THE AMERICAN MINERALOGIST, VOL. 55, MARCH–APRIL, 1970

THERMAL ACTIVATION ENERGY OF SHOCKED AND STRAINED QUARTZ

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ABSTRACT

The thermal activation energy calculated by the initial rise method appears to be an indication of the state of deformation in quartz from shocked and strained quartzites. The data suggests that undeformed material from two widely separated sources have approximately equal eV values.

On the basis of preliminary data similar results can probably be obtained from other rock types.

Shock effects in the vicinity of meteorite impact craters and underground nuclear blasts have been shown to cause modifications in the physical, optical and crystallographic characteristics of quartz (cracking cleavage, isotropism and formation of the high pressure polymorphs, coeiste and stishovite) (Short, 1966). In addition, it has been demonstrated that some of the electronic characteristics of calcite and other minerals as reflected in their thermoluminescence, can also be modified by shock and static loading (Douglas, *et al.*, 1969). However, application of the relative change in thermoluminescence to the investigation of shock and strain effects has been restricted by the knowledge that other factors may produce similar results. Such complicating factors include: variations in natural and artificial radioactivity; the state of saturation of the electron "traps," including draining of "traps" by thermal energy generated during the event which caused the shock or strain; or natural variations in lattice defects (trace elements, vacancies, dislocations).

This paper presents the results of an investigation of some of the electronic characteristics of shocked and strained quartz. Diamond drill core samples of quartzites from the sources of a) the Sedan underground nuclear event, Nevada test site; and b) the Nordic mine, Elliot Lake, Ontario, were used. Brief descriptions of the amount of shock or static loading are given in Tables I and II. Each sample was crushed in a jaw crusher and the 100 mesh size was used in the experiments. The thermoluminescence reader is a modified version of equipment developed at the University of Rome (Bettinali, Ferraresso, Gottardi, 1966 and Bettinali, Ferraresso, Manconi, 1967), with the thermoluminescence emission observed with a RCA 5819 photomultiplier having a S-11 type response.

To enable the sample (approximately one grain thick) to adhere evenly

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TABLE 1. NEVADA TEST SITE: THERMOLUMINESCENCE IN CAMBRIAN AND PENNSYLVANIAN ROCKS

Shock (arb. scale)	Description[a]	Thermoluminescence Peak A nat	Thermoluminescence Peak A X-ray	Thermoluminescence Peak B nat	Thermoluminescence Peak B X-ray	Activation Energy Peak A X-ray	Activation Energy Peak B X-ray
0	Unshocked	—	10.5	6.0	3.8	0.42	0.78
1	Mildly shocked (cracked)	—	5.0	2.8	3.2	0.69	1.03
2	Moderately shocked	—	2.2	1.0	2.0	1.37	1.51
3	Strongly shocked (partly isotropized quartz)	—	1.4	—	0.8	.91	1.86
4	Very strongly shocked (nearly all quartz isotropized)	—	0.8	—	—	—	—
5	Very strongly shocked (isotropized, glassy)	—	0.6	—	—	—	—
6	State of shock unknown (assumed to be very high on basis of TL data)	—	0.4	—	—	—	—

[a] Personal communication, N. M. Short, National Aeronautics and Space Administration. (U.S.)

to the heater plate, the heater was first coated with a thin layer of silicone grease. The samples were heated to about 300°C at a rate of 15°C per minute. For each sample, glow curves were obtained for a) the natural thermoluminescence and b) the thermoluminescence induced by 3.3×10^3 R/hr X-rays. The X-ray excited peaks at circa 40°C and circa 100°C

TABLE 2. THERMOLUMINESCENCE IN URANIUM-BEARING MISSISAGI QUARTZITES FROM THE NORDIC MINE, ELLIOT LAKE, ONTARIO

Stress (estimated)[a] psi	Strength (Compressive)[a] psi	Thermoluminescence Peak A nat	Thermoluminescence Peak A X-ray	Thermoluminescence Peak B nat	Thermoluminescence Peak B X-ray	Activation Energy Peak A X-ray	Activation Energy Peak B X-ray
3,000	[b]	—	1.8	1.0	1.1	0.61	—
4,000	[b]	—	1.5	0.5	0.8	0.65	—
6,000	[b]	—	1.6	0.5	1.15	0.79	—
10,000	29,000	—	2.2	1.0	1.1	1.02	—
14,000	30,000	—	1.6	1.45	1.15	1.92	—

[a] Personal communication, T. S. Cochrane, Mines Branch, Dept. Energy, Mines and Resources. (Can.)

[b] Average compressive strength: 31,000 psi.

are indicated in the Tables as Peak A and Peak B respectively. The symbols "nat" and "X-ray" in Tables I and II serve to distinguish between natural and X-ray induced thermoluminescence. The thermal activation energies in electron volts (eV) were calculated by the initial rise method (Halperin, Braner, and Kristianpoller, 1960 and Bettinali, Ferraresso and Manconi, 1969) for the X-ray excited peaks of the shocked and strained samples. The experimental data: Thermoluminescence (in relative units) and Activation Energy (in eV), is summarized in Table 1 for the shocked samples and in Table 2 for the strained samples. These data are also shown graphically in Figures 1 and 2. The tables are incomplete because in many cases the intensity of the emitted light was too low to provide meaningful results.

In Figure 1, the decrease in both the natural and X-ray excited thermoluminescence with increasing shock is similar to the effects observed in calcareous rocks from the vicinity of some Canadian meteorite craters (unpublished data). It has been observed that in general, the amount of thermoluminescence emitted from rock samples which have previously failed as the result of natural or artificial causes, is markedly less than that from unfailed specimens (Douglas, *et al.*, 1969). In Figure 2, the stress for each sample is an estimated figure for the amount actually

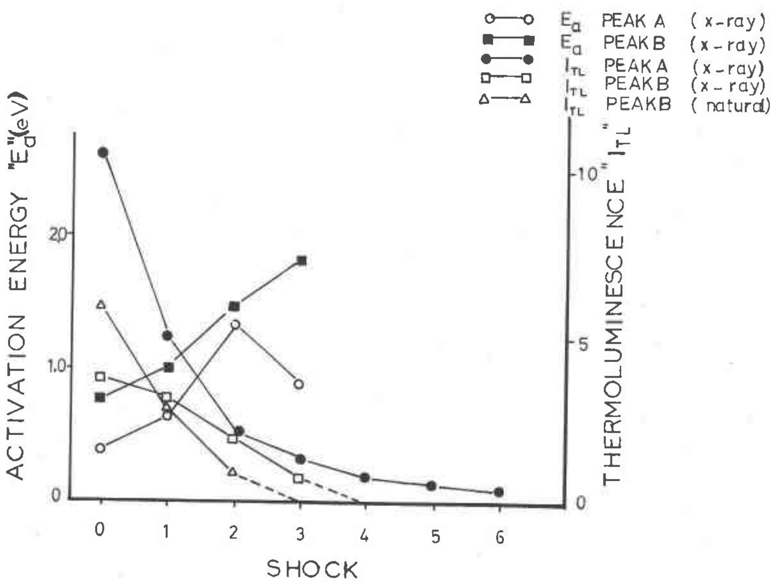

FIG. 1. Activation energy and thermoluminescence vs increasing shock for natural and X-ray excited quartzites from the Nevada Test Site. (See Table 1 for description of amount of shock.)

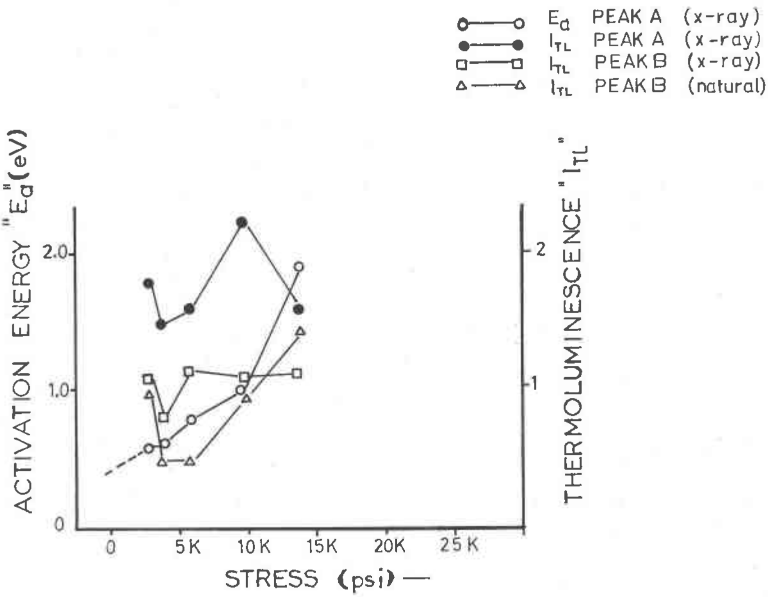

FIG. 2. Activation energy and thermoluminescence vs increasing stress (estimated) for natural and X-ray excited uranium-bearing Missisagi quartzites. (See Table 2 and text for details.)

sustained by the mine pillars from which the samples were obtained (personal communication, T. S. Cochrane). Information on the amount of strain is not available to the writers, but the loading can be considered to be essentially uniaxial. It will be noted that both the natural and artificial thermoluminescence do not vary uniformly with increasing stress. Rather similar "cyclical" thermoluminescence has been reported for samples of limestone and syenite which were artificially strained while confined by a hydrostatic load and then subsequently tested for thermoluminescence (Morency, 1968). However, one portion of the natural thermoluminescence curve (from about 4000 to 14,000 psi) indicates a general increase in thermoluminescence with increasing load. This type of increase may be considered to correspond to a strain-induced increase in thermoluminescence towards (but not into) fault zones (McDougall, 1968).

In Figures 1 and 2, the thermal activation energy tends to increase with both increasing shock and static loading. Two features of the thermal activation energy curves for the X-ray excited peak A require comment:—a) in Figure 2, the curve can be extrapolated (dashed line) to about the same value at zero stress as the unshocked sample in

Figure 1; and b) in Figure 1, the value for No. 2 may be either abnormally high due to interference from a second artificially excited peak at a slightly higher temperature, or, on doubtful grounds, the increase may possibly correspond to the rather similar rise shown in Figure 2 between 10,000 psi and 14,000 psi.

The experimental results suggest that, within limited geological regions, thermal activation energy values derived from artificially excited thermoluminescence glow curves can be a useful indicator of the state of deformation of quartz in quartzites. Preliminary unpublished data indicate that the procedure can be extended to other rock types (granite, granodiorite, calcareous siltstone, limestone). On less satisfactory grounds it can be tentatively inferred, that in the two suites of samples:—a) complicating factors due to variation in radioactivity, electron "trap" saturation and trace element concentrations may have been largely eliminated; and b) similar activation energies may reflect similar levels of deformation.

Acknowledgements

Financial support for the investigation was provided through a National Research Council of Canada operational grant (D. J. McD) and a National Research Council of Canada Post-Doctoral Fellowship (J. W. M.). The assistance of N. M. Short of the U. S. National Aeronautics and Space Administration, D. Coates and T. S. Cochrane of the Mines Branch, Canadian Department of Energy, Mines and Resources, who provided the samples and descriptive data, is gratefully acknowledged. Permission to cite data from the Nordic Mine has been given by Rio Algom Mines Ltd.

Bibliography

Bettinali, C., G. Ferraresso and V. Gottardi (1966) Application of thermoluminescence on glass study, *Vetro Silicati* **10,** 5–12.

———, ———, and J. W. Manconi (1967) Behavior of glow-curves during phase transitions in inorganic compounds. *Atti Accad. Naz. Lincei Mem.* **43,** 536–544.

———, ———, and ——— (1969) Thermoluminescence of ZrO_2, *J. Chem. Phys.* **50,** 3957–3961.

Douglas, G., M. Morency and D. J. McDougall (1969) Detection of strain in rocks using an intrinsic "semi-insulator" characteristic of some minerals [abstr.], *Geol. Ass. Can.-Mineral. Ass. Can. Ann. Meet., Montreal, June, 1969; also Modern Geol.* (in press).

Halperin, A., A. A. Braner and N. Kristianpoller (1960) Thermal activation energies in NaCl and KCl crystals, *Phys. Rev.* **117,** 416–422.

McDougall, D. J. (1968) A "lattice defect-free energy" approach to replacement processes in ore deposition, *Econ. Geol.* **63,** 671–681.

Morency, M (1968) An investigation of the effects of pressure on thermoluminescence *in* D. J. McDougall (ed.) *Thermoluminescence of Geological Materials,* Academic Press, New York, 233-240.

Short, N. M. (1966) Shock processes in geology, *J. Geol. Educ.* **14,** 149–166

Manuscript received, August 5, 1969; accepted for publication, October 31, 1969.