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Parameters that control the development of clay smear at low stress states: an experimental study using ring-shear apparatus

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Abstract

Clay smear involves entrapment of clay or shale within the fault zone, thereby giving the fault a high capillary entry pressure and a low permeability. We examine the coherence of a clay smear as a function of normal stress, deformation rate, and water content in clay and sand. The work is based on drained ring-shear experiments. The samples used in the experiments consist of mixed sectors of sand (Baskarp Sand No. 15) and clay. The tested clays include clay from Trondheimsfjorden (Norway) and Drammensfjorden (Drammen Clay; Norway), London Clay (UK) and three different clays from the Utsira High (offshore Norway).

Three stages are recognised in the development of a clay membrane. In the first stage, utilising low normal stress of 6 kPa, there is a complete absence of any semi-continuous to continuous clay smears for all clays used. Only occasional clay fragments occur on the fault plane. In the second stage, a mixture of clay and sand or patchy clay in a sand matrix developed (normal stress >25 kPa dependent upon clay type), whereas a semi-continuous to continuous clay membrane is typical for the third stage (normal stress >100 kPa dependent upon clay type). Experiments that reflect a transitional stage between the second and third stages are frequently observed.

Comparing experiments with dilation and compaction, which had the same deformation conditions, it is observed that those samples that compacted during deformation became clay-covered to a larger extent than those that dilated. Differences of 2 and 9% were observed in the present study. The potential for developing a continuous clay membrane increases as: (1) normal stress increases, (2) water content of sand and clay increases, and (3) shear strength of the clay decreases. A complex relationship between strain-rate, clay types and normal stress is observed. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Fault seals; Clay smear; Ring-shear experiments; Deformation parameters

1. Introduction

Fault sealing is a key factor in controlling entrapment and migration of hydrocarbons both during migration in geological time and in production (Stearns and Friedman, 1972; Hardman and Booth, 1991; Nelson, 1985). Faults can create barriers for fluid flow, but can also act as lateral and vertical migration paths for fluids, thus influencing the reservoir communication. Fault seals can be divided into different types according to which characteristics rule the reduction in fluid flow along and/or across the fault, such as *juxtaposition seals* (e.g. Smith, 1966, 1980; Allan, 1989; Knipe, 1997; Yielding et al., 1997) and *membrane seals/fault rock seals*. The latter is further sub-divided into *cataclastic seals* (e.g.Aydin and Johnson, 1978; Antonellini and Aydin, 1994; Gabrielsen et al., 1998), *cemented/diagenetic seals* (e.g. Knipe et al., 1997; Sverdrup and Bjørlykke, 1998) and *clay smear seals* (e.g. Bouvier et al., 1989; Knipe, 1992; Lindsay et al., 1993; Gibson, 1994; Ottesen-Ellevset et al., 1998). The development of such seals is primarily dependent upon the original host rock lithology, the deformation process and conditions, as well as the amount of cementation involved (Knipe et al., 1997). Clay smear involves entrapment of clay or shale within the fault zone, thereby giving the fault a high capillary entry pressure and a low permeability. Although such seals are regarded to be of great importance in many hydrocarbon reservoirs, such features are not well understood. One particular problem is related to the continuity of the clay membrane. Because data on clay smear geometry are difficult to access in the field (Lindsay et al., 1993), an experimental approach seems appropriate for investigating the problems of dynamic development of a clay smear and the parameters, which influence its geometry.

Ring-shear experiments have previously been applied to investigate shear processes in homogenous (Hvorslev, 1939; Nowacki, 1967; Bishop et al., 1971; Mandl et al., 1977;

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Brown et al., 1994; Stark and Contreras, 1996), as well as heterogeneous lithologies (Weber et al., 1978; Sperrevik, 1997; Sperrevik et al., 2000). Weber et al. (1978) used ring-shear experiments with alternating sand–shale sequences to model fault zone development and clay smear. These results were compared with natural fault zones in Frechen, Germany. Sperrevik (1997) and Sperrevik et al. (2000) utilised the ring-shear apparatus to investigate development of a clay smear along faults in stratified sand–clay sequences. One main conclusion of these studies was that development and continuity of a clay smear is strongly dependent upon the competency contrast between clay and its surrounding material. In its turn, the competency contrast between clay and porous, unconsolidated sand is mainly influenced by the shear strength of the clay and sand. Also the initial porosity of the sand and the stress under which the experiments are performed is of importance in the development of a clay smear.

The present experimental study expands on the works performed by Sperrevik (1997) and Sperrevik et al. (2000). Hence, the same sand (Baskarp Sand No. 15) in combination with two of the clay types (London Clay and Drammen Clay) used by Sperrevik (1997) and Sperrevik et al. (2000), as well as the same apparatus were utilised in the introductory experiments to make results directly comparable. In addition, several other clay types, including some from the North Sea, were studied. In the present study we further examine the coherence of clay smear as a function of normal stress, deformation rate and water content of clay and sand in some detail. The influences that the clay and sand properties impose on the potential for development of a continuous clay membrane have been particularly emphasised in this study. A characterisation of the different clay types and its significance for clay smear potential is further discussed in a separate contribution (Clausen et al., 2002b).

2. Ring-shear experiments

Experiments (Fig. 1a) were performed at the Norwegian Geotechnical Institute (NGI) in Oslo, Norway utilising

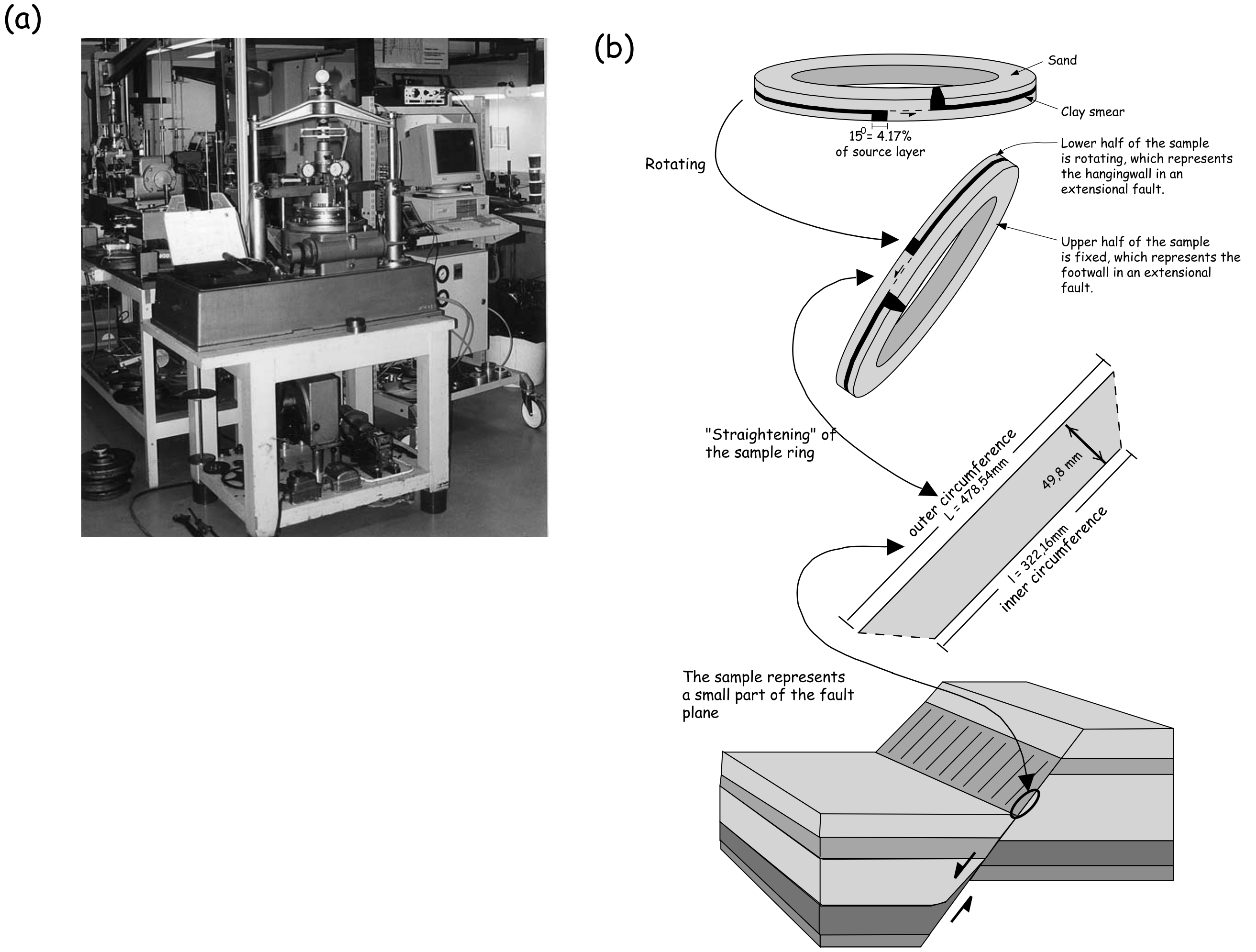
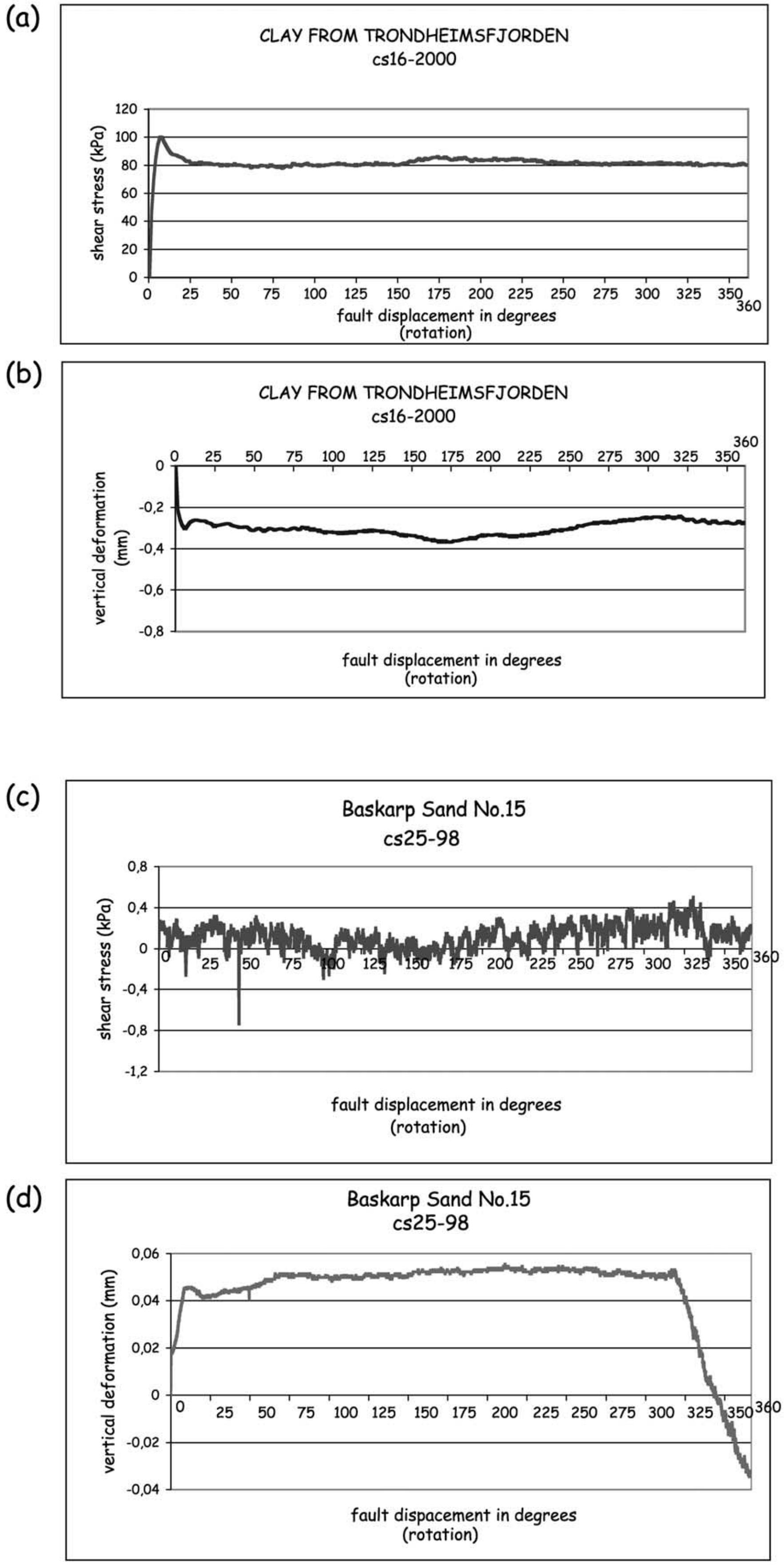


Fig. 1. (a) The ring-shear apparatus at the Norwegian Geotechnical Institute (NGI) in Oslo (Norway). (b) The annular sample, which consists of clay and sand, is corresponding to a small part of a fault plane when straightening.

Table 1

Properties of the clays. In addition, samples also consist of Baskarp Sand No. 15, which is a standard industrial sand from a sandpit at Jönköping, Sweden. It is a ca. 10,000-year-old glacial deposit (AB Baskarpsand, 1988). The sand has a red brownish colour and consists of more than 90% quartz. The contractor sorts it and the grains are classified as angular to sub-angular. At the start of the experiments, the sand had a porosity of ca. 39%, which means that it is characterised as loose sand. The *limits of consistency* are used to classify and characterise clays and clay rich soils. Soils have different mechanical properties that can be found with distinct methods. In the present study, the Norwegian Standard (NS 8000) is utilised. The Norwegian Standard referred to is in accordance with standards used in e.g. Sweden and standards published by the American Society for Testing and Materials. The British Standards Institution uses other symbols. *The plastic limit* (W_P) is decided after the Norwegian Standard NS 8003. *The liquid limit* (W_L) is decided after the fall cone method using the Norwegian Standard NS 8001. The *water content* in the clay is decided using the Norwegian Standard NS 8013, and the *undrained shear strength* is decided using the Norwegian Standard NS 8015 (by use of the fall cone method or a pocket penetrometer)

Trondheimsfjorden Clay	Homogenous, soft, grey Sample depth: 8.40–8.45 m, burial depth: unknown Water content: ca. 30% I_p: 17% (moderately plastic) (*sensu* Aarhaug, 1984) W_p: 18%, W_L: 36%: I_L: 0.68% Undrained shear strength: ca. 21 kPa in an undisturbed sample; ca. 5 kPa in a remoulded sample Age: Quaternary	Clay minerals: kaolinite, illite, clorite (±smectite) Other minerals: quartz, k-feldspar, plagioclase feldspar, calcite
Drammen Clay	Homogenous, soft, bluish darkgrey Sample depth: 7.30–7.60 m, over-consolidated (Bjerrum, 1967) Water content: ca. 43% I_p: 28% (very plastic) (*sensu* Aarhaug, 1984) W_p: 25%, W_L: 526%: I_L: 0.36% Undrained shear strength: ca. 30 kPa in an undisturbed sample; ca. 10 kPa in a remoulded sample Age: post-glacial—ca. 3000 years (Bjerrum, 1967)	40–50% clay minerals (Foss, 1969) Clay minerals: kaolinite, illite, clorite, smectite (Sperrevik et al., 2000)
London Clay	Generally homogenous and dark grey, but occasional accumulations of visible sand grains, limestone cemented sand and fractures Sample depth: 15.25–15.35 m, maximum burial depth: 500 m (Sperrevik et al., 2000) Water content: ca. 43% I_p: 55% (very plastic) (*sensu* Aarhaug, 1984) W_p: 29%, W_L: 846%: I_L: −0.03% Undrained shear strength: ca. 452 kPa in an undisturbed sample Age: Eocene	Quartz is the dominant mineral Illite and swelling clays are predominant (Sellwood and Sladen, 1981) Clay minerals: kaolinite, illite, clorite smectite (Sperrevik et al., 2000)
North Sea Clay No. 1	Homogenous, dark grey Sample depth: 8.70–8.90 m, burial depth: unknown Water content: ca. 17–18% I_p: 17% (moderately plastic) (*sensu* Aarhaug, 1984) W_p: 14%, W_L: 31%: I_L: −0.18% Undrained shear strength: ca. 200–260 kPa in an undisturbed sample; ca. 250 kPa in a remoulded sample Age: Quaternary	Clay minerals: kaolinite, illite, smectite, chlorite Other minerals: quartz, k-feldspar, plagioclase feldspar, calcite
North Sea Clay No. 2	Greenish-greyish laminated with light grey silt Sample depth: 83.15–83.55 m, burial depth: unknown Water content: ca. 21–22% I_p: 22% (moderately plastic) (*sensu* Aarhaug, 1984) W_p: 21%, W_L: 43%: I_L: 0.02% Undrained shear strength: ca. 430–470 kPa in an undisturbed sample; ca. 300 kPa in a remoulded sample Age: Quaternary	Clay minerals: kaolinite, illite, smectite, chlorite Other minerals: quartz, k-feldspar, plagioclase feldspar, calcite
North Sea Clay No. 3	Homogenous, hard, grey Sample depth: 25–10–25–30 m, burial depth: unknown Water content: ca. 14% I_p: 17% (moderately plastic) (*sensu* Aarhaug, 1984) W_p: 15%, W_L: 32%: I_L: −0.08% Undrained shear strength: ca. 720–760 kPa in an undisturbed sample; ca. 500 kPa in a remoulded sample Age: Quaternary	Clay minerals: kaolinite, illite, smectite, chlorite Other minerals: quartz, k-feldspar, plagioclase feldspar, calcite


(a)
CLAY FROM TRONDHEIMSFJORDEN
cs16-2000
shear stress (kPa)
120
100
80
60
40
20
0
0 25 50 75 100 125 150 175 200 225 250 275 300 325 350 360
fault displacement in degrees
(rotation)
(b)
CLAY FROM TRONDHEIMSFJORDEN
cs16-2000
vertical deformation (mm)
0 25 50 75 100 125 150 175 200 225 250 275 300 325 350 360
0
-0,2
-0,4
-0,6
-0,8
fault displacement in degrees
(rotation)
(c)
Baskarp Sand No.15
cs25-98
shear stress (kPa)
0,8
0,4
0
-0,4
-0,8
-1,2
0 25 50 75 100 125 150 175 200 225 250 275 300 325 350 360
fault displacement in degrees
(rotation)
(d)
Baskarp Sand No.15
cs25-98
vertical deformation (mm)
0,06
0,04
0,02
0
-0,02
-0,04
0 25 50 75 100 125 150 175 200 225 250 275 300 325 350 360
fault dispacement in degrees
(rotation)

standard equipment for drained ring-shear (Nowacki, 1967). The sample was positioned with the shear plane oriented horizontally, confined between pairs of upper and lower confining rings. The annular specimen was loaded by weights to create normal stress and was confined laterally. The shear was ultimately caused to activation on a plane of relative rotary motion. All experiments were performed with constant deformation rate. The sample volume was allowed to change, and shear stress and sample volume changes were recorded during deformation. The idea is that the sample corresponds to a small part of a fault plane (Fig. 1b). Hence, rotation of the upper sample ring mimics planar shear along a fault plane, and rotation equals total fault displacement in one sector of the fault plane. The rotating half of the sample represents the hanging wall in an extensional fault and the fixed part represents its footwall. Structures can be studied in three dimensions after the experiment is finalised. The vertical load is such that the experimental conditions correspond to faults developed in soft sediments at a shallow depth of burial (up to ca. 50 m; Sperrevik et al., 2000). More comprehensive descriptions of the ring-shear apparatus are given by Nowacki (1967), Bishop et al. (1971), Mandl et al. (1977) and Sperrevik et al. (2000).

In total, 78 experiments were performed using Baskarp Sand No. 15 in combination with different clays. The clays used in the experiments were post-glacial clays from Trondheimsfjorden (Norway; Trondheimsfjorden clay) and Drammensfjorden (Norway; 'Drammen Clay'), the much studied Eocene London Clay (UK), and three different clays from the Utsira High, offshore Norway (referred to as North Sea clay no. 1, 2 and 3 in the following). The properties of the clays are summarised in Table 1, and a more detailed description is given in Clausen et al. (2002b). Each experimental run utilised one clay type only. For reference, two experiments using sand without a clay layer were also performed.

Previous works applying ring-shear apparatus in the study of a clay smear have concluded that the method gives very useful analogues (Weber et al., 1978; Sperrevik et al., 2000). The present study seems to support this conclusion. Furthermore, comparing repeated experiments where similar experimental conditions were applied, we also conclude that reproducibility of the experiments is good.

3. Results

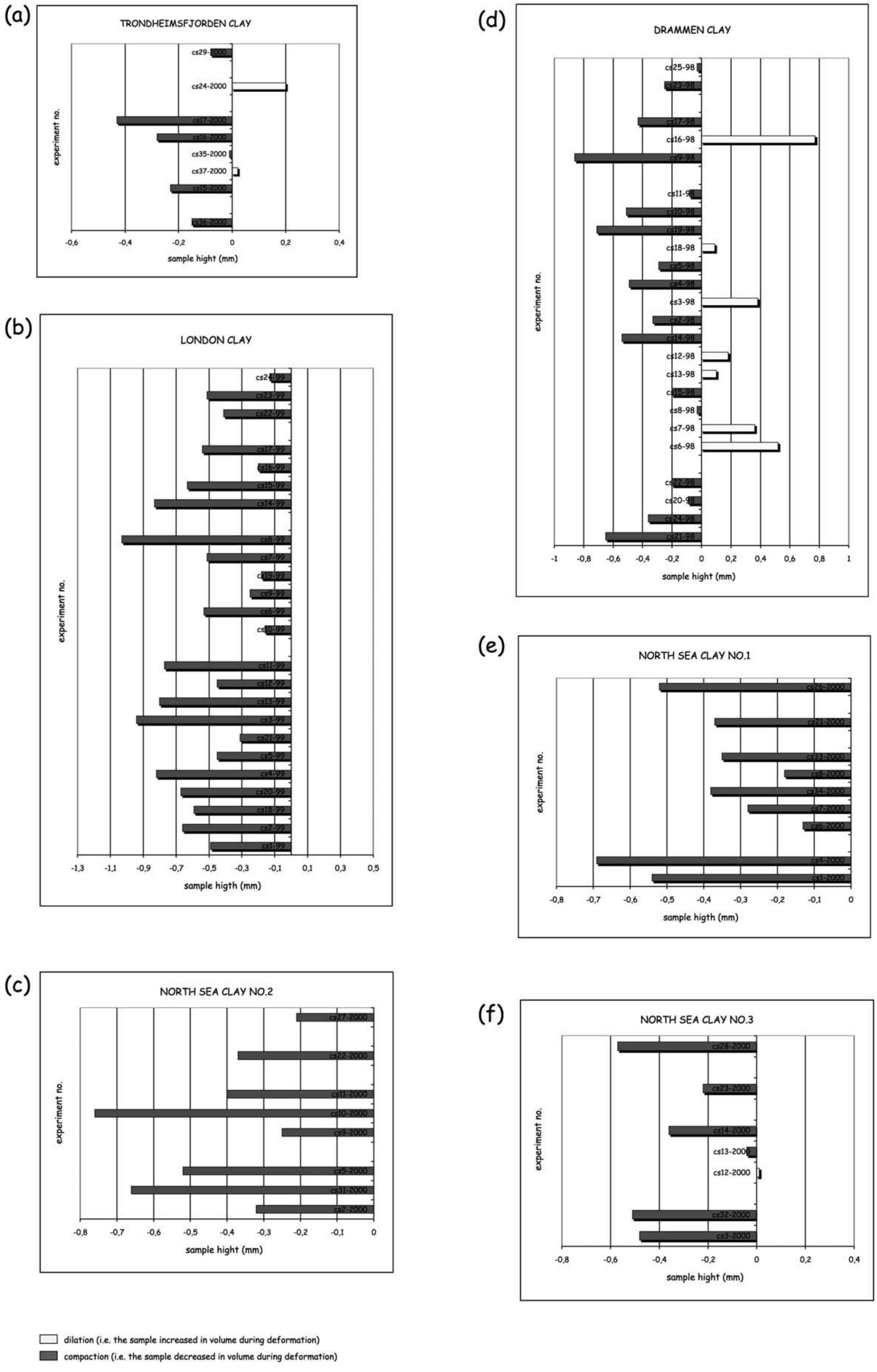
Previous studies of shear zones in porous, geological media (e.g. Mandl et al., 1977) concentrated on describing the intrinsic processes of shear bands in homogenous sands. These experimental conditions facilitated observation of grain reorganisation and dilation, demonstrating that these are important deformation processes.Weber et al. (1978), Sperrevik (1997) and Sperrevik et al. (2000) expanded such experiments to include layered media (sand and clay). Weber et al. (1978) modelled fault zone development and clay smear, and compared the experimental results with natural fault zones in Frechen, Germany. Sperrevik (1997) and Sperrevik et al. (2000) tested the relation between a clay smear cover and its continuity, and varying normal stress, deformation rate, water content in clay, fault displacement and number of clay layers for different clays. They concluded that the amount of clay cover and its continuity depends on the competency contrast between clay and sand, which is mainly dependent upon strength of clay and sand, the initial porosity of sand and the stress. Also, the water content in clay influenced the clay smear continuity and degree of clay cover.

The present work further investigates the findings of Sperrevik (1997) and Sperrevik et al. (2000) in that a larger number of experimental runs are included, and that a more continuous range of conditions has been tested. Thus, a total of 78 experiments have been run systematically measuring the effect of loading normal stress, deformation rate, water content in clay and sand and types of clay. The experiments were run in batches, so that only one parameter was changed in each series. For reference, two experiments were performed using only sand. As realised by Sperrevik (1997) and Sperrevik et al. (2000), the processes associated with dilation and compaction are important in interpreting the final result of the experiments. Accordingly, this phenomenon was given particular attention in all experiments, and vertical deformation was continuously recorded in each case. In the following, the main results from each experimental series is described for each variable parameter.

3.1. Shear stress and sample volume change

Analysis of the stress–strain relations, which were recorded throughout the present experiments, suggest that the development commonly can be subdivided into four separate steps, namely pre-peak, peak, strain-hardening/strain-softening and eventually stick-slip (Fig. 2a). Some experiments followed a different path, and were characterised by only strain-hardening or strain-softening after a pre-peak and peak stadium. Also, in some experiments a

Fig. 2. (a) The stress–strain curves in mixed layer (sand and clay) experiments characterised by pre-peak, peak, strain-hardening/strain-softening and stick-slip steps. (b) Generally, the sample volume changed in harmony with the stress–strain curves, so that the compaction is mainly recorded at an early start of the experiments, which coincides with the initial peak step. The example in (a) and (b) use clay from Trondheimsfjorden and normal stress of 200 kPa. (c) The experiments performed using only Baskarp Sand No. 15 are different from experiments using heterogeneous samples (sand and clay). Notice the characteristic stick-slip path for the stress–strain curve. (d) Dilation, which is largest at the start of the experiment for the heterogeneous samples, occur throughout the experimental run. The last stage of deformation is, however, mainly characterised by compaction resulting in a bulk volume reduction of the sample. The example in (c) and (d) uses low normal stress of 6 kPa.


(a)
TRONDHEIMSFJORDEN CLAY
experiment no.
cs29-2000
cs24-2000
cs17-2000
cs16-2000
cs35-2000
cs37-2000
cs15-2000
cs36-2000
-0,6
-0,4
-0,2
0
0,2
0,4
sample hight (mm)
(b)
LONDON CLAY
experiment no.
cs24-99
cs23-99
cs22-99
cs17-99
cs16-99
cs15-99
cs14-99
cs8-99
cs7-99
cs19-99
cs9-99
cs6-99
cs10-99
cs11-99
cs12-99
cs13-99
cs3-99
cs21-99
cs5-99
cs4-99
cs20-99
cs18-99
cs2-99
cs1-99
-1,3
-1,1
-0,9
-0,7
-0,5
-0,3
-0,1
0,1
0,3
0,5
sample higth (mm)
(c)
NORTH SEA CLAY NO.2
experiment no.
cs27-2000
cs22-2000
cs11-2000
cs10-2000
cs9-2000
cs5-2000
cs31-2000
cs2-2000
-0,8
-0,7
-0,6
-0,5
-0,4
-0,3
-0,2
-0,1
0
sample hight (mm)
(d)
DRAMMEN CLAY
experiment no.
cs25-98
cs23-98
cs17-98
cs16-98
cs9-98
cs11-98
cs10-98
cs19-98
cs18-98
cs5-98
cs4-98
cs3-98
cs2-98
cs14-98
cs12-98
cs13-98
cs15-98
cs8-98
cs7-98
cs6-98
cs22-98
cs20-98
cs24-98
cs21-98
-1
-0,8
-0,6
-0,4
-0,2
0
0,2
0,4
0,6
0,8
1
sample hight (mm)
(e)
NORTH SEA CLAY NO.1
experiment no.
cs26-2000
cs21-2000
cs33-2000
cs8-2000
cs34-2000
cs7-2000
cs6-2000
cs4-2000
cs1-2000
-0,8
-0,7
-0,6
-0,5
-0,4
-0,3
-0,2
-0,1
0
sample higth (mm)
(f)
NORTH SEA CLAY NO.3
experiment no.
cs28-2000
cs23-2000
cs14-2000
cs13-2000
cs12-2000
cs32-2000
cs3-2000
-0,8
-0,6
-0,4
-0,2
0
0,2
0,4
sample hight (mm)
dilation (i.e. the sample increased in volume during deformation)
compaction (i.e. the sample decreased in volume during deformation)

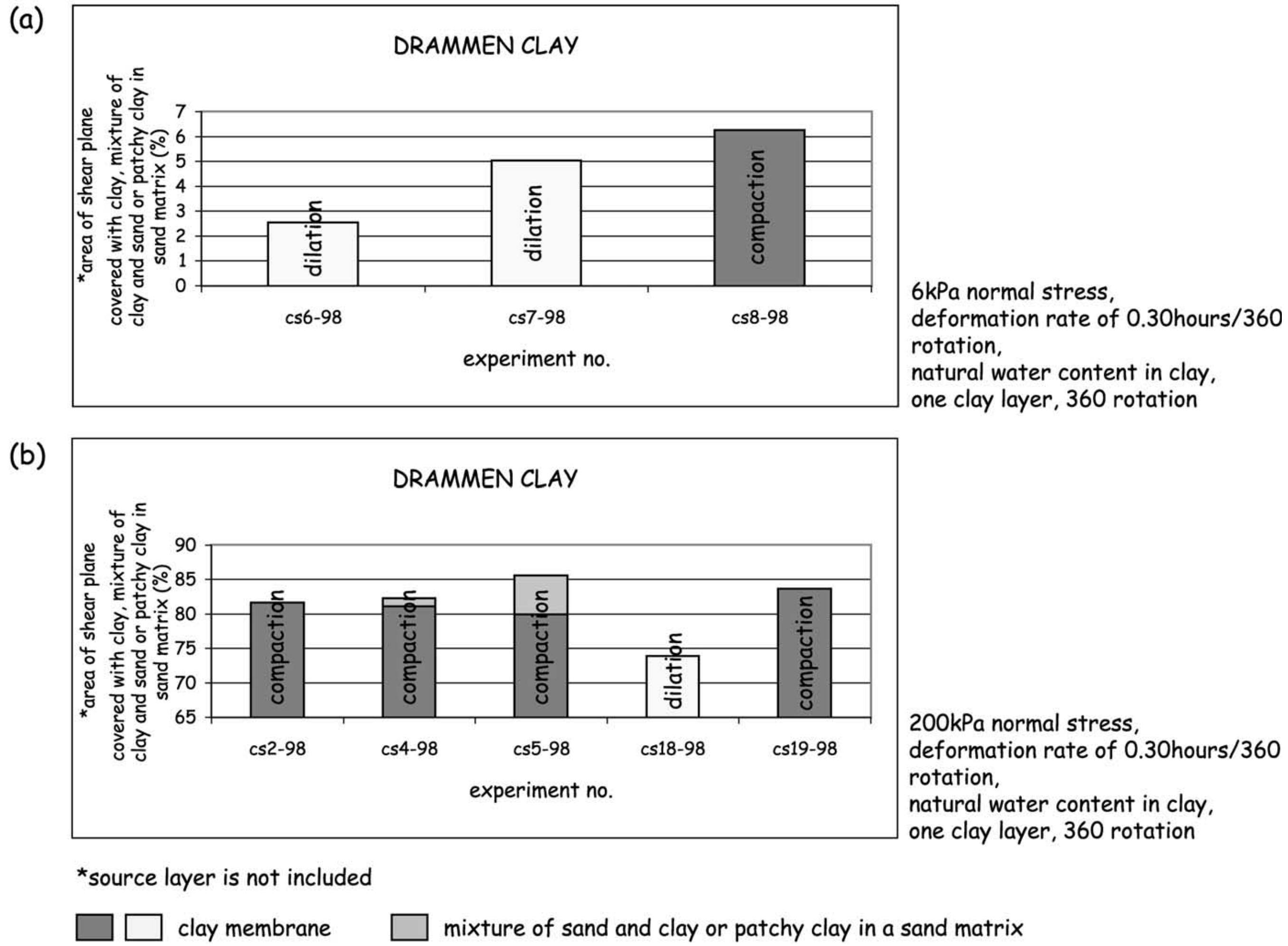


Fig. 4. Comparing experiments with dilation and compaction, which had the same deformation conditions, it is observed that samples that compacted became clay-covered to a larger extent than those that dilated. This observation is valid for experiments at (a) 6 kPa, as well as (b) 200 kPa.

distinct peak stage could not be observed. Generally, the shear stress was lower than the normal stress, even though one exception was observed.

The vertical component of deformation was recorded during all experiments. Dilation (i.e. sample volume increase during deformation) was sometimes observed, whereas compaction (i.e. sample volume decrease during deformation) was most common (Fig. 3). Generally, the sample volume changed in harmony with the stress–strain curves, so that the main compaction or dilation were mainly recorded at the initial peak step, which usually coincides with the initial stage of shearing (Fig. 2a and b). After the initial peak step, following the steps in the stress–strain curves, compaction and dilation of the sample occurred in short distinct intervals, although exceptions to this were observed. The few experiments where dilation occurred were characterised by a normal stress up to 200 kPa, and mainly between 6 and 50 kPa. In contrast, most of the experiments performed at normal stress >200 kPa compacted. Keeping the other deformation parameters constant, and comparing experiments with dilation and compaction, it is observed that those samples that compacted during deformation became clay-covered to a larger extent than those that dilated (Fig. 4). Differences of 2 and 9% were observed. Note that the uncertainty in reproduction of the experiments and calculation of amount of clay on the shear plane is estimated to range between 1 and 3%. There does not seem to be any direct (linear) correlation between magnitude of compaction, and bulk area covered with clay, mixture of sand and clay or patchy clay in a sand matrix.

Experiments performed by use of only Baskarp Sand No. 15 are different from the heterogeneous samples (layered sand and clay). The results show that the homogenous

Fig. 3. Example illustrating variance in vertical strain for the experiments, demonstrating that most of the samples became compacted during deformation. However, experiments performed with normal stress up to 200 kPa were sometimes dilating.

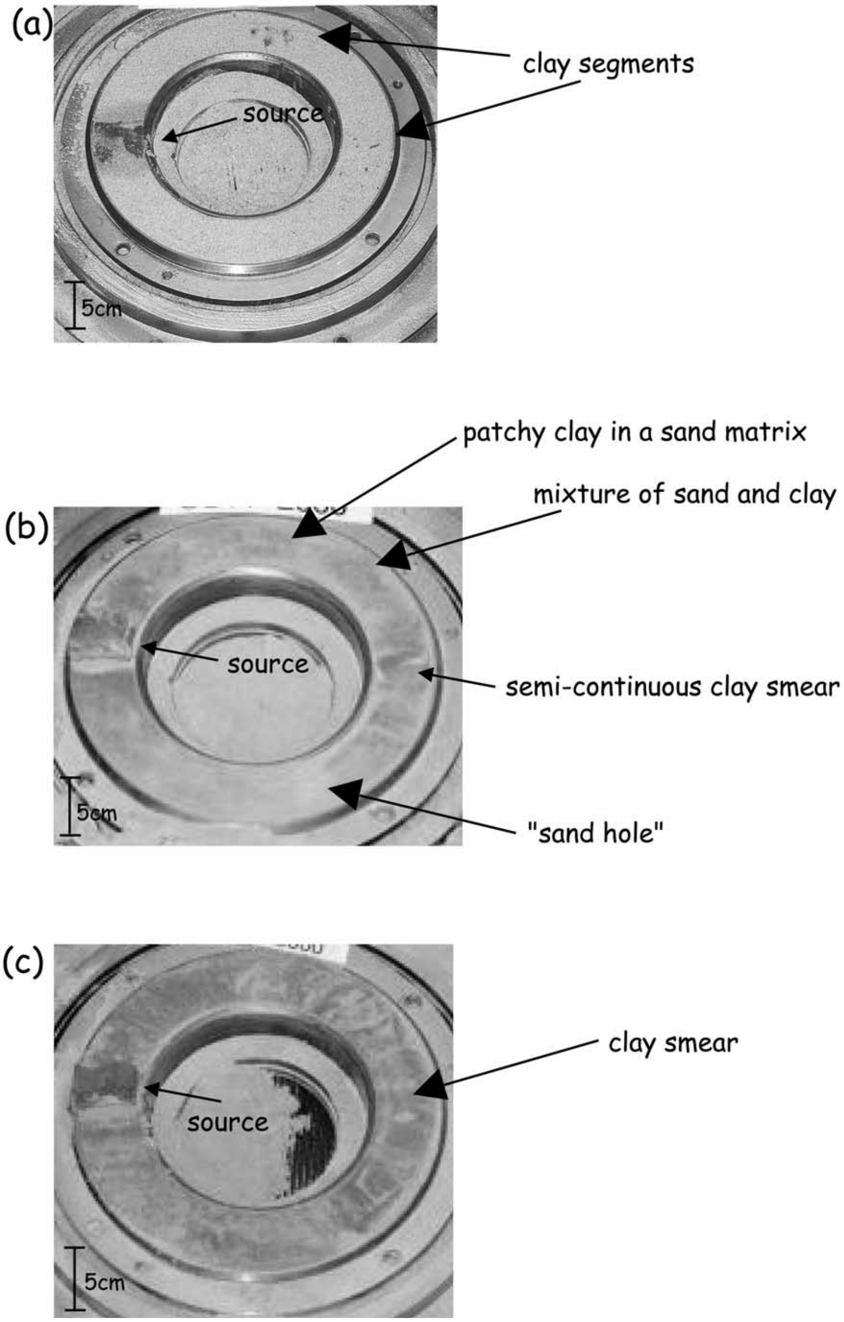


Fig. 5. Ring-shear experiments seen from above, after removal of the upper half of the sample. Three stages are recognised in the development of a clay membrane, namely (a) complete absence of a clay membrane (normal stress of 6 kPa for all clays; Drammen Clay), (b) a mixture of clay and sand or patchy clay in a sand matrix (normal stress of >25 kPa dependent upon clay type; North Sea Clay No. 2), and (c) a semi-continuous to continuous clay membrane (normal stress of >100 kPa dependent upon clay type; Trondheimsfjorden clay).

samples were dominated by dilation during the experimental run, where the largest expansion occurred at the start of the experiment. Thus, the homogeneous samples were characterised by stick-slip throughout the whole experimental run (Fig. 2c and d). Towards the end of the experiment, however, also these samples underwent compaction, resulting in a bulk volume reduction.

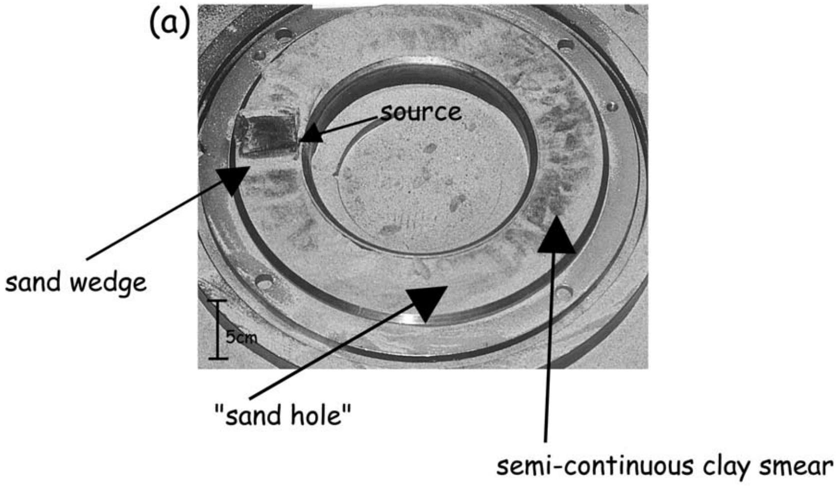
Sperrevik (1997) and Sperrevik et al. (2000) noted that shear stress values during dilation were smaller than those observed during contraction, and ascribed the combined dilation/strain softening to formation of new shear zones. These would follow the most loosely packed zones, defining the weakest zone in the system. This suggests that the sand is actively taking part in the deformation, even when clay is present. On the other hand, the present experiments performed using clean Baskarp Sand No. 15 (without a clay source), display a contrasting behaviour from experiments where heterogeneous samples (layered sand and clay) were used, the main difference being that the homogeneous samples were characterised by stick-slip throughout the entire experimental run (Fig. 2c and d). We take this as an indication that, once it is introduced into the fault plane, the clay strongly influences or even dominates the mode of shear at the more advanced stages of strain.

3.2. Clay smear geometry

Based on the present ring-shear experiments, three stages are recognised in the development of clay membranes (Fig. 5). In the first stage, which is typical for experiments utilising low normal stress (6 kPa), there is a complete absence of a clay membrane for all clays used. Only occasional clay fragments occurred along the fault plane. In the second stage, which is commonly seen at slightly higher normal stress (>25 kPa, varying slightly with clay type), a mixture of sand and clay or patches of clay embedded in a sand matrix were observed. In the third stage, a semi-continuous to continuous clay membrane developed (normal stress >100 kPa dependent upon clay type). Experiments that reflect a transitional stage between the second and third stages were frequently observed.

Sand wedges (Fig. 6a) are developed close to the source layers, occurring in 21 out of the 78 experiments. Such features were also reported by Weber et al. (1978), Sperrevik (1997) and Sperrevik et al. (2000). These wedges connected sand in the lower half with sand in the upper half of the sample, and would provide bridges for hydrocarbon communication across the fault in a real case.

Clay wedges or lenses (Fig. 6b) are observed close to the source layer. Such wedges were recorded in 12 of the 78 experiments, and seem to be associated with rupturing of the clay membrane following drag from the source layer. This is consistent with the findings of Sperrevik (1997) and Sperrevik et al. (2000), who interpreted such structures as indications of brittle deformation associated with initiation of Riedel- and Riedel′-shears.



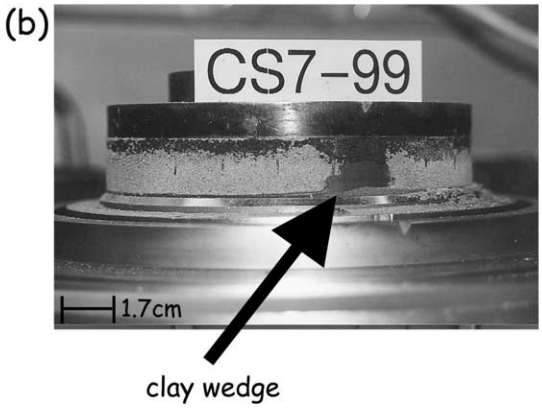


Fig. 6. Ring-shear experiments (a) seen from above where a sand wedge has developed close to the source layer, and where sand 'holes' occur in the clay smear, and (b) seen in profile where a clay wedge has developed close to the source layer.

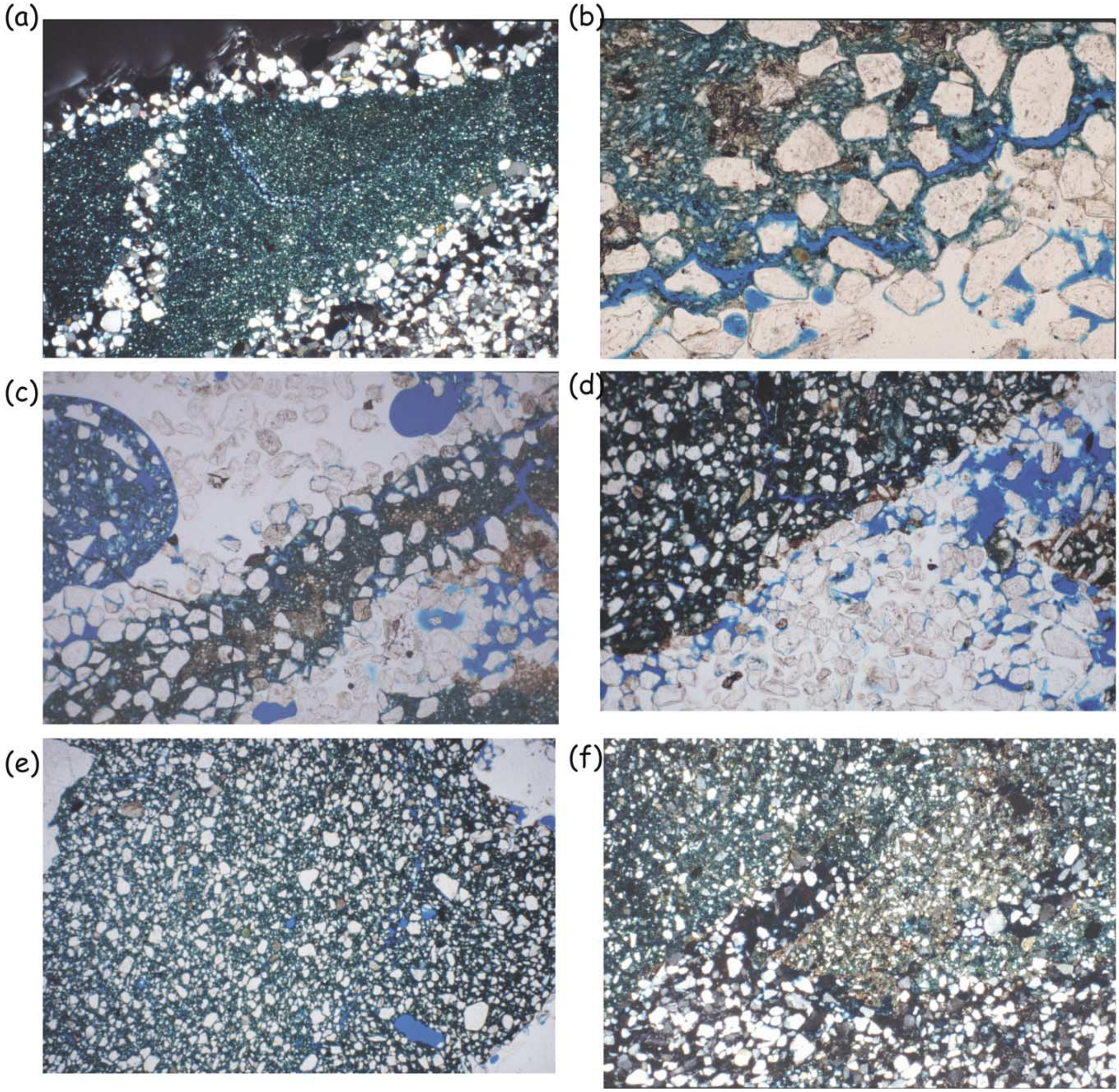


Fig. 7. Microphotographs from clay-smear experiments. (a) Homogeneous lenses of clay separated by micro-ramp of pure sand. (b) Transition zone at the contact between clay lens and sand. Note isolated sand grains embedded in a clay matrix. (c) Zoned and (d) sharp contacts between sand and clay. (e) Homogeneous mixture of sand and clay. (f) Areas of contrasting texture within the mixed zone, perhaps reflecting internal flow, rolling of fragments and amalgamation of smaller clay–sand lenses.

Another type of clay wedge is common close to the source layer, where continuous clay wedges are frequently developed. These are in contact with the source layer, and would, by continued displacement, provide a semi-continuous to continuous clay membrane. In the low-stress experiments continued deformation would cause the rupturing of the clay layer to form sub-rounded to oval-shaped 'sand holes' (Figs. 5 and 6a). The area adjacent to these 'sand holes' was often characterised by a mixture of sand and clay. The continuity of the clay membrane can also be completely lost across the entire annular sample.

Where developed, the semi-continuous to continuous clay membrane had more or less a constant thickness ranging between 1 and 5 mm, along the entire fault plane. In cases where the clay membrane was seen to vary in thickness along the shear plane, this was in harmony with thickness variations in the sand layer beneath it (see also Sperrevik et al., 2000).

The water content of the clay smear was measured before and after deformation, and the results show that the water content decreased when increased normal stress was applied, and with increasing distance from the source

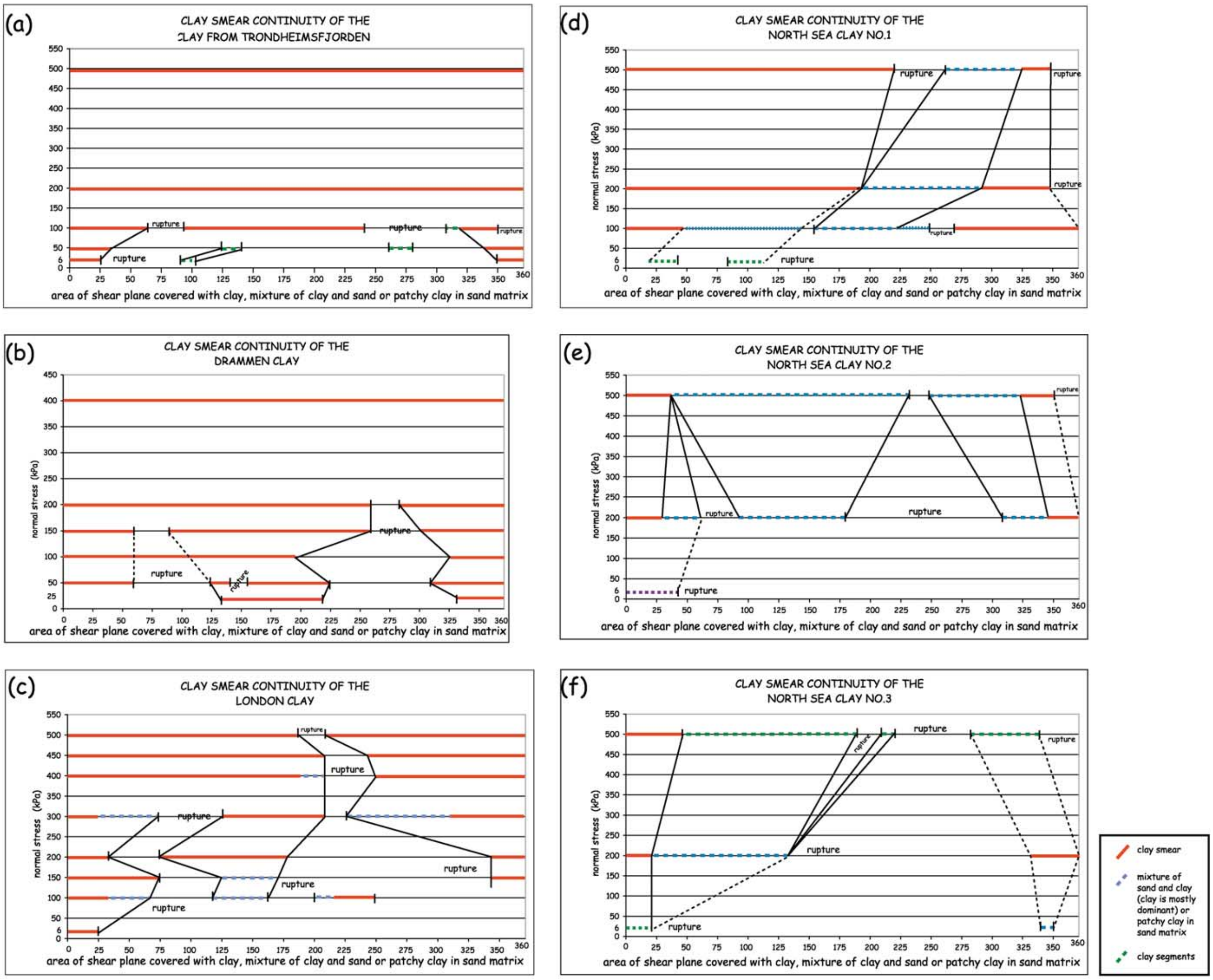
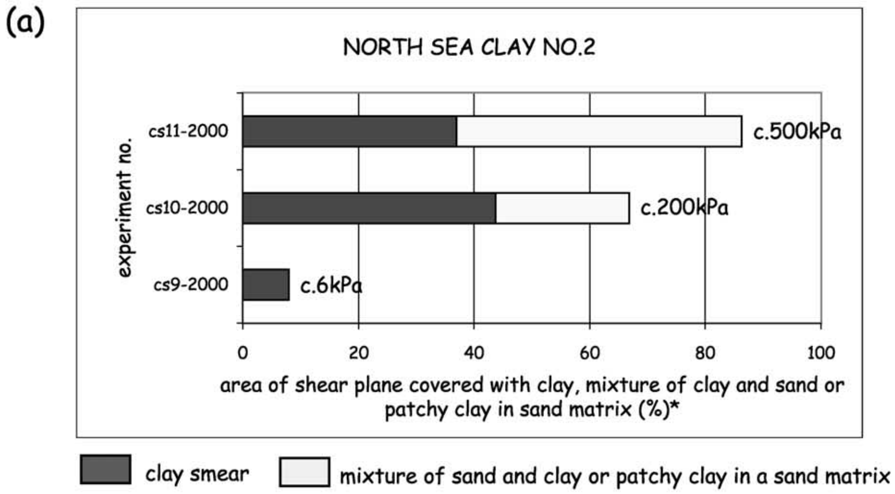


Fig. 8. Clay smear continuity for clays by increasing fault displacement and normal stress. Note that both the area covered by the clay smear and continuity increase with increasing normal stress.

layer. This suggests that shearing may stimulate water expulsion, and that considerable difference in water depletion may exist over short distances. Accordingly, deformation styles and potential for generating a continuous clay smear may be equally variable.

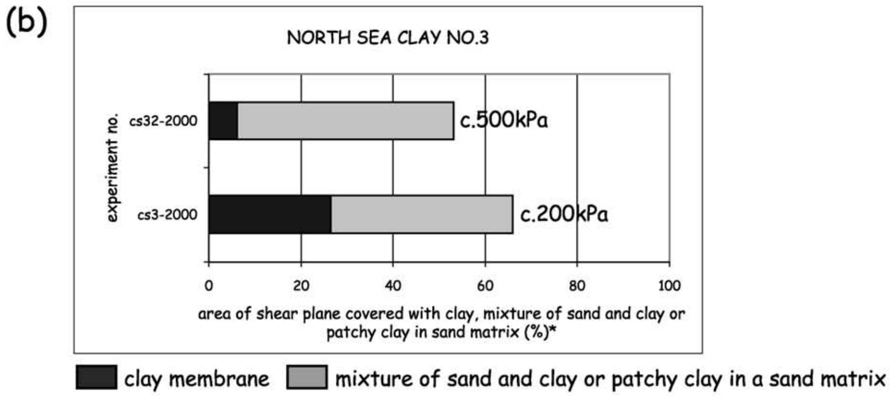
It is noteworthy that many of the types of features observed in the experiments are also observed in the field in Bornholm (Denmark). The structures observed include semi-continuous to continuous clay membranes, patchy clay in a sand matrix and mixtures of sand and clay (Clausen et al., 2002a).

Samples from the shear zone of the experiments were taken after impregnation of the zone with a synthetic glue (a mixture of Araldite M and HY 956 in a relationship of 5:1). After drying and consolidation, conventional thin sections were made at the Norsk Hydro Research Centre in Bergen, Norway. The thin sections display texture and geometry that are akin to the main types of clay smear as defined from visual inspection of the experiments. Hence, arrays of homogeneous lenses of clay separated by simple or complex ramps of pure sand (Fig. 7a) occur on millimetre to centimetre scales. Within the ramp-structures a sorting of quartz grains according to size is sometimes seen. The contact between the clay lenses and the sand is sometimes bordered by a transitional zone where isolated sand grains are embedded in a clay matrix (Fig. 7b), and a zonation may be apparent in some cases (Fig. 7c). In other cases a sharp contact is developed (Fig. 7d). The zones of sand and clay mixtures are generally surprisingly homogeneous (Fig. 7e), and a complete mixing of the two seems to have taken place commonly, even in situations where only small amounts of shearing has occurred. In some cases, circular or oblate areas of contrasting texture are identified within the mixed zones (Fig. 7f), probably reflecting internal flow, rolling of fragments and amalgamation of smaller clay–sand lenses.



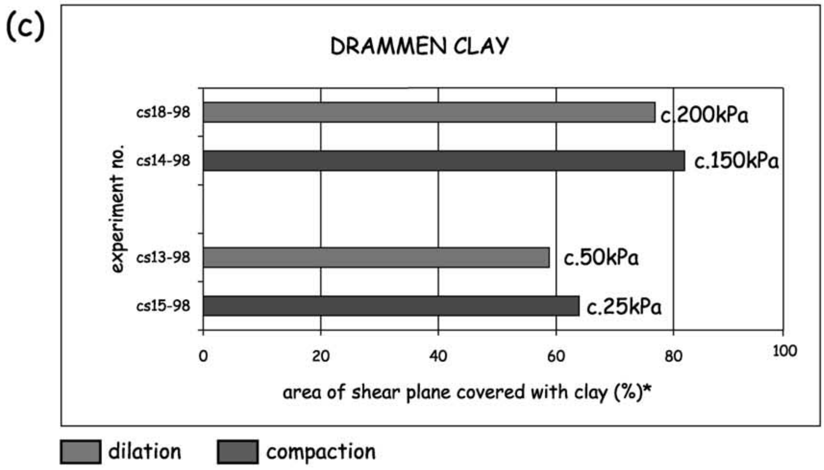
All samples compacted during deformation

*source layer of c.4% is not included



Both samples compacted during deformation

*source layer of c.4% is not included



*source layer of c.4% is not included

3.3. The effects of changing the normal stress

Altogether 54 experiments were included in the analysis of the influence of normal stress on the potential for development and pattern of a clay membrane. This series utilised all the available clay types under normal stress varying from 6 to 500 kPa. The analysis shows that the clay smear continuity and area of shear plane covered with clay systematically became enhanced when the normal stress was increased (Figs. 8 and 9a). This is consistent with observations made by Sperrevik (1997) and Sperrevik et al. (2000). Fig. 8 displays the variance in the clay smear pattern as a function of increasing normal (or loading) stress for the different clay types. It seems obvious that 'sand holes', which prevailed in the low stress experiments, became filled by clay to an increasing degree when the normal stress rose. It is also noteworthy that both the extent and position of the 'sand holes' were similar in repetitive experimental runs, and that the 'holes' became continuously filled from their margins when normal stress was increased.

An exception to the general observation is that the area of shear plane covered with clay, a mixture of clay and sand or patchy clay in a sand matrix became enhanced by decreasing normal stress (Fig. 9b). Two other experiments (Fig. 9c), which were performed with the lowest normal stress, were clay-covered to a larger extent than two experiments performed with higher normal stress. Differences in area of shear plane covered with clay of 5 and 13% are observed. This is probably due to the fact that the two experiments that were characterised by the larger clay-covering were compacting while the two experiments that were less clay-covered was dilating. Note that the uncertainty in the reproduction of experiments and the calculation of amount of clay on the shear plane is estimated to be in the range between 1 and 3%.

3.4. The effect of the water content in sand and clay

Twenty-five experiments were used in investigating the influence of water content in clay on the development of a clay membrane. The water content was increased to 5–13% above the natural water content in the clays. Nine experiments were performed to analyse the influence of water content in the sand. In this experimental series, the water content in the sand was varied between 3 and 20 vol%. The clay smear continuity and area of shear plane covered with clay, mixture of clay and sand or patchy clay in a sand matrix increased when the water content in both sand and clay was increased (Fig. 10a and b), which is in accordance with previous studies (Weber et al., 1978; Knipe, 1997; Bouvier et al., 1989; Sperrevik et al., 2000). In the present study the clay-covered part of the fault plane increased by 12% for the Drammen Clay (normal stress of 6 kPa) and by 52% for the London Clay (normal stress of 200 kPa) by increasing the water content in the sand from 3 to 20 vol%. By increasing the water content in the clay by 5–13% above its natural water content, the area of shear plane covered with clay, mixture of clay and sand or patchy clay in a sand matrix became enhanced by between 14 and 73%.

One exception to the general observation that compacting samples became clay-covered to a larger extent than those that dilated exist, was in one experiment, which was performed with high water content in the clay (the water content of the clay was enhanced by 6% above its natural water content) (Fig. 10c). A difference of 35% is observed in this case.

3.5. The effect of strain rate

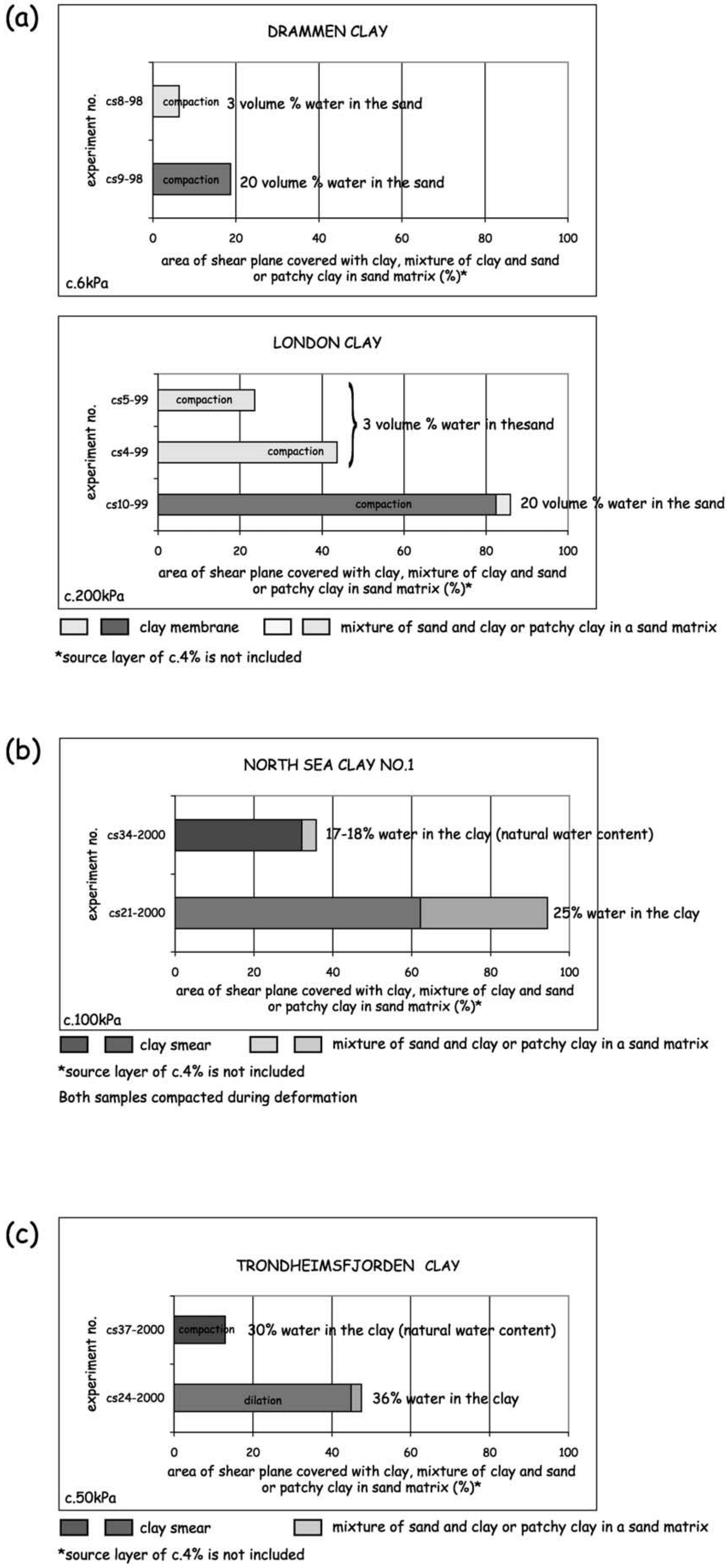
The influence of strain rate on the development of a clay membrane was analysed in an experimental series including 38 separate runs. It is observed that strain-rate does have an influence on the potential for development of a clay membrane. By increasing the strain-rate, both an increase and a decrease in the area of shear plane covered with clay, mixture of clay and sand or patchy clay in a sand matrix is observed (Fig. 11a). A difference in area of shear plane covered with clay, mixture of sand and clay or patchy clay in a sand matrix ranging from 3 to 54% between high and low deformation rate is also seen. However, there seems to be a complex relationship between strain-rate, clay type and normal stress. This is described and discussed in detail in Clausen et al. (2002b).

When comparing two experiments with high and low deformation rates, where the other deformation parameters were constant, it is observed that the sample where dilation occurred became covered with slightly more clay (3%) than in the sample that compacted (Fig. 11b). However, this is within the uncertainty in the reproduction of experiments (1 and 3%).

4. Discussion and conclusions

Lately, several software packages have been developed for the analysis of the sealing potential of faults, and some of those are aimed at estimation of the effect of clay smear (e.g. Knipe, 1997). Parameters like Shale Smear Factor (SSF; Lindsay et al., 1993), Clay Smear Potential (CSP; Bouvier et al., 1989) and Shale Gouge Ratio (Yielding et al., 1997) have been proposed to predict the potential for fault sealing

Fig. 9. (a) Generally, the area of shear plane covered with clay, mixture of clay and sand or patchy clay in a sand matrix was increasing with increasing normal stress (example from North Sea Clay No. 2). (b) Exceptions to the general trend for North Sea Clay No. 3. (c) Comparison using the same clay (Drammen Clay) at changing normal stress showed that those experiments with the highest normal stress were clay-covered to a smaller extent than samples performed by lower normal stress. This is probably due to the fact that the two experiments that were characterised by the larger clay-cover were compacting while the two experiments that were less clay-covered was dilating.


(a)
DRAMMEN CLAY
experiment no.
cs8-98
cs9-98
compaction
3 volume % water in the sand
20 volume % water in the sand
0
20
40
60
80
100
area of shear plane covered with clay, mixture of clay and sand or patchy clay in sand matrix (%)*
c.6kPa
LONDON CLAY
cs5-99
cs4-99
cs10-99
compaction
3 volume % water in thesand
20 volume % water in the sand
c.200kPa
clay membrane
mixture of sand and clay or patchy clay in a sand matrix
*source layer of c.4% is not included
(b)
NORTH SEA CLAY NO.1
cs34-2000
cs21-2000
17-18% water in the clay (natural water content)
25% water in the clay
c.100kPa
clay smear
mixture of sand and clay or patchy clay in a sand matrix
*source layer of c.4% is not included
Both samples compacted during deformation
(c)
TRONDHEIMSFJORDEN CLAY
cs37-2000
cs24-2000
compaction
dilation
30% water in the clay (natural water content)
36% water in the clay
c.50kPa
clay smear
mixture of sand and clay or patchy clay in a sand matrix
*source layer of c.4% is not included

by the introduction of a continuous shale or clay membrane along the fault plane. From the results of Sperrevik (1997), Sperrevik et al. (2000) and the present study, it seems obvious that a great variety in the potential for the development of continuous clay membranes exists for different clays. In addition to thickness of the source layer and fault displacement, as usually suggested to control the development and continuity of a clay membrane (e.g. Lindsay et al., 1993; Yielding et al., 1997), it is evident that smear potential is influenced by variables like water content in sand and clay and not the least, normal stress and hence, depth of burial. A complex relationship between strain-rate, clay type and normal stress seems to exist. This is described and discussed in detail in Clausen et al. (2002b).

The results of the present study are strictly only valid for clay smearing that takes part at a shallow level of burial, i.e. 50 m or less. Still, the results are indeed relevant, because syn-sedimentary faulting is common in most basins and such faults frequently contribute to the segmentation of reservoirs (Nemec et al., 1988; Sverdrup and Bjørlykke, 1998). In this context, it is of particular importance to acknowledge that clay becomes distributed along the fault plane to constitute several possible configurations, of which several different patterns are recognised.

Isolated lensoid or ball-shaped fragments embedded in a matrix of sand, and constituting a patchy look, are observed both in previous (Sperrevik et al., 2000) and present experiments. By deformation of 'dry'clay at very low normal stress (6 kPa) the fragments are small, irregular in shape and widely spread along the fault plane. By slightly increasing normal stress (>25 kPa dependent upon clay typed) and in cases with higher water content in the clay (less shear strength), the clay fragments tend to become larger and orientated with the longest axes parallel to the fault plane. In concert with this observation, clay types that were originally mechanically weak were also more prone to produce the larger clay fragments and more continuous clay membranes.

The development of the clay fragments can be ascribed to either of two mechanisms. One would be by brittle shear with transport of fragments along the fault plane after separation of the fragments from the source layer by the initiation of Riedel- and Riedel′-shears (Sperrevik et al., 2000) or other mechanisms that produce extensional horses (Childs et al., 1997; Gabrielsen and Clausen, 2001). This interpretation seems to be supported by the presence of wedge-shaped, sheared fragments commonly found close to the source layer. Alternatively, the clay lenses could be interpreted to be small-scale bouduins. The low stress, lack of a greater competency contrast between the unconsolidated sand and the clay, and not least the great separation between the fragments, however, makes the latter mechanism unrealistic.

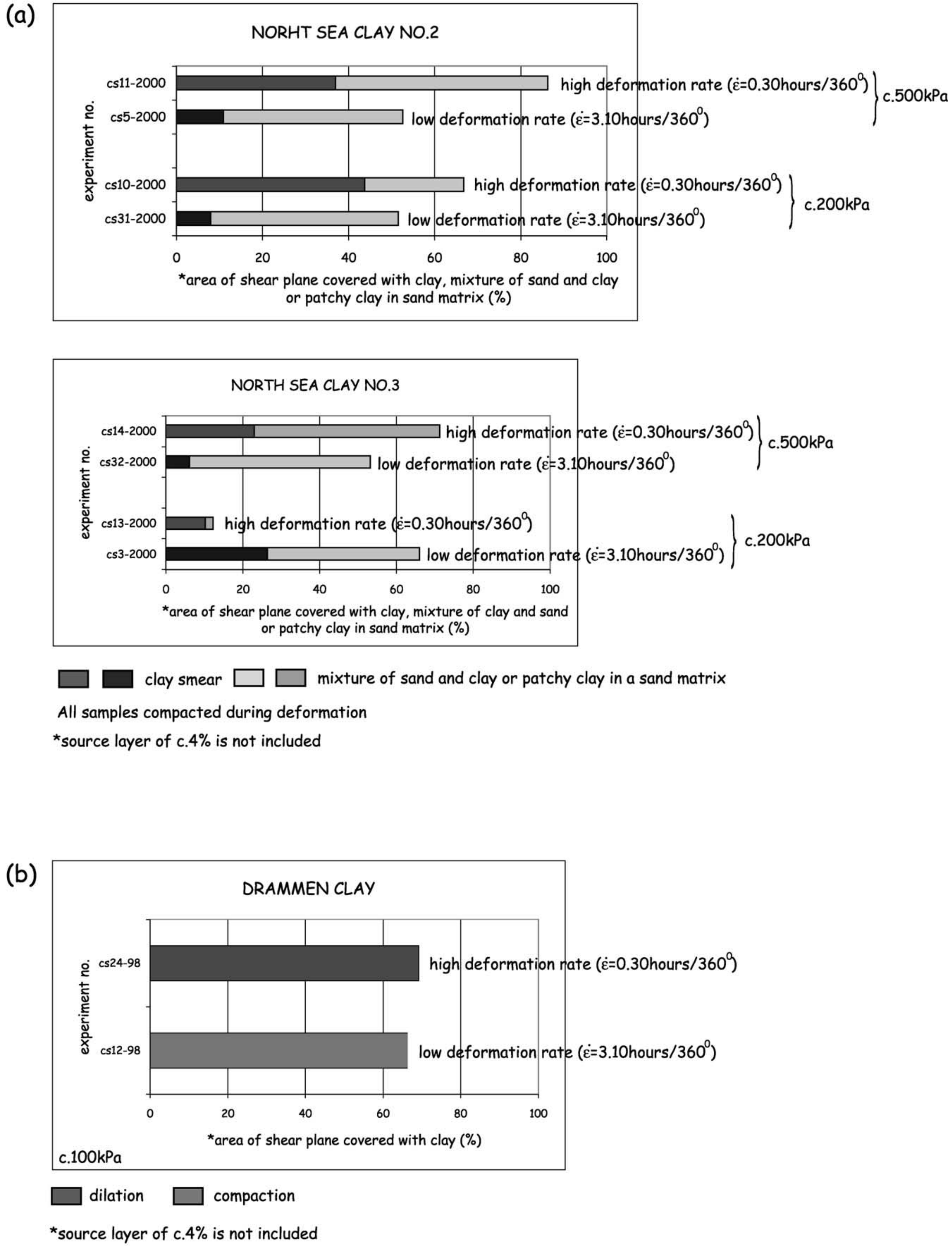
A complete mixture of clay and sand is commonly seen in experiments performed under slightly higher normal stress (>25 kPa, dependent upon clay type). The ability to develop a homogeneous clay–sand mixture seems to vary considerably from one clay type to another (Fig. 7), and there is no unique relation between this type of pattern and strain rate. However, it seems that the zones of the shear plane characterised by a clay–sand mixture are stable in the context that once they are generated, they do not develop into other types of smear. It may be speculated that mixing of clay and sand occurs by local invasion of clay into pores generated in dilation at an early stage of shear under low normal stress. Microscope study shows that clay in the mixed zones may dominate the matrix, and that the texture commonly is completely matrix-born. This would explain the stability of this type of smear during continued shear, since clay and sand would be inseparable.

The development of a *semi-continuous to continuous clay membrane*, which typically varies in thickness between 1 and 5 mm, is promoted by a thick (or multiple) source layer, high applied normal stress (>100 kPa dependent upon clay type in the present experiments), high plasticity of the deforming clay, and hence, high water content. The clay is commonly seen as wedge-shaped accumulations close to the source layer, suggesting that the clay becomes dragged into the fault zone as a larger mass before it is sheared and distributed along the fault plane.

It is noted that samples that compacted became clay-covered to a larger extent than those that dilated in the earliest stage of deformation. This is consistent with the observations of Sperrevik (1997) and Sperrevik et al. (2000). However, the present experiments indicate that the influence of compaction/dilation may be over-ruled by other parameters like deformation rate and water content in clay. One exception to the general trend in that the area of shear plane covered with clay, a mixture of clay and sand or patchy clay in a sand matrix become enhanced by increasing normal stress is also observed. Two experiments, which were performed with the lowest normal stress, was clay-covered to a larger extent than two experiments performed with higher normal stress. This is probably due to the fact that the two experiments that were most clay-covered were compacting while the two experiments that were less clay-covered were dilating.

The geometry and internal structure of the three different patterns described above suggests that a continuum exists between the pattern characterised by isolated lensoid or ball-shaped fragments and a continuous clay smear. This means that isolated clay lenses or fragments can be bridged and connected by the introduction of more clay to the fault plane by continued strain. On the other hand, such processes

Fig. 10. The area of shear plane covered with clay, mixture of clay and sand or patchy clay in a sand matrix was increasing by (a) increasing water content in the sand, and by (b) increasing water content in the clay. (c) The sample, which was dilating, was covered with more clay, mixture of clay and sand or patchy clay in a sand matrix than the sample that compacted.



All samples compacted during deformation

*source layer of c.4% is not included

*source layer of c.4% is not included

involving bridging and amalgamation of clean clay lenses may be hampered when stable zones containing mixture of clay and sand separate them. Unfortunately, due to limitations in the apparatus, it has not yet been possible to investigate this further.

Comparison between experiments performed with samples consisting of clean Baskarp Sand No. 15 and those with a clay source demonstrates that the introduction of even small amounts of clay to the shear zone strongly influences the deformation mode. Hence, the pure sand experiments go directly into a stick-slip mode. In contrast the experiments where clay is involved go through four steps of development, including pre-peak, peak, strain-hardening/strain-softening and eventually stick-slip.

From the study of thin sections, it is concluded that after rupture of the clay layers, the fault zone is dominated by plastic deformational processes, which include transport of single grains from the sand into the clay. Also, trains of quartz and feldspar grains may invade the clay layers, probably resulting in break-down of larger clay lenses into smaller ones. This process is competing with the collision and amalgamation of clay fragments at advanced stages of strain, when clay fragments are stopped from moving along the fault plane by enhanced friction. These events are probably associated with the stick-slip events recorded toward the end of some experiments. Alternatively, amalgamation of clay lenses or fragments may occur when excess clay becomes available due to shearing-off of clay from the wedges associated with the source layer.

A crucial test on the validity of the present experiments is whether or not the geometrical characteristics of the clay smear types described above can be recognised in nature. We have investigated syn-sedimentary faults in unconsolidated sand–clay-sequences in Bornholm (Denmark) and found that intra fault-core layers display similar patterns to those described above (Johnsen, 1998; Clausen et al., 2002a). It is, however, worth emphasising that fault-parallel zones of deformation bands, clay lenses, mixed sand and clay and continuous clay smear occur side by side. Also, sand-bridges separating zones of clay smear were observed, but those were most common in the distal parts of the fault core. This supports our conclusion that the different types of clay smear seen in our experiments are produced during roughly similar physical conditions. Furthermore, it suggests that subtle differences in amount of clay available in each zone, fault displacement, normal stress, water pressure (water content in sand and clay) and strain rate are sufficient to produce a very complex zonation in the fault core.

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Fig. 11. (a) The area of shear plane covered with clay, mixture of clay and sand or patchy clay in a sand matrix was generally increasing with both increasing and decreasing strain-rate. (b) When comparing two experiments with high and low deformation rate, where the other deformation parameters were constant, it is observed that the sample where dilation occurred became covered with slightly more clay (3%) than in the sample that compacted. However, the uncertainty in the reproduction of experiments and the calculation of amount of clay on the shear plane is estimated to be in the range between 1 and 3%.

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