Summary of test results for Daya Bay rock samples

by
Patrick Dobson
Celia Tiemi Onishi
Seiji Nakagawa

October 2004

Summary
A series of analytical tests were conducted on a suite of granitic rock samples from the Daya Bay region of South East of China. The objective of these analyses was to determine key rock properties that would affect the suitability of this location for the sitting of a neutrino oscillation experiment. This report contains the results of chemical analyses, rock property measurements, and a calculation of the mean atomic weight.

Introduction
A total of four granitic rock samples were received from the Daya Bay region for analysis. These samples were obtained from two different rock quarries, the Daya Bay quarry and the Ling Ao quarry illustrated in Figure 1. The visual characteristics of surface samples are shown in Figure 2 and described in Table 1.

Figure 1. Satellite image showing the locations of Daya Bay and Ling Ao Quarries

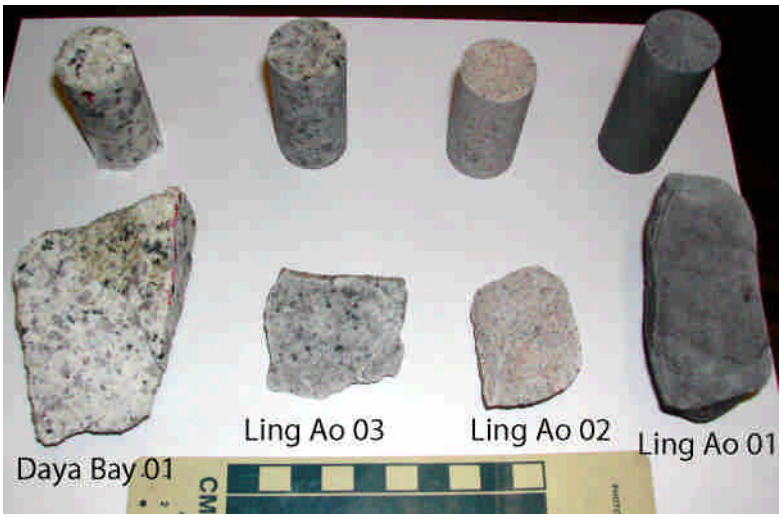

Figure 2. Hand specimens and 1-inch core plugs from the Daya Bay and Ling Ao quarries

Table 1. Summary of sample description

Sample	Description
Daya Bay 01	Light colored, medium grained granitic rock
Ling Ao 01	Dark colored, fine grained granitic rock
Ling Ao 02	Light colored, medium grained granitic rock
Ling Ao 03	Light colored, fine grained granitic rock

Analytical Tests

The following tests were conducted on the Daya Bay region rock samples.

Table 2. List of measurement performed

Test	Samples analyzed	Analyst
Major and trace element chemistry	All	SGS Minerals, Canada
Gamma spectrometry	Daya Bay 01	Dr. A. Smith, LBNL
Porosity, grain and bulk density	Daya Bay 01	Dr. C.T. Onishi, LBNL
Rock strength and elastic property measurements	Daya Bay 01	Dr. C.T. Onishi, Dr. S. Nakagawa, LBNL

Analytical Results

Below are the tabulated results for each of the different test procedures

Major and trace element analyses

The major and trace elements were analyzed by SGS Minerals using X-Ray Fluorescence Spectrometry (XRF) and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS).

Table 3. Summary of chemical analyses

Major elements							
Oxide	Unit	Detection Limit	Ling Ao 01	Ling Ao 01 (duplicate)	Ling Ao 02	Ling Ao 03	Daya Bay 01
SiO_2	%	0.01	76.49	76.58	74.79	75.57	76.18
Al_2O_3	%	0.01	10.62	10.6	13.59	12.88	12.9
CaO	%	0.01	1.45	1.45	0.31	0.49	0.52
MgO	%	0.01	1.33	1.33	<0.01	0.02	0.03
Na_2O	%	0.01	2.84	2.84	4.7	3.53	3.62
K_2O	%	0.01	2.17	2.18	4.05	4.3	4.74
FeO	%	0.1	3.08	3.08	0.45	0.83	0.77
Fe_2O_3	%	0.01	0.49	0.47	0.38	0.51	0.32
MnO	%	0.01	0.07	0.06	0.07	0.13	0.06
TiO_2	%	0.01	0.5	0.5	0.04	0.04	0.05
P_2O_5	%	0.01	0.11	0.11	<0.01	<0.01	<0.01
LOI	%	0.01	0.55	0.5	0.6	0.45	0.6
H2O+	%	0.1	1.19	1.19	0.71	0.88	0.96
H2O-	%	0.1	<0.1	<0.1	0.11	<0.1	0.1
Sum	%	0.01	100.34	100.39	99.20	99.18	100.25
Trace elements							
Ag	ppm	1	<1	<1	<1	1	<1
As	ppm	30	<30	<30	<30	<30	<30
Ba	ppm	20	382	381	<20	31	<20
Ba	ppm	0.5	362.6	357.5	9.1	5.6	3.8
Be	ppm	5	<5	<5	6	<5	5
Bi	ppm	0.1	<0.1	0.1	1	8.7	0.1
Cd	ppm	0.2	<0.2	<0.2	<0.2	1.7	<0.2
Ce	ppm	0.1	49.7	53.8	62.7	46.3	41.2
Co	ppm	0.5	10	10.8	<0.5	<0.5	<0.5
Cs	ppm	0.1	8.9	9.4	6.7	18	7.7
Cr	ppm	10	47	48	73	<10	<10
Cu	ppm	5	39	38	<5	45	<5
Dy	ppm	0.05	4.63	4.91	20.7	21.3	11.5
Er	ppm	0.05	2.82	2.89	14.8	14.1	6.9
Eu	ppm	0.05	0.97	1.05	<0.05	<0.05	0.06
Ga	ppm	1	11	12	24	23	17
Gd	ppm	0.05	4.72	4.74	13.4	15.2	9.29
Ge	ppm	1	1	2	4	3	2
Hf	ppm	1	5	5	14	8	4
Ho	ppm	0.05	0.93	0.96	4.34	4.5	2.25

In	ppm	0.2	<0.2	<0.2	<0.2	0.2	<0.2
La	ppm	0.1	23.6	25.8	21.2	16.4	16.8
Li	ppm	10	47	47	33	211	47
Lu	ppm	0.05	0.49	0.51	3.29	2.58	1.17
Mo	ppm	2	<2	<2	3	54	<2
Nb	ppm	1	9	10	54	66	38
Nb	ppm	2	10	9	65	63	48
Ni	ppm	5	26	26	<5	<5	<5
Nd	ppm	0.1	20.9	22.2	32.3	27.6	22.1
Pb	ppm	5	14	15	43	50	29
Pr	ppm	0.05	5.97	6.44	9.13	6.99	5.79
Rb	ppm	0.2	130.4	138	616.3	799.9	453.3
Rb	ppm	2	132	132	644	721	458
Sc	ppm	5	10	9	12	9	6
Sm	ppm	0.1	4.5	4.8	13	11.7	7.8
Sn	ppm	1	2	2	10	23	7
Sr	ppm	0.1	73.4	75.7	2.2	9.1	9.6
Sr	ppm	2	81	81	7	9	10
Ta	ppm	0.5	0.8	0.9	21.5	9.1	3.9
Tb	ppm	0.05	0.74	0.76	2.93	3.05	1.78
Th	ppm	0.1	11.1	12.1	26.7	37.3	28.9
Tl	ppm	0.5	0.7	0.7	2.5	3.2	2
Tm	ppm	0.05	0.38	0.38	2.74	2.25	1.05
U	ppm	0.05	1.9	1.99	22.9	18.7	8.61
V	ppm	5	63	62	<5	<5	<5
W	ppm	1	1	1	10	21	2
Y	ppm	0.5	26.8	27.4	99.5	140.3	65.2
Y	ppm	2	29	29	124	146	80
Yb	ppm	0.1	3	3.1	21.2	16.2	7.7
Zn	ppm	5	61	62	37	229	20
Zr	ppm	0.5	155.1	145.3	119.2	88.3	65.3
Zr	ppm	2	179	181	127	96	87

Note: Analyses highlighted in yellow represent main radiogenic elements. For several elements (Ba, Nb, Rb, Sr, Y, and Zr), two sets of values are reported, representing results obtained using different analytical techniques.

Gamma Spectrometric Measurements

Results from gamma-ray spectrometry (Table 4) are within 15% of the more precise analyses reported on Table 3 for the Daya Bay 01 sample. The sample was analyzed at the Berkeley Low Background Facility (LBF) using Cs-137 gamma-ray sources. Radionuclide concentrations have been obtained from these spectra by comparison to spectra from standard (calibration) materials. The standards consisted of gamma-sources and reference materials that are traceable to International Atomic Energy Agency (IAEA) gamma-ray standards, CP grade (chemically pure) chemicals (for potassium), or U and

Th assay standards from the New Brunswick Laboratory of the US Atomic Energy Commission (AEC). In this procedure, we first determined the intensities for peaks characteristic of each radionuclide present in a sample. These peak intensities are then translated into absolute elemental abundance or radionuclide activity through comparisons with intensities of the same peaks in the standard calibration samples.

Table 4. Summary of gamma-ray spectrometry results

Sample	**K_2O** (%)	**Th** (ppm)	**U** (ppm)
Daya Bay 01	4.41	33.0	10.4

Rock Property Measurements

The grain density and porosity of samples was determined by the gas displacement-Boyle's law method using helium. The tool used for this measurement is helium pycnometer, which is specifically designed to measure sample volume and to provide the necessary information to calculate the density and porosity. To use the apparatus available at LBNL, the samples were cored to 1-inch (2.54 cm) diameter and oven dried at 90^{o}C for 24 hours. The samples were weighed prior to the measurement.

The density was calculated using the grain volume and sample weight measurements, and were repeated to evaluate reproducibility of measurements. The porosity was determined using estimated average bulk volumes of the sample and the measured grain volume. The bulk volume was calculated using sample diameter and length of the core plugs.

Table 5. Summary of porosity and density measurements

Sample	**Porosity** (%)	**Bulk Density** (g/cc)	**Grain Density** (g/cc)
Daya Bay 01	1.33	2.58	2.62

Rock Elastic Moduli and Strength Measurements

Ultrasonic tests and unconfined compressive strength tests were conducted using core samples with 1-inch (2.54 cm) diameter. The ultrasonic velocity was determined from wave propagation time along a known sample length. The wave velocity of a specimen is influenced by material parameters including elastic moduli of mineral grains, density and microstructural features of the rock.

Poisson’s ratio and Young’s Modulus were calculated to provide information about mechanical properties of *in situ* material (e.g. weathering and fracturing reduces velocity and amplitude of measured waves).

Further, unconfined compressive test was performed using a displacement-controlled loading device. The result is reported in Table 6.

Table 6. Summary of mechanical properties

	Daya Bay 01
S wave (m/s)	1852
P wave (m/s)	2852
Poisson's ratio	0.135
Shear modulus (GPa)	21
Young's modulus (GPa)	48
Unconfined Compressive Strength (MPa)	75 (extensile failure)

Mean Atomic Weight

The mean atomic weights of the rock samples were calculated using the reported compositions for the major rock constituents. First the compositions for the main oxide components were normalized to totals of 100%. The normalized compositions were then converted from oxides to elemental compositions. Finally, the mean atomic weight for each elemental composition was determined. These values are listed in Table 7.

Table 7. Summary of mean atomic weight

Sample	**Mean Atomic Weight**
Ling Ao 01	23.01
Ling Ao 01 (duplicate)	23.00
Ling Ao 02	22.41
Ling Ao 03	22.60
Daya Bay 01	22.57