

MECHANICAL STRENGTH OF ANHYDRITE AND ITS ROLE IN THE SEISMICITY
OF THE DUKE RIVER FAULT, YUKON TERRITORY

by

CHRISTIAN SAMPALLEANU

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE (HONOURS)

in

THE FACULTY OF SCIENCE

(Geology and Geophysics)

This thesis conforms to the required standard

.....

Supervisor

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

APRIL 2010

ABSTRACT

Anhydrite rich fault zones are known to act as zones of weakness and the source of earthquakes in seismically active areas. One of the best known examples is the Apennine Mountains in Italy, which contain neo-tectonic extensional faults hosted in carbonate and evaporite sequences. For this study, anhydrite from the Duke River fault in the Yukon was sampled and triaxial stress tests were conducted to determine the mechanical strength of the anhydrite. Both pure shear experiments and friction experiments were performed. These tests show that anhydrite will begin to undergo brittle-ductile deformation at confining pressures as low as 25 MPa. At atmospheric conditions, anhydrite behaves elastically until brittle failure results in the formation of a shear fracture with associated stress drop. At confining pressures greater than 75 MPa, anhydrite will deform by cataclastic flow, and no longer produce a stress drop. The data indicate that the anhydrite-rich locations in the Duke River fault likely could not be responsible for a stress drop and therefore it is unlikely that the anhydrite-rich portions of the Duke River Fault are the sources of the seismicity. It is proposed that high fluid pressure would be required to promote brittle failure that could cause the seismicity.

LIST OF FIGURES

1. Map of Duke River fault area	3
2. Map of seismicity and tectonism in the north-western Canada and south-eastern Alaska	5
3. Photomicrographs of starting material	8
4. Photos of experimental apparatus	
a. Large Sample Rig	10
b. Experimental assembly	10
5. Photos of starting cores and run products from first suite of experiments	
a. CS-001 initial core	14
b. CS-001 run product	14
c. CS-002 initial core	14
d. CS-002 run product	14
e. CS-003 initial core	14
f. CS-003 run product	14
g. CS-004 initial core	14
h. CS-004 run product	14
i. CS-005 initial core	15
j. CS-005 run product	15
k. CS-006 initial core	15
l. CS-006 run product	15
6. Stress-strain curves of pure shear experiments	16
7. Photomicrographs of CS-001	18
8. Photomicrographs of CS-002	19
9. Photomicrographs of CS-003	19
10. Photomicrographs of CS-004	20
11. Photomicrographs of CS-005 and CS-006	21
12. Photos of starting cores and run products from second suite of experiments	
a. CS-007 initial core	23
b. CS-007 run product	23
c. CS-008 run product	23
d. CS-012 run product	23
e. CS-011 run product	23
f. CS-009 run product	23
13. Photomicrographs of CS-007	25
14. Photomicrographs of CS-008 and CS-012	25
15. Photomicrographs of CS-011	26
16. Photomicrographs of CS-009	26

17. Mohr diagram of pure shear experimental stress regime	30
18. Frictional sliding data	
a. Coefficient of friction vs. displacement	34
b. Differential stress vs. displacement	34
19. XRD Analysis of starting material	50

ACKNOWLEDGEMENTS

I would like to thank my advisor Lori Kennedy for taking me on and for the continued guidance and support while writing this thesis. Working on this thesis was made much easier thanks to the help and support of Jenny Haywood and Peter van de Reep. I'd also like to thank Steve Israel and Rosie Cobbett for their valuable input on the Duke River fault, and the technical staff in the SEM lab and machine shop. I would also like to thank all my friends and family who have guided me through this year and throughout my time at UBC.

Contents

ABSTRACT	ii
LIST OF FIGURES	iii
ACKNOWLEDGEMENTS	v
INTRODUCTION AND BACKGROUND	1
Geological setting.....	1
Tectonic setting and recent seismicity	4
Comparison to the Apennines	6
METHODOLOGY	7
Starting Material Description	7
Sample preparation.....	8
Apparatus	9
Sample assembly	9
Experimental procedure	11
RESULTS	12
Mechanical strength tests: Pure shear experiments.....	12
Table 1: Experimental Results for pure shear and sliding friction experiments.....	12
Microscopic Analysis	17
Frictional Sliding Tests	22
Microscopic Analysis	24
DISCUSSION	27
Analysis of Results.....	27
Mechanical Strength Test: Pure shear experiments.....	27
Frictional sliding testing	31
Comparison to the Apennines	35
Relevance to the Duke River Fault	36
CONCLUSION	38
REFERENCES CITED.....	39
APPENDIX 1 – RELEVANT METHODS AND EQUATIONS.....	41
Helium Pycnometry.....	41
Data Reduction	41

APPENDIX 2 – RELEVANT DATA.....	43
Table 2: Geochemical analysis of two pieces of starting material	43
XRD Analysis of Starting Material	43

INTRODUCTION AND BACKGROUND

Anhydrite found in fault zones is believed to play a role in weakening and failure of the fault zone (De Paola et al., 2008, Hildyard et al., 2009). A very well documented example of this occurs in neo-tectonic extensional faults of the Apennine mountains of northern Italy. Extensive seismic data collection has allowed a deeper understanding of the seismicity in this area in recent years. Field and experimental work has led to the development of fault evolution models for anhydrite rich fault zones (De Paola et al., 2008, Collettini et al., 2009).

Anhydrite also occurs in the Duke River Fault, located in the Yukon Territory. Unlike the Apennines, the mechanics surrounding the seismicity of this area are much less constrained, owing mostly to its remoteness. To determine what effect, if any, anhydrite has on the mechanics of the fault, experimental deformation data was collected and compared to known seismicity of the area. Using the example of the Apennines as an analogue, I compared my experimental data to try and place constraints on the general rheology of anhydrite. Anhydrite from the fault was collected and deformed to measure mechanical strength under a variety of confining pressures, both as whole rocks, and with pre-cut fault surfaces. Data collected in this study is placed in the context of its geological setting and known seismic data.

Previous tests on anhydrite have shown that it is extremely weak compared to most other rock types (Kulhawy, 1975). Handin and Hager (1957) found it to have a cohesion of 43.4 MPa, weaker than most other sedimentary rocks. Anhydrite is stronger than gypsum, a mineral it is usually associated with (Bell, 1994).

Geological setting

The Duke River Fault (DRF) is located in the southwest part of the Yukon Territory (Figure 1), and runs from Alaska (where it is known as the Totschunda Fault), across the Yukon and down into BC, where it connects with the Dalton Fault. It is located approximately parallel to and in between the St. Elias and Kluane ranges. At the latitude of the sample area, the DRF is a thrust fault that places highly metamorphosed rocks of the Alexander terrane above weakly deformed sedimentary rocks of Wrangellia (Israel, et al., 2005). In the region of the study area, Wrangellia is composed of Late Paleozoic volcanic arc

and sedimentary rocks, unconformably overlain by Middle Triassic marine sedimentary rocks, Late Triassic oceanic flood basalts, and shallow marine carbonates of the Chitistone Formation. The Alexander terrane in this area consists of highly deformed phyllites, marbles and meta-sandstones that are intruded by the Pennsylvanian to Permian Mt. Hoge pluton. The Alexander and Wrangellia terranes are both intruded by Late Pennsylvanian age plutons, so it is assumed that they were together by Late Paleozoic. The Duke River Fault has created several strike-slip pull-apart basins that were filled in by the Palaeogene Amphitheatre Formation.

Samples for this study were collected from the Bullion Creek area. At this locality, the Duke River Fault places anhydrites of Wrangellia *over* lower greenschist facies metavolcanic and metasedimentary rocks of the Alexander terrane (J. Haywood, personal communication, Nov. 29, 2009). There are several possible explanations for this geometrical difference along the Duke River Fault (i.e. placing younger rocks over older rocks). The fault in this area may be an overturned thrust, the fault might have been reactivated during younger deformation, such that the unmetamorphosed rocks of Wrangellia were placed over top of the Alexander, or it could be a combination of the two (Israel, personal communication, Dec. 1, 2009). The anhydrite is interpreted to be part of the Upper Triassic Chitistone Formation (Read and Monger, 1976). Israel (2005) describes the Chitistone Formation as being composed of massive to thickly bedded limestone, which includes “white to pale grey gypsum” (2005, pg. 143), from which the anhydrite used in this study was collected. This particular unit of gypsum and anhydrite form a lens approximately 7 km long and 1 km wide (Read and Monger, 1976).

Tectonic setting and recent seismicity

The Duke River and the associated Denali Faults are interpreted to have originated in the Tertiary as dextral strike-slip faults in a transpressional environment (Israel et al., 2005). The northwest-southeast trend of the faults, along with most other structures in this region, is due to the multiple generations of deformation. The Duke River fault is now the geologic boundary between the Alexander and Wrangellia terranes, however, it is not believed to be a remnant of the megathrust which brought the Wrangellia terrane over the Alexander terrane. It is proposed that there has not been any serious vertical movement on this boundary since Late Pennsylvanian (Read and Monger, 1976).

The Duke River fault is considered to be part of the Denali fault network, a still active network, which accommodates deformation associated with the actively uplifting St. Elias orogen (Bruhn et al., 2004). The orogen is a result of the Yakutat terrane currently colliding with the North American plate; part of the Yakutat terrane is subducting under North America and part of it thrust over the North American Plate. Presently, the Yakutat terrane is moving at a rate of 45-50 mm/a towards the continent, approximately to the north-east (Figure 2). The Duke River fault accommodates approximately 3.1 mm/a dextral slip, and 1.5 mm/a shortening, and has accommodated 400 km of dextral displacement since 55 Ma (Leonard, et al., 2008). In the Yukon, the Duke River fault runs roughly parallel to the Denali fault towards the south, but connects with it further west in Alaska.

The most recent major seismic event on the fault network, which occurred on 3 November, 2002, (Haeussler et al., 2004) was an M 7.9 earthquake that started on the Denali fault in Alaska, and transferred to the Totschunda fault. This rupture did not reach the point on the Duke River fault where samples used in this study were collected. Historically, all major earthquakes recorded in St. Elias and Kluane ranges occurred on or near the plate boundary whereas earthquakes further inland have been restricted to the M 6 level, and no major seismicity has occurred north of the Denali fault system (Horner, 1983). Within the Denali fault system, most current seismicity is concentrated on a 20 km wide band that is roughly centred on the Duke River and Dalton faults. Microseismicity studies in this area revealed that most events had focal depths of < 15 km, with predominantly strike-slip faulting pattern. Of interest is that the nodal plane of these events are either in a directly

north-south or east-west orientation, not aligned with the surface faults in that area (Cassidy et al., 2005).

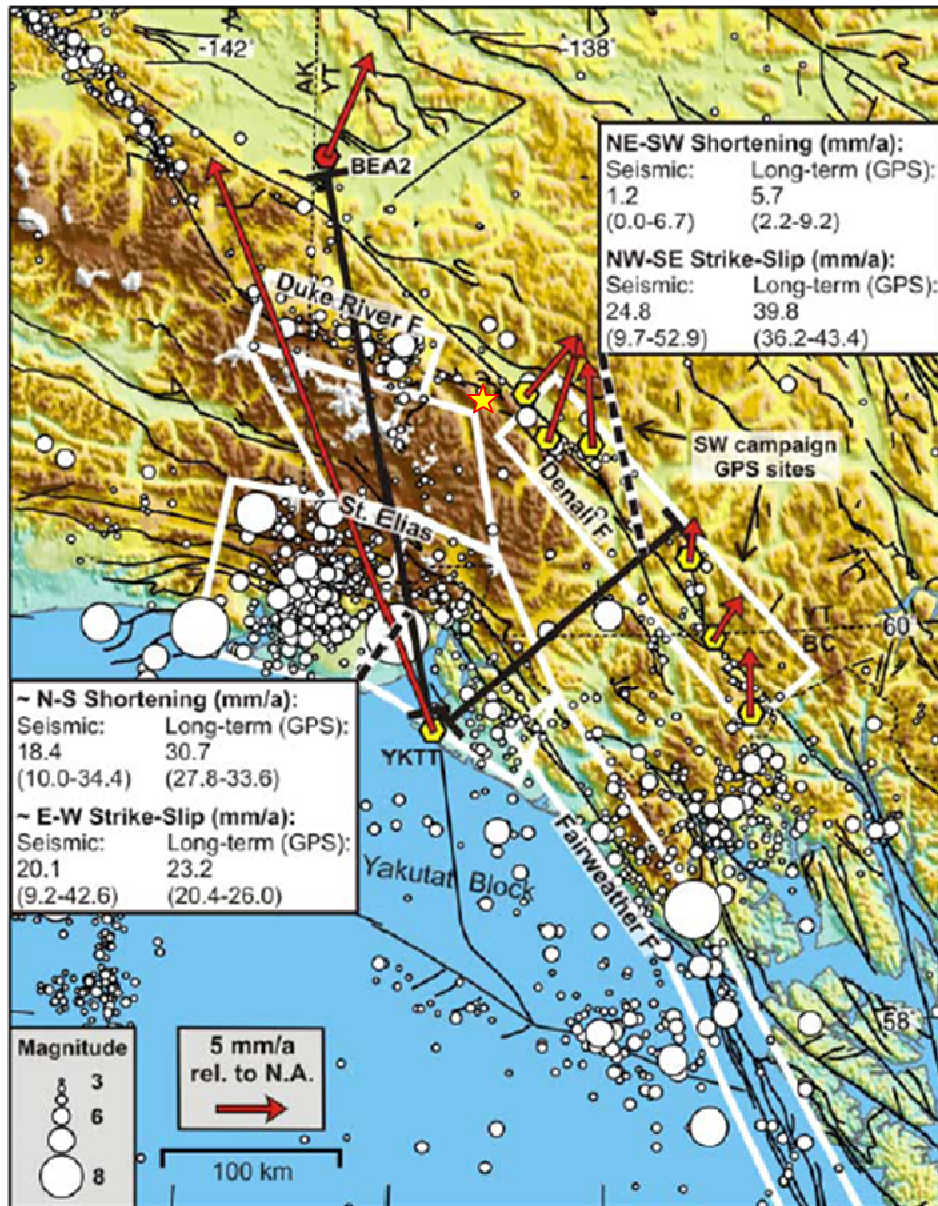


Figure 2: Map showing location of major faults in northwestern Canada and southeastern Alaska, as well as earthquake magnitudes and relative tectonic movement. From Leonard et al., (2008).

Comparison to the Apennines

The Apennines in Northern Italy are another tectonically active region that has been heavily studied, primarily because of several recent major earthquakes in the region (De Paola et al., 2008). Seismic activity originated in the Triassic Evaporite sequences, and so this region can be used as an analogue for the Duke River fault. Unlike the Duke River fault, the Apennines are in an extensional tectonic regime. However, important comparisons can be made regarding mechanics and deformation of evaporites in the Apennines. Evaporites commonly act as zones of weakness and detachment horizons (De Paola et al., 2008, Hildyard et al., 2009), and so the analogue between the Apennines and the Duke River fault is relevant. Work done by Collettini et al. (2009) proposed a fault zone evolution model for this region based on triaxial compression testing of anhydrite. This model suggests that ductile shear zones are formed by cataclastic flow as blocks are fractured, rotated and stretched. Fluid overpressure in the fault core can result in triggering seismic events.

METHODOLOGY

Starting Material Description

Anhydrite used in this project was collected from the Bullion Creek area on the Duke River fault in southwest Yukon Territory. It was collected by L. Kennedy and J. Haywood in the summer of 2009 as part of ongoing research on the geology and seismicity of the area (personal communication, L. Kennedy, 2009). The samples used in this study came from a large (~40cm long) piece of anhydrite which has a well defined foliation, although some thin beds of darker minerals as well as what appeared to be small grains of lithic fragments were present. These small fragments are secondary gypsum. The anhydrite was not collected from within the brittle fault zone, but rather came from the hanging wall and so is considered the protolith to fault rocks generated along the Duke River fault.

Thin section analysis shows that the foliation is defined by elongated anhydrite (Figure 3). The small grains observed in hand sample are gypsum. The anhydrite is fine to medium grained, with some grains reaching 2mm in length and 0.5mm in width. Very fine grains (<0.1 mm across) were interspersed throughout the sample, creating a low porosity. Most grains were angular to sub-angular, with sharp interlocking edges, and more dispersed finer grains. Larger grains display a primary cleavage surface that is parallel to the foliation. Most of the grains became extinct parallel to the cleavage, a characteristic of anhydrite. Undulose extinction and dynamic recrystallization was observed indicating deformation by dislocation creep. Some of the grains show what appears to be twinning at approximately 45° and 135° to the primary orientation, likely due to deformation and contributing to the development of its crystallographic preferred orientation (Hildyard et al. 2009). Overall, the rock can be described as an anhydrite tectonite that developed before the latest brittle deformation movement along the fault. The gypsum is finer grained than the anhydrite and although distributed in thin bands that are parallel to the foliation, the gypsum is randomly oriented does not have significant internal deformation.

Light grey fragments seen in hand sample are also pieces of very fine grained gypsum, likely altered from anhydrite after deformation, as they are randomly oriented and do not match the texture of the surrounding anhydrite.

Samples of the starting material were also analyzed using X-Ray Diffraction (XRD) and X-Ray Fluorescence techniques. Detailed results can be found in Appendix x. XRD analysis (done by J. Haywood) showed a strong presence of anhydrite with some gypsum. XRF analysis (done by ALS Labs Vancouver) showed high values of CaO and S, as expected for anhydrite, as well as relatively low H₂O and LOI values (which might indicate gypsum). SrO values were relatively high, indicating possible replacement of anhydrite with celestite.

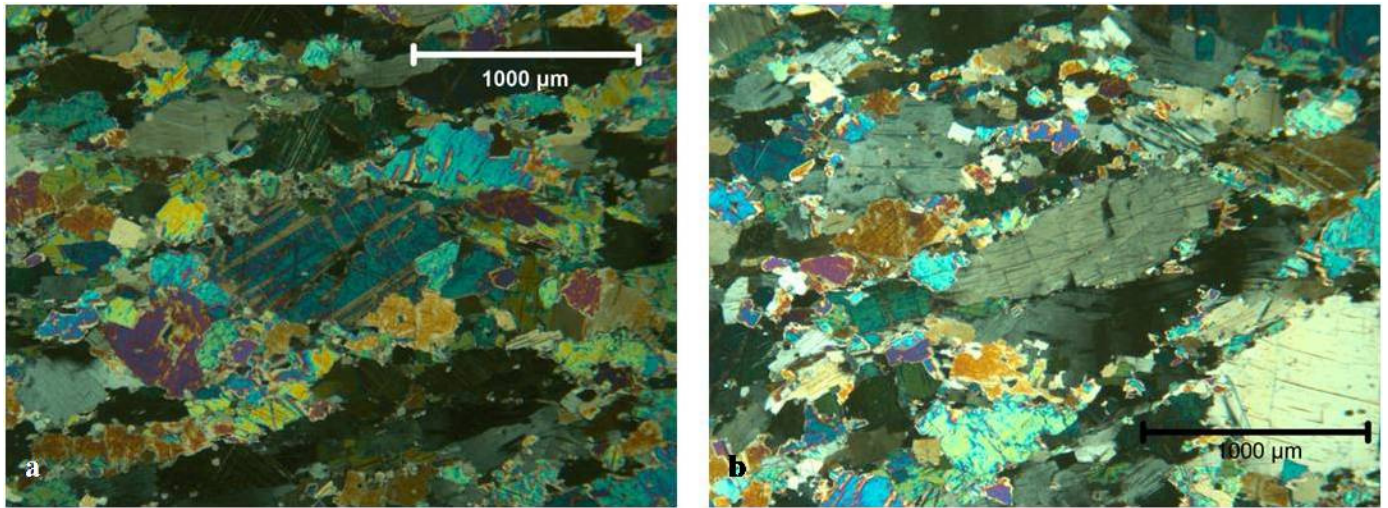


Figure 3: Example photomicrographs of undeformed starting material in cross-polarized light. Note the pre-existing alignment of grains. Crystal in centre of a) displays good example of twinning. Crystals in b) show undulose extinction, evidence that rock had already undergone grain elongation and dynamic recrystallization, mechanisms of ductile deformation.

Sample preparation

One inch diameter by two inch long right circular cylindrical cores were drilled using a drill press and cut on a guided rock saw. Each core was ground down at each end to within 0.001 inches (0.0254mm), to ensure that the ends are flat and parallel, and to produce a 2:1 length to diameter ratio. Each dimension, as well as mass, was measured five times to ensure accuracy. The samples were dried at 100°C overnight and then stored in a desiccator. Porosity and density of the sample was determined using the helium pycnometer in the Volcanology and Petrology Lab at the University of British Columbia (procedure in appendix X). Each sample was photographed prior to being placed into the experimental assembly (described below).

Part of the original sample that was not cored was cut into blocks. Two samples were sent to Vancouver Petrographics for creation of polished thin sections, and two other samples were sent to ALS Chemex in Vancouver for whole rock X-Ray Fluorescence analysis.

Apparatus

The cores were tested in the large sample rig (LSR) located in the Centre for Experimental Studies of the Lithosphere (CESL) at the UBC Department of Earth and Ocean Sciences (EOS) (Figure 4a). The LSR is a triaxial rock press ($\sigma_1 > \sigma_2 = \sigma_3$), with a built in pore fluid pressure system and an argon gas confining pressure system. The pressure vessel is rated to 400MPa. For this research confining was kept at less than 100MPa; the pore fluid system was not used in these experiments. The LSR is capable of exerting 200000 lbs (approx. 890 kN) of force, using an electric motor and gear system that provides the load through a thrust ball-bearing screw (Van de Reep, 2009). The load cell is located externally from the vessel and measures load on the upper piston of the sample assembly. The motor moves a lower plate with a constant displacement rate upward towards a stationary upper plate. The displacement rate can be changed using a variable-speed controller. Displacement is measured using a displacement transducer mounted between the stationary upper plate and mobile lower plate. All data, including confining pressure, displacement, and load force, are measured and recorded in real time at an interval of 0.375 seconds per sample using LabVIEW software.

Sample assembly

Core samples were wrapped in a heat shrinkable polyolefin jacket, and the ends coated in a Molycote lubricant. Each sample was then placed between appropriately sized spacers and piston cups (Figure 4b). The entire assembly was wrapped in another heat shrinkable polyolefin jacket to maintain alignment and to isolate the sample from the confining pressure system. Nichrome steel wire was used to seal the sample assembly at both ends. Plastic spacers were placed over the assembly to reduce the volume of argon needed to create the confining pressure.

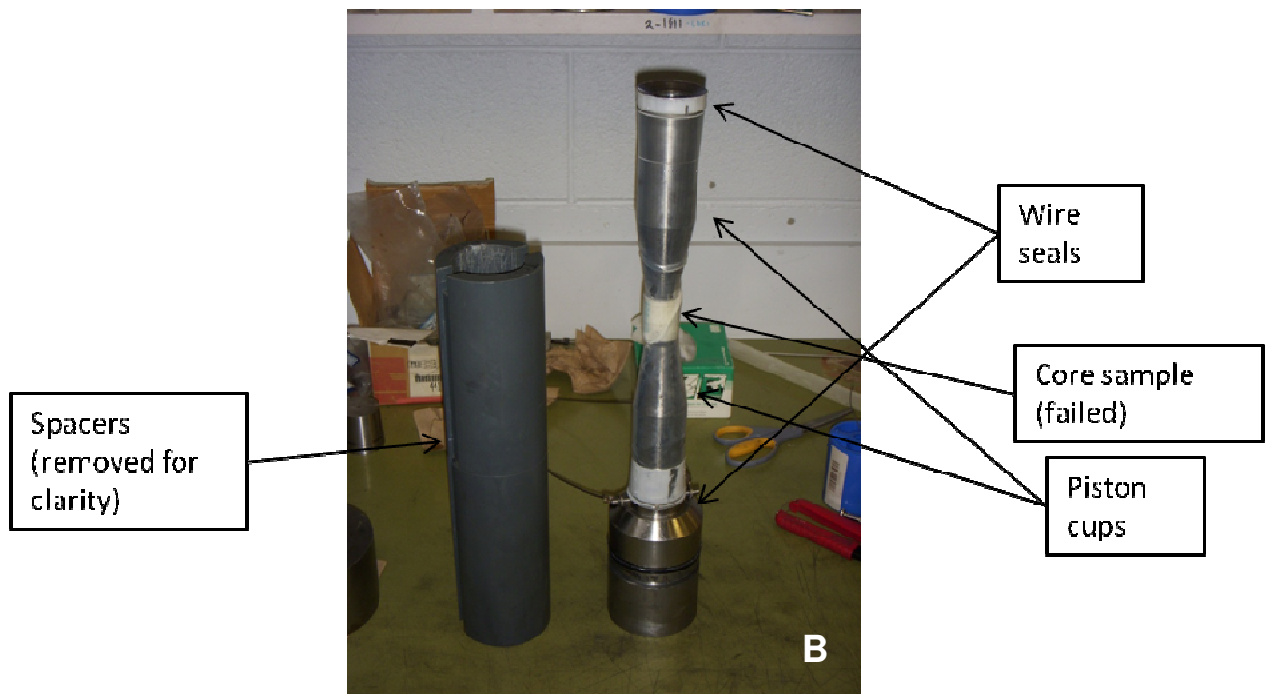


Figure 4: a) LSR photo with sample assembly inserted. b) Sample assembly detail with failed sample, polyolefin jacket and wire seals in place. Sample is 2 inches (50.8 mm) high and 1 inch (25.22 mm) in diameter.

Experimental procedure

The sample assembly was placed in the LSR pressure vessel, which was sealed off using the nut and gland assembly on top, and by rubber o-rings located at the bottom of the lower piston cup. For higher confining pressure experiments, a tube was attached to the bottom of the assembly (normally used for pore fluid pressure) to prevent blowouts in case the jacket was punctured or torn. The load cell was brought into contact with the top spacer of the assembly with only enough force to prevent the assembly from moving while confining pressure was increased.

Following the setup of the LSR, all transducers and gauges were zeroed, and the confining pressure system was tested to ensure that there were no leaks. The confining pressure was then increased to the desired value, and after the LSR was sealed off from the pump system, the variable speed motor was set to the required rate, and started. Experimental progress was monitored on the LabVIEW terminal, with a real-time load vs. displacement curve being displayed. The motor was stopped either after failure had occurred, or after the sample had been deformed 0.3 inches (further displacement would cause jacket tearing and misalignment of the system). Failure was noted by a sharp drop in load.

After the motor was stopped, confining pressure was released slowly, to prevent sudden tensile release fractures. The samples were photographed and sent to Vancouver Petrographics in Langley, BC, to be made into polished thin sections.

RESULTS

Mechanical strength tests: Pure shear experiments

A variety of terms are used to describe deformation and each may have several possible meanings depending on the scale of deformation. For the most part, ductile deformation in this study refers to macroscopic deformation that occurs when stress and strain are no longer linear. Deformation is accommodated through cataclastic flow, which occurs through microscopic brittle fractures, but is considered distributed ductile deformation at the macroscopic scale. Brittle deformation on a macroscopic scale occurs when there is a stress drop in the sample, which is manifested as localized deformation along a fault.

Results from the first suite of experiments are listed in Table 1. Photos of the run products are seen in Figure 5. Differential stress curves are shown in Figure 6. Photomicrographs of the run products are seen in Figures 7 – 11. The figures are oriented such that the load (σ_1) was applied in the vertical direction.

Table 1: Experimental results for pure shear and sliding friction experiments

Sample number	Type of Experiment	Confining Pressure (MPa)	Bulk Density (g/cm ³)	Porosity (%)	Yield Strength (MPa) ¹	Max differential stress (MPa)	Max coefficient of friction
CS-001	Pure shear	0	2.923	0.65	87.50	87.5	
CS-002	Pure shear	25	2.918	0.91	125	171.5	
CS-003	Pure shear	50	2.915	0.69	170	227.9	
CS-004	Pure shear	75	2.920	0.88	190	278.5	
CS-005	Pure shear	100	2.836	0.75	190	283.4	
CS-006	Pure shear	100	2.924	1.00	195	296	
CS-007	Frictional sliding	25	2.922	1.05		7.2	0.13
CS-008	Frictional sliding	50	2.932	0.76		212.7	0.88
CS-009	Frictional sliding	100	2.926	0.58		316	0.802
CS-011	Frictional sliding	75	2.832	0.92		262	0.86
CS-012	Frictional sliding	50	2.914	0.73		288	1.0675

Note: ¹ Yield strength estimated from stress strain curve as point where curve first becomes non-linear.

With no confining pressure, sample CS-001 underwent tensile failure, with one primary thin longitudinal fracture running approximately parallel to the core axis, as well as several other

smaller cracks (Figure 5a). There was also limited strain accumulated before failure, as the stress-strain curve remained linear until failure. This experiment was the only one that produced an audible acoustic emission with failure. Samples that were placed under confining pressure (25 MPa and higher) all produced shear fractures at approximately 30° to the core axis. With the exception of the sample tested at no confining pressure, all samples exhibited barrelling, indicative of ductile deformation. The intensity of the barrelling increased with confining pressure, with the core samples increasing up to 4mm in diameter. The stress strain curves for these samples showed plastic yield and very little strain hardening before attaining a steady state, i.e. constant stress. Samples tested at 25, 50, and 75 MPa confining pressure all produced significant stress drops. The two samples tested at 100 MPa confining pressure did not produce a stress drop and the experiments were stopped after the displacement was greater than 0.3 inches.

The differential stress required for failure increased with increasing steadily with confining pressure until 75 MPa, implying a typical Mohr-Coulomb fracture envelope. However, differential stress at 100 MPa did not show a significant increase over that at 75 MPa (Figure 6). All samples under confining pressure underwent linear elastic deformation at the start of the experiment, followed by plastic yield and flattening of the curve indicating steady state deformation. Two experiments were run at 100 MPa since the first one (CS-005) showed less differential stress at failure than the 75 MPa sample.



Figure 5: a) - h) see explanation next page.

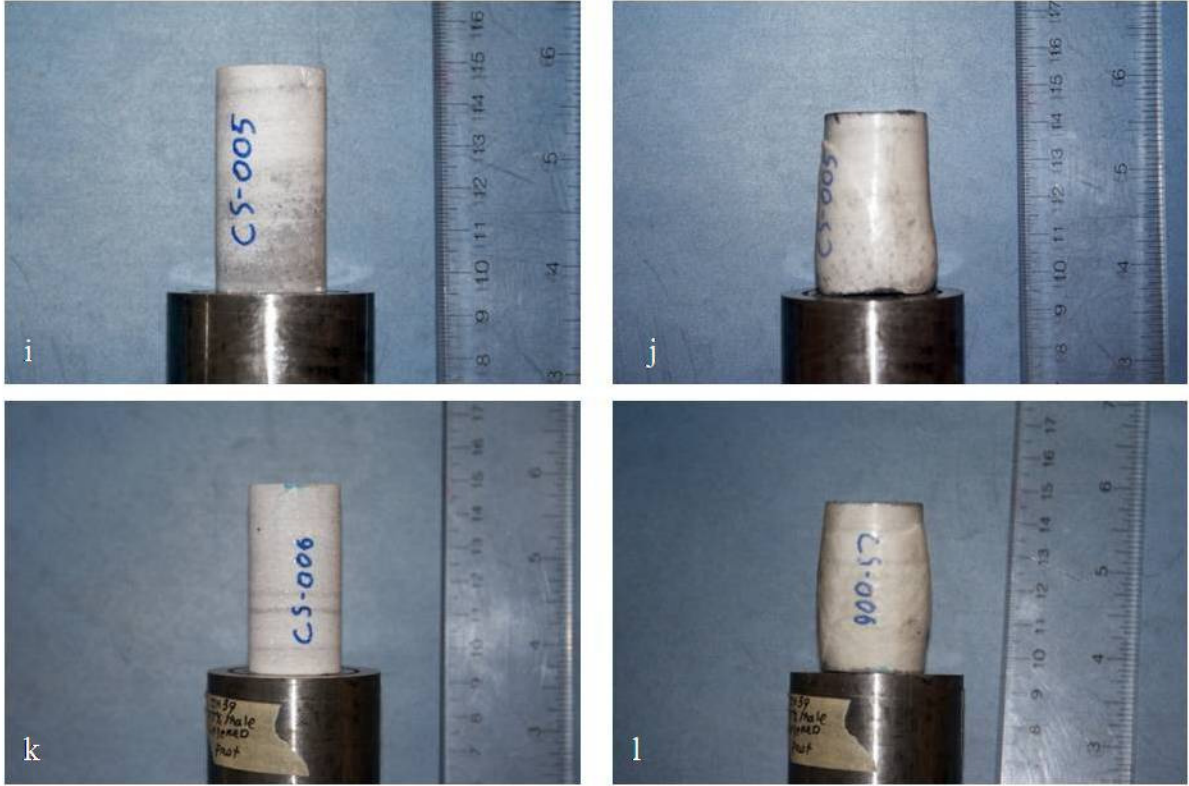


Figure 5: Photographs of core samples before and after triaxial stress testing. a) CS-001, tested at 0 MPa confining pressure. b) Note absence of shear failure, and only thin axial tensile fractures. c) and d) CS-002, tested at 25 MPa. Note minor barreling and shear fracture on failed sample. e) and f) CS-003, tested at 50 MPa. g) and h) CS-004, tested at 75 MPa. i) and j) CS-005, tested at 100 MPa. Note pronounced barreling in gypsum rich bottom section, as well as multiple shear fractures. k) and l) CS-006, tested at 100 MPa.

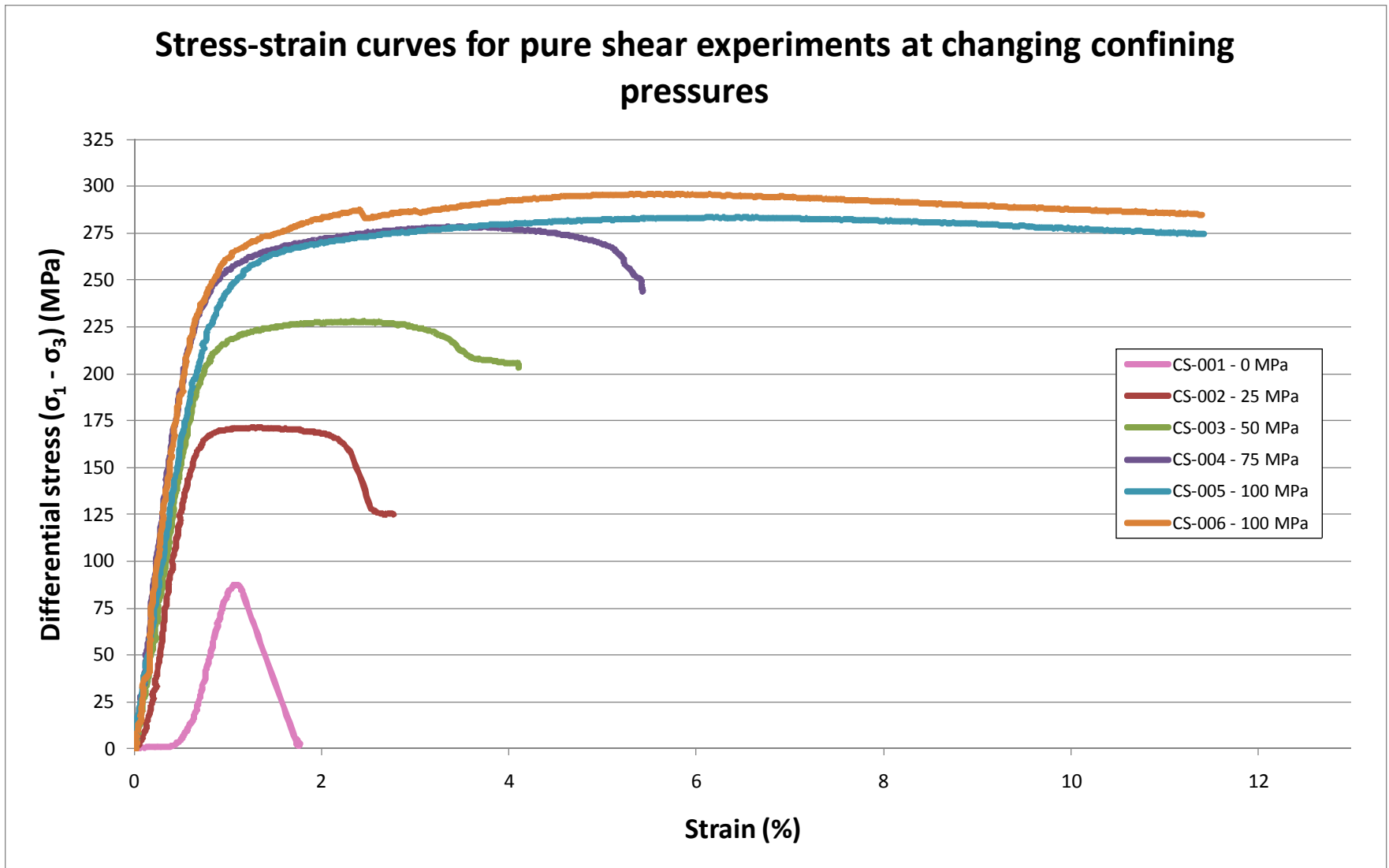


Figure 6: Differential stress vs. strain curve for the six fracture strength experiments. See text for explanation.

Microscopic Analysis

The run products were analyzed in thin section as well as under SEM. The analysis generally showed an increase in distributed deformation with increased confining pressure. Sample CS-001, which was tested under no confining pressure and macroscopically showed tensile fractures, has almost no distributed deformation away from the localized fracture (Figure 7). Grains show no increase in intensity of ductile deformation than those in the starting material. No gouge material was present in or around the fractures. The main fracture is roughly parallel to the primary stress and cuts through some individual grains along planes of weakness (secondary cleavage of anhydrite). Finer grained material is present but it is likely not the result of deformation. Bands of finer grained material within the sample appeared less susceptible to brittle fracture.

Fault zones in the remaining samples contained some amount of gouge material (Figures 8-11). Samples also show varying amounts of distributed deformation away from the fault zone. The intensity of the distributed deformation is generally related to the confining pressure – a higher confining pressure led to greater amounts of distributed deformation. This was characterized by tensile fracturing and shearing of the crystals, grain size reduction, and undulose extinction, in areas away from the shear zone. In general, gypsum appeared to be less susceptible to brittle deformation, although this may be due to the fact that most of the gypsum seen in the samples is much finer grained than the surrounding anhydrite.

Sample CS-002, tested at 25 MPa confining pressure had a relatively narrow shear zone, generally ranging from 0.1-0.25 mm (Figure 8). Secondary cracks appear to splay off from the primary break, and then run sub-parallel to it, and the distance between these cracks was up to 1.5 mm. Within the shear zones, some anhydrite showed an increase in ductile deformation, mostly by more intense undulose extinction and bending of cleavage. Gouge in the shear zone is for the most part angular, and only very well defined in SEM backscatter images (magnification of 315x to 1000x). It is uncertain whether or not all gouge material is present, as it may have been lost in the preparation of the thin section. Grains away from the fault zone appeared more flattened than in the starting material, but grain size reduction and sheared grains were present only in close proximity to the shear zone. As confining pressure is increased, the shear zone generally gets wider and less well defined, indicative of greater

distributed deformation. Samples deformed at higher pressures also tended to have more gouge material in the fault. Signs of ductile shear are also present, such as deformed crystals curved towards the direction of shear. These are more prominent in earlier samples (such as CS-003, deformed at 50 MPa P_c), as later samples underwent much more intense grain size reduction by brittle fracture. Under SEM, tensile fractures parallel to σ_1 away from the fault zone are far more prominent in the higher P_c samples. Many crystals display a ‘domino’ characteristic, where a broken crystal will shear along the fracture surfaces indicating shear sense (Figure 11).

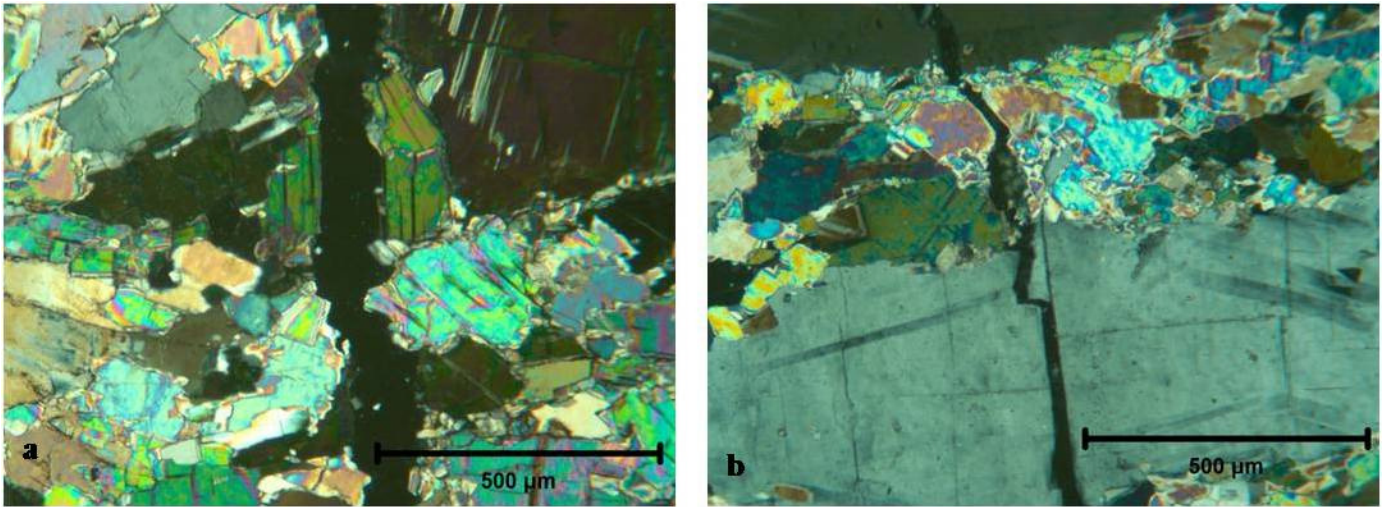


Figure 7: Photomicrographs of sample CS-001, tested at 0 MPa confining pressure, in cross-polarized light. Note tensile crack that crosscuts crystals in both a) and b). Load (σ_1) is from vertical direction.

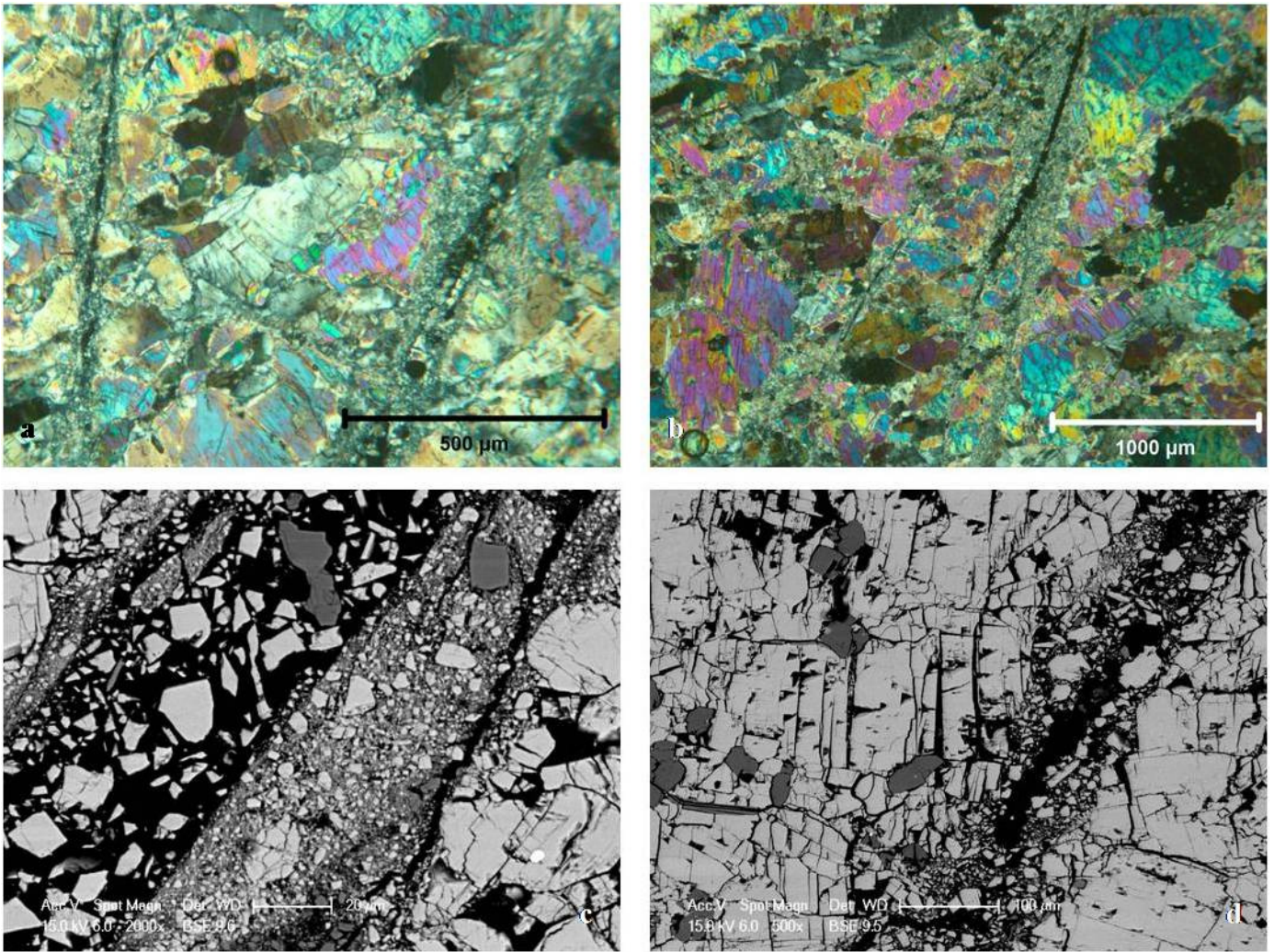


Figure 8: Photomicrographs of sample CS-002 (25 MPa). a) and b) are taken under cross-polarized light showing branching of fault and intense grain size reduction directly next to faults. c) SEM electron backscatter image showing angular gouge material in fault.

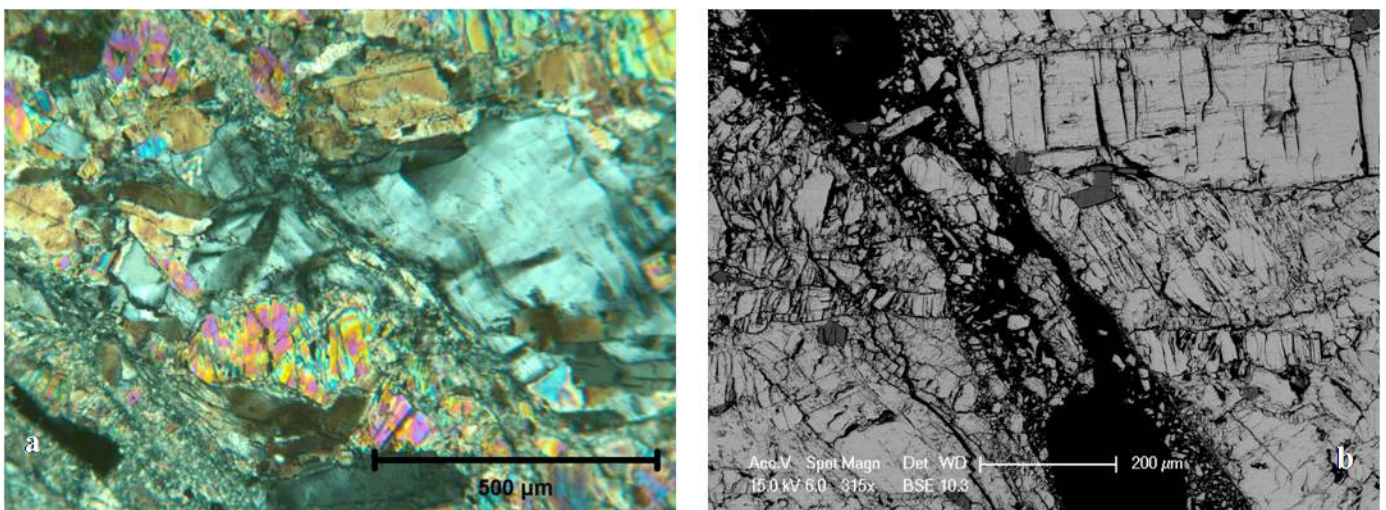


Figure 9: Photomicrographs of sample CS-003, tested at 50 MPa confining pressure, a) cross-polarized light, showing induced undulose extinction in a crystal and b) SEM backscatter, showing tensile fractures and grain size reduction.

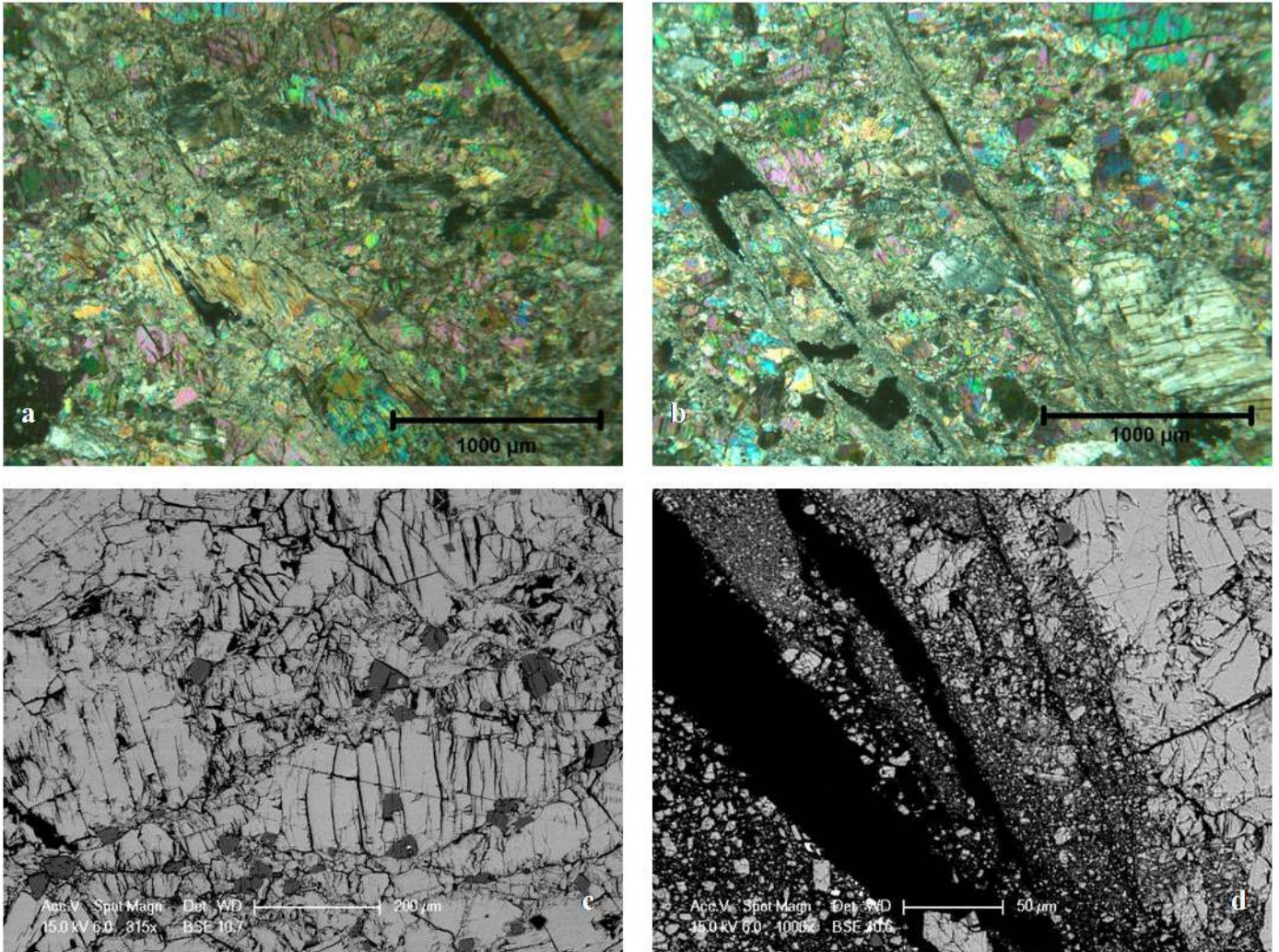


Figure10: Photomicrographs of sample CS-004, tested at 75 MPa confining pressure, a) and b) cross-polarized light, showing induced deformation. a) shows a great example of a sheared crystal c) and d) are SEM backscatter images, showing increased tensile fracture.

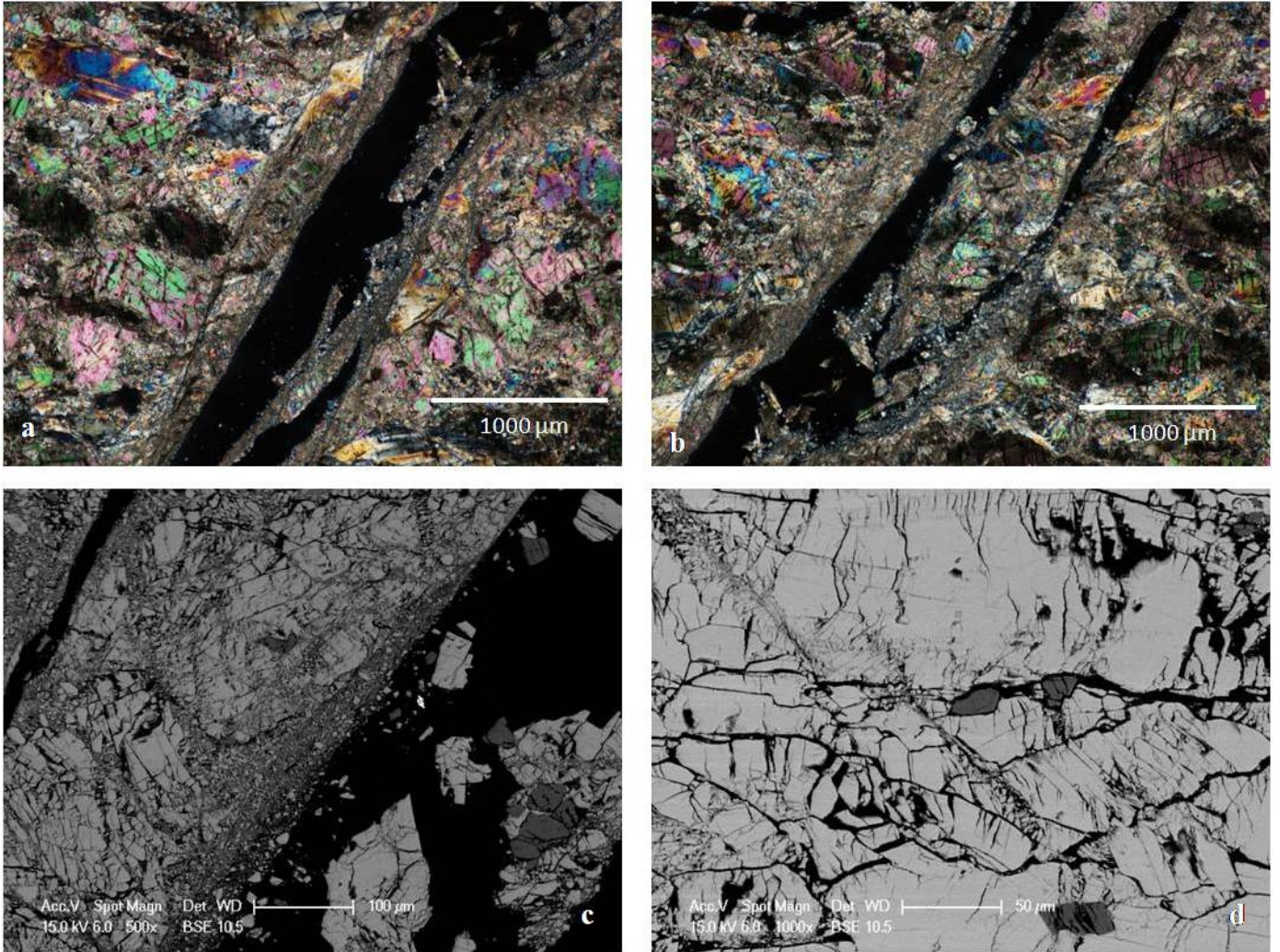


Figure 11: Photomicrographs of sample CS-006, tested at 100 MPa confining pressure, a) and b) cross-polarized light, showing intense induced deformation. Most of the original fabric is destroyed. c) and d) are SEM backscatter images. d) shows early formation of conjugate faults, and shearing of crystals.

Frictional Sliding Tests

Frictional experiments were run on pre-existing saw cuts to determine the frictional strength of the anhydrite. These cores were cut at 30° to the core axis, with the cut surfaces polished. The sample assembly is the same as for the pure shear tests. Raw data from these tests was not as straightforward and there was some variability in behaviour between the various tests. Unlike the previous suite, no experiment was done with zero confining pressure, so the first sample was tested at 25 MPa. This sample (CS-007) did not show an increase in load until it had already been displaced by about 0.035 inches (0.89 mm). After the load reached its maximum of about 12160 lbs (5516 kg), it dropped slightly and maintained a steady state. There was, however, some variability in the line, possibly indicating stick-slip sliding. There was no significant stress drop. Once removed from the apparatus, the sample showed little signs of displacement along the pre-existing saw cut or ductile deformation (Figure 12).

Samples CS-008 and CS-012 were tested at 50 MPa P_c , (CS-008 was redone due to inconsistencies in the assembly). Unlike CS-007, these samples required a significant increase in load (up to around 41000 lbs or 18600 kg for CS-012) before any displacement was noticed. Once this load was reached, the load-displacement curve appeared to show ductile deformation and slight strain hardening. This rapid increase in load with little displacement indicates that the cut fault zone was locked. A stress drop was noted in both experiments and the test was stopped then. Sample CS-008 had a much smaller displacement (0.045 inches, versus 0.16 inches for CS-012). Of interest in sample CS-012 was the formation of a brittle fracture seen after removal from the apparatus. This fracture is a conjugate to the pre-existing saw cut, which explains the very high loads required for failure. However it does not appear that this fracture accommodated significant displacement, as there appears to be a significant amount of displacement along the cut fault. Samples tested at higher P_c also showed brittle fractures, although these were minor and often only visible under the microscope, making CS-012 unique.

Samples CS-011 and CS-009, tested at 75 and 100 MPa P_c respectively, showed similar load-displacement curves, and both underwent a significant stress drop, at 62000 lbs (28100 kg) and 82000 lbs (37200 kg) respectively. Sample CS-011 showed strain hardening before failure, whereas sample CS-009 levelled off and even appeared to have a slight drop

but generally maintained a steady state before having a significant stress drop. These samples both showed significant displacement along the saw cut, and, as previously mentioned, minor brittle fractures. The samples tested at 50 MPa P_c and higher showed some extent of barrelling, although nowhere near as intense as that observed for the pure shear experiments.

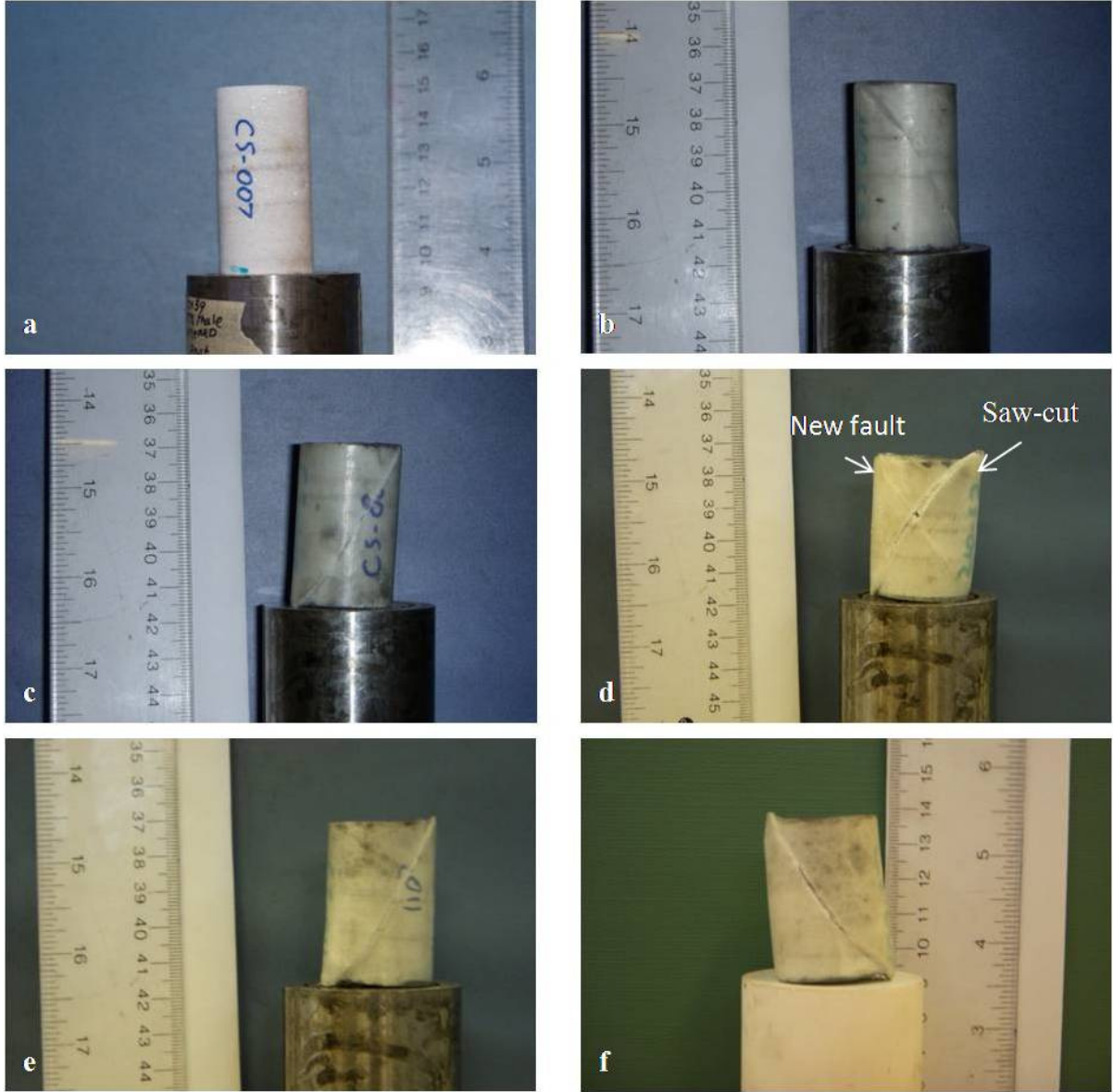


Figure 12: Frictional sliding experiment samples. a) Sample CS-007, prior to being cut and deformed. b) Sample CS-007, tested at 25 MPa. c) Sample CS-008, tested at 50 MPa. d) Sample CS-012, also tested at 50 MPa. This is the only sample to show a complete conjugate fault to the pre-cut fault. e) Sample CS-011, tested at 75 MPa. f) Sample CS-009, tested at 100 MPa. Note significant barreling of sample.

Microscopic Analysis

Microscopic analysis revealed a range of deformation between the samples tested at the various confining pressures. As in the first set of pure shear experiments, increasing P_c generally leads to an increase in distributed ductile deformation, such as grain size reduction and shearing of crystals throughout the core away from the fault surface. There was very little brittle deformation anywhere in the sample in CS-007, tested at 25 MPa. The cut surfaces appeared mostly smooth with very little fault gouge or fracturing (Figure 13). Samples at higher P_c had a tendency for brittle failure such as tensile fractures as well as displacement along the surface cut. All samples tested at 50 MPa P_c or higher showed brittle fractures parallel to the cut surface, as well as substantial fault gouge both in the pre-cut fault, and in the newly formed faults. Sample CS-011, tested at 75 MPa P_c begins to show significant tensile cracking throughout the sample, but especially around the shear zone, as does CS-009 (100 MPa) (Figure 15).

As previously mentioned, sample CS-012 was unique in that it had a brittle fault running across the entire core conjugate to the original cut surface. This fault was similar in nature to those created in the first suite of experiments, in that it displayed intense grain size reduction directly adjacent to the fracture, along with tensile cracking in crystals close to the fault, and branching of the fault. The shear zone is poorly defined as grain size reduction and brittle fracturing gradually decreases away from the fault. Other samples, in particular CS-009, displayed microscopic fractures opposite the cut fault, similar to sample CS-012, though these were not linked across the entire core (Figure 16).

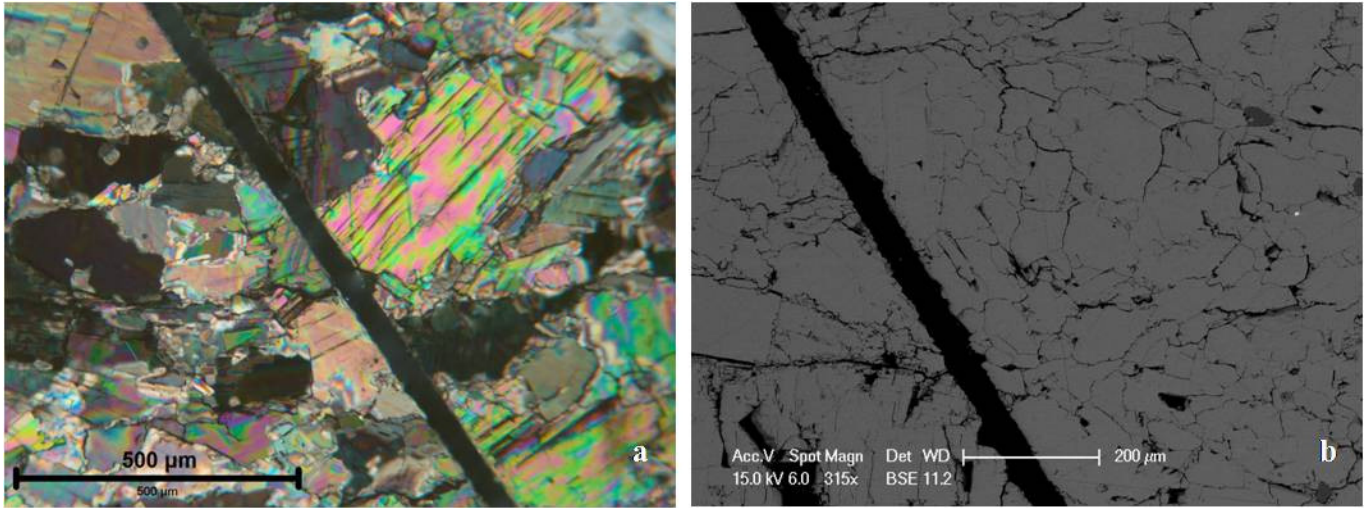


Figure 13: Photomicrographs of CS-007, tested at 25 MPa P_c , a) in cross-polarized light, and b) SEM backscatter image. Sample showed noted lack of deformation in crystals and very little gouge formation in the fault. Surfaces remained very smooth.

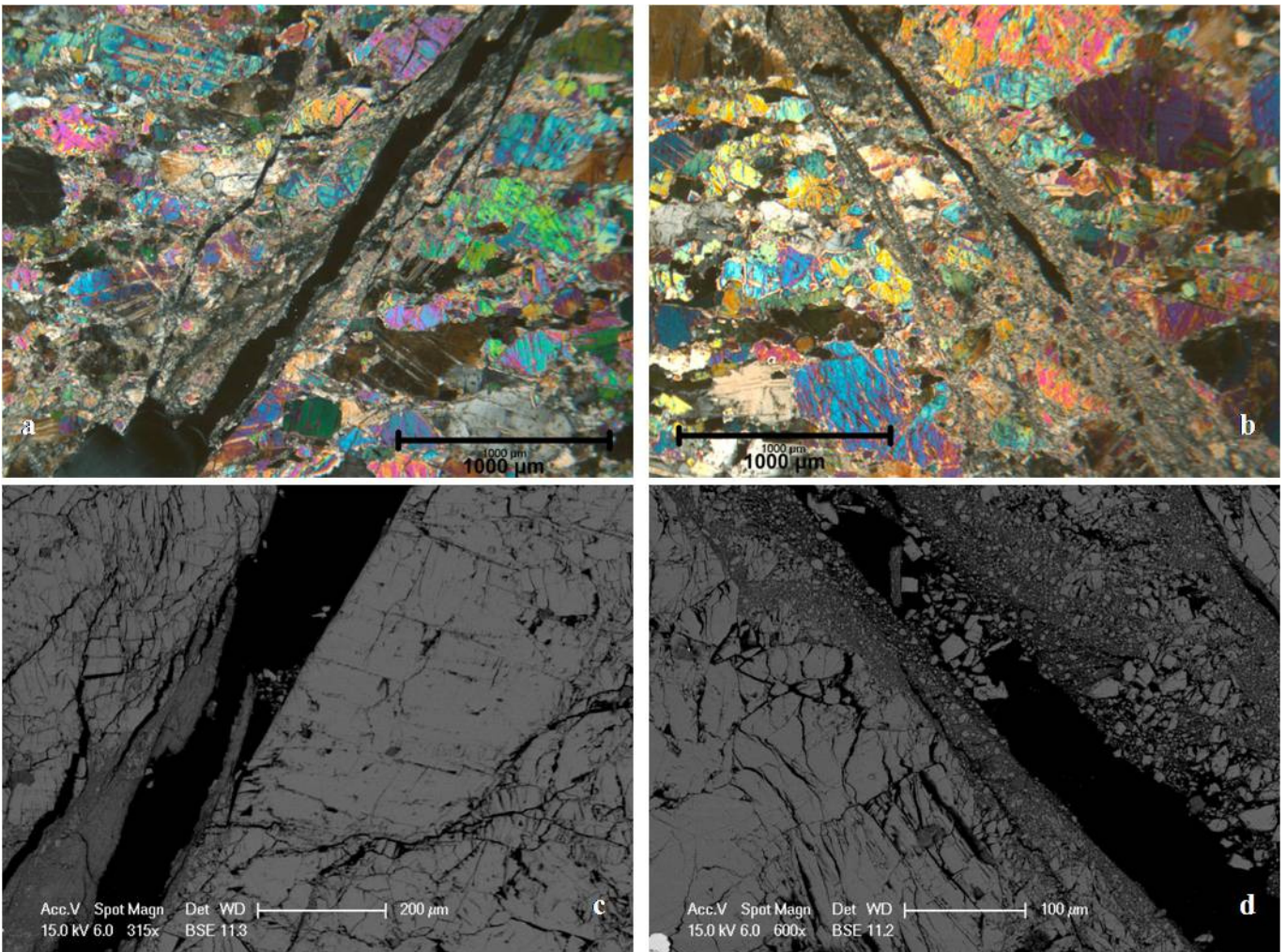


Figure 14: Photomicrographs of sample CS-012, tested at 50 MPa. a) shows the pre-cut fault in cross-polarized light, with extensive fracturing. b) shows the brittle fault that formed. c) SEM backscatter image of the cut fault, with tensile fracturing in adjacent crystals. d) brittle fault, with gouge material and grain-size reduction evident.

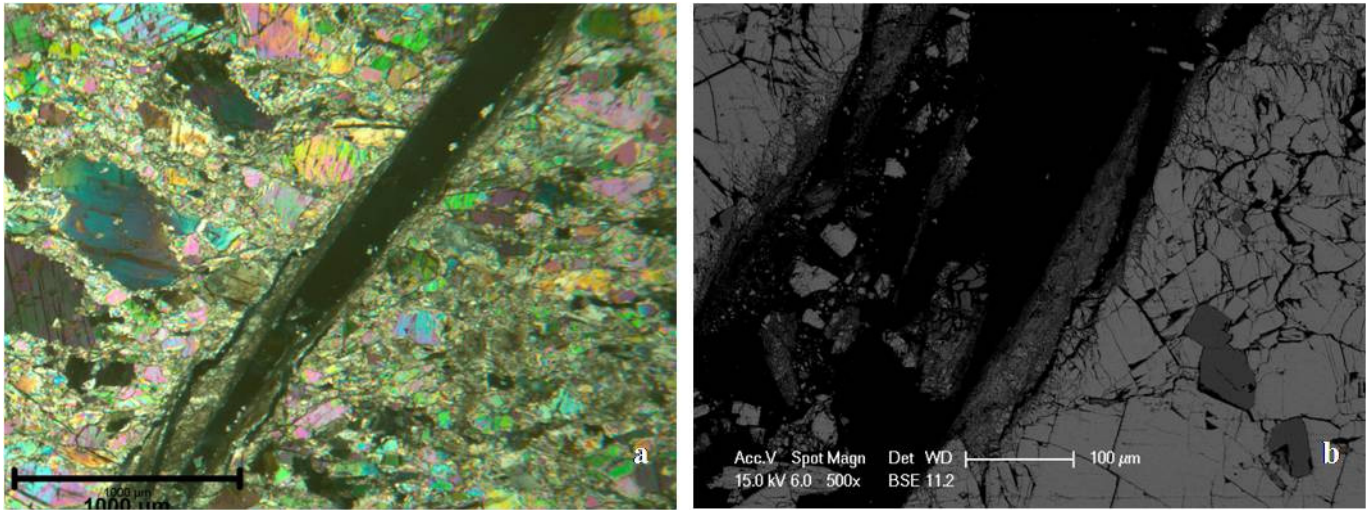


Figure 15: Photomicrographs of sample CS-011, tested at 75 MPa. a) In cross-polarized light, and b) SEM backscatter. Darker grey crystals are gypsum.

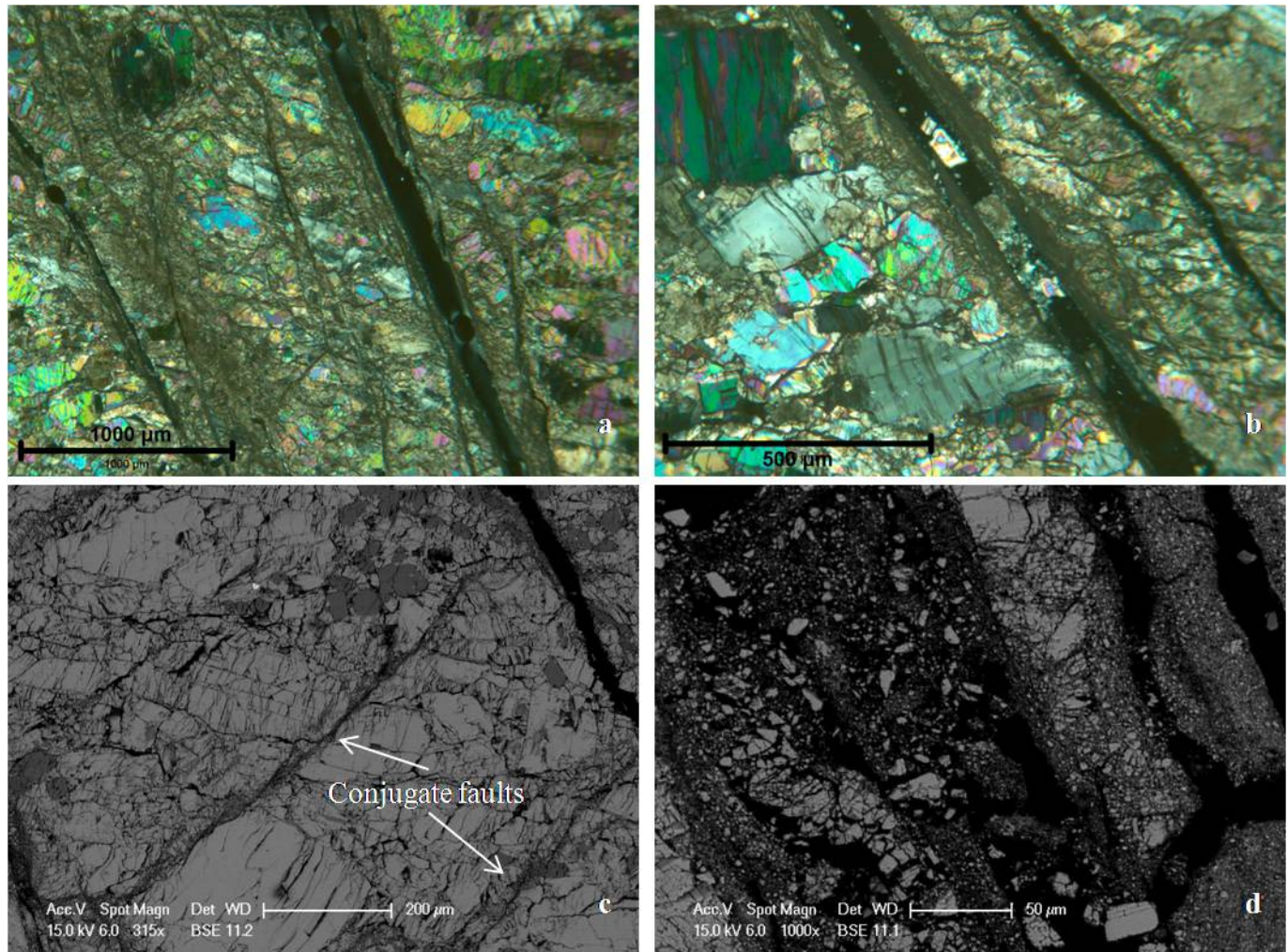


Figure 16: Photomicrographs of Sample CS-009, tested at 100 MPa. a) and b) in cross polarized light, showing intense fracturing and plastic deformation next to the pre-cut surface. c) SEM backscatter image showing development of conjugate faults. A fully formed fault running parallel to the cut surface is in the upper right corner. d) SEM backscatter image showing gouge material in the fault.

DISCUSSION

Analysis of Results

Mechanical Strength Test: Pure shear experiments

The results were plotted on a Mohr diagram to analyze the mechanical behaviour of anhydrite with increasing differential stress ($\sigma_1 - \sigma_3$). The results show that differential stress increases linearly with confining pressure until around 75 MPa (a Mohr-Coulomb failure envelope). After 75 MPa, differential stress remains approximately constant as confining pressure increases, showing a von Mises failure envelope (Figure 17), which indicates ductile deformation. A Mohr-Coulomb failure criterion was determined for P_c up to 75 MPa. The two experiments conducted at 100 MPa did not follow the trend as the failure envelope flattened out. This behaviour is indicative of both an increase in strength and ductility, something demonstrated by early experimental work done by Handin and Hager (1957). The increased bulging and lack of a stress drop in the 100 MPa tests suggests that the sample accommodated considerable cataclastic flow along the through-going shear zone. The cataclastic flow gives rise to ductile behaviour at the macroscopic level e.g. Handin and Hager found no thru-going fracture in samples tested at 2000 atm (202.7 MPa).

The Mohr-Coulomb failure criterion for brittle failure can be described by the equation:

$$\tau = \sigma \tan(\varphi) + c \quad (1)$$

where τ is the shear strength, σ is the normal stress, φ is the angle of shearing resistance, and c is the cohesion. These are calculated by connecting the common tangents to the Mohr circles for each sample. The sample at zero P_c is not considered, as in Bell (1994), since the envelope tends to curve towards the origin at very low P_c . By applying this method, the anhydrite was found to have a cohesion value of 39.5 MPa, and an angle of shearing resistance of 22° (Figure 17).

Mechanical strength experiments similar to ones reported here have previously been done by many workers, including the aforementioned Bell (1994) and Handin and Hager (1957). One of the more recently published data comes from Collettini et al. (2009), who analyzed anhydrite samples collected from the location of the Umbria-Marche seismic

sequence in the Apennines of Central Italy. In all cases, anhydrite is classified as a generally weak rock (Handin and Hager, 1957, Kulhawy, 1975). Handin and Hager found anhydrite to have cohesion of 43.4 MPa, with an angle of friction of 29.4°. This is slightly weaker than values found for limestones and other carbonates (that would be found in the Chitistone Formation in the Duke River area), and much weaker than values for metavolcanic and metasedimentary rocks (Kulhawy, 1975), also found in the Duke River fault. These values should not be taken at face value however, since the geology of any study area is unique and strength can depend on any number of factors. Bell does not give a value for cohesion of anhydrite, but gives an average unconfined compressive strength of 97.5 and 102.9 MPa, for his two samples, and Young's moduli of 78.7 and 69.4 GPa. The unconfined compressive strength of anhydrite in this study was slightly lower at 87.5 MPa. Young's modulus, E , which can be defined by

$$E = \frac{\sigma}{\varepsilon} \quad (2)$$

where ε is strain, was much lower for these samples, and averaged around 32 GPa.

Both the Handin and Hager and Bell strengths listed above are high compared to samples tested in these experiments. However, as previously mentioned, there are a number of factors which would affect the strength of a particular rock type collected from different sources. Collettini et al. (2009) demonstrate that anhydrite can in fact behave anisotropically depending on the fabric. Anhydrite with no internal fabric was found to be strongest, whereas anhydrite with foliation was strongest when the foliation was perpendicular to the load. The presence of foliation is generally indicative of prior deformation which implies that anhydrite that has undergone compressive loading is already weaker. Grain size is also relevant, with results from Collettini et al. showing that finer grained anhydrite is stronger than coarser grained anhydrite. These two factors could account for the lower strength of the samples in this experiment compared to those in literature.

Collettini's experiments showed an initial phase of approximately linear deformation, followed by plastic yielding and failure. Collettini also observed distributed deformation in samples with higher effective pressure (P_e ; the difference between P_c and pore fluid pressure). At higher P_e , his samples did not display a stress drop, similar to my data. While Collettini used pore fluid pressure in his experiments, a high P_e can result from having a high P_c , and so the comparison with my experiments is valid.

Presence of Gypsum

Starting material used had varying amounts of gypsum within them. This gypsum was determined to be secondary hydration of the anhydrite, as it appears to overprint the textures found in the anhydrite. Rehydration in shallow anhydrite is common (DePaola et al., 2008). While care was taken to choose core samples with minimal amounts of gypsum, some was present in most cores and it exerted an effect on the run product, for example, in sample CS-005, the presence of gypsum affected the results so greatly that it needed to be redone. Figure 8 shows the more intense ductile deformation on one end of the CS-005 core, the end which is rich in gypsum.

Bell describes gypsum as being much weaker than anhydrite, (cohesions of 10-18 MPa) but having similar behaviour in terms of the effect of increasing confining pressure. This would explain the more intense barrelling, ductile deformation, and increased number of brittle fractures seen when the sample was removed from the apparatus. This however seems contradictory to what is seen in other samples under the microscope, where the presence of gypsum seems to slow or impede brittle deformation. This may be due to the very fine-grained nature of the gypsum compared to the anhydrite. This may also be due to the fact that gypsum behaves in a ductile manner at a much lower P_c than anhydrite (Bell, 1994).

Mechanical strength experiments

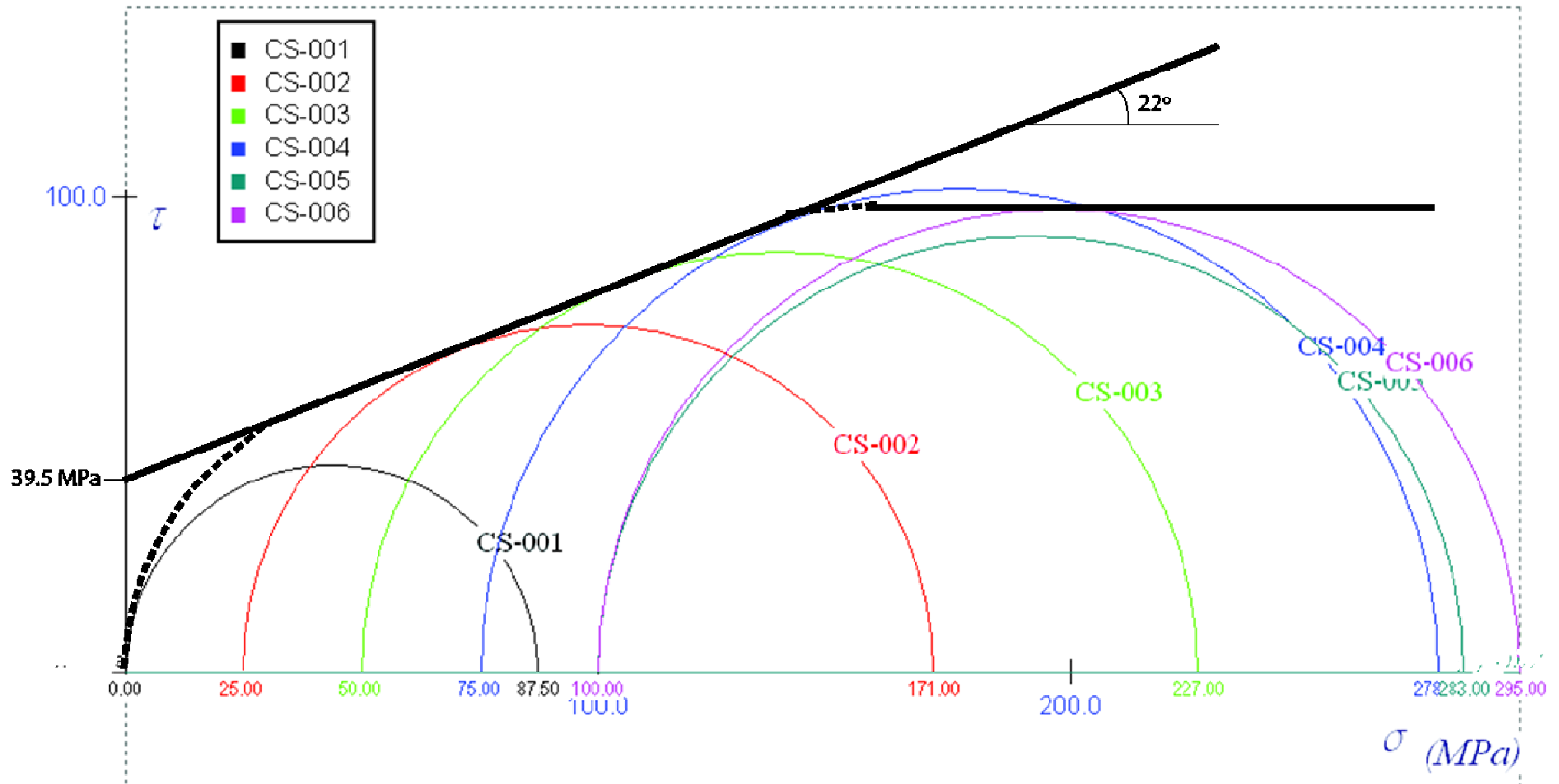


Figure 17: Mohr diagram for the mechanical strength experiments. The Coulomb failure envelope is shown with a slope of 22°, and a cohesion of 39.5 MPa. This envelope curves towards a von Mises failure envelope after around 75 MPa confining pressure. A dotted line shows the curve trend towards the origin as suggested by Bell (1994).

Frictional sliding testing

Data from these tests was analyzed to determine not only differential stress, but also the coefficient of sliding friction. Coefficient of friction μ_s was calculated by:

$$\mu_s = \frac{\sigma_s}{\sigma_n} \quad (3)$$

where σ_s and σ_n are the shear and normal stresses, respectively. See Appendix 1 for details on the data reduction. While μ_s increases as load is applied, most authors use only the steady state value, which is achieved when the curve of the μ_s vs. displacement graph becomes horizontal. A steady state sliding was not only achieved for some samples, however, due to the limitations of displacement on the LSR. In addition, continued sliding would have led to tearing of the polyolefin jacket and infiltration of argon into the sample itself.

Analysis of the data and run products indicates that although there was significant shear strain along the pre-existing saw cut, there was also distributed strain in hanging wall and foot wall, as illustrated by the barrelling of the samples, particularly at higher confining pressures (Figure 18).

Reducing the data revealed atypical behaviour in some of the experiments. In calculating the coefficient of sliding friction (μ_s), only samples CS-011 and CS-009 tested at 75 and 100 MPa P_c respectively had realistic values, as is explained below. CS-007, tested at 25 MPa P_c produced a μ_s value that was unrealistically low. CS-008 and CS-012, both tested at 50 MPa P_c returned unreasonably high values, among other unexpected behaviours that are discussed below. Most work in literature generally takes on a single constant or only slightly changing value for coefficient of friction (Collettini et al., 2009, Sibson, 1984), which appears as the slope of the reactivation envelope on a Mohr-Coulomb stress diagram. This, in effect, is the steady-state coefficient of friction.

A look at each individual sample shows how these results are not as conclusive as desired. Sample CS-007, had the unique behaviour of initial displacement without increasing load, before reverting to a more typical curve. This type of behaviour is generally indicative of porosity reduction (J. Haywood, personal communication, 2010); however this sample (and all the samples) did not have much porosity to begin with (see Table 1). This behaviour may have indicated closing of the fault, which may not have fully closed during initial increase of confining pressure (25 MPa). After an increase in load, the sample returned to

steady-state sliding, which is marked by a distinct jaggedness, indicating the possibility of continuous stick-slip sliding (Byerlee, 1978). The maximum coefficient of friction was found to be around 0.15, which is not an acceptable value found in any work cited. This may, however, be explained by the fact that at low pressures, there is generally a great variation in data, and friction is more dependent on the smoothness of the surface than on the type of rock (Byerlee, 1978). At such low pressures, Byerlee finds coefficients of friction between 0.3 and 10. This may explain the behaviour of this sample, but calls into question its relevance, given that the surfaces were polished to maintain consistency among the samples. Repeating this experiment with a different sample could very likely give an entirely different result.

The experiment on sample CS-008 (50 MPa P_c) was redone with sample CS-012 because of a possible inconsistency in the assembly. The initial behaviour in both samples was essentially the opposite of the previous experiment; the load increased dramatically once the experiment was started, with no initial displacement. The stress drop seen in CS-008 was small and may actually have been an effect of stick-slip sliding. Sample CS-012 may be more representative, as reduction of the data shows a small decrease in stress earlier in the test, indicative of stick-slip. Microscopic analysis indicates that the stress drop in CS-012 was caused by the brittle failure of the sample, and not a sudden slip along the cut fault.

Frictional lock-up cannot be used as an explanation for this behaviour. Lock-up occurs when the reactivation angle of a fault (θ_r) to σ_1 is great enough that σ_1/σ_2 approaches infinity. This explanation requires that the fault angle be approximately twice the optimal reactivation angle, and that the formation of new, more favourably oriented faults would occur (Collettini and Sibson, 2001). The angle of the cut fault in this case was already within the range commonly accepted optimal angles ($\theta_r = 25^\circ - 30^\circ$) (Byerlee, 1978), and the new fault was conjugate to the existing one. At this point, given the extremely high coefficient and atypical initial behaviour, the data from these experiments cannot be used. The assembly likely affected the behaviour and data from CS-008 and some unknown sample inconsistency must have caused CS-012 to not slip, and instead fracture.

The behaviour of the higher confining pressure samples was more similar to the fracture strength experiments. Samples CS-011 (75 MPa P_c) and CS-009 (100 MPa P_c) displayed an initial elastic increase in force, followed by a yield, and a stress drop. This is similar to the basic model shown in Byerlee. The maximum coefficient of friction for both

these samples was around 0.8. While this is a somewhat more realistic value, it is still higher than values found by Mirabella (2002) and used by Collettini et al. (2009), which are around 0.6. Mirabella's experiments were somewhat different, using a hardened anhydrite powder in a fault, as opposed to two anhydrite surfaces in direct contact, and reached confining pressures up to 300 MPa. The maximum stress values in this experiment were similar to Mirabella's for confining pressures of 50 and 100 MPa.

The increase in friction with confining pressure can be explained by the actual or 'real' area of contact along the saw cut. At low confining pressures, sharp asperities in the surface are in contact, which reduces the actual area of contact, and therefore the coefficient of friction. Increasing the confining pressure closes this gap and increases the area of contact, increasing the coefficient of friction and the strength of the shear zone. The strength of the shear zone approached that of the hanging wall and foot wall, which caused greater distributed deformation and widening of the shear zone.

It is worth mentioning that calculations done for these experiments do not take into account brittle or ductile deformation occurring within the sample. Aside from the conjugate fault in CS-012, samples at > 25 MPa P_c showed some amount of faulting alongside the cut surface, grain size reduction and gouge formation adjacent to the fault, and distributed deformation throughout the sample. SEM backscatter images from sample CS-009 show the proliferation of microcracks into conjugate faults (Figure 16).

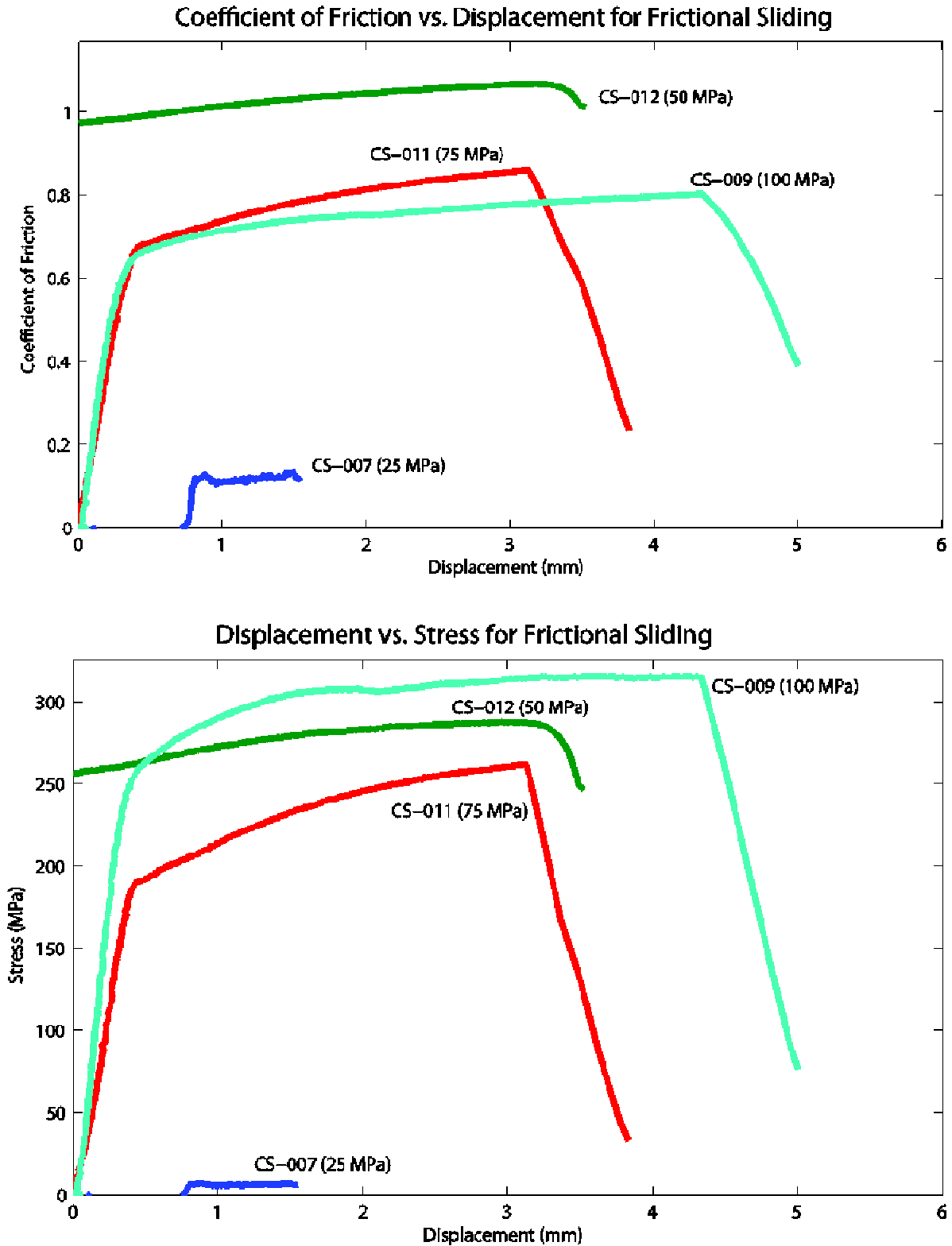


Figure 18: a) Differential stress and b) coefficient of friction over displacement. Notice the anomalous behaviour of sample CS-012. Sample CS-008 is not included because of extremely anomalous behaviour that would not fit on the graphs.

Comparison to the Apennines

The Apennines were chosen as an analogue to these experiments because they contain a good example of a large unit of evaporites that act as the source region for seismicity (DePaola et al., 2008). Seismicity in the Apennines is very well constrained due to the large amount of seismic data available (Collettini et al., 2008). This is in contrast to the Duke River and Denali fault systems, which have a great degree of uncertainty in locating seismic events, as well as determining stress changes (Eberhart-Phillips et al., 2003). Given the aforementioned characteristic of evaporitic rocks to behave ductilely in fault zones, it is reasonable to question whether or not the anhydrite in the Duke River fault plays a major role in seismicity.

One of the most recent and most studied examples of activity was the Umbria-Marche seismic sequence, which was a significant series of seismic events recorded in 1997-1998 (De Paola et al., 2008, Collettini et al., 2008), and is characterized by 7 major earthquakes in 8 months. Seismic evidence shows that the main shocks nucleated in Triassic Evaporites along normal faults, at approximately 6 km depth. It is a 2.0 km thick sedimentary sequence that is composed of interbedded gypsum-anhydrite and dolostones (Collettini et al., 2008).

My experimental results would suggest that stress drops are unlikely at these depths and thus cannot explain the seismic behaviour along the Duke River fault. A 6 km depth would translate to a confining pressure of over 170 MPa, well higher than the confining pressure at which dry anhydrite deforms by cataclastic flow with no stress drop. Unlike my experimental samples, however, the Triassic Evaporites are not dry, but have significant elevated pore fluid pressure at depth, up to 100 MPa (Collettini et al., 2008). The fluid, which is CO₂ rich, was found to have pressures up to 85% of the lithostatic load, which significantly reduces the effective stress on the rocks. Indeed, several models propose that fluid overpressure is the triggering mechanism of the Umbria-Marche sequence, which caused the anhydrite to act in a brittle manner despite the depth. Ideally, my experiments would also have been conducted with pore fluid pressure; however given the extremely low porosity of the samples, properly saturating them would have been far too time-consuming.

Fault zone evolution models by both Collettini et al. and De Paola et al. suggest that faulting is initiated in the anhydrite as opposed to the dolostones due to the much lower strength. During loading at high confining pressures, anhydrite behaves in a ductile manner,

while dolomite rocks remain rigid and brittle. The faulting in anhydrite would be similar to what was seen in samples CS-005 and CS-006, at 100 MPa P_c . This would produce fault zones without a stress drop creating a seismic event. Based on their experimental data, Collettini et al. then suggest that the penetration of fluids along this more permeable, cataclastic fault zone would cause a reactivation leading to a seismic slip event. This is similar to De Paola et al., although they specify that it is dolomite cataclastic seams, acting as cohesionless surfaces that lead to brittle fault reactivation.

Relevance to the Duke River Fault

The seismicity and lithology of the Duke River Fault, particularly in the Bullion Creek area, has not been studied in nearly as much detail as the Umbria-Marche region of the Apennines. Evaporites are not quite as prevalent in this region, and their importance is less well known. The anhydrite samples used in this study come from the Chitistone Formation, and are interbedded with massive limestone. The presence of carbonates adds a parallel that can be drawn with the Apennines. However it should be noted that limestone in general is weaker than dolomite, and achieves ductility at much lower confining pressures (Handin and Hager, 1957), though still not as low as anhydrite. Thus anhydrite would still be the weakest rock in the package.

The Chitistone Formation varies in thickness from thin lenses to several hundred metres. The anhydrite is interpreted to come from the lower portion of the unit, interbedded with limestone, and overlain by more massive limestone (personal communication, Israel, 2009). Based on the work by Collettini et al. (2009), as well as Handin and Hager (1957), it can be suggested that, if this unit were subjected to increased tectonic stresses, the anhydrite layer would be the source of a brittle stress drop at low effective pressures, or ductile and cataclastic flow at higher confining pressures.

While seemingly simple, this situation is made more complicated when comparing actual seismicity to fault activity along the Duke River fault. Microseismicity studies have shown a concentration of seismic events in a 15km wide band that includes the Duke River Fault. However, there has been very little actual active faulting along the Duke River fault, or the rest of the Denali fault system east of the Alaska border (Cassidy et al., 2005). Horner (1983) suggests a readjustment of tectonic stresses as the cause of motion on planes that are

not aligned to current major faults. Two historical earthquakes thought to have occurred in proximity to the system (1920 and 1944) have since been relocated further west.

Horner (1983) gives the location and depths of hypocentres of events in his microseismic study south of Kluane Lake, on the Duke River Fault. Depths range from 1 to 12 km, with standard errors of 1 to 3 km, although most depths are in the 4 to 8 km range. Assuming a mean lithostatic gradient of 30 MPa km^{-1} , this corresponds to pressures of 120 to 240 MPa.

Given the experimentally derived strengths of the anhydrite, it is clear that the confining pressures where most of these microseismic events have occurred are far too large for dry anhydrite to produce a stress drop. At these pressures, anhydrite would undergo ductile deformation through cataclastic flow. Pre-existing faults that are locked might experience a stress drop before attaining steady state displacement. Unfortunately, in this study, it was not determined whether or not these rocks would undergo stick-slip sliding at those pressures. The presence of these deeper quakes indicates one of two scenarios. The first is that there is no anhydrite present, or it is too high in the stratigraphy to accommodate stresses at depth. Being the weakest possible rock (other than gypsum) present in the area, it would be the first to deform in any stress regime. At those depths, it would accommodate the stress through cataclastic flow, but would be unlikely to undergo brittle failure resulting in a stress drop. However, as the Chitistone Formation is only present in lenses in some areas, and is only very well defined further west in Alaska (Read and Monger, 1976, Israel, personal communication, 2009), it is likely that its presence in the Kluane Lake region was not significant enough to accommodate all the stress. Given the varying depths of the earthquakes, it is almost certain that a number of rock units are sources of these events.

The other explanation is that pore fluid pressure at depth weakened the anhydrite to cause brittle fracturing; similar to what is happening in the Apennines. Unfortunately no data is available for pore fluid pressures in this area. The intense amount of faulting in the area does however provide several fluid flow pathways, so it is not unreasonable to assume that pore fluid plays a role in the seismicity of the area, especially in reactivation of faults, as suggested by Collettini et al. (2009).

CONCLUSION

Experimental data revealed that anhydrite collected from the Duke River Fault showed both brittle and ductile behaviour, as a function of confining pressure. For confining pressures lower than 75 MPa, the Mohr-Coulomb failure envelope could be applied giving cohesion of 39.5 MPa and an angle of shearing resistance of 22° . At higher than 75 MPa the Von Mises failure envelope was applied. As confining pressure was increased, samples exhibited more distributed ductile deformation. Results of frictional sliding experiments were not entirely conclusive, but two of the experiments gave coefficient of friction values of around 0.8, which is higher than other experimental data in literature.

This data was compared to work done in the Apennines in Italy. Work there suggested that pore fluid pressure played an important role in the seismicity. This is supported by the experimental data which suggests that dry anhydrite would not produce a seismic event at depths given. In the Duke River Fault, earthquakes at most depths given by Horner (1983) would necessitate a different rock type, or the presence of high pore fluid pressure.

Future work would have to include a duplicate suite of experiments under elevated pore fluid pressures. The presence of elevated pore fluid pressure may promote brittle failure of anhydrite, even under high confining pressures. The Duke River Fault is an upper crustal shear zone and thus the presence of fluids is likely. A comparison of the experimental run products to naturally deformed anhydrite collected along the Duke River fault would also give a better indication of whether or not the experiments are yielding relevant results.

REFERENCES CITED

- Bell, F.G. 1994, A survey of the engineering properties of some anhydrite and gypsum from the north and midlands of England. *Engineering Geology*, 38, 1-23.
- Bruhn, R.L., Pavlis, T.L, Pflaker, G., Serpa, L., 2004, Deformation during terrane accretion in the Saint Elias orogen, Alaska. *GSA Bulletin*, 116, 771-787.
- Byerlee, J. 1978, Friction of rocks, *Pure and Applied Geophysics*, 116, 615-626
- Cassidy, J.F., Rogers, G.C., Ristau, J., 2005, Seismicity in the vicinity of the SNORCLE corridors of the northern Canadian Cordillera. *Canadian Journal of Earth Sciences*, 42, 1137-1148.
- Cleven, N.R. 2008, The Role of Dolomite Content on the Mechanical Strength and Failure Mechanisms in Dolomite-Limestone Composites, Undergraduate Honours Thesis, University of British Columbia, (Canada), 70pp
- Cobbett, R., Israel, S. and Mortensen, J., 2010, The Duke River Fault, southwest Yukon: Preliminary examination of the relationships between Wrangellia and the Alexander terrane. *In: Yukon Exploration and Geology 2009*, K.E. MacFarlane, L.H. Weston and L.R. Blackburn (eds.), Yukon Geological Survey, p. 143-158.
- Collettini, C., Sibson, R.H., 2001, Normal faults, normal friction? *Geology*, 29, 927-930
- Collettini, C., De Paola, N., Faulkner, D.R., 2009, Insights on the geometry and mechanics of the Umbria-Marche earthquakes (Central Italy) from the integration of field and laboratory data, *Tectonophysics*, 476, 99-109.
- De Paola, N., Collettini, C., Faulkner, D. R., Tripetta, F., 2008, Fault zone architecture and deformation processes within evaporitic rocks in the upper crust, *Tectonics*, 27, TC4017, doi:10.1029/2007TC002230.
- Eberhart-Phillips et al., 2003, The 2002 Denali Fault Earthquake, Alaska: A Large Magnitude, Slip-Partitioned Event. *Science*, 300, 1113-1118.
- Haeussler et al., 2004, Surface Rupture and Slip Distribution of the Denali and Totschunda Faults in the 3 November 2002 M 7.9 Earthquake, Alaska. *Bulletin of the Seismological Society of America*, 94, 6B, S23-S53.
- Handin, J., Hager, R.V. 1957, Experimental deformation of sedimentary rocks under confining pressure: Tests at room temperature on dry samples. *Bulletin of the American Association of Petroleum Geologists*. 41, 1-51.

- Hildyard, R.C., Prior, D.J., Faulkner, D.R., Mariani, E., 2009, Microstructural analysis of anhydrite rocks from the Triassic Evaporites, Umbria-Marche Apennines, Central Italy: An insight into deformation mechanisms and possible slip systems, *Journal of Structural Geology*, 31, 92-103.
- Horner, R.B., 1983, Seismicity in the St. Elias Region of Northwestern Canada and Southeastern Alaska. *Bulletin of the Seismological Society of America*, 73, 1117-1137.
- Israel, S., Tizzard, A., Major, J., Bedrock geology of the Duke River area, parts of NTS 115G/2, 3, 4, 6, and 7, southwestern Yukon, *In: Yukon Exploration and Geology 2005*, D.S. Emond, G.D. Bradshaw, L.L. Lewis and L.H. Weston (eds.), Yukon Geological Survey, p. 139-154.
- Kulhawy, F.H., 1975, Stress deformation properties of rock and rock discontinuities. *Engineering Geology* 9, 4 327-350
- Leonard, L.J., Mazzotti, S., Hyndman, R.D., 2008, Deformation rates estimated from earthquakes in the northern Cordillera of Canada and eastern Alaska. *Journal of Geophysical Research*, 113, B08406, doi:10.1029/2007JB005456.
- Mirabella, F., 2002, Seismogenesis of the Umbria–Marche region (Central Italy): Geometry and Kinematics of the Active Faults and Mechanical Behaviour of the Involved Rocks. PhD Thesis, University of Perugia (Italy), 121 pp.
- Read, P.B., and Monger, J.W.H., 1976, Pre-Cenozoic volcanic assemblages of the Kluane and Alsek Ranges, Southwestern Yukon Territory. Geological Survey of Canada, Open-File Report.
- Sibson, R.H., 1985, A note on fault reactivation, *Journal of Structural Geology*, 7, 751-754
- Van de Reep, P. 2009, Permeability of Limestone-Dolomite Composite Fracture Surfaces. Undergraduate Honours Thesis, University of British Columbia, (Canada). 31pp.

APPENDIX 1 – RELEVANT METHODS AND EQUATIONS

Helium Pycnometry

Helium pycnometry was done on every sample to determine porosity. Helium gas is pumped into a sealed evacuated reference chamber of known volume, and the pressure is measured. A connector is then opened to a chamber containing the sample, and helium is allowed to flow into it, until pressure is equalized. Pressure is then measured again. The volume of the sample is calculated by the ideal gas law, which states:

$$P_1 V_1 = P_2 V_2 \quad (1)$$

where P_1 and V_1 are the initial pressure and volume respectively of the reference chamber, and P_2 and V_2 are the final pressure and volume of the reference chamber and sample chamber. Another way of writing this is:

$$V_1 + \Delta V = \frac{P_1 V_1}{P_2} \quad (2)$$

where ΔV is the change in volume when the reference chamber is opened. Knowing the volume of the sample chamber, we can then determine V_{sample} (the solid volume of the sample, not including pore space) by $V_{\text{ref}} - \Delta V = V_{\text{sample}}$. Knowing the dimensions of the sample, we can then find porosity by

$$\Phi = 1 - \frac{V_{\text{sample}}}{\pi r^2 l} \quad (3)$$

where Φ is the porosity, r is the measured radius, and l is the measured length of the core sample.

Data Reduction

Experimental data, which was recorded as displacement in inches and load in pounds was converted to stress and strain using two data reduction methods. The first, for the pure shear experiments, was in Microsoft Excel, whereas the second, for the sliding friction experiments was in Matlab.

Load data was converted from pounds to kg, and then converted to strain by this equation:

$$\sigma_1 = \frac{mg}{A(1+e)} \quad (4)$$

where m is the load in kg, g is the gravitational acceleration (9.80665 m/s^2), A is the surface area of the sample, and e is the strain. Strain was calculated according to the equation:

$$e = \frac{\Delta x - \frac{1}{k}m}{x} \quad (5)$$

where Δx is the displacement, x is the initial length of the sample, k is a correction for rig stiffness, and m is the load in N. The factor k is a linear function of the confining pressure, equivalent to:

$$k = 287770.4 + 565.4P_c \quad (6)$$

It is intended to correct for the elastic energy being absorbed by the rig itself and not the sample. The coefficients in equation (6) were calculated from calibration tests by N. Austen (Cleven, 2008).

Shear and normal stresses for the coefficient of friction were determined by the following equations:

$$\sigma_s = \left(\frac{\sigma_1 - \sigma_3}{2} \right) \sin(2\theta) \quad (7)$$

$$\sigma_n = \left(\frac{\sigma_1 + \sigma_3}{2} \right) + \left(\frac{\sigma_1 - \sigma_3}{2} \right) \sin(2\theta) \quad (8)$$

These equations relate the principle stresses, σ_1 and σ_3 to the angle between normal to the plane of the saw cut and the principle stress, θ . The major principle stress, σ_1 , was corrected for the change in area of the sliding surface.

APPENDIX 2 – RELEVANT DATA

Table 2: Geochemical analysis of two pieces of starting material

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	Cr ₂ O ₃	TiO ₂
SAMPLE	%	%	%	%	%	%	%	%	%
CS-SM-01	0.2	0.03	<0.01	41.54	0.61	0.06	0.01	0.01	<0.01
CS-SM-02	0.44	0.02	<0.01	41.14	1.02	0.06	0.02	0.01	<0.01
	P ₂ O ₅	SrO	BaO	LOI	Total	Sr	S	H ₂ O+	H ₂ O
SAMPLE	%	%	%	%	%	%	%	%	%
CS-SM-01	0.023	0.3	0.06	1.56	44.42	0.254	22.2	0.13	0.34
CS-SM-02	0.023	0.39	0.05	2.57	45.77	0.333	23.4	0.27	0.49

Table 2 shows the results from the ALS Chemex geochemical analysis. Two pieces of starting material were analyzed for major elements, as well as LOI, Sr, S, H₂O+ and H₂O–. Sr was chosen because of the possibility of replacement of anhydrite by celestite (SrSO₄).

XRD Analysis of Starting Material

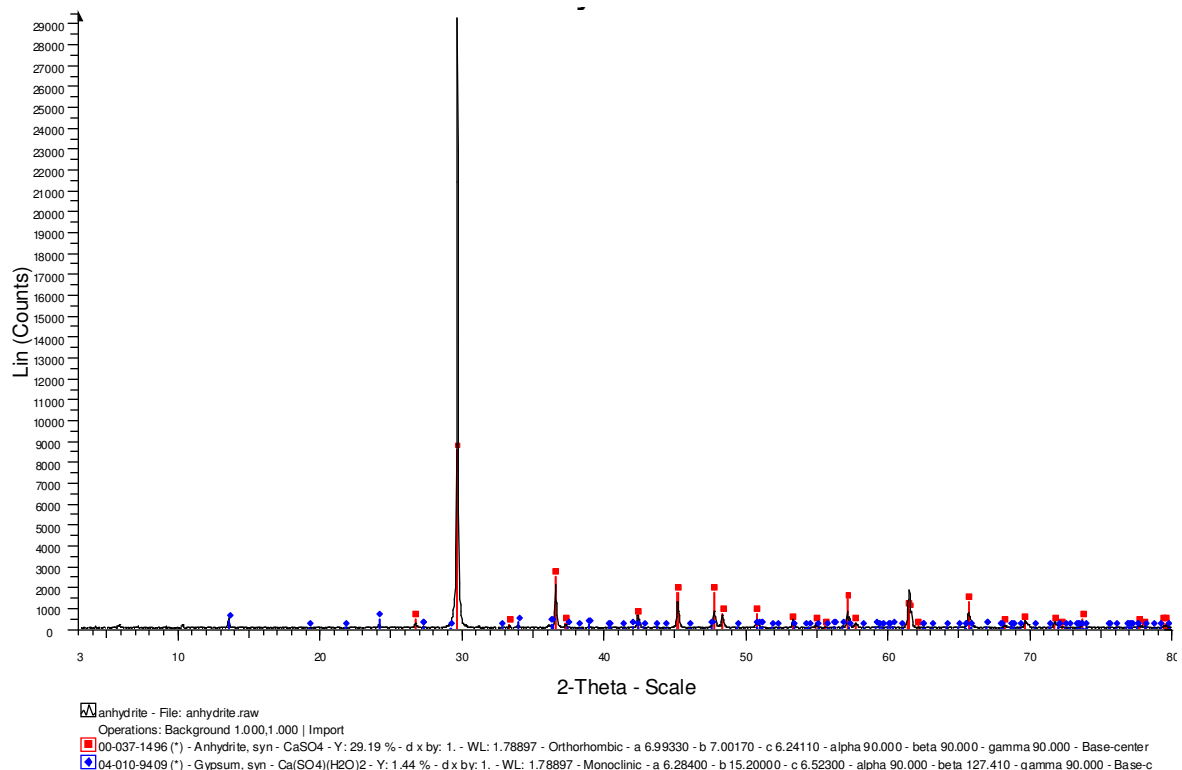


Figure 19: XRD analysis performed by J. Haywood on starting material, indicating high counts of anhydrite (red), and less significant counts of gypsum (blue).