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Direct Shear and Triaxial Shear test Results on Core from Borehole U-15n and U-15n#10, NNSS, in support of SPE

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Abstract

Direct Shear (DS) and Triaxial Shear (FCT) tests from Core holes U-15n and U-15n#10 are part of a larger material characterization effort for the Source Physics Experiment (SPE) project. This larger effort encompasses characterizing a granite body from Nevada both before and after each SPE shot.

Core hole U-15n is the vertically oriented source hole for all SPE shots; pre shot core was taken from this hole for DS and FCT testing. After two SPE shots were executed, an inclined core hole (U-15n#10) was drilled; both DS and FCT tests were conducted from this core hole. The first shot (SPE-1) conducted on May 3, 2011 was a calibration shot. SPE-1 was an order of magnitude smaller than the second shot (SPE-2). After SPE-2 was conducted on October 25, 2011 the aforementioned inclined core hole (U-15n#10) was drilled. At its bottom, the inclined core hole intersects the source hole. The third shot (SPE-3) occurred on July 24, 2012. Vertical and inclined core holes were drilled post SPE-3 and specimens will soon be selected for geomechanical characterization. At the time of this writing, work is ongoing at Nevada in preparation for the fourth SPE shot (SPE-4).

The current test series includes DS and FCT tests on natural fractures within fault material and intact granite specimens. Table 1 shows a summary of results including Specimen #, core hole, depth, test type, material, friction angle and cohesion.

Table 1: Specimen #, core hole, depth, test type, material, friction angle and cohesion.

Specimen #	Core hole	Depth (ft)	Depth (m)	Test type	Wet/Dry	Material	Friction Angle (˚)	Cohesion (psi)	Cohesion (kPa)
SPE-FCT-137.3-56deg	U-15n	137.3	41.8	FCT	W	Intact	31.8	22.4	154.5
SPE2-FCT-17.4-52deg	U-15n#10	17.4	5.3	FCT	W	Fault Mat.	13.8	59.0	406.8
SPE-DS-30.3	U-15n	30.3	9.2	DS	D	Intact	32.3	14.7	101.3
SPE-DS-33.2	U-15n	33.2	10.1	DS	D	Intact	28.4	6.2	42.4

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SPE-DS-81.4	U-15n	81.4	24.8	DS	D	Fault Mat./Remold	28.0	8.8	60.7
SPE-DS-104.0	U-15n	104.0	31.7	DS	D	Fault Mat.	28.8	4.5	31.0
SPE-DS-154.9	U-15n	154.9	47.2	DS	D	Fault Mat.	28.7	6.8	46.6
SPE-DS-172.2	U-15n	172.2	52.5	DS	W	Intact	28.0	5.8	39.9
SPE2-DS-46	U-15n#10	46.8	14.3	DS	D	Intact	33.6	4.0	27.2
SPE2-DS-56	U-15n#10	56.8	17.3	DS	D	Intact	25.5	2.6	18.0
SPE2-DS-109	U-15n#10	109.5	33.4	DS	D	Intact	35.5	6.4	44.3
SPE2-DS-119	U-15n#10	119.3	36.4	DS	D	Fault Mat.	28	5.9	40.6
SPE2-DS-145A	U-15n#10	145.1	44.2	DS	D	Fault Mat.	28.4	8.8	60.8
SPE2-DS-145B	U-15n#10	145.5	44.3	DS	D	Fault Mat.	29.7	5.4	37.4
SPE2-DS-149	U-15n#10	149.7	45.6	DS	D	Fault Mat.	36.7	3.7	25.4
SPE2-DS-162	U-15n#10	162.0	49.4	DS	D	Intact	30.7	9.1	62.8

Background

All DS and FCT testing reported upon herein originated from Core holes U-15n and U-15n#10 both before any SPE shot was conducted and after the second SPE shot; the core hole is drilled in granitic rock (quartz monzonite). Core hole U-15n was drilled at the location of the central SPE borehole, and thus closely represents material in which the explosive charges have occurred. There are two fault zones within U-15n. Fault #1 and Fault #2 intersect U-15n at depths of approximately 82 feet and 107 feet respectively. Specimens for DS tests were selected from a range of depths spanning the length of both U-15n and U-15n#10 core holes; specimens were selected to represent material both from the fault zones and stronger intact granite from both core holes. Two FCT tests have been conducted; one from U-15n on strong intact granite and another from U-15n#10 on weaker fault material. Thus far, the U-15n location has been the site of three SPE's (SPE-1, SPE-2, and SPE-3). The fourth SPE shot is scheduled in the late 2013 timeframe.

Specimen Preparation and Experimental Methods

Direct Shear

Test specimens with natural fracture surfaces were prepared from the 63.5 mm (2.5 inch) diameter field core by cutting them to approximate length using a standard rock saw; cuts were made approximately parallel 25.4 mm (1 inch) from the natural fracture surface. If necessary, the fracture was then cut so that its largest dimension was no greater than 89mm (3.5 inches) (Figure 1a). After the specimen was cut to size, it was cast into a 102mm × 102mm (4 × 4 inch) mold (Figure 1b). The mold is used to support the natural fracture halves in the direct shear machine shear box. The arrows shown in Figures 1a and 1b indicate direction of movement during shearing. The shear direction was chosen based on the fractures ability to slide without locking up due to surface features. Two types of granite were tested both with natural fractures;

intact and fault material. Intact specimens were cut wet using standard tap water for cooling and fault material was cut dry. Specimen SPE-DS-81.4 was tested as a remold shear test within a 63mm (2.49 inch) round shear box; this specimen disintegrated during specimen preparation such that shearing on the natural fracture surface was not possible; pictures are shown in the Appendix of SAND2013-4347P for this specimen.

Prior to placing the specimen in the shear box, as shown in Figure 1b, a profile was taken of the surface at approximately 3 mm increments (0.125 inch). The surface profile is used in the data reduction to determine a tilt correction angle indicating if the specimen was shearing uphill or downhill. In addition to the surface profile, the contact area was determined and digitized so that the stress can be determined at the time of residual shear strength. The contact area is drawn directly on the top and bottom of the natural fracture with black marker as shown in Figure 1b. Horizontal and vertical force and displacement were measured for all traces. DS tests were run at a shear displacement rate of 0.635 mm/min (0.025 in/min).

DS specimens were run with the following normal stresses:

1. 0.05 MPa (7 psi)
2. 0.19 MPa (28 psi)
3. 0.66 MPa (96 psi)
4. 1.38 MPa (200 psi)
5. 2.76 MPa (400 psi)

The highest normal stress was not achievable on three specimens due to the area of the specimen being too large for the load capacity of the direct shear machine. The highest normal stress for the specimens listed below was 2.41 MPa (350 psi).

1. SPE-DS-172.2
2. SPE2-DS-119
3. SPE2-DS-145A

All DS specimens were tested insitu except for specimen SPE-DS-172.2 which was tested submerged in tap water; specimens were neither dried nor saturated prior to testing. DS specimens SPE-DS-30.3, SPE-DS-33.2, and SPE-DS-172.2 were sheared back and forth at the highest normal stress to investigate repeatability of shear stress levels.

Figure 1: Specimen preparation steps for DS specimens: a) black lines on rock core indicate cut locations b) cut specimen supported in mold made from Plaster of Paris prior to placement in shear box.

Triaxial Shear

Natural fractures were prepared for FCT tests by cutting the end of the core at least 51mm (2 inches) from the end of the natural fracture closest to the saw cut. As shown in Figure 2, if the core was too short, the ends of the specimen were cast in Plaster of Paris so that flat ends were available for applying axial force.

FCT tests were conducted under constant confining pressure and constant pore pressure using tap water as the pore fluid medium. Due to the confining pressure pushing the Viton jacket on the side of the specimen and thus sealing the side of the specimen from pore fluid access, it was necessary to develop a pathway for the pore fluid to migrate along the core and across the natural fracture. A slotted groove was cut parallel to the core axis (Figure 2) and a piece of felt metal was placed in the groove to keep the specimen jacket from puncturing on the sharp edge of the groove and also to allow transmission of pore fluid along the groove.

An oversize 76mm (3 inch) Viton specimen jacket was chosen to minimize the jacket strength effect on normal force; the jacket was sealed to steel end caps with epoxy and tie wires. Figure 3 shows the specimen assembly mounted on the 15 MPa pressure vessel base plate; also shown is a radial linear variable differential transformer (LVDT) mounted at specimen mid height to measure shear. The quantities measured during a triaxial shear test included axial displacement, axial force, lateral displacement, confining pressure and pore pressure with respect to time.

The surface of both FCT specimens was preconditioned prior to testing. Preconditioning was performed by tested the specimen in the same configuration as the actual triaxial shear test. Preconditioning was performed to better achieve consistency between traces (i.e. the asperities on the specimen were ground down so that the change of surface roughness between traces was minimal).

The test conditions for FCT tests are given in Table 2. For each test, confining pressure and pore pressure were held constant and normal load was increased until specimen started to displace along fracture surface.

Table 2: Test conditions for FCT tests; Specimen #, Trace #, lateral stress (σ_3), pore pressure (σ_P), effective pressure ($\sigma_3' = \sigma_3 - \sigma_P$).

Specimen #	Trace #	σ_3	σ_P	$\sigma_3' = \sigma_3 - \sigma_P$
SPE-FCT-137.3-56deg	4	1	0.7	0.3
	5	1.5	0.7	0.8
	6	2	0.7	1.3
	7	2	1.3	0.7
	8	2	1.8	0.2
SPE-FCT-17.4-52deg	2	1	0.7	0.3
	3	1.5	0.7	0.8
	4	2	0.7	1.3
	5	2	1.3	0.7
	6	2	1.8	0.2

Figure 2: Specimen SPE2-FCT-17.4-52deg with ends filled with Plaster of Paris for mounting in pressure vessel.

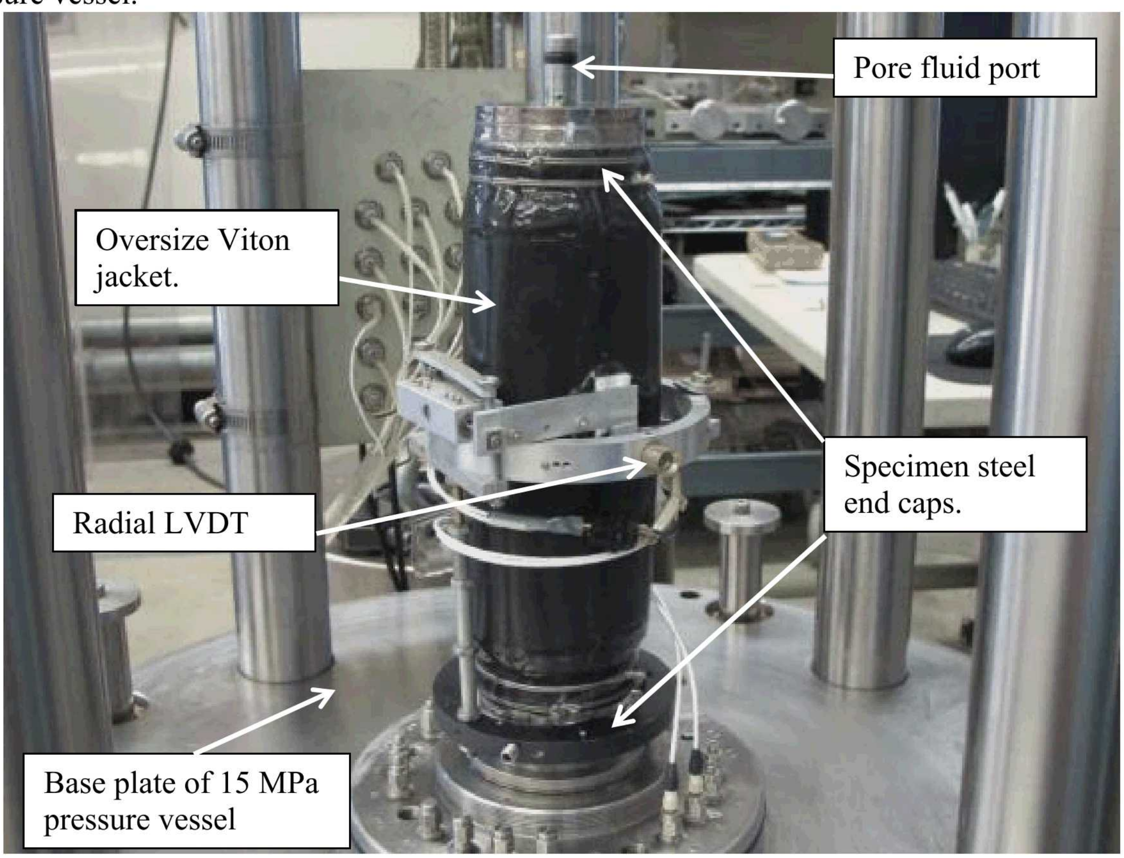

Figure 3: Specimen placed on pressure vessel base showing oversize Viton jacket tie wired and sealed with epoxy to end caps. Radial LVDT is positioned near specimen mid-height and in line with natural fracture so that shear is measured.

Experimental Results

Direct Shear

Residual shear stress points were picked from direct shear traces when shear stress of the natural fracture reached a relatively constant level. The residual shear stress points are then plotted in shear stress versus normal stress space; within this stress space, the friction angle (slope of a least squares fit line) and cohesion (y-intercept) of the specimen is determined. The data in Figure 4 shows residual failure points along with the friction angle and cohesion for all 14 direct shear tests and is grouped into the four categories shown in Table 3.

Table 3: Material/location, friction angle, and cohesion.

Material/location	Friction angle (˚)	Cohesion (KPa)
Intact natural fractures/U-15n	30.2	52.3
Intact natural fractures/U-15n#10	31.4	39.3
Fault Material natural fractures/U-15n	28.3	50.8
Fault Material natural fractures/U-15n#10	30.9	38.7

Force versus displacement and shear stress versus normal stress plots for all 14 DS tests are shown in the appendix of report SAND2013-4347P.

DS specimens SPE-DS-30.3, SPE-DS-33.2, and SPE-DS-172.2 were sheared back and forth at the highest normal stress to investigate repeatability or degradation of shear stress levels. Change of the shear stress was not significant with repeated traces run at the highest normal stresses; back and forth shearing was not performed on specimens from U-15n#10. Force versus displacement plots for specimens sheared back and forth at the highest normal stress are shown in the appendix of report SAND2013-4347P.

Direct Shear and Triaxial Shear

Four sets of direct shear data, represented in Figure 4, are the basis of comparison for the FCT tests. Specimens SPE-FCT-137.3-56deg and SPE2-FCT-17.3-52deg are compared to the direct shear data sets on natural fractures on intact granite from U-15n and fault material from U-15n#10 respectively (red and brown data sets in Figure 4). The equations of the lines are given; the arc tangent of the slope gives the friction angle (30.2˚ and 30.9˚) and the y-intercept gives the cohesion (52.25 KPa and 38.67 KPa) of the intact granite and fault material natural fractures respectively from direct shear tests.

Using the major and the minor principal stresses (σ_1 and σ_3) corresponding to the stress state at residual strength of the natural fracture for each trace for FCT tests SPE-FCT-137.3-56deg and SPE2-FCT-17.4-52deg, Mohr's circles are drawn in the same stress space as Figure 4 resulting in Figures 5 and 6. Pore pressure is factored in by shifting the Mohr's circles horizontally towards the origin by the value of the pore pressure (i.e. if pore pressure is 700 KPa, the failure point is shifted horizontally 700 KPa). Because all FCT tests were conducted with pore pressure, all data is shifted horizontally by the amount of corresponding pore pressure (blue horizontal lines shown on Figures 5 and 6). From a technique outlined in Goodman (1980), a line is drawn based on the angle of the natural fracture from the stress equivalent to σ_3 on the x-axis (left side of Mohr's circle). The residual strength of the natural fracture is where the line intersects the corresponding Mohr's circle. The FCT data sets shown in Figures 5 and 6 were then fit with a least squares method to establish the friction angle and cohesion.

The friction angle and cohesion for SPE-FCT-137.3-56deg is 31.8˚ and 154.4 KPa; the friction angle is similar whereas the cohesion is higher compared to the DS data. The friction angle and cohesion for SPE2-FCT-17.4-52deg is 13.8˚ and 406.9 KPa; the friction angle is much lower and the cohesion is much higher compared to DS data on similar material. The large difference between FCT and DS results for specimen SPE2-FCT-17.4-52deg are likely attributed to testing fault material in a wet condition. Testing fault material in a wet condition in a direct shear configuration was not possible because the specimens, when unconfined, disintegrated.

Shear stresses were calculated in direct shear tests factoring in the area of the specimen in contact at the displacement of the residual shear stress point. The contact area was not calculated but rather estimated for the FCT tests; both specimens started as an ellipse with small dimension of 63.5mm (2.5 inches) which is the core diameter. Where residual shear stresses occur along the axial displacement versus shear stress plots, the specimen contact area decreased from its initial contact area to that of approximately a circle with diameter of 63.5mm (2.5 inches). Data reduction for the FCT tests assumed an apparent contact area of 3167mm^2 (4.91 in^2).

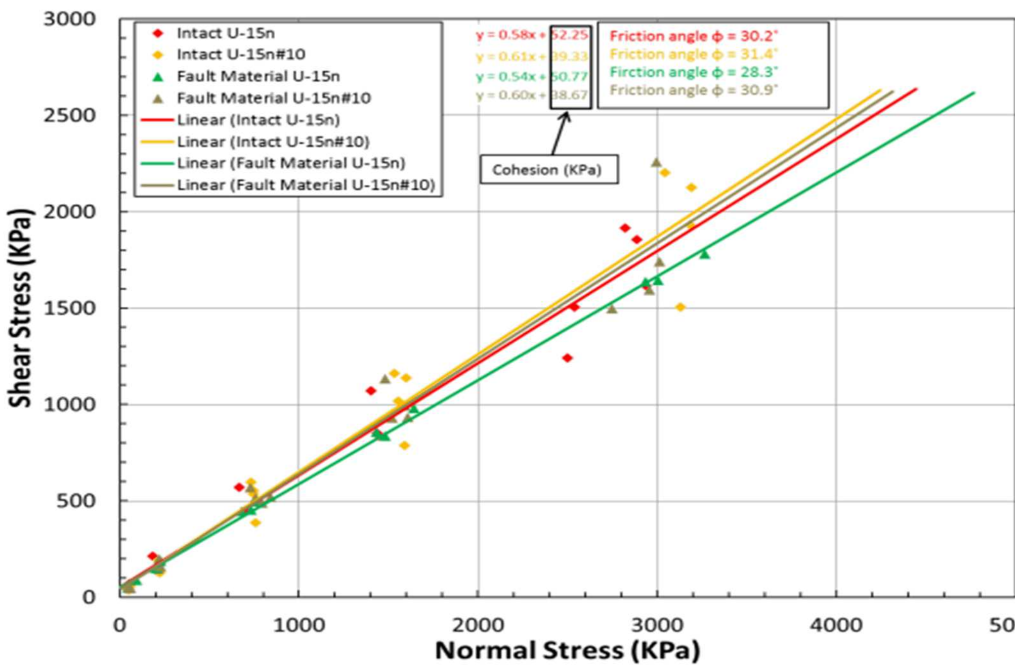

Figure 4: Direct Shear test data from U-15n and U-15n#10 on both intact and fault material natural fractures plotted in shear stress versus normal stress space.

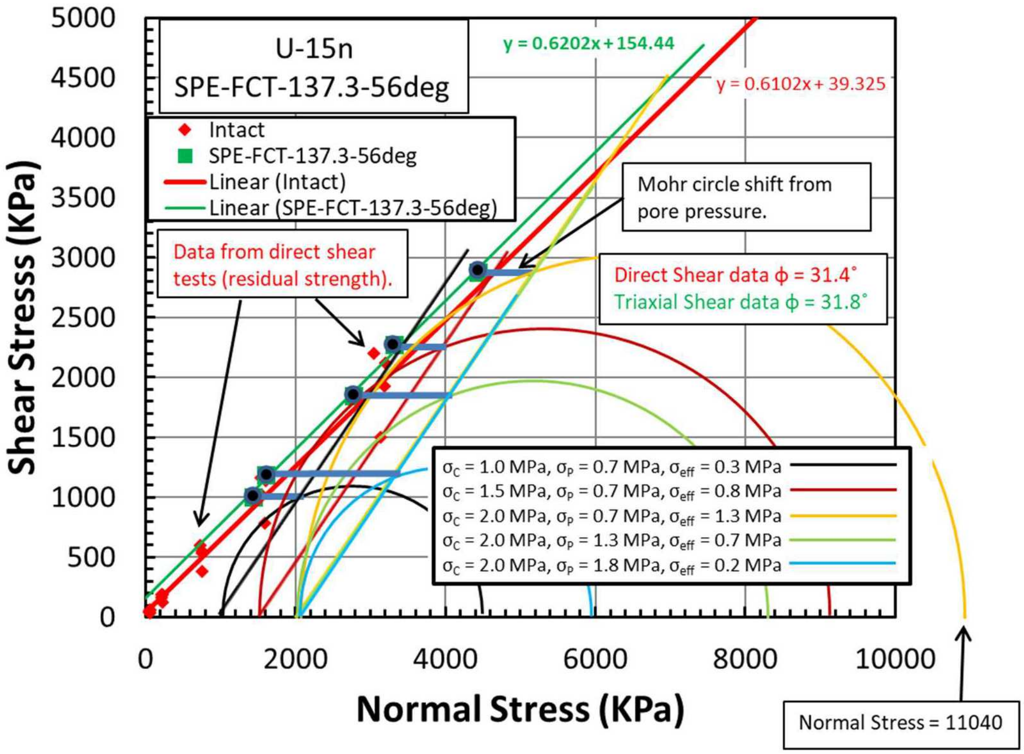

Figure 5: Shear stress versus normal stress data for intact specimens from DS (red) and FCT tests (green).

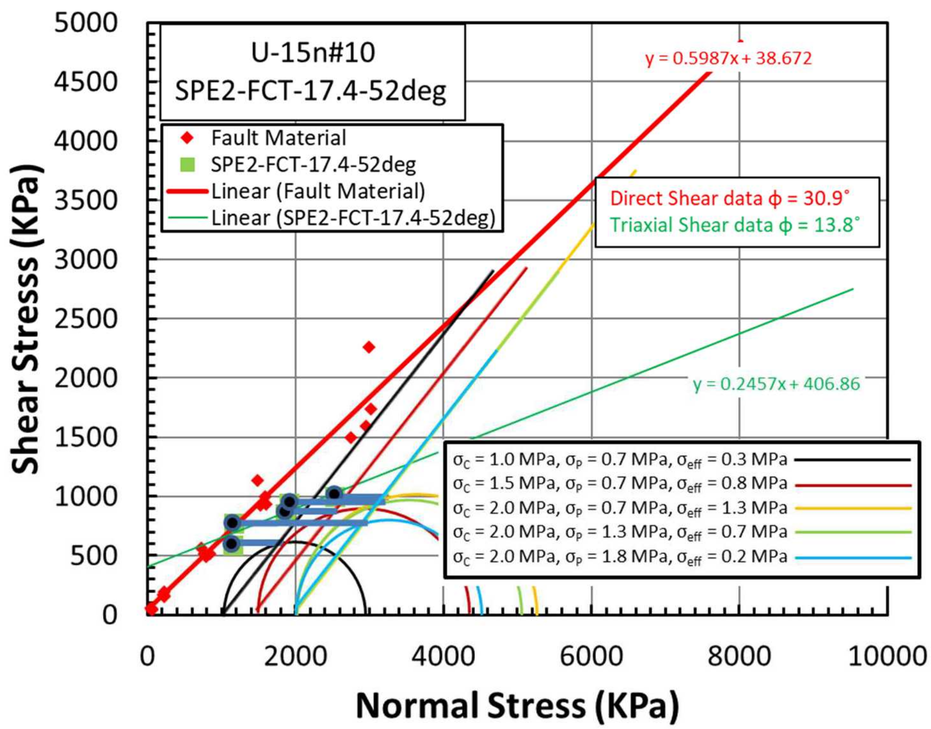

Figure 6: Shear stress versus normal stress data for fault material from DS (red) and FCT tests (green).

Conclusions

Fourteen direct shear and two triaxial shear tests from Core holes U-15n and U-15n#10 have been presented and discussed. Specimens were from pre shot core and post SPE2 core with two material types tested; fault material and intact granite. Table 4 lists the average of results from four groups of natural fractures from direct shear tests and also individual results from both triaxial shear tests.

Table 4: Material/location, specimen #, friction angle and cohesion for four groups of direct shear specimens and each triaxial shear specimen.

Material/location	Specimen #	Friction angle (˚)	Cohesion (KPa)
Intact natural fractures/U-15n	Average, DS	30.2	52.3
Intact natural fractures/U-15n#10	Average, DS	31.4	39.3
Fault Material natural fractures/U-15n	Average, DS	28.3	50.8
Fault Material natural fractures/U-15n#10	Average, DS	30.9	38.7
Intact natural fracture/U-15n	SPE-FCT-137.3-56deg	31.8	154.4
Fault Material natural fracture/U-15n#10	SPE2-FCT-17.4-52deg	13.8	406.9

Direct shear and triaxial shear tests from Core holes U-15n and U-15n#10 are part of a larger material characterization effort for the Source Physics Experiment (SPE) project. This larger effort encompasses characterizing granite rock from Nevada both before and after each SPE shot.

Contents of this report taken from Broome (2013[3]). Broome (2013[3]) contains additional figures, tables, additional discussion of results, and appendices with details of individual tests.

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