of the HE around the CE. In the hanging wall, anticlinal fold trains were developed. Most intense folding occurs at the upper tip of the CE. Note that the markers at the lower tip of the
CE of the hanging wall show opposite vergence of folding with respect to the fold trains. The footwall shows syncline fold trains with most intense folding at the lower tip of the CE. Note that the markers at the upper tip of the CE of the footwall show opposite sense of folding with respect to the fold train. The axial planes of the fold trains are parallel to the CE. Note the extension of the squares at the upper tip of the hanging wall and the lower tip of the footwall. Due to this extension, marker lines are thickened in the fold hinges of the fold trains.

In order to examine the effect of the thickness of the CE, one experiment was done with a piece of overhead-projector transparency paper that also should act as a rigid CE along which no slip can occur. This experiment was carried out under an initial orientation of $\alpha = 90^\circ$. The experiment Attachment 1/Wk = 1.0/CE (No slip)/N90/overhead paper showed exactly the same structure and characteristics as shown by the N90/carton experiment. Because the thickness of the CE did not influence the development of the flanking fold, further experiments were not carried out with the transparent overhead-projector paper.

**N45/Carton:**

Attachment 1/Wk = 1.0/CE (No slip)/N45/carton shows the same characteristics as N90/carton. Note that the extension is larger and that the thickening of the marker lines in the fold hinges is bigger. Also, note that the folds of the fold trains are more isoclinal.

The same series of experiments was carried out with a CE that was deformable, but at which no slip along the CE was possible (a higher viscosity than the PDMS). I used mixtures of PDMS+33.3wt% BaSO$_4$, Rhodorsil Gomme + 38 wt% Plastilina and Rhodorsil Gomme + 25 wt% Plastilina respectively. These experiments were carried out under an initial angle of $\alpha = 135^\circ$. With the experiments of PDMS+33.3wt% BaSO$_4$ and Rhodorsil Gomme + 38 wt% Plastilina (given in Attachment 1/Wk = 1.0/CE (No slip)/N135/PDMS+33.3wt% BaSO$_4$ and Attachment 1/Wk = 1.0/CE (No slip)/N135/Rho + 38% Pla respectively) I had major technical problems. These CE's were heavier than the PDMS and sank down during rotation, dragging marker lines down along the CE and thereby affecting the finite structures in the normal plane of view. With the experiment of Rhodorsil Gomme + 25 wt% Plastilina the sinking problem was smaller and therefore this combination was used for further experiments.

**N165/Rho+25%Pla:**

Attachment 1/Wk = 1.0/CE (No slip)/N165/Rho + 25% Pla shows a buckling structure of the markers around the CE. Although folding is less pronounced than in experiment N165/carton, the characteristics are close to identical. For the left side of the CE as well as for the right side, the vergence of folding at the upper tip of the CE is of opposite sense than the folding at the lower tip. The axial planes of the folds are not parallel to the CE. The difference is that there is minor compression of the squares at the tips of the CE in this experiment and the squares in the centre of the CE are hardly extended (as in N165/carton). The CE is shortened and a little bit thickened due to compression of the CE. Note that the rotation of the CE is less than the rotation of N165/carton.

**N135/Rho+25%Pla:**

Attachment 1/Wk = 1.0/CE (No slip)/N135/Rho + 25% Pla shows the same characteristics as N135/Carton: the development of the buckling structure at an orientation of $\alpha > 90^\circ$ and the development of the necking structure at an orientation of $\alpha < 90^\circ$. The only difference is that the folding is less pronounced in this experiment.
and that the CE is deformed. The CE was shortened during the development of the buckling structures (>90°). During the development of the necking structures, the CE showed minor extension. In addition, the CE sank into the PDMS during the phase at which necking structures develop but this effect had only minor influence on the geometry of the markers.

**N90/Rho+25%Pla:**

Attachment 1/Wk = 1.0/CE (No slip)/N90/Rho + 25% Pla shows the same characteristics as experiment N90/carton, with a necking structure of the marker lines around the CE. The hanging wall develops anticlinal fold trains with most intense folding at the upper tip of the CE. The markers at the lower tip of the CE of the hanging wall show opposite vergence of folding with respect to the fold trains. The footwall shows synclinal fold trains with most intense folding at the lower tip of the CE. The markers at the upper tip of the CE of the footwall show opposite sense of folding with respect to the fold train. The axial planes of the fold trains are parallel to the CE. Extension occurs at the upper tip of the hanging wall and the lower tip of the footwall resulting in thickening of the marker lines in the fold hinges. This extension is largest there where most intense folding occurs. Note that the folding is less pronounced with respect to experiment N90/carton and that the extension resulting in thickening of the marker lines is much less. Also, note that the CE was extended and thinned during its rotation and that the CE sank into the PDMS dragging the marker lines down along the CE. Due to the sinking, marker lines seem to be displaced on the movie (in the normal plane of view), but this is not the case.

**N45/Rho+25%Pla:**

Attachment 1/Wk = 1.0/CE (No slip)/N45/Rho + 25% Pla shows a completely different finite structure than the experiment N45/carton. Still, it contains the same characteristics with respect to the necking structure of the HE and the opposite vergence of folding at the tips of the CE. Note that the folding is much less pronounced and that the extension at the fold hinges and thereby the thickening of the marker lines is very small with respect to N45/carton. Also, note the extension and thinning of the CE during the rotation. Again, the CE sank into the PDMS, dragging markers down along the CE and thereby suggesting displacement of the markers along the CE.

4.1.3 Wk=1.0 / CE (slip)

For the experiments at which slip could take place along the CE, different materials were used. A cut was made in the PDMS under an initial orientation of 90° and this cut was filled with kitchen soap, silicone gel, a piece of overhead sheet surrounded with silicone gel and two pieces of overhead sheet with silicone gel in between were used.

**A90/soap:**

Attachment 1/Wk = 1.0/CE (Slip)/Reverse A90/soap shows that the slip along the CE is of sinistral sense (counter-shearing CE). Displacement is large and folding is very weak. The hanging wall (left of the CE) shows limited development of antiforms and the footwall shows limited development of synforms. At the upper tip of the CE, we see an up stepping marker and at the bottom of the CE, we see a down stepping marker. Note the propagation of the CE during rotation, resulting in lengthening of the CE. Because flanking of the HE is just poorly developed, no further experiments were carried out with the soap.
**A90/silicone gel:**
The gel has a higher viscosity than the soap, but a lower viscosity than the PDMS. The experiment Attachment 1/Wk = 1.0/CE (Slip)/Reverse A90/silicone gel shows that again the displacement is counter-shearing. The offset along the CE is less than with the soap and folding is a little bit more pronounced. The hanging wall shows an anticlinal fold train and the footwall a synclinal fold train, resulting in reverse drag of the HE against the CE (Reverse A-type flanking fold). The folding as well as the displacement is largest in the centre of the CE and they decrease towards the tips of the CE. The hanging wall and the footwall show markers at both tips of the CE that have an opposite vergence with respect to the fold trains. The opposite vergence propagates into the up stepping marker at the upper tip of the CE and a down stepping marker at the lower tip of the CE. Note the propagation of the CE during rotation. If we look in detail at the movie, we see that displacement along the CE is counter-shearing until 4800 sec. The displacement gradually changes into co-shearing displacement. During this transition zone, no displacement takes place until 5700 sec. After this, the displacement is co-shearing, but the finite structure of the flanking fold (following the classification) is still a Reverse A-type.

**A90/overhead+silicone gel:**
In order to create more pronounced folding than in experiment A90/silicone gel, I did the same experiment as A90/silicone gel, but with a peace of transparent overhead-projector paper, surrounded with silicone gel. I made sure that there was no contact of the PDMS with the transparent overhead-projector paper. This experiment Attachment 1/Wk = 1.0/CE (Slip)/Reverse A90/overhead + silicone gel showed exactly the same characteristics, including the transition of counter-shearing into co-shearing CE, as the experiment A90/silicone gel. The only difference is that folding is a little bit more pronounced. Because of this, further experiments were done with a CE of transparent overhead-projector paper and silicone gel. If we look in detail at the development of the fold hinges in the experiment, we can see that the markers in the hinges are thickened during the co-shearing phase of the CE (at the end of the experiment).

**A135/overhead+silicone gel:**
Attachment 1/Wk = 1.0/CE (Slip)/Reverse A135/overhead + silicone gel also shows counter-shear along CE with anticline fold trains at the hanging wall and syncline fold trains at the footwall, resulting in reverse drag of the markers. Maximum displacement and most intense folding occurred in the centre of the CE and both get less towards the tips of the CE. Markers at the tips of the CE (for both the hanging and the footwall) show opposite vergence with respect to the fold trains. Beyond the upper tip up stepping markers are developed and beyond the lower tip down stepping markers are developed. The experiment shows the same characteristics as Reverse A90/overhead + silicone gel, but the experiment does not show the co-shearing phase at the end of the experiment. In addition, folding is much more pronounced (as well as the up and down stepping markers beyond the tips) and the markers do not show any sign of thickening in the fold hinges.

**Reverse shear band165/overhead+silicone gel:**
Attachment 1/Wk = 1.0/CE (Slip)/Reverse shear band165/overhead + silicone gel shows completely different characteristics compared to A135/overhead+silicone gel. The CE is co-shearing and the drag of the markers is reverse with respect of the offset along the CE (Reverse shear band). The markers above the tip of the CE are concave, the markers below the tip of CE are convex, but no up or down stepping markers were
developed as did occur in the experiment *Reverse A135/overhead + silicone gel*. The axial planes of the fold trains are not parallel to the CE. Displacement and folding was largest for the central marker. Note that the markers away from the central marker show opposite sense of folding with respect to the central marker. Also, note that the CE hardly rotated during deformation.

In order to do experiments with CE’s that represent a vein in which the edges contain crystalline material and in the central part still fluid or melt (for example chilled margins), I made the CE of two pieces of transparent overhead-projector paper with some silicone gel between. The transparent overhead-projector papers connect to the PDMS and the PDMS is not in contact with the gel.

**A135/2x overhead + silicone gel:**

*Attachment 1/Wk = 1.0/CE (Slip)/Reverse A135/2x overhead + silicone gel* shows exactly the same characteristics as the experiment *Reverse A135/overhead + silicone gel*. No significant differences could be discovered except that the folding of the footwall is a little bit less pronounced.

**A90/2x overhead + silicone gel:**

*Attachment 1/Wk = 1.0/CE (Slip)/Reverse A90/2x overhead + silicone gel* shows exactly the same development as experiment *Reverse A90/overhead + silicone gel* until 2700sec, with up and down stepping markers and counter-shearing CE. However, after this slip did not take place any more and the structure acts as an N-type. The silicone between the transparent overhead-projector papers was pushed out and the papers touched each other, forming a rigid body. The characteristics of this experiment gradually change into the characteristics of the experiment *N90/carton*. The up and down stepping markers change into the markers that define the necking structure, the most intense folding changes from position (from the centre towards the tips of the CE) and the markers start to show thickening in the fold hinges as in experiment *N90/carton*. The finite structure is still a Reverse A-type flanking fold because of the displacement in the first part of the experiment.

**4.1.4 Wk=0.7/CE (no slip)**

In order to examine the development of flanking folds during general shear, experiments were done with a vorticity number Wk = 0.7. Only CE’s along which no slip could occur were used in general shear. To compare them with the experiments that were done in simple shear, I used the same materials for the CE in general shear (Carton and Rhodorsil Gomme + 25 wt% Plastilina). The movies are given in *attachment 1/Wk = 0.7/CE (No slip)* of Attachment 1 (CD).

**N165/Carton:**

*Attachment 1/Wk = 0.7/CE (No slip)/N165/carton* shows that under these conditions, the CE is counter rotating with respect of the dextral shear. At the upper tip of the CE, we see slightly up stepping markers and at the lower tip, we see slightly down stepping markers. Deflection of the HE is very poor in this experiment.

**N135/Carton:**

*Attachment 1/Wk = 0.7/CE (No slip)/N135/carton* shows shortening of the squares at both tips of the CE, resulting in a buckling structure of the HE around the CE. For the left as well as the right side of the CE (hanging and footwall), the vergence of
deflection at the upper tip is of opposite sense as at the lower tip. Note that the CE rotates just a few degrees. Also, note that the structure is similar to the structure of experiment \( Wk = 1.0/CE \) (No slip)/N165/carton.

**N90/Carton:**

*Attachment 1/Wk = 0.7/CE (No slip)/N90/carton* shows development of a buckling structure of the HE around the CE until 5100 sec. At this time, the CE has an orientation of 60°. After this, development of a necking structure can be seen. The finite structure contains an anticlinal fold train at the hanging wall, with most intense folding around the upper tip of the CE. The footwall contains a synclinial fold train with most intense folding at the lower tip of the CE. Note the opposite vergence of deflection at the lower tip of the CE for the hanging wall and the upper tip of the CE for the footwall. Also, note that there is no sign of thickening of the markers at the fold hinges.

**N45/Carton:**

*Attachment 1/Wk = 0.7/CE (No slip)/N45/carton* shows necking of the HE around the CE during the whole experiment. The hanging wall contains an anticlinal fold train with a marker of opposite vergence at the lower tip of CE. The footwall contains a syncline fold train with a marker of opposite vergence at the upper tip of the CE. Note that the folds are more isoclinal than as developed in experiment \( Wk = 0.7/CE \) (no slip)/N90/carton. Note also that the structure is similar to the experiment \( Wk = 1.0/CE \) (no slip)/N45/carton, except for the thickening of the markers at the fold hinges.

**N165/Rho+25% Pla:**

*Attachment 1/Wk = 0.7/CE (No slip)/N165/Rho + 25% Pla* the experiment hardly shows deflection. The rotation of the CE is counter-rotating with respect to the dextral shear. The hanging wall (right of the CE) shows slightly convex marker lines and the footwall slightly concave markers. The markers above and below the CE show minor development of a buckling structure. Note that the CE was boudinaged in the direction of the shear zone. The CE did not sink into the PDMS.

**N135/Rho+25% Pla:**

*Attachment 1/Wk = 0.7/CE (No slip)/N135/ Rho + 25% Pla* shows that the CE is co-rotating and that the HE around the CE develops a buckling structure with compression at both tips of the CE. The structure contains exactly the same characteristics as the experiment \( Wk = 0.7/CE \) (no slip)/N135/carton except that the deflection is less pronounced. Note that the CE was shortened during rotation.

**N90/Rho+25% Pla:**

*Attachment 1/Wk = 0.7/CE (No slip)/N90/ Rho + 25% Pla* shows the same characteristics as the experiment \( Wk = 0.7/CE \) (No slip)/N190/carton, but with less pronounced folds. Only, the transition between the buckling and the necking phase is not that clear. The development of buckling markers around the CE is poor. However, note that the CE was shortened during the first phase of the experiment (until the CE had an orientation of \(~60°\)) and that after this the CE was extended. During this extension, the necking structure of the HE around the CE was developed. In addition, during the phase of extension, the CE sank faster than during the phase of shortening, dragging markers down along the CE.
N45/Rho+25%Pla:

*Attachment 1/Wk = 0.7/CE (No slip)/N45/ Rho + 25% Pla* shows minor extension of the CE together with sinking of the CE. Due to the sinking of the CE, markers are dragged down along the CE. The characteristics seem to be the same as experiment *Wk = 0.7/CE (No slip)/N45/carton*, but the folding is much less pronounced and the folds are not that isoclinal.

An overview of the finite structures of the experiments is given in figure 4.2a and 4.2b, illustrating the most relevant characteristics. Figure 4.2a shows the experiments in simple shear. The experiments that where done with PDMS + BaSO₄, Rhodorsil Gomme + 38 wt% Plastilina, soap and silicone gel are not given in the figure, because these either resulted in unreliable results due to sinking of the CE or resulted in exactly the same structures as other experiments and no further experiments were carried out with these materials. Figure 4.2b shows the experiments in general shear.

From the experiments that were produces in this report, no finite structure fits into the classification of an S-type flanking structure (following the classification of figure 1.1 and 1.2). In addition, no Normal A-type flanking fold and no Normal shear band structure was created during the experiments.

During deformation, the CE rotates inside the shear zone. In order to test if, during deformation, the angular velocity of marker lines (that are parallel to the CE before deformation takes place) is the same as the angular velocity of the CE, I did following. For each experiment, five lines parallel to the CE were drawn on the first image (the initial situation) of the experiment with the position of these lines being random. The squares of the grid that were cut by these lines could be traced up to the last image of the experiments (the finite stage). The rotation of each line was calculated and the mean value of these five lines was compared with the amount of rotation of the CE. Figure 4.3 gives the results of the difference in rotation of the CE and marker lines that were initially parallel to the CE. Negative differences of rotation mean that the CE rotated less than the material lines. Due to inaccuracy in our measurements, differences smaller than 2.5 degrees should not be considered as relevant.

Large deviations in simple shear only occur for the experiments with a piece of overhead surrounded by silicone gel at 165° (Reverse shear band) and Rhodorsil + 25 wt% Plastilina at 165° (N165). Large deviations in general shear occur by both experiments with a CE at 135°. No systematics was found that could explain the large deviations and thereby the differences in the angular velocities. All other experiments show small deviations in angular velocities between the material lines and the CE’s.
<table>
<thead>
<tr>
<th>Start position</th>
<th>165°</th>
<th>135°</th>
<th>90°</th>
<th>45°</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 Overhead surrounded with silicone gel</td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
<tr>
<td>Overhead (2x) with silicone in between</td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
</tr>
<tr>
<td>Karton</td>
<td><img src="image9" alt="Diagram" /></td>
<td><img src="image10" alt="Diagram" /></td>
<td><img src="image11" alt="Diagram" /></td>
<td><img src="image12" alt="Diagram" /></td>
</tr>
<tr>
<td>Rhodorsil + 25 wt% Plastelina</td>
<td><img src="image13" alt="Diagram" /></td>
<td><img src="image14" alt="Diagram" /></td>
<td><img src="image15" alt="Diagram" /></td>
<td><img src="image16" alt="Diagram" /></td>
</tr>
</tbody>
</table>

Figure 4.2a: Overview of the finite flanking structures of the analogue experiments that were carried out in simple shear. The upper row represents the initial orientation of the CE relative to the shear zone boundaries. A cross means that no experiment was carried out under these conditions. Note that the structures do not propagate into each other and that they are finite structures.

<table>
<thead>
<tr>
<th>Start position</th>
<th>165</th>
<th>135</th>
<th>90</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7 Karton</td>
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<td><img src="image18" alt="Diagram" /></td>
<td><img src="image19" alt="Diagram" /></td>
<td><img src="image20" alt="Diagram" /></td>
</tr>
<tr>
<td>Rhodorsil + 25 wt% Plastelina</td>
<td><img src="image21" alt="Diagram" /></td>
<td><img src="image22" alt="Diagram" /></td>
<td><img src="image23" alt="Diagram" /></td>
<td><img src="image24" alt="Diagram" /></td>
</tr>
</tbody>
</table>

Figure 4.2b: Overview of the finite flanking structures of the analogue experiments that were carried out in general shear (Wk=0.7). The upper row represents the initial orientation of the CE relative to the shear zone boundaries. Note that the structures do not propagate into each other and that they are finite structures.
4.2 Heterogeneity patterns.

In order to learn more about the differences in geometry of flanking structures, I analyzed the heterogeneity of the deformed grid. This was done by subtraction of the heterogeneous deformed grid from the experiments with a homogeneous deformed grid that was deformed under exactly the same conditions but without the CE (as described in chapter 3.4.1). The result of this subtraction is a difference with respect to deformation incase no CE was added to the experiment. Note that the heterogeneity patterns are something else than flow patterns of the deformation!

This analysis method was applied to all experiments in simple shear with a CE of carton under the four initial orientations with respect to the shear zone boundary and those with a CE of transparent overhead-projector paper surrounded with silicone gel under initial orientation of 165, 135, and 90°. For each experiment, the image that was taken at 7500 sec (y = ~1.6) was analyzed in order to get the heterogeneity pattern at the finite state of the experiment. The image that was taken at 3600 sec (y = ~0.8) was analyzed in order to get the pattern half way the experiment. The results are given in figure 4.4 A. This procedure was also done for the experiments in general shear with a CE of carton under all four staring positions. Again, two images were analyzed. Images that were taken at 4500 sec (y = ~0.3) and images at 9500 sec (y = ~0.6). These results are given in figure 4.4 B. This analyzing was not done for the experiments with Rhodorsil + 25 wt% Plastelina because, due to the sinking of the CE, the grid was dragged down along the CE and grid points were not traceable any more.

The results of the heterogeneity patterns (figure 4.4) reveal that there are some structures that contain cell-patterns. The positions of the centers of the cells for the N-type flanking folds in simple shear seem to be characteristic for the initial starting position of the CE and independent of the amount of shear strain. Note that in N 135 no clear cells were detected. In figure 4.5, the positions of the cells are projected perpendicular to the line of the orientation of
the CE. In order to correct for the angular differences between the CE’s of the experiments, the whole system was rotated over the smallest angle until the orientation of the CE was horizontal. The dots represent the position of the centre of the cells. Crosses represent positions where the heterogeneity pattern shows structures that almost form cells. The N 165 shows cells that are occupied inside the CE. N 135 does not show clear development of cells and N 90 contains cells just outside the CE, almost at the tips. N 45 has cells occupied far away from the tips of the CE. Note that the upper cell of N 165 is occupied more to the left tip of the CE and that the upper cell of the other N-types are occupied more to the right tip of the CE. The positions of the centers of the cells are roughly the same for both shear strains of each N-type flanking fold and therefore independent of the amount of shear strain.

Figure 4.5 was only made for N-type flanking folds in simple shear, because only in these experiments the position of the centers of the cells seems to be a function of the initial position of the CE. The A-type flanking folds do not show systematic differences between the heterogeneity patterns of the different types of A-type flanking folds (figure 4.4 A). Development of more than two cells seems to be characteristic for the experiments in general shear (figure 4.4 B). The N 45 structure shows clear development of four cells and the in the N 135 structure, three cells can be distinguished. Again, the position of the centers of the cells is independent of the amount of shear strain. Further, no systematic differences were between the patterns in general shear was recognized.
<table>
<thead>
<tr>
<th>Wk 1.0</th>
<th>3600 sec. (y = -0.8)</th>
<th>7500 sec. (y = -1.6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N 165</td>
<td><img src="image1" alt="Grid Diagram" /></td>
<td><img src="image2" alt="Grid Diagram" /></td>
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<tr>
<td>N 135</td>
<td><img src="image3" alt="Grid Diagram" /></td>
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<tr>
<td>N 90</td>
<td><img src="image5" alt="Grid Diagram" /></td>
<td><img src="image6" alt="Grid Diagram" /></td>
</tr>
<tr>
<td>N 45</td>
<td><img src="image7" alt="Grid Diagram" /></td>
<td><img src="image8" alt="Grid Diagram" /></td>
</tr>
</tbody>
</table>

Figure 4.4 A: Heterogeneities of the deformed grids during simple shear. Dots represent centers of cell forming patterns. Crosses represent positions where the heterogeneity of the deformed grid shows structures that almost form cells.
<table>
<thead>
<tr>
<th>Wk 1.0</th>
<th>3600 sec. ((y = -0.8))</th>
<th>7500 sec. ((y = -1.6))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shear band</strong> 165</td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Reverse A 135</strong></td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Reverse A 90</strong></td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>No CE</strong></td>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
</tr>
</tbody>
</table>

**Figure 4.4 A**: Heterogeneities of the deformed grids during simple shear. Dots represent centers of cell forming patterns. Crosses represent positions where the heterogeneity of the deformed grid shows structures that almost form cells.
<table>
<thead>
<tr>
<th>Wk 0.7</th>
<th>4500 sec. (y = ~0.3)</th>
<th>9500 sec. (y = ~0.6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N 165</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>N 135</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>N 90</td>
<td><img src="image5.png" alt="Image" /></td>
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</tr>
<tr>
<td>N 45</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 4.4 B: Heterogeneities of the deformed grids during general shear. Dots represent centers of cell forming patterns. Crosses represent positions where the heterogeneity of the deformed grid shows structures that almost form cells.
Figure 4.5: Positions of the cell from N-type flanking folds that were made in simple shear, projected perpendicular to the line of the orientation of the CE. The whole system was rotated over the smallest angle in order to correct for the angular differences between the CE's of the experiments, until the orientation of the CE was horizontal. The dots represent the position of the centre of the cells. Crosses represent positions where the heterogeneity of the deformed grid shows structures that almost form cells.

4.3 Flow patterns.

The flow patterns of the experiments were analyzed in order to find out whether different flanking structures are the result of different flow patterns. The flow patterns were made with help of the program PIVSleuth. With this program, flow patterns between two deformation steps (between two images) were made as described in chapter 3.4.2. Flow patterns were made for the experiments in simple shear that resulted in N-type flanking folds (with a CE of carton and Rhodorsil + 25 wt% Plastelina). All four initial orientations were analyzed. In addition, the experiments that resulted in the Reverse shear band, Reverse A 135, and Reverse A 90 flanking structures were analyzed. For all these experiments, flow patterns were created for the images 2400-2700 (y ~ 0.5-0.6), 4800-5100 (y ~ 1.0-1.1), and 7200-7500 (y ~ 1.5-1.6). In general shear, the experiments with a CE of carton were analyzed on their flow pattern. For these experiments, images 3000-3300 (y ~ 0.19-0.21), 6000-6300 (y ~ 0.38-0.42), and 9200-9500 (y ~ 0.59-0.61) were used to obtain the flow patterns. The results are given in appendix 3. These results show circular flow patterns for the simple shear experiments that were carried with a CE of carton. These cells contain a long axis. The position of the long axis of the flow pattern is different for different shear strains. The experiments in simple shear with a CE of Rhodorsil + 25 wt% Plastelina hardly show any development of circular patterns. The experiments that resulted in A-type flanking folds and a Reverse shear band do not show circular patterns. They show an extended zone of deflection that also has different orientations for different shear strains. The flow patterns of the experiments that were carried out in general shear resulted in very weak patterns that sometimes show a weak development of circular patterns.
5. Discussion.

The following chapter describes the results of the analogue modeling on flanking structures and the results that followed from the analysis procedures. First, I will discuss the characteristics that were found from the modeling of different flanking structures and whether these are in agreement with the findings of previous studies or whether these characteristics are new. Second, I will discuss what can be derived from the results of the heterogeneity patterns and from the flow patterns. Following, I will debate about the questions that came up during the study of the natural flanking structures in the Ugab and Goantagab valley, Namibia, with help of the results of the analogue experiments. I will also discuss the reasonableness of the analogue experiments with respect to natural flanking folds. Finally, I will debate about the use of flanking structures as indicators for the type of flow and kinematics.

5.1 The characteristics of different types of flanking structures.

With analogue experiments, I have manufactured flanking structures in which I could not only vary the type of ductile flow and the initial position of the CE, but also to some degree the rheological properties of the CE. The finite flanking structures that were derived from these experiments are N-type flanking folds, Reverse A-type flanking folds and Reverse shear bands following the classification of figure 1.1 and 1.2. If the CE was less viscous than the HE, slip along the vein occurred. If the CE was more viscous than the HE, no slip occurred and N-type flanking folds developed. This is in agreement with previous numerical studies on flanking structures of Grasemann and Stüwe (2001). The analogue modeling of this study showed that viscosity contrast between the HE and the CE does not only determine the type of flanking structure, but also determines the amplification of the folding. The experiments with carton, for example, resulted in more pronounced and more isoclinal folds than experiments with Rhodorsil Gomme + 25 wt% Plastilina, because of the higher viscosity of the CE. The experiment with kitchen soap Attachment 1/Wk = 1.0/CE (Slip)/Reverse A90/soap showed hardly any development of folds and slip along the CE was very large with respect to the experiment with silicone gel Attachment 1/Wk = 1.0/CE (Slip)/Reverse A90/silicone gel, because of the lower viscosity of the soap. The amount of shear strain also influences the interlimb angle of the folds, showing more isoclinal folds with increasing shear strain. These findings, which were derived from analogue modeling on flanking structures, are in agreement with the findings of the previous numerical modeling of Grasemann and Stüwe (2001) who also concluded that increasing viscosity of the vein with respect to the host material and increasing shear strain, both results in a decrease of the interlimb angles of the folds.

An important characteristic of the N-type flanking folds in the experiments is the transition between the phase that resulted in buckling structures of the HE around the CE and the phase that resulted in necking structures of the HE around the CE. In simple shear, the transition occurred if the orientation of the CE relative to the shear zone boundaries was 90° Attachment 1/Wk = 1.0/CE (No slip)/N135/carton. During the phase that resulted in buckling structures (CE orientated >90 ° relative to the shear zone boundaries), fold trains developed with axial planes that were not parallel to the CE. The phase with development of necking structures occurred if the orientation of the CE relative to the shear zone boundary was < 90°. Fold trains developed with axial planes parallel to the CE. In addition, thickening of the markers in the fold hinges took place. From the experiments that were done with Rhodorsil Gomme + 25 wt% Plastilina under simple shear conditions, we learned that the CE was shortened during the phase that results in buckling structures and extended during the phase that resulted in necking structures. This means that N-type flanking folds must have had an initial orientation...
< 90° with respect to the shear zone boundaries if they show axial planes parallel to the CE and/or extension in the fold hinges (parallel to the axial planes) and/or extension of the CE. N-type flanking folds that show axial planes that are not parallel to the CE and/or shortening of the CE, must have had an initial orientation >90° with respect to the shear zone boundaries. Note that this only holds for simple shear. The experiments that were performed with Wk = 0.7 showed that the transition zone between the buckling and the necking structures occurred at an orientation of the CE of 60° with respect to the shear zone boundaries. In addition, no extension at the fold hinges took place in general shear.

An important characteristic of Reverse A-type flanking folds in the experiments is the marker above and below the tips of the CE. Beyond the upper tip, up stepping markers were developed and beyond the lower tip, down stepping markers were developed. Grasemann et al. (2003) already discussed the similarities between a Reverse A-type flanking fold and a Reverse shear band. Because of the geometrical similarities between these structures, it is very difficult to distinguish them in the field, which may result in a misinterpretation of the shear sense. The only criteria that they found (with their numerical model) to distinguish them was that a shear band has to have a sigmoidal shaped CE and that the orientation with respect to the shear zone always has to be less than 25-30 degrees. Above this, the shear band is unstable. The analogue experiment that resulted in a Reverse shear band Attachment 1/Wk = 1.0/CE (Slip)/Reverse shear band165/overhead + silicone gel shows that the markers above the tip of the CE are concave and the markers below the tip of CE are convex. No up or down stepping marker above or below the tips of the CE was developed. On top of the conclusions of Grasemann et al. (2003), this criteria will help to distinguish Reverse A-type flanking folds and Reverse shear bands in the field and thereby it is a useful additional criterion for the interpretation of the shear sense from the flanking structures.

Although no finite S-type flanking folds were developed inside the deformation box, a part of an experiment showed characteristics of a co-shearing CE with a contractional offset. Experiment Attachment 1/Wk = 1.0/CE (Slip)/Reverse A90/overhead + silicone gel, showed transition of a counter-shearing CE until 4800 sec. into a co-shearing CE from 5700 sec. Despite the finite structure still being a Reverse A-type, the end of the experiment showed formation of an S-type flanking fold. If more shear strain was added or α (the initial orientation of the CE relative to the shear zone boundaries) was decreased, the result would probably be a finite S-type flanking fold. This shows that different types of flanking folds can propagate into each other. Grasemann et al. (2003) already carefully proposed that different structures propagate into each other on basis of numerical modeling. The analogue modeling proved that Reverse A-type flanking folds propagate into S-type flanking folds. The zone of transition of an A-type flanking fold into a finite S-type flanking fold can be large, depending on the amount of slip along the CE during the counter-shearing event. From natural flanking structures, we can only interpret the sense of shear along the CE of finite structures and it is impossible to estimate the sense of shear during the complete formation of the flanking structure. If we look in detail at the development of the fold hinges in the experiment Attachment 1/Wk = 1.0/CE (Slip)/Reverse A90/overhead + silicone gel, we can see that the markers in the fold hinges are thickened during the co-shearing phase of the CE (at the end of the experiment). This was never detected during the counter-shearing phase of the CE and therefore it is a characteristic for the formation of S-type flanking folds.

Summarized, the analogue experiments resulted in new criteria's that will be useful for the interpretation of N-type flanking folds in the field. The criteria's are listed below in table 5.1.
Furthermore, the analogue experiments showed that A-type flanking folds show up and down stepping markers at the tips of the CE where shear bands only develop concave and convex markers at the tips of the CE (no up or down stepping markers). From the experiments, we also learned that A-type flanking folds propagate into S-type flanking folds with increasing shear strain. During the co-shearing phase, thickening of the markers at the fold hinges occur.

### Table 5.1: New criteria’s for the interpretation of N-type flanking folds, that followed from the analogue experiments.

<table>
<thead>
<tr>
<th>$W_k$</th>
<th>$\alpha$</th>
<th>Axial planes parallel to the CE</th>
<th>Structure of the HE around the CE</th>
<th>Strain of the CE</th>
<th>Extension of the fold hinges</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>$&gt;90^\circ$</td>
<td>No</td>
<td>Buckling</td>
<td>Shortening</td>
<td>No</td>
</tr>
<tr>
<td>1.0</td>
<td>$&lt;90^\circ$</td>
<td>Yes</td>
<td>Necking</td>
<td>Extension</td>
<td>Yes</td>
</tr>
<tr>
<td>0.7</td>
<td>$&gt;60^\circ$</td>
<td>No</td>
<td>Buckling</td>
<td>Shortening</td>
<td>No</td>
</tr>
<tr>
<td>0.7</td>
<td>$&lt;60^\circ$</td>
<td>Yes</td>
<td>Necking</td>
<td>Shortening</td>
<td>Yes</td>
</tr>
</tbody>
</table>

5.2 What can be derived from the heterogeneity patterns?

The heterogeneity patterns (figure 4.4) show cell-patterns for the experiments that resulted in N-type flanking folds. For each experiment in simple shear, two cells can be distinguished from the pattern. The positions of the centre of the cells for N-type flanking folds in simple shear (figure 4.4 A) seem to be regular and characteristic for the initial orientation of the CE.

In figure 4.5, the positions of the centre of the cells are projected perpendicular to the line of the orientation of the CE. From this figure, we see that the position of the centers of the cells from experiment N165 are inside the CE with the left cell occupied above the CE. For N90, the cells are occupied at the tips of the CE with the left cell below the CE. In N45, the left cell is also occupied below the CE, but the cells are occupied far away from the tips of the CE. N135 does not develop clear cells, probably because of a transition phase of the cells being occupied with the left cell above the CE (N165) and below the CE (N90).

Note that the experiment N135 also shows the transition zone from buckling structures of the markers around the CE into necking structures. The position of the cells seems not to be affected by the amount of shear strain and thus can help us in the interpretation of the initial position of the CE and the shear sense (regardless of the shear strain!). The latter is not of particular benefit, since shear sense is already derived from the fold train geometry. However, from the geometries of the experiments, we can predict whether the initial position of the CE relative to the shear zone boundary ($\alpha$) was above or below $90^\circ$ by looking at the buckling or necking structures around the CE. With help of the positions of the cells, we can predict whether $165^\circ < \alpha > 135^\circ$ (if the cells are occupied inside the CE), or $\alpha \sim 90^\circ$ (if the positions are occupied at the tips of the CE) or $90 < \alpha > 45$ (if the cells are occupied far away from the CE). This gives a more precise determination of the initial starting position of the CE.

For the experiments in general shear, no regular positions for the centre of the cells was found (figure 4.4 B). Although the number of cells differ between the experiments (resulting mostly in more than two cells), the positions of the cells are not affected by the amount of shear sense (except for experiment N90). If we can link the positions of the cells to natural examples, it is a useful tool in field analysis of N-type flanking folds. The initial positions of the CE’s for a set of natural flanking structures can reveal information about the history of the development of the CE’s. For example, are they tension gashes or another set of (conjugate) veins with a particular initial orientation? We need to link the position of the centers of the cells in simple shear to the geometry of the markers around the CE in such way that we can predict the positions of the cells from the images derived from the experiments. If we can, we might be able to predict the position of the centers of the cells in natural field examples of N-type flanking folds and...
thereby predict the initial orientation of the CE. In order to find the link of the positions of the cells to natural examples, the centers of the cells were put onto the photos of the experiments. This is given in Figure 5.1. The figure shows that there is no clear-cut systematic relationship between the geometry and the position of the centers of the cells. At N45, the cells are occupied at the position where the marker lines show maximum deflection, but this is not the case for the other experiments. We cannot predict the initial orientation of the CE with help of the cells, because no link can be made between the positions of the cells and the geometry of the flanking structure. It is also impossible to apply the cell exercise on images from natural flanking folds because the amount of shear strain has to be known in order to distract the shear component from the image.

Figure 5.1: The centers of the cells overlain onto the photos of the N-type flanking folds that were made in simple shear. Crosses represent positions where the heterogeneity of the deformed grid shows structures that almost form cells.

<table>
<thead>
<tr>
<th>Wk 1.0</th>
<th>y = 0.8</th>
<th>y = 1.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>N 165</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>N 135</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>N 90</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>N 45</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Summarized, the experiments in simple shear show regular cell positions that appear unaffected by the amount of shear strain. The positions of the cells with respect to the CE are characteristic for the initial orientation of the CE. No link was found between the cell positions and the geometries of the flanking folds. More research is necessary to find out how we can predict the positions of the cells in natural N-type flanking folds in order to reveal information about the history of the development of the CE’s.

5.3 Flow patterns of flanking structures

Figure 4.3 shows the results of the difference in rotation of the CE and marker lines that were initially parallel to the CE. Due to inaccuracy in our measurements, differences smaller than 2.5 degrees should not be considered as relevant. Large deviations in simple shear only occur for the experiments with a piece of transparent overhead-projector paper surrounded by silicone gel at 165° (Reverse shear band) and Rhodorsil + 25 wt% Plastelina at 165° (N165). Large deviations in general shear occur by both experiments with a CE at 135°. Because the Rhodorsil + 25 wt% Plastelina is not a straight CE, the deviation can be bigger. This might explain the deviation in rotation of -3.4° for the experiment with + 25 wt% Plastelina at 165° (N165). Note that the rotation of the CE in experiment in simple shear are largest for α = 135° and smallest for α = 165°. In general shear the rotation of the CE is largest for α = 90° and smallest for α = 165°. The deviations in rotation for the experiments with a piece of transparent overhead-projector paper surrounded by silicone gel at 165° (Reverse shear band) in simple shear and both experiment with a CE at 135° in general shear might be the result of a local disturbance of the vorticity number around the CE, leading to different angular velocities near the CE. In order to check if the differences in rotation are a result of local disturbances of the vorticity number, flow patterns were constructed with help of the PC-program PIVSleuth.

The flow patterns (appendix 3), show only minor differences for different flanking structures. For N-type flanking folds in simple shear with a CE of carton we see an overall development of a circular pattern that is formed around the position of the CE. The circular pattern often contains a long axis. This axis is always in the direction of the position of the CE at that time. The N-type flanking folds with a CE of Rhodorsil + 25 wt% Plastelina show hardly any development of a circular pattern around the CE. Probably the flow patterns are less pronounced because of the sinking problem that we had with this CE. It sometimes dragged marker lines down along the CE, which will have affect on the pattern. In addition, folding was less pronounced in these experiments than the experiments with carton because of the lower viscosity of Rhodorsil + 25 wt% Plastelina with respect to the carton. This will also result in a less pronounced flow pattern because we look at flow patterns of one single deformation step.

A-type flanking folds and the shear band that were developed during simple shear do not show development of a single circular pattern around the CE as N-type flanking folds do. They show an extended zone of deflection that is more or less in the orientation of the position of the CE at that time.

From the patterns of the experiments in general shear, we can sometimes see development of a single circular pattern. The pronunciation of the circular patterns is very weak. Note that γ for a single deformation step in general shear was 0.02 while in simple shear, γ was 0.06, resulting in less pronounced patterns.

A horizontal flow apophyse, parallel to the shear zone boundaries (as it is expected to be in simple shear), can be recognized from the pattern (figure 5.2 A). The flow patterns of the experiment with carton in general shear clearly show two flow apophyses (figure 5.2 B). The angle between the flow apophyses varies between 40-45°. The cosinus of the angle between two flow apophyses gives the Wk of the flow. This results in a variation of the vorticity
during the experiments in general shear of \( W_k = 0.71 - 0.77 \). The settings of the PC program LabView were set at \( W_k = 0.7 \). The eventual vorticity number of the experiments in general shear is 1.4 to 10.0\% higher, which is a small deviation that should not be considered very relevant. This means that the deformation box satisfies the expectations in terms of vorticity number.

**Figure 5.2:** Examples of flow apophyses from the experiments that follow from the flow patterns that were derived with help of the PC-program PIVSleuth. The flow apophyses are shown in red. A. Single horizontal flow apophyses in simple shear experiments. B. Two flow apophyses in general shear that make an angle of 40-45° with respect to each other.

With the method from which the flow patterns were derived, no significant differences in flow patterns around the CE could be recognized that could explain the deviations in rotation for the experiments with a piece of transparent overhead-projector paper surrounded by silicone gel at 165° in simple shear and both experiment with a CE at 135° in general shear. The large rotation for the experiments in simple shear with \( \alpha = 135° \) and the small rotation for experiments with \( \alpha = 165° \) can be explained with help of the flow apophyse. The flow apophyse in simple shear is horizontal (figure 5.2 A). If the CE is at a low angle with respect to the flow apophyse, it will have a low angular velocity and a high angle means a high angular velocity. The experiments with \( \alpha = 135 \) will be at high angle to the flow apophyse during the experiment, resulting in a lot of rotation of the CE. The experiments with \( \alpha = 165° \) will be at a very low angle to the flow apophyse, resulting in small rotations of the CE.
flow apophyses in general shear with a $Wk = 0.7$ make an angle of $\sim 40-45^\circ$ with one flow apophyses parallel to the shear zone boundary (figure 5.2 B). The experiments with $\alpha = 90^\circ$ will be at high angle to both flow apophyses during the experiment, where experiments with $\alpha = 165^\circ$ will be at a small angle. This results in a lot of rotation of the CE with $\alpha = 90^\circ$ with respect to the small rotation of $\alpha = 165^\circ$.

The PC program that was used to derive the flow patterns from the experiments was capable to recognize the same group of pixel's (interrogation spots) in two different images. Some analyzing deviations of the program could occur, affecting a small area of the flow pattern (for example the upper part of the pattern of $Wk=0.7/N90/carton/9200-9500$). These areas of deviations are too large to be corrected manually. In order to correct for these areas of deviations, a higher amount of traces particles is necessary. With a higher amount of tracer particles, the program can define interrogation spots more precisely, making the flow pattern finer and more accurate.

Summarized, marker lines that were initially parallel to the CE rotated with the same angular velocities as the CE, except for the experiment with a piece of transparent overhead-projector paper surrounded by silicone gel at $165^\circ$ in simple shear and by both experiments with a CE at $135^\circ$ in general shear. These deviations might be a result of local disturbances of the vorticity number around the CE. However, with the method that was applied in order to derive the flow patterns for the experiments, no significant differences between the flow patterns could be recognized that can explain the deviations in rotation. The orientations of the flow apophyses that result from the flow patterns are in agreement with the expectations.

5.4 Natural examples

With the derived knowledge of previous studies, flanking structure in the Ugab and Goantagab valley, Namibia helped in the interpretation of the large-scale geology of the area. Overall, they show that the rocks were exposed to sinistral non-coaxial flow during a phase of brittle/ductile deformation. However, several questions remained open during the interpretation of these natural flanking structures that could not be solved with the knowledge of previous studies. These questions were:

1) How can we get sinistrally as well as dextrally rotated veins that both show development of N-type flanking structures, next to each other in the same structural setting?
2) How can we get A-, S- and N-type flanking folds next to each other in the same volume of rock (under the same rheological conditions with respect to the CE and the HE)?
3) How are differences of the interlimb angles of the folds, thickening of the HE at the fold hinges and different grades of deflection inside a flanking structure generated?
4) Are there types of flanking structures that not fit in the classification of figure 1.1 and 1.2 and what are the characteristics of these types of flanking structures?

Solving these questions will result in a better understanding of the natural examples of the Ugab and Goantagab valley and with that, the contribution of these structures in the interpretation of the large-scale geology of the area will increase. I will now use the results of the analogue experiments to attempt to answer these questions.

5.4.1 Aims River Formation, NE of the contact with the Doros Pluton

The N-type folds in the Aims River Formation, NE of the contact with the Doros Pluton, showed both dextrally and sinistrally rotated veins. An explanation for the occurrence of the different orientations of the veins is differences in the timing of the formation of both veins.
In order to create the N-type flanking folds against both veins, the rocks must have been exposed to dextral as well as sinistral shear. However, no crosscutting relationships were found between the formation of the dextrally and the sinistrally rotated veins. Therefore, it is assumed that both veins formed at the same time.

From the experiments, it is clear that this is possible in pure shear dominated deformation. The experiments Attachment 1/Wk = 0.7/CE (No slip)/N165/carton and Attachment 1/Wk = 0.7/CE (No slip)/N165/Rho + 25% Pla showed that veins can be counter rotating during general shear, if \( \alpha \) is very large. It is possible that we deal with two sets of veins or even a conjugate set of veins. One set with an initial orientation that is at high angle with respect to the shear zone boundaries (will be counter-rotating) and one that is at a low angle (will be co-rotating). The sinistrally rotated veins showed extension in the fold hinges along the axial planes. From the experiments, we learned that this extension occurs if the CE is in the phase of development of necking structures of marker lines around the CE. Therefore, the sinistrally rotated veins must be the co-rotating set in order to get this extension and the dextrally rotated veins are the counter-rotating ones (in the buckling phase). The shear sense would be sinistral, but with a dominated pure shear component. The situation of both veins is illustrated in figure 5.3. Because the folding of the N-type flanking folds in the Aims River Formation did not continue beyond the tips of the CE, we cannot derive the phases of the development of the buckling and necking structures from the field examples. In the field, I found open as well as isoclinal folding against both sets of veins. Because the angle of rotation of the dextrally (counter) rotating veins cannot be very large, we would not expect isoclinal folds here. The experiments showed that an increase in rotation (increase in shear sense) produces more pronounced and more isoclinal folds. In addition, the experiments Attachment 1/Wk = 0.7/CE (No slip)/N165/carton and Attachment 1/Wk = 0.7/CE (No slip)/N165/Rho + 25% Pla did hardly show any deflection of the marker lines. In the field, both sets of veins showed a very low angle with respect to the foliation (5-20\(^\circ\)). From this, I conclude that there was a lot of shear strain that was responsible for strong folding against both veins, but still, isoclinal folds against the counter rotating veins is not likely in this setting. An alternative explanation is a rheological difference between both veins, together with the difference in initial orientation. Viscosity contrast influences the interlimb angle of the folds against the CE. From field analyses, we saw that the sinistrally rotated veins seem to have smaller alteration rims than the dextrally rotated veins. This can be an indication for rheological differences. The dextrally rotated veins would have had a much higher viscosity than the sinistrally rotated veins, resulting in strong folding during minor shear strain.

Summarized, sinistrally as well as dextrally rotated veins, along which N-type flanking folds develop, can be the result of pure shear dominated flow. Isoclinal folding against counter-rotating veins remain questionable in this explanation. Alternative solutions are possible rheological differences between the veins or (although no crosscutting relationships were found) different timing of the formation of the veins. Further research on rheological differences and timing of formation between the veins is necessary to solve this problem.
5.4.2 Lower Gemsbok Formation.

Inside the marbles of the Lower Gemsbok Formation, N-type as well as Reverse A- and Normal S-type flanking folds occur in the same volume of rock and even next to each other. Between these different flanking structures, no difference in orientation or composition of the CE was found. From experiments Attachment 1/Wk = 1.0/CE (Slip)/Reverse A90/overhead + silicone gel and Attachment 1/Wk = 1.0/CE (Slip)/Reverse A90/silicone gel we learned that Reverse A-type flanking folds (counter-shearing) progressively transform into co-shearing structures. With continuing shear strain, this will eventually result in S-type flanking folds. Therefore, it is possible to get A-type flanking folds next to S-type flanking folds in the same volume of rock. Nevertheless, in order to develop an N-type flanking fold, a vein along which no slip can occur is necessary. No evidence was found in the field for different rheologies of the veins. The N-type flanking folds in the Lower Gemsbok Formation are explained as followed: During the transition of A-types into S-types, slip is reversed along the CE. The displacement of the markers will decrease as they move in opposite directions (towards their initial positions along the CE). A phase at which it seems as if no displacement has taken place will occur, resulting in an N-type flanking structure. With progressive deformation, reversed slip will carry on resulting in an S-type flanking fold. The different structures must be a result of different initial orientations of the veins. The S-type flanking fold already passed the transition zone between A- and S-type flanking folds and therefore experienced a small amount of counter-shearing slip that had to be overcome. The Reverse A-type flanking folds did not yet reach the transition and therefore experienced a larger amount of counter-shearing slip (indicating an initial angle that is larger than the S-type). Note that at the upper part of the vein on figure 2.7, a marker with opposite vergence [2] relative to the anticlinal fold in the centre of the vein is situated. This is a characteristic of Reverse A-type flanking folds, which indicates earlier slip along the vein. However, because the structure is just partly exposed and lack markers, it is still questionable whether slip occurred along the vein and whether these N-types are just transitional structures between Reverse A- and Normal S-type
flanking folds. Important is that what can be interpreted in field analyses as being a countershearing vein, might already have experienced co-shearing displacement. This means that the definition of Reverse A-type flanking folds (Figure 1.2) can be subdivided into counter-shearing (first phase) and co-shearing (second phase) A-type flanking folds. However, this subdivision will not be very useful for the classification of natural examples, because the displaced markers of a finite Reverse A-type will not reveal the co-shearing phase of the structure.

Summarized, Reverse A-type flanking folds progressively transform into S-type flanking folds with increasing shear strain. During this transition, a phase occurs at which it seems as if no displacement has taken place. This can result in a N-type flanking fold. We need to keep in mind that we are looking at finite structures in the field that might have had a more complex history that cannot be derived from the finite structures.

5.4.3 Upper Gemsbok Formation.

The Reverse A-type flanking folds of the Upper Gemsbok Formation showed differences in the interlimb angles of the folds, thickening of the HE at the fold hinges and different grades of deflection. From previous studies we already knew that the interlimb angles of flanking folds decrease with increasing shear strain (Hudleston, 1989; Grasemann and Stüwe, 2001) and that an increase in viscosity contrast between the HE and the CE also results in a decrease of the interlimb angles (Grasemann and Stüwe, 2001). The experiments from our analogue modeling support these statements. The CE’s from the Upper Gemsbok Formation are thin faults without any rheological differences. Therefore, the difference of interlimb angles between the different structures must be a result of different initial orientations of the CE. The CE’s that show isoclinal folds must have had a larger initial angle with respect to the shear zone and experienced more rotation than the CE’s that show open folding. The thickening of the HE at the fold hinges is the result of extension parallel to the axial planes of the folds. During experiment Attachment 1/Wk = 1.0/CE (Slip)/Reverse A90/overhead + silicone gel, we saw that markers in the hinges were thickened during the co-shearing phase along the CE (at the end of the experiment). If rotation of the CE is enough to bring the CE in the position at which shear along the CE becomes co-shearing, extension and thereby thickening in the fold hinges can take place. Reverse A-type flanking folds that do not show thickening of the HE in the fold hinges are probably still in the stage with counter-shear along the CE. The differences between different grades of deflection between the hanging wall and footwall cannot be explained with help of the analogue experiments. During the experiments, no different grades of deflection in one structure have been found and therefore we can only speculate about explanations. The faults that form the CE in the Upper Gemsbok Formation are not straight. They branch into each other and sometimes run parallel to the bedding at there tips, forming stair stepping faults. A stair stepping CE shows differences in orientations. Disturbances along the CE can occur that has influence on the different grades of deflection. Summarized, the differences in the interlimb angles of the Reverse A-type flanking folds of the Upper Gemsbok Formation are a result of different initial orientation of the faults. Thickening of the HE at the fold hinges occurs at the co-shearing stage of the CE. For the different grades of deflections in a single A-type, no explanation was found. It was speculated to be a result of stair stepping faults that results in disturbances along the CE. Future experimentation on stair stepping faults is necessary to check our speculations.

5.4.4 Gemsbok Formation, more to the North, near the Phanerozoic cover.

A very different type of flanking structure was studied in the Gemsbok formation, more to the North, near the Phanerozoic cover (mainly basalts of the Cretaceous Etendeka Group). This structure does not fit into the classification of figure 1.1 and 1.2. The veins are counter-shearing in a sinistral shear zone and they make a high angle with the foliation (60°). This position is highly unfavorable in a sinistral shear zone because in this position the vein has a
high angular velocity during flow. In this position they would fit inside the classification of shear bands (see figure 1.2), but with compressional offset (counter-shearing) instead of the extensional offset (co-shearing). The characteristics of the structures in the field are as followed (figure 2.11):
- Counter-shearing vein in sinistral shear zone
- Reverse drag of markers in the centre of the CE
- Max displacement in the centre of the CE, decreasing towards the tips
- Normal drag at the tips of the CE
- Down stepping marker at the lower tip of the CE
- Up stepping marker at the upper tip of the CE
- Folding dies out into the wall rock

If we look in detail to the first part of the experiment Attachment 1/Wk = 1.0/CE (Slip)/Reverse A135/overhead + silicone gel, we see exactly the same characteristics, but in a dextral shear zone. We need to focus on the first part of the experiment, until 3000 sec. The image of 3000 sec is given in figure 5.4. On this image, we can see a counter-shearing CE with development of reverse drag at the centre of the CE. At the centre of the CE, maximum displacement is occupied which decreases towards the tips. At the lower tip, down stepping markers are developed and at the upper tip, up stepping markers are developed. The vergence of folding at the tips is of opposite sense with respect to the reverse drag in the centre of the CE. This image shows exactly the same structure as the structure in the Gemsbok Formation, only not in sinistral, but in dextral shear (reflected). Therefore, these structures are Reverse A-type flanking folds in a very young stadium. They experienced minor shear strain, leaving the veins in a high angle relative to the foliation. The flanking folds in the field are the youngest structures that were found in these rocks, which make minor shear strain acceptable. The youngest tectonic event in the area was an event of sinistral compression (resulting in D3), described by Passchier et al. (2002). The flanking folds probably were formed during this event and therefore are D3-structures. Some of the veins showed jogs that formed during rotation of the veins. These jogs fit inside the stress field in which the veins will be compressed due to the orientation of the veins relative to a shear zone that is of sinistral compression. From field analysis only, another explanation for the flanking structures was opposed. In this option, the structures were a result of a third tectonic event that has not been described yet, post dating the second tectonic event. Although no evidence was found for later stage dextral shear in the Gemsbok Formation, the option appeared quit reasonable at the time, because the orientation of the vein would be in a more stable position. The structure would have been co-shearing and co-rotating, forming a Reverse S-type flanking fold. With help of the analogue modeling, we can now conclude that these structures are Reverse A-type flanking folds, and thus we are not dealing with a new flanking structure. In other words, there is no third tectonic event needed in order to explain these structures. They perfectly fit inside the second and last tectonic event of the area that was responsible for D3.

Summarized, the flanking structures of the Gemsbok Formation are Reverse A-type flanking folds that are in a young stadium of development. We are not dealing with new flanking structures, although they do not fit inside the classification of figure 1.1 and 1.2. A subdivision of the classification of figure 1.1 and 1.2 into Young Reverse A-type and Mature Reverse A-type flanking folds is necessary in order to classify the structures of the Gemsbok Formation. The structures of the Gemsbok Formation are examples of Young Reverse A-type flanking folds ($\alpha > 90^\circ$) and the structure that are described by Grasemann et al. (2003) in figure 1.2 are Mature A-type flanking folds ($\alpha < 90^\circ$)
5.5 Reasonableness of the analogue experiments

In this paragraph I will discuss how the materials that were used and the processes that were carried out in the experiments influenced the reasonableness of the analogue experiments in order to compare them with natural rocks. I will also point out the processes that cause differences between experiments and thereby influence the deflection of the marker lines.

The analogue experiments in the deformation box were carried out under shear strains rates of $2.2 \times 10^{-4}$ s$^{-1}$ for simple shear and $6.5 \times 10^{-5}$ s$^{-1}$ for general shear. Conventional strain rates in the earth are in the order of $10^{-11} - 10^{-13}$ s$^{-1}$ (Weijenmars, 1986). The deformation mechanism of the PDMS depends on arrangement of chains inside the PDMS, which is significantly different from the creep mechanisms in crystalline rocks. The deformation in the deformation box was close to homogeneous. In nature, deformation is often heterogeneous due to impurities. Similarities between our experiments and previous studies (field analyses as well as numerical studies) suggest that the analogue modeling that was done in this study is very reasonable with natural rocks, despite of the differences in shear strain rate, deformation mechanism and homogeneity of the deformation. Therefore, the analogue experiments are good representations of the development of flanking structures in nature. Our host material is supposed to be linear viscous, but natural rocks are not. Because the analogue experiments are similar to natural examples, I support the statement of Grasemann et al. (2003) in which he claimed that linear and non-linear host materials generate topologically equivalent structures.

In order to get a good representation of the deflection of markers that is caused only by the presence of a CE, the deformation inside the box must be as homogeneously as possible. The experiment without a CE (Attachment 1/Wk = 1.0/No CE) showed that deformation was homogeneous in the centre of the deformation box. Towards the edges, deformation becomes gradually more heterogeneous. From the exercise that resulted in the heterogeneity patterns in figure 4.4, we see that the lower and upper parts of the structures were sometimes slightly influenced by the zone of heterogeneous deformation. Some structures are a bit to large and will be affected by the more heterogeneous edges of the box. This effect is minor, but will
have small influences on the deflection of the markers at the upper and lower part of the structures.

The experiments of the analogue study were studied in a two dimensional plane of view. However, in some experiments there was also minor movement in the third dimension. In the experiments that were carried out with a CE of carton, the carton was being pushed out of the PDMS (due to compressional stresses that act on the CE) during the phase at which the CE was at a position > 90° relative to the hear zone boundaries. At a position < 90°, the PDMS was being pushed up against the contact with the CE. These movements in the third dimension effected the deflection of the markers, but the effect was minor. Another effect in the third dimension was the sinking of the CE during the experiments with Rhodorsil + 25 wt% Plastelina. The marker lines were dragged down along the CE due to the sinking. This effect was quit large. Because of the loss of grid-squares that were dragged down along the CE, analyzing these experiments in terms of the heterogeneity patterns became impossible. Therefore, these experiments are less reliable with respect to the experiments that were done with carton. However, they clearly show the different grades of deflection and amplification of folding, between these two CE’s. The experiments that were done in general shear were preformed in plane strain (Program D of the PC program LabView). By measuring the volume of the deformation box before and after each experiment, I noticed that the volume of the box decreased 14-16% during deformation of the box. This large decrease will have effect on the experiments. With the images that were taken during the experiment, I only registered a two dimensional plane. Due to the volume loss of the deformation box, the PDMS gets pushed out at the top of the box (increasing the Z-axis due to a decrease in the x and y-axis of the box). This movement in the third dimension will influence the deflection of the markers.

During the preparation of the experiments, air bubbles were trapped inside the PDMS. The PDMS had to settle a few hours in order to let big air bubbles rise out of the PDMS. Small bubbles remained in and made images turbid. Too much air bubbles will influence the rheology of the PDMS and locally change the Newtonian viscous flow behavior of the PDMS. The amount of air bubbles was different for each experiment but the effects of the air bubbles could not be detected from the experiments. Other differences between experiments that should be notices are differences in the orientation of the CE with respect to the shear zone boundaries. A CE that was put in under an orientation of 135°, for example, sometimes showed deviation a few degrees (never more that 5°) from this orientation. In addition, the grid might show deviation of a few degrees with respect to the orientation of the shear zone boundaries. The horizontal grid lines were orientated as parallel to the shear zone boundaries as possible, but deviations of a few degrees were taken for granted. The effects of these differences are minor and hardly influence the finite structures of the experiments.

Summarized, the analogue experiments are good representations of the development of flanking structures in nature, despite of the differences in shear strain rate, deformation mechanism, homogeneity of the deformation and linear viscosity. Differences in the deflection of the marker lines between the experiments (that are not caused by the presence of a CE) are influenced by the heterogeneity of the deformation along the edges of the deformation box, movements in the third dimension. The presence of air bubbles inside the PDMS, deviation of a few degrees of the initial orientation of the CE as well as the deviation in orientation of the grid with respect to the shear zone boundaries only hardly cause differences in the deflection of the marker lines.

5.6 Flanking structures as indicators for the type of flow and kinematics.

Previous studies showed that N-type flanking folds are useful kinematic indicators (Grasemann et al., 1999, Grasemann and Stüwe, 2001) and that flanking structures with slip along the CE are only useful kinematic indicators if the mechanism that is responsible for the flanking structure is known (Passchier, 2001, Grasemann et al., 2003). From the study of N-
type flanking folds in the Aims River Formation, NE of the contact with the Doros Pluton, together with the results of the analogue experiments, I discussed that N-type flanking folds can occur against counter- and co-rotating veins. This can happen in general shear that is pure shear dominated. If both structures were analyzed separately, the counter-rotating veins of the N-type flanking folds would be interpreted as being co-rotating in a zone with opposite sense of shear. In addition, the idea of pure shear domination in these rocks would not have been proposed. This example shows the importance of analyzing different N-type flanking folds in a volume of rock as being part of one mechanism. It also proves that care must be taken by interpreting shear sense from N-type flanking folds. Before making any conclusions, the mechanism must be known. In order to determine the mechanism, it is useful to study other flanking structures in the same volume of rock.

The flanking structures of the Lower Gemsbok Formation together with the analogue experiments showed that misinterpretation of flanking structures could be easily made, because only the finite structures are interpreted. Along the CE slip can occur, although the finite structure does not show displacement along the CE. In addition, slip that occurred along the CE at the late stage of the deformation might be of opposite sense with respect to the displacement of the HE at the finite state (for example, the transition between Reverse A-type and S-type flanking folds). Finite flanking structures can also occur with a unstable position of the CE relative to the shear zone boundaries (for example the Young Reverse A-type flanking folds of the Gemsbok formation, more to the North, near the Phanerozoic cover). Structures that seem to be in a geometrically unstable position are easily misinterpreted with respect to shear sense. This emphasizes again that flanking structures can only be used as kinematic indicators if their mechanism is known. The characters of different flanking structures during their development (that resulted from the analogue experiments) are useful to determine the mechanism of the finite flanking structure.

The differences between the N-type flanking folds that resulted from the experiments that were done in general shear compared to the experiments in simple shear cannot be used as criteria from which we can interpret the type of flow in field analysis. The differences in the amplification of the folding is not only a function of the type of flow, but can also be established by differences in viscosity of the CE and by the amount of shear strain. The transition between buckling and necking structures of the HE around the CE, occurs at different orientations of the CE relative to the shear zone boundaries, for different vorticity numbers. The orientation of the CE at which this transition zone occurs cannot be established from finite structures. Therefore, it is, at present, impossible to derive Wk from field analysis of flanking structures. Sometimes however, a suggestion can be made whether deformation is simple or pure shear dominated due to the sense of rotation of the CE. More experiments with different Wk must be done and flow patterns of the complete deformation paths should be made before we are able to derive the vorticity numbers from natural flanking structures.

Summarized, previous studies showed that N-type flanking structures are useful kinematic indicators. This study shows that N-type flanking folds can only be used as kinematic indicator if the mechanism of development is known. In order to determine the mechanism, other flanking structures in the same volume of rock can be very useful. Flanking structures with a CE along which slip can occur also can only be used as kinematic indicator if the mechanism of development is known. It is important to keep in mind that natural structures are finite structures. Characters of different flanking structures during their development are useful to determine the mechanism of the finite flanking structure and thereby use them as kinematic indicator. At present, it is impossible to derive Wk from field analysis of flanking structures. Sometimes however, a suggestion can be made whether deformation is simple or pure shear dominated due to the sense of rotation of the CE. More experiments with different Wk must be done and flow patterns of the complete deformation paths should be made before we are able to derive the vorticity numbers from natural flanking structures.
6. Conclusions.

During the study on natural examples of flanking structures in the Ugab and Goantagab valley, Namibia, several questions came up (see chapter 1.3) that could not be solved with the existing knowledge on flanking structures that was derived from previous studies. I hypothesized that flanking structures are not only a function of the type of ductile flow and initial position of the CE (Grasemann et al., 2003) but that also the rheological properties of the CE is important in the development of different types of flanking structures. In order to test this hypothesis, I manufactured flanking structures with the help of analogue modeling, in which I could not only vary the type of ductile flow and the initial position of the CE, but also to some degree the rheological properties of the CE. The knowledge of previous (numerical) studies together with the knowledge that was derived from the new analogue modeling was applied in an attempt to answer the questions regarding to the natural examples from the Ugab and Goantagab valley, Namibia.

From the analogue modeling of flanking structures that was done in this study, the following conclusions can be made:

- Flanking structures are a function of the type of ductile flow, initial position and the rheological properties of the CE.
- The analogue modeling confirms the conclusions of Grasemann and Stüwe (2001), that the amount of deflection of the HE against the CE is a function of the viscosity contrast between the HE and the CE and of the amount of shear strain. From the analogue experiments I can add to this conclusion that it is also a function of the type of flow (Wk).
- The analogue experiments resulted in new criteria’s that will be useful for the interpretation of N-type flanking folds in the field. The new criteria’s are listed in table 5.1 below.

<table>
<thead>
<tr>
<th>$Wk$</th>
<th>$\alpha$</th>
<th>Axial planes parallel to the CE</th>
<th>Structure of the HE around the CE</th>
<th>Strain of the CE</th>
<th>Extension of the fold hinges</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>$&gt;90^\circ$</td>
<td>No</td>
<td>Buckling</td>
<td>Shortening</td>
<td>No</td>
</tr>
<tr>
<td>1.0</td>
<td>$&lt;90^\circ$</td>
<td>Yes</td>
<td>Necking</td>
<td>Extension</td>
<td>Yes</td>
</tr>
<tr>
<td>0.7</td>
<td>$&gt;60^\circ$</td>
<td>No</td>
<td>Buckling</td>
<td>Shortening</td>
<td>No</td>
</tr>
<tr>
<td>0.7</td>
<td>$&lt;60^\circ$</td>
<td>Yes</td>
<td>Necking</td>
<td>Shortening</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 5.1: New criteria’s for the interpretation of N-type flanking folds, that followed from the analogue experiments.

The orientation of the CE at which the transition between the buckling and necking structure takes place, is a function of Wk. However, the point at which this transition occurs cannot be established from natural N-type flanking folds because these are finite structures.

- The analogue experiments adds criteria in order to separate the geometrically very similar Reverse A-type flanking fold and the Reverse shear band on top of the criteria of Grasemann et al. (2003). I conclude that A-type flanking folds show up and down stepping markers at the tips of the CE where shear bands only develop concave and convex markers at the tips of the CE.
- A-type flanking folds propagate into S-type flanking folds with increasing shear strain and during the co-shearing phase, thickening of the markers at the fold hinges occur. Grasemann et al. (2003) already proposed that flanking folds propagate into each other. The analogue experiments confirm this proposal.
From the heterogeneity patterns, I conclude that for simple shear, this exercise results in regular cell-forming patterns that appear to be unaffected by the amount of shear strain. From the position of the cells with respect to the CE the initial orientation of the CE can be derived more precise than from the geometry of the structure. I also had to conclude that no link was found between the cell positions and the geometry’s of the flanking folds. Therefore, the position of the centers of the cells as a function of the initial orientation of the CE cannot be used in field analysis.

The new knowledge that was derived from the analogue experiments was applied to the questions that came up during the analysis of natural flanking structures in the Ugab and Goantagab Valley, Namibia. Answering these questions resulted in the following conclusions that particularly refer to the flanking structures of the Ugab and Goantagab Valley:
- The presence of sinistrally as well as dextrally rotated veins, that both show development of N-type flanking fold next to each other in the same structural setting, is possible if the deformation is pure shear dominated.
- A-, S- and N-type flanking folds can occur next to each other in the same volume of rock due to propagation of A-type flanking folds into S-type flanking folds. During this transition, N-type flanking folds can develop that contain a CE along which slip did occur.
- Differences of the interlimb angles of the folds, thickening of the HE at the fold hinges and different grades of deflection inside a flanking structure can be a function of small differences in initial orientation of the CE, viscosity contrast between the CE and the HE and differences in the amount and sense of shear along the CE.
- The classification for flanking structures in figure 1.1 and 1.2 is insufficient to classify all studied flanking structures. A subdivision of the classification of A-type flanking folds into Young Reverse A-type (α > 90°) and Mature Reverse A-type flanking folds (α < 90°) is necessary.

From the interpretation of the natural examples of the Ugab and Goantagab valley, Namibia with the knowledge that was derived from the analogue modeling, I conclude that the mechanism must be known for all types of flanking structures before making conclusions in terms of shear sense and type of flow. Analyzing other flanking structures in the same volume of rock is a very useful tool in order to discover this mechanism, as well as the characters of different flanking structures that are generated during their development. Nevertheless, flanking structures can be very useful if they are used supplementary with help of other kinematic indicators inside the rocks. In order to interpreted flanking structures in terms of Wk, more analogue experiments with different Wk are needed and flow patterns should be made of the complete deformation.

7. Acknowledgments.

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8. References.


Appendix 1: Improvements of the apparatus

The deformation box that was used for the analogue experiments on flanking structures contains walls that made of Plexiglas segments. These segments are connected with flexible plastic. These walls are being pushed away from each other due to the weight of the PDMS. The walls change from straight walls into oblique walls, increasing the surface of the bottom and decreasing the surface of the top of the box. This influences the width of the zone of heterogeneous deformation. In addition, leakage of the PDMS at the bottom of the box is increased due to the oblique position of the walls. Increasing the strength of the walls will help to solve this problem. Nevertheless, the walls need to be flexible to transfer the movement of the motors into deformation of the PDMS. Connecting the Plexiglas segments with stronger flexible plastic might be a solution.

The PDMS slowly dissolves the glue that connects the springs to the walls of the deformation box. More tapes disconnected results in a larger zone of heterogeneity. Therefore, the tapes have to be repaired frequently. This is a difficult and time-consuming process. Making the connection of the springs with the walls of the box out of one piece will solve the problem. For example, the Plexiglas segments can be made of metal segments that contain a little eye at the back. These segments should be connected with each other by a stronger flexible plastic. The eye should stick out of the flexible plastic and should be directly connected to the springs. This solves also the oblique position of the walls due to the weight of the PDMS. It might be difficult to build and definitely is a time-consuming change, but it will improve the homogeneity of the box and it will save a lot of time during experiments.

The PC-program LabView, which controls the stepping motors, contains a program (Step-Axis-Control) that is responsible for the movement of each individual motor separately. This program is used to bring the deformation box in a preferred initial position. The program does not react appropriately to the comments. The program does not react on positive and negative signs for forward and backward movements of the motors respectively. The program also does not react appropriately on the quantity of displacement that needs to be stated for each motor. Therefore, it takes a lot of trial and error before the dimensions of the box reach the preferred initial position. In order to solve this problem the code of the program needs to be adjusted.

The program that was used for the experiments in general shear should be a program of plane strain deformation (no change of volume during deformation). However, each experiment with this program resulted in a volume loss of 14-16%. This systematic deviation in the volume of the box during deformation needs to be fixed by adjusting the code of the program Transpression D (plane strain).
Appendix 2: Settings of the configuration files of PIVSleuth

Below, the settings for the coarse and fine configuration files of the program PIVSleuth are given. These were used during the analysis of flow patterns from the images of the experiments. A, B and C represent the settings for the coarse configuration file. D, E and F represent the settings for the fine configuration file.

A:

B:

C:
General Policies -
Mean Particle Image Diameter:
Displacement/Velocity Conversion:
- Time separation between exposures = [value] s
- 1 pixel of displacement in x direction = [value] mm
- 1 pixel of displacement in y direction = [value] mm

General Configurations:
- Interrogation Parameters:
  - Window Overlap: [value] %
  - Peak Fit Method: Gaussian
  - Starting Cone: Lower Left
  - Direction: Right

Flow Parameters:
- Mean Flow Direction: Up

Options:
- Perform Second-Order Correlation
- Iterative Interrogation

F:
In this section, we discuss...

D:
...and in this part, we focus...
Appendix 3: Flow patterns

This appendix shows the results of the flow patterns from the experiments that were carried out in the deformation box. The patterns were derived as described in chapter 3.4.2 with help of the program PIVSleuth.
Wk=0.1

carton

N45
$W_k = 0.1$

$\rho + 25\% \text{Pla}$

$N_{45}$
Wk=0.1

overhead + silicone gel

reverse shear band 165
2400-2700

4800-5100

Wk=0.1

overhead + silicone gel

reverse A135

7200-7500
$W_k = 0.1$

overhead + silicone gel

reverse A90