

Unconfined Compression Results on Core from Boreholes U-15n#12 and U-15n#13, NNSS, in support of SPE

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Abstract

The Nevada National Security Site (NNSS) serves as the geologic setting for a Source Physics Experiment (SPE) program. The SPE provides ground truth data to create and improve strong ground motion and seismic S-wave generation and propagation models. The NNSS was chosen as the test bed because it provides a variety of geologic settings ranging from relatively simple to very complex.

Each series of SPE testing will comprise the setting and firing of explosive charges (source) placed in a central borehole at varying depths and recording ground motions in instrumented boreholes located in two rings around the source, positioned at different radii. Modeling using advanced simulation codes will be performed both before and after each test to predict ground response and to improve models based on acquired field data, respectively.

A key component in the predictive capability and ultimate validation of the models is the full understanding of the intervening geology between the source and the instrumented boreholes including the geomechanical behavior of the site's rock/structural features. This report summarizes unconfined compression testing (UCS) from coreholes U-15n#12 and U-15n#13 and compares those datasets to UCS results from coreholes U-15n and U-15n#10.

U-15n#12 corehole was drilled at -60° to the horizontal and U-15n#13 was drilled vertically in granitic rock (quartz monzonite) after the third SPE shot. Figure 1 illustrates at the surface, U-15n#12 and U-15n#13 coreholes were approximately 30 meters and 10 meters from the central SPE borehole (U-15n) respectively. Corehole U-15n#12 intersects the central SPE borehole (U-15n) at a core depth of 174 feet (approximately 150 feet vertical depth). The location of U-15n#12 and U-15n#13 is the site of the first, second and third SPE's, in Area 15 of the NNSS.

Specimen Preparation and Experimental Methods

Specimen Preparation: Test specimens (right circular cylinders) were prepared from the 2.5-inch diameter field core by cutting them to approximate length using a standard rock saw and then grinding the ends flat and parallel to final length such that the length-to-diameter ratio on each test specimen is $\sim 2:1$. Both the sawing and the grinding used tap water for cooling. Specimen

dimensions were sized to assure a minimum of 10 grains across a specimen diameter given that the maximum grain size of this granite ranges from 0.5-6.35 mm (0.02-0.25 in). Phenocrysts in

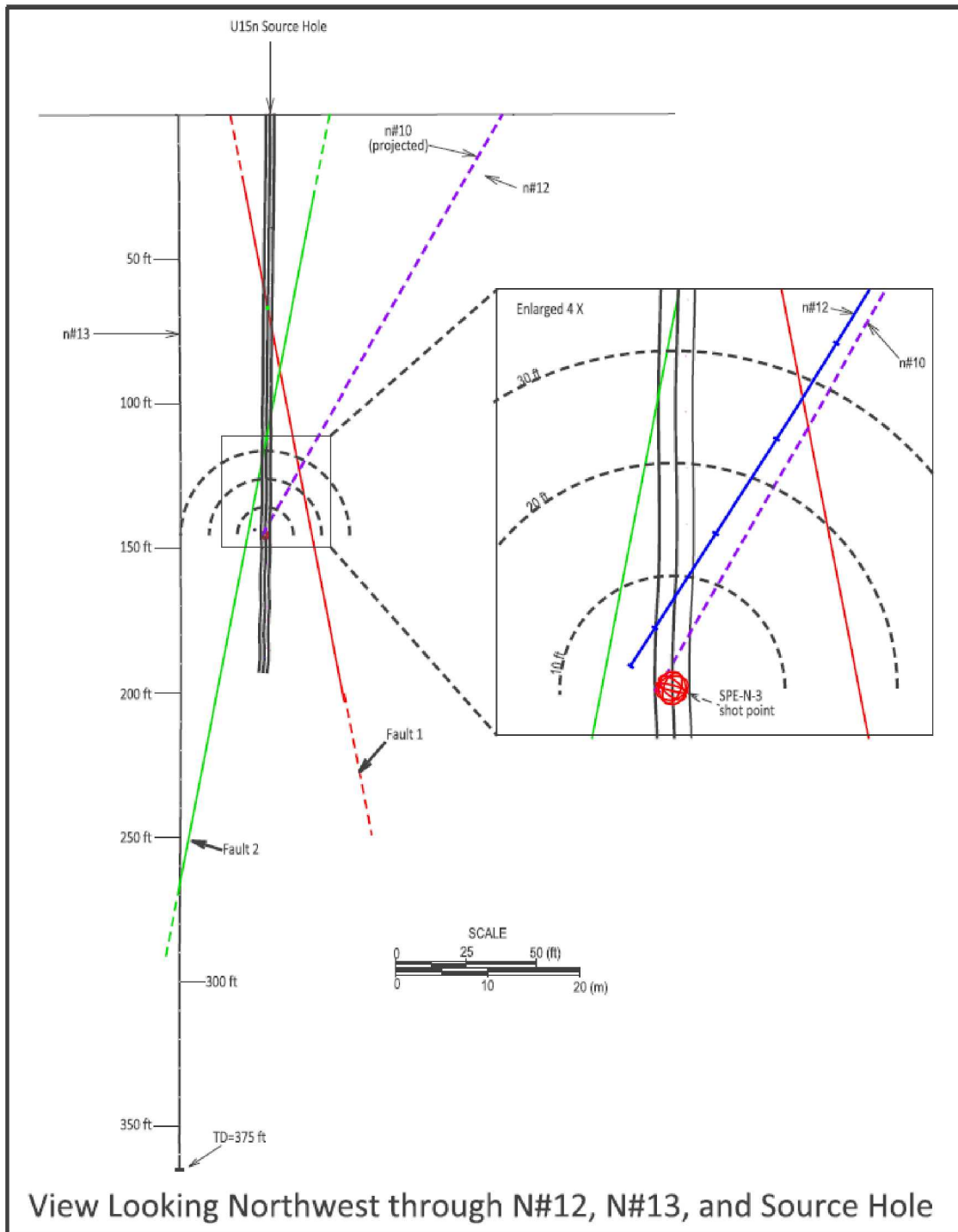


Figure 1. U-15n#12 (-60° to horizontal) angled corehole and U-15n#13 corehole (vertical left).

small quantities were observed along the core length and are as large as ~25.4 mm across; an attempt was made to avoid these phenocryst zones. The dimensions and mass of each specimen were accurately measured to facilitate density determinations. Field cores used in preparing the test specimens were selected from approximately every 15-ft interval of U-15n#12 and U-15n#13 and had a useable length of approximately 15-18 cm so that the 13 cm long specimens were prepared with sufficient material available near one end for thin sections.

Calibration: Annual calibration of the load cell used to measure compressive strength (UCS) is traceable to the U.S. National Institute of Standards and Technology. For all UCS tests, two bi-axial strain gages were bonded at specimen mid-height 180° apart. A shakedown test was performed with a right circular steel specimen (4340 steel) instrumented with the same type strain gages as those used on the SPE granite specimens prior to any SPE UCS testing. The shakedown test verified that all components of the test system were functioning correctly because measured properties (Young's modulus and Poisson's ratio) were consistent with those published for 4340 steel.

Bulk Density Determination: The bulk density of each test specimen was determined by dividing the mass by the volume where volume is calculated using dimensional measurements for the right-circular-cylindrical geometry. Samples waxed in the field after coring were double bagged between preparation steps and testing to preserve the waxed moisture level. The majority of the samples were not waxed and were weighed after having been stored in core boxes for a few months both at the NNSS core library and the Geomechanics laboratory.

Unconfined Compressive Strength (UCS) Testing: Tests were run on what is thought to be both weathered and fresh granite to determine if there are differences in mechanical properties over the entire corehole depth (~174 ft for U-15n#12 and ~375 ft for U-15n#13). UCS tests from U-15n#12 were not performed at core depths below 158 ft due to the extremely low RQD of the core. All specimens were instrumented to measure axial force, from which axial stress was calculated. Axial and radial strains were measured using strain gages.

Specimens were subjected to quasi-static compression loading at an axial strain rate of ~1E-04/sec under ambient pressure and temperature conditions. Loading continued until the peak axial stress (i.e., the unconfined compressive strength) was determined. All specimens were loaded to failure. During loading, unload/reload cycles were performed at various axial stress levels to acquire data to estimate the quasi-static compressive elastic properties – Young's modulus, E_c , and Poisson's ratio, ν_c .

Compressional and Shear Wave Velocity Measurements: Ultrasonic compressional and shear wave velocity measurements, V_p and V_s , were performed on each UCS specimen under ambient conditions prior to UCS testing. Wave speed measurements were made coincident with each specimen axis and also orthogonal to the axis across two diameters separated by 90°. Specifically, a red reference line was marked on all received core and the first orthogonal measurement was made so that the red line was in contact with one of the transducers. The second orthogonal measurement was made 90° clockwise looking down on the top of the core to the first.

Experimental Results

Tables 1 and 2 list the results from UCS tests for boreholes U-15n#12 and U-15n#13. Elastic properties were determined from the unload portion of unload/reload loops performed while the specimen was unloaded at a constant axial strain rate of $\sim 1\text{E-}04/\text{sec}$. The number of unload/reload loops per test performed ranged from one to seven. Elastic properties for specimen SPE13-UCS-246 were not determined due to unavailability of loading and strain gage data; peak stress was determined from a meter on the data acquisition system displaying peak load. Rows in Tables 1 and 2 shaded gray denote waxed specimens. Specimens nominally failed at angles between 70° to 90° resulting in either a fairly intact cone on either end of the specimen or vertical cracks running most the length of the specimen.

Table 1. Specimen #, Depth, Density, UCS, Young's modulus, Poisson's Ratio and Vertical Depth for U-15n#12

Sample	Depth (ft)	Density (g/cc)	$\sigma_{AX, MAX}$ (MPa)	E_c (GPa)	ν_c	Vertical Depth (ft)
SPE12-UCS-011	11	2.634	150.7	69.4	0.19	9.5
SPE12-UCS-020	20	2.623	145.2	59.7	0.18	17.3
SPE12-UCS-022	22	2.639	132.8	66.9	0.21	19.1
SPE12-UCS-033	33	2.554	74.8	25.9	0.14	28.6
SPE12-UCS-043	43	2.594	81.5	54.2	0.15	37.2
SPE12-UCS-057	57	2.654	239.7	90.5	0.23	49.4
SPE12-UCS-062	62	2.637	145.9	76.8	0.26	53.7
SPE12-UCS-066	66	2.643	235.6	80.7	0.17	57.2
SPE12-UCS-075	75	2.643	206.0	91.8	0.25	65.0
SPE12-UCS-085	85	2.490	28.4	18.7	0.12	73.6
SPE12-UCS-089	89	2.668	231.7	91.2	0.22	77.1
SPE12-UCS-098	98	2.657	215.8	86.3	0.22	84.9
SPE12-UCS-107	107	2.655	172.9	81.6	0.23	92.7
SPE12-UCS-117	117	2.646	219.1	85.3	0.21	101.3
SPE12-UCS-123	123	2.653	186.0	82.8	0.20	106.5
SPE12-UCS-130	130	2.665	233.3	84.7	0.20	112.6
SPE12-UCS-140	140	2.653	188.5	83.8	0.21	121.2
SPE12-UCS-149	149	2.610	77.3	64.1	0.24	129.0
SPE12-UCS-158	158	2.651	128.3	80.6	0.21	136.8

Table 2. Specimen #, Depth, Density, UCS, Young's modulus, and Poisson's Ratio for U-15n#13

Sample	Depth (ft)	Density (g/cc)	$\sigma_{AX, MAX}$ (MPa)	E_c (GPa)	ν_c
SPE13-UCS-011	11	2.606	96.5	45.3	0.18
SPE13-UCS-024	24	2.430	17.6	10.4	0.21
SPE13-UCS-052	52	2.621	130.6	72.8	0.19
SPE13-UCS-077	77	2.633	194.7	86.0	0.25
SPE13-UCS-097	97	2.624	164.0	79.8	0.21
SPE13-UCS-112	112	2.660	220.5	87.7	0.18
SPE13-UCS-113	113	2.661	175.7	81.1	0.25
SPE13-UCS-133	133	2.650	212.8	86.4	0.21
SPE13-UCS-154	154	2.648	224.3	85.3	0.22
SPE13-UCS-159	159	2.649	209.4	84.4	0.26
SPE13-UCS-179	179	2.651	200.5	87.5	0.23
SPE13-UCS-195	195	2.638	133.4	74.9	0.24
SPE13-UCS-209	209	2.659	170.9	86.5	0.23
SPE13-UCS-230	230	2.660	235.7	86.7	0.21
SPE13-UCS-246*	246	2.664	255.5	N/A	N/A
SPE13-UCS-262	262	2.673	235.3	88.7	0.27
SPE13-UCS-277	277	2.666	123.9	87.9	0.23
SPE13-UCS-283	283	2.674	243.2	88.1	0.20
SPE13-UCS-306	306	2.663	125.2	96.4	0.27
SPE13-UCS-324	324	2.589	92.3	56.2	0.17
SPE13-UCS-343	343	2.653	192.0	79.7	0.22
SPE13-UCS-363	363	2.651	234.5	79.9	0.19
SPE13-UCS-372	372	2.659	209.7	83.3	0.21

*Strain gauge data not retrievable and therefore elastic properties are not available

Plots of Engineering Axial Stress versus Axial, Lateral, and Volume strain for all UCS tests (19 from U-15n#12 and 23 from U-15n#13) are presented in the appendix of report SAND2014-166590 with the exception of SPE13-UCS-246; the data file for this specimen was unrecoverable and a note is given in the appendix listing the peak stress for this specimen.

Volumetric strain is calculated from the axial and radial strains, i.e., $\epsilon_v = \epsilon_{ax} + 2\epsilon_{rad}$.

Tables 3 and 4 list the results from ultrasonic compressional and shear wave velocity measurements taken coincident with each specimen axis for coreholes U-15n#12 and U-15n#13 respectively; orthogonal measurements to the axis across two diameters separated by 90° for core holes U-15n#12 and U-15n#13 are given in report SAND2014-166590.

Dynamic Young's modulus ranges from approximately 8.7 to 86.0 GPa and Poisson's ratio ranges from approximately 0.12 to 0.30 for all specimens (coreholes U-15n#12 and U-15n#13) measured in the axial direction.

Table 3. P- and S-wave travel time, P- and S-wave velocity and calculated values of $E_{Dynamic}$ and $v_{Dynamic}$ along core axis for U-15n#12

Sample #	Axial					
	P Wave Travel Time (μ s)	P-Velocity (m/s)	S-Wave Travel Time (μ s)	S-Velocity (m/s)	$E_{Dynamic}$ (GPa)	$v_{Dynamic}$
SPE12-UCS-011	25.26	5097	43.16	2970	57.75	0.243
SPE12-UCS-020	26.91	4778	42.70	3000	55.46	0.175
SPE12-UCS-022	23.53	5457	40.82	3130	64.88	0.255
SPE12-UCS-033	52.24	2408	79.44	1580	14.31	0.121
SPE12-UCS-043	27.20	4745	42.79	3005	54.60	0.165
SPE12-UCS-057	20.87	6165	36.78	3478	81.34	0.266
SPE12-UCS-062	21.29	6037	37.29	3428	78.21	0.262
SPE12-UCS-066	21.47	6025	37.27	3452	79.09	0.256
SPE12-UCS-075	21.34	6087	37.58	3437	79.05	0.266
SPE12-UCS-085	30.66	4100	50.76	2468	36.89	0.216
SPE12-UCS-089	20.82	6158	36.76	3468	81.37	0.268
SPE12-UCS-098	20.94	6096	35.11	3617	85.39	0.228
SPE12-UCS-107	20.86	6099	35.76	3538	82.87	0.246
SPE12-UCS-117	20.98	6028	35.92	3502	80.82	0.245
SPE12-UCS-123	21.30	5982	35.83	3538	81.77	0.231
SPE12-UCS-130	20.86	6111	35.61	3561	83.99	0.243
SPE12-UCS-140	20.66	6206	38.73	3290	74.92	0.305
SPE12-UCS-149	22.12	5772	40.04	3171	67.39	0.284
SPE12-UCS-158	20.86	6093	35.63	3548	82.97	0.243

Table 4. P- and S-wave travel time, P- and S-wave velocity and calculated values of $E_{Dynamic}$ and $v_{Dynamic}$ along core axis for U-15n#13

Sample #	Axial					
	P Wave Travel Time (μ s)	P-Velocity (m/s)	S-Wave Travel Time (μ s)	S-Velocity (m/s)	$E_{Dynamic}$ (GPa)	$v_{Dynamic}$
SPE13-UCS-011	35.34	3616	41.95	3042	13.88	N/A

SPE13-UCS-024	59.86	2117	106.80	1184	8.67	0.272
SPE13-UCS-052	22.39	5675	38.61	3274	70.27	0.251
SPE13-UCS-077	21.66	5884	36.79	3446	77.48	0.239
SPE13-UCS-097	22.07	5809	37.42	3409	75.47	0.237
SPE13-UCS-112	20.88	6091	35.68	3545	83.15	0.244
SPE13-UCS-113	21.36	6072	36.77	3509	81.85	0.249
SPE13-UCS-133	21.13	6031	36.91	3434	78.73	0.260
SPE13-UCS-154	20.93	6068	36.45	3465	80.01	0.258
SPE13-UCS-159	21.16	6111	36.68	3506	81.71	0.255
SPE13-UCS-179	20.17	6238	37.43	3340	76.86	0.299
SPE13-UCS-195	21.83	5895	37.50	3414	76.73	0.248
SPE13-UCS-209	20.78	6025	35.49	3509	81.39	0.243
SPE13-UCS-230	20.34	6213	35.26	3564	84.78	0.255
SPE13-UCS-246	20.74	6167	35.42	3591	85.45	0.243
SPE13-UCS-262	20.62	6141	35.99	3499	82.43	0.260
SPE13-UCS-277	20.99	6164	36.84	3492	82.17	0.264
SPE13-UCS-283	20.38	6183	34.87	3593	85.98	0.245
SPE13-UCS-306	20.71	6144	35.54	3560	84.20	0.247
SPE13-UCS-324	24.29	5240	42.42	2986	58.16	0.260
SPE13-UCS-343	21.64	5869	36.57	3455	78.23	0.235
SPE13-UCS-363	21.20	5990	36.01	3508	80.83	0.239
SPE13-UCS-372	21.40	5949	36.10	3508	80.72	0.233

Analysis of Results and Comparison to UCS tests on coreholes U-15n and U-15n#10

Figure 2 plots density, unconfined compressive strength, Young’s modulus and Poisson’s ratio as a function of depth. All plots in Figure 2 compare data between coreholes U-15n, U-15n#10, U-15n#12, and U-15n#13. Depths from coreholes U-15n#10 and U-15n#12 have been converted to equivalent vertical depth based on -60° to the horizontal drilling angle. Color coded vertical lines on the plots in Figure 2 represent average values for each corehole and correspond to the average values given in Table 5.

From ground surface to 100 feet vertical depth, the range of density is greatest (2.43 g/cc to 2.67 g/cc), likely reflecting various weathered layers near the surface. Between a depth of 100 feet to 200 feet, density is reasonably uniform for all coreholes with no excursions below or above 2.61 g/cc and 2.67 g/cc. U-15n#13 is the only core hole drilled deeper than 200 vertical feet; densities generally are highest in this interval (~2.67 g/cc between 200 and 372 feet). Generally, UCS and Young’s modulus follow the same trend as coreholes U-15n, U-15n#10 and U-15n#12; UCS for corehole U-15n#13 exhibits more scatter below 200 feet than the density and Young’s modulus values show; possibly reflecting varied failure modes in this region. In particular, note that at vertical depth of 92.7 feet for corehole U-15n#10, the UCS is low and does not reflect the relatively average density or dynamic Young’s modulus values of 2.63 g/cc and 73.14 GPa

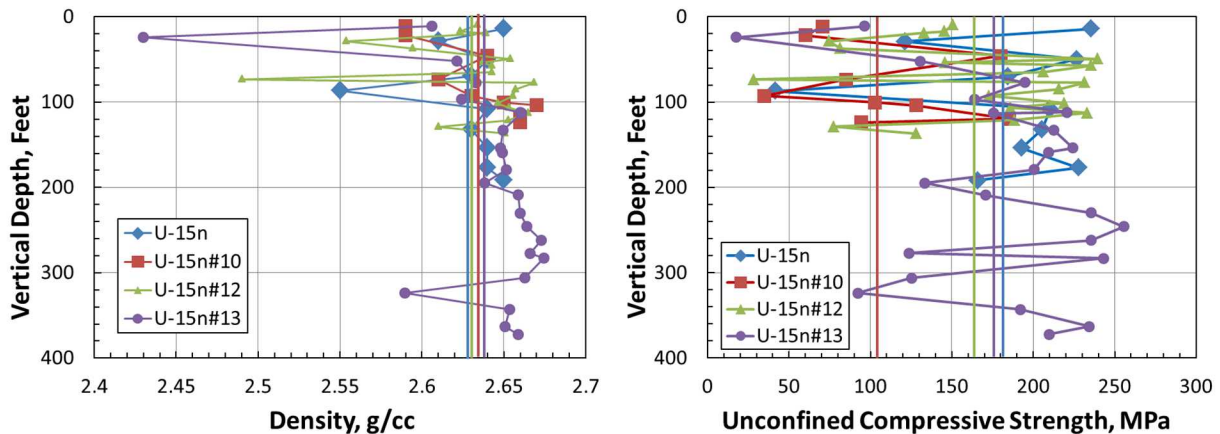
respectively. The low UCS for this specimen was due to failure along a presumed pre-existing weakness plane as opposed to an intact failure mode for the rest of the specimens from U-15n#10. Although not observed, failure along pre-existing weakness planes could be possible for low UCS values for samples from U-15n#13.

The UCS is consistently lower for U-15n#10 compared to the other three core holes; the average decrease in UCS is 42% from U-15n#10 to U-15n. The highest UCS values from U-15n#10 (180.0 and 185.1 MPa) are approximately equal to the nominal strength of specimens from U-15n. Table 5 gives median and average values for all four core holes.

The static determination of Young's Modulus were nominally 72.4 and 78.0 GPa for coreholes U-15n#12 and U-15n#13; in general lower values are found at shallower depths. The values determined indirectly (dynamic methods) were consistently lower than the quasi-static values by an average of 10% (Figure 2) for corehole U-15n#10. Dynamic Young's modulus for coreholes U-15n#12 and U-15n#13 were not significantly different from static values. The values of Poisson's ratio (both measured quasi-statically and dynamically) for all coreholes ranged from about 0.12 to 0.31.

Compressional and shear wave velocities are plotted as a function of depth for measurements made parallel (axial) to the specimen central axis in Figure 3. With the exception of a few specimens at shallow depths indicating regions of weathered or altered granite, compressional wave velocities range from 5.240 km/s to 6.238 km/s and shear wave velocities range from 2.986 km/s to 3.617 km/s.

Five waxed specimens from each corehole (U-15n#12 and U-15n#13) were tested as shown in gray highlighted rows in Tables 1 and 2. All material properties from the waxed specimens fell within the range of values of the dry specimens with the exception of specimen SPE13-UCS-024; this specimen was weathered granite and the low material property values are attributed to the weathering and not that the sample was waxed. Specimens not sealed in wax were stored at room temperature with humidity ranging from ~5% to ~35% for at least 3 months.



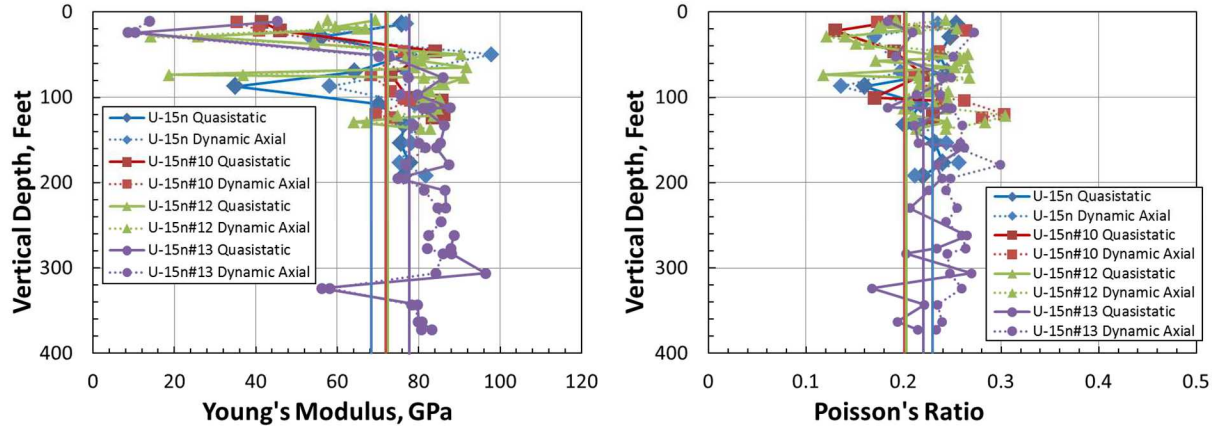


Figure 2. Density, UCS, Young's modulus and Poisson's ratio as a function of depth for Boreholes U-15n, U-15n#10, #12, and #13. Colored vertical lines correspond to the colors in the legend and are the average values for each core hole.

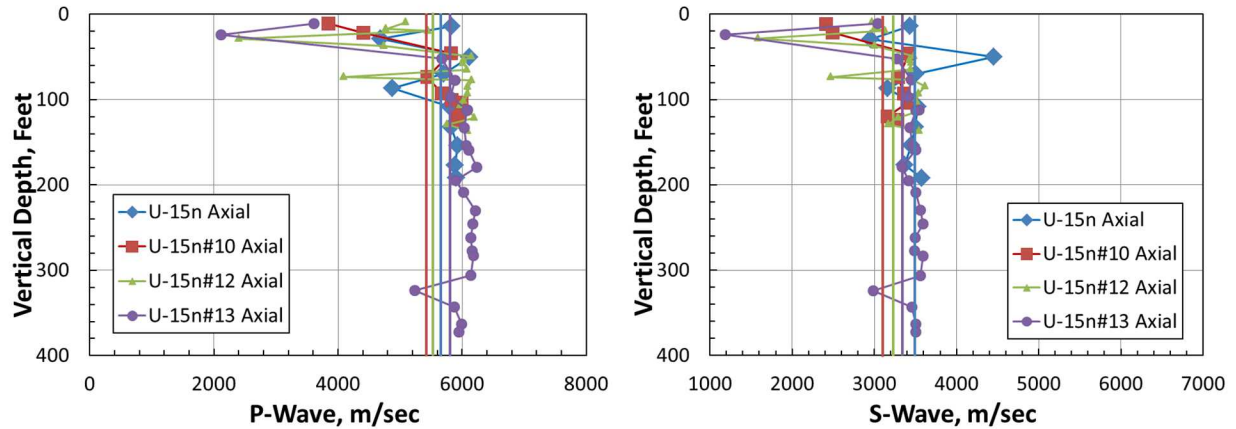


Figure 3. Compressional and shear wave velocities as functions of depth for Boreholes U-15n, U-15n#10, #12, and #13 measured in the axial direction. Colored vertical lines correspond to the colors in the legend and are the average values for each core hole.

Table 5. Median and average values for density, UCS, Young's modulus, Poisson's ratio, P-Wave, and S-Wave for core holes U-15n, U-15n#10, U-15n#12, and U-15n#13.

Median/ Average	Event	Core hole	Density (g/cc)	$\sigma_{AX, MAX}$ (MPa)	E (GPa)	ν	P-Velocity (m/s)	S-Velocity (m/s)
Median	Pre SPE1	U-15n	2.64	199.1	75.8	0.23	5827	3474
Average	Pre SPE1	U-15n	2.63	181.1	68.6	0.23	5656	3492
Median	Post SPE2	U-15n#10	2.64	94.2	80.3	0.20	5819	3290
Average	Post SPE2	U-15n#10	2.63	104.5	72.2	0.20	5433	3138
Median	Post SPE3	U-15n#12	2.64	172.9	80.7	0.21	6028	3437
Average	Post SPE3	U-15n#12	2.63	162.8	72.4	0.20	5550	3220
Median	Post SPE3	U-15n#13	2.65	194.7	84.8	0.22	6031	3492
Average	Post SPE3	U-15n#13	2.64	178.2	78.0	0.22	5726	3341

A limited literature search was conducted to find relevant data sets that could be used for comparison with data acquired under this testing program. The discussion from the literature search was included in the report on UCS results from U-15n corehole from Broome (2011). Corehole U-15n#10 was drilled *after* the SPE-2 test and coreholes U-15n#12 and U-15n#13 were drilled *after* the SPE-3 test; both SPE-2 and SPE-3 consisted of ~2200 pounds of chemical explosive. Because of potential damage to the in-situ core (U-15n#10, #12, and #13) from previous SPE tests, the testing series reported within this report on coreholes U-15n#10, U-15n#12, and U-15n#13 is unique. Properties discussed earlier for corehole U-15n#10 have great similarity to those measured from U-15n core with the exception of UCS. U-15n#10 UCS values are overall lower than UCS values from U-15n by ~42%. UCS values from coreholes U-15n#12 and U-15n#13 are lower than those from U-15n (10% and 2% respectively) but not to the degree as those from U-15n#10. The cause for the lower UCS values from U-15n#10 is unknown. Additional UCS testing from U-15n#10 could improve our understanding of this outlier data set.

Summary and Conclusions

UCS tests were completed for coreholes U-15n#12 (19 tests) and U-15n#13 (23 tests). Both holes U-15n#12 and #13 were drilled after SPE3. For each test, the following material properties were determined:

- Density
- Peak stress (UCS)
- Young's modulus (static and dynamic)
- Poisson's ratio (static and dynamic)
- P-Velocity
- S-Velocity

The material properties measured from U-15n#12 and #13 were compared to those measured on core drilled after SPE2 (corehole U-15n#10) and before SPE1 (corehole U-15n). With the exception of UCS, all other measured material properties are, on average, similar between coreholes. The average UCS is 42% lower from corehole U-15n#10 compared to U-15n. Average UCS for coreholes U-15n#12 and #13 are similar to UCS values measured from U-15n. The greatest variation of material properties for all core-holes is seen at depths shallower than ~100 feet; this variation is attributed to weathered layers near the surface. In general, UCS, density, static Young's modulus and dynamic Young's modulus increase and decrease together for any given specimen. This trend was found to be consistent for all cores. It should be noted that UCS testing was not possible where angled coreholes U-15n#10 and #12 approach the shot points for SPE2 and SPE3 due to extensive damage below 125 vertical feet; the specimens tested represent the strongest component of the core-hole. The laboratory testing reported herein is intended to provide modeling input parameters for the granite medium that has been subjected to repeated chemical explosions.

Contents of this report taken from Broome (2014). Broome (2014) contains additional figures, tables, additional discussion of results, and appendices with details of individual tests.

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