THE AMERICAN MINERALOGIST, VOL. 52, JULY-AUGUST, 1967

SHEAR STRENGTH AND WEAKENING OF ZEOLITIZED TUFFS FROM THE NEVADA TEST SITE, NEVADA

ROBERT E. RIECKER AND THOMAS P. ROONEY, *Air Force Cambridge Research Laboratories (CRJW) Bedford, Mass.*

ABSTRACT

Experimental shear deformation of Tertiary zeolitized tuffs has demonstrated weakening of 43–63 percent at temperatures between 27°C and 500°C. Tests were made to pressures of 60 kb, temperatures to 900°C and at a constant strain rate of 10/sec. Weakening probably results from dehydration of clinoptilolite. Dehydration reduces effective confining pressure by increasing pore pressure.

INTRODUCTION

Contained nuclear testing in various rock types has been carried on at the Nevada Test Site since September of 1957. Short (1965), Nordyke (1962), Cummings (1965), Johnson and Higgins (1965) and others have shown that the physical and mechanical properties of the rocks frequently affect the phemonena of contained explosions. The shear strength and mechanical behavior of NTS tuffs were investigated in 1966 as part of a larger study to determine the behavior of test-site rocks under various pressures, temperatures and loading rates. A complete discussion of results for the materials tested appears elsewhere (Riecker and Rooney, 1966b). We discuss here, a significant weakening effect which appeared during shear deformation tests of tuffs from the U12G tunnel, Rainier Mesa, Nevada Test Site, Nye Co., Nevada.

MEASUREMENTS

Shear tests were accomplished in an opposed anvil shear apparatus (Riecker 1964*a*, 1964*b*) to maximum normal pressures of 60 kb, temperatures to 900°C, at a constant strain rate of 10/sec. This apparatus applies a gross shearing stress to thin sample wafers compressed between the opposed anvils. Shear strength is determined from the resistance to shear exhibited by the sample, as shown in Riecker and Seifert (1964) after Bridgman (1937).

The two tuff samples tested both originated from Tunnel Beds 2 and 4, lower member, Indian Trail Formation (Tertiary) at U12G Tunnel positions 24+00′ and 43+00′. Shear-strength versus normal-pressure curves resulting from deformation of the two samples are shown in Figure 1, with the test conditions appearing in Table 1.

A 63 percent weakening for the Tl samples is exhibited by tests at 40 kb and 500°C as compared with tests at 27°C. Weakening for the T2 samples is 43 percent under similar conditions of temperature and pressure. This large weakening effect at increased temperature is inconsistent with previous experience for deformed silicate rocks and minerals at high temperatures and at relatively fast strain rates (Handin, 1966).

Chemical analyses (Table 2) show that the tuffs are water-rich, containing 4.40 weight percent water for Tl and 5.40 weight percent for T2. Petrographic examination and X-ray diffraction analysis of the tuff specimens indicate that the most abundant phase in the rocks is a zeolite mineral, clinoptilolite. Clinoptilolite, which gives an X-ray pattern almost identical to heulandite, was identified on the basis of X-ray data after heating at 600°C for 24 hours. The identification was confirmed using DTA techniques suggested by Mason and Sand (1960) and Mumpton (1960). Mumpton (1960) states that at about 230°C heulandite transforms to "heulandite B", and at 350°C it becomes amorphous, whereas clinoptilolite remains stable to about 700°C without reaction at lower temperatures (Koizumi and Roy, 1960). Clinoptilolite has been reported in other NTS tuffs by Dickey and Monk (1963), Gibbons *et al* (1960), Shepard (1961), and Wilmarth *et al* (1960). In addition to clinoptilolite, the tuff samples contain phenocrysts (10% by volume) of sanidine, quartz, plagioclase, mica, and iron oxides.

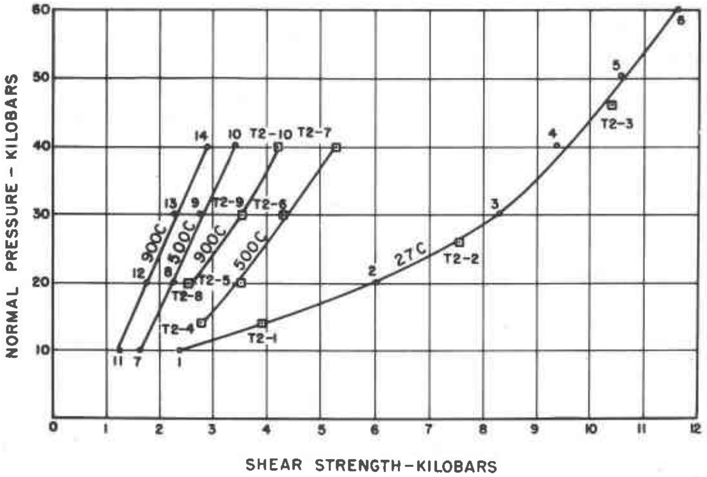

FIG. 1. Shear-strength normal-pressure curves for deformed tuffs showing large strength decrease at high temperatures.

DISCUSSION

The weakening observed in shear tests on tuff may be accounted for by the dehydration of clinoptilolite with a consequent reduction in effective confining pressure caused by the development of a high pore pressure in

TABLE 1. Shear Strengths and Test Conditions (All tests run at strain rate of 10/sec)

Test number	Pressure Kb	Temperature °C	Shear duration (min.)	Shear strength Kb
T1-1	9.95	27	16	2.4
T1-2	19.90	27	12	6.1
T1-3	29.85	27	11	8.3
T1-4	39.79	27	12	9.4
T1-5	49.74	27	9	10.6
T1-6	59.69	27	5	11.7
T1-7	9.95	500	6	1.6
T1-8	19.90	500	6	2.3
T1-9	29.85	500	7	2.8
T1-10	39.79	500	5	3.4
T1-11	9.95	900	3	1.3
T1-12	19.90	900	3	1.8
T1-13	29.85	900	3	2.3
T1-14	39.79	900	3.5	2.9
T2-1	13.93	27	11	3.9
T2-2	25.87	27	5	7.6
T2-3	45.76	27	5	10.4
T2-4	13.93	500	4	2.8
T2-5	19.90	500	6	3.5
T2-6	29.85	500	9	4.3
T2-7	39.79	500	7	5.3
T2-8	19.90	900	5	2.5
T2-9	29.85	900	5	3.5
T2-10	39.79	900	5	4.2

the sample (Terzaghi, 1936). Hubbert and Rubey (1959) have shown that the strength of rocks may be greatly influenced by the presence of water. Raleigh and Paterson (1965) investigated the anomalous embrittlement and weakening of serpentinite from 300 to 600°C. They ascribe the weakening in part to the reduction of effective confining pressure caused by

TABLE 2. CHEMICAL ANALYSES OF TUFF SAMPLES

	Oxides (weight percent)													
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O^-	H_2O^+	CO_2	Total
T1	72.5	0.21	11.4	1.50	0.5	0.046	0.35	0.90	2.42	4.10	1.48	4.40	0.1	99.91
T2	71.0	0.19	12.5	1.47	0.05	0.06	0.35	0.73	3.26	3.40	2.10	5.40	0.1	100.61

pore pressure of water released by dehydration of serpentine. Handin (1964) observed similar weakening in AMSOC Puerto Rico serpentinites. Heard and Rubey (1963) observed a ten-fold strength decrease in gypsum during triaxial compression tests when the temperature was increased from 100 to 150°C. Riecker and Rooney (1966a) found a 30 percent weakening in dunite associated with 5 percent by weight of serpentine and a 55 percent decrease in strength in serpentinite when the temperature was increased from 300°C to 520°C. All of these studies demonstrate that a significant weakening mechanism operates in confined tests at moderate temperatures where water vapor is generated by the breakdown of hydrous minerals.

Griggs (1966) lists four different processes by which water weakening might be explained: (1) increase of pore pressure reducing the effective confining pressure; (2) penetration of water into intergranular boundaries reducing cohesive strength; (3) promotion of recrystallization by the presence of water, greatly reducing strength at low strain rates; and (4) hydrolytic weakening of crystals. It has not been possible to determine in this study whether or not hydrolytic weakening has occurred or to evaluate quantitatively the importance of each of the other three mechanisms. It is probable that the reduction of cohesive strength by the appearance of new phases in pores and the promotion of recrystallization have been effective in reducing strength, but no evidence exists to evaluate their relative importance. We believe that the first process listed by Griggs is reasonable in view of the large amount of water vapor released by dehydration of the zeolite in these tuffs. Therefore, the reduction of strength seen in Figure 1 can be explained by increasing pore pressure and reduction of effective confining pressure due to dehydration of clinoptilolite.

The geologic effects of rocks weakened by high pore pressure was demonstrated originally by Hubbert and Rubey (1959), and more recently by Secor (1965), Evans (1966), and Riecker (1966). Weakening of rocks by dehydration effects provides a powerful tool to explain variations in strength observed in the laboratory and field.

Acknowledgments

This study was performed with Defense Atomic Support Agency funds provided by the Air Force Weapons Laboratory under Program Element 6164601D, Project 5710, Subtask 13.144. We thank Dr. J. M. S. Sun of Air Force Weapons Laboratory for technical assistance. Chemical analyses were made by O. Joensuu.

References

Bridgman, P. W. (1937) Shearing phenomena at high pressures, particularly in inorganic compounds. *Proc. Amer. Acad. Arts Sci.* **71**, 387–460.

Cummings, D. (1965) Kink bands: Shock deformation of biotite resulting from a nuclear explosion. *Science* **148**, 950–952.

DICKEY, D. D., AND E. F. MONK (1963) Determining density and porosity of tuff containing zeolites. *U. S. Geol. Science Prof. Pap.* **475-B,** B169–B170.

EVANS, D. M. (1966) The Denver area earthquakes and the Rocky Mountain Arsenal disposal well. *Mt. Geol.* **3,** 23–36.

GIBBONS, A. A., HINRICHS, E. N., AND T. BOTINELLY (1960) The role of impermeable rocks in controlling zeolitic alteration of tuff. *U. S. Geol. Surv. Prof. Pap.* **400B,** B473–B475.

GRIGGS, D. T., BLACIC, J. D., CHRISTIE, J. M., MCLAREN, A. C., AND F. C. FRANK (1966) Hydrolytic weakening of quartz crystals. (abstr.) Science **152,** 674.

GRIGGS, D. T. AND J. D. BLACIC (1965) Quartz: Anomalous weakening of synthetic crystals. *Science* **147,** 292–295.

HANDIN, J. (1964) Strength at high confining pressure and temperature of serpentinite from Mayaguez, Puerto Rico. *Nat. Acad. Sci. Nat. Res. Counc. Publ.* **1188,** 126–131.

——— (1966) Strength and ductility. *Geol. Soc. Amer. Mem.* **97,** 223–290.

HEARD, H. C. AND W. W. RUBEY (1963) Possible tectonic significance of transformation of gypsum to anhydrite plus water (abstr.). *Geol. Soc. Amer. Spec. Pap.* **76,** 342.

HUBBERT, M. K., AND W. W. RUBEY (1959) Role of fluid pressure in overthrust faulting. *Geol. Soc. Amer. Bull.* **70,** 115–166.

JOHNSON, G. W. AND G. H. HIGGINS (1965) Engineering applications of nuclear explosives: Project Plowshare. *Rev. Geophys.* **3,** 365–385.

KOIZUMI, M. AND R. ROY (1960) Zeolite studies. I. Synthesis and stability of the calcium zeolites. *J. Geol.* **68,** 41–53.

MASON, B. AND L. B. SAND (1960) Clinoptilolite from Patagonia, the relationship between clinoptilolite and heulandite. *Amer. Mineral.* **45,** 341–350.

MUMPTON, F. A. (1960) Clinoptilolite redefined. *Amer. Mineral.* **45,** 351–369.

NORDYKE, M. D. AND W. R. WRAY (1963) A nuclear cratering detonation in basalt. *J. Geophys. Res.* **69,** 675–690.

RALEIGH, C. B. AND M. S. PATERSON (1965) Experimental deformation of serpentinite and its tectonic implications. *J. Geophys. Res.* **70,** 3965–3985.

RIECKER, R. E. (1964*a*) New shear apparatus for temperatures of 1000°C and pressures of 50 kb. *Rev. Sci. Instrum.* **35,** 596–598.

——— (1964*b*) Use of induction heating in rock deformation apparatus. *Rev. Sci. Instrum.* **35,** 1234–1236.

——— (1966) Evidence bearing on earthquake origin. *Earthquake Notes* **37,** 3–9.

——— and T. P. Rooney (1966*a*) Weakening of dunite by serpentine dehydration. *Science* **152,** 196–198.

——— and T. P. Rooney (1966b) Shear deformation of Nevada Test Site Rocks: Tests to 60 kb and 900°C. *U. S. Clearinghouse Fed. Sci. Tech. Inform.* **AD 645938.**

——— AND K. E. SEIFERT (1964) Shear deformation of upper mantle mineral analogs: Tests to 50 kb at 27°C. *J. Geophys. Res.* **69,** 3901–3913.

SHEPARD, A. O. (1961) A heulandite-like mineral associated with clinoptilolite in tuffs of Oak Spring Formation, Nevada Test Site, Nye Co., Nev. *U. S. Geol. Surv. Prof. Pap.* **424C,** C320–C323.

SECOR, D. T. (1965) Role of fluid pressure in jointing. *Amer. J. Sci.* **263,** 633–646.

SHORT, N. M. (1965) A comparison of features characteristic of nuclear explosion craters and astroblemes. *Ann. N. Y. Acad. Sci.* **123,** 573–616.

TERZHAGI, K. (1936) Simple tests determine hydrostatic uplift. *Eng. News Rec.* **116,** 872–875.

WILMARTH, V. R. *et al* (1960) Alteration of tuffs by Rainier underground nuclear explosion, Nevada Test Site, Nye Co., Nev. *U. S. Geol Surv. Prof. Pap.* **400B,** 1B49–B151.

Manuscript received July 1, 1966; accepted for publication September 3, 1966.