

FIG. 4. Thermoluminescence glow curves comparing: (a) unshocked (0) and shocked (5) granodiorite; (b) unshocked (0) and shocked (1 to 6) quartzite; (c, d, e) effect of particle size reduction in unshocked quartzite, syenite, and limestone. The peak heights of the limestone samples should be multiplied by a factor of 2.5 for direct comparison with the other cases.

increases in thermoluminescence may be related to stages of virtually no deformation, whereas decreases in thermoluminescence may be related to stages of deformation (Morency, 1968). Figure 5 illustrates various thermoluminescence parameters of the Bedford limestone at a confining pressure of 2000 psi. There is questionable increase in thermoluminescence at about the middle of the axial load range and a very definite decrease in thermoluminescence at failure (29,000 psi). The peak height ratio curve appears to reflect comparatively low strain conditions up to about 8000 psi (ratio about 0.7), followed by higher strain conditions up to about 28,000 psi (ratio about 0.4), and finally a release of strain at 29,000 psi (ratio about 0.9).

Over a period of a few months there did not appear to be any appreciable change in the strain-induced thermoluminescence due to aging.

## DISCUSSION

Stress-induced changes in the intrinsic semi-insulator characteristics of some minerals, as

reflected in their thermoluminescence, can apparently be considered in three stages:

(1) When strain has caused an initial increase in thermoluminescence, it appears probable that at least part of the photon energy has been stored in lattice dislocations. In some, but not all cases, it is possible to assume that the release of photons on heating may have been accomplished by the annealing of some part of the dislocation network.

(2) Not uncommonly, further strain results in a decreased level of thermoluminescence. A possible explanation lies in the annihilation of previously formed dislocations. The cyclical increase and decrease of thermoluminescence which has sometimes been observed with increasing strain, would thus be due to a cyclical process of formation and repair of dislocations. This cyclical process is readily explained in polycrystalline materials by assuming different levels of strain in crystals of different orientations.

(3) In some cases, very high levels of strain (failure and impact) will cause a marked decrease in thermoluminescence. In part this effect may be

due to the formation of numerous fracture surfaces in the crystals and a resultant increase in light scattering and absorption. However, the effect often appears to be more complex than what might be anticipated from a simple reduction in particle size and may be the result of a change from long-range to short-range order in the material. Some lines of evidence indicate that the change involves approaching the condition of being an insulator instead of a semi-insulator.

A rather unsatisfactory hypothesis to explain the initial increase in thermoluminescence (stage 1 above) is that it may correspond to an anelastic damping effect. Ideally, such a lag of strain behind stress should decrease exponentially with time at constant temperature. However, the continued presence of strain-induced thermoluminescence in artificially deformed materials for several months, as well as its presence in the vicinity of geologically-old faults and meteorite craters would suggest that if there is any time-dependant decrease, it must proceed at an extremely slow rate.

On the other hand, there appears to be some grounds for comparing the first two stages noted

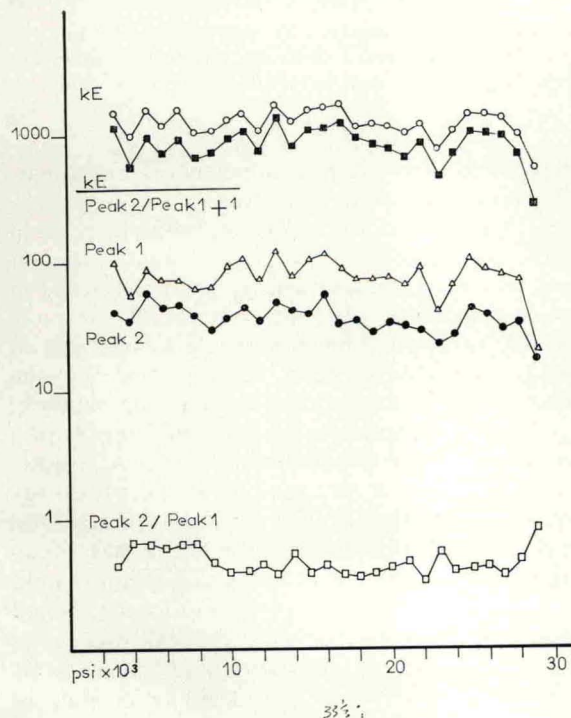


FIG. 5. Variations in thermoluminescence parameters in artificially loaded limestone samples at constant confining pressures.

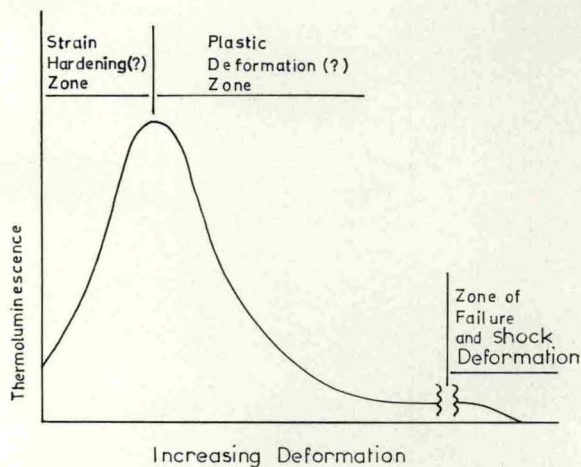


FIG. 6. Tentative proposal of relationships of thermoluminescence to deformation (strain).

above with stress-strain relationships in crystalline materials. The initial increase in thermoluminescence may correspond to strain-hardening due to the development of dislocation nets in the crystals. If this relationship is valid, then strain-induced thermoluminescence should be initiated at about the elastic limit and reach a maximum during the early stages of permanent deformation. The subsequent decrease in thermoluminescence would then correspond to the later stage of plastic deformation and result from the annihilation of dislocations during the recovery from strain-hardening. This suggested relationship is illustrated in Figure 6. The first portion of this curve resembles a Gaussian distribution. If it is assumed that the thermoluminescence is approximately proportional to the number of dislocations and that the number of dislocations are approximately inversely proportional to the amount of deformation, then a suitable cumulative plot of the thermoluminescence should resemble a stress-strain diagram. Some of the cyclical strain-induced thermoluminescence data obtained by one of the authors (M. M.) has recently been treated in this fashion by the senior author, and curves obtained which approximate the somewhat irregular stress-strain curves from the same material. These results, although encouraging, have not yet been able to provide a satisfactory correlation between the amount of deformation and thermoluminescence.

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