Ancient TL

Induced thermoluminescence dating of basalts

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Abstract

Several attempts to date basalts using natural thermoluminescence methods have failed because the phosphor, feldspar, displays anomalous fading. In the late nineteen-seventies R.D. May reported an increase in induced TL with age for Hawaiian basalts. Studies of meteorites have shown that induced TL can increase with time (or heating) due either to production of the phosphor by crystallization of glass or the diffusion of impurity quenchers out of the phosphor. The increase can be many orders of magnitude. I therefore propose that induced TL is a potential new method of thermoluminescence dating of basalts. I also suggest that it may be possible to make the method absolute, i.e. not dependent on empirical calibration, by performing the appropriate laboratory kinetic studies.

Keywords: Keywords: Basalts, induced thermoluminescence, dating

1. Introduction

Not long after the development of the fine-grain method of using natural thermoluminescence (TL) to date archeological artifacts, it was proposed that the method might be applicable to dating fairly young volcanic rocks (e.g. Aitken et al., 1968). However, almost immediately it was realized that volcanic feldspars, the TL phosphor in volcanic rocks, displayed anomalous fading and therefore the method was not practical (Wintle, 1973). Since then, while there have been some successes the approach has been to try to look at the TL produced at alternative (non-visible) wavelengths and other physical methods of avoiding the problem (e.g. Tsukamoto et al., 2011).

Here I propose an entirely different method for dating volcanic rocks, namely to use the time-dependency of the induced TL signal that is present in many rocks. This dependency is caused by the fact that volcanic rocks, for instance, are non-equilibrium systems in many respects. They cool rapidly; so much of the feldspathic component is glassy, or otherwise amorphous, with little or no induced TL. Similarly, they are out of equilibrium compositionally, they may contain impurities that quench the TL. However, in approaching equilibrium, induced TL levels will increase in a time-dependent way and if the kinetics can be quantified then a new and independent method of dating will be possible.

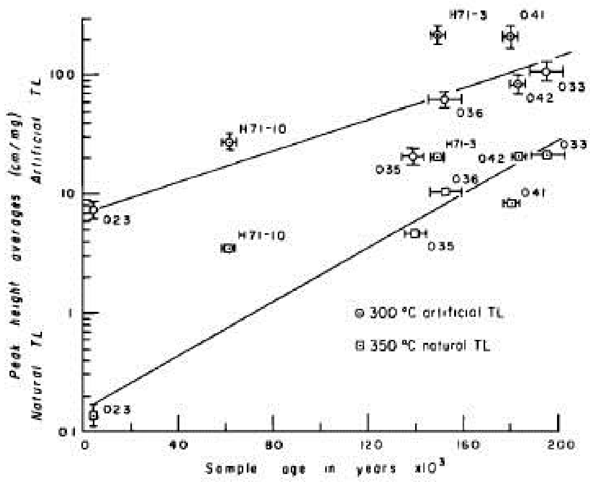

Figure 1. Figure from May (1977, 1979) comparing induced TL (which he called “artificial TL”, upper line), and natural TL (lower line), with sample age for Hawaiian basalts.

2. R.D. Mays study of 1977

May (1977, 1979) attempted to date lavas from the Hawaiian islands using the conventional methods of TL dating based on natural TL. He used the fine-grained matrix method that is so successful in dating archeological artifacts, calculating the dose from the composition of the samples and assuming a nominal cosmic ray dose. He claimed success, despite the problem of anomalous fading.

However, somewhat surprisingly he found that the induced TL, which he called the "artificial TL", also increased with time (Fig. 1). He suggested that the samples were undergoing radiation damage that was producing traps.

3. Correlation between induced TL and age

Shortly before May's study, a Swiss group (Houtermans & Liener, 1966), following up on work performed in Russia (Komovsky, 1961), showed that the induced TL of meteorites increased with potassium-argon age and they also attributed this to the production of traps by radiation damage. May cited their work.

The present writer made similar measurements on a suite of ordinary chondrite meteorites, the largest class of meteorites, and also found a correlation between induced TL and potassium-argon age (Sears, 1980). However, in my case the explanation was very clear. The low induced TL meteorites were heavily shocked by an impact between asteroids in space, while the high induced TL meteorites were effectively unshocked. Impacts generate shock waves that compress the material and heat it, so while some minerals show the effect of compression others show the effect of heat. For example feldspar is melted by the heating, so is the metal and sulphides which form eutectics that spread through the meteorite, especially along cracks also formed by the shock event. The effect of these kinds of shock on meteorite and feldspar induced TL have been studied in some detail by Haq et al. (1988), and Hartmetz et al. (1986).

To further confirm that radiation damage is not causing the age-related induced TL changes, meteorites have been exposed to radiation doses comparable or greater than would have been experienced in the age of the solar system. Alpha, beta, and gamma radiation have been used, so have fluxes of protons, and no change in induced TL was produced (Sears, 1980).

It is clear that the correlation between induced TL and age reported by four groups in the 1960s to 1980s is not due to radiation damage, but physical and mineralogical changes in the meteorites that coincidentally include argon loss. Thus instead of thinking of the TL properties as being dependent on radiation and thermal history, as for natural TL, the induced TL is better considered as a petrographic or mineralogical tool, especially when used conjunction with cathodoluminescence. The CL observations can also be combined with microscopic and electron microprobe studies for a better understanding of the geological processes experienced by the samples.

4. Case study I: Induced TL increases due to the production of feldspar

When a suite of ordinary chondrites that had not experienced any significant shock was examined a spectacular range of induced TL levels was observed, the values covered a factor of about 10^5 (Sears et al., 1980). In this case, the values correlated very strongly with parent body metamorphism (Fig. 2).

Metamorphism, heating of rocks in the solid state, usually by virtue of burial, is an important feature of ordinary chondrites and has been recognized in meteorites since the early sixties (Van Schmus & Wood, 1967). Most meteorites have been highly metamorphosed and the internal properties resulting from their original formation have been largely wiped out. However, a few meteorites have escaped this process and contain within them material that was present in the solar nebula before the Sun and planets formed. They constitute a powerful witness of conditions and processes in the early solar system.

Cathodoluminescence and other studies quickly showed the reason for this correlation with metamorphism. The major TL phosphor, feldspar, was absent in the low TL meteorites and present in the high TL meteorites. When the meteorites formed, the feldspathic elements, calcium, aluminum, sodium and so on were in glass that was located in solidified droplets that are characteristic of these solar system materials. During metamorphism this glass crystalizes to form crystals of feldspar.

What is remarkable is not just that this trend exists, but the remarkable sensitivity of the relationship at the low end of the metamorphic sequence. Induced TL is thus a remarkably sensitive effective indicator of the lowest levels of metamorphism which is also most important when trying to disentangle primary properties from the metamorphic overprint.

The changes brought about by metamorphism are both time and temperature sensitive so that what is really measured is the net alteration. Nevertheless, this is useful information. In fact, the induced TL does a little more since there are systematic changes in the shape of the glow curve which depend on the temperature at which the feldspar crystalized and the post metamorphic cooling rate. So there is considerable information by combining the induced TL level and the shape of the glow curve.

Basalts are glass-rich rocks, and thick gloves are worn when handling them. Thus one working hypothesis is that Mays samples were increasing in induced TL with time since the glassy phase was crystalizing over time and this was creating more of the TL phosphor.

5. Case study II: Induced TL increases due to the composition of the feldspar

The eucrites are a class of meteorites quite different from the ordinary chondrites. In fact, they are essentially basalts. They are widely thought to have been formed on the large asteroid Vesta, which has a basaltic surface and metal core

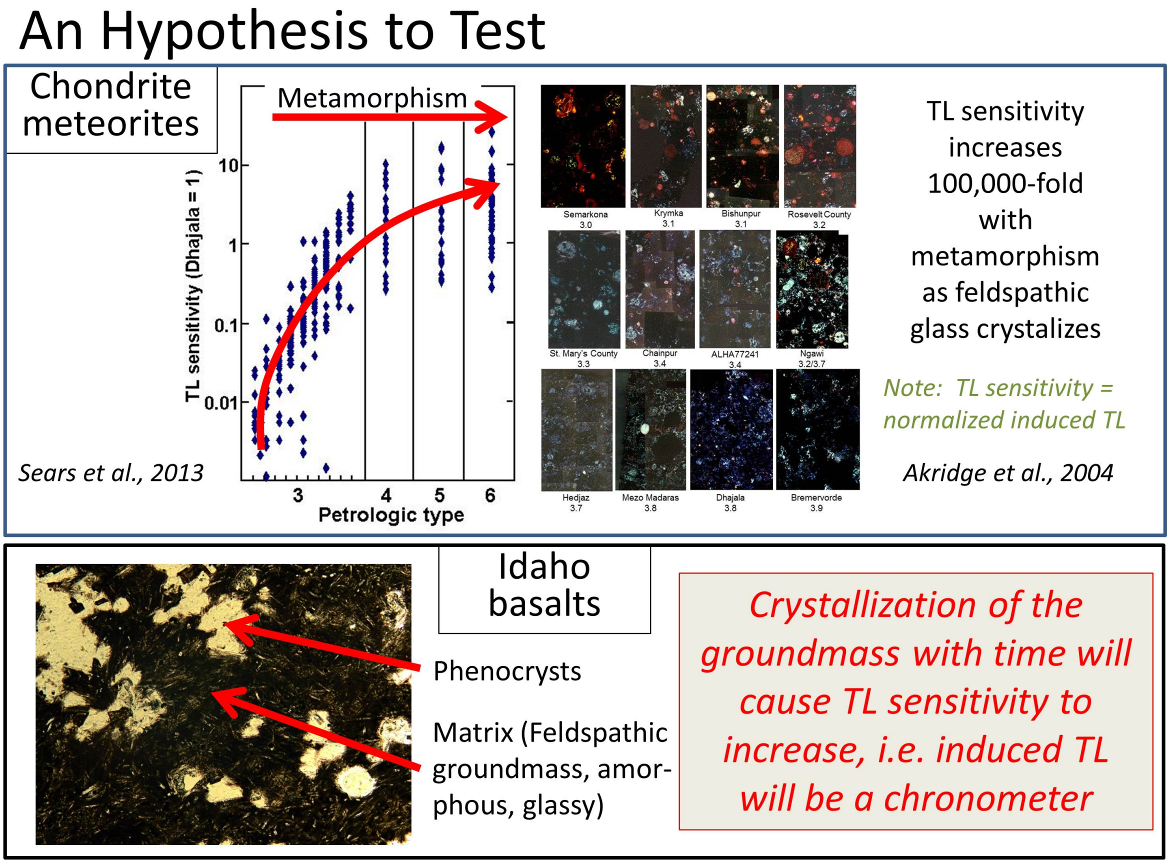

Figure 2. The ordinary chondrite meteorites display a range of alteration due to parent body metamorphism which is described by the "petrologic types", 3 low, 6 high. Thermoluminescence sensitivity increases by a factor of 10^5 over this range of petrologic types (Sears et al., 1980). Cathodoluminescence and other observations indicate that this is due to the formation of the phosphor, feldspar, by the crystallization of glass with feldspathic composition (Akridge et al., 2004; Sears et al., 2013). The analogous situation for the basalts would be the glassy groundmass crystalizing to produce feldspar. This process would be time-dependent and provide a chronometer. The term "TL sensitivity" is used in this and Fig. 3 to mean induced TL of the sample divided the induced TL of a standard meteorite, Dhajala.

(Drake, 2001). In some respects it resembles the Moon, although the details of its igneous history are quite different. However, it is difficult to be sure because of the heavily impacted nature of Vesta's surface. Closely related meteorites are the howardites and diogenites and it is believed the suite of meteorites originated on Vesta, eucrites on the surface, diogenites at depth, perhaps the upper mantle, and the howardites are a mechanical mixture of the two.

Like the chondrites, the eucrites appear to constitute a metamorphic sequence and this has been documented and described in terms of eight "petrologic types". Type 1 has least metamorphic overprint and very heterogeneous mineral compositions; type 8 is most metamorphosed and has homogeneous mineral compositions (Takeda et al., 1983).

The induced TL of a number of eucrites varies over a factor of 100 and correlates with petrologic type (Fig. 3). In this instance, cathodoluminescence and other studies indicated that the cause was not the production of feldspar, but its compositional changes reflecting mineralogical changes caused by metamorphism. In fact, the CL of feldspar in the low type TL was brown/yellow and blotchy while the CL in the high TL samples was a uniform bright yellow. Detailed mineralogical studies showed that that the feldspar in the unmetamorphosed eucrites contained a few percent iron, a known quencher of the TL of feldspar (Geake et al., 1973). With metamorphism, the iron diffused out of the feldspar and moved into other silicate minerals where it was a thermodynamic equilibrium.

Thus we have a second mechanism for explaining May's correlation between induced TL and age. The feldspar in the young basalts contains incompatible quencher elements which diffuse out of the feldspar with time as the rock "equilibrates".

6. Discussion and Conclusions

It is important to keep in mind that rapidly cooled lavas are essentially non-equilibrium assemblages. Thus they contain abundant glass, for instance. Time and elevated temperatures will drive them towards equilibrium, which in our

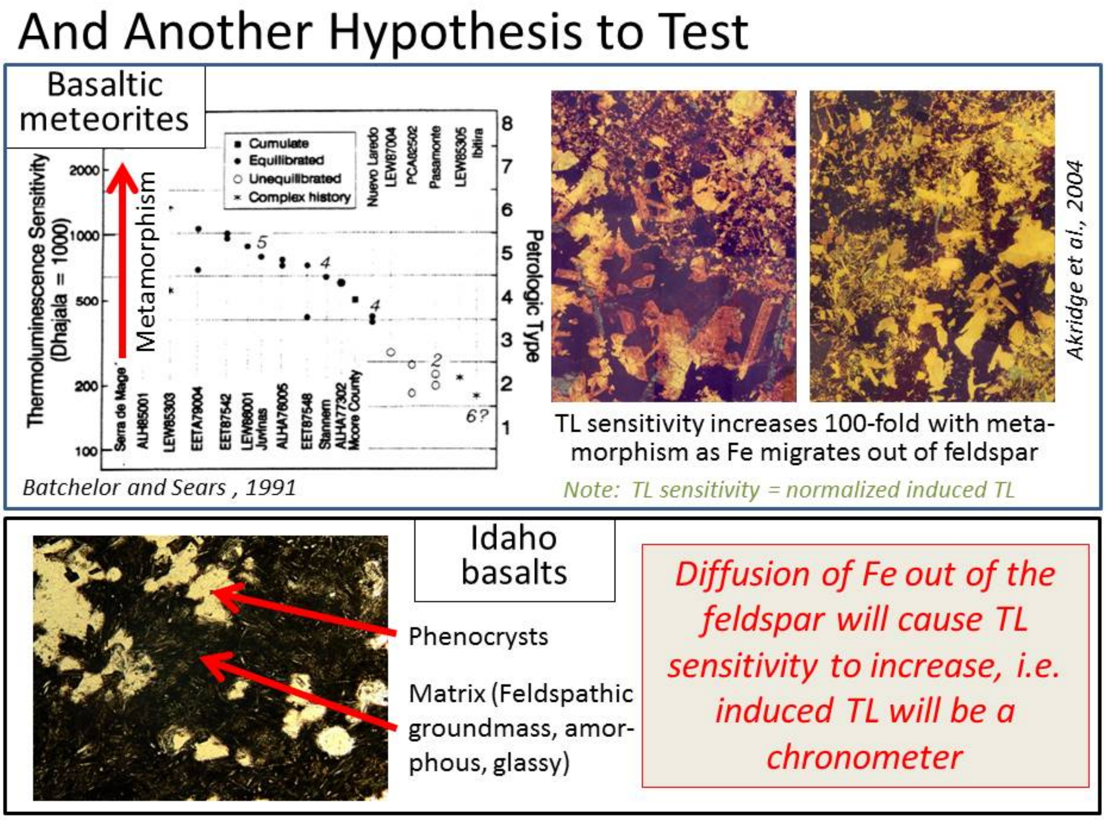

Figure 3. The basaltic meteorites (eucrites, thought to originate on the asteroid Vesta) show a range of metamorphic alteration described by the "petrologic type", 1 low, 6 high. Thermoluminescence sensitivity (induced TL normalized to that of the Dhajala meteorite) shows a factor of 100 range which correlates with petrologic type (Batchelor & Sears, 1991). Catholuminescence images and other data show that this increase in TL sensitivity with metamorphism is a result of Fe diffusing out of the feldspar, little metamorphosed meteorites have feldspar with weak blotchy yellow/brown cathodoluminescence, and highly metamorphosed meteorites have uniform bright yellow cathodoluminescence. Crystals of feldspar in the matrix of terrestrial basalts might increase in induced TL with time as Fe diffuses out of the feldspar.

case means the glass will crystallize and the minerals will achieve "purer" compositions. In the case of terrestrial lavas, once cooled they stay at low temperatures, below 200^{o}C say, so the prime factor controlling the degree of equilibration is time.

It is perfectly possible that both crystallization of the glass and purification the feldspar are playing a part in the time-dependency of the induced TL observed by May. This would not preclude its use as a chronometer. It is possible that by collecting enough data from a variety of sites one could derive an empirical calibration on which to base a technique. Such approaches have been used in the past.

However, it should be possible by performing detailed mineralogical and petrological studies on the basalts of a range of ages to determine whether one of the proposed mechanisms dominates.

It should also be possible to perform laboratory measurements of the kinetics of the process by which induced TL increases. From the kinetics then an absolute dating method should be possible. A variety of sampling sites for the basalts is important because there are many factors that control the rate of equilibration. The amount of water present in the rocks is one, and the composition of the feldspar is another. There are studies of the induced TL properties of the full range of feldspar compositions (Benoit et al., 2001), but not of the kinetics of devitrification of feldspathic glasses.

These are tasks for the future. For the moment I simply wanted to point out that an induced TL procedure might exist for dating lavas that have proved difficult to date using their natural TL because of anomalous fading. Furthermore, this correlation should not be a surprise because similar processes have been found to exist in meteorites, both ordinary chondrites and basaltic meteorites that are, on the face of it, very different rocks. What they have in common is that they all contain feldspar and that feldspar is the dominant luminescent phase in most silicate rocks.

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Reviewer

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